DOE/EE-0834

Vehicle and Systems Simulation and Testing

VEHICLE TECHNOLOGIES OFFICE

2012

annual progress report

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

U.S. Department of Energy

Vehicle Technologies Program
1000 Independence Avenue, S.W.
Washington, DC 20585-0121

Fiscal Year 2012

Annual Progress Report for

Vehicle and Systems Simulation and Testing

Submitted to:
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Vehicle Technologies Program
Vehicle and Systems Simulation and Testing

Lee Slezak, Technology Manager

CONTENTS

I. INTRODUCTION **1**
II. INDUSTRY **12**
PHEV TECHNOLOGY ACCELERATION AND DEPLOYMENT ACTIVITY 12
II.A. Chrysler Town & Country Mini-Van Plug-In Hybrid Electric Vehicle 12
II.B. Ford Plug-in Project: Bringing PHEVs to Market 18
II.C. Development of Production-Intent Plug-In Hybrid Vehicle, using Advanced Lithium-Ion Battery Packs with Deployment to a Demonstration Fleet 24
TRANSPORTATION ELECTRIFICATION 27
II.D. Interstate Electrification Improvement Project 27
II.E. RAM 1500 Plug-In Hybrid Electric Vehicle 32
II.F. ChargePoint America 37
II.G. Electric Drive Vehicle Demonstration & Vehicle Infrastructure Evaluation 41
II.H. Recovery Act – Strategy to Accelerate U.S. Transition to Electric Vehicles 49
II.I. Smith Electric Vehicles Medium Duty Electric Vehicle Demonstration Project 52
II.J. Plug-In Hybrid Electric Medium-Duty Commercial Fleet Demonstration and Evaluation 61
SUPERTRUCK 64
II.K. Technology and System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Trucks 64
II.L. Systems Level Technology Development and Integration for Efficient Class 8 Trucks 70
II.M. Volvo Energy Efficient Vehicle – SuperTruck 73
III. LAB & FIELD VEHICLE EVALUATIONS **77**
LAB & FIELD EVALUATIONS (LIGHT DUTY) 77
III.A. Advanced Vehicle Testing Activity – Light Duty Field and Laboratory Testing 77
III.B. Level 1 Benchmarking of Advanced Technology Vehicles 95
III.C. Extended Level 2 Benchmarking of Advanced Technology LD Vehicles – Peugeot 3008 Hybrid4 105
III.D. Assessment of Conventional Vehicle Technology Baseline 111
III.E. Defining Real World Drive Cycles to Support APRF Technology Evaluations 123
III.F. Evaluation of Existing ANL Benchmark Vehicles at a Range of Temperatures 131
III.G. In-Depth Thermal Testing of PHEV and EV 138
III.H. Electric Drive Vehicle Climate Control Load Reduction 149
III.I. Integrated Vehicle Thermal Management – Combining Fluid Loops on Electric Drive Vehicles 156
III.J. Vehicle Mass and Fuel Efficiency Impact Testing 165
III.K. New York EV Taxi Simulation & Drive Cycle Development 168
TADA LAB & FIELD VEHICLE EVALUATIONS LD 173

III.L. Advanced Vehicle Testing Activity – TADA Test Support to OEM Data Collection.......... 173
LAB & FIELD EVALUATIONS (MEDIUM & HEAVY DUTY) 179
III.M. AVTA Support of USPS Vehicle Electrification Development Activities 179
III.N. Medium and Heavy Duty In-Use Fleet Field Evaluations 183
III.O. Fleet DNA – Common Drive-Cycle Database 193
III.P. MD PHEV/EV Data Collection and Reporting... 198
III.Q. Medium Truck Duty Cycle (MTDC) 206
III.R. Vehicle Systems Integration (VSI) Laboratory 212
IV. MODELING AND SIMULATION 216
LIGHT DUTY MODELING AND SIMULATION.. 216
IV.A. Autonomie Maintenance 216
IV.B. Simulation Runs to Support GPRA 220
IV.C. Fuel Efficiency of CNG Light Duty Vehicles 227
IV.D. GM Volt Vehicle Validation 231
IV.E. HEV Vehicle Level Control Development under Various Thermal Conditions 236
IV.F. Fuel Consumption Benefits of Advanced Engine Technologies 241
IV.G. Optimal Energy Management of a PHEV Using Destination Information, GPS, and Traffic Estimation... 244
IV.H. Impact of Worldwide Test Procedures on Advanced Technology Fuel Efficiency 249
IV.I. Light Vehicle HVAC Model Development and Validation 254
IV.J. Advanced LD Engine Systems and Emissions Control Modeling and Analysis 261
IV.K. Autonomous Intelligent Electric Vehicles.. 267
IV.L. Fuel Consumption Benefit of Low-Temperature, Compression-Ignited Engine for a Conventional Vehicle 273
IV.M. Crosscutting Support Activities (VSATT, LEESS and TSDC) 278
HEAVY DUTY MODELING AND SIMULATION.. 284
IV.N. CoolCab Truck Thermal Load & Idle Reduction 284
IV.O. CoolCalc HVAC Tool 292
IV.P. Advanced HD Engine Systems and Emissions Control Modeling and Analysis 299
IV.Q. Hydraulic Hybrid Vehicle Fuel Consumption Potential.. 305
IV.R. Medium-Duty Electric Drive Vehicle Simulation and Analysis 309
V. COMPONENTS/SYSTEMS EVALUATIONS 318
V.A. Improved Cold Temperature Thermal Modeling and Strategy Development....................... 318
V.B. AVTA EDAB (Battery Mule) Project 325
V.C. PHEV Advanced Series Gen-set Development/Demonstration Activity 332
V.D. PHEV Engine Control and Energy Management Strategy.. 338
V.E. The Meritor Dual Mode Hybrid Powertrain (CRADA) 346

V.F. Impact of Battery Management on Fuel Efficiency Validity ... 352

VI. CODES AND STANDARDS ... 359

VI.A. HEV, PHEV, EV Test Standard Development and Validation ... 359

VI.B. Evaluation and Adaptation of 5-Cycle Fuel Economy Testing and Calculations for HEVs and PHEVs ... 363

VI.C. International Cooperation ... 370

VI.D. Green Racing Initiative ... 374

VI.E. Codes and Standards Support for Vehicle Electrification ... 379

VI.F. SAE Standards Development Support ... 384

VI.G. Grid Connectivity Support ... 391

VI.H. Model Reusability ... 397

VI.I. Green Racing Technical Support ... 403

VII. VEHICLE SYSTEMS OPTIMIZATION ... 410

AERODYNAMIC DRAG REDUCTION CLASS 8 ... 410

VII.A. DOE Project on Heavy Vehicle Aerodynamic Drag ... 410

VEHICLE SYSTEM THERMAL CONTROL ... 420

VII.B. Thermal Control through Airside Evaporative Heat Removal ... 420

VII.C. ANL-Cummins CRADA: "Integrated External Aerodynamic and Underhood Thermal Analysis for Heavy Vehicles" ... 425

VII.D. CRADA with PACCAR – Experimental Investigation of Coolant Boiling in a Half-Heated Circular Tube ... 429

VII.E. Development of Nanofluids for Cooling Power Electronics for HEVs ... 435

FRICTION AND WEAR ... 440

VII.F. Development of High Power Density Driveline for Vehicle Efficiency Improvement ... 440

VII.G. DOE/DOD Parasitic Energy Loss Collaboration ... 445

FAST AND WIRELESS CHARGING ... 452

VII.H. AVTA – Wireless Charging and Other EVSE Data Collection Activities ... 452

VII.I. Mitigation of Vehicle Fast Charge Grid Impacts with Renewables and Energy Storage ... 458

VII.J. Wireless Charging Development/Demonstration ... 461

I. INTRODUCTION

On behalf of the U.S. Department of Energy's Vehicle Technologies Program (VTP), I am pleased to submit the Annual Progress Report for Fiscal Year (FY) 2012 for the Vehicle and Systems Simulation and Testing (VSST) team activities.

Mission

The VSST team's mission is to evaluate the technologies and performance characteristics of advanced automotive powertrain components and subsystems in an integrated vehicle systems context. These evaluations address light-, medium-, and heavy-duty vehicle platforms. This work is directed toward evaluating and verifying the targets of the VTP R&D teams and to providing guidance in establishing roadmaps for achievement of these goals.

Objectives

The prime objective of the VSST team activities is to evaluate VTP targets and associated data that will enable the VTP R&D teams to focus research on specific technology areas. The areas of interest are technologies that will maximize the potential for fuel efficiency improvements, as well as petroleum displacement, and tailpipe emissions reduction. VSST accomplishes this objective through a tight union of computer modeling and simulation, integrated component testing and evaluation, laboratory and field testing of vehicles and systems, vehicle systems optimization, and support for the creation and validation of codes and standards. VSST also supports the VTP goals of fuel consumption reduction by developing and evaluating vehicle system technologies in the area of vehicle ancillary loads reduction.

The integration of computer modeling and simulation, component and systems evaluations, laboratory and field vehicle evaluations, and development and validation of codes and standards for vehicle classes from light-duty to heavy-duty is critical to the success of the VSST team. Information exchange between focus area activities enhances the effectiveness of each activity (illustrated in Figure 1)

Figure 1. VSST Activities Integration – Arrows represent information flow between activity focus areas that enhances effectiveness of individual activities.

An example of beneficial data exchange is the increased accuracy of predictive simulation models for advanced technology vehicles made possible by empirical test data that characterizes a vehicle's real world performance (In the example case Lab & Field Vehicle Evaluations activities feed information to the Vehicle Simulation & Modeling Activity). Another example is that the credibility and scope of Lab and Field Technology Evaluation studies benefit from real world performance data that is collected from thousands of advanced technology vehicles from the Vehicle Electrification Demonstration Projects (under Industry Projects Activity).

Major Accomplishments FY 2012:

1) Quantified the Vehicle Mass Impact on Road Force and Energy Consumption for an Internal Combustion Engine Vehicle (ICE), Hybrid Electric Vehicle (HEV), and a Battery Electric Vehicle (BEV). Coast down and dynamometer testing was conducted on an ICE, HEV, and BEV vehicle at several test weights (both above and below curb weight) to determine the impact of vehicle mass change on road load forces and energy consumption. This was a joint project completed by Idaho National Lab (INL), Argonne National Lab (ANL), and ECOtality North America. It was determined that the mass has a slightly non-linear effect on road load forces (decreased mass resulted in decreased road load force) and powertrain technology (ICE, HEV, BEV) had no measureable impact on changes road load forces. It was determined that energy consumption was significantly impacted by change in vehicle mass for stop and go driving (no significant change for highway driving). The powertrain technology influenced energy consumption impact. The ICE vehicle which has the lowest powertrain efficiency of the three, resulted in the highest net energy consumption change from vehicle mass change. (I.e. the more efficient vehicle means less energy used by the base weight case and therefore less change in energy consumption for a change in mass). A detailed publication is being prepared for SAE World Congress 2013.
2) Performed In-depth Thermal Testing of a Plug-in Hybrid Electric Vehicle (PHEV) and a BEV. Controlled chassis dyno testing performed on 2012MY Chevrolet Volt PHEV and 2011Model Year (MY) Nissan Leaf to determine impact on performance and range with cold ambient temperature (20F) and hot ambient temperature (95F) with solar load. The energy consumption on a UDDS[1] doubled for the BEV at 20F with the cabin temperature setting at 72F. The use of air conditioning at 95F increased the energy consumption by 27%. The research was performed by ANL and focused on reduction of accessory loads that are critical for market success.
3) Performed research to improve the fuel economy of class 8 tractor-trailers through the use of aerodynamics. Lawrence Livermore National Laboratory (LLNL) has designed the most aerodynamic trailer to date based on their research and development utilizing experiments and modeling & simulations. When this new trailer is properly integrated into a more aerodynamic tractor the fuel economy improvements can significantly exceed the DOE target of 10-15% improvement in mpg. Full adoption of this technology into the US class 8 truck population could result in fuel savings of much greater than 5 billion gallons of diesel per year.
4) Developed and performed analysis using the CoolCab Truck Thermal Load & Idle Reduction & CoolCalc HVAC[2] Load Estimation Tool. By changing from black to white paint, the National Renewable Energy Laboratory (NREL) demonstrated a 20.9% decrease in daily long-haul truck sleeper cab rest period air conditioning electrical energy use – which translates into a 16.7% reduction from the standard system battery size. This study also measured an 8.1 °C reduction in cab soak interior air temperature at peak solar load going from black to white paint. These results closely agreed with simulation results from the CoolCalc rapid HVAC estimation tool. The validated CoolCalc model was also used to predict a 2.8°C reduction in average interior air temperature going from blue to an estimated color-matched solar reflective blue paint. These findings have laid the foundation for in-progress testing of advanced paints. A new version of

[1] Urban Dynamometer Drive Cycle (UDDS)
[2] Heating, Ventilation, and Air Conditioning (HVAC)

CoolCalc with expanded capabilities was released to industry partners. NREL performed the work in collaboration with Volvo Trucks, Daimler Trucks, Kenworth Trucks, Oshkosh, E-A-R Thermal/Acoustic Systems, Dometic Environmental Corp., and PPG.

5) Completed Wireless Plug-in Electric Vehicle (PEV) Charging Development/Demonstration Phase 2. Wireless power transfer (WPT) charging of EV's is an emerging technology that is finding widespread and rapid appeal as a safe, convenient and flexible means of charging. Simulation and experimental results on coupling coil performance and efficiency have been presented that show the close association of coil diameter to separation and the shielding benefits of ferrite backed coils. Lessons learned on WPT during the research performed by the Oak Ridge National Laboratory (ORNL) team show the strong influence that the secondary receiver coil, (especially its absence,) has on high frequency (HF) power, inverter output current, and Power Factor (PF).

Approach and Organization of Activities

VSST provides an overarching vehicle systems perspective in support of the technology R&D activities of DOE's VTP and Hydrogen Fuel Cells Technologies Program (HFCTP). VSST uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, verify and benchmark emerging technologies, and validate computer models. Hardware-in-the-loop testing allows components to be controlled in an emulated vehicle environment. Laboratory testing then provides measurement of progress toward VTP technical goals and eventual validation of DOE-sponsored technologies at the Advanced Powertrain Research Facility (APRF) for light- and medium-duty vehicles and at the ReFUEL Facility for heavy-duty vehicles. For this sub-program to be successful, extensive collaboration with the technology development activities within the VTP and HFCTP is required for both analysis and testing. Analytical results of this sub-program are used to estimate national benefits and/or impacts of DOE-sponsored technology development (illustrated in Figure 2.).

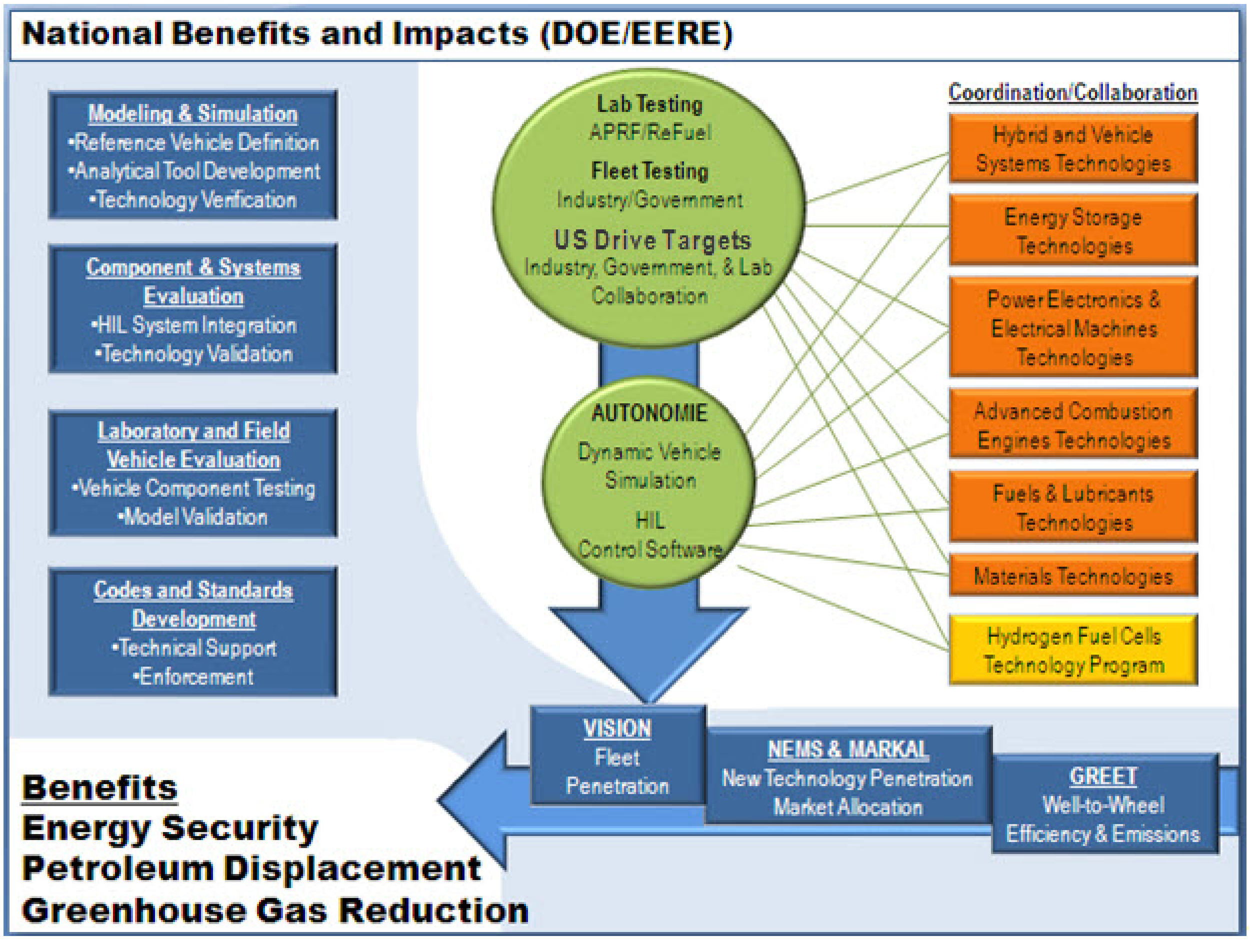


Figure 2. VSST activities providing estimates of national benefits and impacts of advanced technologies.

VSST activities are organized into the six focus areas. A brief description of each focus area and its major accomplishment for FY 2012 are outlined below.

1. *Modeling and Simulation*

   DOE has developed and maintains software tools that support VTP research. VISION, NEMS, MARKAL, and GREET are used to forecast national-level energy, environmental, and economic parameters including oil use, market impacts, and greenhouse gas contributions of new technologies. These forecasts are based on VTP vehicle-level simulations that predict fuel economy and emissions using VSST's Autonomie modeling tool. Autonomie's simulation capabilities allow for accelerated development and introduction of advanced technologies through computer modeling rather than through expensive and time-consuming hardware building. Modeling and laboratory and field testing are closely coordinated to enhance and validate models as well as ensure that laboratory and field test procedures and protocols comprehend the needs of new technologies that may eventually be commercialized.

   Autonomie is a MATLAB-based software environment and framework for automotive control system design, simulation and analysis. This platform enables dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation. Autonomie was developed under a Cooperative Research and Development Agreement (CRADA) with General Motors and included substantial input from other original equipment manufacturers (OEMs), and replaces its predecessor, the Powertrain Systems Analysis Toolkit (PSAT). One of the primary benefits of Autonomie is its Plug-and-Play foundation which allows integration of models of various degrees of fidelity and abstraction from multiple engineering software environments. This single powerful tool can be used throughout all the phases of Model Based Design of the Vehicle Development Process (VDP).

2. *Component and Systems Evaluation*

Hardware-in-the-loop (HIL) simulation provides a novel and cost effective approach to isolate and evaluate advanced automotive component and subsystem technologies while maintaining the rest of the system as a control. HIL allows actual hardware components to be tested in the laboratory at a full vehicle level without the extensive cost and lead time of building a complete prototype vehicle. This approach integrates modeling and simulation with hardware in the laboratory to develop and evaluate propulsion subsystems in a full vehicle level context. The propulsion system hardware components: batteries, inverters, electric motors and controllers are further validated in simulated vehicle environments to ensure that they meet the vehicle performance targets established by the government-industry technical teams.

Through the U.S. DRIVE Vehicle System Analysis Technical Team (VSATT), MATT facilitates interactions between each of the other technical teams by providing a common platform for component integration and testing. Each specific set of technical targets and their impacts on the vehicle and systems can easily be studied using the MATT platform.

High energy traction battery technology is important to the successful development of plug-in electric vehicles (PEVs). To support the evaluation of advanced prototype energy storage systems, in FY 2012 Idaho National Laboratory (INL), with assistance from Oak Ridge National Laboratory (ORNL) continued to developed and implement the Electric-Drive Advanced Battery (EDAB) test platform. This test-bed allows advanced battery packs to be evaluated in real-world operating conditions in an on-road vehicle that emulates a variety of electric-drive powertrain architectures.

3. *Laboratory and Field Vehicle Evaluation*

This section describes the activities related to laboratory validation and fleet testing of advanced propulsion subsystem technologies and advanced vehicles. In laboratory benchmarking, the objective is to extensively test production vehicle and component technology to ensure that VTP-developed technologies represent significant advances over technologies that have been developed by industry. Technology validation involves the testing of DOE-developed components or subsystems to evaluate the technology in the proper systems context. Validation helps to guide future VTP research and facilitates the setting of performance targets.

To date, over 5,400 BEVs, PHEVs, Extented Range Electric Vehicles (EREVs), HEVs, Neighborhood Electric Vehicles (NEVs), fuel cell and hydrogen internal combustion engine vehicles, and propulsion subsystem components have been benchmarked or validated by the VSST team. Combined, they represent more than 100 different electric drive vehicle models. The VSST team has also evaluated the use of more than 5,200 electric vehicle chargers. The results of these evaluations have been used to identify needed areas of improvement for these advanced vehicles and technologies that will help bring them to market faster. They have also been used to identify the most promising new opportunities to achieve greater overall vehicle efficiencies at the lowest possible cost.

The facilities that perform Lab and Field Testing activities include the Advanced Powertrain Research Facility (APRF), INL Transportation Testing Facilities, NREL's ReFuel, and Thermal Test Facilities, and ORNL's Vehicle Systems Integration Lab (VSI).

- The APRF is equipped with-dynamometers (for testing integrated components such as engines, electric motors, and powertrains), and a thermal chamber (for testing BEVs, HEVs and PHEVs in temperatures as low as 20°F, up through 95°F).
- INL's transportation testing facilities encompass the Advanced Vehicle Testing Activity ((AVTA), for Light Duty Vehicles) Facility, the Heavy Duty Transportation Test Facility, and the Energy Storage Technologies Laboratory. AVTA's capability to securely collect, analyze, and disseminate data from multiple field tests located throughout the US is critical to VSST Lab & Field activities.
- NREL's ReFuel facility is equipped with dynamometers (for testing Medium Duty (MD) vehicles and components). NREL's Thermal Test Facilities include capabilities for Light Duty (LD) vehicle cabin thermal studies and outdoor Heavy Duty (HD) vehicle cabin studies. NREL also has facilities for testing subsystems (such as Energy Storage Systems (ESS) and Electric Vehicle Supply Equipment (EVSE)) and functions as the VSST data collection and evaluation hub for MD and HD vehicle fleet tests.
- ORNL's facilities for integrated testing include the Advanced Engine Technologies (E.g. advanced combustion modes, fuels, thermal energy recovery, emissions after-treatment), Advanced Power Electronics and Electric Machines (E.g. motor drives, components, power electronics devices, advanced converter topologies), and Vehicle Testing and Evaluation (E.g. chassis and component dynamometers, integrated powertrain stands, test track evaluations, field operational testing).

The AVTA, working with industry partners, conducts field and fleet testing to accurately measure real-world performance of advanced technology vehicles via a testing regime based on test procedures developed with input from industry and other stakeholders. The performance and capabilities of advanced technologies are benchmarked to support the development of industry and DOE technology targets. The testing results provide data for validating component, subsystem, and vehicle simulation models and hardware-in-the-loop testing. Fleet managers and the public use the test results for advanced technology vehicle acquisition decisions. INL conducts light-duty testing activities. In FY 2012, INL continued its partnership with an industry group led by ECOtality North America. Accelerated reliability testing provides reliable benchmark data of the fuel economy, operations and maintenance requirements, general vehicle performance, engine and component (such as ESS) life, and life-cycle costs. These tests are described below.

Baseline Performance Testing

The objective of baseline performance testing is to provide a highly accurate snapshot of a vehicle's performance in a controlled testing environment. The testing is designed to be highly repeatable. Hence it is conducted on closed tracks and dynamometers, providing comparative testing results that allow "apples-to-apples" comparisons within respective vehicle technology classes. The APRF at ANL is used for the dynamometer testing of the vehicles.

Fleet Testing

Fleet testing provides a real-world balance to highly controlled baseline performance testing. Some fleet managers prefer fleet testing results to the more controlled baseline performance or the accelerated reliability testing.

During fleet testing, a vehicle or group of vehicles is operated in normal fleet (field) applications. Operating parameters such as fuel-use, operations and maintenance, costs/expenses, and all vehicle problems are documented. Fleet testing usually lasts one to three years and, depending on the vehicle and energy storage technology, between 5,000 and 12,000 miles are accumulated on each vehicle.

For some vehicle technologies, fleet testing may be the only viable test method. NEVs are a good example. Their manufacturer-recommended charging practices often require up to 10 hours per charge cycle, while they operate at low speeds (<26 mph). This makes it impractical to perform accelerated reliability testing on such vehicles.

<u>Accelerated Reliability Testing</u>
The objective of accelerated reliability testing is to quickly accumulate several years or an entire vehicle-life's worth of mileage on each test vehicle. The tests are generally conducted on public roads and highways, and testing usually lasts for up to 36 months per vehicle. The miles to be accumulated and time required depend heavily on the vehicle technology being tested. For instance, the accelerated reliability testing goal for PHEVs and BEVs is to accumulate 12,000 miles per vehicle in one year while the testing goal for HEVs is to accumulate 160,000 miles per vehicle within three years. This is several times greater than most HEVs will be driven in three years, but it is required to provide meaningful vehicle-life data within a useful time frame. Generally, two vehicles of each model are tested to ensure accuracy. Ideally, a larger sample size would be tested, but funding tradeoffs necessitate only testing two of each model to ensure accuracy.

Depending on the vehicle technology, a vehicle report is completed for each vehicle model for both fleet and accelerated reliability testing. However, because of the significant volume of data collected for the HEVs, fleet testing fact sheets (including accelerated reliability testing) and maintenance sheets are provided for the HEVs.

4. *Codes and Standards Development*

A comprehensive and consistent set of codes and standards addressing grid-connected vehicles and infrastructure is essential for the successful market introduction of Electric-Drive Vehicles (EDVs). The VTP is active in driving the development of these standards through committee involvement and technical support by the National Laboratories. The VTP also supports activities of the U.S. DRIVE's Grid Interaction Tech Team (GITT), a government/industry partnership aimed at ensuring a smooth transition for vehicle electrification by closing technology gaps that exist in connecting vehicles to the electric grid. In FY 2012, GITT worked with Pacific Northwest National Laboratory (PNNL) and ANL to participate in SAE[3] and NIST[4] standards development for connectivity and communication for grid-connected vehicles.

During FY 2012, VSST supported codes and standards development at the strategic and tactical levels. To help develop a strategy for addressing the needs of a diverse set of stakeholders, VSST supported the development of the Electric Vehicle Roadmap V1.0 by the American National Standards Institute (ANSI). The EV Roadmap V1.0 provides the EV community with a current status of all PEV charging infrastructure/Smart Grid-related standards (and a prioritized list of gaps). VSST supported National Laboratory staff led and served on SAE committees that develop standards including J1772 for connector standards, J2836, J2847, &J2931 for communication standards, and investigations to support development of EV Wireless Charging Standard J2954. VSST supported work with the California Public Utilities Commission (CPUC) to create a framework to implement the accounting for EVs under the Low-Carbon-Fuel Standard Requirements.

The consumer markets for EVs transcend national boundaries. ANL was employed in international cooperative initiatives to adopt international EDV standards and promote market penetration of grid-connected vehicles (GCVs). Many new technologies require adaptations and more careful attention to specific procedures. ANL supported development of interoperability validation procedures of ISO's 15118 Standard. VSST engineers have contributed to the development of many new standards and protocols which have been presented to a wide audience such as U.S. DRIVE partners, other government agencies, the European Commission, and are being adopted as industry standard.

Codes and standards were also developed for sanctioned sporting regulations to stimulate rapid vehicle technology development and to educate consumers about the benefits of fuel efficient technologies. The Green Racing Initiative dramatically increased the number of teams using advanced fuels with significant renewable percentages in ALMS racing to include all but two Grand Touring category cars and two Le Mans Prototype cars. Green Racing worked with the American Le Mans Series (ALMS) to strengthen and improve the visibility of the green racing program through the development of scoring protocols. The Green Racing Initiative supports technology advancement through motorsports competition, and promotes market acceptance of advanced vehicle technologies.

---

[3] Society of Automotive Engineers (SAE)
[4] National Institute of Standards and Technology (NIST)

5. *Vehicle Systems Optimization*

This focus area involves research and development on a variety of mechanisms to improve the energy efficiency of light, medium, and heavy duty vehicles. Projects in this focus area involve reducing the aerodynamic drag of vehicles, thermal management approaches to increase the engine thermal efficiency and reduce parasitic energy losses, the development of advanced technologies to improve the fuel efficiency of critical engine and driveline components by characterizing the fundamental friction and wear mechanisms, and fast and wireless charging technology development.

Aerodynamic Drag Reduction

The primary goal of this focus area is improving the freight-efficiency of vehicles. Aerodynamic drag reduction, thermal management, and friction and wear are the main focuses of this area. Reduction of aerodynamic drag in Class 8 tractor-trailers can result in a significant improvement on fuel economy while satisfying regulatory and industry operational constraints. An important part of this effort is to expand and coordinate industry collaborations with DOE and establish buy-in through CRADAs and to accelerate the introduction of proven aerodynamic drag reduction devices into new vehicle offerings.

The primary approach in drag reduction is through the control of the vehicles flow field. This is can be achieved with geometry modifications, integration, and flow conditioning. During 2012 the goal of the research was to develop and design the next generation of aerodynamically integrated tractor-trailer.

Thermal Management

Thermal management of vehicle engines and support systems is a technology area that addresses reduction in energy usage through improvements in engine thermal efficiency and reductions in parasitic energy uses and losses. Fuel consumption is directly related to the thermal efficiency of engines and support systems. New methods to reduce heat related losses are investigated and developed under this program.

FY 2012 Thermal Management R&D focused on exploring:

A) The possibilities of repositioning the class 8 tractor radiator and modifying the frontal area of the tractor to reduce aerodynamic drag.

B) The possibilities of using evaporative cooling under extreme conditions of temperature and engine load.

C) Nucleated boiling in engine coolant for heavy duty trucks. It is well known that boiling heat transfer coefficients are much higher than the convective heat transfer coefficient of the same fluid. This program is designed to measure the heat transfer coefficient and CHF of several possible coolants, compare the results to theories, and transfer the data to industry.

Friction and Wear

Parasitic engine and driveline energy losses arising from boundary friction and viscous losses consume 10 to 15 percent of fuel used in transportation, and thus engines and driveline components are being redesigned to incorporate low-friction technologies to increase fuel efficiency of passenger and heavy-duty vehicles. Research to improve the fuel efficiency and reliability of critical engine and driveline components included:

- Experimentally investigating fundamental friction and wear mechanisms.
- Modeling and validating the impact of friction on components and overall vehicle efficiency.

- Developing advanced low friction technologies (materials, coatings, engineered surfaces, and advanced lubricants)
- Developing requirements of a high power density driveline system that can be applied across many of the vehicle types regardless of the powertrain or fuel type

Fast and Wireless Charging

Electrification of the transportation sector will be enabled by adoption of vehicle charging technologies that minimize costs in terms of time and money while maximizing energy throughput, battery life, safety, and convenience.

6. *Industry Awards*
   Industry projects for FY 2012 include the categories of PHEV Technology Acceleration Deployment Activities, Transportation Electrification, and SuperTruck. These technology development and demonstration projects were awarded through DOE's competitive solicitation process and involve resource matching by DOE and Industry.

Major projects that were conducted by the National Laboratories and Industry partners in support of these areas in FY 2012 are described in this report. A summary of the major activities in each area is given first, followed by detailed reports on the approach, accomplishments and future directions for the projects. For further information, please contact the DOE Project Leader named for each project.

Future Directions for VSST

Near-term solutions for reducing the nation's dependence on imported oil, such as PHEVs, will require the development, integration, and control of vehicle components, subsystems, and support systems. These solutions will require exploration of high capacity energy storage and propulsion system combinations to get the most out of hybrid propulsion. Analysis and testing procedures at the national labs will be enhanced to study these advanced powertrains with simulation tools, component/subsystem integration, and hardware-in-the-loop testing. DOE-sponsored hardware developments will be validated at the vehicle level, using a combination of testing and simulation procedures.

In FY 2013, the VSST will continue activities in the area of vehicle simulation and modeling, and laboratory and field testing including further baseline performance testing of conversion and original equipment manufacturer (OEM) electric-drive vehicles. Field and laboratory testing will continue to be integrated with modeling/simulation activities, including validation of simulation models for advanced vehicles tested in the APRF. Fleet evaluation of plug-in vehicles will continue, with continued emphasis on evaluation fleets of OEM production vehicles. In FY 2008, DOE VTP issued a solicitation for the purpose of establishing a PHEV demonstration fleet consisting of large volume manufacturers and OEMs as participants. This program launched in FY 2009 and continued in FY 2012.

In addition to the HEV and PHEV activities, a full range of simulation and evaluation activities will be conducted on the BEVs as they are brought to market by OEMs. Because EVs are dependent on a robust charging infrastructure for their operation and ultimate consumer acceptance, VSST will greatly increase efforts to address issues related to codes and standards for EVs, charging infrastructure, and vehicle/grid integration.

VSST will also be deeply involved in the collection and analysis of data from the American Recovery and Reinvestment Act of 2009 (ARRA) Transportation Electrification Demonstration projects. These eight demonstrations will place more than 12,000 electric drive vehicles and 20,000 recharging stations in service, and VSST will direct the collection and analysis of data from these units. In addition to performance, reliability, and petroleum displacement results, VSST will use the data to determine the impact of concentrations of electric dive vehicles on the electricity grid, as well as the changes in operators' driving and recharging patterns as they become more comfortable with this new technology.

Vehicle systems optimization work in the areas of aerodynamics, thermal management, and friction and wear will continue. The focus of these activities will revolve around cooperative projects with industry partners with the goal of bringing developed technologies to market quickly. New efforts will be supported to conduct evaluations of methods to improve thermal heat transfer efficiencies and reduce parasitic loads with coordination from industry partners. Additionally, activities to develop solutions for wireless power transfer and fast charging of electric-drive vehicles, while evaluating the market barriers and technology impacts for deploying this infrastructure, will continue to ramp up within the Vehicle Systems Optimization area.

In order to develop an accurate vehicle cost model for passenger vehicles, VSST identified market costs for technology combinations for new, emerging, and existing light vehicle fuel economy-improving technologies in FY 2012, which will continue and be validated in FY 2013. VSST technologies for advanced power electronics, energy storage, and combustion engines will continue to be validated as each technology closes in on energy efficiency targets.

Inquiries regarding the VSST activities may be directed to the undersigned.

Lee Slezak
Technology Manager
Vehicle and Systems Simulation and Testing
Vehicle Technologies Program

II. INDUSTRY

PHEV TECHNOLOGY ACCELERATION AND DEPLOYMENT ACTIVITY

II.A. Chrysler Town & Country Mini-Van Plug-In Hybrid Electric Vehicle

Principal Investigator: Abdullah A. Bazzi
Chrysler Group LLC
800 Chrysler Drive
Auburn Hills, MI USA 48326-2757
Phone: 1-(248) 944-3093; Email: aab5@Chrysler.com

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

NETL Project Manager: Adrienne Riggi
Phone: (304) 285-5223; Email: Adrienne.Riggi@netl.doe.gov

DOE Award Number: *DE-EE0004529*
Submitted to: *U.S. Department of Energy – National Energy Technology Laboratory*

II.A.1. Abstract

Objective

- Demonstrate 25 minivans (RT) in diverse geographies and climates, spanning from Michigan, California, and Texas and across a range of drive cycles and consumer usage patterns applicable to the entire NAFTA region
- Run the vehicles for 2 years with relevant data collected to prove the product viability under real-world conditions
- Quantify the benefits to customers and to the nation
- Develop & demonstrate charging capability
- Develop and demonstrate Flex Fuel (E85) capability with PHEV technology.
- Support the creation of "Green" Technology jobs and advance the state of PHEV technology for future production integration
- Develop an understanding of Customer Acceptance & Usage patterns for PHEV technology
- Integration of PHEV technology with Renewable energy generation

Major Accomplishments

Vehicle Build & Test

- Utilized the standard Chrysler Group LLC Vehicle Development Process for a production intent program
  - Designed and built all development and test vehicles
  - Augmented development process with modified testing procedures to address specific plug in Hybrid Technologies
- Completed demonstration vehicle build activity in February 2012
- Deployed 23 vehicles to the demonstration partners
- Completed facility based testing: hot static cell, hot drive cell, cold static cell, cold drive cell, altitude chamber, engine dynamometer, transmission dynamometer, NHV cell, EMC cell, end of line, emissions test facility; bench Testing: vibration, SOC, thermal, charge / discharge cycling
- Finalized impact testing: Successfully Completed for FMVSS compliance
- Completed development trips: cold trip (in November 2011), hot trip (August 20, 2012)
- Optimized PHEV Torque Model to accommodate Flex Fuels (E0 to E85) operations

Deployment Fleet

- Decided to withdraw the Chrysler Town and Country Minivan PHEV fleet based on lessons learned from the RAM 1500 PHEV. "This action [was] taken to build upon the lessons from the initial deployment and to concentrate resources and technical development on a superior battery". Although "no similar issues have occurred with the 23 plug-in hybrid minivans deployed as part of a parallel project", The Town and Country Minivan PHEV contains a high voltage battery that contains similar technology to the RAM 1500 PHEV (September 2012)

Future Activities

- Develop a new battery cell to upgrade the high voltage batteries used in the Chrysler Minivan PHEV. These cells are viable for mass production
- Continue vehicle development on a limited basis. Vehicles will be used exclusively for Chrysler LLC future vehicle program development
- Capture vehicle data to support calibration and controls development to increase fuel economy

II.A.2. Technical Discussion. Introduction

The Chrysler Product Creation Process (CPCP) defines the strategy and method used to execute the development of world class vehicles from concept to market. The Chrysler Town & Country PHEV is following the CPCP process. Fundamental principles include:

- Voice of the Customer – Dictates product decisions
- Timeline Compression – Enables speed to market
- Flexibility – Allows for unique vehicle program characteristics
- Consistency of Execution – Facilitates continuous improvement
- Clear Performance Indicators – Drives accountability
- Interdependencies Identified – Aligns activities across functional areas

Approach

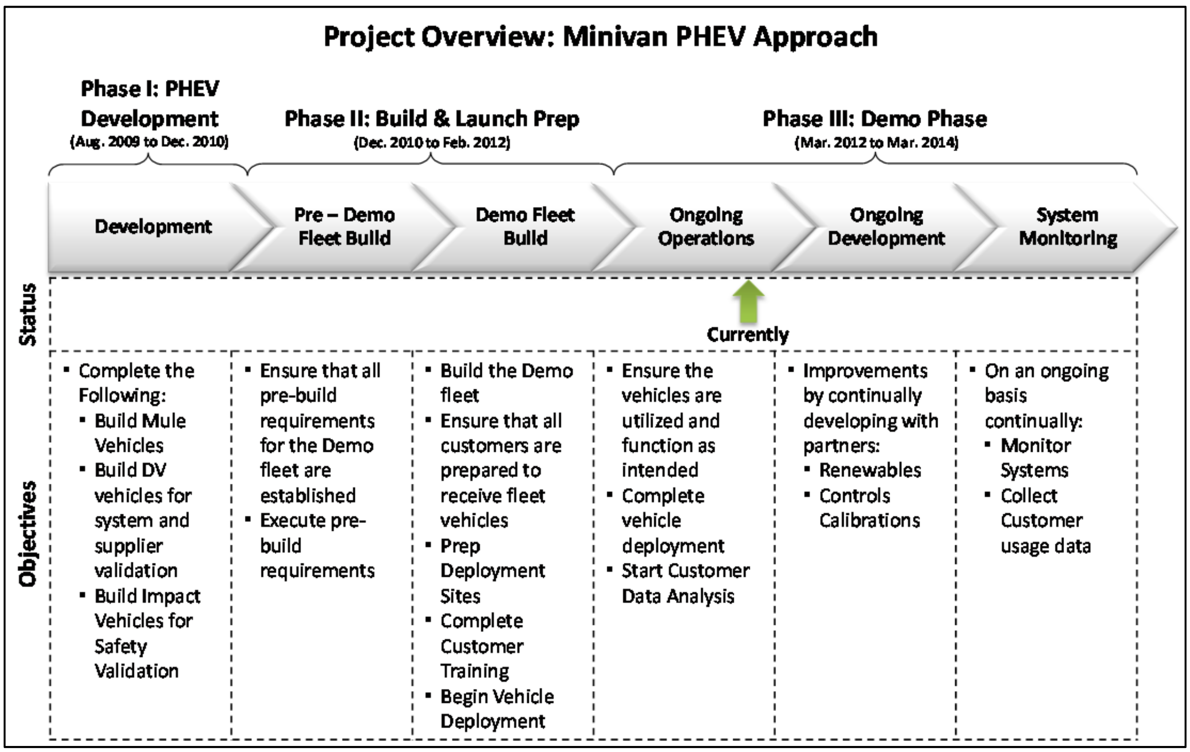


Figure 1. Minivan-PHEV Project Approach.

Results

Federal Test Procedure Results

Table 1. Minivan PHEV Federal Test Procedure Results

	Proposal	Minivan PHEV Status	Procedure
RANGE	22 miles EAER original target; however, DOE agrees to 20 miles EAER target	20 miles EAER; at launch	California Exhaust Emission Standards And Test Procedures, as amended December 2, 2009
EMISSIONS	Tier II Bin 5 Compliance (with both MS8004 & E85 Fuels)	• Complete and passing for T2 Bin 5 with MS 8004 fuel • E85 Testing yielded acceptable levels without margin	CFR Title 40: Part 86 – Control of Emissions from New and In-Use Highway vehicles and Engines; Subpart S.
FUEL ECONOMY	Charge Depleting City -53 MPG (MS8004 Fuel)	**MS 8004 Fuel:** CD CITY Unadjusted: **55 MPG** CD Hwy Unadjusted: 46 MPG CS City Unadjusted: 25 MPG CS Hwy Unadjusted: 34 MPG **E85 Fuel:** CD CITY Unadjusted: 40 MPG CD Hwy Unadjusted: 36 MPG CS City Unadjusted: 18 MPG CS Hwy Unadjusted: 24 MPG	SAE J 1711, Date Published: 2010-06-08. For Test Procedure Guidance. *Reported FE is – Fuel used in CD mode/CD Distance

Real World Results

Minivan PHEV Real-World Results Observed from Vehicles at Partner Locations

	Minivan PHEV Status	Background
FUEL ECONOMY (Real World)	• Charge Depletion: Accumulated Miles – **23,027** – **City**: 33 mpg; **Hwy**: 37 mpg • Charge Depletion / Charge Sustaining: Accumulated Miles – **6,901 (CD) / 26,350 (CS)** – **City**: 26 mpg; **Hwy**: 29 mpg • Charge Sustaining: Accumulated Miles – **66,636** – **City**: 21 mpg; **Hwy**: 28 mpg	• Data taken from 23 partner vehicles deployed throughout the United States • Total mileage : **122,913** (September 2012) • Vehicle fuel economy is based on customer usage and may not be representative of maximum potential fuel economy

Deployment Partner Mileage Accumulation

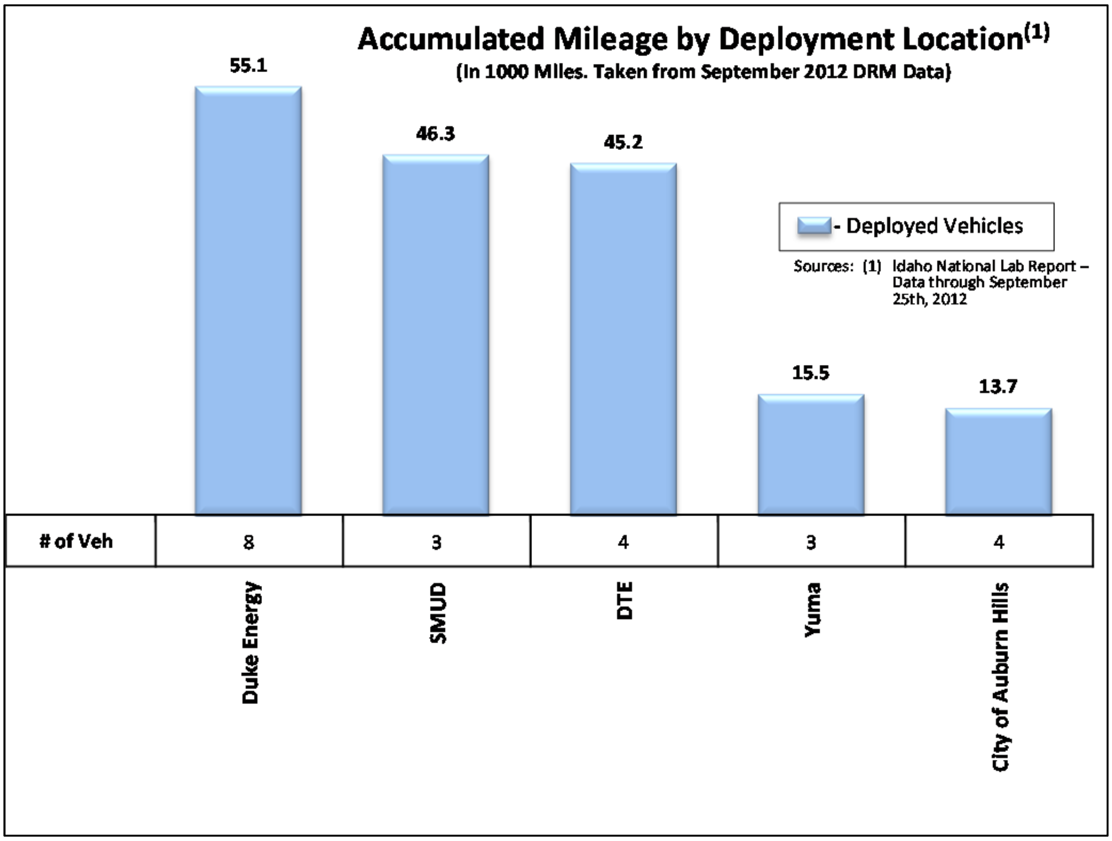


Figure 2. Minivan PHEV Deployment Partner Mileage Accumulation.

Conclusions

Chrysler LLC actively tracked vehicles, and collected vehicle usage and technical data throughout the year. Vehicle Usage Agreements have been finalized and vehicles have been delivered to the following locations:

- City of Yuma, Arizona – 3 vehicles
- Sacramento Municipal Utility District (SMUD) in California – 3 vehicles
- Chrysler Group LLC – 3 vehicles
- Duke Energy in Charlotte North Carolina – 8 vehicles
- City of Auburn Hills, Michigan – 4 Vehicles
- Argonne National Lab (DOE) – 1 Vehicle
- DTE, Detroit, Michigan – 4 Vehicles

II.A.3. Products

Publications

1. A High Efficiency Low Cost Direct Battery Balancing Circuit Using A Multi-Winding Transformer with Reduced Switch Count. IEEE APEC 2012, Orlando, FL, Feb. 5–9, 2012

Public Presentations

1. Annual Merit Review. Washington D.C.

Patents

None to Report

Tools & Data

1. Vector Cantech -- Canalyzer equipment utilized for data collection and software development (communication between vehicle controllers)
2. ETAS -- Equipment utilized for software development and drivability / emissions calibration
3. Security Inspection utilized for upgraded infrastructure environment (increased bandwidth requirements and storage requirements) for implementing Micro strategy vehicle logging and data analysis
4. Bright Star Engineering -- Data Recorder Modules (DRM) for each vehicle and monthly cellular access

II.B. Ford Plug-in Project: Bringing PHEVs to Market

Chris Fortin – Global Electrified Fleet Analyst
Julie D'Annunzio – Global Electrified Fleet Manager
Ford Motor Company
AEC, MD 44
2400 Village Road
Dearborn, MI 48124
Phone: (313) 323-8432 Email: jdannunz@ford.com

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

NETL Project Manager John Jason Conley
Phone: (304) 285-2023, Email: John.Conley@netl.doe.gov

II.B.1. Abstract

Objective

- OVERALL OBJECTIVE: The Ford Escape Plug-in Hybrid (PHEV) Project was started in October of 2008 with an overall goal of identifying a sustainable pathway toward accelerated, successful mass production of plug-in hybrid vehicles. The project objectives were cascaded via four phases:
  - Phase I: Validate and demonstrate plug-in technology on a new, more fuel efficient engine. *Phase I completed in 2009 CY and included the engineering and development of 11 vehicles.*
  - Phase II: Progress battery/controls closer to production intent and demonstrate bi-directional communication and flex-fuel capability. *Phase II completed in 2010 CY and included engineering, development and delivery of additional 10 PHEVs with E85 flexibility*.
  - Phase III: Demonstrate plug-in technology in fleet operation and perform data analysis. *Phase III completed 1Qtr 2011 and included completion of Ford/INL fleet data correlation and algorithm validation.*
  - Phase IV: Continue vehicle demonstrations from Phase III and demonstrate advanced metering interface. *Phase IV - In progress.*
- FY 2012 OBJECTIVE: Complete remaining Phase IV objectives, including final program event and project documentation, as well as initial supplemental program objectives.
  - Complete demonstration of PHEV fleet and support of public information activities
  - Complete vehicle development and testing; complete battery and controls development
  - Complete in-field vehicles service and support
  - Complete data acquisition, analysis and reporting

Major Accomplishments

- The fleet has accumulated over 750,000 miles with data acquisition systems in place and collecting real-world PHEV usage and performance data. Note: Fleet mileage includes pre-deployment mileage accumulated during Ford vehicle development work.
- Over 300 nationwide public outreach activities supported - including auto shows, educational displays and government events in the course of the program
- Updates to the on-board vehicle chargers gave the fleet access to level II 240V EVSE through the installation of SAE J1772 compatible charge ports. Level I 120V charging still possible per project requirements. Fleet upgrades were completed in 1Qtr 2012.

- Electric Power Research Institute (EPRI) has concluded the three affiliated projects: analysis of in-field results of the Escape PHEVs, field demonstration of Smart Meter communication, and creation of a model capable of studying plug-in vehicles as a grid resource.
- NOTE: Ford Escape PHEV fleet utility demonstration project complete December 2012.

Future Activities

- Expansion of project to include three vehicles operating in the 2013 calendar year: one Escape PHEV to be utilized by Ford's Smart and Connected project, and two production PHEVs to be evaluated by the Department of Energy.
- Smart and Connected Project plans to develop and demonstrate new control system concepts in both simulation and hardware which will improve fuel economy and drivability.

II.B.2. Technical Discussion

Background

The Ford Escape PHEV fleet includes 21 advanced research PHEVs deployed to 11 utilities across the US and Canada. Partner utilities include Southern California Edison, Detroit Edison, New York Power Authority, Consolidated Energy, New York State Energy Research & Development Authority, Progress Energy, Southern Company, National Grid, American Electric Power, Pepco Holdings Inc., and Hydro-Quebec. The utility partners utilize the Escape PHEVs in their fleet operations as well as participating in nationwide outreach efforts targeted at education, community and industry/utility events. The Electric Power Research Institute (EPRI) is also a project partner. EPRI coordinates the utility efforts and is leveraging the fleet to conduct vehicle to meter communications interface work.

In June of 2010, the DOE approved a proposal to deploy one Escape PHEV to Ford of China and another to Ford of Europe. In the 2011 CY, these two PHEVs were used to demonstrate Ford electrification technologies to the Chinese and European governments as well as numerous global media and utilities. As shown in Figure 1, the 11 utilities and Ford overseas operations provided a wide geographical area in which to study PHEV technology and operation.

Figure 1. Program Partnership Vehicle Locations.

Vehicle data is collected during fleet operations in order to understand what the vehicles are experiencing in the fleet as well as to assess their infield performance. Driving and charging patterns, fuel and electrical consumption, and influencing factors such as ambient temperature and peripheral electrical loads are being assessed and analyzed.

In 2012 the vehicles were updated with J1772 compatible charge ports. The program was also amended to include testing and implementation of cloud computing capabilities on PHEV19 (Phase IV subtask 4.2). Evaluation of production solutions will be completed by the DOE through the analysis of two production plug-in hybrid vehicles (Phase IV subtask 5.6). In order to facilitate these revisions, the project timing will be extended through December 31st, 2013.

For further information regarding the background and technical specifications of the Escape PHEV fleet, please see the 2011 TADA report.

Introduction

Expanding on the on-road data collection and analysis performed by Ford, program partner EPRI also completed three projects as part of the program activity. These projects focused on the performance of the current Escape PHEV fleet, the potential for communication with the charging hardware, and the fleet-wide potential as a resource to the grid.

The program was also expanded to support Ford's Smart and Connected Project, which aims to develop expanded functionality for plug-in vehicles.

Approach

The Escape PHEV project has been expanded to include support for Ford's Smart and Connected Project. As part of this expansion, an Escape PHEV has been updated for on-road testing of experimental on-road testing of the use of off-board feature computation.

The Smart and Connected project uses cloud based computing and off board information to enhance the fuel economy and drivability of the vehicle. This allows predictive information (e.g. expected route from the navigation system, "green zones" of operation, etc.) to maximize the EV experience and fuel economy. This allows EV operation to be provided at the right time and right location, improving drivability. Cloud-based performance and the accuracy of road information (routes and grade) can also be evaluated through the data received from the vehicle.

In order to perform these functions, the provided Escape PHEV has been modified in several ways. A prototype powertrain control module has been installed, which allows direct modifications to the on-board control system. An additional computer has been installed in the trunk area and is coupled with a secondary monitor installed in the instrument panel. On board connectivity is provided through a mobile hotspot. These additions allow the Vehicle-To-Cloud system to provide a link between the on board control system and the outside world.

Through the use of this vehicle and the program support the Smart and Connected Project plans to develop and demonstrate new control system concepts in both simulation and hardware which will improve fuel economy and drivability.

Results from the Smart and Connected project will be presented in future reports. Results pertaining to the completed EPRI projects are presented in the following section.

Results

Collaboration with the Electronic Power Research Institute has provided insight into vehicle and driver behavior through analysis of the on-road data, the feasibility of bi-directional communication between the vehicle and the charging infrastructure, as well as the potential for vehicle impact on the grid through the creation of a fleet charging aggregator simulation tool.

On-Road Fleet Analysis

(Information made available by Christine Lee, EPRI, clee@epri.com, and Doug Saucedo, EPRI, doug@evosyseng.com)

Data collected to date was analyzed, looking at factors influencing fuel economy and the tradeoff between electricity and fuel use. In order to use the data collected, the trip events were filtered to remove noise and events which did not reflect real-world usage. This included removing impossible events, events which only consisted of a key on/key off cycle, and events shorter than 5 minutes or which travelled less than 0.1 miles. This filtering removed 43.3% of all trip events. However, this removed a minimal amount of drive data, with the analyzed data not including 3.4% of miles, 4.2% of gallons of fuel, and 4.8% of DC kWh of battery consumption.

Eight variables were investigated for their influence on vehicle energy consumption, four each for both fuel consumption and battery energy consumption. These four factors are time since last start-up, vehicle environment (looking at AC usage and ambient temperature), driver aggressiveness, and route type.

Start-up was analyzed comparing time since previous start up against average fuel economy and the drive duration (Figures 2 and 3). The analysis showed that longer charge depleting drives of over 30 minutes experience the highest fuel economy, on average approximately 60 miles per gallon. Similarly, longer charge sustaining drives (20 minutes or longer) experience the highest fuel economy at 40 miles per gallon. However time since last start-up appeared to have a relatively small effect on battery energy consumption.

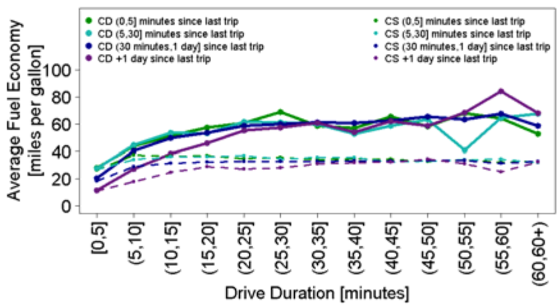


Figure 2. The effect of start up on fuel economy

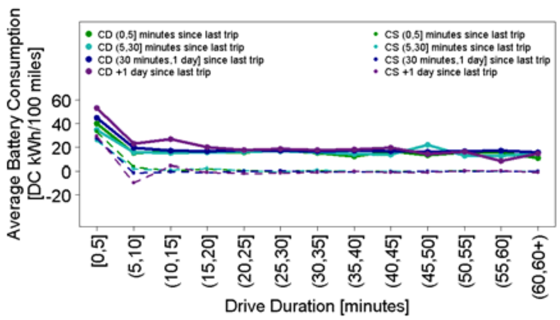


Figure 3. The effect of start up on battery energy consumption

Analyzing the vehicles environments consisted of relating fuel economy and battery energy consumption to the ambient temperature and frequency of air-conditioning usage. No- and low-usage of AC showed increases in fuel economy with increasing temperature, likely due to increased lubrication and decreased fluid viscosity. High-usage of AC delivers reduced fuel economy but also decreases the amount of average battery energy consumed per trip. This is due to the fact the AC is motor driven, forcing the engine on even when the vehicle could otherwise operate on battery power.

Drive aggressiveness was demonstrated comparing average vehicle acceleration to vehicle speed. Fuel economy and battery energy consumption were both maximized around 30 to 35 miles per hour with low acceleration. Fuel economy decreased with increased aggressiveness, however average battery energy consumption was relatively stable across the range of aggressiveness.

Route type used vehicle speed and idle time to group events as congested traffic/delivery routes, city routes, and highway routes. Analysis showed a consistent decrease in fuel economy as the percent idle time increased. For CS operation, low speed trips yield the highest battery energy consumption.

The electricity-fuel trade off was further analyzed using stable energy consumption (Figure 4) analysis, along with the effect of seasonality on vehicle performance and the power load shape of the charging vehicles.

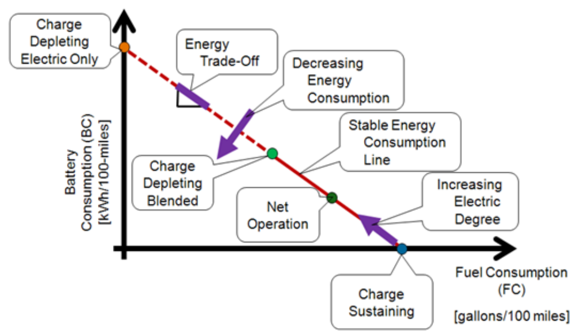


Figure 4. Stable energy consumption characteristics

The energy consumption of a drive event produces an ordered pair comparing the gas consumed and battery energy used during a trip. This allows different usages to be compared by total energy usage and the relationship between electric and gas operation.

The energy trade-off results suggest that highway operation provides a stable environment for the electric drive system to displace fuel consumption. The city events show a higher degree of variation. Overall energy consumption varies little across the seasons, with some increases during colder temperatures (however, this may be within the margin of error).

The charge load shapes similarly show little variation across seasons, but are varied between weekday and weekend (Figure 5).Weekend usage shows reduced daytime charging compared to weekday, which shows two peaks, the first between 10 and 11 A.M. and the second between 9 and 10 P.M.

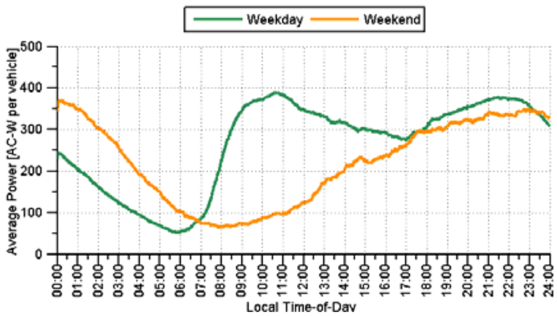


Figure 5. Fleet aggregated load shapes for weekday and weekend.

Overall the aggregated fleet demonstrated between 25% and 45% of the drive energy coming from the battery pack.

Communications Interface

(*Update provided by John Halliwell, EPRI, 942 Corridor Park Blvd. Knoxville, TN 37932*)

One objective of the Escape PHEV project was to research the technical challenges of bi-directional power flow, including communication protocols between the PHEV and the charger. Based on 2011 testing, EPRI demonstrated a response to price signals from the interface, however due to technical limitations the vehicle would not acknowledge a demand response event. For more information, please see the 2011 TADA report.

Fleet Aggregator Tool

(Information made available by Robert Entriken, EPRI, rentrike@epri.com)

The fleet aggregator simulation tool was created to analyze how valuable a plug-in electric vehicle (PEV) can be as a grid resource. During analysis, the tool first ensures each vehicle in the simulated fleet has sufficient battery energy for its scheduled transportation purposes before analyzing the entire fleet's potential to provide energy to the grid. The tool works as an *aggregator*, collecting many small resources (the individual vehicles) and presenting them to the bulk electricity system as a single, large, and potentially distributed resource. EPRI has indicated that the above tool has been completed, and will be used in future EPRI research endeavors.

Conclusions

This DOE sponsored program has:

- Supported the announcement of two mass production PHEV programs in North America and in Europe
- Enabled a nationwide outreach effort including educational, community, and industry/utility events
- Facilitated a deeper understanding of the current and future potential impact of PHEVs on the grid
- Provided a platform for advanced feature development to further increase the capabilities of future PHEVs

The conclusion of the on-road activity of the Escape PHEV advanced research fleet brings with it more than 3 years of data covering more than 750,000 miles, comprising 71,468 drive events and 40,847 charge events. The fleet has successfully demonstrated plug-in hybrid technology, and the ability for the vehicle to respond to price signals. In addition the vehicles have supported over 300 events showcasing the benefits of electrification and the future potential of further plug-in vehicle development.

II.B.3. Products

Publications

1. Idaho National Laboratory – 2010 Ford Escape Advance Research Vehicle – *Baseline Performance (PHEV/America) Testing:* avt.inl.gov/phev.shmtl
2. Idaho National Laboratory – 2010 Ford Escape Advance Research Vehicle – *Summary Results to date*: avt.inl.gov/phev.shmtl
3. Idaho National Laboratory – 2010 Ford Escape Advance Research Vehicle – *2010 Summary Results*: avt.inl.gov/phev.shmtl
4. Idaho National Laboratory – 2010 Ford Escape Advance Research Vehicle – *2011 Summary Results*: avt.inl.gov/phev.shmtl
5. Idaho National Laboratory – 2010 Ford Escape Advance Research Vehicle – *Monthly Summary Results for September 2011, October 2911, November 2011, December 2011 (for additional monthly summary results see library)* avt.inl.gov/phev.shmtl
6. Idaho National Laboratory – 2010 Ford Escape Advance Research Vehicle – *Ford PHEV Report Notes:* avt.inl.gov/phev.shmtl
7. Paper Accepted and Under Development for EVS-26 -- Carlson, R., D'Annunzio, J., Fortin, C., Shirk, M. "*Ford Escape PHEV On-Road Results from US DOE's Technology Acceleration and Deployment Activity*". EVS 26, Los Angeles, California, 2012
8. Plug-in Electric Vehicle Fleet Valuation: Case Study. EPRI, Palo Alto, CA: 2012. 1022643.

II.C. Development of Production-Intent Plug-In Hybrid Vehicle, using Advanced Lithium-Ion Battery Packs with Deployment to a Demonstration Fleet

Principal Investigator: Mr. Greg Cesiel
General Motors
30001 Van Dyke Avenue
Warren, MI 48090
M/C: 480-210-240
Phone: (586) 575-3670; Email: greg.cesiel@gm.com

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee-slezak@ee.doe.gov

NETL Project Manager: Jason Conley
Phone: (304) 904-7590; Email: john.conley@netl.doe.gov

II.C.1. Abstract

Objective

- Overall Objectives
  - The primary goal of the project[5] is to develop the first commercially available, OEM-produced plug-in hybrid electric vehicle (PHEV). The performance of the PHEV is expected to double the fuel economy of the conventional hybrid version of the same vehicle. This vehicle program, which incorporates advanced lithium-ion battery packs and features an E85-capable FlexFuel engine, seeks to develop, fully integrate, and validate the plug-in specific systems and controls by using GM's Global Vehicle Development Process (GVDP) for production vehicles. The Engineering Development related activities include two physical builds that produced 29 mule vehicles and 29 integration vehicles for internal deployment at GM. Continued work includes engineering tasks for the development of a new thermal management design for a second generation battery module.
- FY 2012 Objectives
  - Phase III of the proposed project captures the first half or Alpha phase of the Engineering tasks for the development of a new thermal management design for a second generation battery module. This new design will incorporate reduced complexity, thus allowing for a more cost efficient design. Thermal management of batteries is essential to propulsion system performance. Effective thermal management ensures the maintenance of proper operating temperatures thus increasing range, reliability and durability.

Major Accomplishments

- Two on-site reviews with Department of Energy completed in April and September
- Battery module design
  - Feasibility study finalized
  - Concept selection accomplished
  - Prototype parts procured

[5] Contract ID # DE-FC26-08NT04386

Future Activities

- Once prototype parts are complete, assembly of modules can be accomplished. Testing and further development will continue for critical functions including thermal performance, structural performance and manufacturability. Anticipated outcome will be a refined design based on these results and physical evaluations.

II.C.2. Technical Discussion

Introduction – Engineering Development of Year 1 Mule Vehicles

The first phase of the project captures the first half of the Engineering tasks for the development of key plug-in technologies. This involves the development of components and subsystems required for a PHEV and fully integrate them in a production vehicle.

Approach – Engineering Development of Year 1 Mule Vehicles

This development includes Charge Depletion Development, Lithium-Ion Battery Development, Battery System Integration, Charger Development, Powertrain Systems Integration, and Vehicle Integration.

Results – Engineering Development of Year 1 Mule Vehicles

The PHEV vehicle development team coordinated the above mentioned development testing working towards final designs. At the end of the Mule Vehicle phase, the vehicle packaging and component designs were nearly production intent.

Conclusions – Vehicle and Powertrain Development

All development was completed to the extent required to meet all required Vehicle Technical Specifications (VTS) requirements. This type of development testing will ensure that the vehicle will meet all Federal Motor Vehicle Safety Standards (MVSS).

Introduction – Engineering Development of Year 2 Integration Vehicles

The second phase of the project captures the second half of the Engineering tasks for the development of key plug-in technologies. This involves the development of components and subsystems required for a PHEV and fully integrate them in a production vehicle.

Approach – Engineering Development of Year 2 Integration Vehicles

This development includes Charge Depletion Development, Lithium-Ion Battery Development, Battery System Integration, Charger Development, Powertrain Systems Integration, and Vehicle Integration.

Results – Engineering Development of Year 2 Integration Vehicles

The PHEV vehicle development team coordinated the above mentioned development testing working towards final designs. At the end of the Integration Vehicle phase, the vehicle packaging and component designs are intended to be production intent.

Conclusions – Vehicle and Powertrain Development

All development was completed to the extent required to meet all required Vehicle Technical Specifications (VTS) requirements. This type of development testing will ensure that the vehicle will meet all Federal Motor Vehicle Safety Standards (MVSS).

Introduction – Battery Thermal Development of Alpha Module

Phase III of the proposed project captures the first half or Alpha phase of the Engineering tasks for the development of a new thermal management design for a second generation battery module

Approach – Battery Thermal Development of Alpha Module

The engineering team developed a battery module design based on multiple design concepts. Through detailed design and engineering analysis, a module concept was selected. This design will demonstrated performance requirements. This will be demonstrated through the following testing parameters: thermal, vibration, aging and sealing.

Results – Battery Thermal Development of Alpha Module

A battery thermal module design concepts has been selected. Multiple design refinement has led to parts being procured and testing to being.

II.C.3. Products

Publications

1. Plug-In Charging Symposium (San Jose, CA) - July 22nd, 2008
2. California Air Resources Board (CARB) vehicle demonstration (Milford, MI) – Sept 9, 2008
3. EPA vehicle demonstration (Milford, MI) - Oct 30, 2008
4. Hollywood Goes Green Event - Dec 8, 2008
5. North American International Auto Show (NAIAS) - Jan, 2009

Patents

To date, the project team has generated 31 subject inventions and ten patent applications have been filed. As the contents of these patent applications are not yet subject to public disclosure, GM respectfully refrains from further disclosure regarding these inventions. GM looks forward to sharing the contents of the patent applications once they are publicly available.

Tools & Data

N/A

TRANSPORTATION ELECTRIFICATION

II.D. Interstate Electrification Improvement Project

Principal Investigator: Jon Gustafson
Cascade Sierra Solutions
4750 Village Plaza Loop, Suite 100
Eugene, OR *97401*
E-mail: jgustafson@cascadesierrasolutions.org
DOE Technology Development Manager:Lee Slezak
Phone: (202) 586-2335; Email: lee-slezak@ee.doe.gov
NETL Project Manager: Jason Conley
Phone: (304) 285-2023;Email:John.Conley@netl.doe.gov

II.D.1. Abstract

This demonstration project[6] will accelerate the reduction of petroleum consumption and associated emissions and greenhouse gases by (1) implementing transportation electrification infrastructure at fifty (50) sites along major interstate corridors and (2) providing a 20% rebate incentive for battery operated and/or shore power enabled idle reduction equipment on medium and heavy-duty trucks. Both Truck Stop Electrification (TSE) connections and grid appropriate equipment rebate promotions will be implemented at the travel centers. The project adopted the market title "Shorepower Truck Electrification Project" (STEP) in March, 2011.

Objectives

- Overall Objectives
  - Identify, finalize selection, and secure contracts to build (50) TSE sites.
  - Design and produce build plans for each TSE site.
  - Develop the marketing plan for and introduce the rebate program to the trucking industry.
  - Successfully complete the implementation of the fifty (50) TSE sites.
  - Mark each site opening with an event. Some adjacent sites may hold concurrent events.
  - Successfully distribute all rebates by June 1, 2013.
  - Complete final reporting requirements on time.
  - Responsibly manage Department of Energy funding to accomplish goals of the program.
- Short-term outcomes:
  - The installation and implementation of new, reliable, fuel efficient equipment to support battery operation where feasible and instantly increase fuel economy, maximizing an older trucks environmental performance.
  - Job creation will be tracked and documented through quarterly job reports.
- Medium-term outcomes:
  - Reduce the nation's dependence on petroleum based fuels (9,450,000 gals in 4 years)
  - Reduction in significant amounts of pollution
  - Improve respiratory health of surrounding communities, especially children, the elderly, the poor and minorities who are disproportionately affected by diesel pollution.
  - Reduce heart disease, respiratory disease, asthma attacks, premature deaths, lost productivity and health costs resulting from diesel pollution.

[6] Contract ID# DE-FOA-0000028

- Long-term outcomes:
  - Promoting the use and acceptance of vehicle electrification as a viable alternative to more costly fuel burning choices.

- FY2011 Objectives
  - Complete definitization requirements set in place as a result of DCAA audits.
  - Identify fifty site locations.
  - Launch rebate operations on up to 5,000 truck projects.
  - Set up marketing systems to promote the utilization of grid power to rebated trucks and other fleets that can be recruited to the grid.
  - Initiate the data collection system at installed sites.
  - Formulate a data analysis régime to analyze utilization at the end of the project.

- FY 2012 Objectives
  - Recruit additional trucks/fleets into the project and complete the rebate operations.
  - Identify remaining sites for development to complete the fifty (50) truck stop power distribution goal.
  - Launch marketing systems to promote utilization with the rebated truck fleets.
  - Extend data collection into the installed sites.
  - Form a data collection and analysis alliance with NREL.

Major Accomplishments in 2012

- Operated all DOE Definitization and Administrative Requirements
  - Established job costing and project tracking systems in CSS finance and accounting department for all personnel and operations supporting the DOE grant project.
  - Processed all quarterly reports for Q1 through Q4 on a timely basis.
  - Processed all ARRA reports required by the DOE grant contract.
  - Processed and submitted all management reports to NETL.

- Infrastructure development has progressed toward completion.
  - Contractual relationships between grant recipient and grant sub-contractors operated successfully over the 2012 period. Shorepower and CSS performed contractual agreements to supply pedestals, locate and design, build and accept sites, accomplish grand openings, and operate sites.
  - The project has negotiated and secured site utilization agreements with 67 truck stops/host sites. Of the 67 sites evaluated, 46 have been chosen for development with 17 alternates reserved. These are spread across 31 states along major interstates.
  - Forty-six sites are under construction or complete. The electrical general contractor has completed work on 19 sites with another 27 sites under construction at year. The remaining four sites are being selected from alternates after change outs due to budget issues or failure to meet ARRA and NEPA criteria.
  - All sites are using local subcontractors procured through competitive bid processes prescribed for procurement of construction services using Federal/ARRA guidelines. An estimated 650 vendors and contractors have participated in the project at the subcontractor level to provide construction services and materials to the project.
  - Processes are in place to solicit maximum participation with MBE and DBE.
  - Forty five utility agreements have been reached on the grant project by end of 2012.
  - Seventeen sites are providing power on a free provisional basis.
  - Nineteen sites have completed construction and are in the commissioning stage.

- Thirteen top-bottom site inspections have been completed by CSS with punch-lists issued on ten. Three sites have been accepted as fully operational by CSS.
- Five sites are in the permitting and design stages, primarily as a result of site substitutions. The substitutions have been caused by the inability to reach agreeable business conditions at sites selected earlier in the process. Six sites are awaiting construction starts.
- 278 pedestals have been shipped to sites. Pedestal manufacturing is being performed by Shorepower Technologies.
- Portable HVAC unit design has been finalized and production/assembly of the 100 units has been started at Shorepower Technology in Portland.
- Twenty-four sites have received training for host site personnel. An estimated 150 truck-stop managers and employees have been exposed to the training.
- Software system development has proceeded to the point at which the tracking, billing and payment modules are generally operational. Further refinements are now being made as the sites come on line and the system is being fully exercised. Map: *g.co/maps/5ukja*

- NEPA reviews and approvals were completed on 47 sites in the project.
- Equipment suppliers have provided 3,357 installations to trucks and fleets as a direct result of incentive funding provided from the grant. The number of equipment categories and models are indicated as follows:

Equipment Category	Manufacturers	Models	Units Rebated
Auxiliary Power Units	9	14	1299
Battery A/C Systems	12	25	1020
Thermal Storage Systems	1	2	0
Evaporative Coolers	1	2	60
Trailer TRU & E-hybrid TRU	2	5	726
Straight Truck Refrig Systems	2	2	50
Truck Cold Plate Systems	3	5	195

- 4,197 rebate applications have been processed with value of $8.358 to reach 92% of project goal of $10,544. Approximately 800 applications remain to be committed and completed. About 400 applications are in review with outreach proceeding to recruit the remaining 400.
- A Fleet and Owner-Operator program marketing program has been launched to provide national publicity to the DOE grant project. Surveys were initiated with major fleets from the FleetOwner top 500 Private Fleet List (early 2011) and with smaller refrigerated van fleets (late 2011) to gauge participation at the STEP truck stops.
- E-mail communications and press releases to transportation industry media publications have been launched to keep the project in the public eye.
- STEP Project Website has been created to hold all marketing and project management details. the-step-project.org The content is managed and maintained by Shorepower Technologies (SPT) and CSS, and includes news releases and rebate application information, updates to product showcase, grant opportunities, on-line Rebate Application, STEP program description pages and the current rebate eligible equipment listing page.
- Idle reduction data collection and emission reductions research has been surveyed and settled into a data analysis concept. Initial research was performed throughout 2011 and 2012 to evaluate reliable sources of electrical grid utilization data that can tie to fuel savings from the various equipment categories. Data sources to include pedestal transaction data, telematics used by the fleets, vehicle ECM data and driver logs, records obtained from on-going fleet benchmark tests and blind utilization data from guest (non-rebated) vehicles at the SPT pedestals or obtained from other TSE manufacturer's transaction databases.
- NREL has been engaged as a research support agency for storing and processing the TSE utilization database. Bi-weekly conference calls have guided development of data collection and analysis methodologies, with identification and evaluation of database inputs available from STEP rebate applications.
- Data collection has been initiated at truck stops able to supply electrical power to customers.

- Data extracts of power utilization are being collected at 17 STEP truck stop locations, with additional data sets from 4-5 non-STEP program truck stop locations. Connectivity issues at the truck stop kiosks where power is purchased are being addressed to optimize data capture and validity. Formats for uploading and data transfer have been established to facilitate sharing and reduction of data sets with NREL.
- Working with NREL, initial analysis templates have been defined and preliminary data products to be presented as outputs in quarterly reporting to DOE have been created.
- STEP database of vehicle and vocation profiles, correlated to rebated technology categories, is near completion. STEP IDs have been assigned and distributed for over 2300 rebate projects. Follow-up contact through calls and surveys has provided mechanism for updating/validating database, forging relationships with key contacts for additional data provision, and gathering of information about operational or technical factors impacting initial utilization of power. The remaining IDs will be assigned as installation work is completed.

• Truck Stop Grand Opening Events have been accomplished on 17 sites. CSS providing support for medium and large Grand Openings throughout 2012.
• Promotional TSE connector kits have been procured and distributed at TSE sites and fleets to promote and recruit truckers to the TSE sites. 1,300 connector kits are available through the STEP rebate project but require a different rebate and installation process compared to the other rebated equipment categories
• Marketing has been launched with radio broadcasts, webinars and articles in Transportation Topics and Transportation Latino. the-step-project.org Using a public relationship contractor the project has been featured in no fewer than 70 mentions or feature articles in major trade publications, magazines, and blogs. These activities have achieved awareness for STEP, CSS, Shorepower and their respective roles in Truck Stop Electrification. Launched in social media:
    - truckpr.com
    - truckpr.com/shorepower-technologies
    - facebook.com/shorepowertechnologies

Future Activities

- Complete construction of remaining TSE sites by March 1, 2013. All fifty sites are scheduled for full operation in the project by June 1, 2013.
- Hold grand opening events at all sites. Four openings to be multi-day events featuring vendor fairs with equipment displays of the on-board equipment.
- Complete rebate commitments and installations by December, 2012. Complete distribution of rebate funds by March 1, 2013. Deploy connector kits as incentives to 1,300 truckers coming into the project over 2012 and 2013.
- Launch marketing and promotion to all rebated truckers to promote the adoption of TSE as a key strategy to eliminate idling.
- Form an advisory team made up of leading authorities on idle reduction, emissions, grid power distribution for freight movement and transportation and transportation economics.
- Continue data collection on truck utilization as trucks become equipped along routes hosting TSE sites. Have all trucks in the rebate project on the data collection network by March, 2013.
- Continue tracking utilization data by selected data sorts and begin to study patterns of utilization by June, 2013.
- Review all rebated vehicles to see where there is no utilization and make contact with vehicle owners to launch grid utilization
- Populate the entire database of rebated vehicles/drivers with vehicle and operational data. Preliminary review of the database will reveal topics and correlations of interest for the design of hypotheses to be tested with more specific analyses.
- Develop protocols for quality assurance and quality control of the data.

- Evaluate and select a methodology for a temperature based model for the assignment of engine idle speed (RPM) that will be used to calculate and/or adjust the projected idling fuel use and emissions reductions.
- Collect data and specifications relevant to the assignment of fuel consumption, engine load, and emission factors for engines and idle-reduction equipment.
- Development of methods and measurement techniques to characterize the social, economic, and external variables (e.g. diesel fuel prices) influencing the utilization rates and patterns of fleets and drivers.
- Survey and interview drivers on a quarterly basis to create scientific samples that can be used to supplement, sharpen, and validate power utilization, idle reduction, fuel savings and emissions reduction computations.
- Improve and expand the capability of the program to collect, analyze and interpret the database will continue in an ongoing basis. CSS will enlist the support and expertise of stakeholders and research partners in the design and execution of extended analyses when available.

II.D.2. Technical Discussion

- See STEP website - an information clearinghouse for all target audiences. the-step-project.org
- See awareness promotion products for STEP, CSS, Shorepower and their respective roles in Truck Stop Electrification. truckpr.com and truckpr.com/shorepower-technologies
- Launched and managed social media campaigns: facebook.com/shorepowertechnologies
- facebook.com/CascadeSierraSolutions
- twitter.com/CascadeSierra
- youtube.com/user/CascadeSierra
- See education and awareness campaigns via email and blog with above average open and click rates. the-step-project.org/program-progress/blog
- See map of all existing and future TSE locations.

II.D.3. Products

Patents – None

Publications – None

II.E. RAM 1500 Plug-In Hybrid Electric Vehicle

Principal Investigator: Abdullah A. Bazzi
Chrysler Group LLC
800 Chrysler Drive
Auburn Hills, MI USA 48326-2757
Phone: 1-(248) 944-3093; Email: aab5@Chrysler.com

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

NETL Project Manager: John Jason Conley
Phone: (304) 285-2023; Email: John.Conley@netl.doe.gov

DOE Award Number: *DE-EE0002720*
Submitted to: *U.S. Department of Energy – National Energy Technology Laboratory*

II.E.1. Abstract

Objective

- Demonstrate 140 pickup trucks in diverse geographies and climates, spanning from New York to Arizona & California to Massachusetts, and across a range of drive cycles and consumer usage patterns applicable to the entire NAFTA region
- Verify plug-in charging mode performance based on charger and battery model
- Verify AC power generation mode
- Prove product viability in "real-world" conditions
- Develop bi-directional (communication and power) charger interface
- Support the creation of "Green" Technology jobs and advance the state of PHEV technology for future production integration
- Develop an understanding of Customer Acceptance & Usage patterns for PHEV technology
- Quantify the benefits to customers and to the nation

Major Accomplishments

Vehicle Build & Test

- Utilized the standard Chrysler Group LLC Vehicle Development Process for production intent programs:
  - Designed and built all development and test vehicles
  - Augmented development process with modified testing procedures to address specific plug in Hybrid Technologies
- Completed demonstration vehicle build activity in December 2011
- Increased demonstration partner vehicle deployments to 109
- Completed facility based testing: hot static cell, hot drive cell, cold static cell, cold drive cell, altitude chamber, engine dynamometer, transmission dynamometer, NHV cell, EMC cell, end of line; bench testing: SOC, thermal, charge / discharge cycling
- Completed development trips: cold trip (in November 2011), hot trip (August 20, 2012)
- Completed retrofit of Charge tool box to support Reverse Power Flow (August 2012)
- MicroStrategy was upgraded to allow for faster data retrieval and analysis. Trials of the new "ParAccel" database where successfully completed. Data retrieval rates are now significantly faster. Full implementation to occur in the 4th Quarter of 2012

- All Chrysler defined engineering reports were completed and are online. Also, the ad hoc/customization reporting feature has been implemented

- Interfaces to MicroStrategy for Reverse Power Flow and Scheduled Charging was completed and demonstrated successfully

Deployment Fleet

- Implemented a fleet wide high voltage battery inspection and re-work program was completed. Engineers performed onsite reviews of each of the high voltage batteries to assess performance cross-functionally. Completed in May 2012
- Analyzed battery pack and cells to determine cause of the damaged prototype batteries
- Decided to temporarily withdraw the RAM 1500 PHEV fleet based on lessons learned. "This action [was] taken to build upon the lessons from the initial deployment and to concentrate resources and technical development on a superior battery"

Future Activities

- Develop a new battery cell to upgrade the high voltage batteries used in the RAM 1500 PHEV. These cells used are viable for mass production
- Redeploy a fleet of RAM 1500 PHEVs with upgraded battery technology
- Work with our development partners to develop rate based vehicle charging controls
- Continue developing Bi-directional (communication and power) charging
- Capture vehicle fleet data to support calibration and controls development to increase fuel economy

II.E.2. Technical Discussion

Introduction

The Chrysler Product Creation Process (CPCP) defines the strategy and method used to execute the development of world class vehicles from concept to market. The RAM 1500 PHEV is following the CPCP process. Fundamental principles include:

- Voice of the Customer – Dictates product decisions
- Timeline Compression – Enables speed to market
- Flexibility – Allows for unique vehicle program characteristics
- Consistency of Execution – Facilitates continuous improvement
- Clear Performance Indicators – Drives accountability
- Interdependencies Identified – Aligns activities across functional areas

Approach

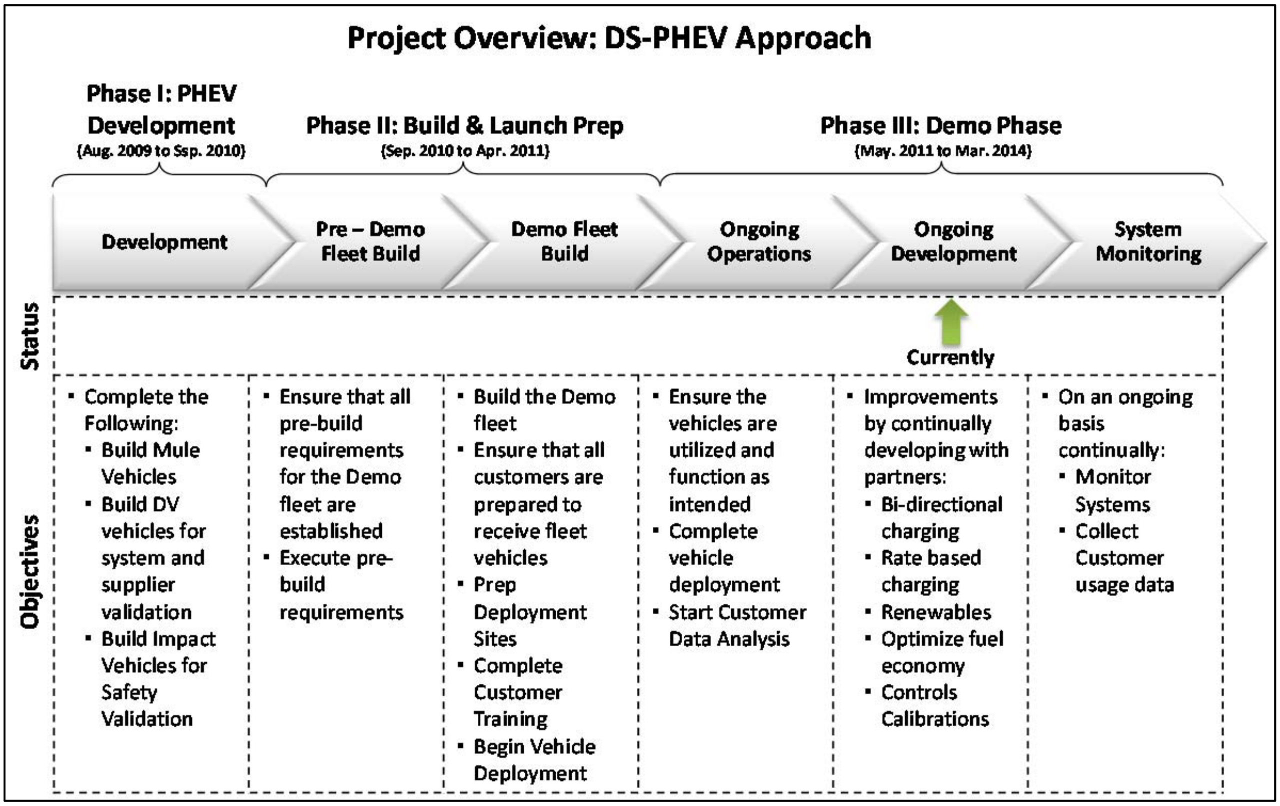


Figure 1. RAM 1500 PHEV Project Approach.

Results

Federal Test Procedure Results

Table 1. RAM 1500 PHEV Federal Test Procedure Results

<table>
<tr><th></th><th>Proposal</th><th>DS-PHEV Status</th><th>Procedure</th></tr>
<tr><td>RANGE</td><td>Equivalent All Electric Range (EAER) of 20 miles</td><td>20+ miles EAER achieved</td><td>California Exhaust Emission Standards And Test Procedures, as amended December 2, 2009</td></tr>
<tr><td>EMISSIONS</td><td>ATPZEV Compliance</td><td><table>
<tr><th>Test</th><th>Test Mode</th><th>Standard</th><th>Results</th></tr>
<tr><td>FTP City</td><td>CD & CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>US06</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>SC03</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>Highway</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>50 F City</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>20 F Cold</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>Evaporative</td><td>CS</td><td>PZEV</td><td>Passed ✓</td></tr>
<tr><td>Purge Volume</td><td>CS</td><td>PZEV</td><td>Passed ✓</td></tr>
</table></td><td>California Exhaust Emission Standards And Test Procedures, as amended December 2, 2009</td></tr>
<tr><td>FUEL ECONOMY</td><td>Charge Depleting City 32 MPG</td><td>– Charge Depletion:
– City: 37.4mpg
– Hwy: 32.5 mpg</td><td>SAE J 1711 as published</td></tr>
</table>

Real World Results

Table 2. RAM 1500 PHEV Real-World Results Observed from Vehicles at Partner Locations

	DS-PHEV Status	Background
FUEL ECONOMY & Mileage Accumulation (Real World)	— Charge Depletion: Accumulated Miles – **230,741** – **City**: 22 mpg; **Hwy**: 26 mpg — Charge Depletion / Charge Sustaining: Accumulated Miles – **88,728 (CD) / 155,504 (CS)** – **City**: 19 mpg; **Hwy**: 21 mpg — Charge Sustaining: Accumulated Miles – **564,843** – **City**: 16 mpg; **Hwy**: 19 mpg	— Data taken from 109 partner vehicles deployed throughout the United States — Total mileage : 1,039,138 (September 2012) — Vehicle fuel economy is based on customer usage and may not be representative of maximum potential fuel economy

Deployment Partner Mileage Accumulation

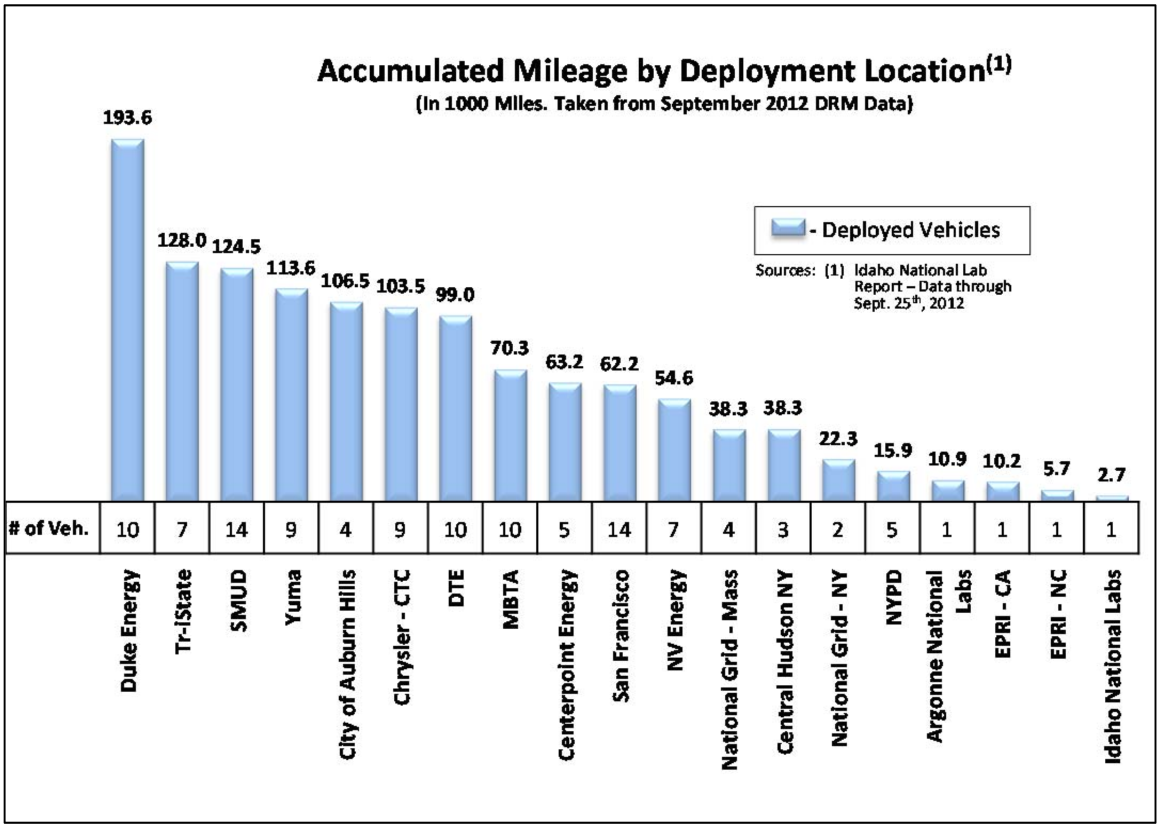


Figure 2. RAM 1500 PHEV Deployment Partner Mileage Accumulation.

Conclusions

Chrysler actively tracked vehicles, and collected vehicle usage and technical data throughout the year. Vehicle Usage Agreements have been finalized and vehicles have been delivered to the following locations:

- City of Yuma, Arizona – 10 vehicles
- Sacramento Municipal Utility District (SMUD) in California – 14 vehicles
- City of San Francisco in California – 14 vehicles
- Duke Energy in Charlotte North Carolina – 10 vehicles
- Central Hudson in Albany, New York – 3 vehicles.
- National Grid placed vehicles in New York, Massachusetts & Rhode Island – 6 Vehicles
- Massachusetts Bay Transit Authority (MBTA) – 10 Vehicles
- City of Auburn Hills, Michigan – 4 Vehicles
- EPRI (North Carolina and California) – 2 Vehicles
- CenterPoint, Houston, Texas – 5 Vehicles
- Argonne National Lab (DOE) – 1 Vehicle
- Idaho National Lab (INL) – 1 Vehicle
- NV Energy, Las Vegas and Reno , Nevada – 7 Vehicles
- DTE, Detroit, Michigan – 10 Vehicles
- NYPD, New York – 5 Vehicles
- TriState, Colorado – 7 Vehicles

II.E.3. Products

Publications

1. A High Efficiency Low Cost Direct Battery Balancing Circuit Using A Multi-Winding Transformer with Reduced Switch Count. IEEE APEC 2012, Orlando, FL, Feb. 5 – 9, 2012
2. Hybrid / Plug-in-Hybrid Technology Overview – Torque Feed forward Control for IPM Motors

Public Presentations

1. Annual Merit Review. Washington, D.C.

Patents

None to Report

Tools & Data

1. Vector Cantech -- Canalyzer equipment utilized for data collection and software development (communication between vehicle controllers)
2. ETAS -- Equipment utilized for software development and drivability / emissions calibration
3. Security Inspection utilized for upgraded infrastructure environment (increased bandwidth requirements and storage requirements) for implementing Microstrategy vehicle logging and data analysis
4. Bright Star Engineering -- Data Recorder Modules (DRM) for each vehicle and monthly cellular access

II.F. ChargePoint America

Principal Investigator: Richard Lowenthal
Coulomb Technologies, Inc. d/b/a ChargePoint
1692 Dell Avenue
Campbell, CA 95008
Phone: 408-841-4501 Email: Richard.Lowenthal@chargepoint.com

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-8055; Email: Lee.Slezak@ee.doe.gov

NETL Project Manager: John Jason Conley
Phone: (304) 285-2023; Email: John.Conley@NETL.DOE.GOV

II.F.1. Abstract

Objective

- CHARGEPOINT® AMERICA will demonstrate the viability, economic and environmental benefits of an electric vehicle charging infrastructure. With the arrival of electric vehicles (EVs) and plug in electric vehicles (PHEVs) late 2010, there is a substantial lack of infrastructure to support these vehicles. CHARGEPOINT AMERICA will deploy a charging infrastructure in ten (10) metropolitan regions in coordination with vehicle deliveries targeting those same regions by our OEM program partners: Chevrolet, BMW, THINK, Nissan, CODA, Fisker, Tesla, Ford and smart USA. The metropolitan regions include Austin/San Antonio (TX), Bellevue/Richmond (WA), Boston (MA), Southern Michigan, Los Angeles (CA), New York (NY), Orlando/Tampa (FL), Sacramento (CA), San Francisco/San Jose (CA) and Washington (DC). CHARGEPOINT AMERICA will install more than 4000 Level 2 (220v) SAE J1772™ compliant, UL Listed networked charging stations in home, public and commercial locations to support more than 2000 program vehicles. ChargePoint will collect data to analyze how individuals, businesses and local governments are using their vehicles. Understanding driver charging behavior patterns will provide the DOE with critical information as EV adoption increases in the United States. Deployment of the charging station infrastructure has begun in July 2010.
- The project will provide public and private Level 2 charging stations from which data will be collected and forwarded to INL for compilation and analysis. The project will leverage other company efforts and infrastructure. The project is also working with the local press to expand awareness and receptivity. The first phase of the program, which began in June 2010, involved the deployment of the charging stations. Phase 2 will have a two-year duration, during which time data will be collected concerning the times of highest charging, charging rates, and load on the grid.

Major Accomplishments

- We are extremely pleased with the progress of the program and met the 2000 program vehicles milestone and installed more than 4050 charging stations. We are fully allocated our supply of stations and are no longer accepting applications for free residential and public charging stations. More and more EVs in our program were available (BMW, Fisker, Nissan, CODA, THINK and Ford) and home stations have been provided to qualified vehicle owners.
- ChargePoint America program deployed over 4050 charging stations.
  - Public committed - 100%
  - Public shipped - 100%
  - Private Committed - 100%
  - Private shipped – 100%
  - Installed public and residential charging stations over 4050
  - Met 2000 program vehicles milestone

- Public stations are fully assigned.
  - Boston region (City of Boston, MBTA, National Grid, MassPort, etc.)
  - New York region (Edison Parking, GMC Parking, Icon Parking, NYPD, NY DOT, Stony Brook University, Rutgers, LaGuardia/Kennedy Airports)
  - DC/Baltimore Region (DC DOT, City of Baltimore, University of Maryland, VA Tech, Verizon, Dulles/Reagan Airport)
  - Detroit region (Detroit, Dearborn, Flint, Consumers Energy, Michigan State, Whirlpool, Compuware, GM, UAW, Mercedes, Kohl's, Lansing)
  - Orlando/Tampa region (OUC, Orlando, Tampa, Marriot, Best Western, UCF, USF, AAA, Dali Museum, Give Kids the World, Hyatt)
  - Austin/San Antonio region (Walmart, HEB, Kohl's ERCOT, Port of San Antonio, Wyndham, Dell Children's Hospital, Austin Energy, CPS Energy)
  - Bellevue/Redmond region (City of Redmond, City of Bellevue, Tacoma, Valley Medical, University of Washington, Microsoft, Honeywell etc.)
  - Los Angeles region (Irvine Company, UCLA, CSUF, CSULA, Cities of Orange, Burbank, Anaheim, Ventura, Riverside, UCSB, Caltech)
  - Sacramento region (UC Davis, County of Sacramento, USAA, California Department of General Services, Marriott)
  - San Francisco region (City of San Francisco, City of San Jose, City of Oakland, SFO Airport, SunPower, Bloom Energy, Stanford University, UCSF, County of Marin)
  - Residential stations are fully assigned through OEM customers and MDU's
  - Chevrolet
  - Ford
  - smart USA
  - BMW
  - Nissan
  - CODA
  - THINK
  - Fisker
  - Tesla
  - Multi-Dwelling Units in California, New York and Boston
- We stopped accepting applications for the residential program and reached out to all customers who applied. We communicated to applicants, that they would be placed on a wait list. The ChargePoint America web site was updated with this information.
- In April 2012, ChargePoint announced the completion of more than 2400 shipments of its public and commercial charging stations for electric vehicles through its ChargePoint America program. ChargePoint has seen exceptional demand in all 10 regions of the program and is finalizing the installation of charging stations within these regions.
- ChargePoint announced that it has partnered with BMW for its unique, premium electric vehicle (EV) car-sharing service program in San Francisco. ChargePoint connects the new charging stations throughout San Francisco, Burlingame, Palo Alto and Oakland. BMW recently announced its DriveNow and ParkNow programs, which provide drivers the opportunity to experience BMW's first all-electric vehicle, the BMW ActiveE with zero-emission driving.
- ChargePoint announced its latest mobile application for iPhone and Android smart phones. Available for free, the updated ChargePoint app provides electric vehicle drivers direct access to their social network accounts including Facebook and Twitter. Drivers can easily upload check-ins, and comments to Facebook from the more than ten thousand charging spots in the United States. The mobile 'charging station' app continues to provide the ability to locate, check availability, and reserve a charging station,. The app lists detailed station information including pricing and status of your home charging station. ChargePoint provides the industry's first and only mobile app

that give drivers real-time charging station status, reservations, smartphone payments, location information and navigation.

- ChargePoint announced the availability of the ChargePoint 4.0 platform for electric vehicle drivers and charging station owners. ChargePoint 4.0 is a free upgrade for all ChargePoint account holders and is now live for all station owners and drivers. For station owners, ChargePoint 4.0 is a groundbreaking release with new features including: patent-pending ChargePoint Connections, support for multi-site deployments, and additional pricing models for charging services. ChargePoint 4.0 optimizes management workflows, allowing station owners to operate more efficiently and with less effort while maintaining tight control over access and management rights.

Future Activities

ChargePoint is planning to wrap up installations of the residential and public charging stations in 2012 and we will continue with data collection and reporting until the end of the program.

- Public charging stations deployment will be completed in 2012.
- Residential program deployment will be completed in 2012.
- Continue to coordinate completion of the remaining 500 installations.
- Data collection and reporting will continue and data will be uploaded to INL on a regular basis.
- INL will continue to provide CPA reports.

II.F.2. Technical Discussion

- All charging stations data is regularly forwarded to Idaho National Labs for analysis and summary. INL released first report on ChargePoint America program in November 2011. The vehicle charging infrastructure summary report provides information on:
  - Charging unit by state
  - Charging units installed to date
  - Number of charging events performed
  - Charging unit usage by type (residential, commercial and public stations)
  - Electricity consumed (AC MWh)
  - Percent of time with a vehicle connected
  - Percent of time with a vehicle drawing power
  - Charging availability
  - Charging demand
- Commercial and Residential EVSE report:
  - Number of charging events
  - Charging energy consumed
  - Percent of time with a vehicle connected to EVSE
  - Percent of time with a vehicle drawing power from EVSE
  - Average number of charging events started per EVSE per day
  - Charging availability
  - Charging demand
  - Average length of time with a vehicle connected per charging event
  - Average length of time with a vehicle drawing power per charging event
  - Average energy consumed per charging event
- ChargePoint 4.0 New features include:
  - A new driver experience with enhanced workflows and a great new look.
  - ChargePoint Connections delivering a new concept that provides businesses the ability to market to the large and growing ChargePoint driver community.
  - Simplified administration for any station owner configuring access control or preferred pricing.
  - Multi-site deployment support allowing organizations to view and manage their charging stations worldwide from a single location and login. At the same time, organizations can grant selectable levels of control over any group of stations to local installation and support teams.

- New pricing options in flex billing include combined hourly and kWh pricing (where allowed) and the ability to change the hourly rate if a driver is plugged in longer than a specified amount of time
- Advanced analytics engine for reporting and analyzing key station metrics.
- A new administration model with Rights Granting allowing station owners to outsource some or all of the tasks of managing their charging stations to third parties.
- New web services APIs that provide unified access to development resources, along with "Push Event" subscription services to improve application efficiency.

Figure 1. Number of Charge Point Chargers by Location.

Detailed ChargePoint product information can be found at: chargepoint.com/products

Watch the new ChargePoint 4.0 Services Video located here:
chargepoint.com/chargepoint-servicesvideo

Sample ChargePoint customer list can be found at: chargepoint.com/ecosystem-stats
Number of Charge Point Chargers by Geographic Location Map

II.F.3. Products

Patents

1. We did not file any patents using DOE funds.

Below is a map of all the publicly available charging stations:

Below are links to press releases, media coverage, events, and photo gallery.

chargepointamerica.com/press-releases
chargepointamerica.com/press-coverage

II.G. Electric Drive Vehicle Demonstration & Vehicle Infrastructure Evaluation

Principal Investigator: Donald Karner
ECOtality North America
430 S. 2nd Avenue
Phoenix, AZ 85003-2418
Phone: (602) 345-9000; Email: dkarner@ecotality.com

DOE Manager, Vehicle Systems
Vehicle Technologies Program: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

NETL Project Manager: John J. Conley
Phone: (304) 285-2023; Email: John.Conley@netl.doe.gov

II.G.1. Abstract

Objectives

- Overall Objectives
  - The objective of the Electric Drive Vehicle Demonstration and Vehicle Infrastructure Evaluation[7] is to use production electric vehicles (EVs) to develop, implement, and study techniques for optimizing the effectiveness of infrastructure supporting widespread EV deployment. It will utilize the deployment of these 'production' plug-in EVs for the purpose of evaluating and/or optimizing (1) vehicle use, (2) charge infrastructure utilization, (3) charging interface with smart grid operations, and (4) charge infrastructure sustainability models.
  - This project is scheduled to collect and evaluate data from vehicles and charging infrastructure through December 2013. It was awarded to Electric Transportation Engineering Corporation (now doing business as ECOtality North America, referred to in this document as ECOtality) at the end of September 2009.
- FY 2012 Objectives
  - Deploy approximately 8,000 Level 2 residential electric vehicle supply equipment (EVSE) units.
  - Deploy approximately 5,200 Level 2 EVSE and DC fast chargers in non-residential locations in order to characterize charging infrastructure and vehicle use in diverse topographic and climatic conditions.
  - Collect data from up to 8,300 Nissan Leaf EVs, General Motors Volt EREVs, and Smart EVs

Major Accomplishments to Date

- 5,560 Level 2 Residential EVSE installed
- 2,487 Level 2 Commercial EVSE installed (publicly accessible, fleet, workplace)
- 37 DC Fast Chargers (DCFC) installed
- Data collected from 5,631 vehicles
- Documented 41.6 million test miles and recorded data on 1.2 million charging events
- Networked location maps available via mobile apps
- "Over the Air" software updates
- Access fee administration for open access to EVSE network

Future Activities

- Deploy up to 2,440 additional Level 2 Residential EVSEs

[7] Contract ID# DE-EE-00002194

- Deploy up to 2,676 additional Level 2 Commercial EVSEs and DCFCs
- Continue accumulating both vehicle and EVSE use data
- Report recharging and vehicle use patterns
- Report petroleum reduction impact of the recharging infrastructure and vehicles
- Evaluate and report on various revenue streams from deployed EVSE including access fees, advertising, memberships, etc.

II.G.2. Technical Discussion

Introduction

The EV Project is an American Recovery and Reinvestment Act (ARRA) funded Department of Energy (DOE) project for deploying and testing plug-in electric vehicles (PEV) and the recharging infrastructure. Led by ECOtality, it is the largest deployment and testing of EVSE and fast chargers ever attempted. Approximately 13,200 Level 2 EVSE and DCFCs, along with approximately 8,000 Nissan Leafs and Chevrolet Volts are being deployed in the major population areas of:

- Phoenix and Tucson, Arizona
- San Diego, San Francisco and Los Angeles, California
- Atlanta, Georgia
- Chicago, Illinois
- Portland, Eugene, Salem and Corvallis, Oregon
- Philadelphia, Pennsylvania
- Seattle, Washington
- Nashville, Knoxville, Chattanooga, and Memphis, Tennessee
- Dallas, and Houston, Texas
- Washington, D.C.

The project intent is to deploy Level 2 EVSE in the residents of each Leaf or Volt purchaser in the project areas, deploy Level 2 EVSE and DCFCs in public locations in order to characterize charging infrastructure and vehicle use in diverse topographic and climatic conditions, evaluate the effectiveness of public versus private charge infrastructure, and conduct trials of various revenue systems for public charge infrastructures. The Smart EVs are all rental cars, so there is no residential EVSE associated with these vehicles.

Approach

The locations for commercial and public charging infrastructure in the project's original five markets were determined through a series of stakeholder reviews that involved organizations such as local government, electric utilities, local employers, large retailers, and other stakeholders with interest in deploying charge infrastructure. Level 2 EVSE and DCFCs are being installed using a Certified Contractor Network (CCN). Novel charge infrastructure and vehicle use demonstrations will be undertaken to evaluate solar-assisted charging, subscription public charging, vehicle rental, and transportation corridor development.

Data is being collected from both vehicles and the charge infrastructure. Data is then sent to the DOE's Idaho National Laboratory (INL). Data is being qualified and analyzed by the INL. Some of the data is also being evaluated by university participants and industry experts to evaluate the effectiveness of deployed infrastructure, develop lessons learned, and suggest methods for improving infrastructure effectiveness. These methods for improving effectiveness will be implemented and their effects monitored and evaluated.

Data collected and information developed will be disseminated on a periodic basis to participants, stakeholders, and the DOE. Task reports will be prepared to document methods, metrics, results, and lessons learned from implementation and operation.

Results

As FY 2012 ended and this report was being compiled, the total reported project mileage was 42.2 million test miles on the 5,631 Leafs, Volts and Smart EVs reporting results. The more than 7,600 public and residential Level 2 EVSE have reported 1.2 million charging events.

A more in-depth discussion will have to be limited to the most recent published and approved reports that cover the second quarter of calendar year 2012 (April – June 2012). At this point, data had been collected from 4,322 Nissan Leaf battery electric vehicles (Figure 1), 676 Chevrolet Volt extended range electric vehicles, and 6,319 ECOtality EVSE were then providing data from (Figure 2) six states and the District of Columbia. A total of 32.9 million test miles and 881,000 charging events have been documented on the Project Overview Report for the EV Project to date (avt.inel.gov/pdf/EVProj/EVProjOverviewQ22012.pdf)

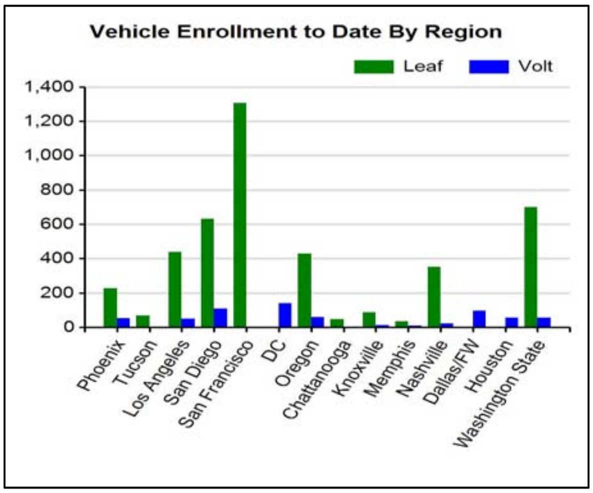


Figure 1. Number of EV Project vehicles providing data and deployment by major cities as of the end of June 2012.

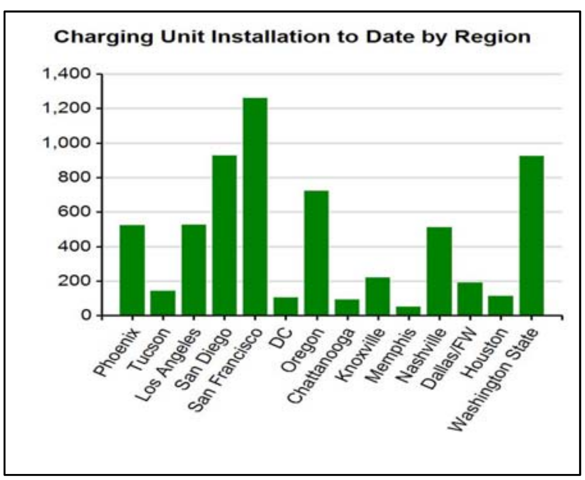


Figure 2. Number of EV Project EVSE deployed and providing data by major cities as of the end of June 2012.

The EV Project's Nissan Leaf summary report for April to June 2012 (avt.inel.gov/pdf/EVProj/EVProjNissanLeafQ22012.pdf) provides national and regional Leaf usage statistics and this data includes the national vehicle usage data seen in Table 1. Additional data for each region can be found in the same above PDF.

Figures 3 and 4 document the Nissan Leaf battery SOC before and after charging events. It will be interesting to see if SOC before-charging changes as operators become more familiar with the vehicles and if SOC at end-of-charging changes as drivers use public charging, including fast chargers for shorter periods of time.

Table 1. EV Project Nissan Leaf BEV usage data for the July 2011 to September 2011 quarter.

Number vehicles	2,911
Total miles	5,666,469
Average miles per trip	7.2
Average miles driven per day when driven	30.6
Average # trips between charge events	3.9
Average miles driven between charge events	28.1
Ave # of charges per day when driven	1.1
Number of at home charging events	152,862
Number of away from home charging events	37,148
Unknown charging event locations	11,969

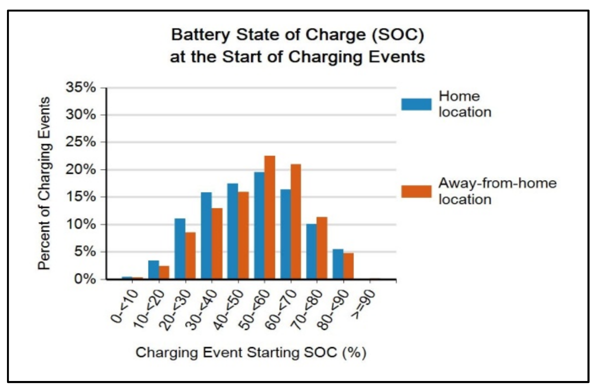


Figure 3. EV Project Nissan Leaf battery SOC at start of charging events.

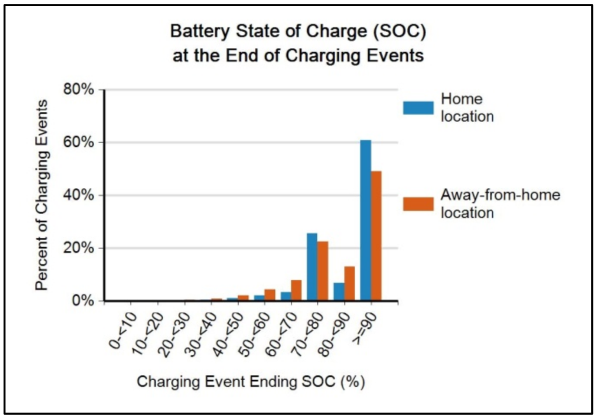


Figure 4. EV Project Nissan Leaf battery SOC at end of charging events.

The EV Project's Chevrolet Volt Leaf summary report for April to June 2012 (avt.inel.gov/pdf/EVProj/EVProjChevroletVoltQ22012.pdf) provides national and regional Volt usage statistics and this data includes the national vehicle usage data seen in Table 2. Additional data for each region can be found in the same above PDF.

Figures 5 and 6 document the Volt battery SOC before and after charging events.

Table 2. EV Project Chevy Volt EREV usage data for the April to June 2012 quarter.

Number vehicles	408
Total miles	1,184,265
Overall mpg	155
Overall electricity consumption (AC Wh/mi)	242
Average miles per trip	8.0
Average miles driven per day when driven	39.6
Average number trips between charge events	3.2
Ave miles driven between charge events	26.0
Ave number of charges per day when driven	1.5
Number of at home charging events	36,015
Number away from home charging events	6,374
Unknown charging event locations	3,179

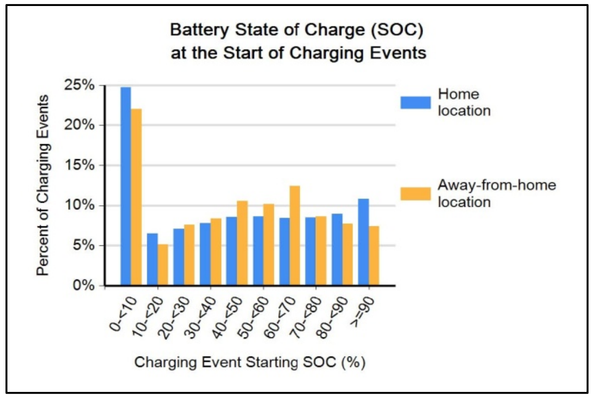


Figure 5. EV Project Chevy Volt battery SOC at start of charging events.

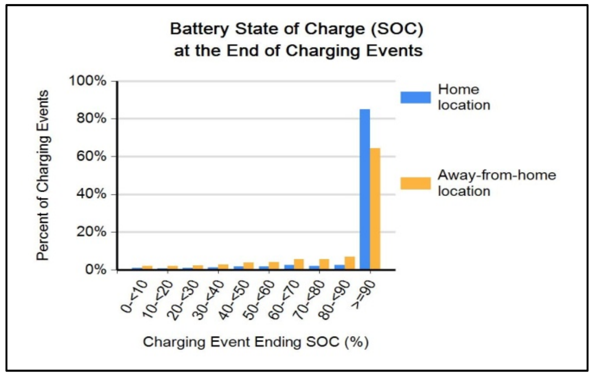


Figure 6. EV Project Chevy Volt battery SOC at end of charging events.

The April – June 2012 quarterly Infrastructure Summary report documents infrastructure utilization nationally and regionally for residential Level 2 EVSE and publicly available Level 2 EVSE. As additional units are installed, this report ([avt.inel.gov/pdf/EVProj/EVProj InfrastructureQ22012.pdf](avt.inel.gov/pdf/EVProj/EVProjInfrastructureQ22012.pdf)) will also include Fact Charge data.

Figure 7 highlights the percent of all national Level 2 EVSE charging units in 15-minute increments with an EV Project vehicle connected during week days. Figure 8 gives the same information for weekend days.

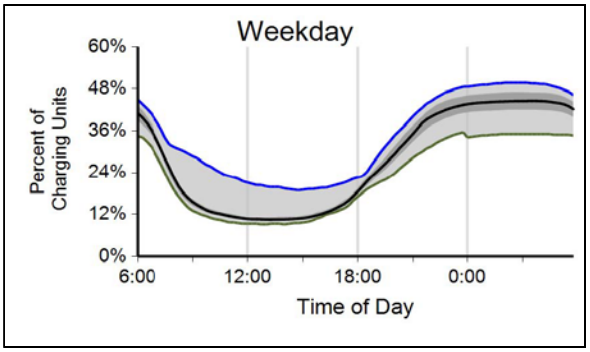


Figure 7. EV Project percent of all national Level 2 EVSE with a vehicle connected during weekdays. Data is in 15-minute increments for any time in the reporting quarter.

Note that for both figures, the blue line is the peak for the reporting period, green line is the minimum, and the black line is the mean, and the darker gray areas above and below the black line are the 25 to 50% and 50 to 75% quartiles. This is true for all figures in this section that report percent of charging units with a vehicle connected, and the electricity demand in AC MW.

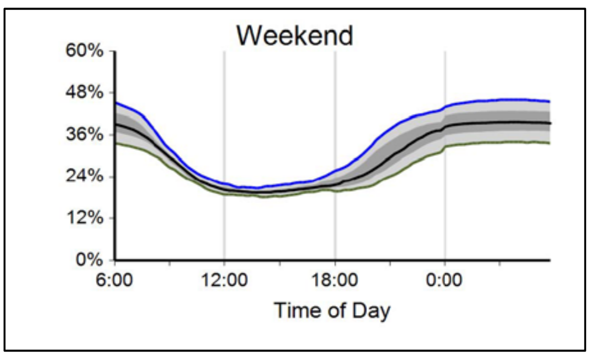


Figure 8. EV Project percent of all national Level 2 EVSE with a vehicle connected during weekends. Data is in 15-minute increments for any time in the reporting quarter.

Figure 9 is the charging profile in AC MWh for all Level 2 EVSE in the EV Project for weekdays and Figure 10 is for weekends. Note the heavy use of post-midnight charging.

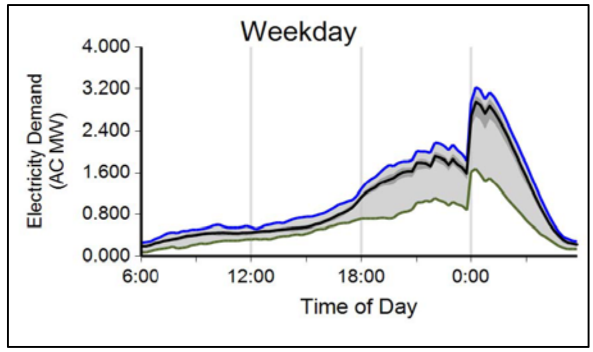


Figure 9. EV Project charging profile based on national energy demand for weekdays. Data is in 15-minute increments for any time in the reporting quarter.

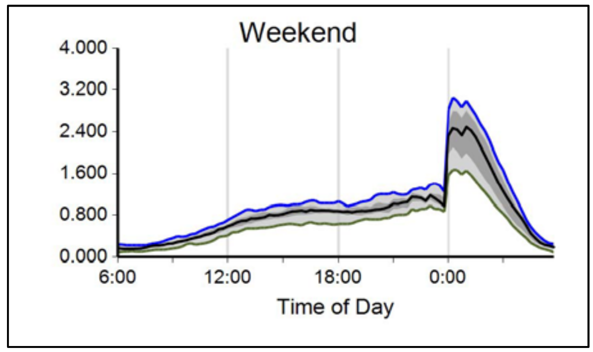


Figure 10. EV Project charging profile based on national energy demand for weekends. Data is in 15-minute increments for any time in the reporting quarter.

Figure 11 documents the length of time vehicles are connected to residential EVSE. The two sets of peaks suggest short opportunity charging for less than one or two hours, and overnight charging for 10 to 14 hours. Figure 12 shows the same set of vehicles drawing power for much shorter periods of time than when they were connected as shown in Figure 11. The general shape of Figure 13 matches Figure 12 as would be expected as the distribution of energy consumed would have a similar profile to the length of time the vehicles draw power.

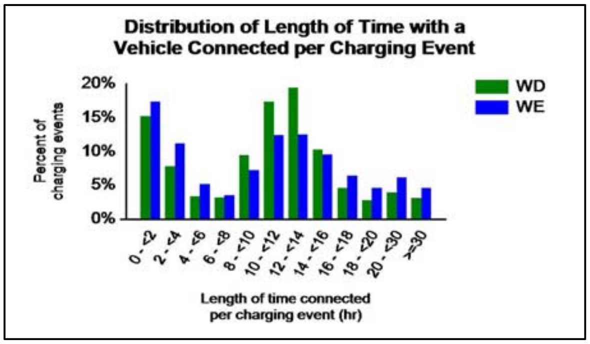


Figure 11. EV Project distribution of length of time with a vehicle connected per charging unit for residential Level 2 EVSE.

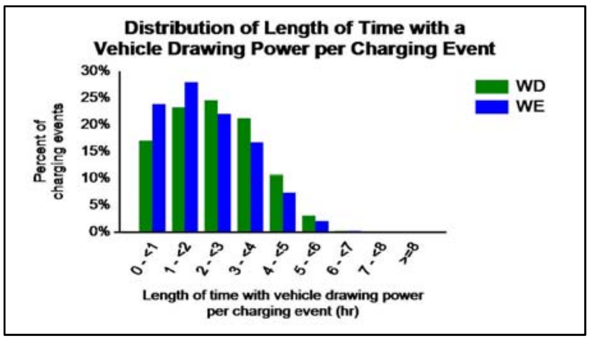


Figure 12. EV Project distribution of length with a vehicle drawing power per charging event for residential Level 2 EVSE.

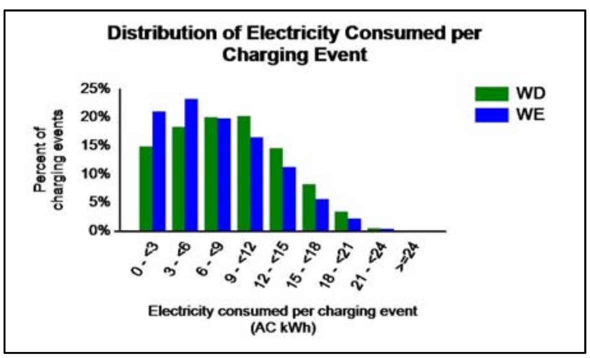


Figure 13. EV Project distribution of electricity consumed per charging event for residential Level 2 EVSE.

The EV Project will continue accumulating both vehicle and EVSE data, with the first fast chargers coming on line during FY 2012. As FY 2012 ended, more than three quarters of a million miles of data was being collected weekly.

Figure 14 is the charging profile for public access Level 2 EVSE as measured by the number of vehicles connected as a percent for weekdays and Figure 15 is the weekend data. It is assumed that at work, or near work public access charging is creating the higher peak in weekday public charging.

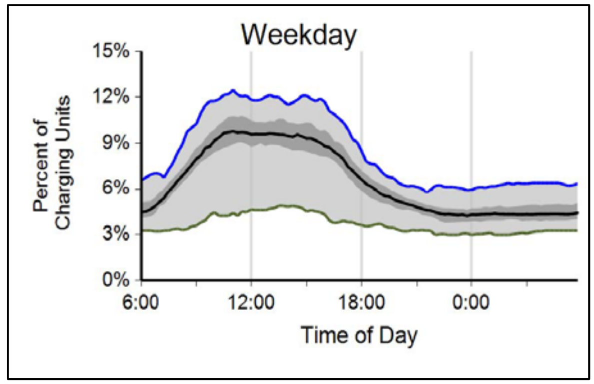


Figure 14. EV Project percent of all publicly available Level 2 EVSE with a vehicle connected during weekdays. Data is in 15-minute increments for any time in the reporting quarter.

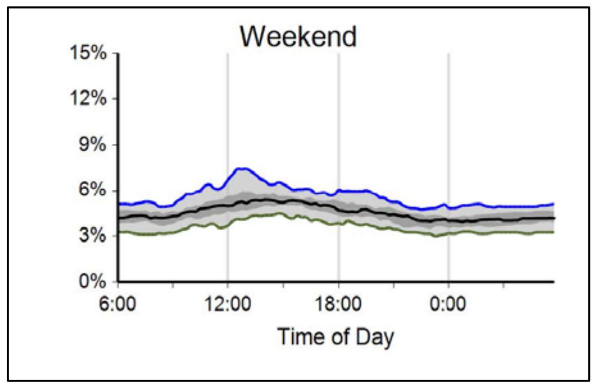


Figure 15. EV Project percent of all publicly available Level 2 EVSE with a vehicle connected during weekends. Data is in 15-minute increments for any time in the reporting quarter.

Figure 16 documents a similar work day peak profile when vehicles are connected to public EVSE and start drawing power about 9 a.m. on weekdays Figure 17 documents the less significant peak in public charging on weekends.

Time of use (TOU) electric utility billing rates for residential charging warrants an expanded discussion. While Figures 9 and 10 clearly show national peak demand at night as measured in AC MW, regional residential profiles significantly highlight TOU rate impacts. Figure 18 shows San Diego weekday peak demand that is influenced by the TOU rates that start at midnight. Figure 19 shows similar impacts that also occur weekends.

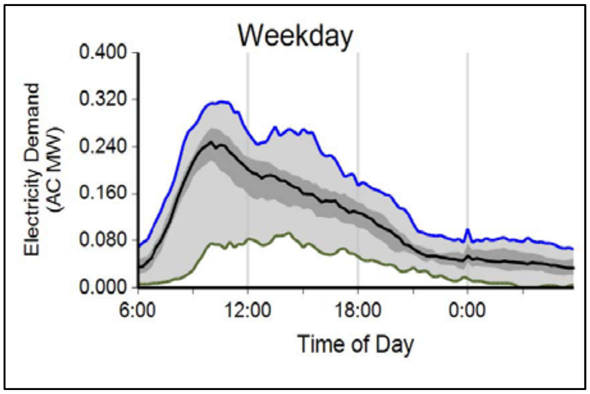


Figure 16. EV Project publicly available Level 2 EVSE charging profile based on energy demand for weekdays. Data is in 15-minute increments for any time in the reporting quarter.

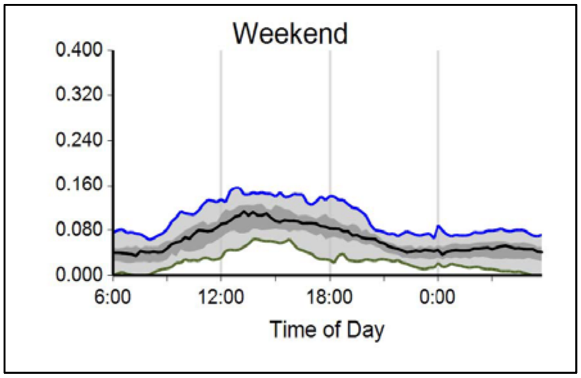


Figure 17. EV Project publicly available Level 2 EVSE charging profile based on energy demand for weekends. Data is in 15-minute increments for any time in the reporting quarter.

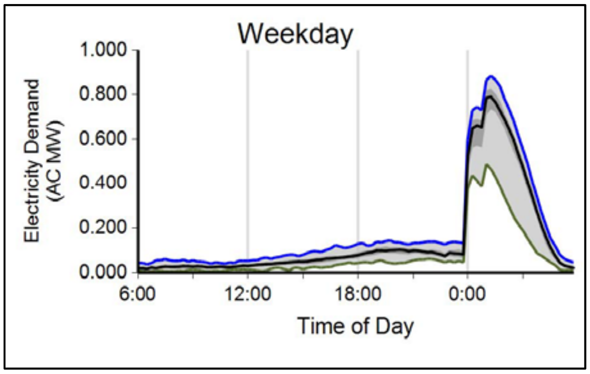


Figure 18. San Diego residential EVSE electric demand for weekdays.

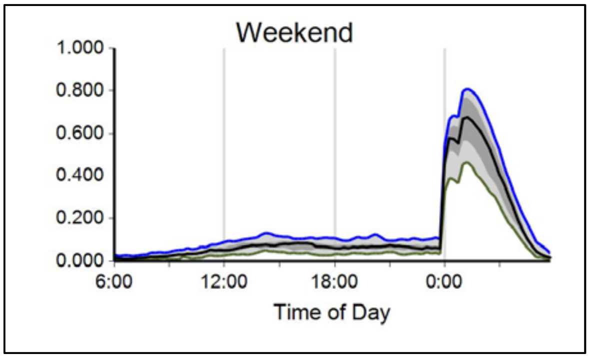


Figure 19. San Diego residential EVSE electric demand for weekends.

A contrast to the San Diego profiles is the weekday and weekend (Figures 20 and 21), demand curves for Washington State. Washington has relatively low electricity rates due to its extensive hydropower generation system. San Diego has more expansive rates, so incentives to shift demand to midnight is successful with TOU charging and TOU whole house rates. In Washington State, there is simply not the ability to offer much lower rates when general electricity rates are low to start with.

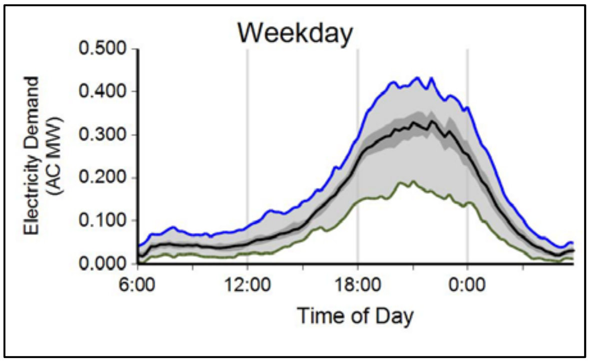


Figure 20. Washington State residential EVSE electric demand for weekdays.

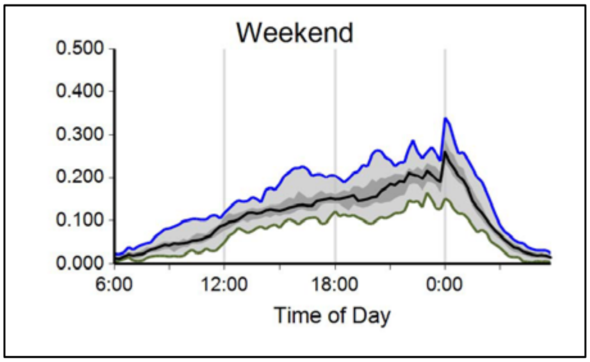


Figure 21. Washington State residential EVSE electric demand for weekends.

Conclusions

- Vehicle deployment is market driven, as is commercial market enthusiasm and support.
- The rate of vehicle sales is lower than original equipment manufacturers (OEMs) forecasted.
- Data collection and transmission are continuously undergoing improvement in reliability and content.

II.G.3. Products

Publications

EV Project Quarterly Reports

- EV Project EVSE and Vehicle Usage Report: 2nd Quarter 2011
- EV Project EVSE and Vehicle Usage Report: 3rd Quarter 2011
- EV Project EVSE and Vehicle Usage Report: 4th Quarter 2011
- EV Project EVSE and Vehicle Usage Report: 1st Quarter 2012
- EV Project EVSE and Vehicle Usage Report: 2nd Quarter 2012

Electric Vehicle Charging Infrastructure Deployment Guidelines

- Electric Vehicle Charging Infrastructure Deployment Guidelines for the Central Puget Sound Area
- Electric Vehicle Charging Infrastructure Deployment Guidelines for the Oregon I-5 Metro Areas of Portland, Salem, Corvallis and Eugene
- Electric Vehicle Charging Infrastructure Deployment Guidelines for the Greater Tucson Area
- Electric Vehicle Charging Infrastructure Deployment Guidelines for the State of Tennessee
- Electric Vehicle Charging Infrastructure Deployment Guidelines for the Greater San Diego Area
- Electric Vehicle Charging Infrastructure Deployment Guidelines for the Greater Phoenix Area

Long-Range EV Charging Infrastructure Plans

- Long-Range EV Charging Infrastructure Plan for Arizona
- Long-Range EV Charging Infrastructure Plan for Greater San Diego
- Long-Range EV Charging Infrastructure Plan for Western Oregon
- Long-Range EV Charging Infrastructure Plan for Tennessee

EV Project Lessons Learned Reports

- EV Project: Accessibility at Public EV Charging Locations
- Lessons Learned - EV Project: First Responder Training
- DC Fast Charge-Demand Charge Reduction
- The EV Micro-Climate Planning Process
- Signage
- Greenhouse Gas (GHG) Avoidance and Fuel Cost Reduction
- Battery Electric Vehicle Driving and Charging Behavior Observed Early in the EV Project
- A First Look at the Impact of Electric Vehicle Charging on the Electric Grid in the EV Project

Presentations

- Technologies required to fully integrate electric vehicles and the smart grid
- Clean Cities Webinar

II.H. Recovery Act – Strategy to Accelerate U.S. Transition to Electric Vehicles

Principal Investigator: Mr. Greg Cesiel
General Motors
30001 Van Dyke Avenue
Warren, MI 48090
M/C: 480-210-420
Phone: (586) 575-3670; Email: greg.cesiel@gm.com

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

NETL Project Manager: Jason Conley
Phone: (304) 904-7590; Email: John.Conley@netl.doe.gov

II.H.1. Abstract

Objective

- Overall Objectives
  - The objective of this project[8] is to develop Extended Range Electric Vehicles (EREV) advanced propulsion technology and demonstrate a fleet of EREVs to gather data on vehicle performance and infrastructure to understand the impacts on commercialization while also creating or retaining a significant number of jobs in the United States. This objective will be achieved by developing and demonstrating EREVs in real world conditions with customers in several diverse locations across the United States and installing, testing and demonstrating charging infrastructure.
- FY 2012 Objectives
  - In 2012, we continued the project demonstration leveraging the unique OnStar telematics platform, standard on all Chevrolet Volts, to capture the operating experience that will lead to better understand of customer usage. The project utility partners continued to install charging infrastructure in order to demonstrate and test charging infrastructure located in home, workplace and public locations. This provides a better understanding of installation issues, customer usage and interaction with the electric grid. In 2012, we continued to work with the Volt owners at the electric utility company participants as the continued to gather data for the demonstration portion of this project.

Major Accomplishments

- Customer usage of demonstration fleet maintained
- Regular data delivery to Idaho National lab continues
- Quarterly reports continue to be published by Idaho National Lab
- 293 charging stations installed to date
- OnStar smart charging demonstrations continue
- Launch of the Smart Grid APIs (smartgrid.developer.onstar.com)

Future Activities

- Continue smart Charging OnStar demonstrations to exhibit capabilities with various utilities
- Demonstrate Application to show vehicle and home energy consumption at PecanStreet.org subdivision

---

[8] Contract ID# DE-EE0002628

- Demonstrate initiation of Charge flow based on NFC (Near Field Communication) for an EVSE manufacturer
- Initiate PLC smart charging demonstrations
- Initiate battery to grid demonstration
- Fast Charging demonstration with Home Plug Green PHY
- Continue to collect data from demonstration vehicles across the United States
- Utilize first generation vehicle information to refine the technology and enhance adoption of the second generation technology into the marketplace

II.H.2. Technical Discussion

Introduction – Smart Charging

The capability to identify and manage electric vehicle charging loads through OnStar and Power Line Communications (PLC) will be developed and demonstrated. This technology will support managing interaction with the electric grid using the current grid infrastructure.

Approach – Smart Charging

OnStar's task is to design, develop and implement smart charging to interface with utility systems.

The PLC portion will design, develop and implement the interface that enables communication between a smart meter and the vehicle.

Results – Smart Charging

Utility control of the Volt was successfully demonstrated by Duke Energy, DTE, SMUD and Progress Energy, all program partners. All participants leverage the Smart Grid APIs developed under this program to show charge control using either Rate Table or Demand Response events signals sent to the vehicle via OnStar connectivity.

The project team successfully demonstrated taking a renewable energy signal from PJM and applying that signal to Google's fleet of Volts (25).

Benches were built in order to develop and demonstrate the PLC portion. The first bench built was a proof of concept bench, consisting of a utility and vehicle simulator connected by a Zigbee smart meter and Zigbee to PLC Communication Bridge. This setup uses Smart Energy Profile (SEP) 1.0. A second bench has been developed using a live Utility interface, or simulator, connected through a Zigbee smart meter and Zigbee to PLC/CAN Communication Bridge to a vehicle simulator. This setup provides multiple means of connection to the vehicle simulator for the Utility to test. The third bench is currently in development. It will consist of a live utility connection through a Zigbee to PLC/CAN Communication Bridge and connected to a 2011 Volt. For 2012, communication will use SEP1.0. In 2013 the hardware and software will be modified to use SEP 2.0 messaging to control the vehicle.

Introduction – Fast Charging

Charging an EV battery in less than 30 minutes provides additional opportunities for the customer to fuel with electricity and increase petroleum displacement. Fast charging shall support development of standard electrical and communication interfaces between the EV and the charger and increase the understanding of the vehicle and grid impacts of fast charging.

Approach – Fast Charging

This approach starts with the development of a standard DC connection interface and communication standard for fast charging; this includes integration of this into a vehicle. From here, the demonstration period will be utilized to collect and analyze data to study grid impacts, vehicle impact, thermal management, charging profiles, user ergonomics and efficiency.

Results – Fast Charging

The fast charge development team completed tasks for internal development as well as standards feedback and development. The fast charge station development work has been initiated to switch to the Home Plug Green PHY interfaces over the control pilot line and is the proposed standard for DC charging communication. Both receptacle testing and plug testing is ongoing.

Introduction – Battery to Grid

The increased demand for stationary energy storage on the electric grid to enable renewable energy sources and reduce infrastructure stress through load management is an opportunity to extend the usage of automotive batteries. This task will study the technical challenges of automotive battery reuse for grid storage and demonstrate this application.

Approach – Battery to Grid

This task studies the stationary energy storage requirements and compares them to battery capabilities following vehicle use. In order to demonstrate battery to grid functionality, a grid-tied bidirectional power converter with a battery pack will be utilized. Communication requirements for grid to storage systems shall be developed to provide dispatched power capability. A demonstration period will collect and analyze data to study the grid and battery impacts of bidirectional power flow.

Results – Battery to Grid

Modes of operation have been identified and defined. Control modes necessary to deliver grid operating modes have been demonstrated in the lab. A single stage topology with galvanic isolation has been demonstrated, and future areas that need work have been identified. These areas are in managing voltage spikes during transition modes and technology improvements in reverse blocking IGBT's will be essential for production viability. This project provided experiences necessary for GM to make decisions on bi-directional power transfer between batteries and the grid.

II.H.3. Products

Publications

1. Idaho National Laboratory website; listed under "General Motors Chevrolet Volt Vehicle Demonstration" – aggregated data report avt.inel.gov/evproject.shtml

Patents

1. To date, this demonstration program has not generated any subject inventions or made any related patent filings.

Tools & Data

Driving and charging data is being transferred from the vehicles via the OnStar telematics to the OnStar lab. OnStar personnel receive the data and process it appropriately for transfer to Idaho National Labs. The following data is a list of what is collected by OnStar and transferred to Idaho National Lab:

All trips combined:

- Overall fuel economy
- Total number of trips
- Total distance traveled
- Average ambient temperature
- Vehicle maintenance records

Trips in charge depletion mode:

- Fuel economy
- Number of trips
- Percent of trips city/highway
- Distance traveled
- Average trip aggressiveness (scale of 0-10)
- Percent of total distance traveled

Trips in both charge depletion and charge sustaining mode:

- Fuel economy
- Number of trips
- Percent of trips city/highway
- Distance traveled
- Average trip aggressiveness (scale of 0-10)
- Percent of total distance traveled

II.I. Smith Electric Vehicles Medium Duty Electric Vehicle Demonstration Project

Principal Investigator: Robin J.D. Mackie, President & Chief Technology Officer
Smith Electric Vehicles U.S. Corp.
12200 N.W. Ambassador Drive, Suite 326
Kansas City, MO 64163
Phone: (816) 243-1611;Email: robin.mackie@smithelectric.com

DOE Technology Development Manager: Lee Slezak
NETL Project Manager: Nicholas D'Amico
Phone: (412) 386-7301; Email: nicholas.damico@netl.doe.gov

II.I.1. Abstract

Objective

- The objective of the SEV-US Demonstration Project[9] is to obtain performance information from an All Electric Vehicle (AEV) fleet to accelerate production, reduce costs, enhance the technology, and procure early acceptance of AEV's in the US commercial vehicle marketplace.
- Smith will demonstrate 510 electric vehicles based on the Newton medium duty platform. The vehicles will be placed in locations including California, Missouri, Ohio, Michigan, Washington, DC, New York, and Texas. A Generation II Newton platform will be developed during the project utilizing the performance data collected. The development of this platform will enable the Company to reduce cost, expand the vehicle range from class 4 through 7, and additional improvements will be made in powertrain and battery technology. It is intended that the base vehicle platform be applied to both shuttle bus and step-through van applications.

FY 2012 Objectives-

- Deploy to customers the remainder of the 510 vehicle fleet.
- Continue to expand and upgrade Smith Link providing data to:
  - NREL
  - Smith service
  - Smith engineering
  - Selected Smith customers.

Sales & Marketing:

- Expand the market boundaries to support the overall fulfillment of the DOE objectives through the introduction of additional launch partners and new Newton platforms- step van, school and shuttle buses.
- Continue to establish the Smith brand as the pre-eminent supplier of Zero Emission Electric Commercial Vehicles,
- Continue to develop our route analysis capabilities to provide more comprehensive duty cycle studies enabling customers to better manage the battery capacity to the required customer applications.
- Continue development of Smith's service capabilities including infrastructure definition, pre delivery training, vehicle handover and post-deployment driver training and optimization to ensure the customers gain the maximum benefit from their vehicles.

***Operationally*:**

- Expansion of the Smith assembly facility to match demand,

---

[9] Contract ID# EE0002614

- Continued recruitment and cross-discipline training of assembly staff,
- Continued expansion of the service team and resources to meet customer deployment plans,
- Continuous improvement of Gen 2 Newton platform incorporating Smith Power, Smith Drive and Smith Link.

Supply Chain:

- Develop suitable supply chain to support engineering activities, production requirements for Gen 2 systems, cost down activity and meet "Buy America" criteria.

Engineering:

- Addition of a long wheelbase version of the step van to accommodate the laundry and uniform markets,
- Expansion of Smith Power to augment our 80 kWh battery configuration with 40, 60, 100 and 120 kWh alternatives allowing Smith to match battery capacity to customer requirements.
- Continued development of the school and shuttle bus platforms,

Quality:

- Obtain final ISO certification.

Finance and Administration:

- Continued development and maturation of internal administrative processes, including strengthening the enterprise software, building a public company consolidated external financial reporting platform, developing written internal accounting and operating policies, and adding a dedicated internal audit function.
- Comply with all project reporting requirements for the DOE and ARRA.

Corporate:

- Fund raising to support ongoing development and company growth.
- Develop different and appropriate business relationships to support entry into multiple countries within the global market where there is identified latent demand for AEVs.

Major Accomplishments

- Deployed to customers 355 vehicles under the Participation Program through September 30, 2012, including the initial delivery of 25 step vans of a 100 vehicle order. The balance of the order will be deployed by the end of Q1 2013.
- Continued to reliably deliver data to NREL and received back NREL's initial feedback reports of operating data.
- In collaboration with key customers continued to develop the Smith Link portal, improving reliability and providing enhanced data internally to both engineering and service teams.
- Developed and trialed prognostic capabilities across the system.

Sales & Marketing:

- Continued to expand the customer base and received significant re-orders from initial launch partners.
- Continued to participate in local, national and international conferences to support awareness creation for commercial AEV's.
- In association with our customers we have supported several marketing campaigns and have received significant media exposure.

Operations:

- In Q2 and Q3 launched our Gen 2 products, incorporating Smith Power, Smith Drive and Smith Link.
- In Q3 completed the introduction of the all-electric stripped chassis in support of the Newton step through completing delivery of the first 25 units.
- Allowing for the disruption from introducing our Gen2 systems and the stripped chassis, delivered 115 vehicles into the 510 vehicle project fleet.

Supply Chain:

- Further reduced purchasing and manufacturing costs by additional 5%, and remained on schedule to meet our cost down goals by 2013.
- Transitioned the Smith Drive from our bridge-to-production supplier to the volume production supplier, with initial production to begin in Q1 of 2013.

Engineering:

- Supported launch of Gen 2 systems into production.
- Completed development and launch support of the all-electric stripped chassis.
- Finalized production specifications for the Newton bus configuration.
- Introduced the option of hydraulic brakes for the all-electric stripped chassis.
- Continued to improve reliability and efficiency of vehicle sub-systems, including HVAC and air brake systems.
- Maintained regulatory compliance and extended the scope on a global basis to include European whole vehicle approval, and specific requirements for markets including Russia, the Middle East and the Far East.

Quality:

- Received the final ISO 9001 certification in May 2012.

Finance and Administration:

- Continued development and maturation of internal administrative processes, including strengthening the enterprise software, building a public company consolidated external financial reporting platform, developing written internal accounting and operating policies, and adding a dedicated internal audit function.
- Complied with all project reporting requirements for the DOE and ARRA.

Corporate:

- Maintained fund raising activities in line with corporate goals.
- Submitted revised Form S-1 Registration Statement to the SEC in July and September 2012 in anticipation of an IPO. However, market conditions led Smith management to delay an IPO and remain a privately funded company in the near term.

Future Activities

- Deliver vehicles to committed customer orders for the balance of the demonstration fleet by February 28, 2013.
- Continuously develop Smith Power, Smith Drive and Smith Link, enhancing reliability, efficiency and reducing cost.
- Maintain supplier development and cost down activities to reduce overall vehicle cost by a targeted incremental 23%, improving market competitiveness with traditional ICE commercial vehicles.
- Expand Smith Link to support the requirements of the demonstration fleet for the full duration of the project, ensuring the timely delivery of data to NREL.
- Revisit the opportunity to successfully complete the IPO process, and thus obtain long-term public financing.

Development *Activities*:

- Investigation of the application of a hydrogen fuel cell based range extender;
- Development of a Smith vehicle-to-grid solution;
- Integration of wireless/inductive charging;
- Develop application of multi-speed transmission to Smith Drive;
- Development of second generation Smith Link hardware, bi-directional communication and vehicle diagnostics.
- Support the DOE funded project to develop and apply a non-rare earth electric drive to commercial vehicles.

II.I.2. Technical Discussion

Introduction

Smith's overall technical objectives are to leverage the 80 years of knowledge and experience of its UK subsidiary within the electric vehicle market in Europe, and apply it to the North American marketplace. This activity can be broken down into two main phases:

Phase1: The homologation of the European Newton Gen 1 platform to US Department of Transportation standards to support immediate production during 2010-2011.

Phase 2: The development of Smith proprietary driveline, battery and telemetry systems under the technical sub-brands of Smith Power, Smith Drive and Smith Link.

The Gen 1 driveline and battery systems were developed in conjunction with vendor system providers with the final vehicle integration being carried out by Smith. By using this approach Smith limited its ability to influence both cost and development, suffering from early quality issues.

It was decided that the experience gained through the use of these system providers that Smith should develop its own powertrain, battery and telemetry systems, thus enabling greater control over the specification, test and validation of the new system to improve quality and reduce warranty issues.

This approach also enables the Company to buy at the component level and reduce overall systems costs in line with its goals.

Smith Drive-

System objectives over Gen1-

- More efficient drive motor- 150kw permanent magnet.
- Drive motor and controller to be compatible with electric gearbox development.
- Higher speeds- 65 mph.
- Improved gradeability.
- Fully integrated drive controller including auxiliary inverters for power assisted steering and brakes.
- Drive motor and controller compatible with cooling system.

Smith Power-

System objectives over Gen1-

In-house development of the Smith battery management system (BMS) with the following capabilities-

- Management of different cell chemistries,
- Support a modular approach to battery pack sizing,
- Active thermal management.

Modular approach to the mechanical and electrical integration of cells allowing battery pack sizes from 40 KWh to 120 KWh.

On-vehicle modular charging strategy to support differing battery pack configurations.

Smith Link-

System objectives-

- Development of the telemetry unit for vehicular use, interfacing with Smith Drive and Smith Power systems,
- Real time collection of over 1200 data points per second per vehicle,
- Secure transmission of the data to in-house server arrays for post-processing,
- The development of portals to create appropriate access to vehicular data for use by the following internal and external customers-
  - Smith service
  - Smith engineering
  - Department of Energy agent NREL
  - Customers.

II.I.3. Products

Existing Products-

Figure 1. Top left - cargo van, Top right - utility truck with lift, Bottom left - refrigerated van (cold plate), Bottom right - military transport vehicle.

Figure 2. Above - stake bed truck.

Figure 3. Above - cargo van.

Figure 4. Above - step van.

Figure 5. Above - School bus.

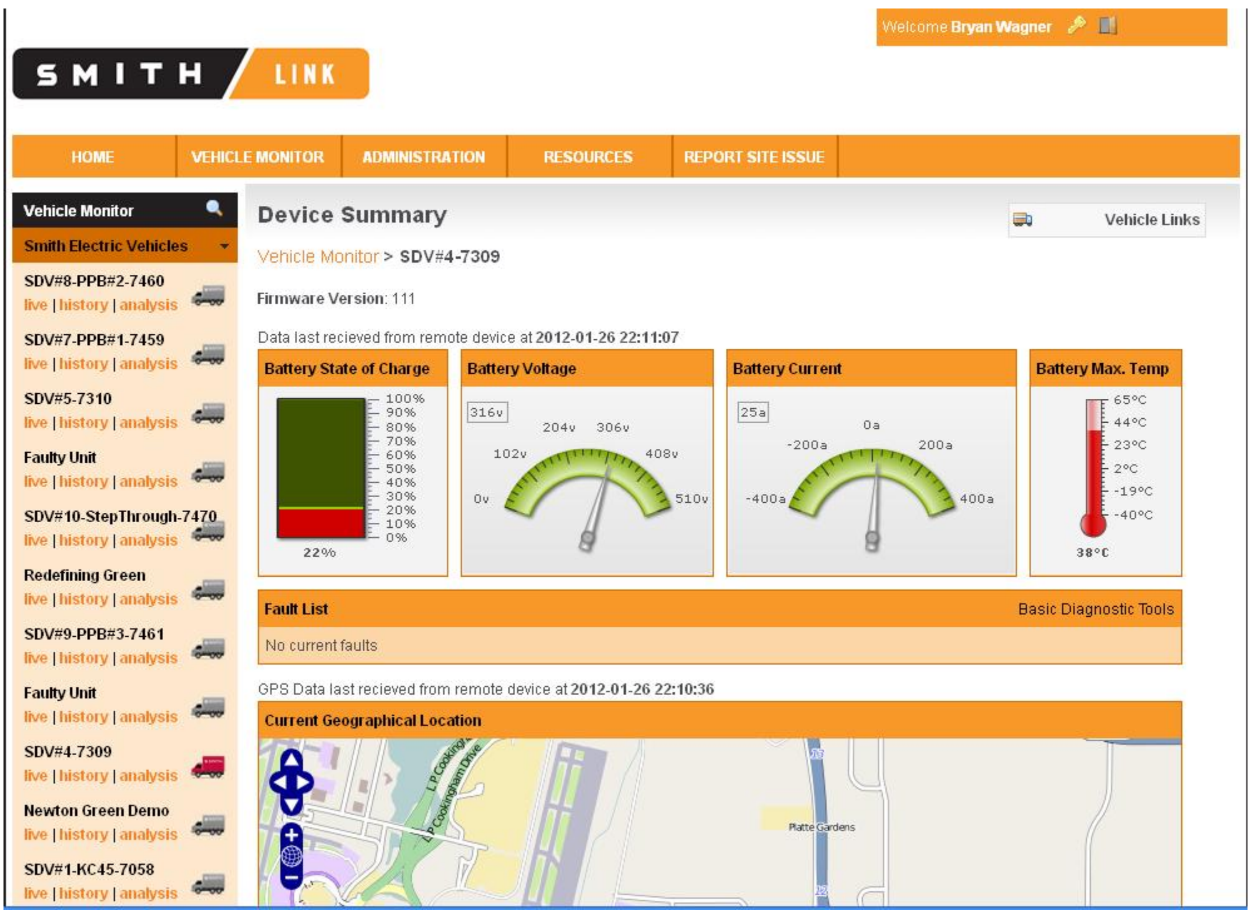


Figure 6. Above - Smith Link.

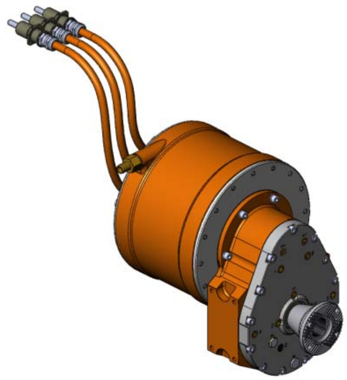


Figure 7. Above - Smith Drive motor.

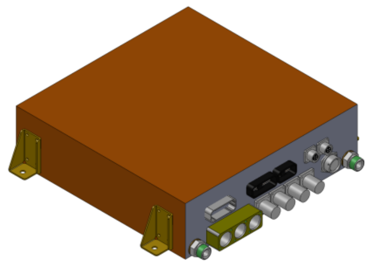


Figure 8. Above - Smith Drive motor controller.

Figure 9. Above - Smith Gen 2 cab.chassis.

Products still in final development/prototype stages-

Figure 10. Above - shuttle bus.

Publications

None.

Patents

None.

Tools & Data

None.

II.J. Plug-In Hybrid Electric Medium-Duty Commercial Fleet Demonstration and Evaluation

Principal Investigator: Matt Miyasato
Organization: South Coast Air Quality Management District
Address: 21865 Copley Drive, Diamond Bar, CA 91765
Phone: (909) 396-3249; Email: mmiyasato@aqmd.gov

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

NETL Project Manager: Jason Conley
Phone: (304) 285-2023; Email: john.conley@netl.doe.gov

II.J.1. Abstract

Objective

The objective of this program is to successfully migrate plug-in hybrid technology beyond the passenger car segment through the following:

- Develop a production-ready plug-in hybrid electric vehicle system with a high capacity Lithium-Ion battery system for Class 2 and Class 6-8 trucks (10,050 pounds – 33,001 and higher pounds Gross Vehicle Weight).
- Establish production at a ship-through facility for commercial assembly and installation of the PHEV systems.
- Develop production-ready smart charging capability for vehicle and the supporting charging infrastructure for these vehicles.
- Evaluate technical feasibility and build substantial customer familiarity and interest in a nationwide fleet test and demonstration program.
- Launch system into commercial ship-through production in 2013 with goal of building enough demand for high volume line production in 2015.
- Use project results for system development to optimize performance and reduce costs.

Approach

The program will deploy a combination of VIA Motors Class 2 PHEV pickup trucks, SUVs, and vans; Quantum Technologies Class 2 PHEV pickup trucks; and Odyne Class 6-8 PHEV aerial trucks. The precise number of each type of vehicle will depend on the fleet participants' choice based on preference, features, and schedule. The nominal nationwide demonstration fleet size is expected to be 280 vehicles.

Major Accomplishments

- The program was restructured after the bankruptcy filing announced by Azure Dynamics on March 26, 2012. Prior to the filing, Azure Dynamics was the technology developer for two of the three PHEV systems that were intended to be deployed as part of this program. However, their bankruptcy created uncertainty towards their organization's future product portfolio and their ability to continue to support the program. Consequently, the program was restructured to fill the void created by Azure. The restructuring efforts result in VIA Motors and Quantum Technologies being identified as PHEV drive system suppliers for light-duty trucks, in addition to the retention of Odyne as the PHEV supplier for Class 6 – 8 work trucks. As of the close of FY 2012, the project team is still collaboratively working with the DOE to generate a contract modification that would allow the restructured program to move forward.

Future Activities

- Complete the contract modification process with the DOE
- Complete validation testing of the PHEV drive systems for VIA, Quantum and Odyne.
- Finalize the legal agreements with the fleet participants
- Field a fleet of 280 PHEV's
- Analyze the field data to quantify the performance attributes of the PHEV's along with capturing the user's experience
- Complete reporting activities to close-out the project

II.J.2. Technical Discussion

The program will deploy three discrete plug-in hybrid drive system architectures. These architectures include a series hybrid developed by VIA Motors, a parallel hybrid system developed by Quantum Technologies, and a worksite dominant hybrid system developed by Odyne.

The VIA plug-in hybrid system is based on a series architecture that will retain the stock IC engine. The transmission is removed and a generator is directly coupled to the engine. An electric motor will be attached to a shortened drive shaft and will have the sole responsibility for providing the vehicle's tractive power. The Front End Accessory Drive (FEAD) will be modified to run the water pump only. The following accessories are added: a 42V power steering system, a high voltage electric HVAC compressor, and a 12V electric vacuum boost for the brakes. A large energy battery pack is used to provide fuel displacement during traction events. An overview of the VIA PHEV system is shown in Figure 1.

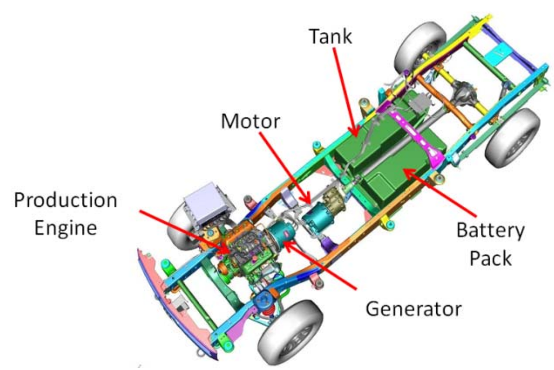


Figure 1. VIA Series Hybrid.

The VIA system will be comprised of:

- GM 4.8L V6 gasoline engine
- High energy Lithium-Ion battery by A123 (24.4 kWh)
- Blended regenerative braking
- Capability to provide traction power and cab comfort independent of the IC engine
- On-board charger (>6 kW)
- Charging – Level 1 (120 VAC) and Level 2 (240 VAC)
- Electrified accessories (steering, brakes, and HVAC)
- Export power (up to 5 kW, 120 VAC, 60 Hz)
- Approximately 35 miles of all-electric driving range
- At least 300 miles of total range
- Charge time of approximately 4 hours (Level 2)

Quantum's PHEV system is based on parallel hybrid architecture. The Quantum hybrid configuration is a post-transmission architecture that integrates the electric machine into the transfer case. The gearbox after the transmission is removed and replaced with a newly designed proprietary gearbox integrated with an electric motor. The Front End Accessory Drive (FEAD) will be modified to run the water pump only. The following accessories are added: a high voltage electric HVAC compressor, and a 12V electric vacuum boost for the brakes. The power steering is the production 12V electric system. A large energy battery pack is used to provide fuel displacement during traction events. An overview of the Quantum plug-in hybrid system is provided in Figure 2.

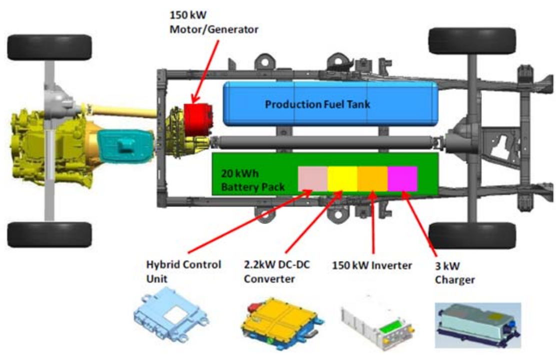


Figure 2. Quantum Parallel Hybrid System.

The Quantum system will be comprised of:

- Ford 3.7L V6 gasoline engine
- High energy Lithium-Ion battery by Dow Kokam (21.4 kWh)
- Blended regenerative braking
- Capability to provide traction power and cab comfort independent of the IC engine
- On-board charger (3.3 kW)
- Charging – Level 1 (120 VAC) and Level 2 (240 VAC)
- Electrified accessories (steering, brakes, and HVAC)
- More than 30 miles all electric range
- At least 300 miles of total range
- Charge time less than six hours with Level 2

The Odyne PHEV system is based on a parallel hybrid architecture that interacts with the drive train through the transmission's power take-off. The stock powertrain is not modified, but augmented with a through-shafted 60 kW continuous motor which drives the PTO from one side and a hydraulic pump on the other side. A large energy battery pack (~28 kWh) is used to provide fuel displacement during traction events as well as electrifying the jobsite use of the hydraulic devices. An overview of the Odyne system is provided in Figure 3.

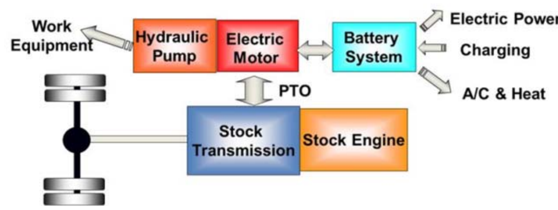


Figure 3. Odyne Hybrid Architecture.

These hybrid systems will be deployed on a nationwide basis, largely amongst utility fleets. The demonstration and evaluation program combines daily fleet field trials with controlled testing and a comprehensive, accelerated battery durability test plan. Each vehicle is equipped with a telemetry system for data capture and a strong focus on rigorous data analysis is planned to understand and optimize performance and to reduce system costs. Vehicles are projected to be capable of intelligent, flexible charging through smart metering infrastructure or other gateways to the utility system and will be compliant with both SAE J1772 and J2836 charging standards. It is planned that a sub-set of each of the three vehicle types will be tested by a third party. It is expected the vehicle deployments will conclude around Q4 of 2013, with the evaluation period being completed by Q4 of 2015.

II.J.3. Products

Publications - *None*

Patents - *None*

Tools & Data - *None*

SUPERTRUCK

II.K. Technology and System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Trucks

David Koeberlein
Cummins Inc.
PO Box 3005
Columbus, IN 47201-3005
Phone: (812) 377-5285; Email: david.e.koeberlein@cummins.com

DOE Technology Development Manager: Roland Gravel
Phone: (202) 586-9263; Email roland.gravel@hq.doe.gov

NETL Project Manager: Ralph Nine
Phone: (304) 285-2017; Email ralph.nine@netl.doe.gov

II.K.1. Abstract

Objectives

- Objective 1:
  - Engine system demonstration of 50% or greater brake thermal efficiency in a test cell at an operating condition indicative of a vehicle traveling on a level road at 65 mph.
- Objective 2
  - a: Tractor-trailer vehicle demonstration of 50% or greater freight efficiency improvement (freight-ton-miles per gallon) over a defined drive cycle utilizing the engine developed in Objective 1.
  - b: Tractor-trailer vehicle demonstration of 68% or greater freight efficiency improvement (freight-ton-miles per gallon) over a defined 24 hour duty cycle (above drive cycle + extended idle) representative of real world, line haul applications.
- Objective 3:
  - Technology scoping and demonstration of a 55% brake thermal efficiency engine system. Engine tests, component technologies, and model/analysis will be developed to a sufficient level to validate 55% brake thermal efficiency.

FY 2012 Objectives

- Complete a demonstration of a 50% thermal efficient engine system.
- Complete the build of the 50% freight efficiency demonstration vehicle.
- Complete vehicle component development tests to be used in the demonstrator vehicle.
- Complete WHR vehicle cooling system development tests.

Accomplishments

- Demonstrated the interim milestone of 50% or greater BTE with a combination of hardware demonstration and simulation of optimized components.
- Vehicle cooling testing with a fully integrated waste heat recovery system, demonstrating the recovery and fuel economy improvements.
- Completed build and initial testing of the higher cylinder pressure capability, low pump parasitic engine.
- Completed aerodynamic aid hardware fabrication and follow-on testing of this hardware to correlate with analytical results.

- Completed design and build of the demonstrator #1 vehicle.
- Completed the on-vehicle integration of the intelligent electronic modules' comprising the road load management and cycle efficiency manager systems'; conducted initial system calibration and vehicle tests.
- Completed build and initial development testing of the advanced heavy duty transmission.
- Completed the installation and vehicle start-up and initial load testing of the solid oxide fuel cell auxiliary power unit on the demonstrator #1 vehicle.

Future Directions

- Complete the 50% freight efficiency vehicle demonstration testing.
- Analysis and targeted testing of technologies for achievement of a 55% thermal efficient engine.
- Complete the build of the 68% 24hr freight efficiency demonstration vehicle.

II.K.2. Technical Discussion

Introduction

Cummins Inc. is engaged in developing and demonstrating advanced diesel engine technologies to significantly improve the engine thermal efficiency while meeting US EPA 2010 emissions. Peterbilt Motors is engaged in the design and manufacturing of heavy duty class 8 trucks.

Together, Cummins and Peterbilt provide a comprehensive approach to achievement of a 68% or greater increase in vehicle freight efficiency over a 24 hour operating cycle. The integrated vehicle demonstration includes a highly efficient and clean diesel engine with 50% or greater brake thermal efficiency including advanced waste heat recovery, aerodynamic Peterbilt tractor-trailer combination, reduced rolling resistance tire technology, advanced transmission, and an efficient solid oxide fuel cell APU for idle management. In order to maximize fuel efficiency, each aspect associated with the energy consumption of a Class 8 tractor/trailer vehicle will be addressed through the development and integration of advanced technologies.

In addition, Cummins will scope and demonstrate evolutionary and innovative technologies for a 55% BTE engine system.

Approach

Cummins and Peterbilt's approach to these program objectives emphasizes an analysis led design process in nearly all aspects of the research. Emphasis is placed on modeling and simulation results to lead to attractive feasible solutions. Vehicle simulation modeling is used to evaluate freight efficiency improvement technologies. Technologies are evaluated individually along with combination effects resulting in our path to target measure of program status and for setting program direction.

Data, experience, and information gained throughout the research exercise will be applied wherever possible to the final commercial products. We continue to follow this cost-effective, analysis-led approach both in research agreements with the Department of Energy as well as in its commercial product development. We believe this common approach to research effectively shares risks and results.

Results

- Demonstrated the interim milestone of 50% or greater BTE with a combination of hardware demonstration and simulation of optimized components. The demonstration engine was based on the Cummins 15 liter ISX with SCR aftertreatment and waste heat recovery (WHR) system. The demonstration engine showed approximately a 20% reduced friction compared to the current production ISX15 engine. The engine exhibited an improvement in gross indicated efficiency compared to the baseline engine, and a modest improvement in open-cycle efficiency. Waste heat recovery reduced fuel consumption in the range of 4-5 percent.

  The demonstration engine with the WHR system combined with AT fueling improvements resulted in an effective BTE of 49.0%; the estimated engine-only brake thermal efficiency from the system is 46.3% BTE. The engine system also showed compliance with current prevailing SET emissions requirements of 0.2 g/bhp-hr. The engine was operated at the 13 SET modes, and the cycle-weighted SET emissions were 0.08 g/bhp-hr system-out.

The WHR system tested low global warming potential working fluid (GWP) with results indicating a 0.2% system BTE improvement. Testing was terminated due to a leak that resulted in losing the fluid; additional replacement fluid was not available at the time. The above results do not include these observed low GWP fluid formulation benefits.

- Multiple WHR equipped vehicles are operating in test conditions. The vehicles have each completed cooling tests in a Modine climactic tunnel to understand WHR system performance on-vehicle in varying ambient and various applied heat loads.

  A key objective included generating cooling module performance data to validate analysis and assist in condenser development. The critical question sought during the testing was "is the WHR condenser capacity sufficient to reject the WHR system's highway cruise heat rejection without cooling fan assist?" Also, data was collected to help with understanding of this cooling modules capacity at other ambient temperatures and vehicle velocities.

  Results of an 85 degree F ambient condition, fan off and 300hp engine output, the WHR achieved 15hp of recovered power, 5% recovery. This result validates a key design point of the cooling module that the cooling module the capacity of rejecting WHR heat at greater than the highway cruise power point without fan assist.

- The build of the integrated Demo 1 truck including a higher efficiency WHR equipped engine, an advanced transmission and a solid oxide fuel cell (SOFC) was completed. Over the course of 3 days, the truck ran down the production assembly line to complete its build. Over the next several weeks, custom completion and charging of the WHR system, installation and tests of the battery system and the SOFC were completed. The truck was driven bobtail on local Denton, Texas roads to evaluate the advanced transmission. The truck was delivered to Cummins, in Columbus, IN for calibration and development of engine, WHR and route management systems. In late August, Demo 1 returned to Denton for upfit of the truck and trailer aero package, tires, and wheels and along with additions for fuel economy test equipment.

- Truck and trailer aero aid fabrications were completed and initial truck on-road evaluations completed. A Model 587/trailer combination was equipped with design intent in preparation for freight efficiency testing. The 65,000 lb ballasted truck with current production super single tires system achieved a 28% fuel economy improvement over the baseline 2009 Model 386 with a standard trailer.

- A Fuel cell APU unit was re- installed and drive tested with full vehicle electrical system's functional, development issues found were remedied in preparation to be available for truck testing. A functional SOFC APU was initially installed on the Demo 1 truck in May2012 for truck interface, start, and run evaluation. Following successful on-truck trials, the unit was replaced by a non-functional unit and returned for upgrades to replace the desulfurization subsystem with a bypass tube. Rebuild of the system was completed and underwent sulfur conditioning, calibration, and testing. The unit continues to show good performance in idle fuel consumption, noise level and cool down time but recent output and efficiency have suffered in the sulfur-conditioned configuration. An increase in both internal stack temperature and parasitic electrical loads are the general causes for decreased peak power and efficiency.

  The exterior noise level at all recording points was below the 65dBA target. Measurements inside the cab were less than 50 dBA. The rebuilt unit was re-installed on the Demo 1 truck and will undergo future system level testing.

- The advanced transmission was initially built in Nov 2011 and since then has been undergoing numerous development tests. The transmission has been subjected to shift tests, full load dyno, lube and cooling tests and installed in a mule truck completing mileage accumulation tests. Shift calibration and software development has been a critical focus of attention, with progressive improvements are being reported with focused jury evaluation vehicle trials. The Demo 1 truck was initially built with the transmission and enabled demonstration of the improvements the transmission will bring to the vehicle, including marked improvements to downsped engine driveability. The transmission has since been completing parallel development tests in lab and vehicle environments.

- A vehicle power train system analysis is a tool to evaluate freight efficiency improvements. The path to target roadmap study involved an analysis of various power train component changes, including both hardware and control algorithms, with their resulting freight efficiency impacts. Figure 1 shows the path to target roadmap for both the drive cycle 50% improvement and 68% improvement on the 24hr cycle. This figure also shows current expected status toward both objectives of 68% and 80% respectively, we have determined uncertainty in these values of +/- 5%.

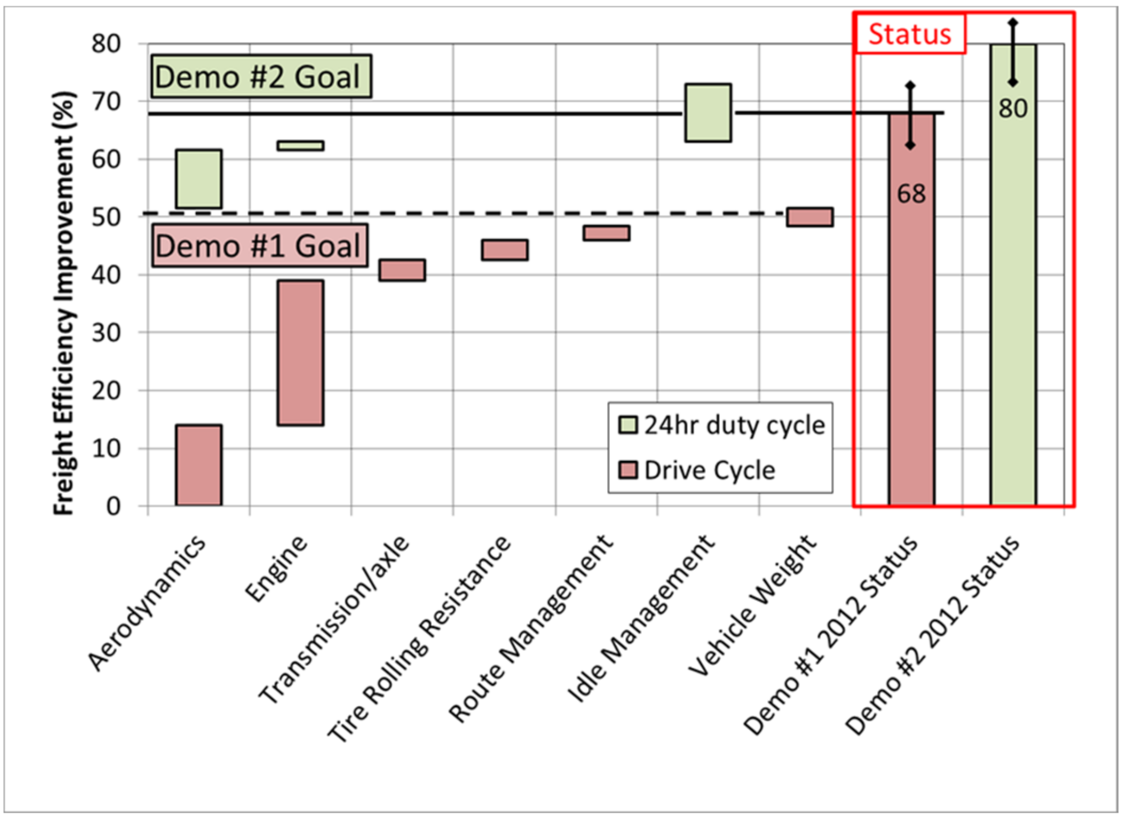


Figure 1. Path to Target Roadmap.

Conclusions

The SuperTruck Engine and Vehicle System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Truck program has successfully completed the second year of the four year program. The following conclusions have come from the second year:

- Vehicle power train system analysis shows path to achievement of program freight efficiency goals.
- Demonstrated the interim milestone of 50% or greater BTE with a combination of hardware demonstration and simulation of optimized components.
  Freight Efficiency Roadmap and Status
- The build of the integrated Demo 1 truck including a higher efficiency WHR equipped engine, an advanced transmission and a solid oxide fuel cell (SOFC) was completed
- Waste heat recovery vehicle cooling tests were conducted with fan-off system performance and system power recovery demonstrating results as expected from analysis.
- Truck and trailer aero aid fabrications were completed with initial truck on-road evaluations showing a 28% improvement.

II.K.3. Products

FY 2012 Publications/Presentations

Journal Paper Submissions:

1. Karla Stricker, Lyle Kocher, Dan Van Alstine, *Input Observer Convergence and Robustness: Application to Compression Ratio Estimation*, IFAC Control Engineering Practice, 3/5/2012
2. L. Kocher, E. Koeberlein, K. Stricker, D.G. Van Alstine, and G.M. Shaver, *Control-Oriented Gas Exchange Model for Diesel Engines Utilizing Flexible Intake Valve Actuation*, J. of Dyn. Sys., Meas., and Control, 10-24-2011
3. L. Kocher, K. Stricker, E. Koeberlein, D.V. Alstine, and G.M. Shaver, *In-cylinder Oxygen Fraction Estimation for Diesel Engines Utilizing Flexible Intake Valve Actuation*, IEEE Trans. on Control Systems Technology, 11-21-2011

Conference papers and presentations:

1. Dan Van Alstine*, Lyle Kocher, Ed Koeberlein, Karla Stricker, and Gregory M. Shaver, *Control-Oriented PCCI Combustion Timing Model for a Diesel Engine Utilizing Flexible Intake Valve Actuation and Higher EGR Levels,* presented at the 2012 American Control Conference, 6/2012.
2. Karla Stricker*, Lyle Kocher, Ed Koeberlein, Dan Van Alstine, and Gregory M. Shaver, *Effective Compression Ratio Estimation in Engines with Flexible Intake Valve Actuat*ion, presented at the 2012 American Control Conference, 6/2012.
3. Lyle Kocher*, Karla Stricker, Dan Van Alstine, Ed Koeberlein, and Gregory M. Shaver, *Oxygen Fraction Estimation for Diesel Engines Utilizing Variable Intake Valve Actuatio*n, presented at the 2012 American Control Conference, 6/2012.
4. Lyle Kocher, Karla Stricker, Dan Van Alstine, and Gregory M. Shaver, *Robust Oxygen Fraction Estimation for Diesel Engines Utilizing Variable Intake Valve Actuation*, submitted 3-12-2012 to IFAC Workshop
5. Karla Stricker, Lyle Kocher, Dan Van Alstine, and Gregory M. Shaver, *Guaranteed Convergence of a High-Gain Input Observer Robust to Measurement Uncertainty: Application to Effective Compression Ratio Estimation*, submitted 3-12-2012 to IFAC Workshop
6. David Koeberlein, *Cummins SuperTruck Program, Technology Demonstration of Highly Efficient Clean, Diesel Powered Class 8 Trucks*, 2012 DEER conference.
7. Lyle Kocher, *Estimation and Control of Diesel Engine Processes Utilizing Variable Intake Valve Actuation,* 2012 DEER conference.

Special Recognitions & Awards/Patents Issued

NONE

Acronyms

APU – Auxiliary Power Unit

WHR – Waste Heat Recovery

CFD – Computation Fluid Dynamics

BTE – Brake Thermal Efficiency

EGR – Exhaust Gas Recirculation

SOFC – Solid Oxide Fuel Cell

PSAT – Powertrain System Analysis Toolkit

SCR – Selective Catalytic Reduction

II.L. Systems Level Technology Development and Integration for Efficient Class 8 Trucks

Principal Investigator: Derek Rotz (Vehicle)
Daimler Trucks North America LLC
Mailcode POC-AE
4747 North Channel Avenue
Portland, OR 97217
Phone: (503) 746-6303; Email: Derek.Rotz@Daimler.com

Principal Investigator: Kevin Sisken (Engine)
Detroit Diesel Corporation
HPC A-08
13400 Outer Drive West
Detroit, MI 48239-4001
Phone: (313) 592-5815; Email: Kevin.Sisken@Daimler.com

DOE Technology Development Manager :Roland Gravel
Phone: (301) 938-3347; Email: roland.gravel@ee.doe.gov

NETL Project Manager: Carl Maronde
Phone: (412) 386-6402; Email: Carl.Maronde@netl.doe.gov

II.L.1. Abstract

Objective

- Overall Objectives
  - Demonstration of a 50% total increase in vehicle freight efficiency measured in ton-miles per gallon (at least 20% improvement through the development of a heavy-duty diesel engine)
  - Development of a heavy-duty diesel engine capable of achieving 50% brake thermal efficiency on a dynamometer under a load representative of road load
  - Identify key pathways through modeling and analysis to achieving a 55% brake thermal efficient heavy-duty diesel engine
- FY 2012 Objectives
  - Experimental demonstration of technology building blocks that achieve 25% vehicle freight efficiency improvement on a systems level.
  - Experimental demonstration of technology building blocks that achieve 46% engine brake thermal efficiency.

Approach

- Technologies were individually designed, installed on vehicles on a system level and on-highway fuel economy tests were conducted.
- Aerodynamic systems for the tractor and trailer were tested in a scale model wind tunnel and correlated with Computational Fluid Dynamics (CFD)

Major Accomplishments

- Phase 3: Preliminary System Prototypes
  - Powertrain Integration Testing: tires, axle configuration and lubrication management = 7.5% FEI
  - Lightweight Testing: Frame design and materials, chassis components = 5% FEI

- Energy Management Testing: Idle reduction and predictive technology controls = 3.5% FEI
- Parasitic Losses Testing: Clutched air compressor and electronic air controls = just under 1% FEI
- Aerodynamics Testing: Tractor-trailer aero improvements in wind tunnel & CFD = 10% FEI combined

Future Activities

- Phase 4: Target System Optimization
  - Optimize vehicle systems to reach efficiency targets including SuperTruck integration
- Phase 5: SuperTruck Buildup
  - Build and test final SuperTruck vehicle to demonstrate 50% vehicle freight efficiency

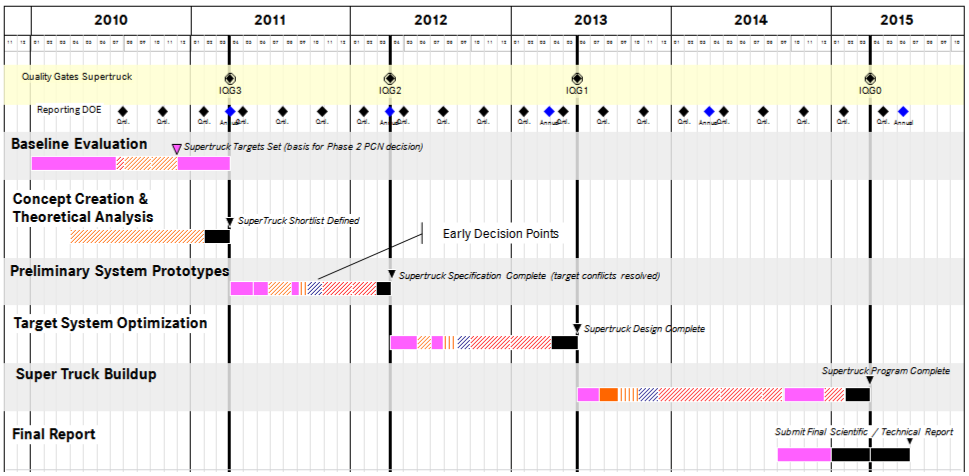


Figure 1. SuperTruck Project Schedule.

II.L.2. Technical Discussion

Introduction

SuperTruck is a 5 year research and development program with a focus on improving diesel engine and vehicle efficiencies. The objective is to develop and demonstrate a class 8, long haul tractor-trailer which achieves a 50% vehicle freight efficiency improvement (measured in ton-miles per gallon) over a best-in-class 2009 baseline vehicle. The engine for the SuperTruck program will deliver 50% brake thermal efficiency.

Approach

In FY 2012, SuperTruck completed the second phase and entered the third phase of the program. The phase 2 approach entailed modeling simulation and analysis of various vehicle technologies and concepts which resulted in the specification of major systems and components to be included in the final SuperTruck demonstrator.

Phase 3 activities encompass the detailed design, installation and testing of technologies on a system level by conducting on-highway fuel economy tests. In this phase the program target of experimentally demonstrating 25% vehicle freight efficiency was successfully reached. In parallel the engine target of 46% brake thermal efficiency was reached by means of dynamometer tests.

Installation of vehicle systems occurred on two 'Tinker' Trucks, from which basic functionality, performance and fuel economy tests were conducted. One truck is equipped with an A-sample hybrid electric powertrain and high voltage electric HVAC system. The second truck has installed powertrain/drivetrain systems along with auxiliary systems which were optimized for efficiency.

Figure 2. 'Tinker' Trucks used for functional and Fuel Economy Tests.

Several SAE Fuel Economy tests were conducted on numerous systems, spanning powertrain drivetrain, auxiliary components, idle reduction, and control systems. Furthermore aerodynamics testing was accomplished via scale model wind tunnel testing and Computational Fluid Dynamics. Lastly prototype lightweight chassis component were built and tested for strength and stiffness.

Results

The figure below illustrates the aggregate results to date. As can be seen the 25% vehicle freight efficiency target was exceeded with an aggregate total of 27% improvement measured.

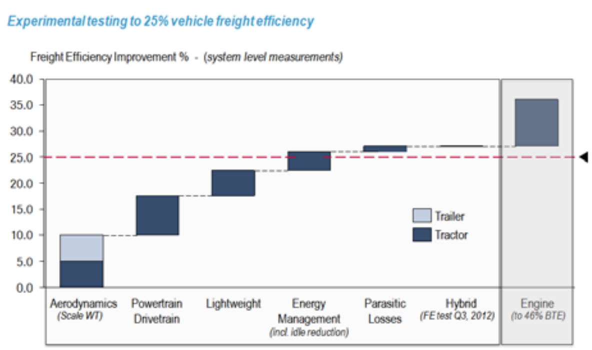


Figure 3. Experimental Freight Efficiency results to date.

Conclusions

The analysis in phases 1&2 provided a technology path that when implemented and tested will demonstrate the overall 50% freight efficiency target and 50% engine brake thermal efficiency. Phase 3 builds upon these results through the design, implementation and on-vehicle testing of systems which met the interim program target. The SuperTruck Program is on track towards reaching its overall goal and the vehicle design is scheduled to be completed at the end of phase 3 in Q2, 2013. Similarly, engine sub-system specifications are being defined and components procured to be tested at system level prior to the overall integration of technologies for meeting the overall goal of 50% brake thermal efficiency.

II.L.3. Products

Publications

1. Sisken, Kevin: "Super Truck Program: Engine Project Review Recovery Act –Class 8 Truck Freight Efficiency Improvement Project", Project ID:ACE058, DoE Annual Merit Review, May 17, 2012
2. Rotz, Derek: "Super Truck Program: Vehicle Project Review Recovery Act –Class 8 Truck Freight Efficiency Improvement Project", Project ID ARRAVT080, DoE Annual Merit Review, May 17, 2012

Patents

1. None

II.M. Volvo Energy Efficient Vehicle – SuperTruck

Principal Investigator: Pascal Amar
Volvo Technology of America
7825 National Service Road
Mail Stop: AP1/3-41
Greensboro, NC 27409
E-mail: pascal.amar@volvo.com

DOE Technology Development Manager: Roland Gravel

NETL Project Manager: Ralph Nine

II.M.1. Abstract

Objective

- Overall objectives
  - Reduce friction and parasitic losses to improve overall fuel efficiency
  - Reduce fuel use during long haul driving cycle
  - Reduce fuel use during 'hotel mode'
  - Reduce curb weight of complete vehicle
  - Optimize energy usage in the complete vehicle
- FY 2012 Objectives
  - Implement first set of advanced components on a test vehicle for testing
  - Evaluate key technologies on road to refine choice of concepts for final demonstration

Major Accomplishments

- A drag reduction of 23% using trailer add-on devices was identified through CFD simulations. Full scale prototypes were built and installed on a truck, which confirmed the expected 11% fuel consumption reduction through on-road testing.
- A complete body-in-white (BIW) side assembly was built with aluminum outer panels and successfully tested for coating and thermal properties. We expect to reduce cab weight by 15% compared with the MY2009 tractor.
- A new roof concept was defined, which is expected to reduce weight and cost by structural simplification. A prototype will be built by the end of the year.
- Prototype tractor headlamps using energy efficient LED lights were designed, fabricated and successfully tested during the calendar year. A new lighting system for the trailer consisting of light-gauge harness and LightForm LED film was developed, installed and tested.
- Virtual installation of the new powertrain in the test chassis is complete, and hardware procurement has begun in preparation for the build at the end of the year.
- The Waste Heat Recovery (WHR) system is being calibrated on the new engine, and is capable of operating closed-loop.

Future Activities

- Correlate CFD results of complete vehicle aerodynamic performance with full scale vehicle test results for aerodynamic drag evaluation
- Install the new powertrain system including new combustion components and waste heat recovery sub-system in a test chassis for on-road testing and verification
- Build and install lightweight sleeper cab and roof on test vehicle for further evaluation
- Determine concepts to include in final demonstration vehicle

II.M.2. Technical Discussion

Introduction

Aerodynamic drag force accounts for the major part of the tractive load of a vehicle-trailer moving at highway speeds, and must be reduced in order to improve complete vehicle efficiency. The project team is investigating ways to increase the aerodynamic performance of standard trailers, and optimize tractor design with regard to shape and contour to reduce aerodynamic drag and provide a smooth interface to the trailer.

Reducing the weight of the vehicle directly benefits the freight efficiency of a long-haul truck. New materials are therefore evaluated to provide maximum weight reduction without sacrificing structural integrity, safety, durability or ergonomics.

Another key contributor to freight efficiency is the efficiency of the powertrain. We are therefore exploring various solutions to improve the combustion process, recover energy which would otherwise be rejected in the form of heat, and reduce friction losses in the complete driveline in order to maximize the amount of energy which actually contributes to moving freight.

Such changes to the driveline will impact packaging and heat rejection. Therefore the installation, cooling and venting concepts need to be modified to provide optimum vehicle efficiency.

Earlier studies have shown that auxiliary devices account for 5–7% of the total fuel consumption. The Volvo SuperTruck team is designing a complete energy-balancing system to optimize the trade-off between mission performance and energy consumption. A new high-efficiency lighting system will help reduce electrical consumption of the complete truck. The reduced power requirements will also enable redesign of some components for lighter weight and/or lower air resistance.

Field data shows that some long haul fleets idle as much as 40% of vehicle operating time. In order to address the efficiency of long-haul trucks under their complete operating cycle it is crucial for long-haul applications to address energy use during idling time.

Approach

The Volvo team uses its complete vehicle simulation capabilities to support the SuperTruck concept selection. It consists of models of the truck concept, which consist of the sub-models for the vehicle, driver and the road and environment. Each of these sub-models is further built from its component models in a modular form. This platform provides a quantitative insight into potential interactions between vehicle systems, allowing the development of a completely integrated vehicle.

Many new component models need to be developed to represent the new technologies that are considered in the SuperTruck project. Significant progress was made in this area, primarily with the addition of thermal modeling of the engine and exhaust aftertreatment systems to support the new Waste Heat Recovery models.

There are a large number of possible Waste Heat Recovery (WHR) system configurations. A detailed comparison of the possibilities concluded that a system layout comprised of an EGR heat exchanger in parallel with an exhaust stack heat exchanger was best suited for the SuperTruck long-haul truck application. The energy captured is transferred back to the driveline through a piston expander.

Complete vehicle CFD simulations are used to balance the conflicting requirements of increased heat rejection and improved tractor aerodynamics. The complete test truck was scanned to ensure accuracy of the geometries modeled, and the simulated coefficient of drag was confirmed with road test data collected with the same truck. CFD simulations are also used to identify the most effective geometries of add-on devices to improve the aerodynamic performance of the trailer. Freight Wing then produces prototypes which are installed on a trailer for full size road testing to validate the improvements predicted by simulations. Each device is then optimized virtually to deliver a final geometry that will be fabricated and field tested for operational effectiveness. The same approach is taken to improve the shape of the tractor in order to reduce the coefficient of aerodynamic drag of the complete vehicle.

A study was completed for a lightweight Cab/Sleeper concept, which combines a stainless steel frame and aluminum skin. The complete cab should be approximately 15% lighter than its baseline. Several assemblies were built at our Cab plant in Virginia, with varying methods of attaching the skin to frame to evaluate their performance with regards to coating and thermal expansion.

A new lightweight roof concept is also being investigated and is in the process of prototyping. The material options for a light weight truck roof consist primarily of long and continuous glass fiber roll goods primarily in dry form. Carbon fiber is potentially an option but the cost is much higher than glass fiber. Another way to achieve it in a cost effective manner is by structural simplification. This will yield a lighter component as well as reduce the parts count and eliminate assembly steps.

The SuperTruck demonstrator will be equipped with state-of-the art low friction tires which the team will select from existing suppliers and industry partners. The team will further reduce the rolling resistance of the complete vehicle by optimizing synthetic lubes for axles and transmission, as well as using improved bearings for axles and wheel ends.

The team has deployed efficient LED lights for both interior and exterior lighting to further reduce the energy consumption of the vehicle. The trailers' exterior lighting uses Grote's LightForm technology to replace incandescent bulbs and fixtures, and a new set of LED headlamps was designed, built and tested during this fiscal year.

In order to reduce energy usage during idling, the team will develop an energy management system that shuts down the main engine after parking, and utilizes the most efficient energy source / storage system to power typical Hotel Mode loads. Volvo will also introduce energy saving materials, like better thermal insulation and reflective coating to minimize power requirements when the truck is parked, while creating a more comfortable climate for the driver. This study also includes alternative solutions for energy storage.

In order to reduce driver impact on the efficiency of the complete vehicle, the Volvo team plans on implementing advanced driver assistance solutions for powertrain, and controls optimized for best fuel economy and safety based on preview information. Telematics will also be investigated as a mean to improve transport efficiency.

Results

The front cooling package was redesigned to include low temperature radiators for the Waste Heat Recovery system, and several solutions were identified using CFD simulations to increase or maintain airflow through the radiators while improving cab front end aerodynamics.

A lightweight trailer was built to be used as a test platform for aerodynamic devices and innovative lighting technologies. It was delivered in March 2012 and has been used for road testing of several iterations of aerodynamic geometries and lighting components.

The initial geometries of trailer add-on devices resulted in a fuel consumption reduction of over 11%, which confirmed the simulated impact on aerodynamic drag reduction. These geometries were further optimized and could yield an additional 3% fuel savings; the main areas of improvement were the side skirt height, the tail piece length, angles and location of the bottom panel, and the tapering of the side skirts at the back of the trailer. The final design for these trailer add-on devices has been completed and prototypes are being built in preparation for fuel economy validation road testing later this year. The focus of the simulation effort has now shifted to the first iteration of tractor aerodynamic design enhancements, including the optimization of the tractor side skirts in conjunction with the optimized trailer. The initial CFD simulations show a potential for 2% reduction in aerodynamic drag.

The results from lightweight Cab/Sleeper test assemblies were applied to a full Body in White prototype build, which was successful and allowed the team to move directly to the design phase of the concept truck, approximately 6 months ahead of the original schedule.

A prototype roof based on the simpler structural design described above is planned to be fabricated before the end of the year. The master model was completed and an A surface mold is now complete to produce a first prototype.

The Waste Heat Recovery system was installed on the new engine for calibration and optimization. The system is now capable of operating closed-loop, and it will be installed in a chassis later this year for further evaluation.

The very complete vehicle model has allowed the team to identify the target areas for improvement, and to predict the impact of vehicle improvements on the operating requirements of the complete powertrain. For example, Figure 1 below shows the predicted effect of reduced friction and aerodynamic drag on exhaust aftertreatment system temperatures.

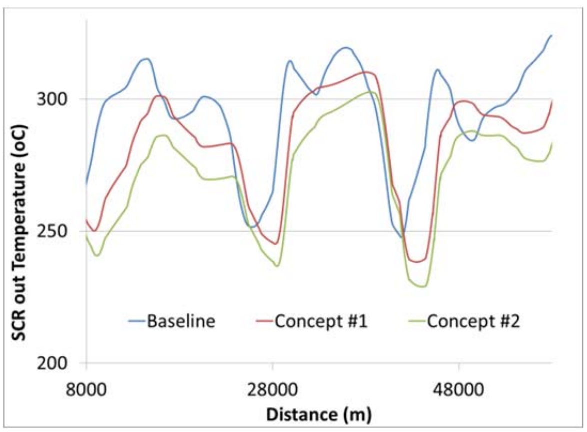


Figure 1. Simulated SCR out temperature.

The complete vehicle model for the baseline truck was thoroughly validated using road test data collected with the baseline truck during the reporting period.

Conclusions

During this fiscal year the Volvo SuperTruck team has focused on building and testing the various concepts identified at the beginning of the project. This comprehensive evaluation delivered the data and knowledge needed to verify assumptions made when developing the project's roadmap. Simultaneously, new analytical tools and methods needed to support the upcoming challenge of complete vehicle integration and optimization were put in place. These products are critical in securing that the team continues into the next phase of the project with the right focus. The next fiscal year will see the selection of a complete vehicle concept for the final demonstrator, and the continued improvements to key components based on this past year's testing and verification efforts.

III. LAB & FIELD VEHICLE EVALUATIONS

LAB & FIELD EVALUATIONS (LIGHT DUTY)

III.A. Advanced Vehicle Testing Activity – Light Duty Field and Laboratory Testing

Principal Investigator: James Francfort
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2209
Phone: (208) 526-6787; Email: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.A.1. Abstract

Objective

- Continue to provide to DOE, OEMs, taxpayers and other stake holders, fully independent, benchmarked feedback on DOE technology investments.
- Benchmark grid-connected plug-in electric drive vehicles (PEV) and hybrid electric drive vehicles to determine the contribution PEV and HEV technologies can make to reduce petroleum consumption in the United States.
- Benchmark individual PEV and HEV models from original equipment manufacturers (OEMs).
- Reduce the uncertainties about PEV and HEV performance, and most importantly, battery performance and life.
- Reduce the uncertainties about drivers' recharging practices and PEV acceptance.
- Provide PEV and HEV testing results to the U.S. Department of Energy (DOE), vehicle modelers and designers, technology target setters, and industry stakeholders.
- Provide PEV and HEV testing results to fleet managers and the general public to support their acquisition and deployment decisions.

Approach

- Document via various testing methods real-world fuel use over various trip types and distances.
- Report liquid and vapor fuel use, and electricity use separately.
- Document PEV electric vehicle supply equipment (EVSE) and fast charger performance (profile and demand), charging times, and infrastructure needs, as well as operator behavior impact on charging times and frequencies.
- Document any environmental factors, such as temperature and terrain that impact PEV and HEV fuel consumption.
- Use published testing specifications and procedures developed by the AVTA that are reviewed by industry, national laboratories, and other interested stakeholders.
- Obtain access to Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs), Extended Range Electric Vehicles (EREVs), all of which are considered to be PEVs, as well as HEVs, EVSE, and fast chargers for testing to the reviewed testing specifications and procedures.
- Perform baseline performance track and laboratory tests, accelerated on-road tests, and fleet demonstrations on vehicles, components and charging infrastructure as appropriate.
- Place vehicles in environmentally and geographically diverse test fleets.
- Continue to use and develop cost-shared partnerships with public, private, and regional groups to test, deploy, and demonstrate vehicles and infrastructure technologies in order to leverage DOE funding resources.

- Expand the use of automated data collection, transmission, analysis, and reporting processes.
- As needed, reach additional cooperative research and development agreements (CRADAs) and non-disclosure agreements (NDAs) in preparation for the testing of vehicles and components from OEMs.

Major Accomplishments

- Performed data collection and reporting for 150 General Motors Volts EREVs as part of an ARRA funded demonstration between DOE and General Motors. As FY 2012 ended, 1.2 million test miles of vehicle operations, charging profiles and fuel use was documented. This mostly electric utility personnel operated fleet was using 174 AC WH per mile and 70.0 mpg. In electric only mode, the Volt used 352 AC Wh per mile and in gasoline mode it was averaging 35.4 mpg.
- Performed data collection from a fleet demonstration of 111 Chrysler Ram PHEV Pickups. As FY 2012 ended, 1.0 million test miles of vehicle and charging profiles, as well as mpg increases of up to 35% were documented when comparing operations with at least a partially charging PHEV traction battery pack.
- Continued the data collection from what will eventually be approximately 14,000 Level 2 EVSEs and fast chargers from ECOtality North America as part of the EV Project as well as Nissan Leafs, Chevy Volts and Smart EVs. As FY 2012 ended, data had been collected from 5,631 Nissan Leaf BEVs, Chevrolet Volt EREVs, and Smart EVs, as well as 7,600 ECOtality EVSE being operated in nine states and the District of Columbia. A total of 42.2 million test miles and 1.2 million charging events have been documented, and for the Nissan Leafs, there is a complete elimination of in-vehicle use of petroleum for transportation.
- Continued the data collection from what will eventually be approximately 4,500 Coulomb ChargePoint America EVSE. At the end of June 2012 (most recent published and approved results), data had been collected from 3,085 EVSE and 365,664 charge events in twelve states.
- Supported the memorandum of understanding (MOU) between the Departments of Energy (DOE) and Defense (DOD) that specifies DOE technical support to DOD to help DOD reduce petroleum use for non-strategic vehicle transportation, by conducting a Micro Climate study of Joint Base Lewis McCord’s ability to install EVSE and electric drive vehicles. A similar study was initiated with the Jacksonville and Mayport naval facilities in Florida. In addition, 18 Blink EVSE were provided to Andrews Air Force Base for installation.
- Initiated data collection from a fleet demonstration of 17 Quantum Ford Escape PHEV conversions. As FY 2012 ended, 69,000 test miles of vehicle and charging profiles, as well as mpg increases of up to 22% were documented when comparing operations with at least a partially charged PHEV traction battery pack.
- Supported international petroleum reduction activities via a Shanghai / Los Angeles data sharing partnership sponsored by DOE that requires the reporting of EV Project data by the AVTA.
- Obtained and supported PEVs for DOE Headquarters and Clean Vehicles education activities.

Future Activities

- Continue to report on the performance of up to 140 Chrysler Ram PHEV Pickups and report the petroleum reduction capabilities and operations of the same vehicles.
- Continue to report on the performance of up to 150 General Motors Volts EREVs and report the petroleum reduction capabilities and operations of the same vehicles.
- Continue to report on the performance of up to 8,300 Nissan Leaf EVs and General Motors Volt EREVs being deployed as part of the EV Project as well as approximately 14,000 ECOtality Blink EVSE and fast chargers. Reporting will include recharging and vehicle use patterns, as well as the petroleum reduction capabilities of the charging infrastructure and vehicles. The data collection for this project will conclude in late FY 2013 and at that point significant analysis will commence.
- Continue to report on the operations of up to 4,500 Coulomb ChargePoint America EVSE.
- Continue Quantum PHEV Explorer conversion testing in partnership with the South Coast Air Quality Management District in California.
- Continue performing due diligence on potential vehicle, component, and charging infrastructure suppliers and obtain such for testing as appropriate. Candidate PHEVs, HEVs, BEVs, CNG, and diesel vehicles with advanced propulsion and energy storage components will enter benchmarking.

- Develop additional low-cost vehicle and charging infrastructure demonstration relationships and support the deployment of PEVs and electric drive vehicles (EDVs) in these testing fleets.
- Continue to coordinate PEV, EDV, and charging infrastructure testing with industry and other DOE directed entities. This includes supporting the data collection from EVSE deployed via the DOE Clean Cities activities, FEMP, and the Office of Electricity Reliability and Energy Delivery.

III.A.2. PEVs Technical Discussion

Background

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing (AVTA) is part of DOE's Vehicle Technologies Program (VTP), which is within DOE's Office of Energy Efficiency and Renewable Energy (EERE). The AVTA is the only DOE activity tasked by DOE to conduct field evaluations of vehicle technologies that use advanced technology systems and subsystems in light-duty vehicles to reduce petroleum consumption. A secondary benefit is the reduction in exhaust emissions.

Most of these advanced technologies include the use of electric drive propulsion systems and advanced energy storage systems. However, other vehicle technologies that employ advanced designs, control systems, or other technologies with production potential and significant petroleum reduction potential, are also considered viable candidates for testing by the ATVA.

The AVTA light-duty activities are conducted by the Idaho National Laboratory (INL) for DOE. INL has responsibility for the AVTA's execution, direction, management, and reporting; as well as data collection, analysis and test reporting. INL is supported in this role by ECOtality North America (ECOtality), which has a competitively awarded contract that is managed by DOE's National Energy Technology Laboratory (NETL). The AVTA sections of the FY 2012 Annual Program Report jointly cover the testing work performed by INL and ECOtality. When appropriate, the AVTA partners with other governmental, public, and private sector organizations to provide maximum testing and economic value to DOE and the United States taxpayers, via various cost sharing agreements.

Introduction

DOE's AVTA is evaluating grid connected plug-in electric drive vehicle (PEV) technology in order to understand the capability of electric grid recharged electric propulsion technology to significantly reduce petroleum consumption when vehicles are used for transportation. In addition, many companies and groups are proposing, planning, and have started to introduce PEVs into their fleets.

It should be noted that grid-connected PEVs include several vehicle / energy storage schemes that include: battery electric vehicles (BEVs or simply EVs) such as the Nissan Leaf, plug-in hybrid electric vehicles (PHEVs) such as the Ford Escape and Chrysler Ram PHEVs, and extended range electric vehicles (EREVs) such as the General Motors Volt.

During FY 2011, a transition occurred from testing mostly PEV conversions to testing PEVs from OEMs. When testing conversion vehicles, the primary focus during FY 2011 was to study the PEV technology's potential contribution to petroleum reduction and to understand and document charging patterns. The drive to focus on the overall petroleum reduction potential of PEV technology versus testing individual PHEV conversion models was driven by the mostly conversion nature of the available PEVs during pre-FY 2012 years, and the non-likelihood the conversion vehicles would be the majority of PEV deployments in future years. During late FY 2011, this transition was completed when the last of the PEV conversions completed testing.

This transition in focusing on PEV conversions to focusing on PEVs from OEMs was made possible as several OEMs made available during late FY 2011, PEVs for the first time in about a decade.

The PHEV conversions available for public purchase in the few years prior to FY 2012 used an HEV as the base vehicle, and either added a second PHEV battery or replaced the base HEV battery with a larger PHEV battery pack, with a 5 kWh PHEV battery size the most typical size for secondary batteries. However, some PHEVs and EREVs used a single battery pack that ranged from 10 to 15 kWh. PHEV control systems and power electronics are also added to the base vehicle to complete the upgrade. These larger additional or replacement battery packs are sometimes recharged by the onboard regenerative braking and generator subsystems, but all of them must also use onboard chargers connected to the off-board electric grid to fully recharge the PHEV battery packs.

Today's OEM PEVs mostly have 10 to 15 kWh of onboard battery storage in PHEVs and EREVs, and more than 20 kWh of onboard storage for BEVs. However, some other OEMs are introducing PHEVs with smaller battery packs.

Within the AVTA, INL and ECOtality make extensive use of in-vehicle and in-charging infrastructure data loggers to collect a variety of vehicle and infrastructure generated performance parameters. Experience has shown that automated data collection in fleet environments is the only way to ensure accurate data is collected.

The concept of advanced onboard energy storage and grid-connected charging raises questions that include the life and performance of these larger batteries; the charging infrastructure required; how often the vehicles will actually be charged – driver and "smart grid" behavior and controls; and the actual amount of petroleum displaced over various missions, drive cycles, and drive distances; all achieved with automated data loggers.

Approach

Three basic types of test methods are used to test vehicles and they discussed below.

Baseline performance testing during which a vehicle is track and dynamometer tested. The track testing includes acceleration, range, braking, and fuel use (both electricity and gasoline) at different battery states-of-charge (SOC). The vehicles are also coast-down tested to determine dynamometer coefficients, which are used during the various urban and highway dynamometer test cycles. Note that the AVTA dynamometer testing is conducted by Argonne or Oak Ridge National Laboratories for the AVTA. This sharing of vehicles and testing expertise also reduces costs to DOE.

Accelerated Testing uses dedicated drivers to complete a series of drives and charges (for PEVs) on city and highway streets. This testing is often used to ensure PEVs can accomplish several charge and drive cycles in one day. For some vehicles, this can include more than 5,000 miles of operation per month.

Fleet Testing is normally conducted by placing vehicles into fleets with no highly controlled structure to repeatable drive missions. The AVTA partners with government, private, and public fleets for fleet testing as these fleets are often overwhelmingly the earliest adaptors of advanced technology vehicles. Note that the AVTA fleet testing does sometimes include operations by the general public.

For PHEVs and EREVs, these vehicles can operate on gasoline even when the vehicles' battery packs are not charged. The fuel-use result reporting is normally broken down into three operating modes for these vehicle technologies:

Charge Depleting (CD) Mode: During each entire trip, there is electric energy in the traction battery pack to provide either all-electric propulsion or electric assist propulsion throughout the entire trip.

Charge Sustaining (CS) Mode: During a trip, there is no electrical energy available in the PHEV or EREV traction battery pack to provide any electric propulsion support beyond normal HEV operations.

Combined (or Mixed) Charge Depleting and Charge Sustaining (CD/CS) Mode: There is electric energy in the traction battery pack available at the beginning of a trip. However, during the trip, the PEV battery is fully depleted.

For EVSE benchmarking, the results are broken down a variety of ways, including:

- Public versus private EVSE use
- Weekday versus weekend use
- By time of day
- National versus regional results.

Results

General Motors Chevrolet Volt EREV

During FY 2011, a NDA was signed with OnStar that detailed data collection, analysis and reporting by the AVTA for the vehicle performance, fuel use, and charging patterns for approximately 150 General Motors Chevrolet Volt EREVs. This work is being performed to support an ARRA grant General Motors received from DOE.

Using server-to-server data transmission, the INL receives raw data generated by OnStar from onboard data loggers installed on the Volts. With this data, which is generated for every key on and off event, INL generates a series of periodic reports which can be accessed at: avt.inl.gov/gmvehicledemo.shtml.

Quarterly reports are being generated for this project, and for the project-to-date report, May 2011 to June 2012 (the third quarter 2012 report was not yet published when this report was prepared), the 150 Volts where averaging 70.0 mpg and 174 AC Wh per mile (Wh/mi) overall after 1.2 million test miles. When operating in electric vehicle mode operation (EV mode), the vehicles were averaging 352 AC Wh/mi. In extended range mode operations (ERM), the Volts were averaging 35.4 mpg.

During EV mode, only electricity is being used to propel the Volt; the gasoline engine does not operate. In ERM, the vehicle operates like a traditional HEV, with the traction battery accepting regenerative braking energy. However, the Volt does have to be recharged from the grid for EV mode operations to resume.

As Figure 1 shows more EV mode trips occurred during shorter distance trips as would be expected. Figure 2 documents the near full battery state of charge (SOC) at the end of each charge event prior to driving events and Figure 3 documents the low SOC at the end of the drive prior to charging.

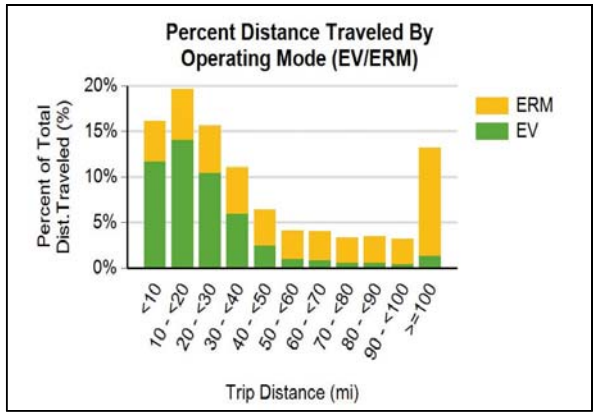


Figure 1. ERM and EV operations for the Volt as measured by the percent of total distance traveled.

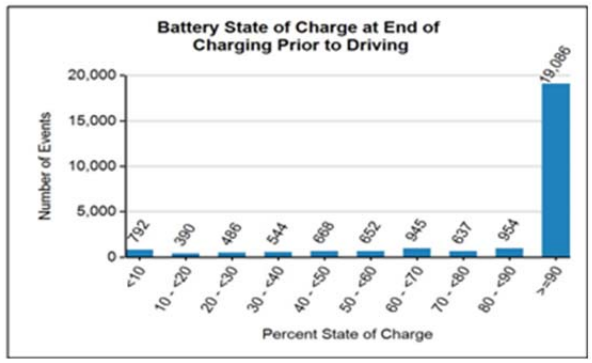


Figure 2. Volt SOC at end of charging events prior to driving events.

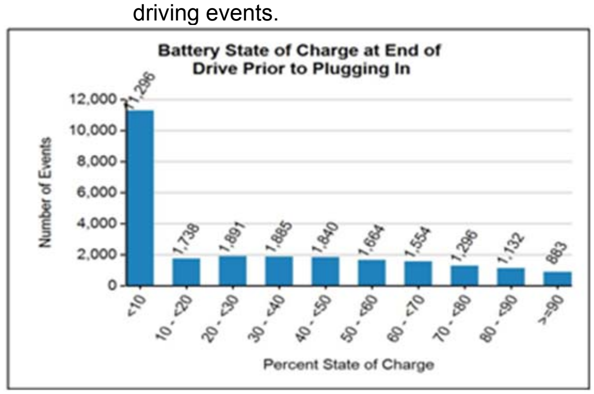


Figure 3. Volt SOC at the end of drives that occur prior to start of charging events.

Table 1 below documents the Volt recharging information statistics.

Table 1. Volt summary charging information for the July through September 2011 reporting period.

Average # charging events per vehicle month	17
Average # of charging event per vehicle day	1.3
Average miles between charging events	43
Average # trips between charging events	3.4
Average hours charging per charging event	3.2
Average energy (AC kWh) per charging event	7.2
Average energy (AC kWh) per vehicle month	125
Total charging energy (AC kWh)	216,689

It should be noted that these Volts were mostly being driven in fleet operations modes and the fleet drivers do not normally pay for fuel use, so they may not be overly motivated to maximize ERM operations by ensuring the vehicle's traction battery packs are charged as often as possible.

Chrysler Ram Pickup PHEV

During FY 2011, the AVTA signed a NDA with Chrysler that detailed data collection, analysis and reporting by the AVTA for the performance, fuel use, and charging patterns for approximately 140 Chrysler Ram PHEV Pickups. This work is being performed to support an ARRA grant Chrysler received from DOE.

Using server-to-server data transmission, the INL receives raw data generated by Chrysler from onboard data loggers installed on the Ram PHEVs. With this data, INL generates a series of periodic reports which can be accessed at: avt.inel.gov/evproject.shtml.

The most recently published project to date report covers July 2012 to September 2012 (avt.inel.gov/pdf/phev/ChryslerRamJuly11-September12.pdf) and it documents 1.0 million test miles accumulated by 111 of the deployed Ram PHEVs. The 111 Ram PHEVs providing data exhibited a 35% increase in mpg when comparing CD trips (23 mpg) to CS trips (17 mpg). As shown in Figure 4, the Ram operating scheme allows the internal combustion engine (ICE) to be off 37% of the time, including 15% engine off while the vehicle was being driven.

Figure 5 documents the driving aggressiveness impact on mpg, with less aggressive driving resulting in an average of approximately 22 mpg while the most aggressive driving results in an average of approximately 12 mpg.

Table 2 documents the Ram recharging information. It should be noted that the vehicle is being charged only 0.79 times per day for those days the vehicle is operated.

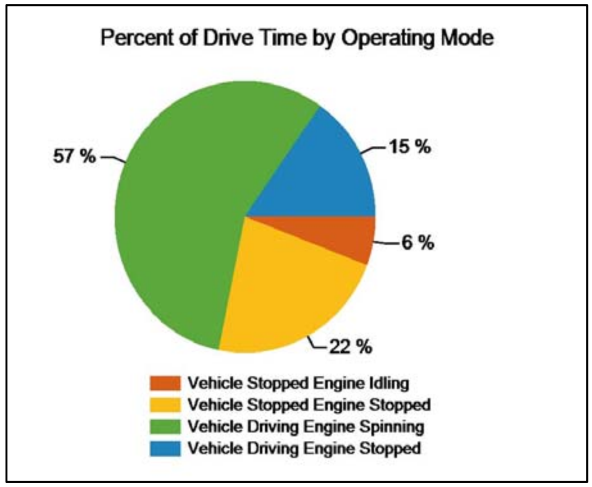


Figure 4. Chrysler Ram PHEV percent of drive time the engine is spinning or stopped.

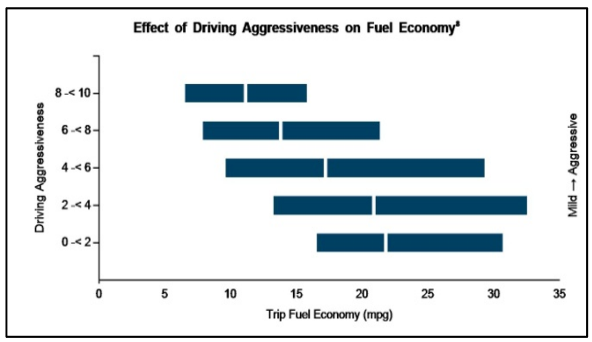


Figure 5. Chrysler Ram Pickup PHEV fuel efficiency impacts from aggressiveness driving.

Table 2. Chrysler Ram PHEV charging information for the July through September 2011 reporting period.

Average # charging events per vehicle month	11.3
Average # of charging event per vehicle day	0.79
Average miles between charging events	70.6
Average # trips between charging events	7.6
Average hours charging per charging event	2.4
Average energy (AC kWh) per charging event	6.35
Average energy (AC kWh) per vehicle month	71.6
Total charging energy (AC kWh)	93,374

Quantum Escape PHEV Testing

During FY 2012, the INL signed a NDA with Quantum Fuel Systems Technologies Worldwide to allow the AVTA to collect, analyze, and report on a fleet of Quantum Ford conversion PHEVs operating in fleets associated with the South Coast Air Quality Management District (SCAQMD). During the period January to June 2012, the 17 Quantum Escapes have accumulated 69,000 test miles. Using the most recently approved and published June 2012 report's (avt.inel.gov/pdf/phev/QuantumJune2012main.pdf) 9,837 test miles, the vehicles are averaging 37 mpg in CD mode, 39 mpg in mixed mode, and 32 mpg in CS mode. While the miles accumulated in June are relatively low and the timing of fueling events may impact mpg reporting, CD and mixed modes operations are demonstrating 16 to 22% increases to the CS mode's 32 mpg. Table 3 provides charging information for the month of June 2012.

Table 3. Quantum Escape PHEV conversions charging information for the June 2012.

Average # charging events per vehicle month	8.0
Average # of charging event per vehicle day	0.7
Average miles between charging events	71.3
Average # trips between charging events	7.8
Average hours charging per charging event	32.7
Average energy (AC kWh) per charging event > 200 W	3.4
Average energy (AC kWh) per vehicle month	39.4
Total charging energy (AC kWh)	670

It should be noted that these Quantum Escapes were mostly being driven in fleet operations and the fleet drivers do not normally pay for fuel use, so they may not be overly motivated to maximize CD operations by ensuring the vehicle's traction battery packs are charged as often as possible.

EV Project Charging Infrastructure Demonstration

The EV Project is a DOE funded ARRA project for deploying and testing PEV recharging infrastructure. Lead by ECOtality North America, it is the largest deployment and testing of EVSE and fast chargers ever attempted. Approximately 14,000 Level 2 EVSE and fast chargers, along with approximately 8,000 Nissan Leafs, Chevrolet Volts and Smart EVs are being deployed in the major population areas of:

- Phoenix and Tucson, Arizona
- San Diego, San Francisco and Los Angeles, California
- Atlanta, Georgia
- Chicago, Illinois
- Southern New Jersey
- Portland, Eugene, Salem and Corvallis, Oregon
- Philadelphia, Pennsylvania
- Chattanooga, Nashville, Knoxville and Memphis, Tennessee
- Dallas, Fort Worth and Houston, Texas
- Washington, D.C.

The project intent is to deploy Level 2 EVSE in the residents of each Leaf or Volt purchaser, and Level 2 EVSE and fast chargers in public locations in order to characterize charging infrastructure and vehicle use in diverse topographic and climatic conditions, evaluate the effectiveness of public versus private charge infrastructure, and conduct trials of various revenue systems for public charge infrastructures. The Smart EVs are all rental cars, so there is no residential EVSE associated with these vehicles.

As FY 2012 ended and this report was being compiled, the total reported project mileage was 42.2 million test miles on the 5,631 Leafs, Volts and Smart EVs reporting results. The more than 7,600 public and residential Level 2 EVSE have reported 1.2 million charging events.

A more in-depth discussion will have to be limited to the most recent published and approved reports that cover the second quarter of calendar year 2012 (April – June 2012). At this point, data had been collected from 4,322 Nissan Leaf battery electric vehicles (Figure 6), 676 Chevrolet Volt extended range electric vehicles, and 6,319 ECOtality EVSE were then providing data from (Figure 7) six states and the District of Columbia. A total of 32.9 million test miles and 881,000 charging events have been documented on the Project Overview Report for the EV Project to date (avt.inel.gov/pdf/EVProj/EVProjOverviewQ22012.pdf)

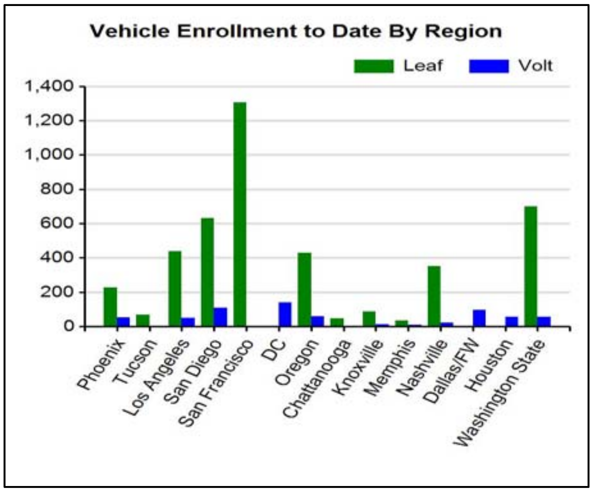


Figure 6. Number of EV Project vehicles providing data and deployment by major cities as of the end of June 2012.

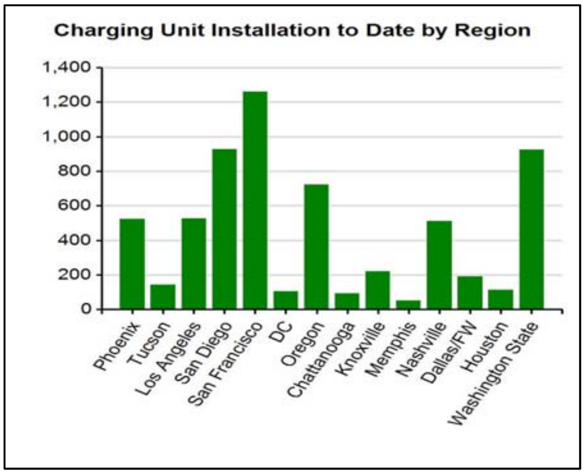


Figure 7. Number of EV Project EVSE deployed and providing data by major cities as of the end of June 2012.

The EV Project's Nissan Leaf summary report for April to June 2012 (avt.inel.gov/pdf/EVProj/EVProjNissanLeafQ22012.pdf) provides national and regional Leaf usage statistics and this data includes the national vehicle usage data seen in Table 4. Additional data for each region can be found in the same above PDF.

Figures 8 and 9 document the Nissan Leaf battery SOC before and after charging events. It will be interesting to see if SOC before-charging changes as operators become more familiar with the vehicles and if SOC at end-of-charging changes as drivers use public charging, including fast chargers for shorter periods of time.

Table 4. EV Project Nissan Leaf BEV usage data for the July 2011 to September 2011 quarter.

Number vehicles	2,911
Total miles	5,666,469
Average miles per trip	7.2
Average miles driven per day when driven	30.6
Average # trips between charge events	3.9
Average miles driven between charge events	28.1
Ave # of charges per day when driven	1.1
Number of at home charging events	152,862
Number of away from home charging events	37,148
Unknown charging event locations	11,969

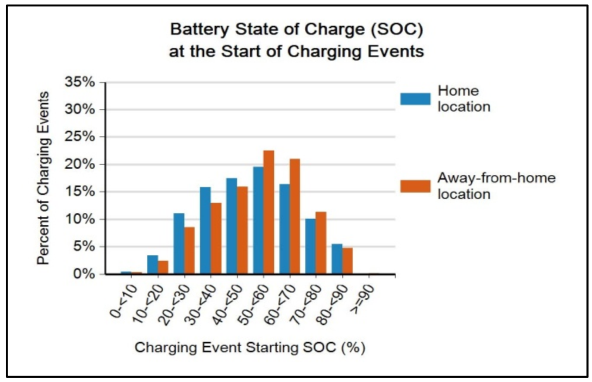


Figure 8. EV Project Nissan Leaf battery SOC at start of charging events.

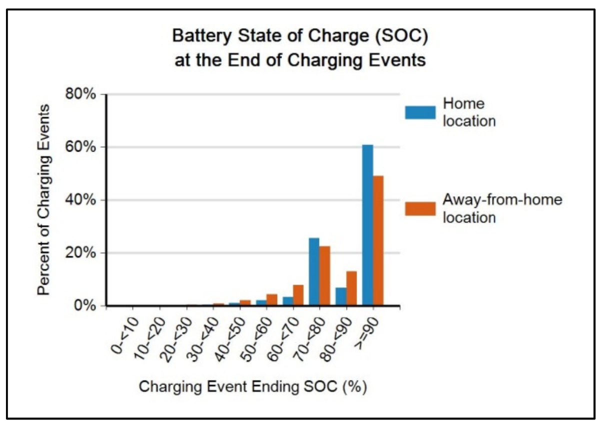


Figure 9. EV Project Nissan Leaf battery SOC at end of charging events.

The EV Project's Chevrolet Volt Leaf summary report for April to June 2012 (avt.inel.gov/pdf/EVProj/EVProjChevroletVoltQ22012.pdf) provides national and regional Volt usage statistics and this data includes the national vehicle usage data seen in Table 5. Additional data for each region can be found in the same above PDF.

Figures 10 and 11 document the Volt battery SOC before and after charging events.

Table 5. EV Project Chevy Volt EREV usage data for the April to June 2012 quarter.

Number vehicles	408
Total miles	1,184,265
Overall mpg	155
Overall electricity consumption (AC Wh/mi)	242
Average miles per trip	8.0
Average miles driven per day when driven	39.6
Average number trips between charge events	3.2
Ave miles driven between charge events	26.0
Ave number of charges per day when driven	1.5
Number of at home charging events	36,015
Number away from home charging events	6,374
Unknown charging event locations	3,179

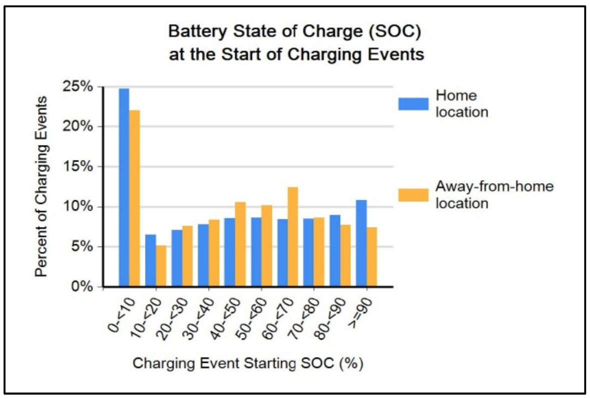


Figure 10. EV Project Chevy Volt battery SOC at start of charging events.

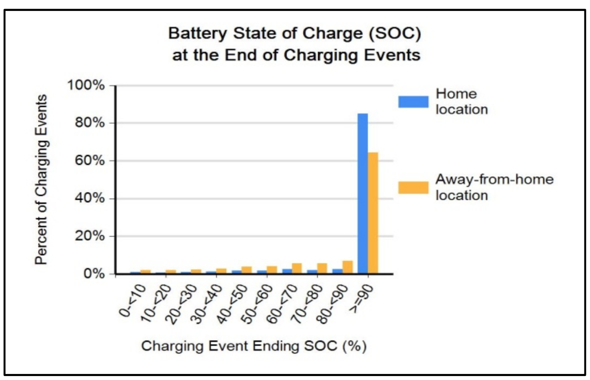


Figure 11. EV Project Chevy Volt battery SOC at end of charging events.

The April – June 2012 quarterly Infrastructure Summary report documents infrastructure utilization nationally and regionally for residential Level 2 EVSE and publicly available Level 2 EVSE. As additional units are installed, this report (avt.inel.gov/pdf/EVProj/EVProjInfrastructureQ22012.pdf) will also include Fact Charge data.

Figure 12 highlights the percent of all national Level 2 EVSE charging units in 15-minute increments with an EV Project vehicle connected during week days. Figure 13 gives the same information for weekend days.

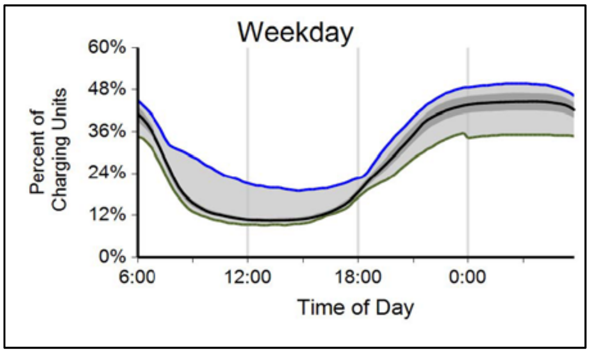


Figure 12. EV Project percent of all national Level 2 EVSE with a vehicle connected during weekdays. Data is in 15-minute increments for any time in the reporting quarter.

Note that for both figures, the blue line is the peak for the reporting period, green line is the minimum, and the black line is the mean, and the darker gray areas above and below the black line are the 25 to 50% and 50 to 75% quartiles. This is true for all figures in this section that report percent of charging units with a vehicle connected, and the electricity demand in AC MW.

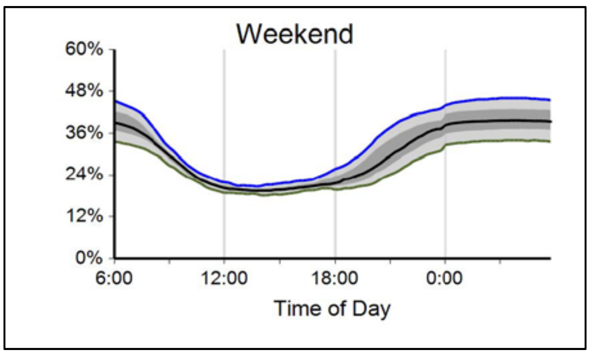


Figure 13. EV Project percent of all national Level 2 EVSE with a vehicle connected during weekends. Data is in 15-minute increments for any time in the reporting quarter.

Figure 14 is the charging profile in AC MWh for all Level 2 EVSE in the EV Project for weekdays and Figure 15 is for weekends. Note the heavy use of post midnight charging.

Figure 16 documents the length of time vehicles are connected to residential EVSE. The two sets of peaks suggest short opportunity charging for less than one or two hours, and overnight charging for 10 to 14 hours. Figure 17 shows the same set of vehicles drawing power for much shorter periods of time than when they were connected as shown in Figure 16. The general shape of Figure 18 matches Figure 17 as would be expected as the distribution of energy consumed would have a similar profile to the length of time the vehicles draw power

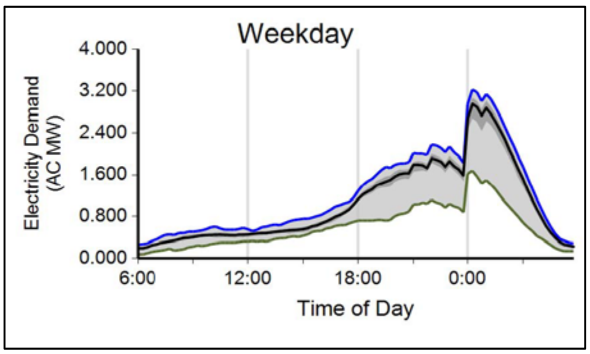


Figure 14. EV Project charging profile based on national energy demand for weekdays. Data is in 15-minute increments for any time in the reporting quarter.

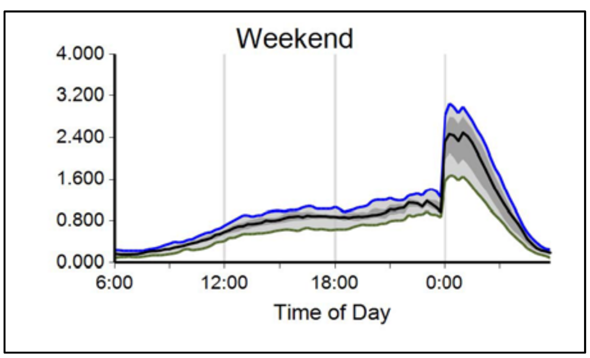


Figure 15. EV Project charging profile based on national energy demand for weekends. Data is in 15-minute increments for any time in the reporting quarter.

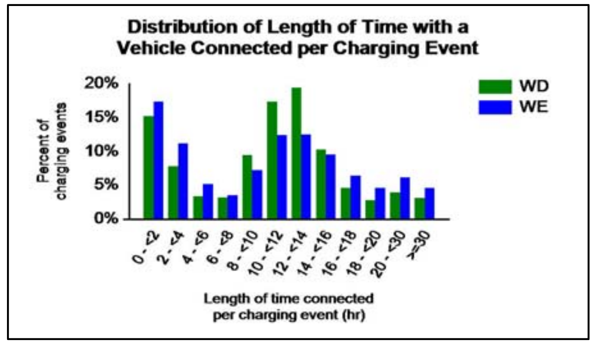


Figure 16. EV Project distribution of length of time with a vehicle connected per charging unit for residential Level 2 EVSE.

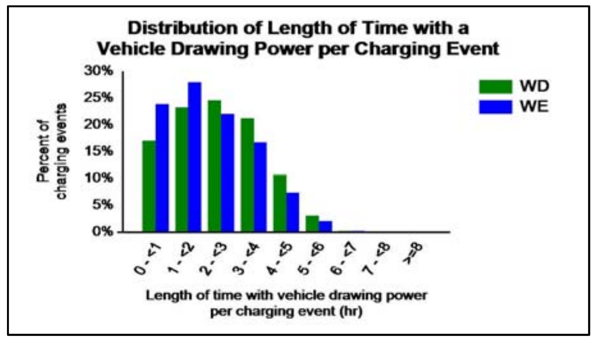


Figure 17. EV Project distribution of length with a vehicle drawing power per charging event for residential Level 2 EVSE.

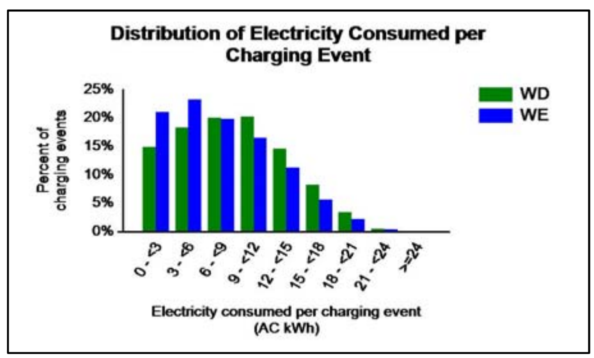


Figure 18. EV Project distribution of electricity consumed per charging event for residential Level 2 EVSE.

The EV Project will continue accumulating both vehicle and EVSE data, with the first fast chargers coming on line during FY 2012. As FY 2012 ended, more than three quarters of a million miles of data was being collected weekly.

Figure 19 is the charging profile for public access Level 2 EVSE as measured by the number of vehicles connected as a percent for weekdays and Figure 20 is the weekend data. It is assumed that at work, or near work public access charging is creating the higher peak in weekday public charging.

Figure 21 documents a similar work day peak profile when vehicles are connected to public EVSE and start drawing power about 9 a.m. on weekdays Figure 22 documents the less significant peak in public charging on weekends

Time of use (TOU) electric utility billing rates for residential charging warrants an expanded discussion. While Figures 14 and 15 clearly show national peak demand at night as measured in AC MW, regional residential profiles significantly highlight TOU rate impacts. Figure 23 shows San Diego weekday peak demand that is influenced by the TOU rates that start at midnight. Figure 24 shows similar impacts that also occur weekends.

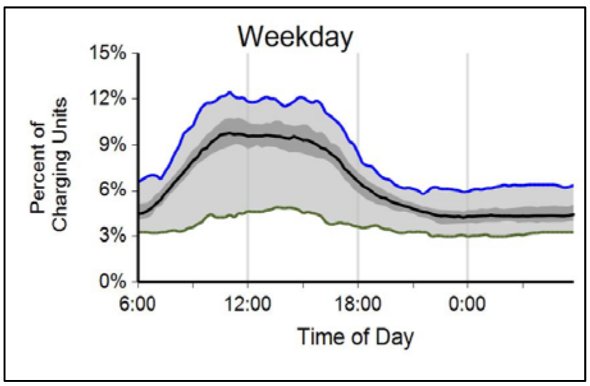


Figure 19. EV Project percent of all publicly available Level 2 EVSE with a vehicle connected during weekdays.

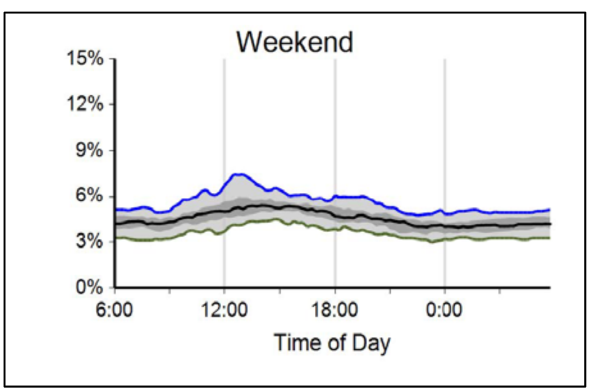


Figure 20. EV Project percent of all publicly available Level 2 EVSE with a vehicle connected during weekends.

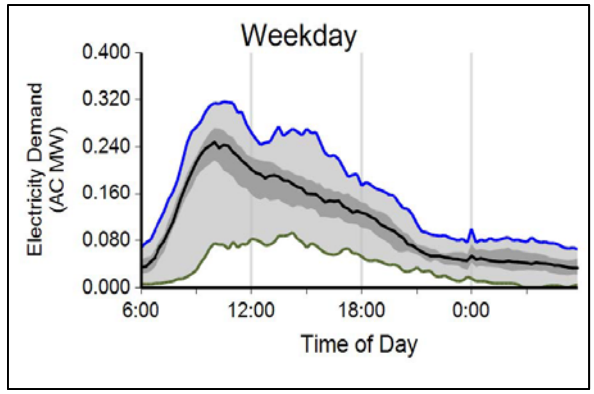


Figure 21. EV Project publicly available Level 2 EVSE charging profile based on energy demand for weekdays.

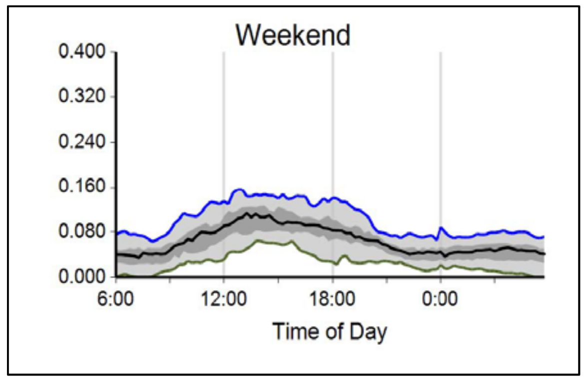


Figure 22. EV Project publicly available Level 2 EVSE charging profile based on energy demand for weekends.

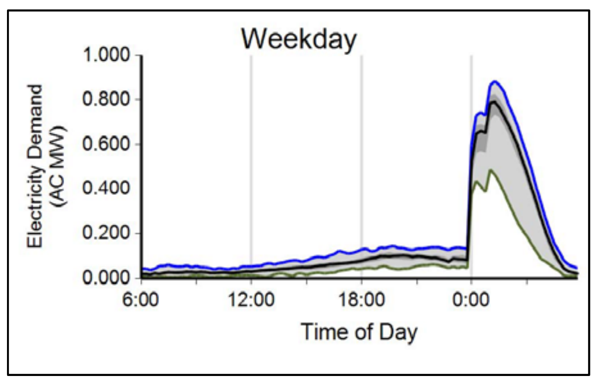


Figure 23. San Diego residential EVSE electric demand for weekdays. Data increment is 15 minutes.

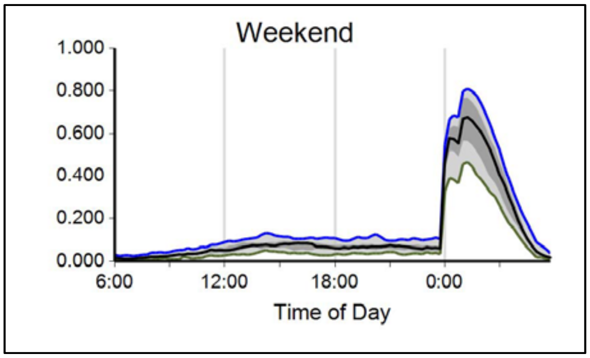


Figure 24. San Diego residential EVSE electric demand for weekends.

A contrast to the San Diego profiles is the weekday and weekend (Figures 25 and 26), demand curves for Washington State. Washington has relatively low electricity rates due to its extensive hydropower generation system. San Diego has more expansive rates, so incentives to shift demand to midnight is successful with TOU charging and TOU whole house rates. In Washington State, there is simply not the ability to offer much lower rates when general electricity rates are low to start with.

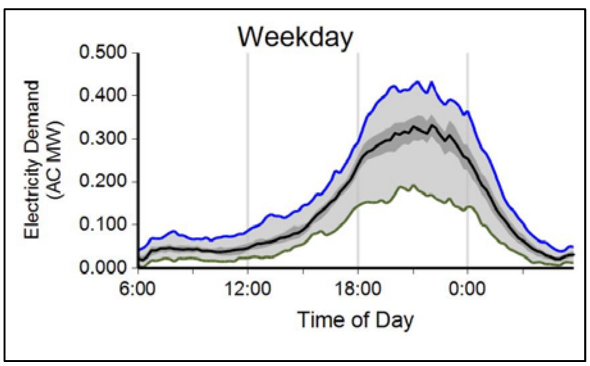


Figure 25. Washington State residential EVSE electric demand for weekdays.

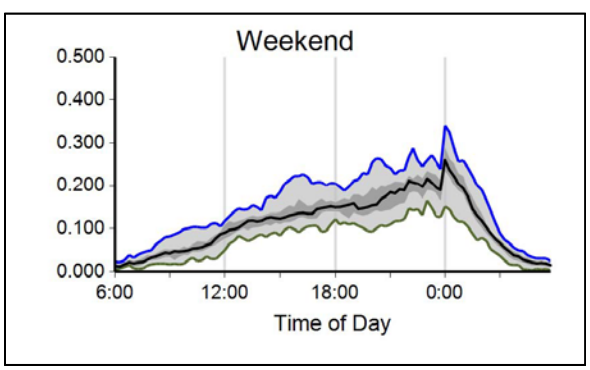


Figure 26. Washington State residential EVSE electric demand for weekends.

ChargePoint America (Coulomb) EVSE Project

The ChargePoint America project is a DOE funded ARRA project for deploying and testing PEV recharging infrastructure. Lead by Coulomb, it will deploy approximately 4,500 Coulomb EVSE. At the end of June 2012, data had been collected from 3,085 EVSE, with most deployed in California (1,351 units). The Project To Date June 2012 report documents 365,664 charging events and the use of 2,509 AC MWh in eleven states and the District of Columbia (avt.inel.gov/pdf/evse/CoulombQ1Combine2012.pdf). Note that there is no vehicle data as part of this project.

Figures 27 and 28 document the use of the ChargePoint America EVSE as measured both by number of charging events and electricity consumed during the April through June 2012.

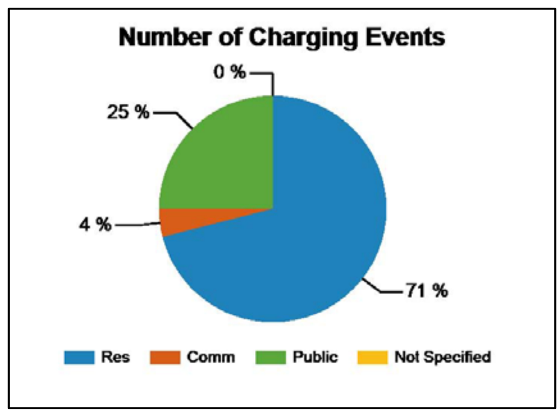


Figure 27. ChargePoint EVSE use as measured by number of charging events.

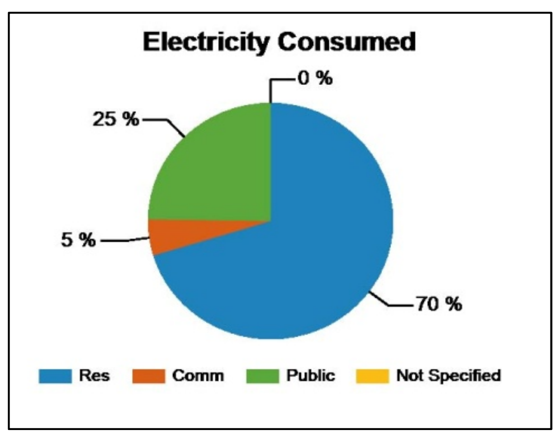


Figure 28. ChargePoint EVSE utilization as measured by number of electric consumer.

DOD / DOE MOU Support

During July 2010, DOE and the U.S. Department of Energy signed the Memorandum of Understanding (MOU) "Concerning Cooperation in a Strategic Partnership to Enhance Energy Security", which covers several energy efficiency areas, including transportation, fueling and grid issues. In support of the MOU, the AVTA has nearly completed a Micro Climate study at Joint Base Lewis McCord in Tacoma Washington. This study takes into account traffic patterns, attractions, transportation hubs, and existing and potential electric infrastructure and charging locations. A subset of the Base's vehicle fleet has also been instrumented to document mission profiles. This work will support the future deployment of charging infrastructure and electric drive vehicles (EDVs) on DOD bases. As FY 2012 ended, the AVTA kicked off a second Micro Climate study at combined Naval Air Station Jacksonville and Naval Seaport Mayport.

The AVTA has also supplied eighteen Blink Level 2 EVSE to Andrews Air Force Base, outside of Washington D.C. for installation by base personnel.

Other Federal Fleet Support

In addition to the above DOD support, the AVTA has been able to benchmark the first 100 of 800 Federal fleet vehicles as FY 2012 ended. This exercise will support the identification of vehicles and missions that will be suitable for replacing current internal combustion engine vehicles with various electric drive vehicle technologies, with the main emphasis on introducing PEVs. This is a joint EERE and FEMP project.

International Testing Support

The AVTA is supporting the outreach by DOE with the European Union, China and Canada. For the EU activities, the AVTA is setting up a cooperative data activity with the Electric Supply Board of Ireland to collect data from fifteen Mitsubishi iMev electric cars and five Nissan Leafs operating in Ireland.

The AVTA is also conducting a U.S. / China sister cities type of data sharing activity, with both the AVTA and various research centers in China, sharing PEV results for Shanghai and China.

The AVTA has been collecting data from approximately 40 PEVs operating across Canada and providing fact sheets to each of the 40 ownership organizations. As FY 2012 ended, discussion was focusing on additional mutual cooperative research activities.

Hybrid Electric Vehicle Testing

Today's light-duty HEVs use a gasoline internal combustion engine (ICE), electric traction motors or electric stop-start technology, along with less than 2000 watt-hour (Wh) of onboard energy storage to increase petroleum efficiency as measured by higher mpg results compared to non-HEV models. HEVs are never connected to the grid for charging the battery. The HEV batteries are charged by an onboard ICE-powered generator, as well as by regenerative braking systems.

At the end of FY 2012, AVTA has performed, or is performing testing on 58 HEVs, comprised of 23 HEV models. The HEV models and number of each model tested are listed below:

- Generation (Gen) I Toyota Prius - 6
- Gen II Toyota Prius - 2
- Gen I Honda Insight - 6
- Honda Accord - 2
- Chevrolet Silverado - 2
- Gen I Honda Civic - 4
- Gen II Honda Civic - 2
- Ford Escape - 2
- Lexus RX400h - 3
- Toyota Highlander - 2
- Toyota Camry - 2
- Saturn Vue - 2
- Nissan Altima - 2
- Chevrolet Tahoe - 2
- Gen II Honda Insight - 2
- Gen III Toyota Prius - 2
- Ford Fusion - 2
- Mercedes S400 - 2
- Honda CRZ - 2

- Smart Fortwo Pure Coupe (MHV) - 3
- MAZDA 3 Hatchback (MHV) - 2
- Volkswagen Golf TDI (MHV) - 2
- Hyundai Sonata - 2
- Honda Civic with advanced lead acid battery - 1.

At the end of FY 2012, the 58 HEVs had accumulated 6.9 million total fleet test miles (Figure 29).

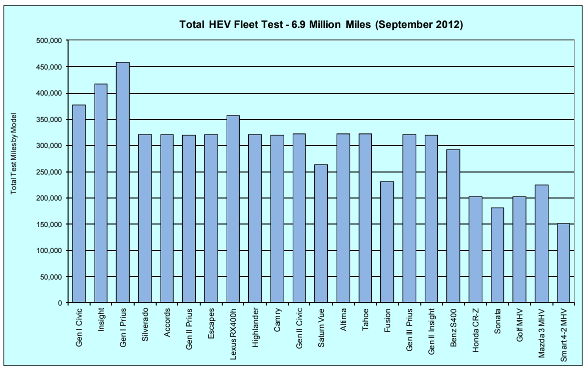


Figure 29. Total HEV test miles by vehicle model.

The average fuel use per HEV model since testing started ranges from 17.9 mpg for the Silverado to 45.2 mpg for the Gen I Honda Insight (Figure 30). Among the more recent HEV models, the mpg has ranged from 25.7 mpg for the Mercedes S400 to 44.2 mpg for the Generation III Prius. For the stop – start micro hybrids from Europe, the Golf MHV is averaging 42.9 (Table 6).

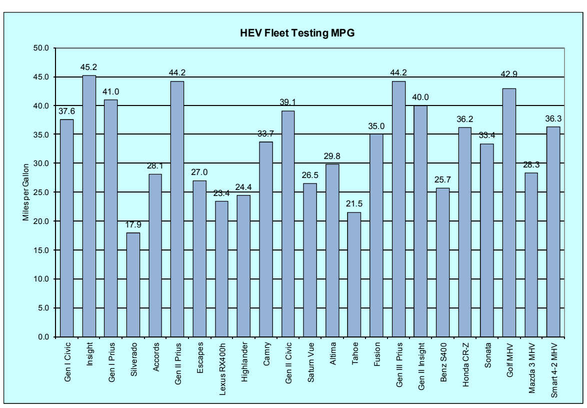


Figure 30. HEV mpg by model.

The AVTA continues to collect data that allows it to publish several fact sheets for each HEV (see: avt.inel.gov/hev.shtml), including:

- Maintenance Fact Sheets - mileage, date, maintenance event, cost for repair, or if repair was under warranty
- Fleet Testing Summary Fact Sheets – includes operating costs based on the purchase and sale delta, and the maintenance and operating costs (insurance, fuel and registration). The monthly and cumulative mpg, and monthly mileage accumulation are also provided.
- Battery Fact Sheets and Testing Reports for when the vehicles are new and at 160,000 miles.
- Fleet Testing Results to date Fact Sheets which is discussed in greater detail below.

Table 6. Onroad accelerated testing mpg for the most recent HEV test models, including the micro hybrid vehicles (MHVs) from Europe.

HEV Model	Onroad MPG
Fusion	35.0
Gen III Prius	44.2
Gen II Insight	40.0
Benz S400	25.7
Honda CR-Z	36.2
Golf MHV	42.9
Mazda 3 MHV	28.3
Smart Fortwo MHV	36.3

More recent advances in data collection techniques and costs have allowed the AVTA to provide more complete analysis of HEV operations as can be found on the Fleet Testing Fact Sheet and examples are provided in the next paragraphs for the Fusion HEV. In addition, the AVTA has been documenting life cycle costs for individual HEVs, including purchase and sale costs, maintenance costs per mile, operating cost per mile, and total ownership cost per mile. The web page, avt.inel.gov/pdf/hev/4699FordFusion10factsheet.pdf provides an example of the costs. This Ford Fusion fact sheet documents the $0.29 per mile total ownership cost for the Fusion.

The fleet testing fact sheet for one of the Fusions (avt.inel.gov/pdf/hev/2010Fusion_4699_June2011.pdf) also provides additional vehicle operations information that can help readers both understand the testing conditions as well as optimal performance ranges.

Figure 31 shows that the Fusion gasoline engine is stopped 31% of the time when the vehicle is either moving or stopped. Minimizing ICE operations at least partially contributes to the Fusion achieving between 30 and 40 mpg more than 60% of the time as measured by the percentage of the miles driven (Figure 32).

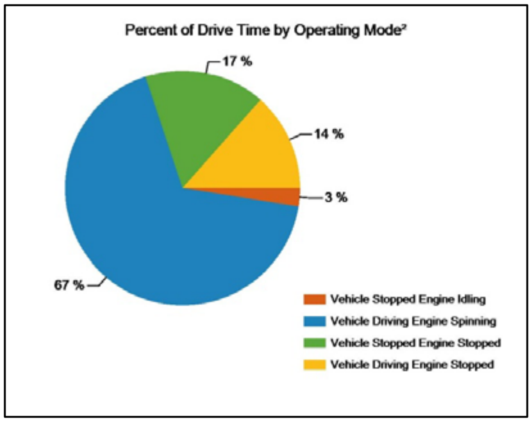


Figure 31. Ford Fusion HEV engine operating mode.

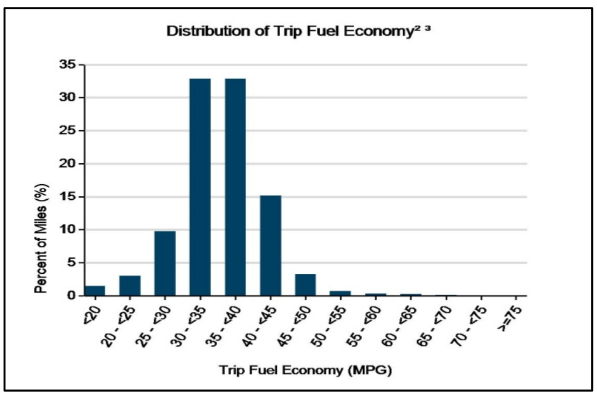


Figure 32. Ford Fusion HEV mpg by percent of miles driven.

Figure 33 clearly documents the vehicle speeds the Fusion should be operated at by fleets and private operators seeking to maximize petroleum reduction. However, safe operations should be the primary consideration over operating speed. As seen, the Fusion has been averaging 40 mpg when driven at vehicle speeds of 40 to 60 mph.

Ambient temperature and operators' use of climate controls also has an impact on mpg. As seen in Figure 34, there is significant decrease in mpg at warmer to hot temperatures.

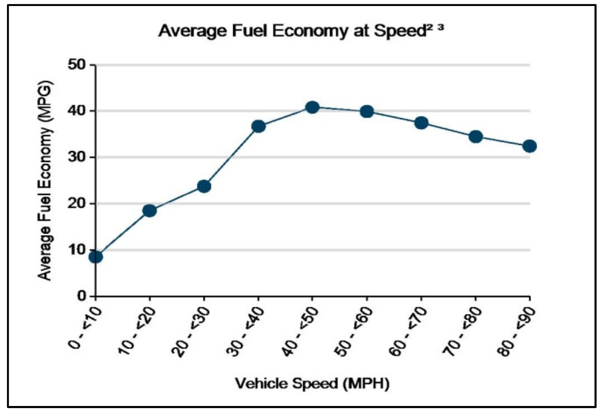


Figure 33. Ford Fusion HEV average mpg at various vehicle speeds.

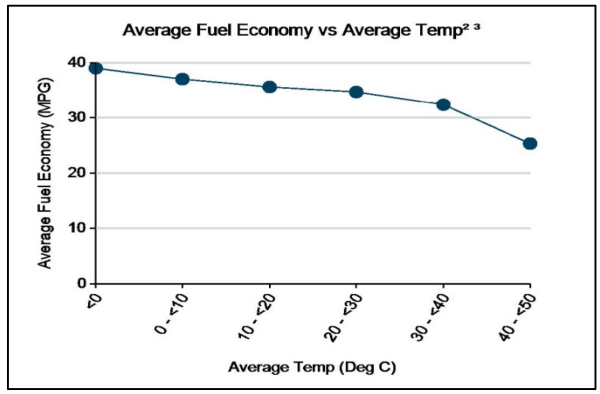


Figure 34. Ford Fusion HEV average fuel economy vs. average temperature.

In addition to the above mpg and vehicle operations profiles, data is also collected on battery use. Figure 35 shows the battery current in amp-hours during battery assistance and regenerative breaking.

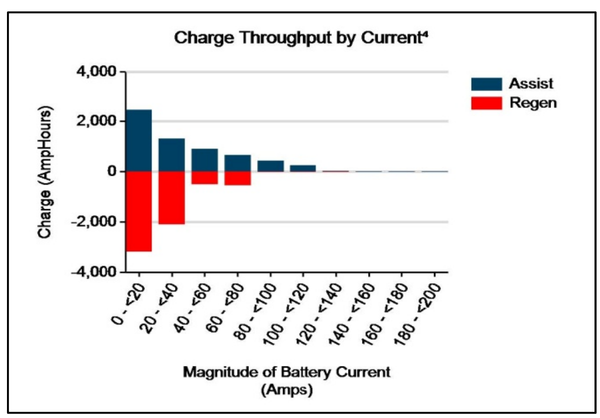


Figure 35. Ford Fusion HEV traction battery throughput by current.

Battery pack charge throughput by battery temperature is documented in Figure 36.

Figure 37 shows the significantly higher amount of assistance in amp-hours per mile at various speeds, with the lowest speeds having the largest difference as the vehicle accelerates from zero or very low mph.

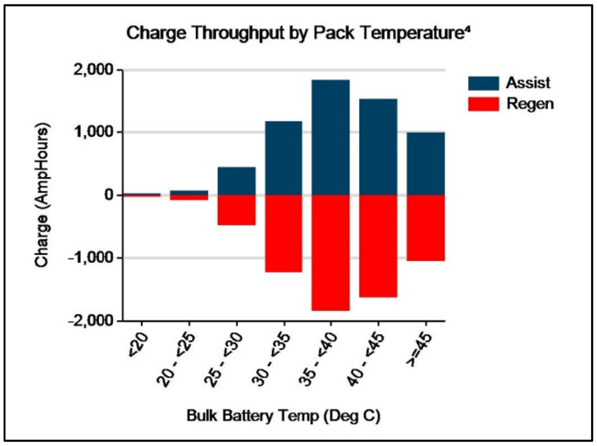


Figure 36. Ford Fusion HEV battery charge throughput by pack temperature.

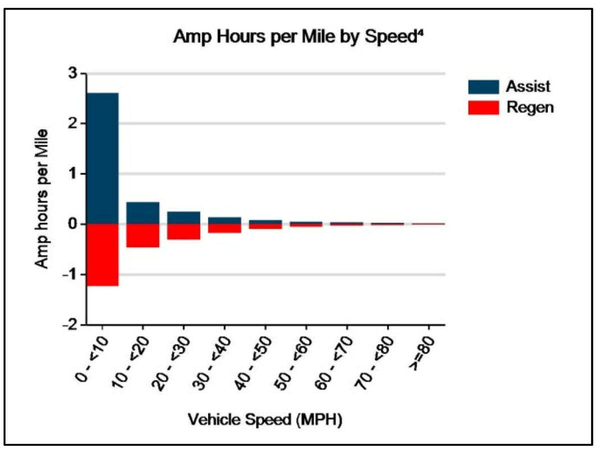


Figure 37. Ford Fusion HEV amp hours per mile by speed.

At the end of FY 2012, the AVTA had published 30 HEV battery tests for when vehicles were new or at 160,000 miles and these can be found at avt.inl.gov/hev.shtml

Using the BOT(beginning of testing, when A HEV first starts fleet testing) and end of testing (EOT) at 160,000 miles report for the Nissan Altima HEV ([avt.inel.gov/pdf/ hev/battery altima2351.pdf](avt.inel.gov/pdf/hev/batteryaltima2351.pdf)) as an example, Figure 38 shows battery voltage versus energy discharged. This graph illustrates voltage values during constant current discharge versus cumulative energy discharged from the battery at a C/1 constant current discharge rate at BOT and EOT.

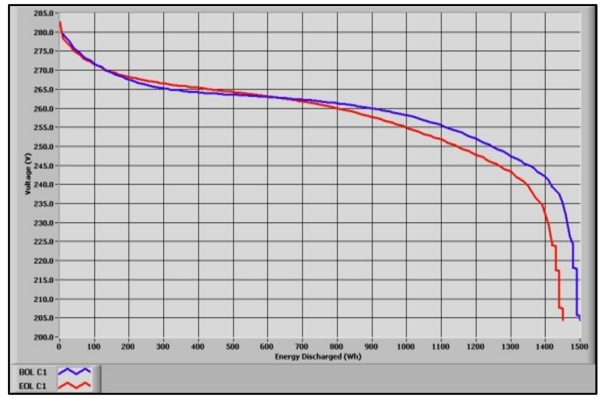


Figure 38. Nissan Altima HEV battery static capacity test results.

Figures 39 and 41 illustrate the battery's charge and discharge pulse resistance graphs, showing internal resistance over a range of 10 to 90% depth of discharge. Each curve represents the specified HPPC BOT or EOT resistance at the end of the 10-second pulse interval. Figures 40 and 42 illustrate the battery's charge and discharge pulse power graphs, showing the pulse power over a range of 10 to 90% depth of discharge. Each curve represents the specified HPPC BOT or EOT available power at the end of the 10-second pulse interval at the cell voltage limits.

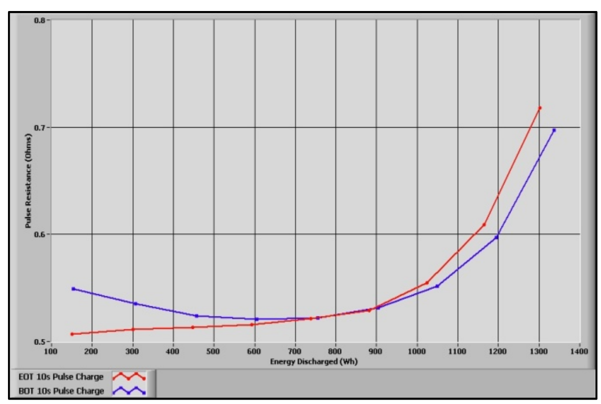


Figure 39. Nissan Altima ten-second charge pulse resistance versus energy discharged.

AVTA has partnered with private fleets to conduct the high mileage HEV testing. All 6.9 million HEV test miles have been accumulated with no driver costs to DOE. In addition, several of the HEV models get secondary test value after completing the 160,000 miles of HEV testing.

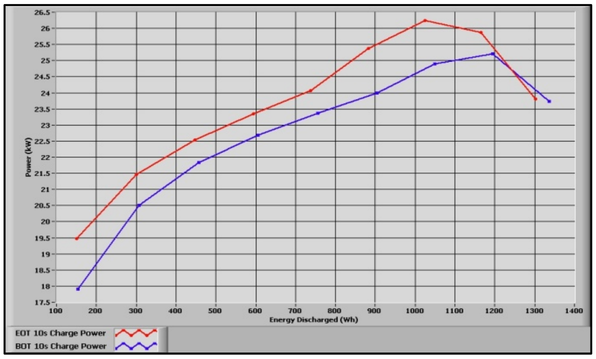


Figure 40. Nissan Altima ten-second charge pulse power versus energy discharged.

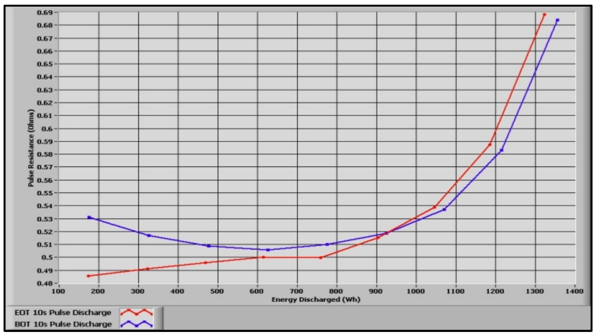


Figure 41. Nissan Altima ten-second discharge pulse resistance versus energy discharged.

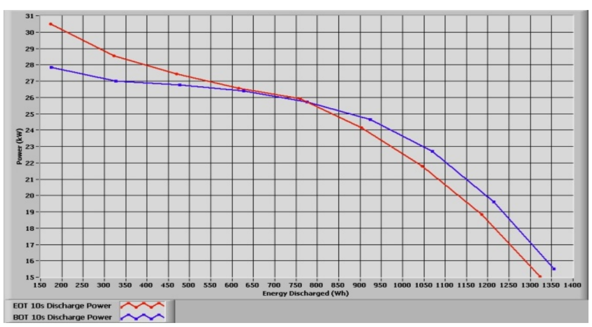


Figure 42. Nissan Altima ten-second discharge pulse power versus energy discharged

Oak Ridge and Argonne National Laboratories have purchased several used HEVs and they use the HEV power electronics subsystems and other subsystems for end-of-life testing. The EPA has purchased several HEVs at vehicle testing completion so they can conduct their own end-of-life testing to support their HEV life-cycle models. The National Renewable Energy Laboratory has also used end of life HEVs for thermal testing.

New HEVs available from U.S., Japanese, and European manufacturers will be benchmarked during FY 2013. These will introduce advanced technologies such as lithium or advanced lead acid designs. Most new HEVs will be tested to reduce uncertainties about HEV technologies, especially the life and performance of their batteries, and any other onboard energy storage systems.

UltraBattery HEV Project

Two special HEV vehicle projects, The UltraBattery Retrofit Project and Carbon Enriched Project C3, aim to demonstrate the suitability of advanced lead battery technology in hybrid electric vehicles (HEVs). It is partially funded by DOE and by the Advanced Lead Acid Battery Consortium (ALABC), and conducted by ECOtality for the AVTA.

An important objective of the project has been to benchmark the performance of the Ultra Batteries from both Furukawa Battery Co., Ltd., Japan (Furakawa) and East Penn Manufacturing Co., Inc. (East Penn). Accordingly, UltraBattery packs from both Furakawa and East Penn have been characterized under a range of conditions. Resistance measurements and capacity tests at various rates show that both battery types are very similar in performance. Both technologies, as well as a standard lead-acid module (included for baseline data), were evaluated under a simple HEV screening test. Both Furakawa and East Penn UltraBattery packs operated for over 32,000 HEV cycles with minimal loss in performance, whereas the standard lead-acid unit experienced significant degradation after only 6,273 cycles. The high-carbon, ALABC battery manufactured in Project C3, also was tested under the advanced HEV schedule. Its performance was significantly better than the standard lead-acid unit, but was still inferior compared with the UltraBattery. The batteries supplied by Exide as part of the C3 Project performed well under the HEV screening test, especially at high temperatures. The results suggest that higher operating temperatures may improve the performance of lead-acid based technologies operated under HEV conditions; it is recommended that life studies be conducted on these technologies under such conditions.

The Project DP1.8 consists of a retrofit of the original NiMH battery with a pack of 14 UltraBattery modules, manufactured by East Penn, in a new 2010 Honda Civic HEV. In

October 2011, the converted HEV was put into the AVTA fleet of test vehicles in Phoenix, Arizona, and it currently is still being tested. The converted HEV accumulates approximately 5,000 miles on a monthly basis and is experiencing a wide range of driving conditions. The monthly data being collected from the vehicle is an array of battery parameters, such as the following:

- Most restrictive temperature
- Pack voltage
- Power
- Vehicle parameters, such as speed.

The individual module voltages and cell/module voltage deviation are being measured separately on a monthly basis, as well as monitoring the health of individual battery modules. The mileage driven and gallons of gasoline used monthly are being recorded to monitor the vehicle average fuel economy. A status report for this project is available at: avt.inel.gov/pdf/hev/UltraBatteryReport.pdf.

Conclusions

Both the Idaho National Laboratory and ECOtality, through the AVTA, continue to provide the critical real world testing needed to benchmark DOE technology investments, including the critical tasks of determining suitability for deployment, and life time performance and costs of new technology components and vehicle systems. This testing includes understanding the infrastructure requirements of PEVs as well as other alternative fuels, as well as the proper placement of that infrastructure.

Some of the future test vehicles and the number of units that will be entering AVTA testing in the near term include:

- Honda CNG (4)
- Volkswagen Jetta TDI (4)
- Chevrolet Malibu with e-assist (4)
- 2013 Nissan Leaf (4)
- 2013 Chevrolet Volt (4)
- Mitsubishi i EV (4)
- Toyota Prius PEV (4)
- Ford Focus EV
- Volkswagen Jetta Hybrid (4)
- Ford C-Max ENERGI PHEV
- Toyota RAV4 EV
- Coda EV (4)
- Honda Civic Hybrid HEV (4)
- Honda Accord PHEV.

III.A.3. Products

Publications

Specific fact sheets and reports have been referenced in the report by including their locations on the AVTA website. The AVTA is generating a significant number of reports, fact sheets, conference papers, and presentations each fiscal year. Just the EV Project alone has generated more than 400 documents during FY 2012. The Chrysler PHEV projects are responsible for another 300 reports and fact sheets. Therefore, report locations are listed below by projects or vehicle technologies.

1. Hybrid Electric Vehicle benchmarking avt.inel.gov/hev.shtml
2. Plug-in Hybrid Electric Vehicle and Extended Range Electric Vehicle benchmarking avt.inel.gov/phev.shtml
3. Micro Hybrid Electric Vehicle benchmarking avt.inel.gov/microHEV.shtml
4. Electric Vehicle Supply Equipment benchmarking avt.inel.gov/evse.shtml
5. Full Size Electric Vehicle (including US Postal Service) benchmarking avt.inel.gov/fsev.shtml
6. Chrysler Ram PHEV benchmarking avt.inel.gov/chryslerram.shtml
7. EV Project avt.inel.gov/evproject.shtml
8. ChargePoint America Project avt.inel.gov/chargepoint.shtml
9. Chevy Volt Project avt.inel.gov/gmvehicledemo.shtml

III.B. Level 1 Benchmarking of Advanced Technology Vehicles

Principal Investigator: Henning Lohse-Busch, Ph.D.
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-9615; Email: hlb@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.B.1. Abstract

Objective

- Provide independent evaluation of advanced automotive technology by benchmarking of hybrids, plug-in hybrids, battery electric vehicles and alternative fuel vehicles as part of the U.S. Department of Energy's (DOE's) mission of laboratory and field evaluations
- Establish the state-of-the-art automotive technology baseline for powertrain systems and components through test data and its analysis.
- Disseminate vehicle and component testing data to partners of the DOE, such as national laboratories, the U.S. Council for Automotive Research, OEMs, suppliers and university. Provide data to support codes and standards development. Support model development and validation with test data.

Approach

- Use advanced and unique facilities with extensive instrumentation expertise. The Advanced Powertrain Research Facility at Argonne includes a 4WD and 2WD chassis dynamometer with a wide range of equipment and a focus on measuring energy consumption (fuel and electric). A decade of experience in testing vehicles refined the test procedures and test plans
- Perform baseline dynamometer testing of DOE's Advanced Vehicle Testing Activity vehicles before the accelerated fleet testing.
- Test the powertrain systems as well as components of the systems.

Major Accomplishments

- Extensively benchmarked the first designed battery electric vehicle from a major manufacturer: Nissan Leaf. Furthermore a conventional vehicle and a hybrid electric vehicle were tested on the chassis dynamometer with complete instrumentation.
- Distributed the test results and analysis through several mechanisms such as reports, presentations, and sharing of raw data.
- The testing activity helped directly in the development of some codes and standards and supported the model development and validation.

Future Activities

- Provide testing and vehicle systems analysis to further contribute to DOE's missions.

III.B.2. Technical Discussion

Background

The Advanced Powertrain Research Facility (APRF) at Argonne has been testing advanced-technology vehicles to benchmark the latest automotive technologies and components for the U.S. Department of Energy (DOE). The staff has tested a large number of vehicles of different types such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles, and conventional vehicles, including alternative-fuel vehicles.

Introduction

Over the last decade, the staff has developed a fundamental expertise in the testing of the next wave of energy-efficient vehicles. During this time, the instrumentation of the powertrains has evolved and the test procedures have been refined. Two main levels of testing exist today. The first level involves a basic but complete non-invasive instrumentation of a vehicle, which leaves the vehicle unmarked after the testing. The second level involves an in-depth and comprehensive invasive instrumentation of a vehicle and powertrain components, which leaves the vehicles with irreversible alterations.

This report summarizes the level-1 benchmark activities of FY 2012. In the first section the test approach is described, and then the DOE's Advanced Vehicle Testing Activity (AVTA) vehicle tests results are presented.

Approach

General Test Instrumentation and Approach

The testing presented in this report is focused on the basic and complete non-invasive level-1 type. Typically, Argonne receives these vehicles on loan from partners; therefore, the vehicles need to leave the test facility in the "as-received" condition. This limits the instrumentation to sensors that can be easily removed without leaving any damage.

Despite this limitation, Argonne strives to achieve a minimum level of instrumentation. If the vehicle has an internal combustion engine, instrumentation is applied to monitor the speed, fuel flow (at least from modal emissions or a fuel flow meter if possible) and engine oil temperature (achieved through dipstick instrumentation). For electrified vehicles, a power analyzer is used to record, at a minimum, the voltage and main current of the stored energy. If the vehicle requires charging, the electric power from the source is recorded. Furthermore, any sensors that can be implemented without permanent damage, such as temperature sensors, are typically included in locations of interest (a battery pack vent, for example). These additional sensors vary from vehicle to vehicle. A final part of the level-1 benchmark is the recording of messages from the vehicle's information buses, and this information will also vary widely from vehicle to vehicle.

In addition to the minimum instrumentation described above, further sensors may be added, depending on the vehicle powertrain and special interests, as long as they are non-invasive.

Purpose of Benchmarking

A major goal of the benchmarking is to enable petroleum displacement through data dissemination and technology assessment. The data generated from the vehicle testing and analyses are shared through several mechanisms, such as raw data, processed data, presentations and reports.

A fundamental gateway to the data is Argonne's Downloadable Dynamometer Database (D^3), which is a public website (transportation.anl.gov/D3/index.html). The D^3 website provides access to data and reports from vehicles tested on the standard test cycles. The data directly serves the development of codes and standards as well as the development and validation of simulation models. These activities impact the modification of test plans and instrumentation. Further partners in the testing are U.S. manufacturers and suppliers, through the U.S. Council for Automotive Research (USCAR).

Many of the research activities of the DOE rely on the benchmark laboratory and fleet testing results to make progress towards their own goals. Figure 1 details some of these DOE research activities and partners.

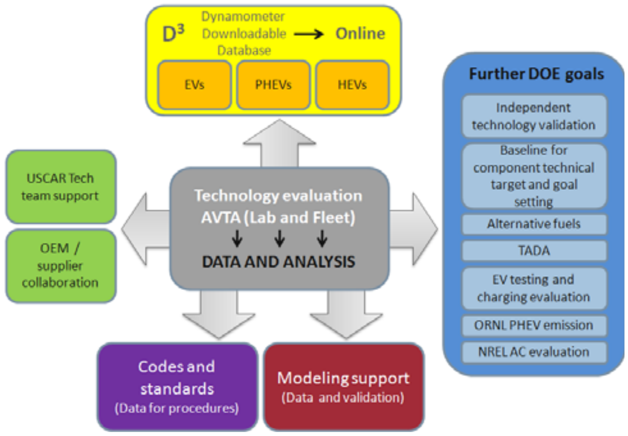


Figure 1. Data dissemination and partners.

The benchmark program leverages DOE's AVTA activities. INL procures new advanced-technology vehicles to test them in accelerated fleet testing. As part of the evaluation, these vehicles are benchmarked in the APRF. Figure 2 illustrates the process.

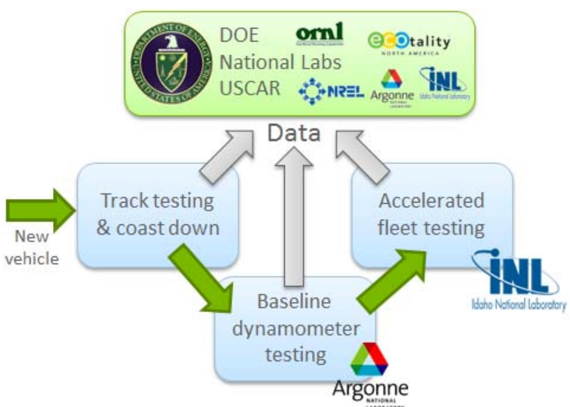


Figure 2. Advanced Vehicle Testing Activity process.

Further information on the AVTA is available at avt.inel.gov.

Advanced Powertrain Research Facility

In FY 2012, the 4WD chassis dynamometer of the APRF was upgraded to be EPA 5 cycle capable test cell. The test cell now includes a thermal chamber and an air handling unit with a large refrigeration system that enables vehicle testing at EPA 'Cold CO Test' ambient temperature of 20F (-7C). The other standard test temperatures are 72F (25C) and 95F (35C). A set of solar emulation lamps can provide 850 W/m^2 of radiant sun energy. The new capability is illustrated in Figure 3.

Figure 3. Illustration of testing at 95F with the sum emulation on the left and testing at cold ambient temperature.

This report focuses on ambient testing at 72F test results. Task 1000109 and 1000110 present the impact of different temperatures on vehicle behavior and energy/fuel consumption.

Results

Each year the AVTA partners select a set of vehicles which best represents the new fuel saving technologies available in the market. The 2012 Hyundai Sonata Hybrid and the 2012 Chevrolet Volt, which is a plug-in hybrid, were tested between FY 2011 and FY 2012 and their analysis can be found in the annual report of FY 2011.

Additionally to the analysis presented in this report, the APRF team performed level 1 testing on a significant number of conventional vehicles (engine and transmission only) to build a database of baseline vehicle data to enable comparisons points for Advanced Technology Vehicles. The details of this study can be found in task 1000107.

This report will focus on the Nissan Leaf, which is a battery electric vehicle, as well as a Ford Fusion Hybrid and Fusion with a conventional V6 engine, which were used in a mass impact study.

2012 Nissan Leaf (Battery Electric Vehicle)

Vehicle description

The Nissan Leaf is a pure battery electric vehicle. It a vehicle designed and built as an electric vehicle in the market place. A single electric motor coupled with a large battery pack move the vehicle. Table 1 presents the technical specifications.

Table 1. Nissan Leaf powertrain specifications

Architecture	Battery Electric Vehicle
Engine	None
Motor	Electric PM motor 80 kW AC synchronous
Battery	Lithium Ion battery 24 kWh (Nominal capacity)* 18.5 kWh (usable DC energy)** Charging 3.3 kW onboard charger (J1772 connector) DC Fast charge connector (no used during testing)
* Nissan data ** Test data	

Vehicle operation

Figure 4 illustrates the powertrain operation of the Leaf. This battery electric vehicle powertrain relies on the single electric motor and the battery pack to provide the tractive power to move the vehicle. The electric motor and battery are capable of regenerative braking during decelerations.

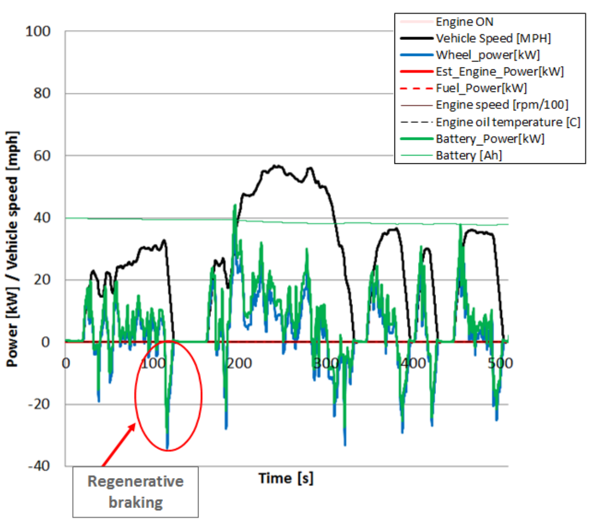


Figure 4. Leaf operation on a section of the UDDS cycle.

When the vehicle is fully charged the regenerative braking is limited as the battery pack cannot accept the electric power thus the vehicle needs to blend in the mechanical brakes to slow the vehicle down. From the data in Figure 5 it is clear that the battery charge power is limited for the fully charge battery pack. With a fully charged battery pack at the beginning of the test, the Leaf recovers 61% of the available braking energy at the wheel compared to 69% for the partially charged pack on the UDDS test.

Cycle	Dyno neg.	Battery neg.
UDDS#1	-0.772 kWh	-0.473 kWh
UDDS#2	-0.777 kWh	-0.534 kWh

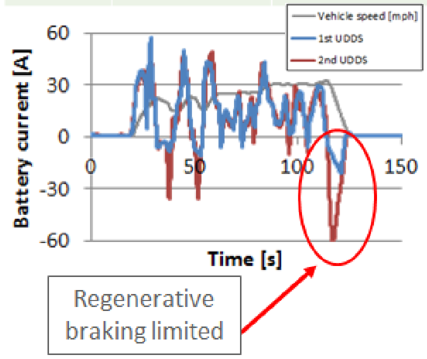


Figure 5. Regenerative braking comparison between a fully charged and a partially discharged pack.

BEV test protocol and basic results

The Leaf was tested using the new SAE J1634 Shortcut Multi Cycle Test (MCT) procedure. The APRF staff, as active participants of the committee, provided independent Leaf test data to the committee to demonstrate the validity of the proposed shortcut method. More detail on the test procedure can be found in task 1000197

The long version of the test procedure requires charging the vehicle to full before testing a single drive cycle over and over again until the battery is so depleted that the vehicle cannot meet the trace anymore, then the energy required to charge the vehicle to full is measured. The short cut version procedure also starts with a fully charged vehicle but multiple drive cycles are used to fully deplete the vehicle before it is recharged. The UDDS and Highway cycles are mixed so that each test is run at several different battery state-of-charge levels. The full AC recharge energy is then redistributed to each test cycle type by a weighted average of the cold start and hot start tests based on the DC energy measure for each test and the total usable DC battery energy. Based on past APRF BEV data, the MCT short cut method does:

- Match Efficiency
- Extrapolate Range
- Include "First Cycle Effect"
- Fixes ambiguous end-of-range
- Spreads cycles to different SOCs

The Leaf was tested using a modified SAE J1634 Shortcut Multi Cycle Test (MCT) procedure which included US06 cycle. Figure 6 illustrates test sequence applied to the Leaf as well as the energy consumption and range test results.

Calculated Cycle Results	UDDS	HWY	US06
Energy consumption [DC Wh/mi]	194	228	334
Energy consumption [AC Wh/mi]	233	274	395
Range [mi]	92	78	54

Measured Charging results	UDDS
Grid Charge Energy [AC Wh]	21352
DC Charge Energy [DC Wh]	18234
DC Charge Energy [DC Ah]	49.20

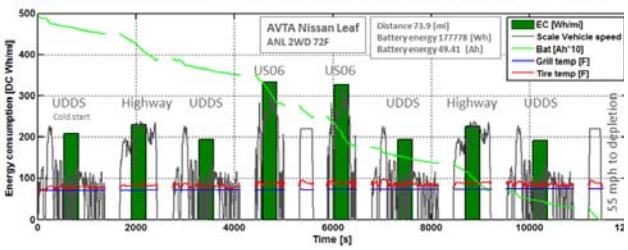


Figure 6. J1634 shortcut MCT test sequence applied to the Leaf.

Points of interest

Powertrain efficiency

Of particular interest is the average powertrain efficiency on transient drive cycles. Equations 1-2-3 define the powertrain efficiency and vehicle efficiency for this section. Figure 7 shows the resulting powertrain and vehicle efficiency for the Leaf on the drive cycles as described in the test protocol section.

$$PowertrainEfficiency_{positive} = \frac{\int (BatteryPower_{positive} - DCDCPower)dt}{\int (DynoTractiveEffort_{positive})dt}$$

$$PowertrainEfficiency_{negative} = \frac{\int (DynoTractiveEffort_{negative})dt}{\int (BatteryPower_{negative} + DCDCPower)dt}$$

$$VehicleEfficiency_{net} = \frac{\int (BatteryPower)dt}{\int (DynoTractiveEffort)dt}$$

Equation 1-2-3 Efficiency definitions

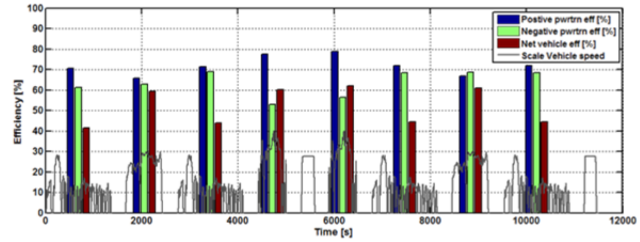


Figure 7. Powertrain and vehicle efficiencies for the Leaf on several drive cycles.

The powertrain efficiencies on these transient drive cycles varies from 60 to 80%. The higher the powertrain load the higher the powertrain efficiency. Note that the negative powertrain efficiency, also as known a regenerative braking recovery, is limited on the first UDDS compared the second UDDS (test#3) which is explained in Figure 5. On the aggressive US06 cycles the propulsion powertrain efficiency is as high as 80% due to the higher powertrain load, but the proportion of regenerative braking recovered is lower compare to the UDDS cycles. Some of the energy is not recovered during the larger deceleration on the US06. Regenerative braking is pulled back for deceleration events greater than 0.20~0.22 g's as shown in the US06 data in Figure 8. Furthermore the data shows that regenerative braking is fully blended out and the mechanical brakes are fully blended in at 5~6 mph during decelerations.

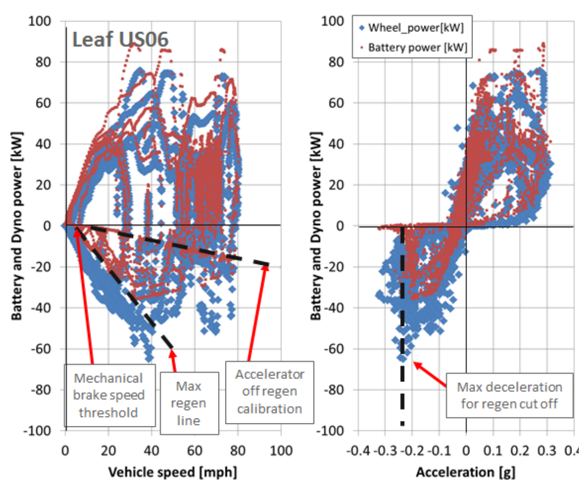


Figure 8. Regenerative braking limitations demonstrated with US06 data.

Figure 9 shows the energy analysis for the vehicle on the UDDS cycle. Note the energy analysis is based on positive and negative power at the wheel which is slightly different from positive or negative acceleration. The regenerative braking energy recovered by the electric powertrain is reused during the cycles as shown by the feedback arrow. The net battery energy is used to calculate the proportion of energy distribution on cycles in Figure 10, thus the regenerative braking is a negative percentage.

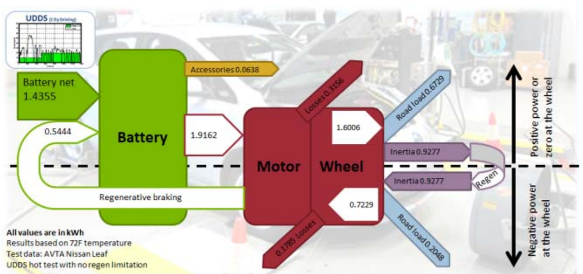


Figure 9. Leaf energy loss diagram for the UDDS at 72F.

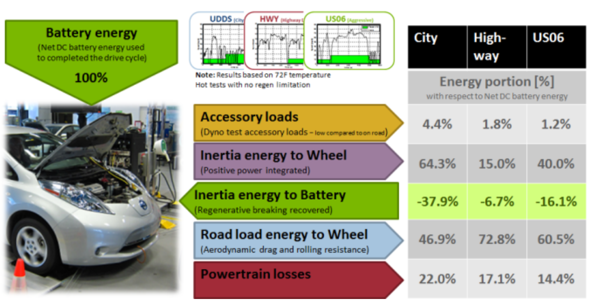


Figure 10. Energy distribution on the three major US test cycles.

The proportion of energy that goes to move the vehicle by overcoming the road load energy and inertial energy is quite high in a BEV thanks to the higher energy conversion efficiency and the large regenerative braking envelop compared to conventional vehicles.

Accessory load

Accessory loads can have a large impact on the range of a BEV due to the higher efficiency of the powertrain and the limited electric energy available in the battery. On average the Leaf uses 3.8 kW, 10.8 kW and 16.0 kW of net average battery power on the UDDS, the highway and the US06 cycles respectively. So the 4 kW of electric heater power can double the energy consumption or cut the range in half in city type driving. Table 2 presents some of the accessory loads measured in the lab. It should be note that during dynamometer testing the average accessory load is typically lower then on the road as power steering and some other accessories are never used. The heater and the air conditioning are the largest loads and these are explored in task 1000110.

Table 2. Leaf accessory load summary

Action	Net Power [W]	
Vehicle ON	280	
The power numbers below this row are in addition to the base 280W load		
Brakes	10	
	Peak	Settled
AC ON max cool auto	2000	1800
	Pulse min	Pulse max
Heater Cabin warm up	4000	6000
Maintaining cabin temperature	2000	4000
	Pulse min	Pulse max
Front window defroster* (pulsing)	1420	3420
Rear window defroster	200	Tested at 20F
	Peak	Settled
Panic brake	457	70
Running lights	10	
Full lights	60	
Full bright	190	

Battery characterization

The Leaf uses a Lithium Ion battery pack for the energy storage system. Figure 11shows the battery polarization curve in contrast to other battery technologies tested in the APRF. The operating voltage of the Leaf is very similar to that of the Volt. The higher voltage helps to reduce the operating currents at a given power levels with reduces the ohmic losses in the powertrain and increases the maximum power output. The relatively low measured system resistance helps to reduce the ohmic losses as well.

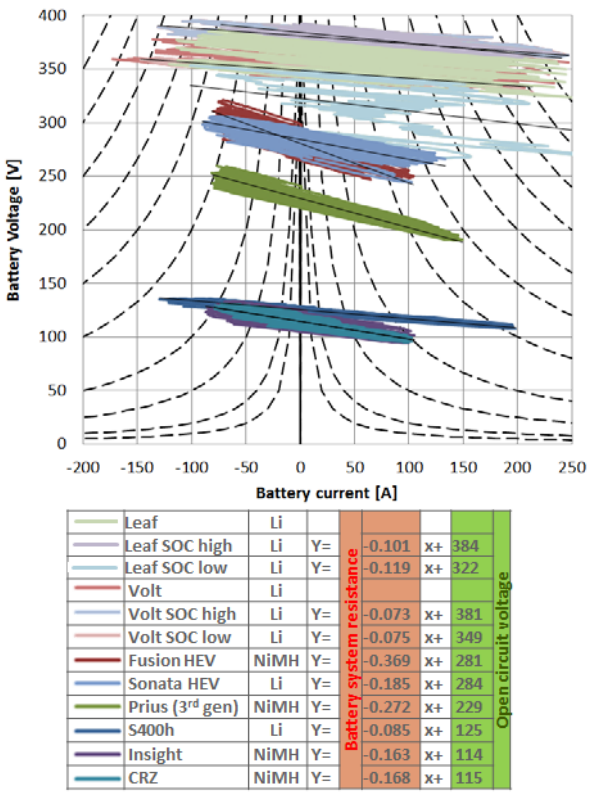


Figure 11. Leaf battery performance characterization

Charging performance

Figure 12 summarizes several full charge events after the battery was fully depleted. Level 2 charging takes less than 6 hours from fully depleted to full charge.

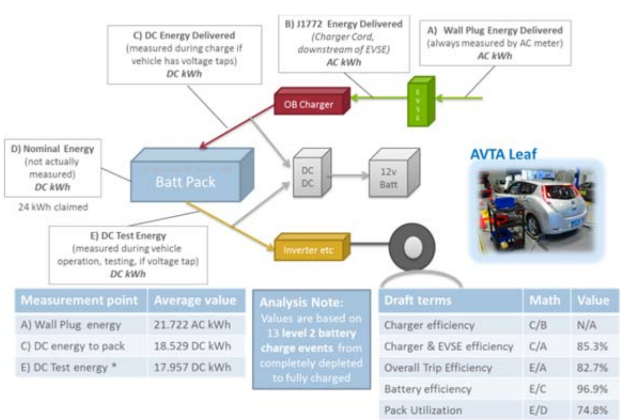


Figure 12. Statistical summary of battery charges from fully depleted to full charge.

The Leaf's average usable DC battery energy is 18.5 DC kWh. The overall average EVSE and charge efficiency is 85. 3%.

2012 Ford Fusion HEV

Vehicle description

The Fusion is Ford's first car to add a hybrid powertrain and can be considered the second generation of Ford's hybrid system after the hybrid Escape. Similar to the Prius, the Fusion uses an Atkinson-cycle engine, two electric machines and a power split device used to control the proportion of power transfer between the mechanical and the electrical path. Table 3 presents the technical specifications.

Table 3. Ford Fusion HEV powertrain specifications

Architecture	Power split hybrid
Engine*	2.5L In-line 4 cylinder DI Atkinson-cycle • 156 bhp 116(kW) @ 6000 rpm • 135 ft.lb (183 N.m) @ 2250 rpm
Transmission	Power split (eCVT)
Motor *	PM AC synchronous motor • 105 hp (78kW) • 153 ft.lb (207 N.m)
Battery *	Nickel Metal Hydride (NiMH) • 35 hp (26 kW) • 275 V nominal
* Ford data	

Vehicle operation

The Fusion operation features which enable fuel savings are engine idle stop, electric operation at low road lows up to 47 mph, regenerative braking, electric assist and operating the engine at higher efficiency by decoupling it from the road load. The vehicle acceleration performance is at a high level due to the larger engine.

Figure 13 presents the hybrid operation appears to include a brief electric launch with an acceleration phase with the engine ON followed by an electric cruise and regenerative braking. Compared to the Prius the engine is cycled ON/OFF more frequently but the overall ON time of the engine over a hot start UDDS cycle is the same as the 66% with the Prius.

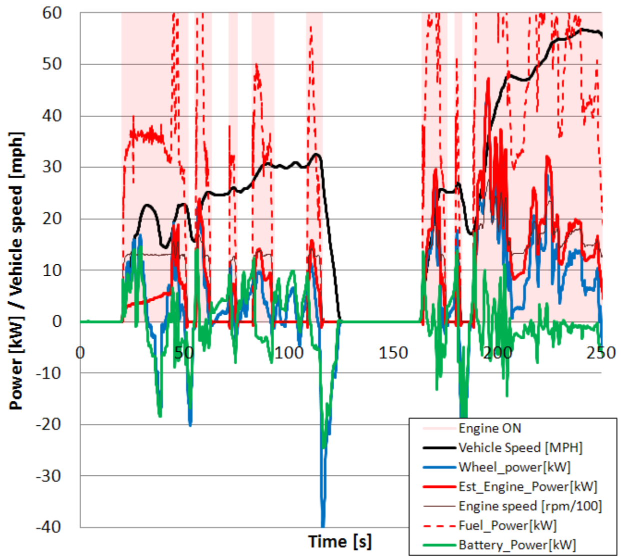


Figure 13. Fusion HEV operation on a hot start UDDS.

Points of interest

In comparison to the Leaf, the chosen point of interest is the regenerative braking operations envelop presented in Figure 14. The regenerative braking is power limited to about 22 kW which is a hardware limitation. That limitation is not present in a battery electric vehicle. Interestingly the regenerative braking is not limited by maximum deceleration rate on the US06 cycle. The Leaf zeroed the regenerative braking at deceleration rates above 0.2~0.22 g's while the Fusion maintains a maximum regenerative braking power of 22 kW to the 0.4 g's of deceleration on the US06 cycle.

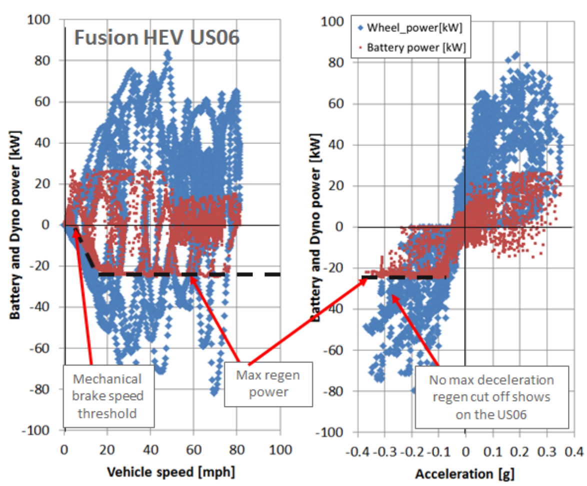


Figure 14. Regenerative braking limitations demonstrated with US06 data

2012 Ford Fusion Conventional (V6)

Vehicle description

This Ford Fusion conventional vehicle was selected as a test vehicle for a mass impact study. The powertrain is composed of the 3 liter V6 engine matted to a 6 speed automatic transmission. Table 4 presents the technical specifications.

Table 4. Ford Fusion V6 powertrain specifications

Architecture	Conventional Vehicle
Engine*	3.0L V 6 cylinder PI • 240 bhp (179 kW) @ 6550 rpm • 223 ft.lb (300 N.m) @ 4300 rpm
Transmission	Automatic transmission 6 speed
* Ford data	

Vehicle operation

The conventional uses the engine as the only power source. The engine speed is locked in by the vehicle speed and the transmission gear ratio. The engine load is directly proportional to the accelerator pedal request form the driver. The transmission gear is typically selected to yield the best fuel economy based on vehicle speed and accelerator pedal request. Figure 15 show the operation of the conventional vehicle.

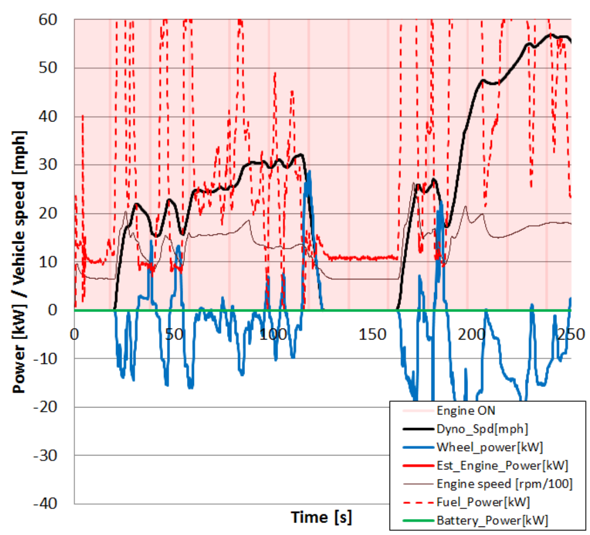


Figure 15. Fusion V6 operation on a hot start UDDS

Points of interest

Conventional vehicles with a discrete ratio transmission do not have the freedom to operate engine as efficiently as hybrid electric vehicles.

But deceleration fuel cut off is a technology employed to reduce the fuel consumption of conventional vehicles as shown in Figure 16.

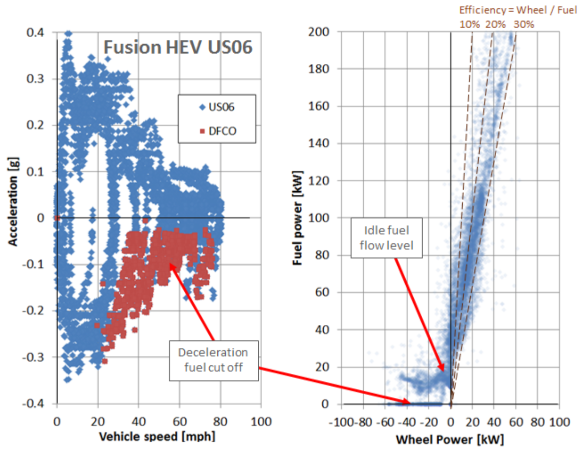


Figure 16. Deceleration fuel cut off.

Mass impact study

Study setup and raw results

The study's goal is to quantifying the impact of vehicle mass on fuel or energy consumption. A conventional vehicle (Fusion V6), a hybrid electric vehicle (Fusion HEV) and electric vehicle (Leaf) were tested at test weights ranging from their EPA test weight minus 500 lbs. to plus 500 lbs. Idaho National Laboratory performed the track testing to determine the impact of mass on the vehicles road load force. Using those parameters the vehicles were tested on the UDDS, Highway and US06 test cycles multiple times at the different test weights. Figure 17, Figure 18, and Figure 19 show the raw average fuel consumption results for the different vehicles.

Study Assumptions and limitations

The following assumptions and limitations bound this study:

- Study does not include mass compounding, because the vehicles and their powertrain were unchanged throughout the study.
- Results are based on single car per vehicle technology category
- The road load inputs to the dynamometer are based on track test data

Manufacturer recommended tire pressure was maintained for all weight cases per vehicle on the track as well as on the dynamometer.

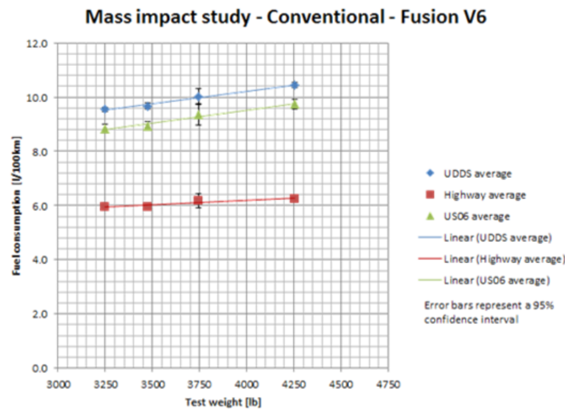


Figure 17. Conventional average dynamometer fuel consumption results as a function of test weight.

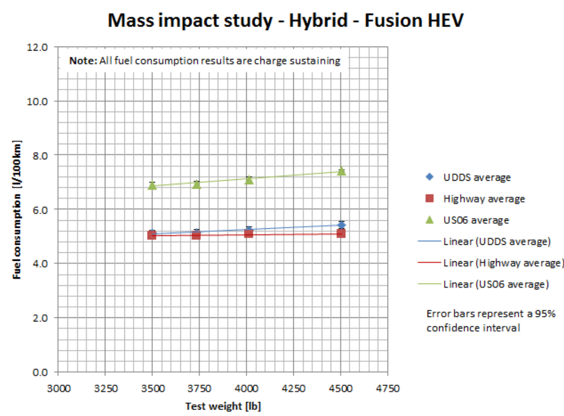


Figure 18. Hybrid vehicle average dynamometer fuel consumption results as a function of test weight.

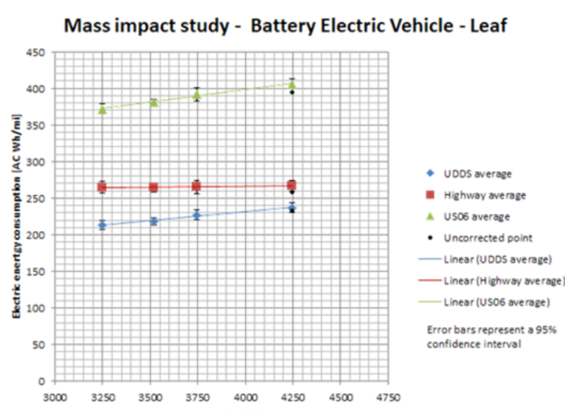


Figure 19. Electric vehicle average dynamometer fuel consumption results as a function of test weight.

Mass impact summary

The energy consumption impact depends on the driving type. On highway type driving, which is dominated by relative steady cruising speeds, the energy consumption does not vary much as the vehicle mass is changed. Since the speed changes (a.k.a. accelerations) are minimal on highway type driving, the inertia energy components, which are directly proportional to mass, are low as well.

On city type driving, which is dominated by stop and go traffic with many accelerations and decelerations, the mass change has a measurable impact on the energy consumption. Figure 20 and Figure 21 present percentage and absolute energy consumption change as a function of percent mass change on the UDDS.

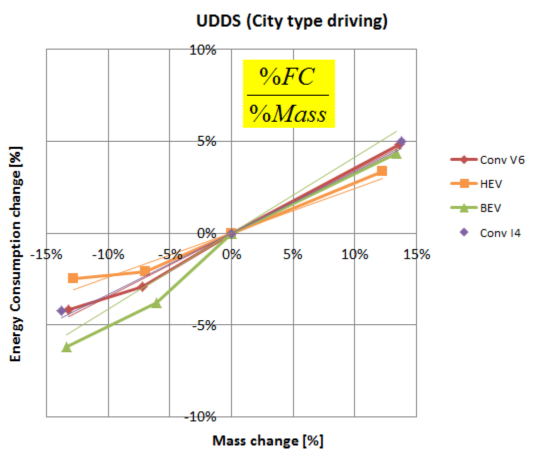


Figure 20. Percent energy consumption change as a function of percent mass change.

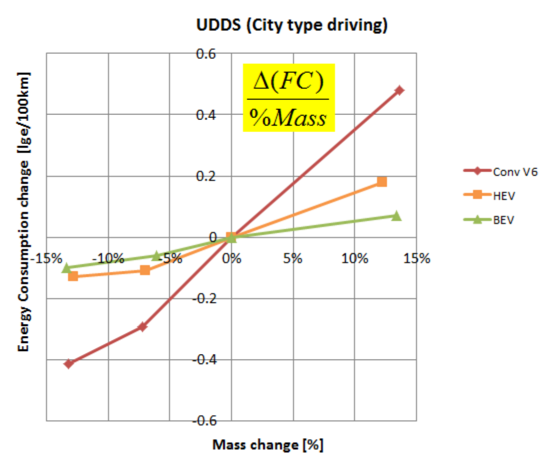


Figure 21. Absolute fuel change as a function of percent mass change.

Light weighting a battery electric vehicle will provide the greatest increase in range compared to a conventional or hybrid vehicle. But light weighting a conventional vehicle will provide the largest improvement in absolute fuel consumption reduction due to the relative lower powertrain efficiency compared to a battery electric vehicle.

Conclusions

The APRF benchmarked several AVTA vehicles. The test results and analyses were distributed through several mechanisms such as reports, presentations, and sharing of raw data. The testing activity helped directly in the development of some codes and standards and supported the model development and validation.

This report summarizes Argonne's basic vehicle benchmark activity for FY 2012. For more detailed information on each vehicle and further analysis, the reader is encouraged to read the vehicle reports.

III.B.3. Products

Publications

1. Leaf DOE update EV Everywhere
2. Leaf VSATT
3. DOE EV Everywhere workshop
4. SAE paper thermal
5. SAE Mass impact
6. IEEE Leaf
7. MASS impact VSATT
8. MASS impact at DOE
9. MASS impact to materials group

Tools & Data

1. The basic vehicle test data is uploaded to the APRF's Downloadable Dynamometer Database and available of public download. Both the test results as well as 10Hz data is posted. transportation.anl.gov/D3/index.html
2. Some of the dynamometer test results are also integrated into the AVTA website maintained by INL. avt.inel.gov/

III.C. Extended Level 2 Benchmarking of Advanced Technology LD Vehicles – Peugeot 3008 Hybrid4

Principal Investigator: Eric Rask
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-3110; Email: erask@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.C.1. Abstract

Objective

- Establish work plan that involves thorough vehicle instrumentation, testing, and analysis of the selected vehicle (Peugeot 3008 Hybrid4). Data collected will be used for a wide range of evaluations and related tasks, including technology benchmarking and evaluation, simulation validation, advanced vehicle component evaluation, and vehicle testing procedure/methodology development. This work was done in collaboration with staff from IFP Energies Nouvelles of France, who assisted in test plan development, vehicle procurement, and data analysis.

Approach

- Work with IFP to import test vehicle and develop specific test/analysis plan
- Leverage previous high-level data collection and insight
- Install drive shaft torque sensors and other relevant instrumentation
- Decode and record Controller Area Network (CAN) signals through testing as a means of measuring parameters that would otherwise be too difficult, too expensive, or impossible to obtain
- Run a broad range of tests for cycle fuel economy, energy consumption, performance, and steady-state operation for vehicle assessment, component evaluation, and technology benchmarking

Major Accomplishments

- Successfully conducted significant vehicle/component testing and analysis for selected vehicle
- Evaluated a wide range of drive cycles and operating modes
- Decoded and recorded significant CAN bus information through the development and leveraging of improved tools

Future Activities

- Continue additional data collection by leveraging instrumentation installed in vehicle. Areas of particular interest include further component efficiency testing/mapping and vehicle temperature sensitivity testing under extreme ambient conditions.

III.C.2. Technical Discussion

Background

This work focuses on in-depth instrumentation, testing, and analysis of new and emerging vehicle technologies. Vehicles are selected for evaluation on the basis of technical merit for technology assessment and data collection. Vehicles are tested primarily on a chassis dynamometer by using state-of-the-art instrumentation and data analysis equipment. Testing and instrumentation plans are developed specifically for each vehicle and reflect its particular technical merits and unique features.

Introduction

The Peugeot 3008 Hybrid4 is a particularly interesting and unique vehicle, which makes it an excellent candidate for in-depth vehicle testing. The vehicle can provide tractive effort though either the front or rear axles because of its unique configuration. The front axle is powered by a 2.0-L diesel engine mated to a 6-speed sequential manual gearbox, as well as a stop-start system. Peugeot claims the engine is capable of providing 120 kW, and testing has shown similar results. The rear axle is powered by a rear motor that can be used for electric vehicle operation, launch assist, regenerative braking, or engine load buffering. This unit can maximally provide a claimed 27 kW of power with a peak torque of 200 Nm. The vehicle is a fairly large (for a European vehicle) crossover and is claimed to offer a mix of high fuel economy and excellent driving characteristics, given the diesel engine and rear electric capability. Also interesting is that this vehicle offers a range of selectable operating modes, which can be used to alter the vehicle's behavior, depending on the desired type of operation. Figure 1 shows the 3008 on the dynamometer in Argonne's Advanced Powertrain Research Facility (APRF).

Figure 1. Peugeot 3008 Hybrid4 on the Dynamometer in the APRF.

Instrumentation

While not discussing all of the instrumentation included in this vehicle, the following paragraphs seek to highlight some of the important instrumentation for this vehicle.

Table 1 provides a summary of most signals used in the testing and analysis of this vehicle. CAN bus data were used fairly extensively for this vehicle and offered a wide range of signals relevant to overall vehicle operation, as well as specific component capability and usage. When required, more invasive instrumentation was used to investigate certain power flows in the vehicle. For example, Figure 2 shows some of the voltage and current instrumentation used to find the power provided by the main high- voltage battery pack and DC-DC converter.

Table 1. Highlighted 3008 Hybrid4 Data Signals

CAN Data Signals	**Power Analyzer Signals**
Accel Pedal [%]	HV Battery Voltage (V)
Wheel Speed [kph]	HV Battery Current (A)
Veh_Spd_CAN[kph]	HV Battery Power (W)
Brake Switch	DCDC Outlet Voltage (V)
Gear	DCDC Outlet Current (A)
Battery Current [A]	DCDC Outlet Power (W)
Battery Voltage [V]	12V Battery Voltage (V)
Engine Speed [rpm]	12V Battery Current (A)
Engine Torque [Nm]	12V Battery Power (W)
Eng. Coolant Temp. [C]	
Alternator Torque [Nm]	**Additional Signals**
Motor Speed [Nm]	Front Axle Torque (Nm)
Battery SOC [%]	Rear Wheel Torque (Nm)
Battery Temp. [C]	Engine Oil Dipstick Temp. (Nm)
	THC (mg/s)
	CH_4 (mg/s)
	NO_x (mg/s)
	COlow (mg/s)
	COmid (mg/s)
	CO_2 (mg/s)
	HFID (mg/s)
	NMHC (mg/s)
	Fuel (g/s)

Figure 2. High-Voltage Battery and DC-DC Electrical Instrumentation.

Highlighted Vehicle Results

The following sections describe some of the noteworthy findings related to tests of this vehicle. These discussion items represent a small fraction of the information and insight gained during testing.

Although a variety of both U.S.- and European-based drive-cycles were used in the evaluation of the Peugeot 3008 Hybrid4, of particular interest are the UDDS, Highway, and US06 cycles. Figure 3 shows the resulting fuel economy of the 3008 for the major U.S. regulatory cycles tested at 25°C nominal ambient test conditions. Note that these results are in miles-per-gallon of diesel fuel, which has higher energy content per gallon. As can be seen in the figure, the 3008 provides high fuel economy across the range of drive cycles. Unlike many power-split-type hybrid vehicles, the Peugeot shows higher Highway fuel economy, as compared to the UDDS cycle. Higher fuel economy is due to its diesel engine, as well as its hybrid architecture that utilizes a relatively higher efficiency path during highway type driving. The vehicle's response in terms of fuel economy to more aggressive driving, as estimated by the US06 drive cycle, is slightly lower than that of other recently tested hybrid vehicles, but it is still in the commonly seen range of roughly 30%.

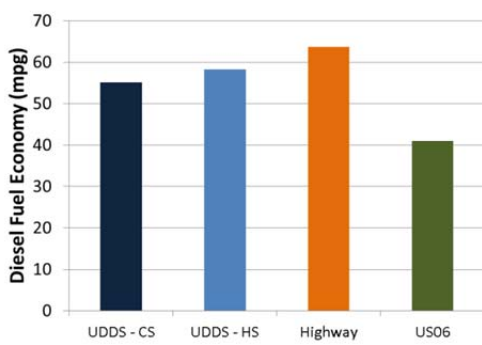


Figure 3. Tested U.S. Cycle Fuel Economy.

Figure 4 shows estimated engine and battery power of a segment of the UDDS drive cycle. In this zoomed-in snapshot, most of the 3008 Hybrid4's operating modes can be observed. During initial launch (~20 s), the vehicle is powered electrically, as evidenced by the increase in battery power with minimal engine power. Following this operation, the engine is started, and a mix of battery and engine power can be observed. During decelerations, engine power again falls to zero, indicating that fueling does not occur during decelerations. Figure 4 shows that from 200 to 300 s, the battery charges off the engine power, which is used to propel the vehicle. This phenomenon is indicated by the negative battery power and positive engine power.

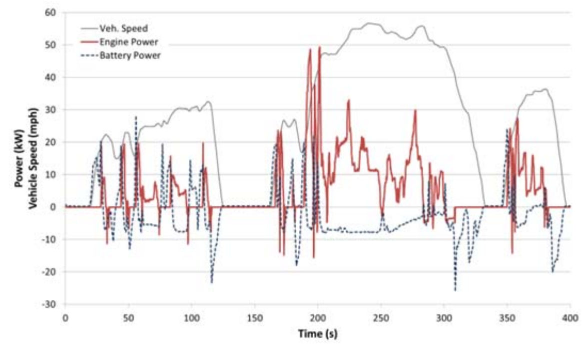


Figure 4. Mix of Battery and Engine Power during Subset of UDDS Driving.

Given the Peugeot 3008's ability to generate power and capture regenerative braking energy though either its front starter-generator or its rear motor, the chosen split of power is of interest. Figure 5 shows tractive power during UDDS operation for both the front and rear axles. Higher absolute power levels on the rear axle indicate that the rear motor is providing the majority of tractive power; conversely, higher front absolute power levels indicate that the front-drive diesel engine is providing the majority of traction. The 3008's electric launch, followed by engine-powered operation, can be observed in Figure 5. Additionally, the majority of braking energy on the UDDS appears to be handled by the rear brakes and, thus, the rear motor for capturing regenerative braking energy. While more aggressive accelerations may have a more balanced mix of front and rear braking energy, the UDDS segment shown is logical, given the rear motor's increased size and capability compared to the front axle's starter-generator.

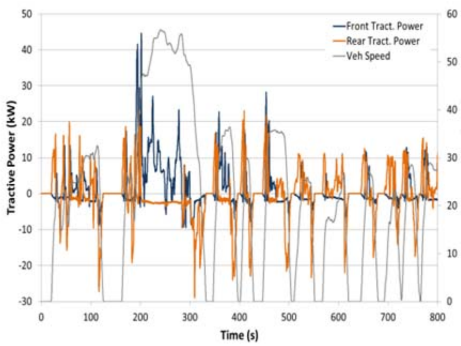


Figure 5. Mix of Front and Rear Axle Power during Subset of UDDS Driving.

One of the well-known challenges of diesel vehicles is their increased production of certain criteria emissions, especially nitrous oxides — commonly referred to as NO_x. Figure 6 shows the NO_x emissions from the 3008 Hybrid recorded over the UDDS cycle when operating "cold" (i.e., no prior operation, lack of cold ambient temperature). Figure 6 also contrasts the 3008's emissions with those of the Toyota Prius under the same operating conditions. The dramatically increased emissions dwarf those of the Prius, and large spikes of emissions can be seen during every restart — in contrast, the Prius shows relatively low emissions during warm-up, followed by extremely low emissions during the remainder of the test. Note that the spike in the Prius's emissions is just barely visible because of the scaling required for the 3008.

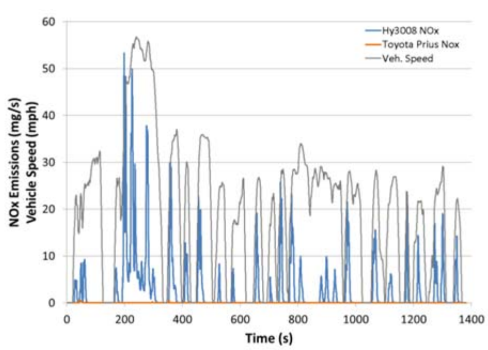


Figure 6. NO_x Emissions during Cold-start UDDS Operation (diesel 3008 vs. gasoline Prius).

To help illustrate the 3008's ability to provide electric assist during performance driving, Figure 7 shows battery power, engine power, and gear during two back-to-back aggressive accelerations. As would be expected for a vehicle providing electric assist, a large spike of battery power is followed by a corresponding spike in engine power as the engine increases its speed. The sharp drops in battery power during shifts are also noteworthy.

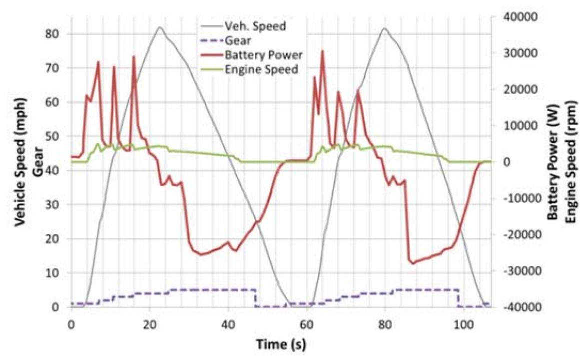


Figure 7. Engine and Battery Usage during Aggressive Accelerations.

In addtion to high-level, vehicle-type analysis, the testing of the 3008 also considered specific components of the vehicle. Of particular interest in this vehicle are the rear electric traction motor and the diesel engine, both of which are fairly unique for a hybrid vehicle. Figure 8 shows the estimated motor torque and speed observed across the major U.S. drive cycles of interest. From this figure, the motor's maximum capability of roughly 200 Nm can easily be observed.

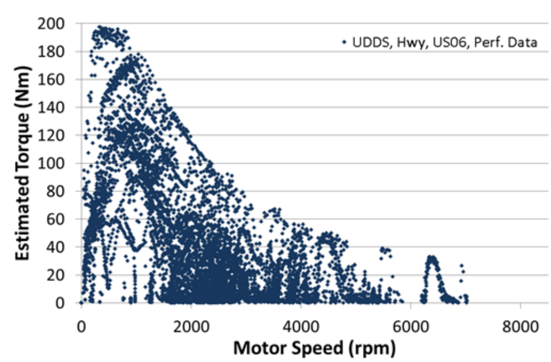


Figure 8. Rear Motor Usage and Torque Capability (only positive usage shown).

Figure 9 shows similar usage information for the rear-drive motor, but it shows motor power as opposed to torque. From the figure, the maximum available motor power of roughly 25 kW can be easily observed. The maximum observed motor torque and power are close to the values claimed by Peugeot. The scatter plots provide much added detail regarding the shape of the capapcity curves, as wells as the usage seen during standard operation.

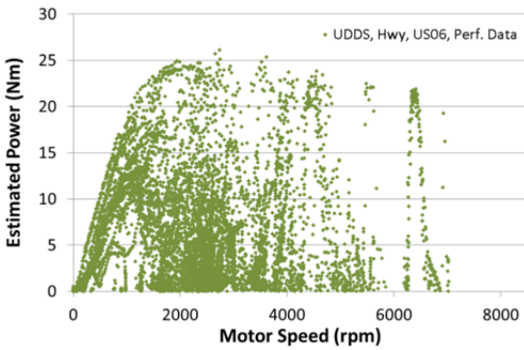


Figure 9. Rear Motor Usage and Power Capability (only positive usage shown).

Figure 10 shows similar information for the 3008's diesel engine. A peak torque of roughly 300 Nm is observed, and peak power seen during operation is roughly 113 kW, both of which are close to the reported values given by Peugeot. The usage information provided in Figure 10 is particularly interesting given the differences between gasoline and diesel engines, which typically have a much flatter efficiency map relative to a gasoline engine. In Figure 10, it can be seen that the vehicle spends a significant amount of time between ~1100 and 2000 RPM across a wide range of torque values. These data suggest that the vehicle operates in this region quite extensively in order to maintain high engine efficiency.

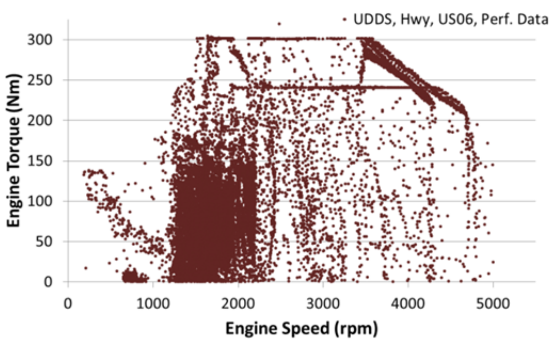


Figure 10. Engine Usage and Capability.

Figure 11 shows engine versus vehicle speed for several drive cycles. From this plot, one can easily observe the different ratios of the 3008's 6-speed gearbox. This information is also helpful for observing the varying time spent in different gears during a mix of driving.

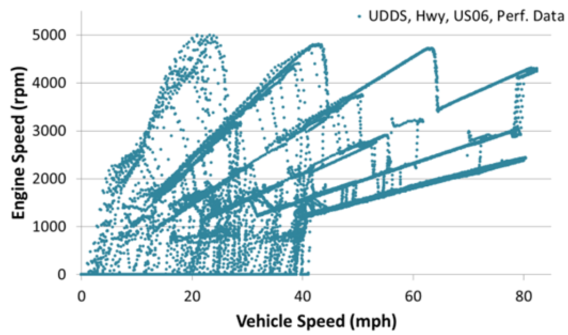


Figure 11. Engine Speed versus Vehicle Speed.

Another interesting feature of the 3008 Hybrid is that it offers a variety of driver-selectable operating modes. These modes include Standard (Auto) mode, which uses a traditional hybrid vehicle operating strategy; Sport mode, which adjusts the engine on/off operation and shift points; a 4x4 mode, which runs the engine the entire time and utilizes the electric rear motor to provide 4x4 driving; and a zero emissions vehicle (ZEV) mode, which seeks to provide EV operation whenever possible (but switches to Auto mode once the EV envelope has been exceeded).

Figure 12 shows the engine speed for three of the possible modes on a subsection of the UDDS drive cycle. The differences between the modes from an engine operation perspective can be clearly seen in the figure. As mentioned previously, the 4x4 mode runs the engine continuously, even during idle. Sport mode retains engine-off during vehicle stop, but it does not show engine-off operation while the vehicle is in motion (60–120 s). ZEV mode is not shown below because it is nearly identical to Standard mode for this testing. The ability to operate the vehicle in these different operating modes is particularly interesting from the perspective of observing the impacts of control strategy on fuel consumption and emissions; considerable work has been done in this area, but the results of that work are not included in this summary report because of space constraints.

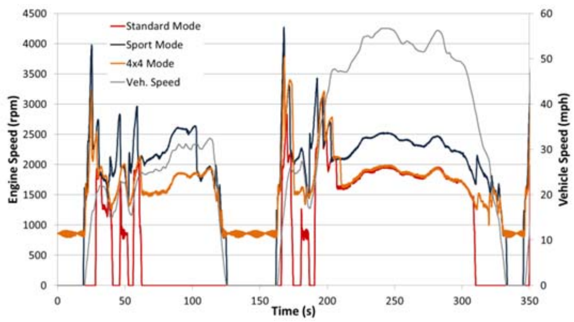


Figure 12. Engine Speed in Different Selectable Driving Modes for a Segment of the UDD.

Figure 13 shows the battery power during the same segment of UDDS driving for the different operating modes. Note the differences in battery usage as the engine operation is changed in response to the selectable mode. For example, the 4x4 mode shows minimal battery usage, aside from some light launch assist and braking regeneration. In comparison, the Sport mode shows a fair amount of engine charging, as evidenced by negative battery power during driving. In contrast to the previous modes, Standard mode shows a mix of battery usage, indicating electric launch, EV driving, engine charging, and load buffering.

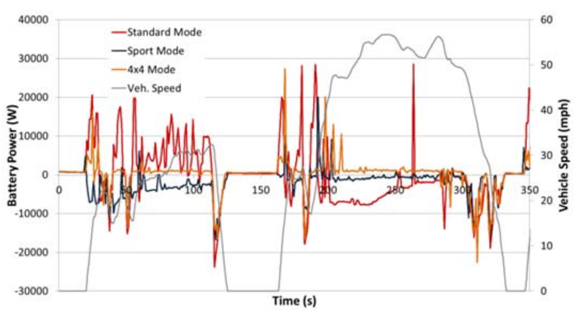


Figure 13. Battery Power in Different Selectable Driving Modes for a Segment of the UDDS.

Conclusions

As with previous years and Level-2 vehicle testing, significant time and effort were invested on the instrumentation, testing, and analysis of the selected Peugeot 3008 Hybrid4. Efforts were made to evaluate the most noteworthy aspects of this vehicle, especially its unique hybrid architecture and diesel engine. Additionally, testing was tailored to this vehicle's European origin, and a mix of U.S. and EU drive cycles were used for this evaluation. The results and analysis contained in this report represent a small but important subset of the entire project. given the ever-changing dynamics of the advanced vehicle marketplace Research regarding this unique vehicle, as well as previous Level-2 vehicles, will likely continue.

III.C.3. Products

Publications

NONE to date.

Tools & Data

The plan is for the data to be made available as part of the APRF Downloadable Dynamometer Database (D3) at:

transportation.anl.gov/D3/index.html

III.D. Assessment of Conventional Vehicle Technology Baseline

Principal Investigator: Henning Lohse-Busch, Ph.D.
Argonne National Laboratory
9700 South Cass Avenue
Building 361, Office B-217
Argonne, IL 60439
Phone: (630) 252-9615; Email: hlb@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.D.1. Abstract

Objectives

- Benchmark fuel consumption and performance of conventional vehicles available in 2012 while collecting powertrain component information.
- Build a database of powertrain technologies in conventional vehicles to enable a comparative study.
- Investigate the potential for petroleum displacement by new automotive technologies.
- Disseminate vehicle and component test data to partners of the DOE, such as the national laboratories, the U.S. Council for Automotive Research, original equipment manufacturers (OEMs), and suppliers, by populating the Downloadable Dynamometer Database (D3).

Approach

- Develop a comprehensive test plan with the DOE partners (e.g., simulation groups and OEMs) to collect relevant vehicle-level data. The primary focus of the data includes fuel consumption, vehicle efficiency, and shift patterns for standard drive cycles. Furthermore, data about acceleration performance, steady-state speed performance, idle fuel flow rates, cold-start penalties, deceleration fuel cutoffs, and accessory loads are desired.
- Implement the comprehensive, but noninvasive, Level 1 instrumentation and perform the testing on a two-wheel drive (2WD) chassis dynamometer at Argonne National Laboratory's (Argonne's) Advanced Powertrain Research Facility (APRF).
- Develop a test summary template to facilitate direct vehicle-to-vehicle comparisons.
- Leverage a decade of experience in testing vehicles to refine the test procedures and test plans.

Major Accomplishments

- Benchmarked vehicles of multiple engine and transmission configurations through comprehensive testing on the chassis dynamometer with a consistent test plan and instrumentation.
- Completed testing and summary sheets for eight conventional vehicles.
- Distributed the test results and analysis through several mechanisms, such as reports, presentations, and sharing of raw data by using a standardized template for data representation.

Future Activities

- Use the vehicle data that were generated to determine the potential for petroleum displacement by electrified powertrains or alternative fuel powertrains.

III.D.2. Technical Discussion

Introduction

The Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (Argonne) has been testing advanced-technology vehicles to benchmark the latest automotive technologies and components for the U.S. Department of Energy (DOE). Recently, DOE expressed an interest in acquiring conventional (non-hybrid gasoline and diesel) vehicle data for comparison purposes. To enable these comparisons, Argonne staff has tested a number of conventional vehicles of different configurations. These configurations include naturally aspirated and turbocharged gasoline with torque converter automatic transmissions and automated manual transmissions of varying ratio counts, as well as one continuously variable transmission. Summary sheets for all of the vehicles tested can be found in Appendix A.

Over the last decade, the staff has developed expertise in automotive testing. During this time, the instrumentation of the powertrains has evolved and the test procedures have been refined. Two main levels of testing exist today. Level 1 testing involves basic, but complete, non-invasive instrumentation of a vehicle, which leaves the vehicle unmarked after the testing. Level 2 involves a comprehensive invasive instrumentation of a vehicle and its powertrain components and leaves the vehicle with irreversible alterations. All vehicles in this study were tested with Level 1 instrumentation.

This report summarizes the Level 1 conventional vehicle benchmarking activities of year FY 2012. The dynamometer testing and instrumentation plans are described and data summary sheets are attached.

Approach

General Test Instrumentation and Approach

The results presented in this report are focused on the basic and complete non-invasive Level 1 testing type. Typically, Argonne receives these vehicles on loan from partners or obtains them through commercial rental agencies. The vehicles, therefore, need to leave the test facility in the "as-received" condition. This limits the installation of instrumentation to those sensors that can be easily removed without damaging the vehicles.

Despite this limitation, a significant amount of data has been collected successfully for all vehicles. Instrumentation was applied to monitor the engine speed, fuel flow (using a fuel flow meter where possible and verified by modal emissions), and engine oil temperature (achieved through dipstick instrumentation). A power analyzer was used to record 12-V loads and modal emissions were taken by using a Semtech mobile emissions analyzer. Additional measured parameters include the temperature of the vehicle cabin and, often, the position of the accelerator pedal. These signals can vary from vehicle to vehicle. A final part of the Level 1 benchmark is the recording of messages from the vehicle's onboard information buses, where available.

Test Matrix

To facilitate direct vehicle-to-vehicle comparisons, a test matrix was developed to provide a consistent and wide range of driving conditions. Testing was largely focused on the existing U.S. Environmental Protection Agency (EPA) cycles, including the Urban Dynamometer Driving Schedule (UDDS), US06, and the Highway Fuel Economy Driving Schedule (HWFET) tests. Additional tests were included to gather data on acceleration performance, steady-state speed performance, idle fuel flow rates, cold start penalties, deceleration fuel cutoffs, and accessory loads. Table 1 lists the details about the tests that were performed.

Table 1. Conventional Vehicle Test Summary

Test	Distance [mi]	Phases	Time [s]
UDDS#1 Cold Start	7.49	2	1374
UDDS#2	7.49	2	1374
UDDS#3 or 505 (until SS temp)	7.49	2	1374
HWYx2	20.63	2	3090
US06x2	16.11	4	2580
SSS (55 mph until Eng Oil > 95C)	N/A	1	N/A
JC08	5.1	1	1205
NEDC	6.92	2	1180
LA 92	9.87	1	1435
Idle Test	N/A	1	N/A
Cycle Beating UDDS	7.49	2	1374
Steady State Speed 0-80-0 30 sec	N/A	1	N/A
WOTx3	N/A	1	N/A
1.2 HWYx2 ED	20.63	2	1287
1.2 UDDS ED	7.49	2	1147
1.4 UDDS ED	7.49	2	986
Accessory Test	N/A	1	N/A
Gear Shift Test	N/A	1	N/A
Engine Map Test	N/A	1	N/A

Results

Results Sharing

As previously discussed, data summaries for vehicles tested for this study can be found in Appendix B. However, the RAW 10-Hz data will also be made available on Argonne's Downloadable Dynamometer Database (D^3). D^3 is a public website that provides access to vehicle testing data collected at Argonne. (transportation.anl.gov/D3/index.html). The data directly serve the development of codes and standards, as well as the development and validation of simulation models. These activities impact the modification of test plans and instrumentation. Additional partners in the testing are U.S. manufacturers and suppliers, through the U.S. Council for Automotive Research (USCAR).

As of this writing, the study is ongoing. It is anticipated that two additional vehicles will be tested: a 2013 Honda Civic and a vehicle with an 8-speed automatic, pending availability.

Selected Results

Figure 1 of Appendix A summarizes fuel economy results over EPA urban, highway, and US06 cycles. The conventional vehicle data obtained as part of this study have been supplemented with existing data for a Ford Fusion hybrid electric vehicle (HEV) and a Hyundai Sonata HEV, for comparison purposes. Several conventional engine technologies are represented in the results, including naturally aspirated and turbocharged gasoline engines with port fuel injection and direct fuel injection, as well as a turbo-diesel. Transmission technologies are equally diverse, with torque converter, automated dual-clutch, and continuously variable transmission (CVT) varieties represented.

Figure 2 of Appendix A summarizes overall vehicle powertrain efficiency (positive energy at the wheel divided by fuel energy) over the aforementioned cycles.

Figure 2 shows that the typical vehicle efficiency for the urban cycle ranges from 15 to 20%. Because of the lack of engine idle time and higher required loads, vehicle efficiency on the highway cycle improves to 25–30%. The results of the Fusion and Sonata hybrids included for comparison purposes show that these powertrains are able to improve on the urban vehicle efficiency numbers by as much as 15%. This improvement is due in large part to the hybrid's capacity for regenerative braking, as well as the technology's greater flexibility in operating the internal combustion (IC) engine at more efficient speed/load points. On the highway cycle, this advantage is negated because of the higher loads required of the powertrains and fewer opportunities for regenerative braking.

Attachments

Appendix A – Selected Results Figures

Appendix B – Summary of Conventional Vehicle Data

Appendix A – Selected Results Figures

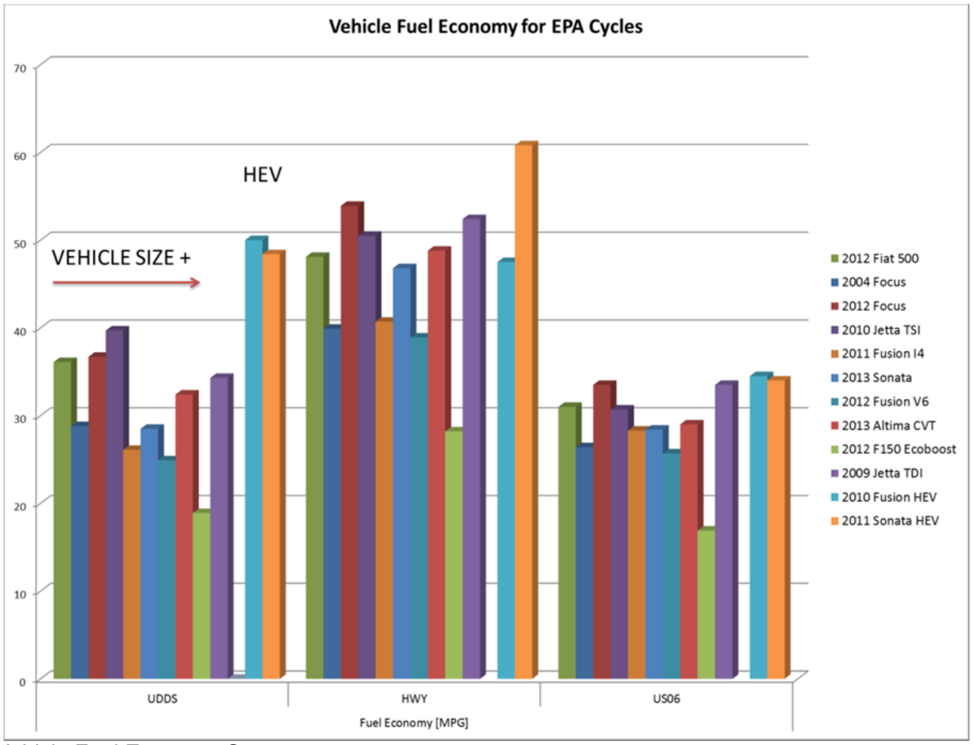


Figure 1. Vehicle Fuel Economy Summary.

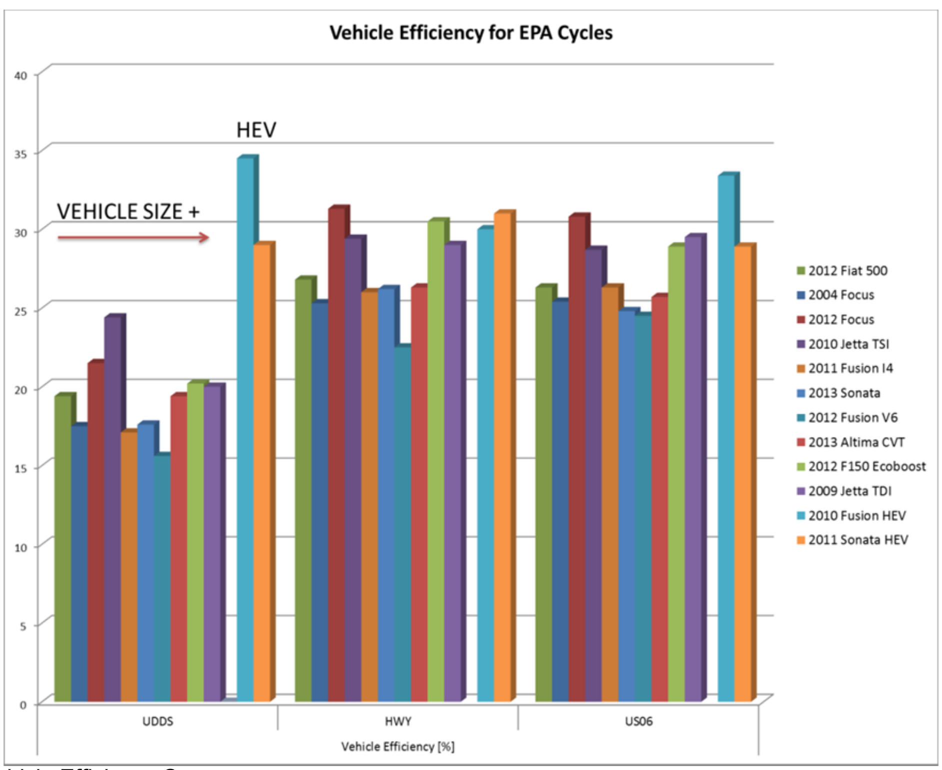
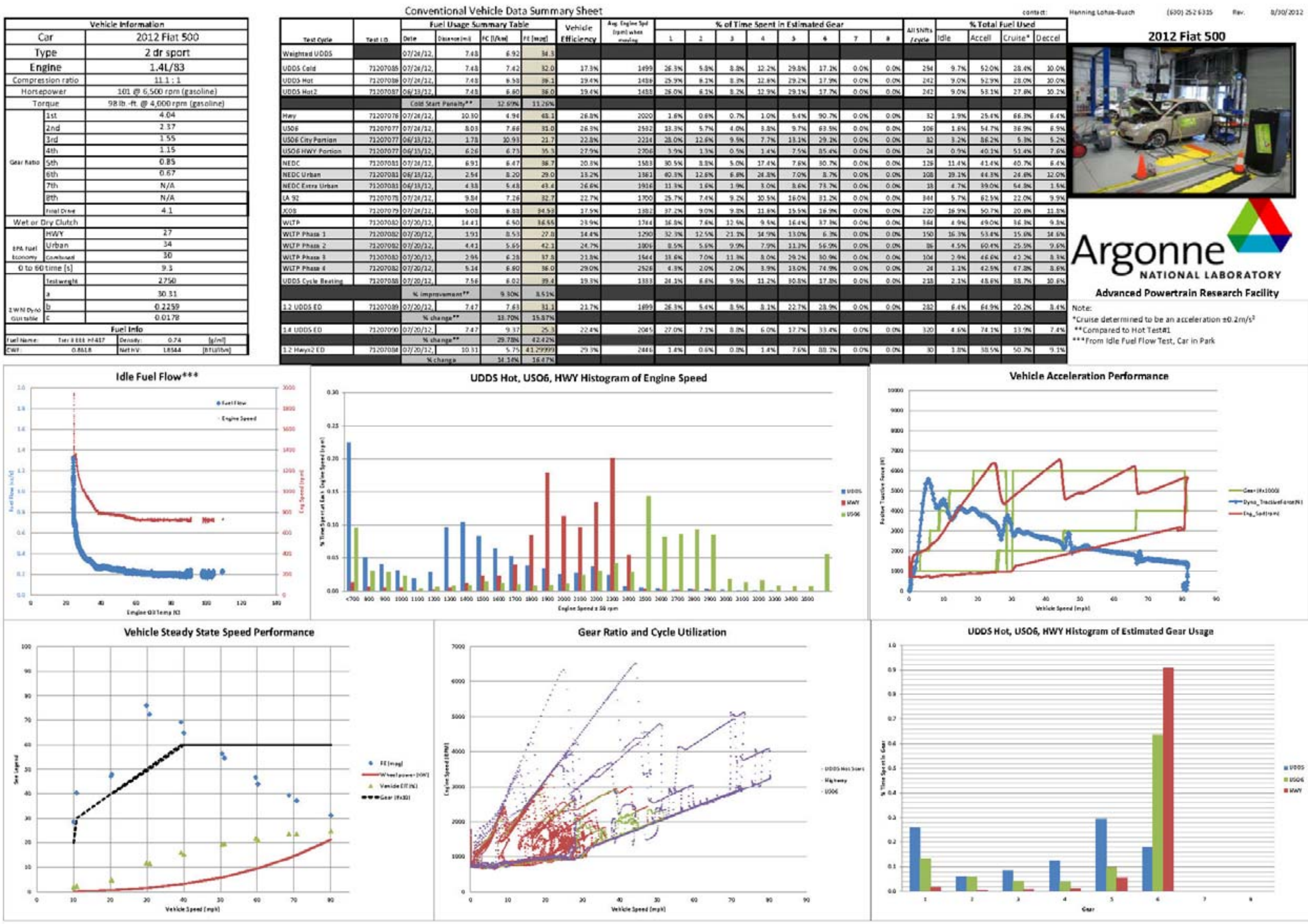


Figure 2. Vehicle Efficiency Summary.

Appendix B – Summary of Conventional Vehicle Data



Vehicle Information		
Car		2012 Fiat 500
Type		2 dr sport
Engine		1.4L/83
Compression ratio		11.1 : 1
Horsepower		101 @ 6,500 rpm (gasoline)
Torque		98 lb.-ft. @ 4,000 rpm (gasoline)
Gear Ratio	1st	4.04
	2nd	2.37
	3rd	1.55
	4th	1.15
	5th	0.85
	6th	0.67
	7th	N/A
	8th	N/A
	Final Drive	4.1
Wet or Dry Clutch		
EPA fuel economy	HWY	27
	Urban	34
	Combined	30
0 to 60 time [s]		9.3
2 WM Dyno GUI table	Test weight	2750
	a	30.31
	b	0.2259
	c	0.0178

Fuel Info				
Fuel Name:	Tier II EEE HF437	Density:	0.74	[g/ml]
CWF:	0.8618	Net HV:	18544	[BTU/lbm]

Conventional Vehicle Data Summary Sheet

contact: Henning Lohse-Busch (630) 252 6315 Rev. 8/30/2012

Test Cycle	Test I.D.	Date	Distance [mi]	FC [l/km]	FE [mpg]	Vehicle Efficiency	Avg. Engine Spd (rpm) when moving	Gear 1	Gear 2	Gear 3	Gear 4	Gear 5	Gear 6	Gear 7	Gear 8	All Shifts /cycle	Idle	Accell	Cruise*	Deccel
Weighted UDDS		07/24/12,	7.48	6.92	34.3															
UDDS Cold	71207085	07/24/12,	7.48	7.42	32.0	17.3%	1499	26.3%	5.8%	8.8%	12.2%	29.8%	17.1%	0.0%	0.0%	254	9.7%	52.0%	28.4%	10.0%
UDDS Hot	71207086	07/24/12,	7.48	6.58	36.1	19.4%	1486	25.9%	6.1%	8.3%	12.6%	29.2%	17.9%	0.0%	0.0%	242	9.0%	52.9%	28.0%	10.0%
UDDS Hot2	71207087	06/13/12,	7.48	6.60	36.0	19.4%	1488	26.0%	6.1%	8.2%	12.9%	29.1%	17.7%	0.0%	0.0%	242	9.0%	53.1%	27.8%	10.2%
		Cold Start Penalty**		12.69%	11.26%															
Hwy	71207076	07/24/12,	10.30	4.94	48.1	26.8%	2020	1.6%	0.8%	0.7%	1.0%	5.4%	90.7%	0.0%	0.0%	32	1.9%	25.4%	66.3%	6.4%
US06	71207077	07/24/12,	8.03	7.66	31.0	26.3%	2532	33.3%	5.7%	4.0%	3.8%	9.7%	63.5%	0.0%	0.0%	106	1.6%	54.7%	36.9%	6.9%
US06 City Portion	71207077	06/13/12,	1.78	10.93	21.7	22.8%	2214	28.0%	12.6%	9.5%	7.7%	13.1%	29.2%	0.0%	0.0%	82	3.2%	86.2%	5.3%	5.2%
US06 HWY Portion	71207077	06/13/12,	6.26	6.73	35.3	27.9%	2306	3.9%	1.3%	0.5%	1.4%	7.5%	85.4%	0.0%	0.0%	24	0.9%	40.1%	51.4%	7.6%
NEDC	71207081	07/24/12,	6.91	6.47	36.7	20.3%	1583	30.5%	8.8%	5.0%	17.4%	7.6%	30.7%	0.0%	0.0%	126	11.4%	41.4%	40.7%	6.4%
NEDC Urban	71207081	06/13/12,	2.54	8.20	29.0	13.2%	1361	40.3%	12.8%	6.8%	24.8%	7.0%	8.7%	0.0%	0.0%	108	19.1%	44.3%	24.6%	12.0%
NEDC Extra Urban	71207081	06/13/12,	4.38	5.48	43.4	26.6%	1916	11.3%	1.6%	1.9%	3.0%	8.6%	73.7%	0.0%	0.0%	18	4.7%	39.0%	54.8%	1.5%
LA 92	71207078	07/24/12,	9.84	7.26	32.7	22.7%	1700	25.7%	7.4%	9.2%	10.5%	16.0%	31.2%	0.0%	0.0%	344	5.7%	62.5%	22.0%	9.9%
JC08	71207079	07/24/12,	5.08	6.88	34.53	17.5%	1382	37.2%	9.0%	9.8%	11.6%	15.5%	16.9%	0.0%	0.0%	220	16.9%	50.7%	20.8%	11.8%
WLTP	71207082	07/20/12,	14.41	6.90	34.55	23.9%	1744	16.8%	7.6%	12.5%	9.5%	16.4%	37.3%	0.0%	0.0%	364	4.9%	49.0%	36.3%	9.8%
WLTP Phase 1	71207082	07/20/12,	1.91	8.53	27.8	14.4%	1290	32.3%	12.5%	21.1%	14.9%	13.0%	6.3%	0.0%	0.0%	150	16.3%	53.4%	15.6%	14.6%
WLTP Phase 2	71207082	07/20/12,	4.41	5.65	42.1	24.7%	1806	8.5%	5.6%	9.9%	7.9%	11.3%	56.9%	0.0%	0.0%	86	4.5%	60.4%	25.5%	9.6%
WLTP Phase 3	71207082	07/20/12,	2.95	6.28	37.5	21.8%	1544	13.6%	7.0%	11.3%	8.0%	29.2%	30.9%	0.0%	0.0%	104	2.9%	46.6%	42.2%	8.3%
WLTP Phase 4	71207082	07/20/12,	5.14	6.60	36.0	29.0%	2526	4.3%	2.0%	2.0%	3.9%	13.0%	74.9%	0.0%	0.0%	24	1.1%	42.5%	47.8%	8.6%
UDDS Cycle Beating	71207088	07/20/12,	7.56	6.02	39.4	19.3%	1383	24.1%	6.6%	9.5%	11.2%	30.8%	17.8%	0.0%	0.0%	218	2.1%	48.6%	38.7%	10.6%
		% improvement**		9.30%	8.51%															
1.2 UDDS ED	71207089	07/20/12,	7.47	7.63	31.1	21.7%	1699	26.3%	5.4%	8.5%	8.1%	22.7%	28.9%	0.0%	0.0%	282	6.4%	64.9%	20.2%	8.4%
		% change**		13.70%	15.87%															
1.4 UDDS ED	71207090	07/20/12,	7.47	9.37	25.3	22.4%	2045	27.0%	7.1%	8.0%	6.0%	17.7%	33.4%	0.0%	0.0%	320	4.6%	74.1%	13.9%	7.4%
		% change**		29.78%	42.42%															
1.2 Hwyx2 ED	71207084	07/20/12,	10.31	5.75	41.29999	29.3%	2446	1.4%	0.6%	0.0%	1.4%	7.6%	88.3%	0.0%	0.0%	30	1.8%	38.5%	50.7%	9.1%
		% change		14.14%	16.47%															

Fuel Usage Summary Table; % of Time Spent in Estimated Gear; % Total Fuel Used

Note:
*Cruise determined to be an acceleration ±0.2m/s²
**Compared to Hot Test#1
***From Idle Fuel Flow Test, Car in Park

Figure 3. Composite of FIAT 500 Testing Charts.

Figure 4. Composite of FIAT 500 Testing Charts.

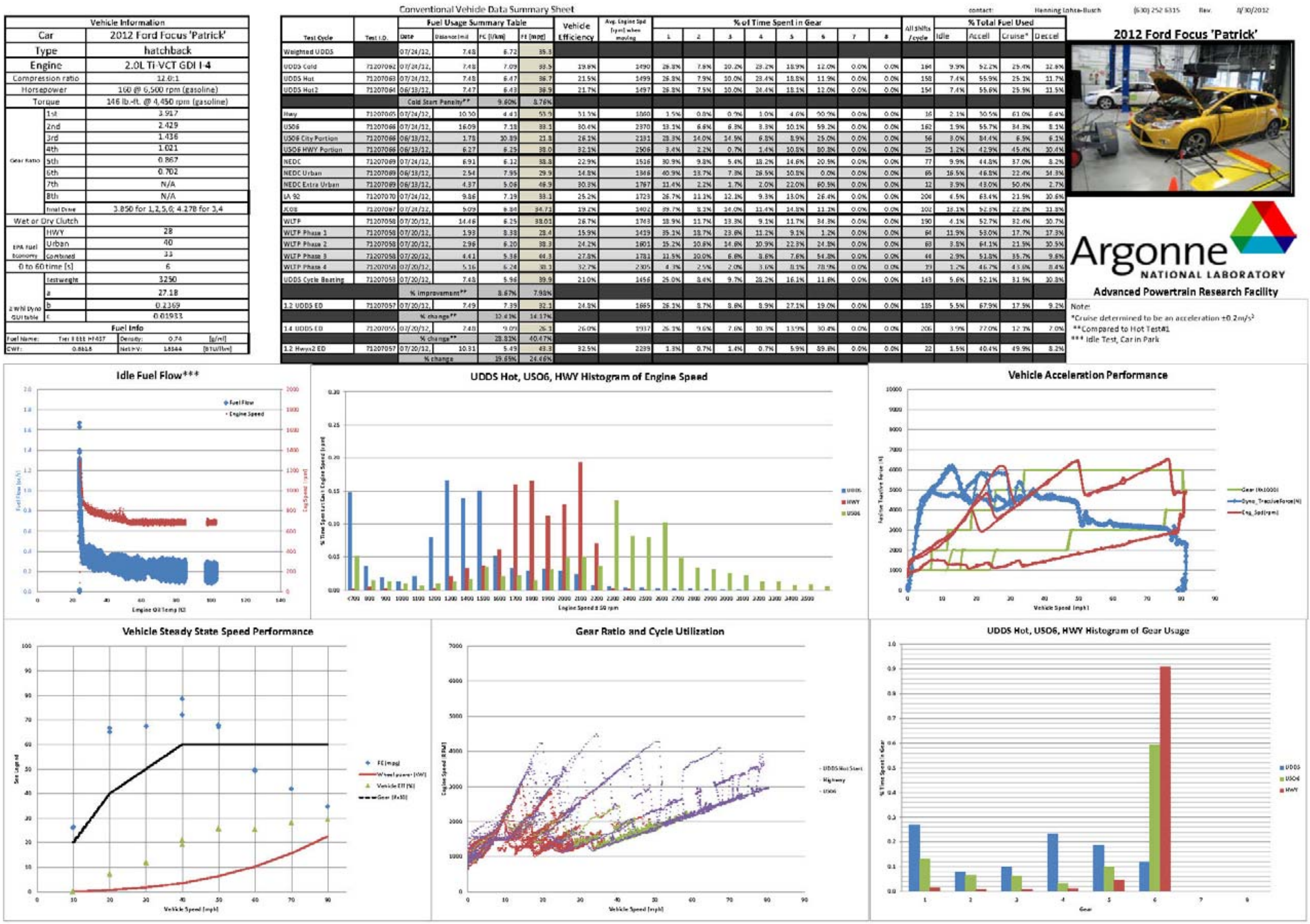


Figure 5. Composite of 2012 Ford Focus Testing Charts.

Figure 6. Composite of 2010 VW Jetta TSI Testing Charts.

Figure 7. Composite of 2013 Hyundai Sonata Testing Charts.

Figure 8. Composite of 2012 Ford Fusion V6.

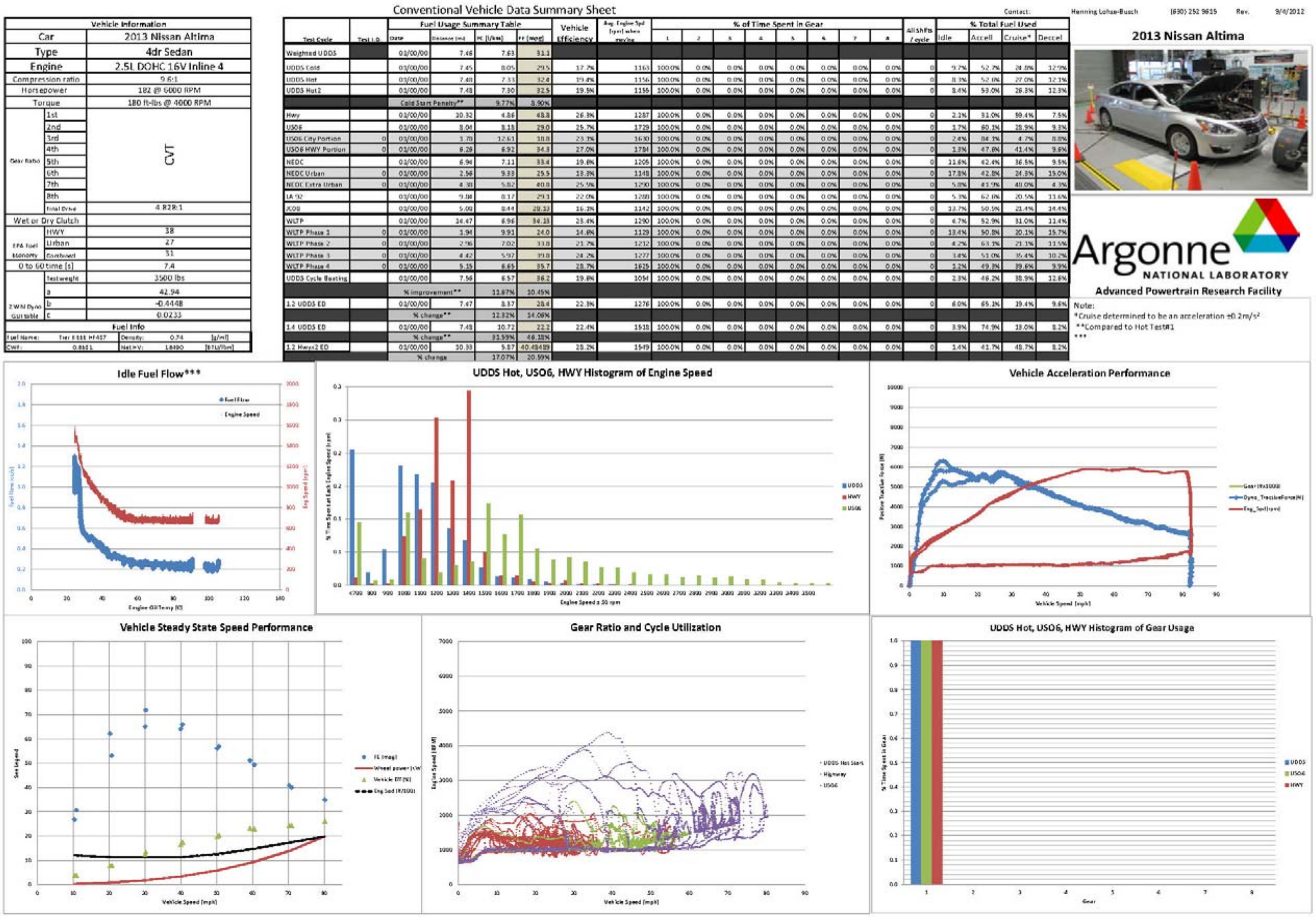


Figure 9. Composite of 2013 Nissan Ultima.

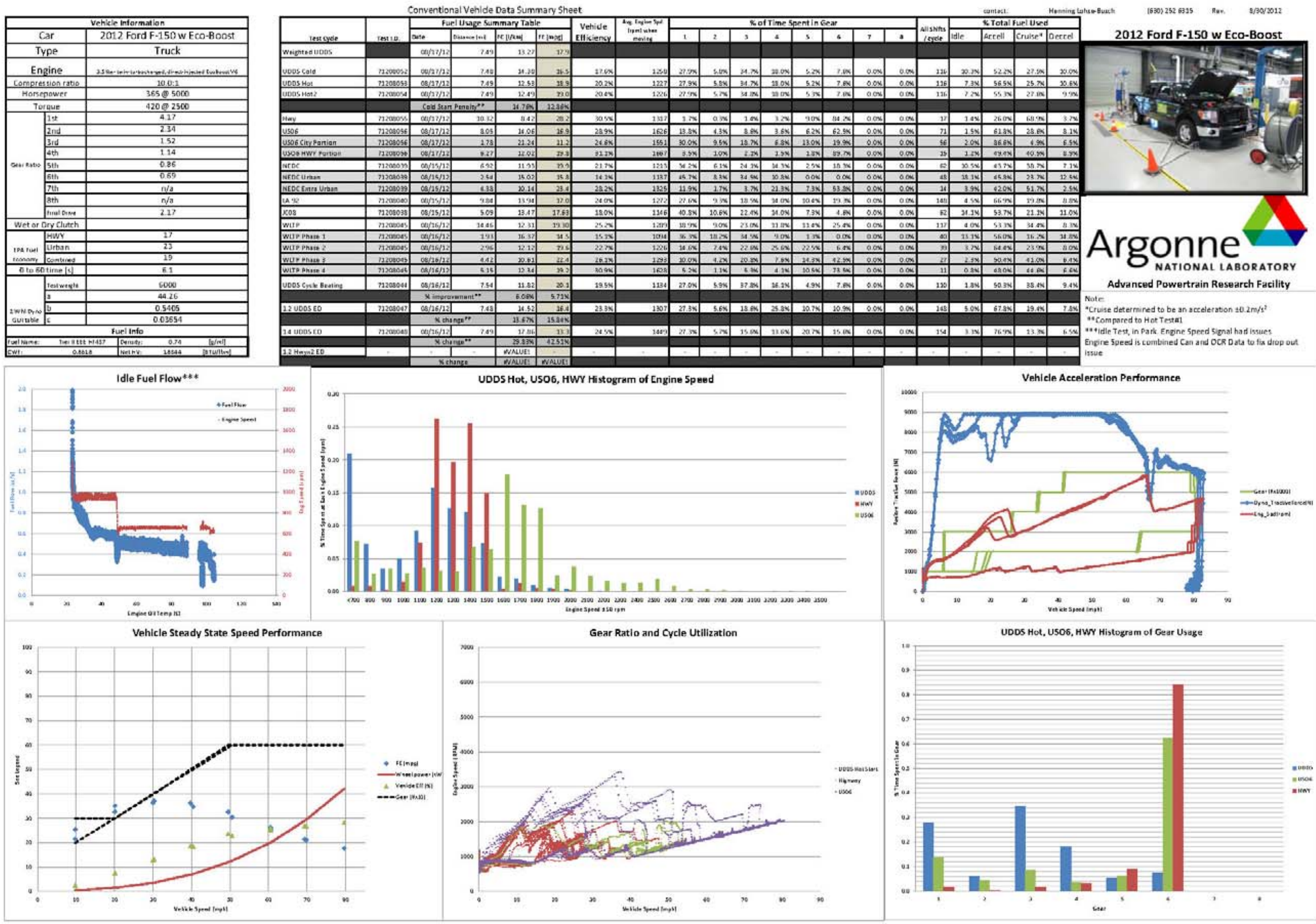


Figure 10. Composite of 2012 FORD F-150 with ECO-Boost.

III.E. Defining Real World Drive Cycles to Support APRF Technology Evaluations

Principal Investigators: E. Rask, R. Vijayagopal
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-3110; Email: erask@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.E.1. Abstract

Objective

- This work seeks to develop techniques to improve the estimation of real-world energy consumption using chassis dynamometer testing. Although numerous cycles can easily be assessed in simulation, the resource and time constraints of dynamometer testing necessitate an intelligent approach to reducing the amount of testing and increasing the information provided by testing. These goals are addressed in two distinct ways. First, a range of real-world drive cycles have been evaluated using both simulation and actual testing to assess the variability observed over these cycles. These data have then been processed to observe trends and select representative cycles that appear to be most relevant. Secondly, alternative techniques for improved usage data in-filling and consumption prediction have been developed.

Approach

- Utilize Autonomie to simulate numerous real-world drive cycles across a wide range of vehicle technologies.
- Supplement simulation runs with selected testing using a chassis dynamometer and Argonne test vehicles.
- Process simulation and chassis testing results to identify relevant cycles and issues/sensitivities to be addressed with further vehicle testing.

Major Accomplishments

- Assessed a wide variety of real-world drive cycles across a wide range of technologies and found two cycles to represent the observed consumption within one standard deviation for the range of cycles and technologies evaluated.
- Created vehicle mapping techniques for a range of vehicle technologies that have been shown to be accurate in predicting the fuel consumption characteristics of additional cycles (without additional testing).
- Developed a space-filling technique for increased test data relevance and prediction accuracy.

Future Activities

- Expansion of techniques to comprehend differences due to real-world driving at a range of ambient operating temperatures. Continued improvement of space-filling techniques to improve both positive and negative (regenerative braking) vehicle power consumption estimation.

III.E.2. Technical Discussion

Background

The majority of dynamometer-based vehicle testing is done using the traditional suite of U.S. regulatory cycles comprised of UDDS, Highway, US06 and SCO3. This suite is typically used in order to evaluate vehicles on a consistent basis as well as to allow lab-to-lab and vehicle-to-vehicle comparisons to be made. Furthermore, many testing facilities are mainly interested in EPA fuel-economy testing and validation. In contrast, technology evaluation testing done at Argonne National Laboratory's Advanced Powertrain Research Facility is concerned with both the EPA schedule results and obtaining a broad view of how a technology performs during real work conditions. When assessing a vehicle's behavior relative to real-world driving, the cycles used for assessment are particularly important. For example, Figure 1 shows the benefits of vehicle start-stop for both the U.S. UDDS and European NEDC cycle. As can be seen in the figure, the benefits of start-stop are dramatically higher on the NEDC as compared to the UDDS cycle.

Figure 1. Comparison of UDDS versus NEDC with Respect to Start-Stop Fuel Consumption Benefit.

Plug-in hybrid vehicles (PHEVs) pose even more difficulty in terms of assessing how the vehicle responds to real-world driving, which may include more aggressive accelerations and decelerations as well as higher average speeds as compared to the standard regulatory cycles. Figure 2 shows some of the possible energy and fuel-consumption responses for a PHEV, depending on the characteristics of a particular driving style. For each case, both the energy and fuel consumption change, and it is likely unknown a priori which direction a particular vehicle may move in for a specific driving cycle. Figure 3 shows some real-world test data overlaid with the regulatory cycles. In this figure, the wide range and multiple directions of real-world fuel and electricity consumption adjustment can easily be observed.

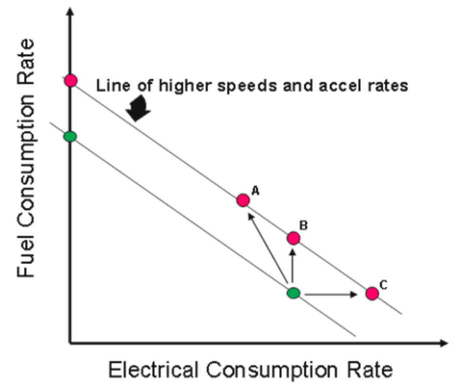


Figure 2. Possible Fuel and Energy Consumption Responses to Alternative Driving Style.

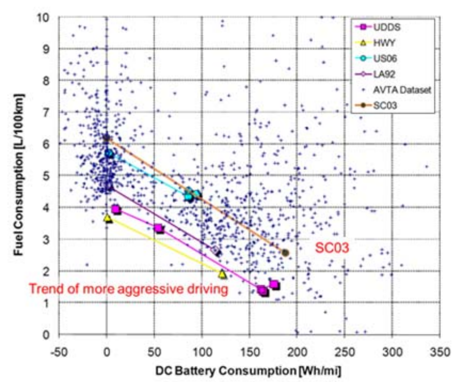


Figure 3. Scatter of Real-World Driving versus Regulatory Cycle Results.

Comparison of Real-World Drive Cycle Simulations

Introduction

The current methods for testing advanced vehicles using the UDDS and Highway drive cycles have many disadvantages. The UDDS and Highway [a.k.a. Highway Fuel Economy Test (HWFET)] cycles no longer represent the way vehicles are actually driven on the road. Hence, the fuel economy observed in those tests differs from what is observed in real-world driving. The EPA uses correction factors, which help to make the UDDS/Highway test results more realistic; however, a better approach might be to use drive cycles that are more representative of real-world driving. Another issue with the current regulatory test cycles is that the benefits we observe during these tests due to varying degrees of hybridization do not reflect the benefits we see during real-world driving.

Hence, the objective of this study is to investigate how EPA-prescribed drive cycles compare with real-world driving situations in terms of (a) various drive-cycle characteristics and (b) the fuel consumption associated with various vehicle technologies.

Methodology

The methodology followed for this study is shown in Figure 4. Autonomie® (an Argonne developed software tool for powertrain modeling and vehicle simulation) allows the modeling and simulation of various vehicle technologies over real-world drive cycles (RWDCs) recorded by the EPA in Kansas City, MO. The vehicles considered for this study are all midsize sedans with varying degrees of hybridization. A conventional vehicle, a starter-generator hybrid, a pre-transmission hybrid and a split hybrid were considered. In addition to RWDCs, these vehicles were simulated over the EPA test cycles. It is assumed that a normal distribution is obtained when we plot the fuel consumption observed over a RWDC (Figure 5).

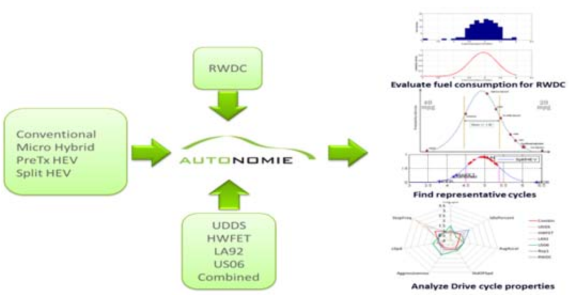


Figure 4. Autonomie Allows Running Multiple Vehicle-Cycle Combinations

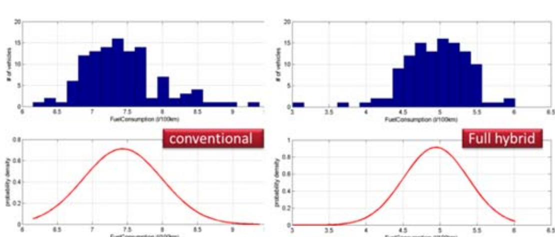


Figure 5. It Is Assumed that a Normal Distribution Is Obtained for the Fuel Consumption over a RWDC.

It is not clear which number can accurately represent the fuel consumption as plotted in these figures. We assume that any prediction within one standard deviation (SD) or less of the mean value is a relatively good one.

Analysis

A conventional mid-size vehicle, when simulated over the entire RWDC, provides a miles-per-gallon distribution as shown in Figure 6. We see that the unadjusted Highway fuel economy prediction is 40 mpg, which is an overestimation. The unadjusted UDDS cycle gives a slightly lower mpg number than the mean value. With adjustment equations, we get different estimates which fall at different regions of the distribution.

The fuel-economy distribution observed for a hybrid is shown in Figure 7. Comparing Figure 6 and Figure 7, we see that the drive cycle that provides a good fuel economy estimate for the conventional vehicle does not do so for the hybrid, and vice versa. So, which drive cycle we choose to test could determine how much improvement we obtain with hybridization. To ensure a fair comparison of the performance of a conventional and a hybrid vehicle, it is necessary to compare them over a fair drive cycle. It is imperative that the drive cycle chosen represent the real-world driving scenario.

There are many ways to find a representative drive cycle. The studies done at the University of Michigan and the National Renewable Energy Laboratory (NREL) are notable in this regard. However, in this case, we are asking which cycle can represent the RWDC from a fuel-economy perspective. We hope to find at least one cycle that can provide a mean +/−1-SD fuel economy for all the technologies we are considering.

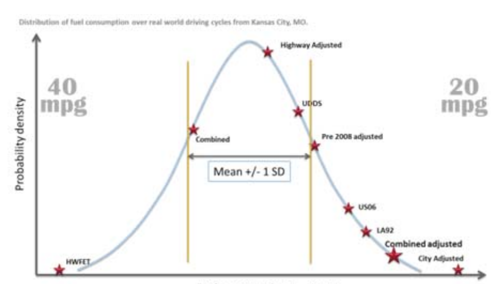


Figure 6. Distribution of mpg for a Conventional Vehicle.

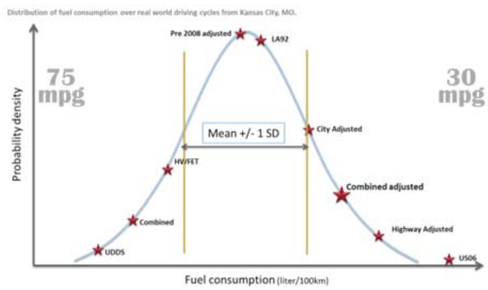


Figure 7. Distribution of mpg for a Hybrid Vehicle.

Such a cycle may not exist, but if it does, it will be interesting to conduct studies with such a cycle and compare the results against the representative cycle selections made by other methods.

We found that there are at least 27 separate daily driving patterns (Figure 8) that can predict the real-world fuel economy with a +/−1-SD accuracy.

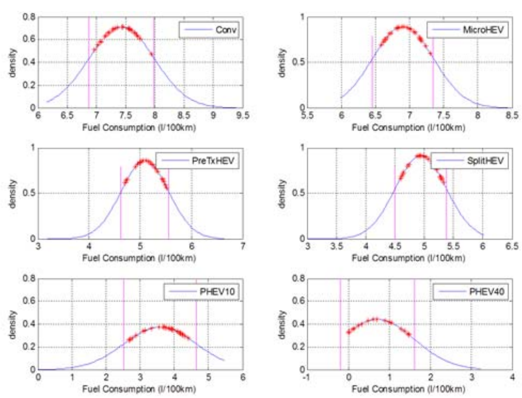


Figure 8. 27 RWDCs that Provide a Representative Fuel Consumption Figure for All Technologies Considered in This Study

If we reduced the margin of error to +/−0.5 SD, there was still one cycle that could predict the fuel economy for all the technologies considered. That cycle is shown in Figure 9.

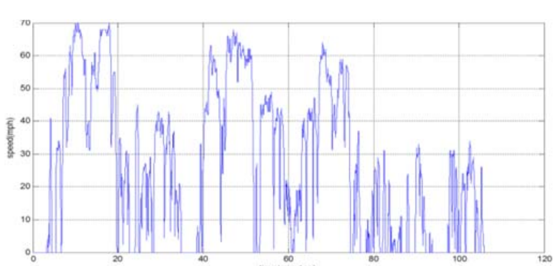


Figure 9. Representative Daily Cycle: 46 mi, 106 min, 36 Stops, 25 min Idling.

However, at 106 min, this cycle is too long to be used for a dynamometer test. So a decision was made to look at the individual trips (portions between two key-on events) and find a representative trip (Figures 10 and 11).

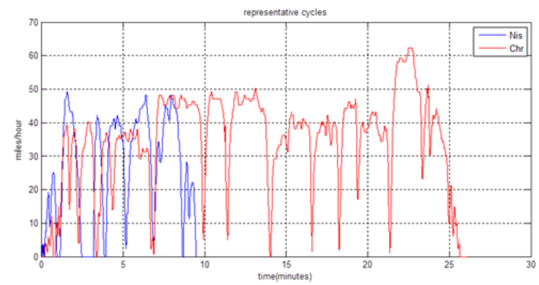


Figure 10. Two Trips that Can Represent Real-World Driving.

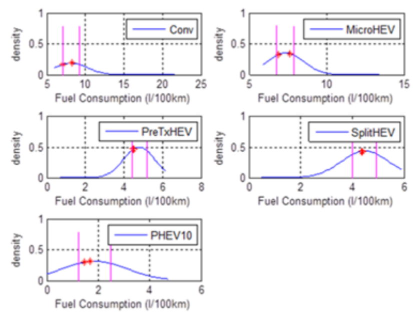


Figure 11. The Two Representative Trips Provide Fuel Consumption Results that Are Very Close to the Average Observed Values for All the Vehicle Technologies Considered in this Study.

Owing to the reduced distance covered by these individual trips, it was no longer meaningful to have a PHEV with a 40-mile all-electric range in this study. So the study is focused on conventional, mild and strong hybrids and a PHEV with a 10-mile all-electric range.

As a result of that exercise, we found that there are two cycles that can predict the fuel economy within the mean +/− 0.5 SD for all the technologies considered in this study. These two cycles are shown in Figure 7. These two cycles are remarkable in that the fuel consumption data observed over these cycles are very close to the mean value observed over all the RWDCs, for all vehicle technologies considered in this study.

These two cycles are being further analyzed for their suitability for dynamometer testing. For simulation tests, these cycles provide an interesting baseline test case. If a particular technology can provide a 10% improvement on these test cycles, it is very likely that we will observe a similar gain when that technology is implemented on a vehicle in a real-world driving scenario.

Vehicle Dynamometer Testing for Additional Real-World Performance Testing Insights

The following paragraphs seek to provide some selected insights and results from the dynamometer portion of this work. Although a range of vehicle technologies were evaluated, only illustrative highlights are provided in this brief summary document.

Although selecting a small subset of additional cycles is an appealing concept for streamlined dynamometer testing, several issues arise that complicate one's ability to truly evaluate real-world performance for a particular vehicle or technology. First, while the previous simulation revealed some promising cycles that appear to provide a representation of the "average" real-world performance for a variety of technologies, this value may not necessarily provide all the information desired for a particular vehicle technology. It is often equally important to assess how well a technology performs for a particular driving style, and that information may be lost in the averaging that the reduced subset of cycles provides. Figure 12 shows the relative rank for several of the RWDCs evaluated in the previous simulation discussion. It is clear that certain cycles show a very high rank (i.e., high fuel consumption) for the conventional and Integrated Starter Generator (ISG) case, whereas the hybrid (pretrans, split) and PHEV rank very low (i.e., low fuel consumption). Cycles 4 and 6, marked with asterisks, represent two selected cycles from the simulation assessment. Cycle 4 in particular shows a large discrepancy in ranking between the conventional and hybrid cases and suggests that these technologies may be behaving differently relative to the overall mix of RWDCs.

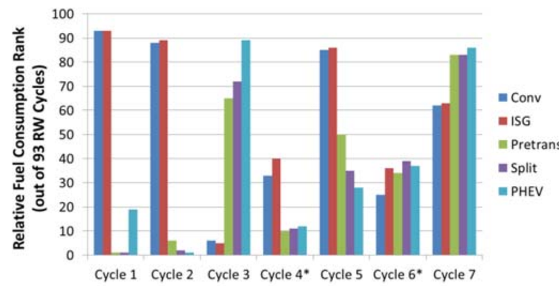


Figure 12. Relative Fuel Consumption for Selected Kansas City RWDCs across Technologies Evaluated.

Furthermore, it was observed that many of the supplemental RWDCs provide minimal information relative to the information obtained from the standard regulatory tests. While the fuel consumption for a particular cycle may differ significantly from that for the standard cycles, the actual usage was found to be typically very close to that observed for the envelope provided by UDDS, Highway and US06 testing. Moreover, many RWDCs had several very similar accelerations and decelerations, which are very representative of real-world driving but provide no additional insight beyond the first cycle. Figure 13 illustrates this issue by showing the speed and tractive load of two RWDCs overlaid with the usage provided by the standard U.S. regulatory cycles. As discussed above, there is improved in-filling of the usage envelope, but usage data in a new operating area is not evident.

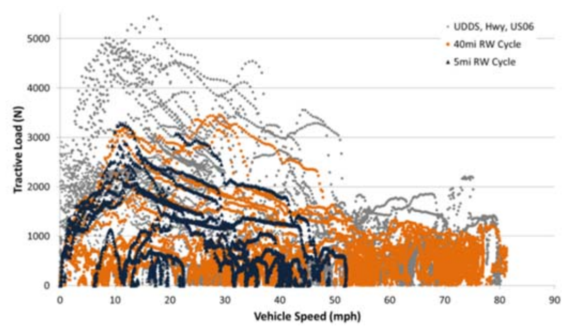


Figure 13. Selected RWDC Loads and Speeds, Overlaid with Regulatory Usage.

With these two key insights in mind, the scope of the vehicle testing was adjusted to focus on techniques and issues related to improving space-filling in addition to evaluating supplemental cycles, which may or may not provide additional information.

Although a range of vehicle technologies, including conventional, hybrid, plug-in hybrid, and electric, were evaluated for this work, the next section of this summary focuses on electric vehicles. A walkthrough highlighting some important steps in the analysis for an electric vehicle is provided below.

Figure 14 shows the overall efficiency calculated for an electric vehicle over a variety of drive cycles. On the basis of this information, it appears that the efficiency varies significantly cycle-to-cycle, and thus each of these cycles must be evaluated on a dynamometer to properly assess the energy consumption.

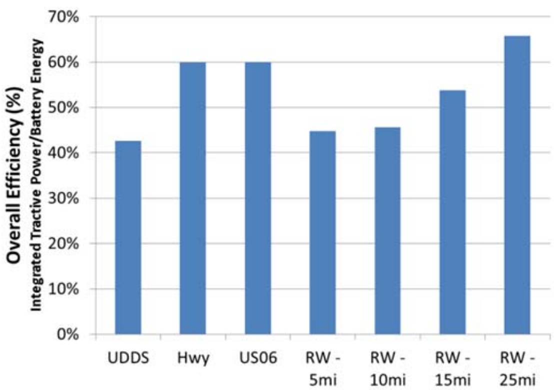


Figure 14. Overall Vehicle Efficiency for an Electric Vehicle over a Subset of Regulatory and Real-World Driving Cycles.

Fortunately, some intelligent processing was found to dramatically decrease the range of observed efficiencies, enabling certain cycles to be predicted using previously run tests.

Figure 15 shows an estimate of accessory load, which was found to vary linearly with time. Since this load changes minimally with usage but changes efficiency as a function of time, it is very helpful to remove this usage when performing efficiency calculations.

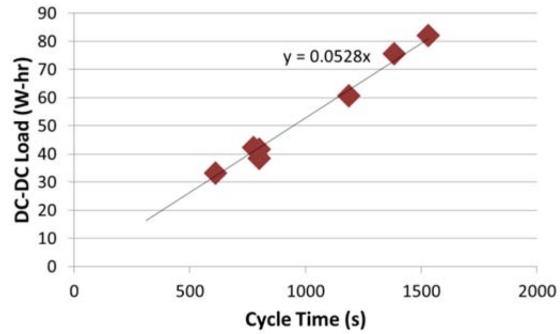


Figure 15. Accessory Energy Consumed versus Operating Time.

Figure 16 shows an additional step that is important for estimating representative efficiency for the entire range of vehicles tested. Namely, this figure illustrates the breakdown of the various cycles relative to acceleration, deceleration, and idle. This step facilitates identifying separate efficiency factors for acceleration and deceleration events, which often differ dramatically.

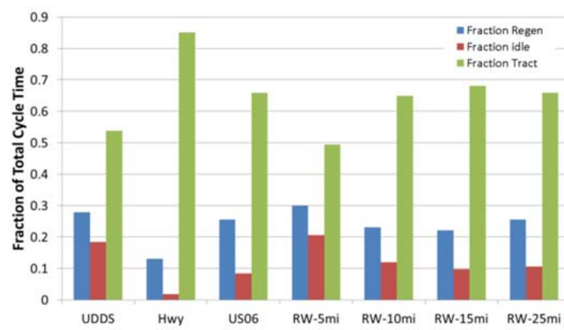


Figure 16. Breakdown of Acceleration, Deceleration, and Idle for Various Drive Cycles.

Using the breakdown provided in the previous two figures, Figure 17 shows the estimated efficiency for both positive and negative traction events for the cycles selected. One of the most interesting results from this analysis is that the majority of efficiencies are close together, which enables estimation of the different energy consumption values using prior testing as opposed to additional testing.

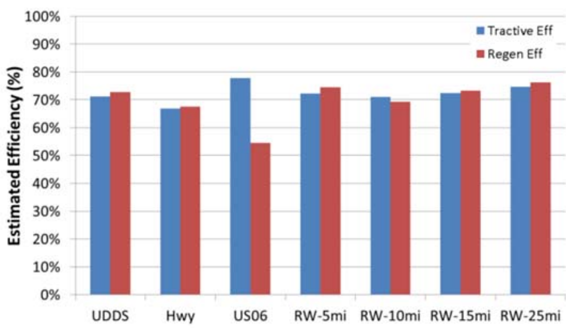


Figure 17. Tractive and Braking Efficiency for Selected Cycles.

Taking this procedure a step further, the ultimate technique for predicting real-world consumption would be to produce a power versus vehicle speed/tractive effort mapping that would allow the effective evaluation of any drive cycle given sufficient test data to support the mapping. Figure 18 shows the speed and tractive effort observed over the standard U.S. cycles plus a maximum acceleration. This information is then used to create a map of battery power corresponding to each usage point. This map can then be used to estimate the positive tractive energy consumption for a particular vehicle.

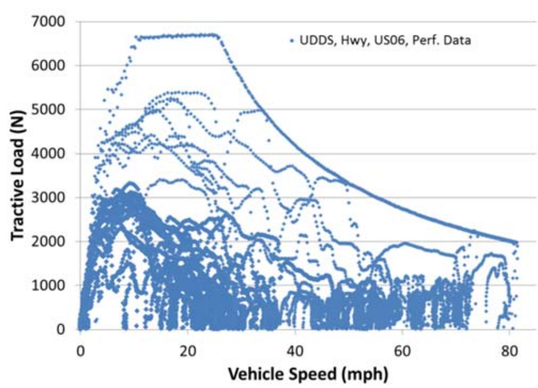


Figure 18. Speed and Dynamometer Tractive Effort Observed Over the Standard U.S. Cycles.

While this process is fairly straightforward for a vehicle moving with positive tractive effort (a simple power-to-road-loading mapping), the process for analyzing regenerative braking is much more difficult to map because of vehicle-specific capability constraints. Fortunately, these data could be mapped as well, using a similar power-versus-speed/ tractive-effort approach with some additional braking-system constraints. Figure 19 shows the estimated regenerative braking envelope for the example vehicle. As with most vehicle regenerative energy, recapture is minimal at lower speeds and then ramps up to a maximum near 10 mph. Maximum regenerative braking is then held constant (lower than the maximum braking force) and thereafter begins to decrease and follow the system power/capability limits. The red line in Figure 19 illustrates a simple force constraint that was added to include the vehicle's regenerative braking limitations. Using this information in conjunction with the mapping technique discussed previously, regenerative energy capture could be estimated with sufficient accuracy.

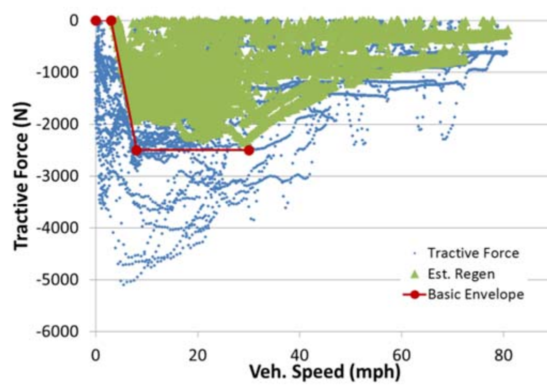


Figure 19. Regenerative Braking Envelope for Example Vehicle.

Using these two maps created from a minimal amount of standardized testing, the estimated energy consumption was compared to the tested consumption for a variety of RWDCs. Figure 20 shows the comparison of estimated versus actual energy consumption for a selection of RWDCs. All of these cycles have been estimated within 2%, which seems adequate given the large amount of time and effort saved by creating these estimates as opposed to evaluating these additional cycles on the dynamometer. Furthermore, the main differences between the actual and estimated data are actually related to the fact that idle loading shows some variability owing to vehicle standstill. This behavior is likely an artifact of the 12-V battery usage and can likely be estimated with greater fidelity if more accurate results are needed.

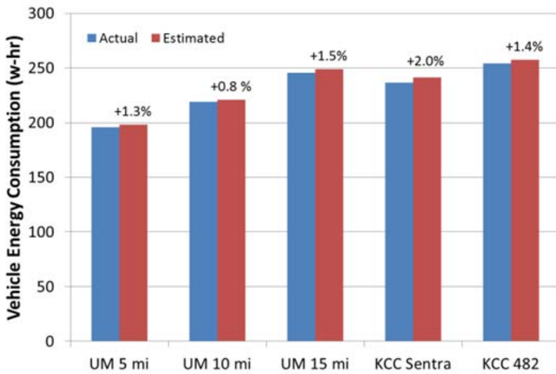


Figure 20. Actual versus Estimated Energy Consumption for Selected RWDCs [Source: UM- U. of Michigan and KCC- Kansas City Consortium data sets].

This walkthrough has provided an example for an electric vehicle; this technique was also evaluated for conventional and hybrid vehicles. Although the individual accommodations for each technology might differ (i.e., idle fueling for the conventional vehicle and state-of-charge control for the hybrid), this technique appears promising for enabling the robust estimation of energy/fuel consumption for a large range of driving styles.

The last technique developed for this work was a methodology to create a simple procedure for mapping additional usage points that may not be observed during typical UDDS, Highway, US06, and maximum-performance testing, thus filling the space of possible operation. This technique uses a set of special road load and vehicle mass values to distribute usage points across the capability envelope by running a vehicle through a series of constant accelerations up to roughly 80 mph. The vehicle mass can be increased significantly, which allows for much higher tractive loads while removing the need for fast accelerations that tend to lead to vehicle wheel slip. This supplementary data, in concert with the standard data collected, can then be used to create a more accurate vehicle map, as discussed previously. Figure 21 shows both the standard and supplemental data collected for an example conventional vehicle. As would be expected, the supplemental data helps to in-fill areas where some data are not available during standard testing. It should be noted that this procedure can be done iteratively and thus, if needed, another pass could be used to in-fill the usage space even more.

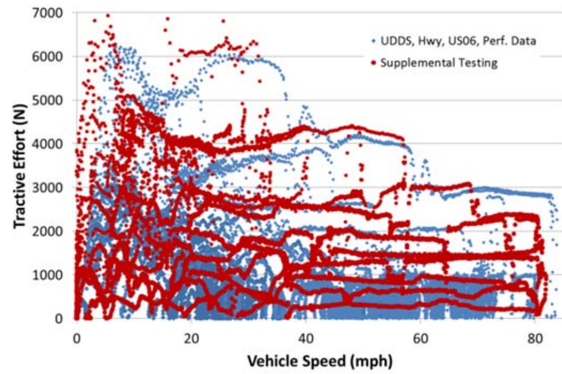


Figure 21. Speed and Tractive Effort Points for Standard Test Cycles and Supplemental Testing Procedure.

Conclusions

In summary, a significant amount of both simulation and dynamometer testing effort was spent investigating how to improve the estimation of a given technology's impact on real-world driving. The simulation component of this study was able to identify two supplemental cycles that appear promising for gauging the overall impact of real-world driving within roughly one standard deviation. The dynamometer-testing portion of this work focuses on ways to improve overall data collection and space-filling techniques so that the data collected during testing may be used to accurately assess a range of new cycles without the need for significant additional testing.

III.F. Evaluation of Existing ANL Benchmark Vehicles at a Range of Temperatures

Principal Investigator: Henning Lohse-Busch Ph.D.
Argonne National Laboratory
9700 South Cass Avenue
Argonne IL 60439-4815
Phone: (630) 252-9615; Email: hlb@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.F.1. Abstract

Objective

- Provide understanding of the ambient temperature impact on the fuel and energy consumption of a range of vehicles from conventional vehicle technology to full hybrid electric vehicle and battery electric vehicles. The test temperature range considered in this project is from a freezing 20F to a hot 95F with emulated radiant sun energy.
- Disseminate vehicle and component testing data to partners of the DOE, such as national laboratories, the U.S. Council for Automotive Research, OEMs, suppliers and university. This data is also used to support codes and standards development as well as support for powertrain model development and validation.

Approach

- In FY 2012, the Advanced Powertrain Research Facility (APRF) completed the thermal chamber upgrade of the 4WD chassis dynamometer test cell. Now vehicles can be tested at the standard 72F as well as the freezing 20F ambient condition and hot 95F with 850 W/m^2 of radiant sun energy emulation. With these new capabilities, the APRF staff can test vehicles in all of the EPA 5 cycle fuel economy testing conditions.
- This study utilized the unique facilities of the APRF such as the chassis dynamometer in the thermal chamber that includes with extensive instrumentation expertise. A wide range of instrumentation equipment with an emphasis on measuring energy consumption, both fuel and electric are available. Argonne staff has over a decade of experience in testing advanced vehicles, and uses that expertise to refine the test procedures and test plans.

Major Accomplishments

- In general, a higher degree of hybridization of the powertrain will yield a larger fuel/energy consumption increase at the 20F and 95F than the standard 72F test condition.
- The cold start UDDS causes the largest fuel/energy consumption increases for both hybrid and electric vehicles. At 20F the hybrid depends on running the engine more frequently to provide heat to the cabin, while the electric vehicle is penalized by the use of the electric heater.
- The highway fuel/energy consumption penalty is less severe compared to the UDDS across the different vehicles architectures. At 95F, the average powertrain load required to move the vehicles on the highway and US06 cycles is significantly higher compared to the UDDS cycle so the average load of the air conditioning system remains constant. For hybrids at a cold 20F, engines operate more frequently on the highway and the US06 cycles compared to the UDDS, thus enough engine heat is generated to provide adequate cabin heating with no increased penalty.

Future Activities

- In the future the 5 cycle test conditions will be included as part of the standard test protocol at the APRF for the majority of vehicles tested.

III.F.2. Technical Discussion

Background

The Advanced Powertrain Research Facility (APRF) at Argonne has been testing advanced-technology vehicles to benchmark the latest automotive technologies and components for the U.S. Department of Energy (DOE) for well over a decade. The staff has tested a large number of vehicles of different types such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles, in addition to conventional vehicles including those powered by alternative-fuels.

During FY 2012, the APRF integrated a thermal chamber into the 4WD chassis dynamometer test cell. With this thermal chamber the following EPA 5 cycle fuel economy test conditions can be replicated:

- 72F ambient temperature
- 20F ambient temperature for the cold CO test
- 95F with 850 W/m^2 radiant sun energy for the SC03 test.

The UDDS (Urban Dynamometer Driving Schedule), the highway cycle and the US06 are fuel economy test cycles which are performed at an ambient temperature of 72F. The UDDS and the highway are the classic city and highway test cycles used by the EPA for fuel economy testing since the 1970s. The US06, which is an aggressive drive cycle with heavy accelerations and high speed sections, is now part of the fuel economy label calculation. The fourth test is the UDDS performed in a sub-freezing ambient temperature of 20F. The fifth and final test is the SC03 which is urban type driving in ambient temperatures of 95F with emulated solar radiant energy levels of 850 W/m^2 including cooling air proportional to the vehicle speed. Figure 1 illustrates the cycles and the test conditions for the EPA fuel economy label calculations.

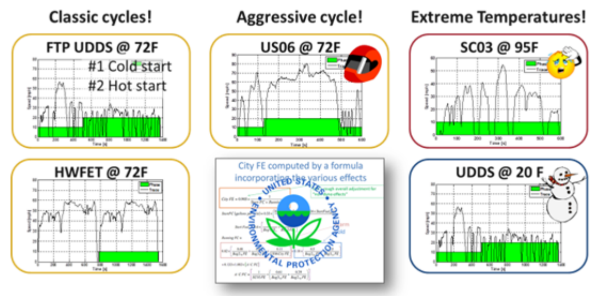


Figure 1. Illustration of the EPA 5 cycle fuel economy tests.

Approach

Through years of benchmark testing of advanced technology vehicles, the APRF has acquired a number of instrumented test vehicles ranging from a conventional vehicle to many hybrid electric vehicles and a plug-in hybrid electric vehicle. This study uses these vehicles as test objects.

A fundamental gateway to the data is Argonne's Downloadable Dynamometer Database (D^3), which is located on a public website at (transportation.anl.gov/D3/index.html). The D^3 website provides access to data and reports from vehicles tested on the standard test cycles. The data directly serves the development of codes and standards as well as the development and validation of simulation models. These activities impact the modification of test plans and instrumentation. Further partners in the testing are U.S. vehicle manufacturers and suppliers, through the U.S. Council for Automotive Research (USCAR).

Many of the research activities of the DOE rely on benchmark laboratory and fleet testing results to make informed progress towards desired goals. Figure 2 details some of these DOE research activities and partners.

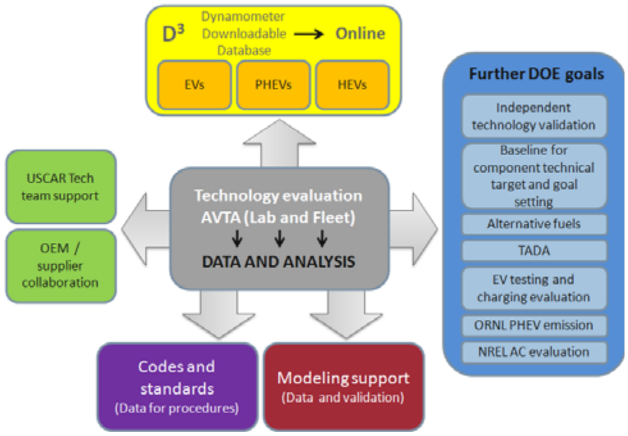


Figure 2. Data dissemination and partners.

Advanced Powertrain Research Facility

In FY 2012, the 4WD chassis dynamometer test cell of the APRF was upgraded to enable running the EPA 5 cycle procedures. The test cell now includes a thermal chamber and an air handling unit with a large refrigeration system that enables vehicle testing at ambient temperature of 20F (-7C) to 95F (35C). A set of solar radiant emulation lamps can provide 850 W/m^2 of radiant sun energy. The new capability is illustrated in Figure 3.

Figure 3. Nissan Leaf testing displayed at 95F with solar emulation on the left and testing at cold ambient temperature on the right.

In addition to requiring ambient test temperatures of 95F with the 850 W/m^2 of radiant sun energy, the SC03 cycle, which acts as the air conditioning test, requires a blower fan that can provide an air flow proportional to the vehicle speed. The test cell now includes such a variable speed fan as shown in Figure 4.

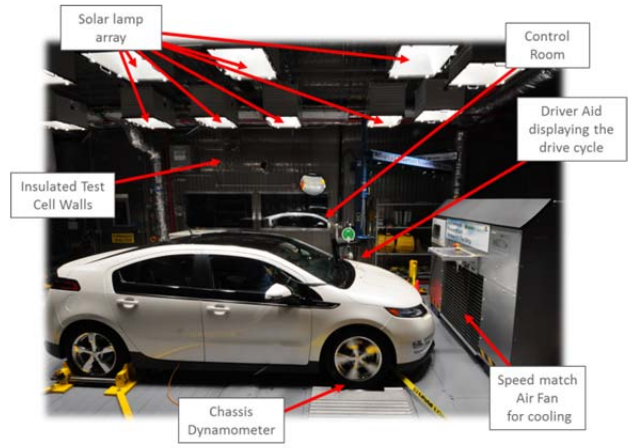


Figure 4. Details of the upgraded test chamber during Chevrolet Volt testing at 95F with sun emulation.

Due to the evolution of the distinct tests over a period of almost 40 years, some differences in test conditions and vehicle setup exist such as different vehicle cooling fan requirements and climate control settings. Additionally the 5 cycle equations consider the UDDS and the SC03 test cycles to be similar to city type driving that the air conditioning fuel is derived by the fuel consumption difference between the two cycles. Considering all these facts, the APRF staff carefully decided to harmonize some of the test conditions to achieve the most consistent test environments, even if that requires deviating from certification conditions.

The following test conditions apply to all the results below unless otherwise specified:

- The vehicle cooling fan is always run in vehicle speed matching mode and the hood is closed at all ambient test temperatures.
- All test sequences include a cold start UDDS, a hot start UDDS, a highway cycle and a US06 cycle at all ambient temperatures. The SC03 cycle was not always conducted over all vehicles
- 72F ambient tests: The vehicle climate control was turned off for all tests at an ambient temperature of 72F. The driver window is down at 72F.
- 20F ambient tests: The climate control was set to 72F in automatic mode at ambient test temperatures of 20F which causes the heat to be turned on. The target road load coefficients are not adjusted or re-derived at the

recommended 10% longer coast down period. This was done in order to be able to dissociate the temperature related vehicle losses and accessory loads only.

- 95F ambient tests: The climate control was set to 72F in automatic mode at ambient test temperatures of 95F which causes the air conditioner to turn on. During all 95F tests, the solar emulation lamps were turned on and the 850 W/m^2 of radiant sun energy level was calibrated at the base of the windshield of the test vehicle.

The test ambient temperature is the test cell temperature. This is the temperature experienced by the vehicle and the powertrain during testing as well as the soak period.

The cold start terminology refers the first test after the vehicle and its powertrain has been temperature soaked for at least 12 hours. The powertrain is off during the soak period and the powertrain is turned on as the cold start cycle is started. Typically at the APRF, the vehicle soak period preceding the cold start tests was between 14 and 16 hours. A cold start test can be run at all test temperatures- 20F, 72F, and 95F.

Results

Overview of Vehicles in the Study

The vehicles in this study span from a conventional vehicles and hybrid electric vehicles to a battery electric vehicle including a plug-in hybrid vehicle. Table 1 summarizes all the vehicles along with select details related to their powertrain thermal management.

Table 1. Test vehicle summary

04 Focus	09 Insight	11 Sonata HEV	10 Prius	11 Volt	12 Leaf
Conventional 2.0L PI 4 spd auto	*Mild HEV* 1.3L CVT 10kW motor	*Pre-trans HEV* 2.4L DI 6 spd auto 30kW motor	*Full HEV* 1.8L DI Power split 60kW prim motor	*PHEV EREV* 1.4L DI 111kW prim motor	*BEV* Single gear 80kW motor
					
Air conditioning: Mechanical	**Air conditioning:** Mechanical	**Air conditioning:** Mechanical	**Air conditioning:** HV electrical	**Air conditioning:** HV electrical	**Air conditioning:** HV electrical
Heater: Engine waste heat	**Heater:** Engine waste heat	**Heater:** Engine waste heat	**Heater:** Engine waste heat Exhaust heat redistribution	**Heater:** Engine waste heat HV electrical	**Heater:** HV electrical
Battery thermal: N/A	**Battery thermal:** Forced air from cabin	**Battery thermal:** Forced air from cabin	**Battery thermal:** Forced air from cabin	**Battery thermal:** Actively heated or cooled through coolant	**Battery thermal:** Internal convection but no active external cooling

The hybrid electric vehicles were strategically selected to represent the major different types of hybrid architectures available. The Honda Insight is a mild hybrid which does not have the ability to launch or drive the vehicle in electric only mode. The 10kW motor enables engine idle stop, regenerative braking and can provide some electric assist during accelerations.

The Hyundai Sonata is a full hybrid which can operate in electric mode at very high vehicle speeds using its P2 hybrid architecture. The 30kW electric motor can be declutched from the engine and drive the transmission input directly, allowing for only the electric motor to move the vehicle.

The Toyota Prius is also a full hybrid. The power split architecture does not enable the high vehicle speed electric mode operations, but it does provide a higher degree of freedom to operate the engine optimally.

Overview of the Test Process

Each car was tested on a cold start UDDS cycle, a hot start UDDS cycle, a highway cycle and a US06 cycle at the three EPA 5 cycle test conditions which are 20F, 72F and 95F with 850 W/m^2 of emulated sun energy.

To prepare for a cold start test, the test cell was set to the target test conditions of the cold start test, and then a UDDS cycle was performed to prepare the vehicle. This step is especially important to condition the battery state of charge level for the hybrid vehicles. After this ‘prep’ cycle, the vehicle was temperature soaked in the test cell at the target temperature for at least 12 hours.

The battery electric vehicle and the plug in vehicles were left on charge over night to enable the full charge test sequence the next day.

For the charge sustaining cold start tests, the plug-in hybrid performed two charge sustaining UDDS preparation cycles the evening before the cold start test.

Impact of Ambient Temperature on Fuel or Energy Consumption

Cold testing results (20F)

Figure 5 shows the increase in fuel required to complete the drive cycles at 20F with respect to the fuel consumption of the 72F drive cycles.

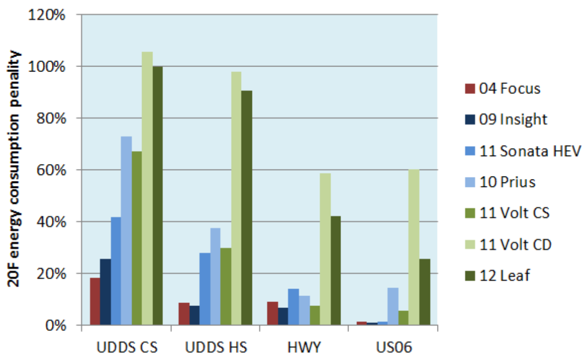


Figure 5. Extra energy used at 20F ambient temperature compared to the standard 72F testing.

At 20F ambient temperatures, the first cold start city cycle has the largest fuel penalty with respect to the 72F testing. All vehicles have to overcome the higher friction losses of the cold powertrain systems at 20F. Hybrid electric vehicles incur a large fuel consumption penalty compared to the conventional vehicle because the engine has to operate more frequently compared to the 72F ambient temperature test to provide the heat from the engine to warm up the cabin. On the hot start UDDS at 20F, the conventional vehicle and the hybrid electric vehicles significantly reduce the fuel consumption penalty compared to the cold start.

The fuel or energy consumption penalty is much lower for the highway and the aggressive US06 cycle which is partially due to the powertrain systems reaching their normal operating temperatures and the cabin is already warm from the previous tests.

The BEV, as well as the PHEV in charge depleting mode, endure a much larger energy consumption penalty on all the cycles compared to the conventional and hybrid electric vehicles. The use of electric heaters to warm up the cabin and some powertrain components is the primary factor behind the higher energy consumption penalty.

Hot testing results (95F + 850 W/m^2)

Figure 6 shows the additional fuel required to complete the drive cycles at 95F with respect to the fuel consumption of the 72F drive cycles.

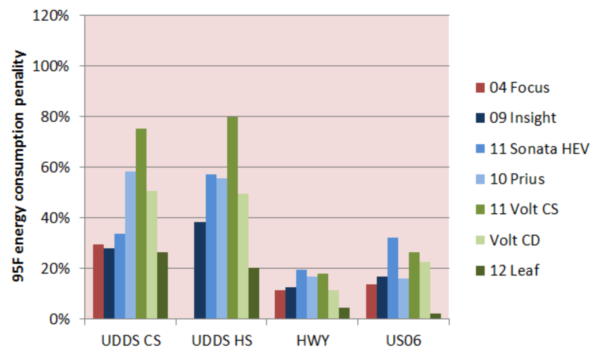


Figure 6. Extra energy used at 95F ambient temperature compared to the standard 72F testing.

At 95F ambient temperatures, the fuel and energy consumption increases are a lot more consistent between the cold start and the hot start tests. The powertrain systems have to provide the extra energy to run the compressor in the air conditioning system in order to cool down the cabin.

The energy consumption penalty is much lower on the highway and the US06 cycle compared to the UDDS cycle. The average powertrain load required to move the vehicles on those cycles is significantly higher compared to the UDDS cycle while the extra average load of the air conditioning system remains constant, thus the ratio of air conditioning load to powertrain load is low which results in a lower energy consumption penalty. The 17% vehicle idle time of the UDDS, also contributes to the increase in fuel penalty for some hybrids with mechanical compressors for the air conditioning system. These hybrids no longer stop the engine while the vehicle is stopped as the engine is required to run the compressor to maintain cooler cabin temperatures.

City Type Driving Results and Details

The degree of hybridization provides a perspective on some of the trends in the energy consumption penalty increase at 20F and 95F with respect to the 72F testing. The terminology "degree of hybridization" as referred to in this study is defined in Equation 1.

$$\text{Degree of Hybridization} = \frac{MotorPower}{(EnginePower + MotorPower)}$$

Equation 1: Degree of hybridization

Figure 7 shows the energy consumption penalty of all the test vehicles as a function of the degree of hybridization for the UDDS cycle. In general, the higher the degree of hybridization results in a higher energy consumption penalty. Figure 8 shows the percentage of the time the engine is used for the different vehicles at the different test temperatures. Full hybrids on the UDDS at 72F can operate the engine less than 40% of the time, but in the cold or hot ambient temperatures the engine usage is increased to either warm the cabin or provide additional power to the air conditioning compressor. During the 20F cold start UDDS test, the engine usage is significantly higher for all the full hybrids compared to the hot start UDDS where enough powertrain heat is available to maintain a heated cabin temperature.

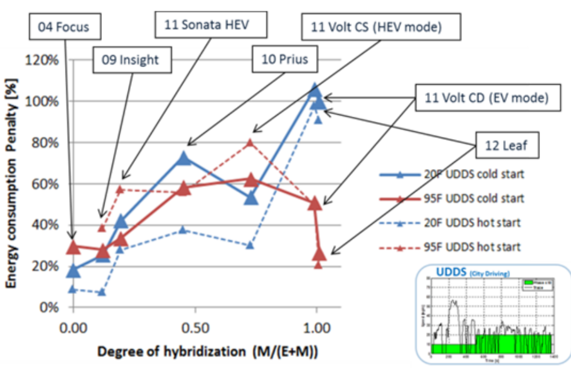


Figure 7. Energy penalty as a function of degree of hybridization for the UDDS cycle.

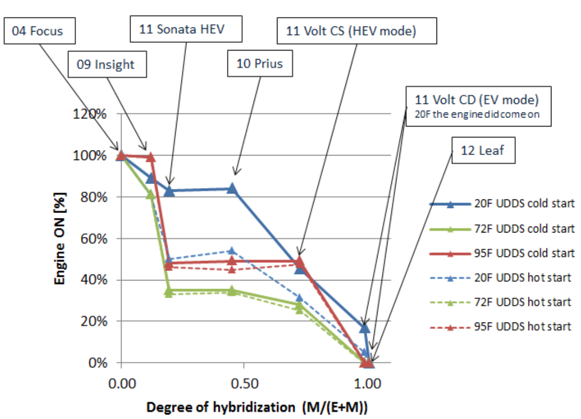


Figure 8. Engine ON time from the test vehicles for the UDDS cycle.

The mild hybrid in the study (Honda Insight) relies on the engine to move the vehicle and thus its engine ON percentage is quite close to the conventional vehicle and the fuel consumption penalty for both of these vehicles is quite low at 20F and 95F. Since the Insight uses a mechanical compressor for the air conditioning system, its engine usage increases to 100% in the 95F test in order to maintain a cool temperature in the cabin even when the vehicle is stopped. Both the conventional and the Insight are the only vehicles that experienced a higher fuel consumption penalty at 95F compared to 20F.

Highway Type Driving Results and Details

Figure 9 shows the energy consumption penalty of all the test vehicles as a function of the degree of hybridization for the highway cycle. Figure 10 shows the percentage of the time the engine is used for the different vehicles at the different test temperatures.

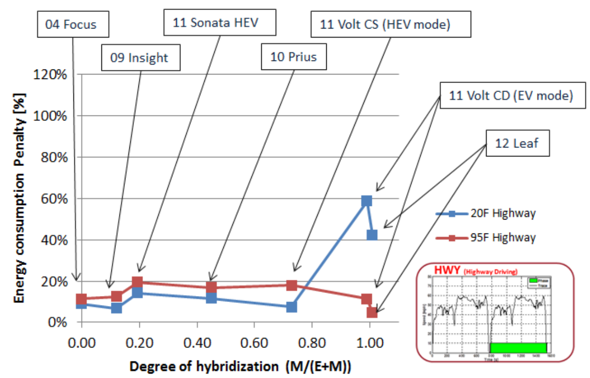


Figure 9. Energy penalty as a function of degree of hybridization for the highway cycle.

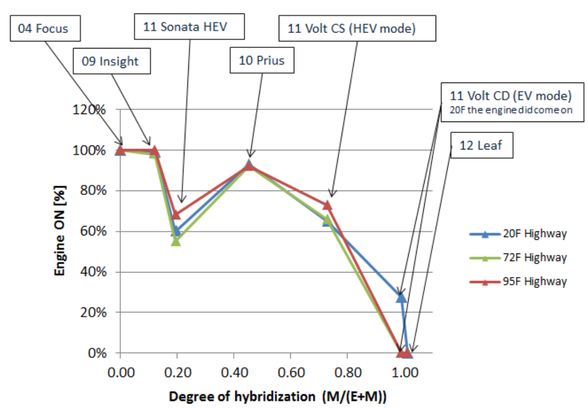


Figure 10. Engine ON time from the test vehicles for the highway.

In general, on the highway cycle, the vehicle operation due to the higher speeds includes higher engine usage regardless of ambient temperatures. This is a primary reason of lower energy consumption penalties on the highway cycle compared to the UDDS cycle.

At 20F ambient temperatures the energy consumption penalty is much lower compared the UDDS cycle. As previously mentioned, the powertrains have reached normal operating temperatures and can provide heat to maintain the 72F cabin temperatures. The Volt is an interesting exception as it uses the engine at 20F in the charge depleting mode to generate some heat for the cabin and some powertrain components.

For hybrids the energy consumption penalty on the highway cycle is slightly higher for the 95F test condition compared to the 20F, since the powertrain has to provide extra power to run the compressor of the air conditioning system.

Figure 10 shows high vehicle speed EV mode operation of the P2 hybrid with the lowest engine ON percentage of all the hybrids. The Sonata also shows the largest percent increase on the highway at 95F.

Conclusions

The APRF determined the impact of extreme temperatures on the energy/fuel consumption for a range of vehicles from a conventional through hybrid electric vehicles to a BEV, and a PHEV.

The energy/fuel consumption increase at 20F ambient test conditions on the cold start UDDS ranges from 20% for the conventional vehicle to 100% for the battery electric vehicle compared to a baseline condition of 72F. The BEV depends on running a 4kW electric heater to warm up the cabin, whereas the conventional vehicle uses waste heat from the engine. In general, the higher the degree of hybridization, the higher the energy consumption penalty at varying temperatures. The electric vehicle is set apart as it does not have an engine.

On the highway and the US06 cycle, the energy consumption penalty is lower compared to the UDDS regardless of the temperature. At 95F ambient temperature, the average powertrain load required to move the vehicles on those cycles is significantly higher compared to the UDDS cycle. Meanwhile, the incremental average load of the air conditioning system remains constant, thus the ratio of conditioning load to powertrain load is comparatively low which results in a lower energy consumption penalty when driving at higher speeds/loads. This differs from the 20F environment, where on the highway and the US06 cycles the engines operate frequently at any ambient temperatures compared to the UDDS generating enough engine heat for the cabin.

The test results and analyses were distributed through several mechanisms such as reports, presentations, and sharing of raw data. The testing activity helped directly in the development of some codes and standards, as well as supporting model development and validation.

III.F.3. Products

Publications

1. Leaf DOE update EV everywhere
2. Leaf VSATT presentation
3. DOE EV Everywhere workshop 5
4. SAE Technical Paper submitted for 2013 SAE Congress, “Comparing the Impact of Temperature on PHEV and EV Energy Consumption”

Tools & Data

1. The basic vehicle test data is uploaded to the APRF’s Downloadable Dynamometer Database and available of public download. Both the test results as well as 10Hz data is posted. transportation.anl.gov/D3/index.html
2. Some of the dynamometer test results are also integrated into the AVTA website maintained by INL. avt.inel.gov/

III.G. In-Depth Thermal Testing of PHEV and EV

Principal Investigator: Henning Lohse-Busch, Ph.D.
Argonne National Laboratory
9700 South Cass Ave.
Argonne, IL 60439-4815
Phone: (630) 252-9615; Email: hlb@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.G.1. Abstract

Objective

- Provide understanding of the ambient-temperature impact on the fuel and energy consumption of a Plug-in Hybrid Electric Vehicle and Battery Electric Vehicle. The temperature range considered in this project is from a freezing-range 20°F to a warm 95°F with emulated radiant sun energy.
- Characterize the battery-pack performance change at the different temperatures.
- Disseminate vehicle and component testing data to partners of the DOE, such as national laboratories, the U.S. Council for Automotive Research, OEMs, suppliers and universities. Provide data to support codes and standards development. Support model development and validation with test data.

Approach

- In FY 2012, the Advanced Powertrain Research Facility (APRF) completed the thermal-chamber upgrade of the 4WD chassis dynamometer test cell. Now vehicles can be tested at the standard 72°F as well as the freezing 20°F ambient condition and at 95°F with 850 W/m^2 of radiant sun energy emulation. The APRF staff can now test vehicles under all of the EPA's 5-cycle fuel economy testing conditions.
- Use advanced and unique facilities with extensive instrumentation expertise. A wide range of equipment and a focus on measuring energy consumption (fuel and electricity) is available. A decade of experience in testing vehicles refined the test procedures and test plans
- Test the powertrain systems as well as components of the systems.

Major Accomplishments

- The range of a BEV can be cut in half in city-type driving in 20°F ambient temperatures with the heater on to maintain a 72°F cabin temperature. On the UDDS (Urban Dynamometer Drive Schedule) cycle, the air conditioning will decrease the range by less than 20%. The more aggressive or higher speed the cycle, the lower the proportional impact of the climate control.
- A PHEV may choose to turn on its engine at 20°F even if the battery is fully charged, to generate heat for the cabin and battery pack. The largest impact on energy consumption occurs at 20°F in charge-depleting mode. In charge sustaining mode the largest energy impact occurs at 95°F ambient temperature.
- The battery-system resistance at 20°F can be double the resistance at 72°F. The resistance may be decreased slightly at 95°F ambient temperature compared to 72°F.

Future Activities

- In the future, the 5-cycle test conditions will be included as part of the standard test protocol at the APRF for the most relevant research vehicles.

III.G.2. Technical Discussion

Background

The Advanced Powertrain Research Facility (APRF) at Argonne has been testing advanced-technology vehicles to benchmark the latest automotive technologies and components for the U.S. Department of Energy (DOE) for well over a decade. The staff has tested a large number of vehicles of different types such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and conventional vehicles, including alternative-fuel vehicles.

During FY 2012, the APRF integrated a thermal chamber into the 4WD chassis dynamometer test cell. With the thermal chamber, the EPA 5-cycle fuel economy test conditions can be replicated:

- 72°F ambient temperature;
- 20°F ambient temperature for the EPA 'cold CO (Carbon monoxide)' test; and
- 95°F with 850 W/m2 radiant sun energy for the SC03 test.

The UDDS (Urban Dynamometer Driving Schedule), the highway cycle and the US06 are fuel economy test cycles that are performed at an ambient temperature of 72°F. The UDDS and the highway cycle, respectively, are the classic city and highway test cycles used by the EPA for fuel economy testing since the 1970s. The US06, which has an aggressive drive cycle with heavy accelerations and high-speed sections, was an emissions test and is now part of the fuel economy label calculation. The fourth test is the UDDS performed at a sub-freezing ambient temperature of 20°F. The fifth and final test is the SC03, which is urban-type driving at ambient temperatures of 95°F with emulated radiant sun energy levels of 850 W/m^2 as well as cooling air proportional to the vehicle speed. Figure 1 illustrates the cycles and the test conditions for the EPA fuel economy label calculations.

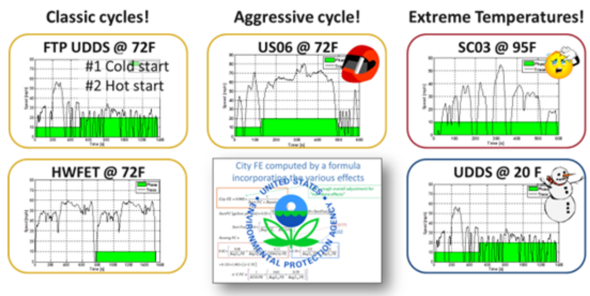


Figure 1. Illustration of the EPA 5- cycle fuel economy tests.

Introduction

The energy consumption and range impact of different ambient temperatures on BEVs and PHEVs is potentially more significant than that for HEVs and conventional vehicles. BEVs and PHEVs have higher powertrain efficiency and lower energy consumption, and therefore the auxiliary loads of climate control systems have a proportionally larger impact on the overall vehicle energy consumption.

Approach

The APRF staff has extensively tested a Nissan Leaf and a Chevrolet Volt on the chassis dynamometer in the new thermal chamber. The Nissan Leaf represents the production BEV and the Chevrolet Volt represents the production PHEV.

A fundamental gateway to the data is Argonne's Downloadable Dynamometer Database (D^3), which is a public website (transportation.anl.gov/D3/index.html). The D^3 website provides snapshot of data and reports from vehicles tested on the standard test cycles. The data directly serve the development of codes and standards as well as the development and validation of simulation models. These activities impact the modification of test plans and instrumentation. Further partners in the testing are U.S. manufacturers and suppliers, through the U.S. Council for Automotive Research.

In many of its research activities, the DOE relies on the benchmark laboratory and fleet testing results to make progress towards its own goals. Figure 2 details some of these DOE research activities and partners.

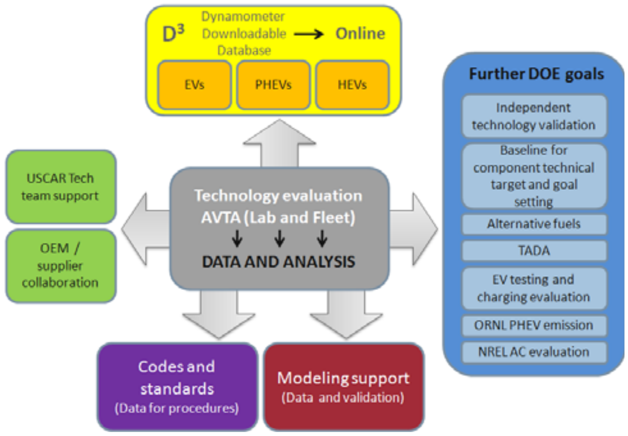


Figure 2. Data dissemination and partners.

In FY 2012, the 4WD chassis dynamometer of the APRF was upgraded to be an EPA 5-cycle-capable test cell. The test cell now includes a thermal chamber and an air-handling unit with a large refrigeration system that enables vehicle testing at ambient temperatures of 20°F (-7°C) to 95°F (35°C). A set of solar emulation lamps can provide 850 W/m^2 of radiant sun energy. The new capability is illustrated in Figure 3.

Figure 3. Nissan Leaf testing: (left) at 95°F with sun emulation and (right) at cold ambient temperature.

In addition to ambient test temperatures of 95°F with the 850 W/m^2 of radiant sun energy, the SC03 cycle (which is the air-conditioning test) requires a fan that can provide an air flow proportional to the vehicle speed. The test cell now includes such a variable-speed fan, as shown in Figure 4.

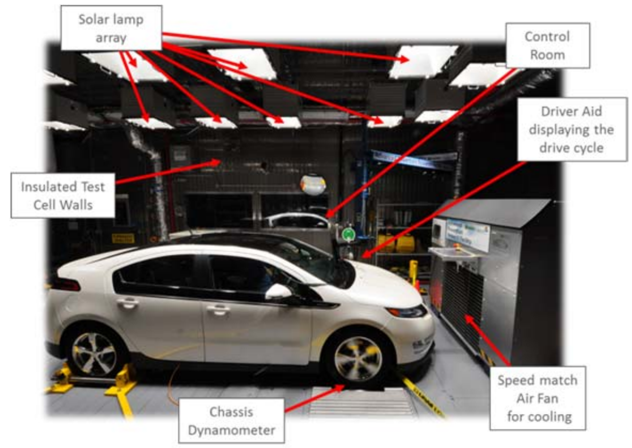


Figure 4. Details of the Chevrolet Volt testing at 95°F with sun emulation.

Owing to the evolution of the various tests over the last almost 40 years, some differences in test conditions and vehicle setup exist; for example, different tests require different vehicle cooling fan and climate control settings. Additionally, the 5-cycle equations consider the UDDS (72°) and SC03 (95°) test cycles so similar that the fuel consumed by the air conditioning is derived simply by calculating the fuel consumption difference between the SC03 and UDDS test results. Considering all these facts, the APRF staff carefully decided to harmonize some of the test conditions to achieve the most realistic and consistent tests, even if that required deviating from certification conditions.

The following test conditions apply to the results below unless otherwise specified:

- The vehicle cooling fan is always run in vehicle speed match mode and the hood is closed at all ambient temperatures.
- All test sequences include a cold-start UDDS, a hot-start UDDS, a highway cycle and a US06 cycle at all ambient temperatures. (The SC03 cycle was not tested for all vehicles.) A test is considered cold-start after the vehicle has been soaked at the target temperature for at least 12 hours with the powertrain turned off.
- For all tests at 72°F ambient temperature, the vehicle climate control is turned off and the driver window is down.
- For all tests at 20°F ambient temperature, the climate control is set to 72°F in automatic

mode, which causes the heater to be activated. All windows are closed. The target road load coefficients are re-derived using the 10% longer coast-down period. Keeping the road load the same at all temperatures allows dissociating the temperature-related vehicle losses from losses due to accessory loads only.

- For all tests at 95°F ambient temperature, the climate control is set to 72°F in automatic mode, which causes air conditioning to be activated. All windows are closed. During all 95°F tests, the sun emulation lamps are turned on and the 850-W/m^2 radiant sun energy level is calibrated at the base of the windshield of the test vehicle.

The test ambient temperature is the test cell temperature or the temperature experienced by the vehicle and the powertrain during the testing.

Battery Electric Vehicle: 2012 Nissan Leaf

Vehicle description

The Nissan Leaf is a pure BEV. A single electric motor coupled with a large battery pack moves the vehicle. Table 1 presents the technical specifications of the vehicle.

Table 1. Nissan Leaf powertrain specifications

Architecture	Battery Electric Vehicle
Engine	None
Motor	Electric Permanent Magnet motor • 80 kW AC synchronous
Battery	Lithium Ion battery • 24 kWh (nominal capacity)* • 18.5 kWh (usable DC energy)** Charging • 3.3-kW on-board charger (J1772 connector) • DC fast-charge connector (not used during testing)
Battery pack cooling	The helium in the pack is stirred by agitators to increase internal convective heat transfer. There is no active thermal management of the battery pack through coolant use.
Climate control features	Electric air-conditioning compressor system; 4kW electric heater for heating.
*Nissan data **Test data	

The battery pack contains helium, which is stirred to increase the pack internal heat transfer convection. The pack is mounted under the vehicle and convective heat transfer from the case to the environment provides the cooling mechanism. This convective heat transfer increases with vehicle speed.

The passenger cabin is heated with a 4-kW electric heater with heated coolant that is pumped to the heater core of the vehicle. A high-voltage electric air compressor provides the work of the air-conditioning system to cool down the cabin.

Impact of ambient temperature on energy consumption and range

Figure 5 presents the energy consumption on the UDDS, highway and US06 cycles at 20°F, 72°F and 95°F with sun emulation.

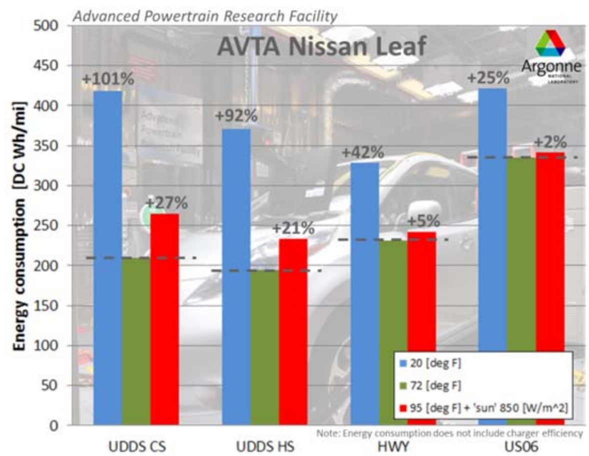


Figure 5. Nissan Leaf energy consumption for different test cycles and ambient temperatures.

The energy consumption doubles between 72°F and 20°F ambient temperatures in city-type driving. The average battery power used to move the Leaf on the UDDS cycle at 72°F ambient temperature is about 3.8 kW, which is about the power used by the electric heater during the UDDS cycle to reach and maintain a cabin temperature of 72°F while the ambient temperature is 20°F. The 20°F ambient temperature is a challenging condition for an electric vehicle, as it cannot rely on waste heat from its powertrain, such as the waste heat of an internal combustion engine.

The air-conditioning system increases the energy consumption by less than 30% in city-type driving. An electric vehicle uses an electric compressor which can be modulated at different speeds and power levels to increase operating efficiency. The low average electric energy consumption of the powertrain in city-type driving makes the power consumption of the air-conditioning system relatively significant.

The Leaf needs 10.8 kW and 16.0 kW of average power on the highway and US06 cycle, respectively. So proportionally, the power consumption of the heater or the air-conditioning system is less significant relative to the propulsion power requirements during these cycles.

The increased energy consumption at the ambient temperature extremes has a direct impact on the vehicle's range, as shown in Figure 6. The range in the graph is calculated using the J1634 MCT shortcut method for each individual cycle at the specified temperatures.

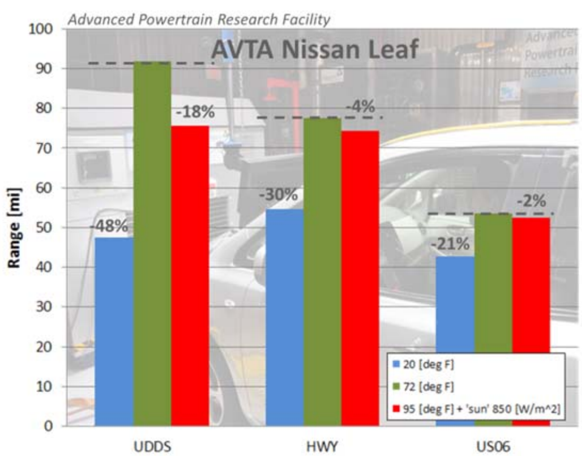


Figure 6. Range for different test cycles and ambient temperatures.

For all driving cycles, the additional load of the heater has the largest impact on range. In terms of range, the worst case for an EV is perhaps being delayed in a traffic jam on a very cold winter day. But even under those conditions, the Leaf can operate for hours, which constitute a more relevant dimension. The battery is depleted fast in aggressive and high speed driving with the heater on, but under those driving conditions, distances are covered quickly.

The Leaf was tested using the SAE J1634 Multi-Cycle Test Shortcut method, which is described in Project 1000197. Figure 7 presents the details of the energy consumption during that test sequence under the different ambient-temperature test conditions.

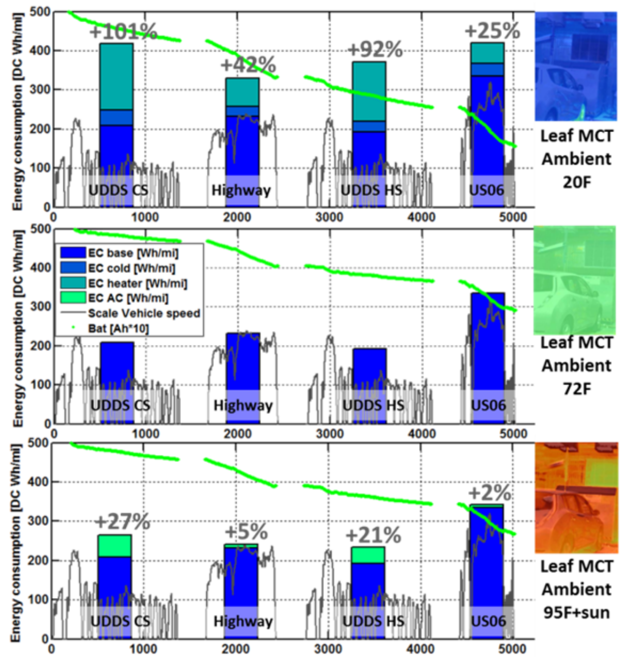


Figure 7. Details of Nissan Leaf energy consumption distribution for the different drive cycles at different temperatures.

The energy measurements performed during the test sequence enable detailed energy tracking for the different drive cycles at the different ambient temperatures, as presented in Figure 8.

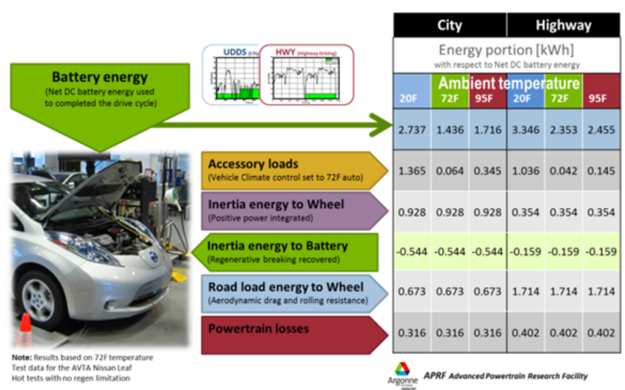


Figure 8. Nissan Leaf energy distribution on the UDDS and highway cycles at 20°F, 72°F and 95°F.

Battery characterization at extreme temperatures

Figure 9 presents the polarization curves of the Leaf battery pack at 20°F, 72°F and 95°F for the first UDDS cycle of each test sequence. The graph is based on the 10-Hz data collected by a power analyzer, which measures the battery-pack voltage and current. Note the extra power pulled by the air-conditioning system and the heater. The battery-system resistance is derived from a linear regression. The resistance increases from 0.1 ohm at 72°F to 0.23 ohm at 20°F. The increased resistance also contributes to the increase in energy consumption through increased powertrain losses, which are proportional to the system resistance and the square of the current.

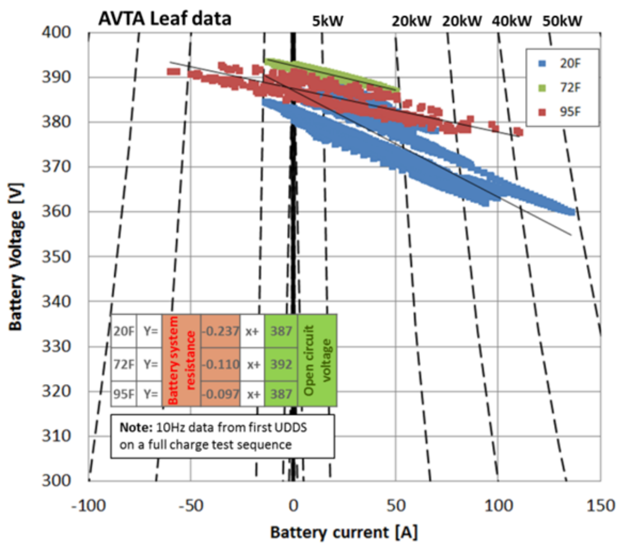


Figure 9. Nissan Leaf battery characterization at 20°F, 72°F and 95°F.

Plug-in Hybrid Electric Vehicle: 2012 Chevrolet Volt

Vehicle description

The Volt is considered to be an extended-range plug-in hybrid because it achieves full performance in the charge-depleting mode, i.e., it achieves full performance without needing to use its internal combustion engine. Table 2 presents the technical specifications.

Table 2. Chevrolet Volt powertrain specifications

Architecture	Extended-range plug-in hybrid
Engine	1.4-L in-line 4-cylinder DI VVT-i Atkinson-cycle • 83 bhp
Motor	Traction PM motor • 149 hp • 273 ft·lb Generator • 80 hp
Battery	Lithium ion battery • 16-kWh capacity (10.4-kWh usable)
Battery pack cooling	The pack is actively cooled or heated using coolant. The coolant can interface with the air-conditioning system to cool down the pack, or with an electric heater to warm up the pack.
Climate control features	Electric air-conditioning compressor system; 360-V PTC heater for heating, supplemented by the waste heat from the internal combustion engine.

The thermal management of the battery pack allows for cooling as well as heating. The cooling is achieved by using the air-conditioning system in the vehicle to chill the coolant before circulating it through the battery pack. An electric high-voltage heater is used to warm up the coolant before circulating it through the battery pack.

The cabin climate control uses a high-voltage electric compressor for the air-conditioning system. The cabin heating system can use a small high-voltage heater or waste heat from the engine to warm up the cabin. Electric seats provide individual heating for the driver and passenger. These electric seats warmers are enabled during 20°F tests but manually turned off at the beginning of the testing.

Vehicle operation

The Volt has two distinct operating modes. The first mode is the charge-depleting mode, where the vehicle operates in electric-only mode using only electric power for propulsion and therefore depleting the battery. The second mode is the charge-sustaining mode, which occurs only after the battery is depleted. In the charge-sustaining mode, the Volt operates similarly to a charge-sustaining hybrid, relying on the burning of fuel for energy.

Figure 10 shows the charge-depleting operation: the Volt operates in electric mode while depleting the battery. Figure 11 shows a cold-start UDDS cycle at 72°F in charge-sustaining mode. The Volt starts the cycle in electric mode. Since the powertrain can obtain all the tractive effort from the electric motor, the engine is completely isolated from the power required at the wheels. In fact, the engine is maintained at a constant 1400 rpm for the first 60 seconds with a 6-kW load. This approach allows a very clean and controlled warm-up of the exhaust after-treatment system. Even in charge-sustaining mode, the Volt appears to operate in electric mode frequently, using the engine to regulate the battery state of charge.

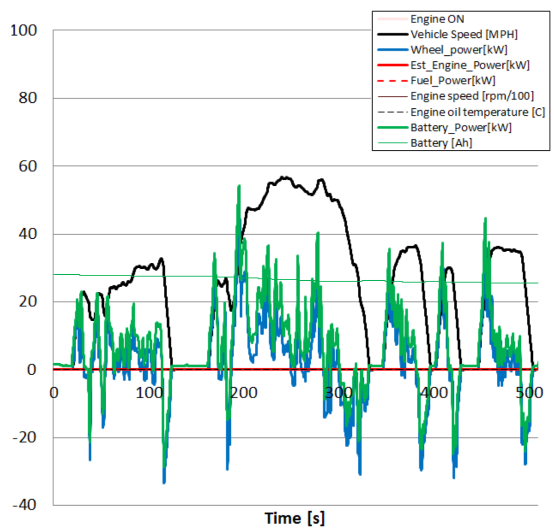


Figure 10. Chevrolet Volt operation on a cold-start UDDS cycle in electric mode with a fully charged battery.

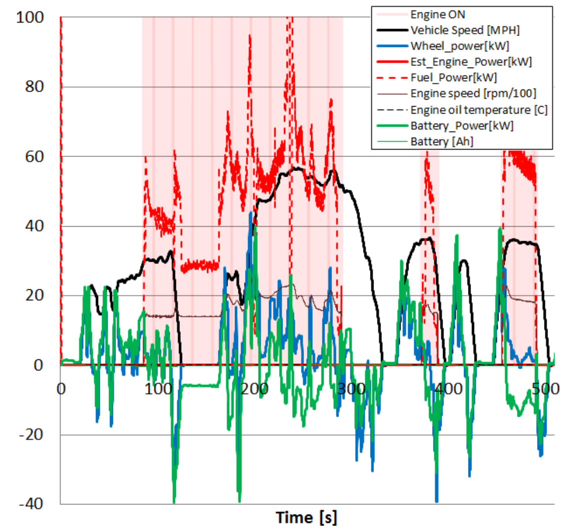


Figure 11. Chevrolet Volt operation on a cold-start UDDS cycle in charge-sustaining mode with a depleted battery.

Impact of ambient temperature on energy consumption and range

Test protocol and results organization

To test a PHEV, the vehicle is charged until the battery pack is full. Then the vehicle is tested repetitively on a single drive cycle until the vehicle is charge-sustaining over a full drive cycle. The recharge energy after the test is used to determine the AC energy consumption. Such full-charge tests (FCTs) were completed on the UDDS, the highway and the US06 cycles at 20°F, 72°F and 95°F with solar emulation. This test matrix is quite labor-intensive to implement.

For each FCT, time history results are first presented for 20°F, 72°F and 95°F with fuel and electric (DC) energy consumption for each test. Then the fuel and electric energy consumption for each test sequence is summarized in a single graph.

Each test cycle set (UDDS, highway and US06) is deliberately presented on a single page to help the reader focus on a single test sequence.

Energy consumption and range on the UDDS cycle

Figure 12 and Figure 13 present the FCT data for the Volt on the UDDS cycle for all the temperature conditions.

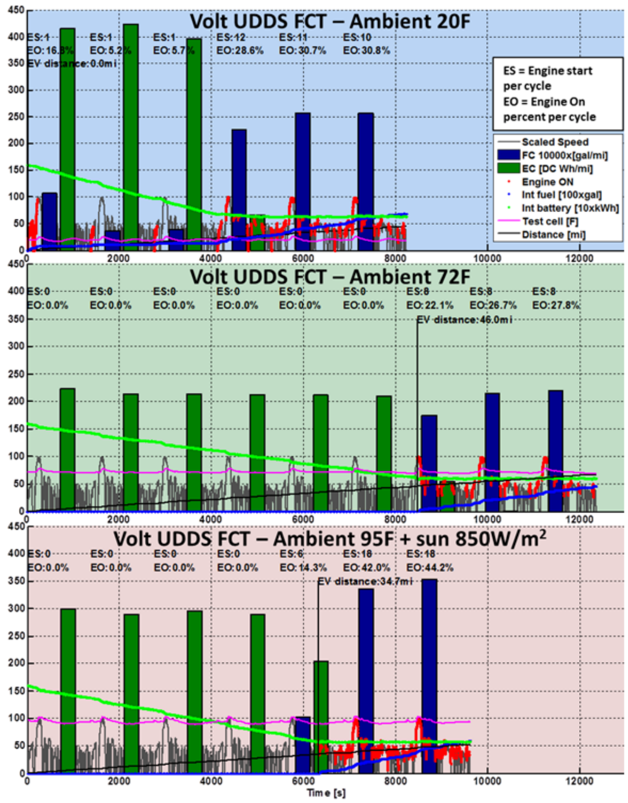


Figure 12. Fuel and energy consumption as a function of time on the UDDS cycle.

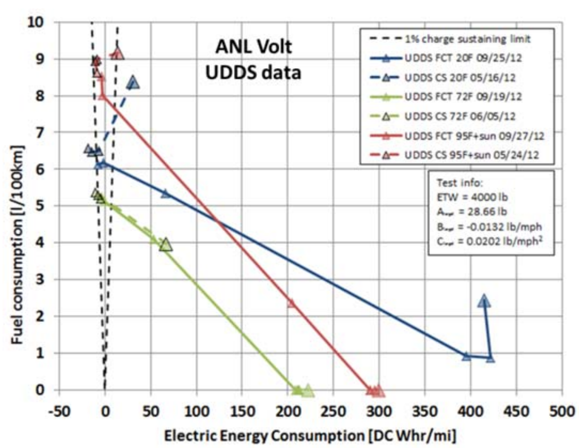


Figure 13. Fuel consumption as a function of energy consumption on the UDDS cycle.

The lowest energy consumption and longest electric range are achieved at 72°F. The 46-mile all-electric range is reduced to 34.7 miles in the 95°F environment, owing to additional energy usage by the air-conditioning system. The electric energy consumption is increased by about 30%. All-electric vehicle operation is maintained at the warmer temperature, as the air-conditioning system is fully electric. Once the vehicle is operating in charge-sustaining mode, the fuel consumption is increased by 40%. The engine-on time is increased from 30% to over 40% to provide the extra energy for the air-conditioning compressor.

For the 20°F test condition, the internal combustion engine is turned on at the beginning of the test to generate heat to warm up the cabin and possibly the battery pack as well. It is interesting to note that under 20°F ambient-temperature conditions, the engine comes on at every start of every UDDS cycle or at every key start. On the very first UDDS cycle, the engine is on 17% of the time, and during the subsequent key events the engine is on for only 5 to 6% of the cycle. Once the vehicle transitions to charge-sustaining operation, the energy consumption is only increased by 15%; the heat is provided by the internal combustion engine; the extra energy goes to additional loads for the battery pack and higher vehicle losses at the lower temperatures.

Figure 13 illustrates that the energy consumption impact is higher at 20°F compared to 95°F in the charge-depleting mode and at the same time the impact is lower at 20°F compared to 95°F in the charge-sustaining mode. This observation is explained by the availability of engine waste heat in the charge-sustaining mode at 20°F.

Energy consumption and range on the highway cycle

Figure 14 and Figure 15 present the FCT data for the Volt on the highway cycle for all the temperature conditions.

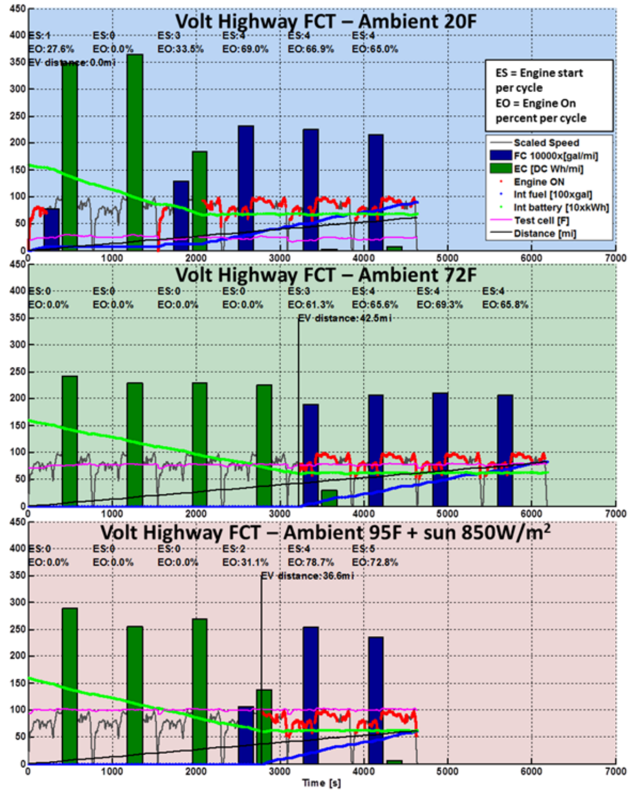


Figure 14. Fuel and energy consumption as a function of time on the highway cycle.

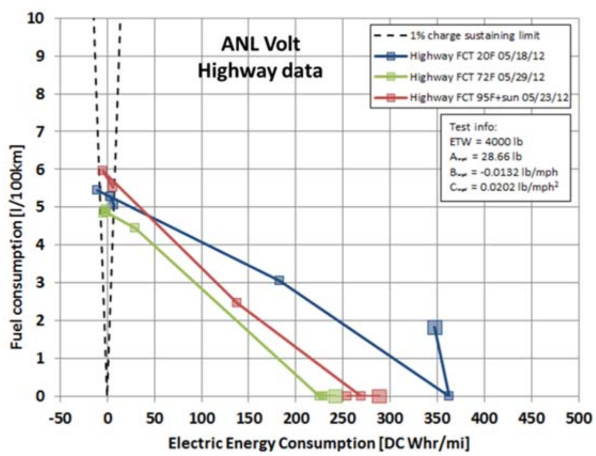


Figure 15. Fuel consumption as a function of energy consumption on the highway cycle.

Again, the lowest energy consumption and longest electric range are achieved at 72°F. The 36.6-mile all-electric range is reduced to 32.5 miles in the 95°F-with-sun environment because of additional energy usage by the air-conditioning system. The electric energy consumption is increased by about 18%. This reduced effect on range compared to the UDDS cycle is explained by the fact that the air-conditioning load is proportionally lower compared to the higher average power at the wheels. All-electric vehicle operation is maintained at the warmer temperature, as the air-conditioning system is fully electric. Once the vehicle is operating in charge-sustaining mode, the fuel consumption is increased by 20%. The engine-on time is increased from 65% to over 75% to provide the extra energy for the air-conditioning compressor.

For the 20°F ambient-temperature test condition, the internal combustion engine is turned on at the beginning of the test to generate heat to warm up the cabin and possibly the battery pack as well. This test confirms that the engine comes on at the key-on event, since the highway cycles were performed in pairs and the engine came on at the start of the first and third highway cycles. Once the vehicle transitions to charge-sustaining operation, the energy consumption is only increased by 15%, since the heat is provided by the internal combustion engine; the extra energy goes to additional loads for the battery pack and higher vehicle losses at the lower temperatures. The engine-on time is 65% in charge-sustaining mode for both 20°F and 72°F operation.

Figure 15 illustrates that the energy consumption impact is higher at 20°F compared to 95°F in the charge-depleting mode, and at the same time the impact is lower at 20°F compared to 95°F in the charge-sustaining mode. This observation is explained by the availability of engine waste heat in the charge-sustaining mode at 20°F.

Energy consumption and range on the US06 cycle

Figure 16 and Figure 17 present the FCT data for the Volt on the US06 cycle for all the temperature conditions.

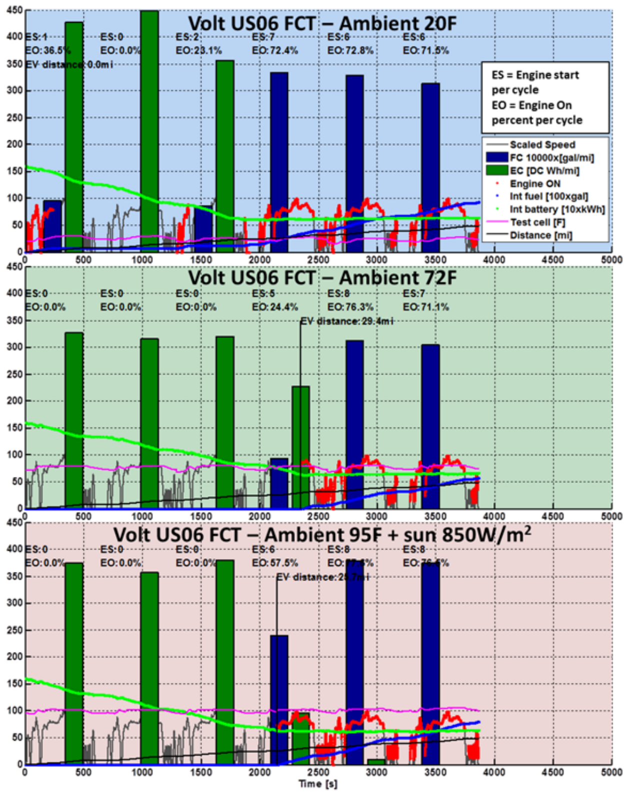


Figure 16. Fuel and energy consumption as a function of time on the US06 cycle.

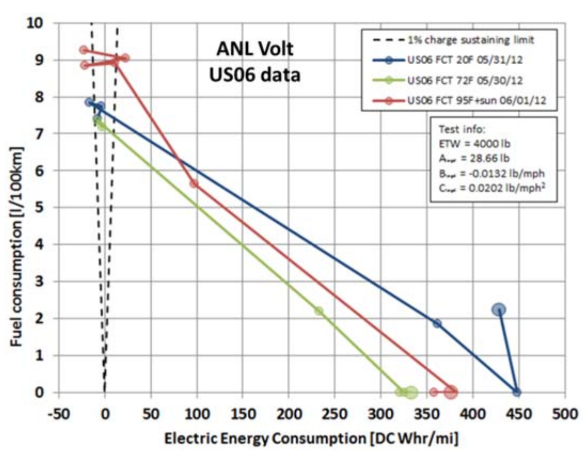


Figure 17. Fuel consumption as a function of energy consumption on the US06 cycle.

The lowest energy consumption and longest electric range are achieved at 72°F. The 29.4-mile all-electric range is reduced to 25.7 miles in the 95°F-with-sun environment, owing to additional energy usage by the air-conditioning system. The electric energy consumption is increase by about 12%. All-electric vehicle operation is maintained at the warmer temperature, as the air-conditioning system is fully electric. Once the vehicle is operating in charge-sustaining mode, the fuel consumption is increased by 7%. The engine-on time is very similar at the two temperatures.

For the 20°F ambient test condition, the internal combustion engine is turned on at the beginning of the test to generate heat to warm up the cabin and possibly the battery pack as well. Again, this test confirms that the engine comes on at the key-on event, since the US06 cycles were performed in pairs and the engine came on at the start of the first and third highway cycles. Once the vehicle transitions to charge-sustaining operation, the energy consumption is only increased by 6%, since the heat is provided by the internal combustion engine; the extra energy goes to additional loads for the battery pack and higher vehicle losses at the lower temperatures.

Again, Figure 17 illustrates that the energy-consumption impact is higher at 20°F compared to 95°F in the charge-depleting mode, and at the same time the impact is lower at 20°F compared to 95°F in the charge-sustaining mode. This observation is explained by the availability of engine waste heat in the charge-sustaining mode at 20°F.

Battery characterization at extreme temperatures

Figure 18 presents the polarization curves of the Volt battery pack at 20°F, 72°F and 95°F for the first UDDS cycle of each test sequence. The graph is based on the 10-Hz data collected by a power analyzer, which measures the battery-pack voltage and current. Note the extra power pulled by the air-conditioning system and the heater under the 20°F and 95°F conditions. The battery-system resistance, derived by linear regression analysis, increases from 0.08 ohm at 72°F to 0.20 ohm at 20°F. The increased resistance also contributes to increased energy consumption through increased powertrain losses, which are proportional to the system resistance and the square of the current.

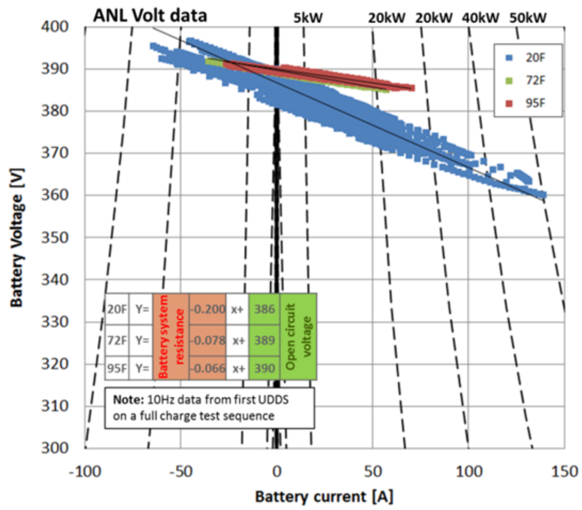


Figure 18. Volt battery characterization at 20°F, 72°F and 95°F.

Conclusions

Testing at the APRF was used to determine the impact of extreme temperatures on the energy/fuel consumption and range of a BEV and a PHEV.

The impact of ambient temperature on the driving range can be very significant, owing to the extra auxiliary load to maintain cabin temperature. In city-type driving, the range of an electric vehicle can be cut in half by the extra load of the electric heater for maintenance of cabin comfort.

At 20°F, the engine in the PHEV came on to provide heat to the cabin and the battery pack. In charge-depleting mode, the PHEV experiences a higher energy consumption impact at 20°F and a lower impact at 95°F with the air-conditioning system on, but in charge-sustaining mode the largest impact on fuel consumption is observed in the 95°F test with the air-conditioning system on, as the heat used during the 20°F test is from the waste heat of the engine.

The more aggressive and higher speed the drive cycle, the lower the proportional impact on energy consumption and range, as the average power at the wheel increases while the heater or air-conditioning load stay the same. It is also worthwhile to note that even a traffic jam in city-type driving at cold temperatures has the greatest impact on vehicle range, that situation generally requires the lowest range.

Temperatures of 20°F can double the system resistance of the battery pack compared to the resistance at 72°F. The higher resistance has a direct impact on powertrain efficiency

The test results and analyses were distributed through several mechanisms such as reports, presentations, and sharing of raw data. The testing activity helped directly in the development of some codes and standards and supported the model development and validation.

The data points to the research need for a reduction in vehicle accessory load and alternative means to heat or cool the vehicle occupants.

III.G.3. Products

Publications

1. Leaf DOE update EV everywhere
2. Leaf VSATT
3. DOE EV everywhere workshop 5
4. Pending 2012 SAE world congress paper

Tools & Data

1. The basic vehicle test data are uploaded to the APRF's D^3, where they are available for public download. Both the test results and the 10-Hz data are posted at transportation.anl.gov/D3/index.html.
2. Some of the dynamometer test results are also integrated into the AVTA website maintained by INL, at avt.inel.gov/

III.H. Electric Drive Vehicle Climate Control Load Reduction

Principal Investigator: John P. Rugh
National Renewable Energy Laboratory
Center for Transportation Technologies and Systems
15013 Denver West Parkway. MS 1633
Golden, CO 80401
Phone: (303)275-4413; Email: john.rugh@nrel.gov

DOE Program Manager: Lee Slezak and David Anderson
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

III.H.1. Abstract

Objectives

- Minimize of the impact of climate control on PHEV and EV range
- Reduce the size of the battery by minimizing
  - Energy consumption of vehicle climate control
  - Time the battery exceeds the desired temperature range
- Increase electric range by 10% during operation of the climate control system through improved thermal management while maintaining or improving occupant thermal comfort.

Approach

- Develop and evaluate the effectiveness of strategies to reduce climate control loads
- Leverage zonal climate control approach developed under DOE's thermoelectric HVAC projects
- Develop new strategies for thermal comfort evaluation.

Major Accomplishments

- Signed CRADA with Ford
- Initiated testing on two Ford Focus Electric vehicles
  - Completed baseline hot weather characterization testing
    - Thermal soak and cooldown
  - Determined that most thermocouples matched well; adjustments were defined to compensate for the inherent differences between vehicles in future tests
- Completed initial thermal soak CFD simulations; most locations compared well to test data.

Future Activities

- Engage team members (manufacturers and suppliers) to obtain in-kind support and guidance for NREL research
- Complete cold weather characterization testing
- Develop and evaluate promising techniques in outdoor vehicle thermal soak and transient tests
  - Heating and cooling
- Investigate new thermal comfort evaluation techniques.

III.H.2. Technical Discussion

Background

As in conventional vehicles, passenger compartment climate control is required for electric drive vehicles (EDVs) for occupant comfort and safety (e.g., demisting and defrosting). A challenge in meeting this requirement is that electrical energy consumed for climate control can significantly reduce the range of an EDV. For example, air conditioning (A/C) and heating can reduce the range of a Mitsubishi iMiEV by 46% and 68%, respectively[1]. A Nissan Leaf tested at Argonne National Laboratory's Advanced Powertrain Research Facility showed a reduction in range of 48% due to heating and 18% due to air conditioning over the UDDS drive cycle[2]. Range anxiety will impact customer acceptance of EDVs and the penetration of these vehicles into the national fleet.

Introduction

Currently, manufacturers are building EDVs at a low volume. They design vehicles to maximize customer satisfaction, and range and thermal comfort are linked to this satisfaction. If climate control exacerbates an already challenging range problem and leads to increased range anxiety, future sales of EDVs could be at risk.

Energy for heating EDVs is a new challenge for automobile manufacturers because there is no engine waste heat. Conventional vehicles heat cabins with engine waste heat, but EDVs do not have an engine. Using stored electrical energy for cabin heating takes valuable energy away from propulsion. Electric heaters are a lower-cost option, but only have a coefficient of performance (COP)=1.

Historic climate control system designs are validated using air temperatures and limited subjective testing, with little regard for energy use. EDVs cannot afford excessive energy use for climate control. Cooling and heating the entire interior mass of the vehicle may not be necessary since, typically, not all of the seats are occupied. A new way of looking at climate control design with a focus on thermal comfort is required. Improved thermal comfort test and analysis techniques would assist in the design and development of technologies to reduce climate control loads. A zonal approach to climate control could also reduce climate control energy consumption.

With current battery technology, the premium price for EDVs is a barrier. The climate control system and interior cabin temperatures impact the battery in two ways. First, climate control impact on range affects battery size. If a range target is identified with the climate control operating, a larger battery will be required compared to no climate control operation. What if the battery size (and initial cost) could be reduced through lower energy consumption by the climate control system? Second, depending on battery location and cooling strategy, the cabin climate control system can impact battery temperature. Higher Li-ion battery temperatures can lead to degradation and reduced life. Designing batteries to account for high temperature degradation leads to larger (and higher-cost) batteries.

Approach

The objective of this task is to increase in-use EDV range by minimizing climate control energy requirements. Our initial goal is to increase range by 10% with improved thermal management during operation of the climate control system. This may lead to increased customer acceptance of EDVs through the reduction of range anxiety. In addition, improving thermal comfort upon entry into a hot-soaked or cold-soaked vehicle may lead to additional motivation for drivers to adopt EDVs, and may also improve safety through reduced driver thermal distraction.

Our approach is to collaborate with the automotive industry to research and develop techniques which will reduce cooling and heating loads on EDVs to improve range. The following areas will be considered:

- Thermal load reduction technologies
- Occupant thermal comfort optimization
- Climate control using a zonal approach
- Intelligent heating, ventilating and air conditioning (HVAC) control to minimize energy use
- Advanced seating concepts

- Unique thermal needs of EDV batteries and power electronics
- Secondary fluid loop options
- Thermal preconditioning.

Test and analysis techniques will be used to develop and evaluate the effectiveness of strategies to reduce the climate control loads.

Vehicle Thermal Testing

Under a cooperative research and development agreement (CRADA), Ford has provided two Ford Focus Electric vehicles. These battery-electric vehicles (BEVs) were used in outdoor thermal tests at NREL's Vehicle Testing and Integration Facility (VTIF). During the summer of 2012, baseline thermal soak and cooldown tests were conducted to characterize the inherent differences between the two vehicles.

Figure 1. Ford Focus Electric vehicles (Photo by Matthew Jeffers, NREL).

Hot Thermal Soak

Prior to testing, the Focus Electric vehicles were each outfitted with 48 K-type thermocouples: 18 equipped with radiation shields for air measurements; 17 on opaque surfaces; 4 on glazing surfaces; and 9 reserved for future HVAC systems measurements. The thermocouples were connected to a National Instruments SCXI data acquisition system, and then calibrated using a silicone oil micro-bath and RTD (resistance temperature detector) reference probe. Hot-weather thermal soak tests were performed to evaluate the baseline thermal performance of the vehicles. Both vehicles were parked in a south-facing orientation and remained closed and undisturbed for the duration of the 24-hour thermal soak tests. All test days were warm days with minimal cloud cover to ensure that solar impacts were included in the baseline characterization. Actual local weather conditions at the test pad were recorded by NREL's new weather station located at the VTIF.

After performing baseline thermal soak tests, the average temperature differences between the vehicles were calculated and adjustments were applied to the control vehicle measurements in order to "calibrate" it to the test vehicle. This is necessary to account for any inherent differences in the thermal behavior of the vehicles. Improving the correlation between the vehicles in this way enables the control vehicle to accurately predict the performance of the unmodified test vehicle during future tests.

A/C Cooldown

In addition to the vehicles, Ford also supplied the communication database (DBC) files for vehicle CAN bus communication in support of A/C cooldown testing. The DBC files were used to identify and select the CAN bus channels containing relevant thermal systems data and to configure the data logger which was connected to the vehicle. Communication was established with the Focus CAN bus and several preliminary cooldown tests were performed to characterize the performance of the on-board A/C system.

Air Infiltration

Lastly, tracer gas decay tests were performed on the Focus Electric vehicles to establish baseline air infiltration rates for the passenger compartment and trunk. A Bruel and Kjaer multi-gas, photoacoustic gas analyzer was used to measure the rate of decay of sulfur hexafluoride, from which the average air infiltration rate was calculated. The weather conditions for the air infiltration test days were similar to those of the baseline thermal soak test days.

The next step is to conduct baseline winter tests: cold thermal soak and heating. After baseline characterization of the Focus BEVs, promising thermal load reduction techniques will be evaluated in outdoor vehicle thermal soak tests. Transient and steady-state thermal tests will be conducted using the standard vehicle on-board thermal systems as well as an off-board vehicle climate control load hardware emulator system. Characterizing the baseline thermal performance of the vehicles, as well as the inherent differences between them, will enable accurate measurement of the impact of load reduction technologies in upcoming tests.

Thermal Analysis

Thermal analysis tools (including computational fluid dynamics, Radtherm, and human thermal comfort) will be used to evaluate the effectiveness of potential strategies to reduce the climate control loads. Under a CRADA, Ford has provided the CAD geometry of a Ford Focus Electric. Using this geometry, a RadTherm mesh and a CFD mesh were developed. These meshes are fundamentally different, as the CFD mesh is a volume mesh and the RadTherm mesh is a surface mesh. Thermal soak simulations were performed to calibrate and validate the model. After calibration, the model will be used for cooldown and warmup simulations, with human comfort simulations after the model is validated.

RadTherm Analysis Methodology

The thermal model includes a numerical representation of a passenger compartment. The numerical representation consists of a surface mesh as shown in Figure 2. The thermal analysis tool used for this analysis was RadTherm (Thermo Analytics, Inc.). In the analysis, the heat transfer between the interior and environment is calculated. Inputs to the model include vehicle geometry, material properties including glass properties, and environmental (weather) data. One of the strengths of RadTherm is the ability to apply measured solar data (from the NREL test site) to the model, so that the analysis uses exactly the same solar and weather conditions under which the vehicle testing was performed.

The environmental conditions were obtained from the NREL weather station on August 8, 2012. Heat transfer coefficients on the interior surfaces and interior air temperatures were computed during Fluent computational fluid dynamics (CFD) simulations and then mapped to the RadTherm model.

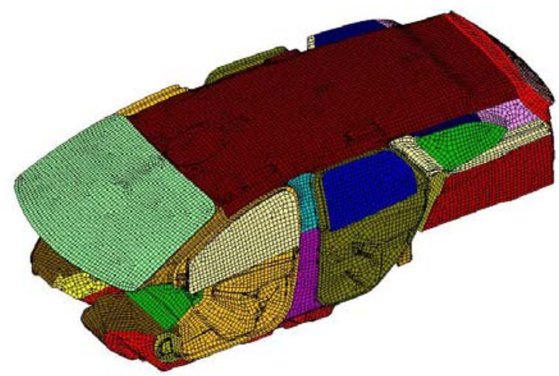


Figure 2. RadTherm model – Ford Focus Electric.

Fluent Analysis Methodology

The CFD tool used for this analysis is Fluent (ANSYS, Inc.). A numerical representation of the cabin was also developed using the CAD model provided by Ford. The numerical representation was a volume mesh of tetrahedral cells, with prism cells in the boundary layer. Figure 3 shows a section of the mesh through the driver seat. The flowrate of air through the model was based on measurements performed on the test vehicles, and was approximately one-third volume change per hour. The temperatures of all surfaces in the model were mapped from results of the RadTherm simulation. Results of the Fluent simulation were used to map fluid temperatures and calculated heat transfer coefficients to the RadTherm model described previously.

Figure 3. Cross section of Fluent mesh.

Results

Vehicle Thermal Testing

Hot Thermal Soak

During the baseline soak test period, four good test days were observed at the VTIF. Overall, the Focus BEVs displayed very similar thermal behavior. During the hours of 10:00 am to 4:00 pm MST, the average difference in interior air temperature between the test BEV and control BEV was only 0.08°C; the maximum difference was only 0.22°C. Breath-level temperature readings were, on average, 14.4°C hotter than the footwell temperatures, demonstrating typical temperature stratification during a hot thermal soak. These results are shown in Figure 4 below.

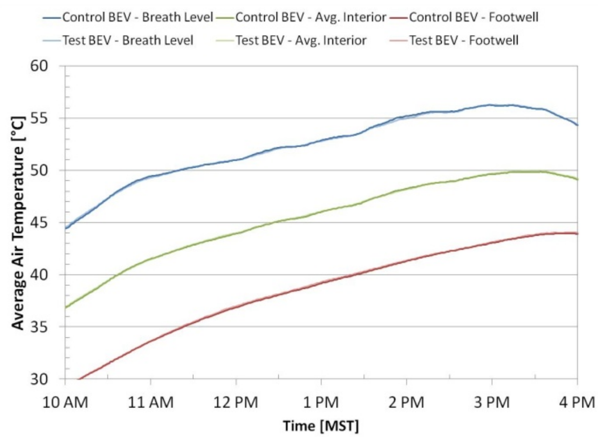


Figure 4. Baseline thermal soak test – interior air temperatures, September 5, 2012.

Surface temperature readings matched closely as well, as illustrated in Figure 5, for the seat back, seat bottom, and interior door trim on the passenger side. The dips in the trends show that even the shading of the thermocouples by the vehicle A-pillars match closely in magnitude and time-response.

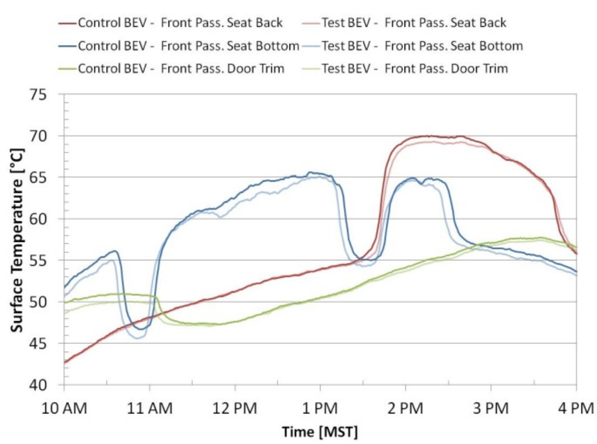


Figure 5. Baseline thermal soak test – passenger seat and door trim temperatures, September 5, 2012.

Because the temperature measurements at corresponding locations between vehicles do not match exactly, temperature adjustments were calculated from the baseline thermal soak data (4 days) and applied to the control vehicle measurements to calibrate them to the corresponding test vehicle measurements. In this way, the inherent differences between the vehicles are accounted for, and the control vehicle can be used to accurately predict the thermal behavior of the test vehicle. Figure 6 shows an example temperature adjustment applied to the instrument panel (IP) measurement of the control BEV.

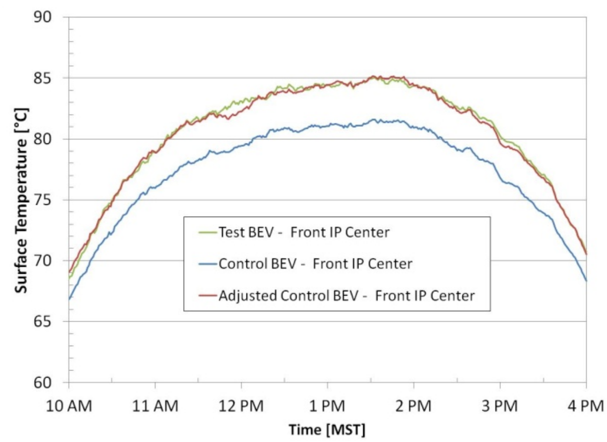


Figure 6. Control BEV temperature adjustment for IP, September 5, 2012.

A/C Cooldown

Several preliminary A/C cooldown tests were conducted with the Focus BEVs. The vehicles were allowed to thermally soak throughout the morning, and then the on-board A/C system was started at midday which dropped the passenger compartment air temperature to the desired set point. The A/C system settings that were investigated include “MAX A/C” and “AUTO A/C”, with temperature set points of 72°F (22.2°C) and 59°F (15°C). Blower speed, degree of air recirculation (%), and air distribution (panel vs. floor vents) were automatically controlled by the vehicle A/C system. Several CAN bus channels were recorded with the data logger, including interior air temperature, evaporator temperature, compressor speed and power, and battery voltage and current. The performance of the vehicle A/C systems will be evaluated under various control settings and compared between vehicles. Figure 7 shows the evaporator temperature, interior air temperature, and compressor power for the AUTO A/C with a 15°C set point case.

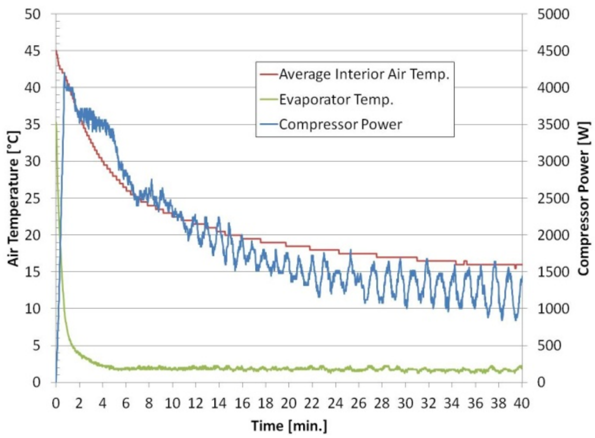


Figure 7. A/C cooldown test results, "AUTO A/C" settings, 15°C air temperature set point.

Air Infiltration

Tracer gas decay tests were performed on the Focus Electric vehicles. The measured average air infiltration rates (Figure 8) of 0.35 and 0.32 air changes per hour (ACH) for the test and control vehicles, respectively, show the passenger compartments are well sealed.

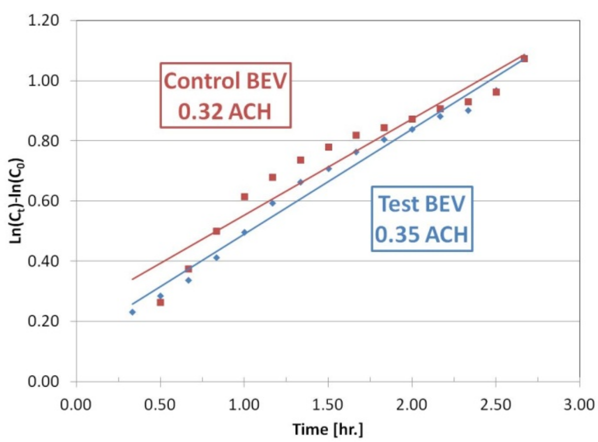


Figure 8. Tracer gas decay test – average air infiltration in passenger compartment.

Thermal Analysis

Steady-State Soak Results

Figure 9 shows the interior temperatures predicted by the RadTherm model (the roof, pillars and doors are not shown for clarity). Note the shadow cast by the A-pillar on the passenger seat cushion. As expected, the instrument panel has the highest temperatures. Figure 10 shows the air temperatures predicted by Fluent on a plane through the driver seat. The air temperatures show stratification with hotter temperatures near the roof and windshield.

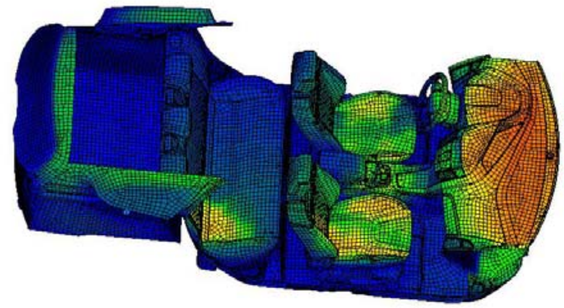


Figure 9. RadTherm-predicted surface temperatures.

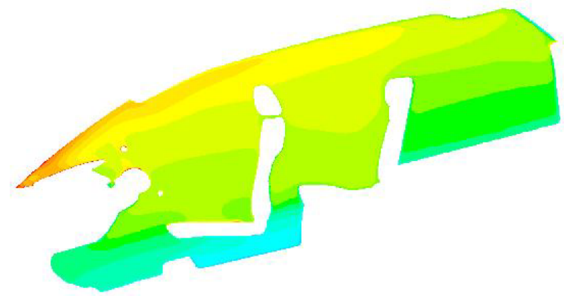


Figure 10. Fluent-predicted air temperatures.

The steady-state temperatures at 1:30 p.m. were compared to soak test data from August 19, 2012, averaged over 20 minutes from 1:20 to 1:40 p.m. MST. Minor adjustments were made to the model parameters to improve correlation.

The baseline soak analysis temperatures in Figure 11 compared favorably to the test data. The most important locations (air, dash, windshield, and driver seat) matched well. Locations that are partially shaded by other vehicle components can be challenging for comparison of the test and analysis. For example, as the sun moved to the right side of the car, the passenger seat had a shadow cast on it by the A-pillar. Caution must be used when comparing partially-shaded locations.

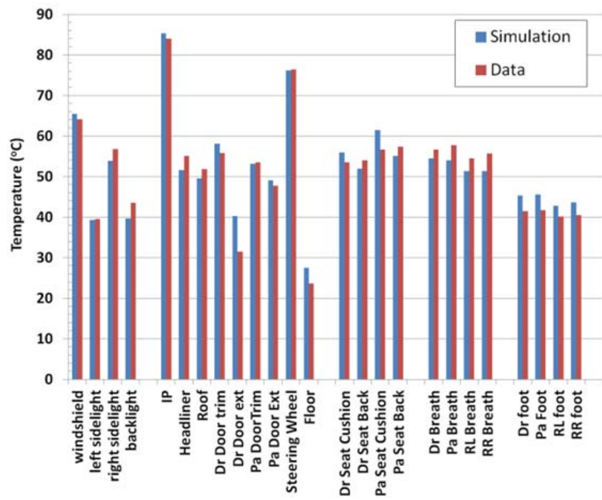


Figure 11. Baseline comparison of analysis temperature results to test data.

The close match to soak data validated the inputs to the steady-state model. The model will be used to compare load reduction technologies, or as the initial conditions for a transient cooldown model. Some of the next steps include performing a transient cooldown analysis with comparison to data. The same type of analysis will be performed with a winter heatup. Driver and passenger manikins will be added to the model, and a thermal comfort analysis performed.

Conclusions

As part of a four-year CRADA project with Ford, NREL researchers completed baseline summer testing on two Ford Focus Electric vehicles. Researchers installed numerous thermocouples in the vehicles, established communication with the vehicle CAN bus, and performed preliminary cooldown tests (after a thermal soak) to characterize the power requirements of the Focus' on-board A/C system. The vehicles were thermally very similar. These hot-weather and upcoming cold-weather baseline tests will characterize the inherent differences between the vehicles, and enable accurate measurement of the impact of load reduction technologies in future tests. Initial computational fluid dynamics and thermal simulations were also conducted. The simulation results compared well with the test data. After refining and adding thermal comfort capability, the model will be used to assess potential energy saving and comfort optimization strategies.

References

1. Kohei Umezu and Hideto Noyama, Mitsubishi, Presented at the 2010 SAE Automotive Refrigerant and System Efficiency Symposium
2. ANL APRF data, EV Everywhere Workshop presentation, Lee Slezak, September 13, 2012.

Acknowledgements

- Coauthors: Lawrence Chaney, Matthew Jeffers (NREL)
- Special thanks to our industry partner: Ford Motor Company

III.I. Integrated Vehicle Thermal Management – Combining Fluid Loops on Electric Drive Vehicles

Principal Investigator: John P. Rugh
National Renewable Energy Laboratory
Center for Transportation Technologies and Systems
15013 Denver West Parkway. MS 1633
Golden, CO 80401
Phone: (303) 275-4413; Email: john.rugh@nrel.gov

DOE Program Manager: Lee Slezak and David Anderson
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

III.I.1. Abstract

Objectives

- Collaborate with industry partners to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains
- Improve vehicle range and reduce cost from combining thermal management systems
- Reduce volume and weight
- Reduce advanced power electronics and electric motor (APEEM) coolant loop temperature (less than 105°C) without requiring a dedicated system.

Approach

- Build a one-dimensional thermal model of EV thermal management systems (using KULI software)
- Identify the synergistic benefits from combining the systems
- Identify strategies for combining cooling loops
- Solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains.

Major Accomplishments

- Improved the individual thermal models of the cabin air conditioner (A/C), cabin heater, APEEM, and energy storage system (ESS) fluid loops
- Completed a baseline EV thermal system model
- Added sophisticated controls to the A/C system and energy storage system (ESS) cooling loops
- Investigated combined cooling loop strategies
- Identified advantages of combining fluid loops.

Future Activities

- Based on the analysis results, select, build, and evaluate prototype systems in a lab bench test to demonstrate the benefits of an integrated thermal management system
- Collaborate with automotive manufacturers and suppliers on a vehicle-level project to test and validate combined cooling loop strategies.

III.I.2. Technical Discussion

Background

In the first year of the project (FY 2011), Visteon Corporation, a Tier 1 automotive HVAC component supplier, supplied detailed thermal component and system information. This included drawings, thermal and flow component data, and system performance data. NREL researchers built component models in KULI using the geometry, heat transfer, and pressure drop information. The individual component models were verified to function as expected. Next we developed A/C, cabin thermal, and APEEM cooling loop models by combining the individual component models into systems. These systems were then compared to test data. This formed the basis for the complete analysis of EV thermal systems and the assessment of combining cooling loop strategies that was performed in FY 2012.

Introduction

Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) have increased vehicle thermal management complexity (e.g. power electronics, motors, energy storage, and vehicle cabin). Multiple cooling loops may lead to reduced effectiveness of fuel-saving control strategies. The additional cooling loops increase weight, volume, aerodynamic drag, and fan/pump power, thus reducing electric range. This reduces customer acceptance of electric drive vehicles (EDVs) by increasing range anxiety, and presents a barrier for the penetration of EVs into the national vehicle fleet. Our goal is to improve vehicle performance (fuel use or EV range) and reduce cost by capturing the synergistic benefits of combining thermal management systems. The overall goal is to solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains.

The objective of this project is to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains. Currently, EDVs typically have a separate cooling loop for the APEEM components. It would be beneficial to have an APEEM coolant loop with temperatures less than 105°C without requiring a dedicated system. Range would be increased in the winter with a combined thermal management system that maximizes the usage of waste heat from the APEEM and ESS components to minimize electrical resistive heating using battery energy. With increased focus on aerodynamics, minimizing the area and number of heat exchangers in the front end of the vehicle has the potential to reduce drag. Combining cooling loops enables the capability to thermally precondition the ESS and passenger compartment as well as the thermal management fluid loops.

Approach

The overall approach is to build a one-dimensional thermal model (using KULI software). This includes APEEM, energy storage, and passenger compartment thermal management systems. The model is used to identify the synergistic benefits from combining the systems. Once promising combined cooling loop strategies are identified, bench tests will be conducted to verify performance and identify viable hardware solutions. The National Renewable Energy Laboratory (NREL) will then collaborate with automotive manufacturers and suppliers on a vehicle-level project.

There are three main parts to the modeling process: the vehicle cost/performance model [1], the thermal model, and the battery life model. The vehicle cost/performance model simulates an EV over a drive cycle. An output of the model is the time-dependent heat generated in the APEEM and ESS components. These data are used as an input to the thermal model. KULI [2] was used to build a model of the thermal systems of an EV, including the passenger compartment, APEEM, and ESS. The thermal model calculates the temperatures of the components and the power required by the various cooling systems, including the fans, blowers, pumps, and A/C compressor. The power consumption profile is then used in the vehicle cost/performance model, and a new heat generation is calculated. If the heat generation is significantly different from the initial run, it is entered into the KULI thermal model again, and the cycle is repeated. An overview of the analysis process is shown in Figure 1.

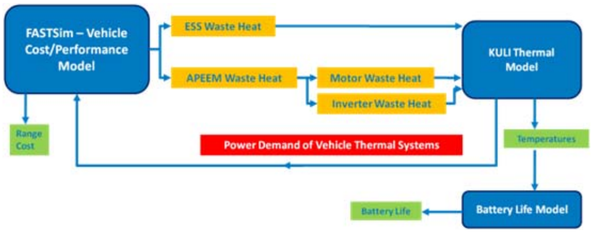


Figure 1. EV integrated vehicle thermal management analysis flow diagram.

The performance of the vehicle thermal management system was evaluated over three vehicle drive profiles, and each were created to represent different driving conditions for hot and cold environments. A summary of the drive profiles and ambient thermal conditions is summarized in Table 1.

Table 1. Drive profiles and environmental conditions

Condition	Drive Cycle Profile	Ambient Temperatures (°C)	Relative Humidity (%)
Hot soak with cooldown*	US06	43, 35, 30, 25	25
Hot soak with cooldown*	Davis Dam	43	25
Cold soak with warmup	Bemidji	-18	40

* In each of the hot soak tests, the vehicle cabin was assumed to be soaked to an initial temperature of 20°C above the ambient temperature.

The US06 drive profile [3] was selected as a standard test cycle with aggressive driving to evaluate the ability of the thermal management system to manage thermal loads over aggressive transient driving with multiple acceleration and braking events. The Davis Dam drive profile represents accelerating from a stop to 55 mph, and maintaining 55 mph up a constant 5% grade in a hot ambient environment. This profile provided a test of the thermal management system at extreme operating conditions. The Bemidji drive profile was selected to represent less aggressive driving conditions with a cold ambient temperature. The drive profile is based on the standard UDDS cycle [4]. A less aggressive drive cycle was selected to reduce the waste heat generated within the components and reduce self-heating. The intent was to provide an extreme cold weather test. A comparison of the motor heat load for each of the drive profiles is shown in Figure 2.

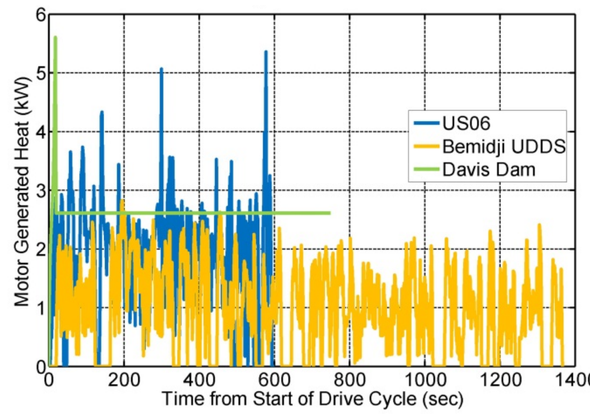


Figure 2. Comparison of drive cycles in terms of motor heat load.

The baseline electric vehicle thermal management system is illustrated in Figure 3 and Figure 4. Figure 3 provides a schematic of the thermal management system that enables heating and cooling of the vehicle passenger compartment or cabin, cooling for the electric drive system consisting of power electronics and an electric motor, and heating and cooling of the ESS or battery. Heating for the vehicle cabin is provided by an electric heater that heats a fluid loop and transfers heat to the cabin with a conventional heater core. Cooling for the vehicle cabin is provided by a conventional vehicle A/C system and an electric compressor. The power electronics and motor are cooled through a radiator that is located at the front of the vehicle behind the A/C condenser. The ESS or battery has multiple operating modes. Cooling is provided by two methods using either a chiller connected to the air conditioning system or a radiator at the front of the vehicle. The chiller is used for hot ambient conditions to provide chilled liquid coolant to the battery. Battery warmup can also be improved during cold conditions through the use of an electric heater to heat the liquid coolant circulating through the battery.

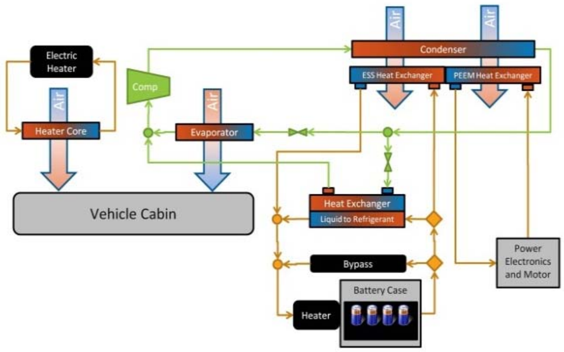


Figure 3. Baseline cooling system and primary components.

In addition to modeling the liquid and refrigerant loops of the vehicle thermal management system, the model also simulates the external airflow through the heat exchanger surfaces as shown in Figure 4. As outside air passes through upstream heat exchangers, the air is heated. For this reason, the performance of the down-stream heat exchangers are impacted by the heat rejection of the upstream heat exchangers. The model is capable of capturing this interaction between heat exchanger placement and airflow.

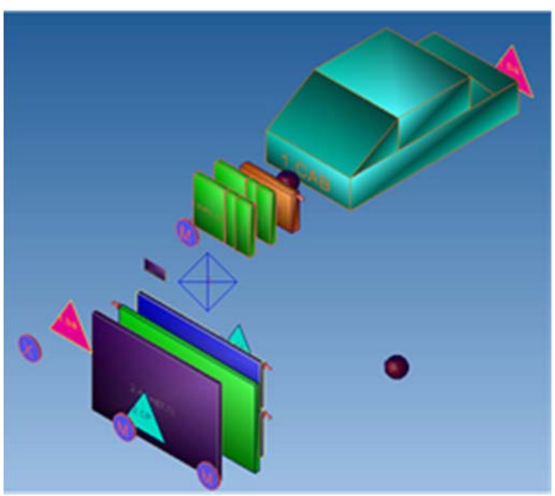


Figure 4. Air-side components of baseline thermal model.

During FY 2012, modeling work focused on improving the baseline vehicle thermal model and developing preliminary thermal models of alternative thermal management configurations. The improvements to the baseline vehicle thermal model were based on input from component specialists and comparisons to available thermal data. The baseline model improvements can be broken down into the following areas:

- System thermal loads
- System thermal model enhancements
- System controls.

The thermal loads for the battery, power electronics, and motor were revised based on the latest updates to the FASTSim vehicle model for a compact-sized electric car. In addition to updating the vehicle model, additional drive profiles were added to the vehicle model to evaluate the vehicle operation over more operating conditions (i.e. Davis Dam and Bemidji).

Improvements to the original baseline component and system thermal models include the addition of new system thermal models and the improvement of existing models based on reviews with component experts. The battery cooling loop was revised to enable multiple cooling modes for cooling and heating the battery. The ability to heat the battery coolant was added to improve battery warmup during the new cold environment tests. The updated battery thermal model thermal performance and properties were reviewed with the NREL ESS group. The power electronics and motor thermal systems were improved based on input from the NREL APEEM group. The initial motor thermal model parameters were updated, and a new inverter thermal model was created based on feedback from the Electrical and Electronics Technical Team (EETT) within US Drive. Also, thermal models for cabin heating components were created and integrated into a working cabin heating system to enable vehicle warmup tests from cold environmental temperatures. This feature was added based on previous feedback from the annual merit review. Finally, the air-side positions of the vehicle heat exchangers were adjusted to more closely match current EVs with the condenser in the front.

System controls were created for the baseline thermal model to control the battery and cabin to the desired target temperatures. The cabin temperature was controlled by regulating the airflow into the cabin, activating an electric heater, and controlling the refrigerant loop compressor speed. The battery temperature was controlled by controlling the battery coolant loop pump speed, and the valves controlling the flow through the multiple fluid loop branches. When the refrigerant loop was active to cool the vehicle cabin, the controller adjusted compressor rpm to prevent evaporator freezing. The thermal system control logic was based on a state controller with multiple operating states. The thermal management operating state was determined from the environment temperature, component temperatures, and the cooling system fluid temperatures. Each control state adjusted the control variable for the multiple actuators in the vehicle thermal system model. The control for each of the actuators was based on a proportional integrator (PI) antiwindup controller with the general logic shown in Figure 5.

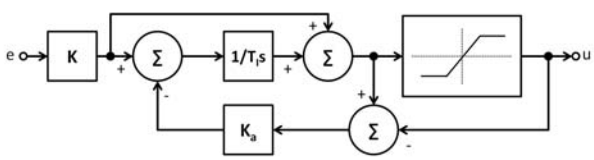


Figure 5. Antiwindup PI Controller [5.]

In addition to improving the baseline thermal model, new system thermal models were developed to investigate potential combined cooling loop strategies. The overall goal of combining cooling loops was to identify the potential use of waste heat from the electric drive components, and to evaluate concepts that could reduce the number of heat exchangers at the front of the vehicle. Figure 6 shows an illustration of the combined cooling system concept. The system enables the use of waste heat from the power electronics and electric motor for battery heating or cabin heating. The concept reduces front-end heat exchangers in the baseline system from three to one. The combined system uses a single chilled liquid loop for cabin and battery cooling at hot ambient temperatures that enables a compact refrigerant loop and heat pump operation.

The key features of the combined cooling system were evaluated to determine feasibility and effectiveness. The ability to utilize waste heat from the power electronics and electric motor was evaluated along with the ability to satisfy cooling demands during hot ambient conditions with a single front-end heat exchanger. Figure 7 shows the system schematic when operating in heating mode. The refrigerant cooling loop is off and cabin heating is provided with an electric heater, similar to the baseline thermal system. The primary difference is the connection between the electric drive cooling system, battery thermal management, and cabin. Waste heat from the electric drive system can be used to enhance the warmup of either the vehicle cabin or battery. To prevent component overheating, the radiator cooling branch can be activated as needed.

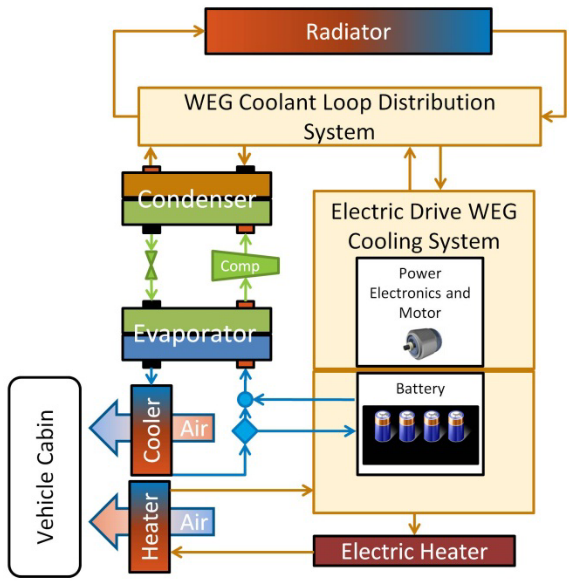


Figure 6. Combined system drawing.

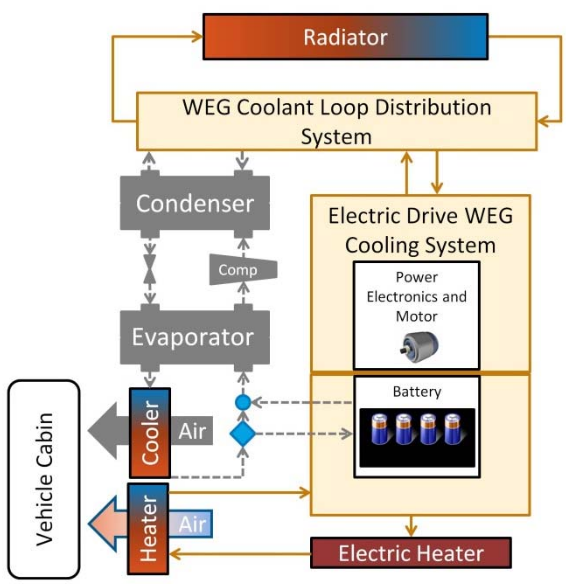


Figure 7. APEEM waste heat utilization for battery or cabin heating.

Figure 8 shows the schematic when operating in cooling mode for a hot ambient condition when a chiller is needed for cabin and battery cooling. The battery is cooled using a common chilled fluid that is also used for cabin cooling. For the illustrated condition, the battery is located downstream from the cabin cooling heat exchanger. For this reason, the battery coolant inlet temperature is affected by the cabin cooling airflow.

The intent of the analysis is to evaluate a worst-case condition where the cabin cooling airflow is set at the maximum value with a hot ambient temperature. The heat removed from the chilled liquid is transferred through another liquid loop that circulates through a radiator at the front of the vehicle. In addition to rejecting heat from the chilled liquid system for the air conditioning and battery, the radiator also rejects heat from the power electronics and electric motor.

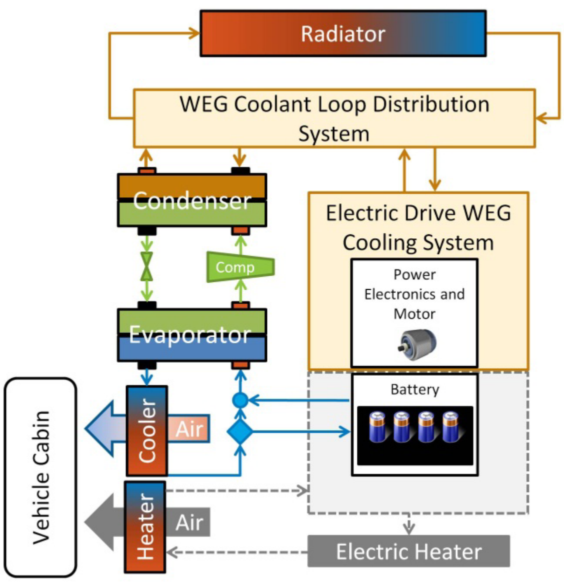
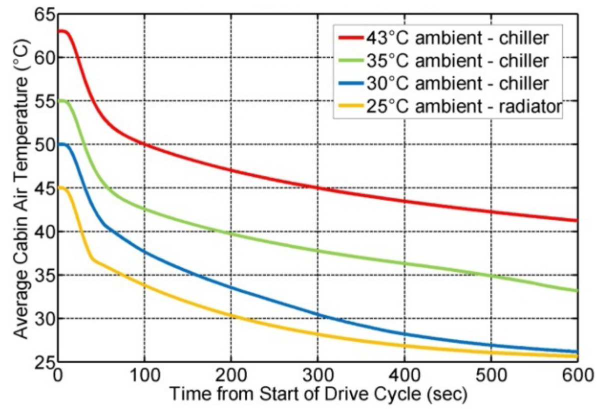


Figure 8. Combined radiator system and cabin/battery chiller.

Results

The performance of the baseline thermal management system is shown in Figures 9-12 over the US06 aggressive transient drive cycle at multiple ambient temperatures. The initial soak temperature of the vehicle cabin is assumed to be 20°C above ambient, and the initial soak temperature of the battery was assumed to be 1.6°C above ambient. The cabin target temperature was set to 25°C, and the battery cell target temperature was also set to 25°C.

The cooldown curves for the cabin in Figure 9 show reasonable cooldown profiles. The cooldown curves for the battery cell temperature are shown in Figure 10. The reason for the increasing battery cell temperature for the 25°C ambient test case is because the system controls were adjusted to force cooling through the radiator in the moderate environment.



.Figure 9. Baseline cabin air temperature over the US06 drive profile.

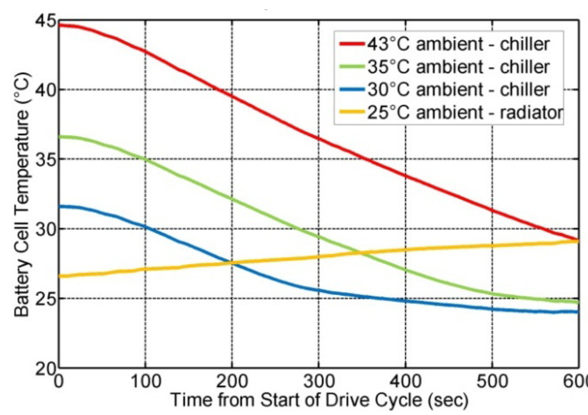


Figure 10. Baseline battery cell temperature over the US06 drive profile.

The ability to cool the battery through the radiator and not the chiller is reflected in the reduced power needed for the thermal management system in Figure 11. The coolant inlet temperature to the APEEM system is shown in Figure 12. The coolant temperature is below the 70°C maximum inlet temperature limit [6]. Figure 12 also shows the interactions between the air-side heat exchanger placement and the coolant loops. For the 30°C ambient case, the cabin and battery approach the target temperature and the total vehicle thermal management power drops. The reduced cooling demand on the condenser reduces the outlet air temperature of the condenser and reduces the inlet air temperature to the APEEM radiator.

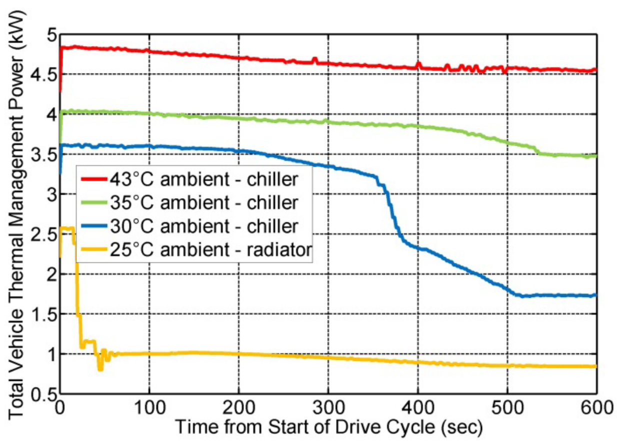


Figure 11. Baseline vehicle thermal management power over the US06 drive profile.

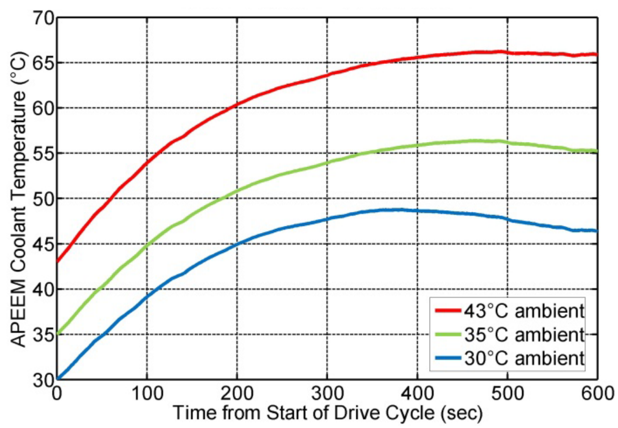


Figure 12. Baseline APEEM coolant inlet temperature over the US06 drive profile.

The baseline heating performance over the Bemidji test profile is shown in Figures 13-15. The baseline heating performance uses 7 kW for cabin heating and 1 kW to supplement the battery warmup. The baseline results are compared against two different combined cooling loop strategies using the APEEM waste heat (Figure 7). The first scenario links the APEEM cooling system with the cabin heater. The cabin heater power is reduced to 5.8 kW and the waste heat from the APEEM components is used to maintain equivalent cabin heating performance as seen in Figure 13. While meeting the same cooling performance, the coolant temperature to the APEEM components remains below the upper temperature limit of 70°C as seen in Figure 14. The second scenario links the APEEM cooling system with the ESS thermal management loop. The waste heat from the APEEM system is used to improve the warmup of the battery, and the 1 kW battery heater is off (Figure 15). The total vehicle thermal management power was reduced 1 to 1.2 kW with these configurations.

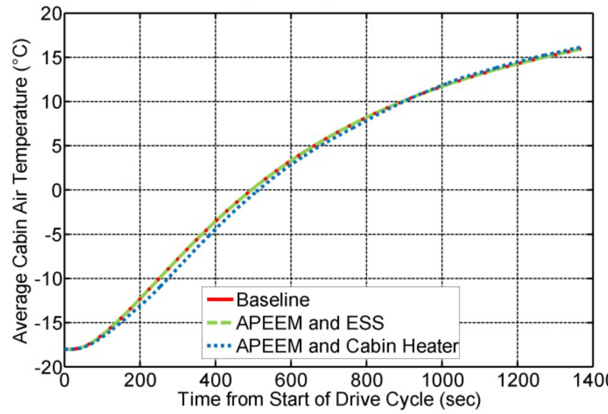
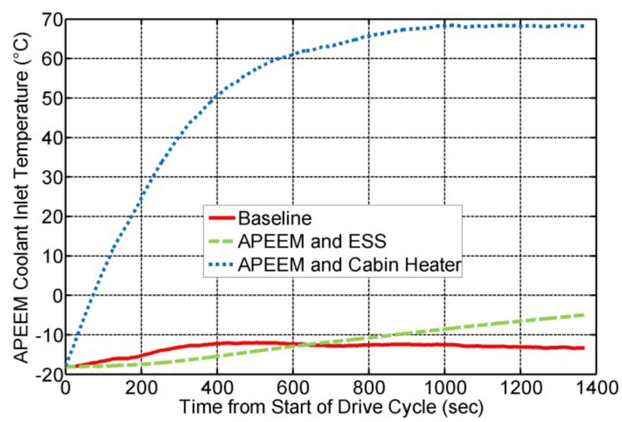
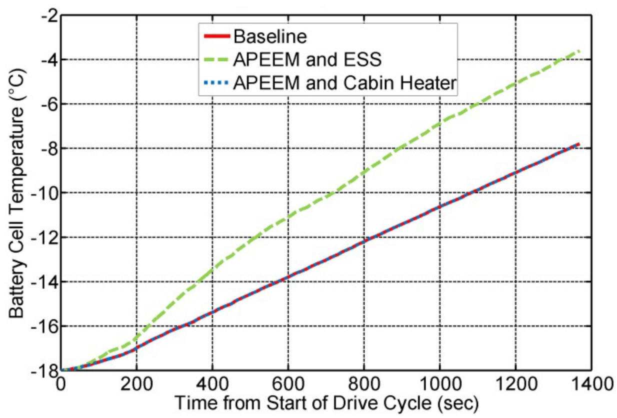


Figure 13. Comparison of cabin air temperature for baseline and alternative heating configurations for Bemidji -18°C condition.



.Figure 14. Comparison of APEEM coolant temperature for baseline and alternative heating configurations for Bemidji -18°C condition.



. Figure 15. Comparison of battery cell temperature for baseline and alternative heating configurations for Bemidji -18°C condition.

Besides the alternative warmup configurations, the ability to reduce the front-end heat exchangers from three to one (as shown in Figure 8) was evaluated. In this configuration, the condenser, APEEM radiator, and ESS radiator are combined into a single low-temperature radiator. The air-to-refrigerant condenser and evaporator are replaced with a liquid-to-refrigerant condenser and evaporator. The results of the combined system are compared with the baseline system in Figures 16-18. The single radiator configuration uses a radiator that is 0.71 m tall and 0.51 m wide with a maximum airflow per frontal area of 3.87 kg/(s-m^2). Both the size and airflow are within the range of typical automotive radiators.

Figure 16 compares the cabin cooldown performance and shows the combined system has slightly reduced cabin air cooling performance. This reduced cooling performance is typical for a secondary loop system. The reduced performance in cooling the battery (Figure 17) is because of the increased emphasis on cabin cooling in the combined cooling system. Both the cabin and battery are cooled with the same secondary loop chiller, although the battery is placed downstream of the cabin cooling heat exchanger. The impact on the battery could be mitigated by adjusting the cabin cooling airflow.

Figure 18 compares the coolant temperature for the APEEM system. The combined cooling configuration provides a lower temperature coolant temperature relative to the baseline system, and eliminates the dedicated liquid loop and heat exchanger for the APEEM system.

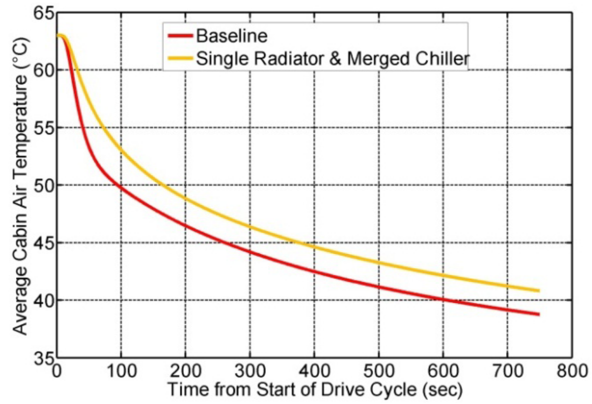


Figure 16. Comparison of cabin cooldown performance of baseline and combined configuration for Davis Dam 43°C condition.

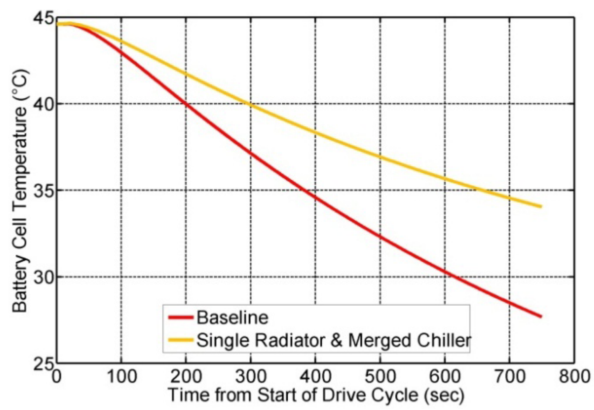


Figure 17. Comparison of battery cell temperature of baseline and combined configuration for Davis Dam 43°C condition.

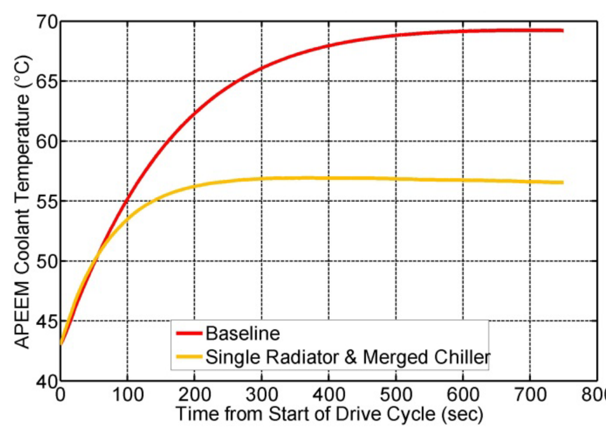


Figure 18. Comparison of APEEM coolant temperature of baseline and combined configurations for Davis Dam 43°C condition.

Conclusions

NREL researchers developed a modeling process to assess synergistic benefits of combining cooling loops. A KULI thermal model of a compact-sized EV was built, which produced reasonable component and fluid temperatures. This model was then used to assess combined cooling loop strategies. By using the waste heat from APEEM components, the total vehicle thermal management power was reduced. Replacing the air-to-refrigerant heat exchangers with refrigerant-to-liquid heat exchangers resulted in slightly reduced cabin air and battery cooldown performance. By adjusting component sizes and flowrates, it is likely the baseline cooldown performance could be matched, and the benefits of a secondary loop and perhaps heat pump systems realized.

References

1. "NREL: Vehicle Systems Analysis - Future Automotive Systems Technology Simulator." [Online]. Available: nrel.gov/vehiclesandfuels/vsa/fastsim.html. [Accessed: 01-Oct-2012].
2. "Kuli: Overview." [Online]. Available: kuli.ecs.steyr.com/. [Accessed: 01-Oct-2012].
3. U.S. EPA, "EPA US06 or Supplemental Federal Test Procedure (SFTP) | Emission Standards Reference Guide | US EPA." [Online]. Available: epa.gov/otaq/standards/light-duty/sc06-sftp.htm. [Accessed: 01-Oct-2012].
4. U.S. EPA, "EPA Urban Dynamometer Driving Schedule (UDDS) | Emission Standards Reference Guide | US EPA." [Online]. Available: epa.gov/otaq/standards/light-duty/udds.htm. [Accessed: 01-Oct-2012].
5. G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*. Addison-Wesley, 1994.
6. "Electrical and Electronics Technical Team Roadmap." [Online]. Available: eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_12-7-10.pdf. [Accessed: 11-Oct-2011].

Acknowledgements

- Susan Rogers, Steven Boyd, DOE VTP
- Kevin Bennion, Kandler Smith, Aaron Brooker, Jana Jeffers, NREL
- John Meyer, Visteon Corporation
- Albert Tuertscher, Magna Powertrain-Engineering Center Steyr

.

III.J. Vehicle Mass and Fuel Efficiency Impact Testing

Principal Investigator: James Francfort
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2209
Phone: (208) 526-6787; Email: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.J.1. Abstract

Objective

- Provide fully independent test track and dynamometer testing results documenting the vehicle mass reduction contributions to improved petroleum efficiency for a battery electric vehicle (BEV), hybrid electric vehicle (HEV), and an internal combustion engine vehicle (ICEV).

Approach

- Development testing approach and plans in agreement between Idaho National Laboratory, ECOtality, and Argonne National Laboratory (ANL).
- Minimize all testing variables, including vehicle height changes, temperature impacts, and wind directions.
- Conduct coastdown testing at a Phoenix area test track.
- Conduct dynamometer testing.
- Analysis and reporting of results.

Major Accomplishments

- Performed vehicle mass and fuel efficiency impact tests on internal combustion engine (ICEV), hybrid electric (HEV), and battery electric (BEV) vehicles. As FY 2012 concluded, presented initial findings, and prepared the extensive result for industry forum presentations and publications.

Future Activities

- Publication of results and presentations in several formats that include via DOE / USCAR technical teams, SAE conferences, and independent peer reviewed publications.
- Consider expanding testing to other vehicle technologies and weight classes.

III.J.2. PEVs Technical Discussion

Background

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing (AVTA) is part of DOE's Vehicle Technologies Program (VTP), which is within DOE's Office of Energy Efficiency and Renewable Energy (EERE). The AVTA is the only DOE activity tasked by DOE to conduct field evaluations of vehicle technologies that use advanced technology systems and subsystems in light-duty vehicles to reduce petroleum consumption. A secondary benefit is the reduction in exhaust emissions.

Most of these advanced technologies include the use of electric drive propulsion systems and advanced energy storage systems. However, other vehicle technologies that employ advanced designs, control systems, or other technologies with production potential and significant petroleum reduction potential, are also considered viable candidates for testing by the ATVA.

The AVTA light-duty activities are conducted by the Idaho National Laboratory (INL) for DOE. INL has responsibility for the AVTA's execution, direction, management, and reporting; as well as data collection, analysis and test reporting. INL is supported in this role by ECOtality North America (ECOtality), which has a competitively awarded contract that is managed by DOE's National Energy Technology Laboratory (NETL). The AVTA sections of the FY 2012 Annual Program Report jointly cover the testing work performed by INL and ECOtality. When appropriate, the AVTA partners with other governmental, public, and private sector organizations to provide maximum testing and economic value to DOE and the United States taxpayers, via various cost sharing agreements.

Introduction

DOE, vehicle original equipment manufacturers (OEMs), and others are all investigating in a plethora of methods to maximize vehicle energy efficiencies from advanced vehicle and engine technologies. In addition to electric drive technologies, direct injection engines, and other methods such as drag reductions, vehicle mass reductions are also being investigated. However, publicly known mass reduction research to date has mostly been estimated via modeling activities, with no published real-world testing to support the development of the modeling variables. The AVTA conducted a real-world vehicle mass impact testing study to support DOE's modeling activities.

Approach

The objective of this study was to isolate and quantify the impact of vehicle mass changes on vehicle energy efficiency for three different powertrain types. This mass variation study quantified the liquid fuel consumption impacts for an internal combustion engine vehicle (ICEV) and hybrid electric vehicle (HEV), and the electrical energy consumption impact for a battery electric vehicle (BEV) at various masses. The study began by conducting a coastdown procedure on each vehicle to obtain the coastdown coefficients at varying weights. The coefficients were then utilized in dynamometer testing to determine the impact of mass changes on rolling resistance variation. The results of this study will be used in modeling efforts for future design and modeling-based optimizations dependent on mass.

The overall process and testing methodology were reviewed in a project kickoff meeting between INL, Argonne National Laboratory (ANL) and ECOtality.

It was agreed that the test weights would consist of:

- +500 lbs
- EPA certified weight
- -250 lbs
- -500 lbs.

Results

Three vehicles (one ICEV, one HEV, and one BEV) were tested per coast down procedure ETA-TP001 (see: avt.inel.gov/pdf/fsev/eva/etatp1r2.pdf) with modifications at varying weights. The results of this testing was the set of coastdown coefficients obtained for each ETP and weight variation. The three vehicles chosen for this study were:

- Ford Fusion 6 cylinder (ICEV)
- Ford Fusion Hybrid (HEV)
- Nissan Leaf (BEV) (Figure 1).

Figure 1. Mass impacts test vehicles.

The same three vehicles were then tested on the dynamometer over standard drive cycles. The dynamometer test results quantified the fuel economy and electrical energy consumption impacts of mass over the range in this study.

The testing was conducted in two phases: after the initial break-in period, the ETP underwent coastdown tests at the proving grounds and then dynamometer testing.

The testing results showed:

- A slightly non linear trend of decreasing vehicle mass results in decreased vehicle drag
- Slight difference in trends (from vehicle to vehicle) is likely due to tire technology, not due to powertrain technology
- **City driving:** 3 to 4% Energy consumption for a 10% mass reduction despite a powertrain efficiency reduction. The more efficient the vehicle powertrain the larger the energy consumption benefits for a mass reduction
- **Aggressive driving:** 3% Energy consumption for a 10% mass reduction across different powertrain architectures
- **Highway driving:** Little benefit is derived from a mass reduction on smooth highway cruising
- **Vehicle efficiencies impact:** engine/motor load change, idle to average load proportion, more powered deceleration as light weighted, regenerative breaking.

As FY 2012 ended, a formal SAE paper was being prepared as the testing results were receiving additional revaluation.

Conclusions

All three vehicles showed a non-linear trend (Figure 2):

- 12% to 13% mass increase ➔ 2% to 7% increase in low speed road load
- 6% to 7% mass decrease ➔ 7% to 12% decrease in low speed road load

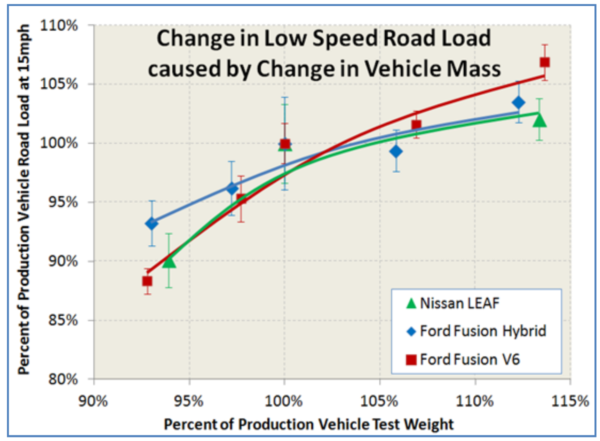


Figure 2. Non linear change in speed road load.

Difference in trend between Fusion ICEV and Fusion HEV versus the LEAF BEV but there may be impacts in that the Fusion HEV and LEAF BEV utilize low rolling resistance tires and the Fusion V6 ICEV utilizes conventional tire technology.

Vehicle mass impact on vehicle road load and drag losses was determined and coastdown testing conducted for:

- Three Vehicles (BEV, HEV, ICE)
- Five weight classes for each vehicle.

Analysis of coastdown testing data provided road load data to enable accurate chassis dynamometer testing.

Mass impact on vehicle road load determined:

- A slightly non linear trend of decreasing vehicle mass results in decreased vehicle drag
- Slight difference in trends (from vehicle to vehicle) is likely due to tire technology, not due to powertrain technology.

Publication

1. Only preliminary presentation (INL/MIS-12-26951) had been prepared at the end of FY 2012. However, SAE and other industry forum peer reviewed publications were being developed.

III.K. New York EV Taxi Simulation & Drive Cycle Development

Principal Investigator: P.T. Jones
Model Creation and Vehicle Systems Controls: Dr. David Smith and Paul Chambon
Oak Ridge National Laboratory
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1472; Email: jonespt@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov:

III.K.1. Abstract

Objective

- Project performance for Nissan Leaf Taxicabs that will be placed into service by the New York City Taxi and Limousine commission (NYTLC).
- Develop representative drive/duty cycles for a typical NYC Taxi shift using existing HEV in-use Taxi drive cycle data.
- Construct a basic Autonomie model of the Leaf to exercise created drive cycles and predict performance.
- Report to NYTLC initial performance projections and support field data set-up.

Approach

- Obtain Ricardo in-use data from Ford Escape HEV Taxi field trail
- Format data for use with ORNL DC_GEN tool for drive cycle creation
- Develop representative drive cycle modules for various types of taxi field use
- Identify appropriate components in AUTONOMIE and create baseline Leaf EV model
- Obtain Leaf test data from ANL level 1 AVTA testing to validate baseline model results

Major Accomplishments

- Basic Leaf EV AUTONOMIE model constructed and validated using Argonne National Laboratory (ANL) test data
- Representative drive cycles created for performance projections
- Range and energy consumption projections presented to NYTLC for appropriate planning of field evaluation project.

Future Activities

- No planned activities in FY 2013

III.K.2. Technical Discussion

Battery Electric Vehicles (BEVs) have inherent efficiency benefits over conventional internal combustion engine (ICE) and Hybrid Electric vehicles (HEVs) in certain drive cycles. Drive cycles with high idle times, and aggressive stop/start profiles will often highlight the fuel reduction and energy recovery opportunities available when replacing an ICE powertrain with an electrified one. Pure BEVs, however, must address the limitations with regard to recharging the energy storage system (ESS) when faced with longer drives cycles or high levels of accessory loading which can deplete the ESS.

Fleet and organized purchases of BEVs will require appropriate infrastructure deployment for the recharging of BEVs. Recharging of these vehicles may be required in the field, for the BEV to perform satisfactorily for the customer/operator. Additionally some operations will have lost revenue if the time for recharging is long or required at a multiple times throughout the expected daily operation.

Understanding the in-use impacts on BEVs in appropriate drive cycles is imperative to their mass adoption. Developing a representative drive cycle is critical for that evaluation. New York City taxi operation is a unique and demanding driving application that is well suited for the development and evaluation of BEVs and required infrastructure.

Figure 1. Selected as NYC's Taxi of tomorrow the NV200 will start to replace Crown Victorias in 2013. e-NV200s are in field test with an electrified powertrain very similar to the Nissan Leaf.

Background

In seeking to maximize efficiency and reduce emissions produced for inter-city mobility, the New York Taxi and Limousine Commission (NYTLC) will place Nissan Leafs, which are production BEVs, into limited service as taxis in the New York City area. The NYTLC requested assistance from Oak Ridge National Laboratory (ORNL) to determine the capability of the Leaf's all electric powertrain to provide adequate range of operation under various conditions. It is understood that the Leaf's production body was not intended for use as a taxi, and that the focus of this pilot project was powertrain evaluation and performance projections leading to a field trial. As the NV200 taxi vehicles begin service (figure 1), the information from this study and the field trial would be directly applicable to the e-NV200 development.

Introduction

This study attempts to provide performance projections for a production Nissan Leaf BEV if placed into service as a New York City Taxi Cab. The drive/duty cycle created utilized actual HEV taxi field data, though this data was of limited sample size and time of year use was only for the month of June. The data included nearly 3000 trips of speed versus time information similar to that shown in Figure 2. A math model of the vehicle was created using AUTONOMIE and vehicle level controls developed for other DOE funded activities. The simulation test vehicle was operated over drive cycles 4 and 8 hours in duration.

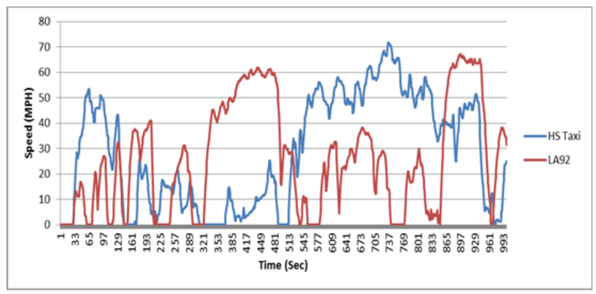


Figure 2.Portions of Speed Vs. Time cycles compared.

These AUTONOMIE simulations take only minutes by computer and allow for multiple variations of key vehicle component parameters to be evaluated in a fraction of the time it would take to change components on a vehicle and perform a test.

Approach

Simulations and resulting projections of vehicle performance require field data and validated component/system math models. This project utilized previously gathered data as well as tools developed under other DOE Vehicle Technology Program (VTP) projects.

Previous NYC taxi demonstration fleets have had vehicle information recorded for research and development. Ricardo, a multi-industry consultancy, recorded Ford Escape HEV data during a previous taxi service data collection program (figure 3). Ricardo provided this data to ORNL for analysis and composition into synthetic NYC taxi drive cycle segments using a

DOE/ORNL developed tool called DC_Gen tool. The data provided to ORNL was reformatted into a DC_Gen tool compatible file for analysis.

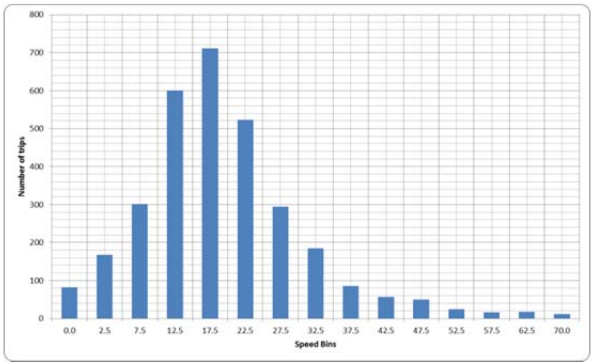


Figure 3. Analysis of field data yields characteristics of typical NYC taxi operation.

The DC_Gen tool produces statistical plots of the field data, seen in figure 4, which are further used to apply proper weighting to the types of 'trips' that are more frequent, and therefore more typical of NYC taxi operation. Characteristics of 'trips' which occurred frequently were used in the generation of the drive cycle modules. Modules were developed, rather than simply developing a full drive cycle, due to the limited sample size and unique vehicle from which the field data was taken.

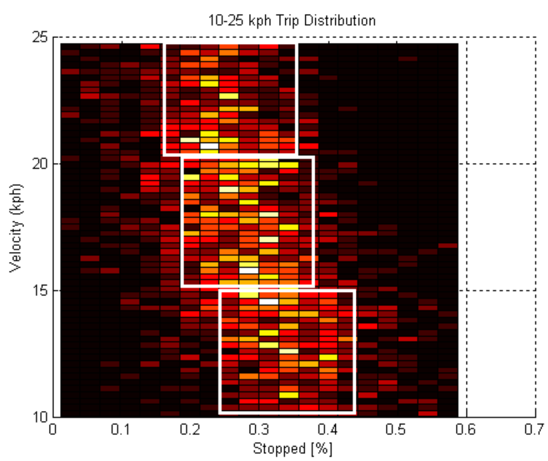


Figure 4. The lighter shaded boxes indicate a higher number of trip segments with the axis values

The resulting analysis of the HEV taxi data and use of the DC_Gen tool produced drive cycle modules (Speed vs. Time data files) that can be used to build combined drive cycles with appropriate speed, distance, idle frequency and durations, to properly emulate NYC taxicab operation.

The synthesized drive/duty cycles compare favorably with in use field data, however, the field data did not include information for HVAC loads. Since the vehicle was only operated in June and July, no heater usage data was collected from the HEV. Fortunately the ANL climate capable Advanced Powertrain Research Facility (APRF) was conducting Nissan Leaf testing about the same time as this project. The ANL researchers were able to add some testing processes onto their planned tests to gain additional information about the impact of HVAC usage – and multiple passenger entries and exists might have on energy consumption. From the ANL data collected on HVAC energy consumption, two energy usage rates were set for typical accessory consumption during the simulation drive cycles. One to emulate low HVAC use (minimum impact to range) and high HVAC use to highlight the impact of the heater on the expected range of the vehicle.

The ORNL Leaf vehicle components were selected from the AUTONOMIE library, but the control system used was developed as part of another VTP project. This project, The Advanced Battery Mule vehicle, is an Idaho National Lab field evaluation project that required a Leaf control system to emulate that vehicle's regenerative braking and propulsion strategy in a complex series/parallel vehicle that was built to evaluate various battery systems. The developed control strategy and system model was further exercised using certification drive cycles, and then compared to actual ANL test data over the same drive cycles. The results for consumption rates varied within 5% between simulation and actual test, which was determined acceptable for this projection project.

Results

The modeled EV taxi and control strategy was run through various drive cycle configurations and SOC initial values to determine appropriate range and time of use values for the NYTLC.

Table 1. The combination of developed modules is shown above for the two drive cycles (Nominal and High Load) that were used to project the performance of the Nissan Leafs placed into taxi service in NYC.

Drive Cycle	Module Type and Number			
	LS	MS	MH	HS
Nominal	1	5*	1	1
High Load	1	4**	2	1

Table 2. The two focus drive cycles of this study exhibit very different parameters using a different combination of the same modules.

Drive Cycle	Specifications			
	Time (hours)	Distance (miles)	Avg Spd (mph)	Avg Spd (kph)
Nominal	4	56.0	14.0	22.5
High Load	4	69.4	17.3	27.8

The two primary drive cycles for this study were assembled from the developed modules, output from the DC_Gen Tool as displayed in Table 1. The modules, LS-HS, represent segments of the drive trace that were synthesized from various bands of speed data. Assumptions relating to State of Charge (SOC) were of significant importance as the performance predictions show that the EV taxi range would not be sufficient to run for an 8 hour shift, and recharging would be required. The primary drive cycles shown in Table 2 reflect the range limitations (and time of operation) of the EV taxi based on the production Leaf ESS. If the EV taxis are able to complete the 4 hour drive cycle; then only one recharge (and resulting non-operational time) will be required per shift.

Table 3. The highlighted cells indicate that the vehicle would not be able to complete the cycle.

Vehicle Configuration	Nominal cycle	High Load	Comments
Base Vehicle	238 wh/mi	231 wh/mi	0.5kW, 80% SOC
Base Veh w/ Htr	584 wh/mi 39.1 / 56.0mi	553 wh/mi 42.8/ 69.4 mi	3.5kW heater load, 80% SOC

As shown in Table 3, when considerations for full heater HVAC accessory loads are taken into account, the 80% SOC that a DC fast charge will enable in 30 minutes is not sufficient to complete the High Load cycle.

Conclusions

This project utilized previously generated lab and field vehicle data combined with simulation and modeling tools to project the performance of a production based EV placed into NYC taxicab service.

Based on the two drive cycles and an estimation of start of shift SOC of the vehicle; performance predictions of an EV Taxi with the drivetrain of a production Leaf with a similar vehicle mass, capability were produced. The results were presented to the NYTLC in support of their planned field evaluation program.

For complete satisfaction of the operator and the end-use customer, driving restrictions will need to be considered during in-field use in cold environments. As a result of this study, the NYTLC is considering route restrictions for the EV taxi fleet.

III.K.3. Products

Publication

1. Planned presentation at the SAE HEV/EV symposium in 2013.

Tools & Data

ORNL used a variety of VTP funded tools and previously gather or otherwise available data to complete this study.

1. Ricardo Ford Escape HEV Taxi NYC field data
2. Argonne National Lab (ANL) chassis data from Level 1 Leaf Testing
3. DC Gen Tool, a drive cycle generation tool developed by ORNL
4. AUTONOMIE vehicle simulation and modeling software developed by ANL
5. Basic Leaf control Strategy developed for INL advanced battery testing mule vehicle

TADA LAB & FIELD VEHICLE EVALUATIONS LD

III.L. Advanced Vehicle Testing Activity – TADA Test Support to OEM Data Collection

Principal Investigator: James Francfort
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2209
Phone: (208) 526-6787; Email: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.L.1. Abstract

Objective

- Continue to provide to DOE, OEMs, taxpayers and other stake holders, fully independent, benchmarked feedback on DOE technology investments and emerging industry transportation platforms.
- Benchmark grid-connected plug-in electric drive vehicles (PEV) to determine the contribution PEV and HEV technologies can make to reduce petroleum consumption in the United States.
- Benchmark individual PEV models from original equipment manufacturers (OEMs).
- Reduce the uncertainties about PEV and HEV performance, and most importantly, battery performance and life.
- Reduce the uncertainties about drivers' recharging practices and PEV acceptance.
- Provide PEV and HEV testing results to fleet managers and the general public to support their acquisition and deployment decisions.

Approach

- Document via various testing methods real-world fuel use over various trip types and distances.
- Report liquid and vapor fuel use, and electricity use separately.
- Document any environmental factors, such as temperature and terrain that impact PEV and HEV fuel consumption.
- Use published testing specifications and procedures developed by the AVTA that are reviewed by industry, national laboratories, and other interested stakeholders.
- Place vehicles in environmentally and geographically diverse test fleets.
- Continue to use and develop cost-shared partnerships with public, private, and regional groups to test, deploy, and demonstrate vehicles and infrastructure technologies in order to leverage DOE funding resources.
- As needed, reach additional cooperative research and development agreements (CRADAs) and non-disclosure agreements (NDAs) in preparation for the testing of vehicles and components from OEMs.

Major Accomplishments

- Collected and published onboard data from a fleet demonstration of 21 Ford Motor Company Advanced Research Escape PHEVs. As FY 2012 ended, 567,000 miles of vehicle use and charging profiles and up to 66% petroleum use reductions were documented.
- Initiated data collection from a fleet demonstration of 23 Chrysler Town and Country Minivan PHEV. As FY 2012 ended, 43,000 test miles of vehicle and charging profiles, as well as mpg increases of up to 36% were documented when comparing operations with at least a partially charging PHEV traction battery pack.

Future Activities

- Complete the reporting on the performance of 21 Ford Escape Advanced Research PHEVs and report the petroleum reduction capabilities and operations of the same vehicles. However, this task will complete during FY 2012.
- Continue to report on the performance of 23 Town and Country PHEV minivans and report the petroleum reduction capabilities and operations of the same vehicles.
- Develop additional low-cost vehicle and charging infrastructure demonstration relationships and support the deployment of PEVs and electric drive vehicles (EDVs) in these testing fleets.

III.L.2. PEVs Technical Discussion

Background

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing (AVTA) is part of DOE's Vehicle Technologies Program (VTP), which is within DOE's Office of Energy Efficiency and Renewable Energy (EERE). The AVTA is the only DOE activity tasked by DOE to conduct field evaluations of vehicle technologies that use advanced technology systems and subsystems in light-duty vehicles to reduce petroleum consumption. A secondary benefit is the reduction in exhaust emissions.

Most of these advanced technologies include the use of electric drive propulsion systems and advanced energy storage systems. However, other vehicle technologies that employ advanced designs, control systems, or other technologies with production potential and significant petroleum reduction potential, are also considered viable candidates for testing by the ATVA.

The AVTA light-duty activities are conducted by the Idaho National Laboratory (INL) for DOE. INL has responsibility for the AVTA's execution, direction, management, and reporting; as well as data collection, analysis and test reporting. INL is supported in this role by ECOtality North America (ECOtality), which has a competitively awarded contract that is managed by DOE's National Energy Technology Laboratory (NETL). The AVTA sections of the FY 2012 Annual Program Report jointly cover the testing work performed by INL and ECOtality. When appropriate, the AVTA partners with other governmental, public, and private sector organizations to provide maximum testing and economic value to DOE and the United States taxpayers, via various cost sharing agreements.

Introduction

DOE's AVTA is evaluating grid connected plug-in electric drive vehicle (PEV) technology in order to understand the capability of electric grid recharged electric propulsion technology to significantly reduce petroleum consumption when vehicles are used for transportation. In addition, many companies and groups are proposing, planning, and have started to introduce PEVs into their fleets.

It should be noted that grid-connected PEVs include several vehicle / energy storage schemes that include: battery electric vehicles (BEVs or simply EVs) such as the Nissan Leaf, plug-in hybrid electric vehicles (PHEVs) such as the Ford Escape and Chrysler Town and Country Minivan PHEVs, and extended range electric vehicles (EREVs) such as the General Motors Volt.

During FY 2011, a transition occurred from testing mostly PEV conversions to testing PEVs from OEMs. When testing conversion vehicles, the primary focus during FY 2011 was to study the PEV technology's potential contribution to petroleum reduction and to understand and document charging patterns. The drive to focus on the overall petroleum reduction potential of PEV technology versus testing individual PHEV conversion models was driven by the mostly conversion nature of the available PEVs during pre-FY 2012 years, and the non-likelihood the conversion vehicles would be the majority of PEV deployments in future years. During late FY 2011, this transition was completed when the last of the PEV conversions completed testing.

This transition in focusing on PEV conversions to focusing on PEVs from OEMs was made possible as several OEMs made available during late FY 2011, PEVs for the first time in about a decade.

The PHEV conversions available for public purchase in the few years prior to FY 2012 used an HEV as the base vehicle, and either added a second PHEV battery or replaced the base HEV battery with a larger PHEV battery pack, with a 5 kWh PHEV battery size the most typical size for secondary batteries. However, some PHEVs and EREVs used a single battery pack that ranged from 10 to 15 kWh. PHEV control systems and power electronics are also added to the base vehicle to complete the upgrade. These larger additional or replacement battery packs are sometimes recharged by the onboard regenerative braking and generator subsystems, but all of them must also use onboard chargers connected to the off-board electric grid to fully recharge the PHEV battery packs.

Today's OEM PEVs mostly have 10 to 15 kWh of onboard battery storage in PHEVs and EREVs, and more than 20 kWh of onboard storage for BEVs. However, some other OEMs are introducing PHEVs with smaller battery packs.

Within the AVTA, INL and ECOtality make extensive use of in-vehicle and in-charging infrastructure data loggers to collect a variety of vehicle and infrastructure generated performance parameters. Experience has shown that automated data collection in fleet environments is the only way to ensure accurate data is collected.

The concept of advanced onboard energy storage and grid-connected charging raises questions that include the life and performance of these larger batteries; the charging infrastructure required; how often the vehicles will actually be charged – driver and "smart grid" behavior and controls; and the actual amount of petroleum displaced over various missions, drive cycles, and drive distances; all achieved with automated data loggers.

Approach

Three basic types of test methods are used to test vehicles and they discussed below.

Baseline performance testing during which a vehicle is track and dynamometer tested. The track testing includes acceleration, range, braking, and fuel use (both electricity and gasoline) at different battery states-of-charge (SOC). The vehicles are also coast-down tested to determine dynamometer coefficients, which are used during the various urban and highway dynamometer test cycles. Note that the AVTA dynamometer testing is conducted by Argonne or Oak Ridge National Laboratories for the AVTA. This sharing of vehicles and testing expertise also reduces costs to DOE.

Accelerated Testing uses dedicated drivers to complete a series of drives and charges (for PEVs) on city and highway streets. This testing is often used to ensure PEVs can accomplish several charge and drive cycles in one day. For some vehicles, this can include more than 5,000 miles of operation per month.

Fleet Testing is normally conducted by placing vehicles into fleets with no highly controlled structure to repeatable drive missions. The AVTA partners with government, private, and public fleets for fleet testing as these fleets are often overwhelmingly the earliest adaptors of advanced technology vehicles. Note that the AVTA fleet testing does sometimes include operations by the general public.

For PHEVs and EREVs, these vehicles can operate on gasoline even when the vehicles' battery packs are not charged. Therefore, with some exceptions, the fuel-use result reporting is normally broken down into three operating modes for these vehicle technologies:

Charge Depleting (CD) Mode: During each entire trip, there is electric energy in the traction battery pack to provide either all-electric propulsion or electric assist propulsion throughout the entire trip.

Charge Sustaining (CS) Mode: During a trip, there is no electrical energy available in the PHEV or EREV traction battery pack to provide any electric propulsion support beyond normal HEV operations.

Combined (or Mixed) Charge Depleting and Charge Sustaining (CD/CS) Mode: There is electric energy in the traction battery pack available at the beginning of a trip. However, during the trip, the PEV battery is fully depleted.

For EVSE benchmarking, the results are broken down a variety of ways, including:

- Public versus private EVSE use
- Weekday versus weekend use
- By time of day
- National versus regional results.

Results

Ford Escape Advanced Research PHEV

During FY10, the AVTA signed a CRADA with the Ford Motor Company that detailed data collection, analysis and reporting by the AVTA for the vehicle performance, fuel use, and charging patterns for 21 Ford Escape Advanced Research PHEVs. This work is being performed to support a Transportation Acceleration and Demonstration Activity (TADA) grant Ford received from DOE.

Using server-to-server data transmission, the INL receives raw data generated by data loggers installed onboard the 21 Escape PHEVs. With this data, INL generates a series of periodic reports and year to date summary fact sheets which can be accessed at: avt.inel.gov/phev.shtml.

The November 2009 to September 2012 report documents 567,000 miles of operation during which the vehicles had an overall fuel economy of 38 mpg. However, when operating in CD mode, the vehicles averaged 52 mpg, which is 63% higher than the 32 mpg result in CS mode operations.

These vehicles provide excellent documentation that ambient temperatures impact mpg results in all operating modes. As seen in Figure 1, the biggest impact is during CD mode operations (green line in the graph) where mpg results are more than twice as high as during 60 to 75 degrees Fahrenheit operations compared to very hot and cold operations.

The monthly reports also document seasonal impacts on mpg results with August 2012 reporting 58 mpg in CD mode and January and February 2012 both reporting 47 mpg in the same operating mode. For the monthly results see the web site: avt.inel.gov/library.shtml#F.

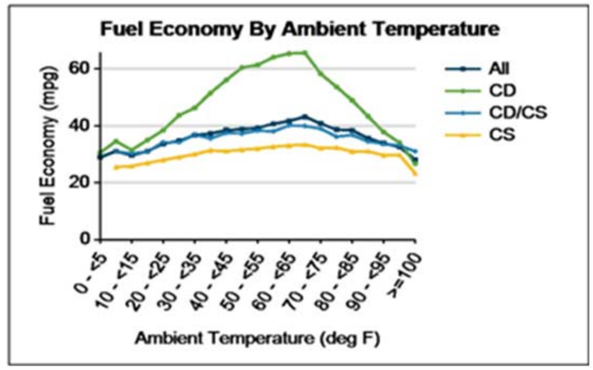


Figure 1. Ford Advanced Research PHEV mpg for all Explorers impacts at a range of ambient temperatures.

Using the November 2009 to September 2012 results, when operating in CD mode during city driving events the mpg is 60% higher (48 mpg) than city driving CS mode (30 mpg). During highway driving in CD mode, the mpg is 81% higher (58 mpg) than highway driving in CS mode (32 mpg).

Table 1 documents the Minivans recharging information. It should be noted that the vehicle is being charged 1.9 times per day for those days the vehicle is operated.

Table 1. Ford Escape PHEV charging information for the November 2009 through September 2012 reporting period.

Average # charging events per vehicle month	28
Average # of charging event per vehicle day	1.9
Average miles between charging events	30.2
Average # trips between charging events	2.5
Average time plugged per charging event	7.4
Average hours charging per charging event	2.2
Average energy (AC kWh) per charging event	3.0
Average energy (AC kWh) per vehicle month	85.5
Total charging energy (AC kWh)	57,301

It should also be noted that the Escapes were mostly being driven in fleet operations and the fleet drivers do not normally pay for fuel use, so they may not be overly motivated to maximize CD operations by ensuring the vehicle's traction battery packs are charged as often as possible. However, compared to other fleets, these vehicles are seeing fairly high operations with some energy in the battery packs. Only 28% of trips commenced with no electricity in the traction battery packs. It should be noted that these are technology demonstration vehicles, not production intent vehicles.

It should be noted that these Escapes were mostly being driven in fleet operations and the fleet drivers do not normally pay for fuel use, so they may not be overly motivated to maximize CD operations by ensuring the vehicle's traction battery packs are charged as often as possible. It should be noted that these are technology demonstration vehicles, not production intent vehicles.

Chrysler Town and Country Minivan PHEV

During FY 2012 the AVTA initiated the data collection, analysis and reporting for a demonstration fleet of 23 Chrysler Town and Country Minivan PHEVs. This technology development is being supported by DOE with a competitively awarded funding grant from the Technology Acceleration and Demonstration Activity (TADA).

Using the most recently published quarterly report for April through June 2012, (avt.inel.gov/pdf/phev/ChryslerMinivanQ2_2012.pdf) the vehicles had accumulated 43,000 test miles. In addition, the individual monthly reports for July, August and September 2012 document an additional 80,000 miles of operations, but the project to date report covering the entire 123,000 miles was not yet completed when this report was written.

During August and September, the minivans were not charged as often per direction from Chrysler, so the July monthly report will be used here to discuss the petroleum reduction benefits of a minivan with PHEV technology. During July 2012 a total of 26,000 miles was accumulated on the 23 Town and Country Minivan PHEVs avt.inel.gov/pdf/phev/ChryslerMinivanJuly2012.pdf. For combined city and highway operations in charge depleting mode, the minivan was averaging 35 mpg and 24 mpg for charge sustaining operations. Therefore, by simply maximizing charge depleting operations, the vehicles were able to achieve a 46% improvement in fuel use. For city only types of driving, the minivan averaged 34 mpg in charge depleting operations and 21 mpg in charge sustaining operations, a 62% improvement in mpg.

As shown in Figure 2, the Minivan operating scheme allows the internal combustion engine (ICE) to be off 32% of the time, including 14% engine off while the vehicle was being driven.

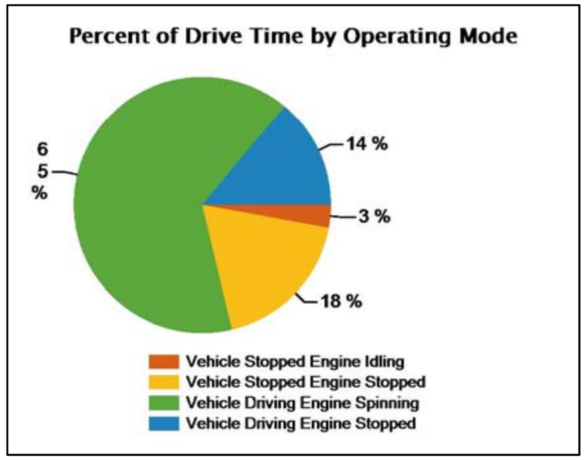


Figure 2. Chrysler Town and Country Minivan PHEV percent of drive time the engine is spinning or stopped by whether or not the vehicle is moving.

While the Minivan PHEV does not exhibit a linear mpg and aggressiveness driving profile, Figure 3 documents the driving aggressiveness impact on mpg, with less aggressive driving results in an average of approximately 30 mpg while the most aggressive driving results in mpg in the low 20's.

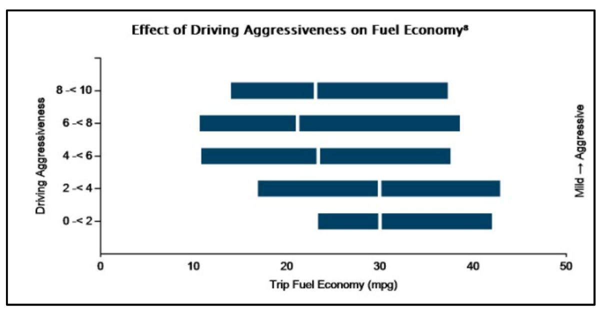


Figure 3. Chrysler Town and Country Minivan PHEV fuel efficiency impacts from aggressiveness driving.

Table 2 documents the Minivans recharging information. It should be noted that the vehicle is being charged only 0.82 times per day for those days the vehicle is operated.

Table 2. Chrysler Town and Country Minivan PHEV charging information for the July through September 2012 reporting period.

Average # charging events per vehicle month	16.9
Average # of charging event per vehicle day	0.9
Average miles between charging events	65.8
Average # trips between charging events	6.1
Average hours charging per charging event	1.8
Percent total charging energy at Level 1	3%
Percent total charging energy at Level 2	97%
Average energy (AC kWh) per charging event	5.6
Average energy (AC kWh) per vehicle month	93.7
Total charging energy (AC kWh)	2,155

It should be noted that the Town and Country Minivans were mostly being driven in fleet operations and the fleet drivers do not normally pay for fuel use, so they may not be overly motivated to maximize CD operations by ensuring the vehicle's traction battery packs are charged as often as possible. In fact, as measured by total distance traveled, 44% of the total distance is in trips that start with no energy in the tractor battery pack. It should be noted that these are technology demonstration vehicles, not production intent vehicles.

Conclusions

The Idaho National Laboratory, through the AVTA, continues to provide the critical real world testing needed to benchmark DOE technology investments, including the critical tasks of determining suitability for deployment, and life time performance and costs of new technology components and vehicle systems. This testing includes understanding the infrastructure requirements of PEVs as well as other alternative fuels, as well as the proper placement of that infrastructure.

While neither the Escape or Town and Country are production intent vehicles, the PEV technology knowledge both Ford and Chrysler are learning from the TADA demonstrations are being applied to other vehicle platforms that are production intent.

Publications

Specific fact sheets and reports have been referenced in the report by including their locations on the AVTA website. The AVTA is generating a significant number of reports, fact sheets, conference papers, and presentations each fiscal year. Therefore, report locations are listed below by projects or vehicle technologies.

1. Hybrid Electric Vehicle benchmarking avt.inel.gov/hev.shtml
2. Plug-in Hybrid Electric Vehicle and Extended Range Electric Vehicle benchmarking avt.inel.gov/phev.shtml
3. All of the Town and Country PHEV reports can be found at: avt.inl.gov/library.shtml#C2
4. The approximately 40 Ford Escape PHEV reports can be found at: avt.inl.gov/library.shtml#F

LAB & FIELD EVALUATIONS (MEDIUM & HEAVY DUTY)

III.M. AVTA Support of USPS Vehicle Electrification Development Activities

Principal Investigator: James Francfort
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2209
Phone: (208) 526-6787; Email: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.M.1. Abstract

Objective

- Benchmark grid-connected plug-in electric drive vehicles (PEV) to determine the contribution PEV technologies can make to the U.S. Postal Service's (USPS) efforts to reduce petroleum consumption in the United States.
- Provide the AVTA's testing results of the five USPS PEVs to the U.S. Department of Energy (DOE), USPS, vehicle modelers and designers, technology target setters, and industry stakeholders.

Approach

- Document any environmental factors, such as temperature and terrain that impact PEV fuel (electric and non-electric) consumption.
- Use published testing specifications and procedures developed by the AVTA that are reviewed by industry, national laboratories, and other interested stakeholders.

Major Accomplishments

- Collecting and publishing onboard data from a fleet demonstration of five USPS electric Long Life Vehicles (eLLV) converted from standard LLVs to pure battery electric operations. The five companies performing the conversions were:
  - Autoport/AC Propulsion/University of Delaware
  - Bright Automotive
  - EDAG, Inc. – USA
  - Quantum Technologies
  - ZAP.
- While all five vehicles completed the FY 2011 baseline performance testing, fleet mission testing was problematic for some models. A total of only 3,965 fleet miles were documented with one model unable to operate for a life time total of 50 miles.

Future Activities

- Continue to support USPS activities directed towards introducing petroleum reduction vehicle technologies into their mail delivery and distribution system as such vehicles are procured.

III.M.2. PEVs Technical Discussion

Background

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing (AVTA) is part of DOE's Vehicle Technologies Program (VTP), which is within DOE's Office of Energy Efficiency and Renewable Energy (EERE). The AVTA is the only DOE activity tasked by DOE to conduct field evaluations of vehicle technologies that use advanced technology systems and subsystems in light-duty vehicles to reduce petroleum consumption. A secondary benefit is the reduction in exhaust emissions.

Most of these advanced technologies include the use of electric drive propulsion systems and advanced energy storage systems. However, other vehicle technologies that employ advanced designs, control systems, or other technologies with production potential and significant petroleum reduction potential, are also considered viable candidates for testing by the ATVA.

The AVTA light-duty activities are conducted by the Idaho National Laboratory (INL) for DOE. INL has responsibility for the AVTA's execution, direction, management, and reporting; as well as data collection, analysis and test reporting. INL is supported in this role by ECOtality North America (ECOtality), which has a competitively awarded contract that is managed by DOE's National Energy Technology Laboratory (NETL). The AVTA sections of the FY 2012 Annual Program Report jointly cover the testing work performed by INL and ECOtality. When appropriate, the AVTA partners with other governmental, public, and private sector organizations to provide maximum testing and economic value to DOE and the United States taxpayers, via various cost sharing agreements.

Introduction

DOE's AVTA and the USPS have a long history of cooperative vehicle research and benchmarking. Previous activities included the data collection and reporting support given to the USPS demonstration of 500 Ford electric Long Life Vehicle (eLLV) conversions operated mostly in California, with some on the East Coast of the United States (see avt.inel.gov/vehicles.shtml#U and scroll down to the USPS section for 33 USPS reports and fact sheets). This activity occurred from approximately 1999 to 2003. It should be noted that LLVs are the standard mostly boxed shaped local delivery USPS vehicles seen throughout the United States that operates on an internal combustion engine.

More recently, the AVTA performed baseline performance testing on five eLLVs that were converted from standard LLVs to pure battery electric operations. The five conversion companies / consortiums performing the conversions were:

- Autoport/AC Propulsion/University of Delaware
- Bright Automotive
- EDAG, Inc. – USA
- Quantum Technologies
- ZAP.
- The same five eLLVs were then introduced into fleet delivery operations in the greater Washington, D.C. area.
- The AVTA installed instrumentation and data loggers to quantify both the vehicles' performance and operating duty cycles.

Approach

The AVTA installed instrumentation and data loggers to quantify both the vehicles' performance and operating duty cycles and it was agreed that the fleet delivery results would be presented in summary for all five vehicles.

Results

All five conversion eLLVs met the minimum requirements of the baseline performance testing. However, the fleet demonstration resulted in less than stellar delivery fleet mileage accumulations as various problems had been encountered with the vehicles. A total of only 3,965 miles per accumulated in the March to December 2011 time period (avt.inel.gov/pdf/fsev/usps/USPS_SummaryReportMar11-Dec11.pdf).

It should be noted that this was not intended to be a high mileage fleet and there was significant variability in several vehicles ability to accumulate test miles. Two manufacturers' vehicles accumulated approximately 1,300 and 1,600 miles respectively, while one manufacturer's vehicle was only able to operate for approximately 50 life time miles due to various vehicle problems. The Summary Fact sheet for the USPS eLLVs is available at: avt.inel.gov/pdf/fsev/usps/USPS_SummaryReportMar11-Dec11.pdf and it does provide some insight into the types of missions the eLLVs encountered.

The summary results are presented in several categories:

- All Trip Combined
- Stop & Go Trips (> 5 stops per mile)
- City Trips (<= 5 stops per mile and <37 mph average)
- Highway Trips (<=5 stops per mile and >=37 mpg average).

Overall (All Trips Combined), the eLLVs averaged about 70% charging efficiency, consuming 452 DC Wh per mi and 645 AC Wh per mile, with DC Wh per mile efficiency ranging from 396 to 486 DC Wh per mile (Figure 1).

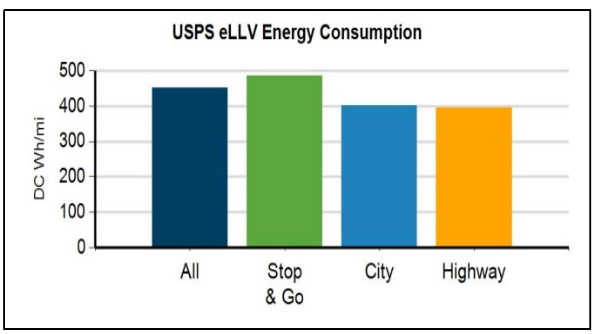


Figure 1. USPS eLLV DC Wh per mile efficiencies in various driving missions.

As would be expected, regenerative braking energy returned to the traction battery varied by drive missions (Figures 2 – 4).

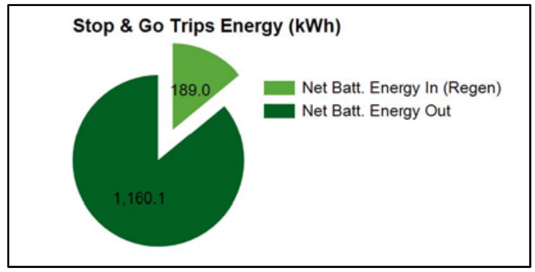


Figure 2.

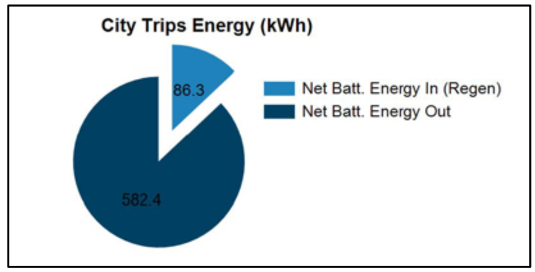


Figure 3.

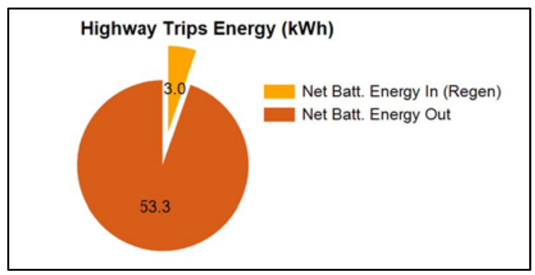


Figure 4.

Figures 2 to 4 show USPS eLLV regenerative energy and energy out of the traction battery pack by trip type.

Figure 5 documents the high state of charge (SOC) for the eLLVs at the start of daily operations.

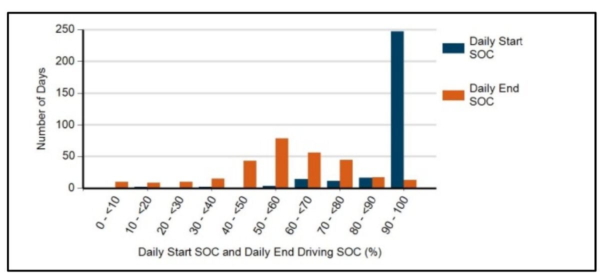


Figure 5. eLLV SOC at start of daily operations.

Figure 6 documents the mostly short daily operations of the USPS eLLVs, with the majority under 15 miles per day. This corresponds to past LLV operations experience (a documented source was not found, but the author is aware of this).

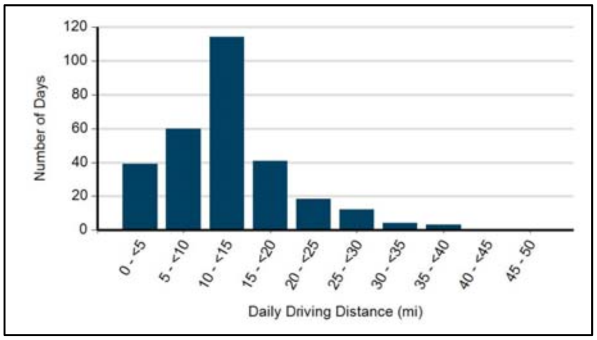


Figure 6. eLLV daily driving distances in miles.

Conclusions

The total miles the conversion eLLVs were able to obtain in fleet delivery operations was certainly less than the AVTA, conversion companies, and USPS had hoped to document.

Publications

1. Fact sheets that document baseline performance testing and monthly fleet demonstration results can be found at: avt.inel.gov/fsev.shtml.
2. The Summary Fact Sheet for the fleet demonstration of ELLs can be found at: avt.inel.gov/pdf/fsev/usps/USPS_SummaryReportMar11-Dec11.pdf.

III.N. Medium and Heavy Duty In-Use Fleet Field Evaluations

Principal Investigator: Kevin Walkowicz
National Renewable Energy Laboratory
Center for Transportation Technologies and Systems
15013 Denver West Parkway
Golden, CO 80401
Phone: (303) 275-4492; Email: Kevin.Walkowicz@nrel.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.N.1. Abstract

Objective

- Validate and document the performance and costs of advanced technologies in medium- and heavy-duty applications
- Provide third-party, unbiased report results for interested parties to further optimize and improve the systems
- Facilitate purchase decisions of fleet managers by providing needed information.

Approach

- Cooperate with commercial fleets to collect operational, performance, and cost data for advanced technologies;
- Characterize vehicle drive/duty cycles
- Analyze performance and cost data over a period of six months to one year or more
- Test and analyze in-use performance of advanced technologies in a laboratory setting to duplicate observed real-world conditions
- Produce fact sheets and reports on advanced heavy-duty vehicles in service
- Provide updates on new, advanced technology to DOE and other interested organizations.

Major Accomplishments

- Published final results of 36-month effort in Phoenix, Arizona, to evaluate Gen I UPS hybrid electric vehicle (HEV) delivery vans: nrel.gov/docs/fy12osti/53503.pdf
- Published final results of 18-month effort in Minneapolis, Minnesota, to evaluate Gen II UPS HEV delivery vans: nrel.gov/docs/fy12osti/55658.pdf
- Published final results of 13-month effort in Miami, Florida, to evaluate Coca Cola's Class 8 HEV beverage delivery tractors: nrel.gov/docs/fy12osti/53502.pdf
- Initiated 6-month evaluation in Ontario, California, to evaluate FedEx Class 7 box trucks: Effort started in March 2012 and will be completed in December 2012; results to date are included in this report
- Initiated effort to collect field data in New York and California on Verizon Class 3 & 4 light aerial HEV bucket trucks: effort is focused on drive cycle analysis and analysis of deployment options; effort started in July 2012 and will be completed in October 2012; results to date are included in this report.

Future Activities

- Complete evaluations on current fleet vehicles, and initiate new evaluations
- Coordinate activities with other DOE projects such as 21CT as well as other DOE laboratories
- Monitor and evaluate promising new technologies and work with additional fleets to test the next generation of advanced vehicles.

III.N.2. Technical Discussion

Introduction

Understanding how advanced technology vehicles perform in real-world service, and the associated costs, is important to enable full commercialization and acceptance in the market. DOE's Medium and Heavy Duty Advanced Vehicle Testing Activity (AVTA) works with fleets that operate these vehicles in medium- and heavy-duty applications. AVTA collects and analyzes operational, performance, and cost data and then uses the data to populate simulation models and vocational databases for additional research focused on removing barriers to commercialization. The data analyzed typically cover one year of service on the vehicles to capture any seasonal variations. Because of this, evaluation projects usually span more than one fiscal year. The Medium and Heavy Duty AVTA team also works on shorter-term projects designed to provide updates on current applications to DOE and other interested organizations.

Approach

In FY 2012, AVTA focused on fleet evaluations which were in various stages of completion. Evaluations discussed in this document include: 1) Eleven Class 6 HEV delivery vans operating in a UPS Minneapolis fleet, 2) Five Class 8 HEV beverage delivery tractors operating in Coca Cola's Miami fleet, 3) Ten Class 7 HEV 'box trucks' operating in FedEx's Ontario, CA fleet and 4) Assessing potential Class 4-6 aerial bucket trucks with the Verizon Fleet in New York and CA.

Preliminary efforts to evaluate class 5 EV food delivery trucks operating in Frito Lay's fleet were initiated in FY 2012, but data collection efforts have not yet started so this project is not reported here.

An effort to evaluate 36 months of operation of HEV UPS delivery trucks in Phoenix was completed and published in FY 2012, but is not discussed here. Final results can be found at nrel.gov/docs/fy12osti/53503.pdf.

1. UPS Minneapolis Generation II 18-Month HEV Study

This report discusses an 18-month in-use evaluation of 11 model year (MY) 2010 Freightliner P100H hybrid step delivery vans that were placed in service at UPS's facility in Minneapolis, Minnesota during the first half of 2010. The new hybrids featured more advanced control algorithms and an integrated "engine off at idle" feature. These hybrid vehicles were evaluated against 11 MY 2010 Freightliner P100D conventional step delivery vans that were placed in service at the same facility a couple months after the hybrids. The conventional vans were chosen using UPS's database and comparing the average miles per day of the 11 hybrids to that of conventional vans of the same size and cargo capability. Even so, the route profiles were very different, requiring a route assignment switch between the groups.

UPS has custom delivery vans built to the company's specifications. The P100 vehicles in this study were manufactured by Freightliner for UPS. Table 1 provides brief descriptions of the vehicle systems.

Table 1. Vehicle Descriptions

Van Specification	Hybrid Electric Vans	Conventional Vans
Van manufacturer	Freightliner Corp.	Freightliner Corp.
Van model	P100H step van	P100D step van
Van model year	2010	2010
Engine manufacturer and model	Cummins ISB 200 HP MY 2009	Cummins ISB 200 HP MY 2009
Emissions equipment	DPF	DPF
Retarder/regenerative braking	Regenerative braking	None
Air conditioning type	None	None
Gross vehicle weight rating	23,000 lbs	23,000 lbs

Van Use

Figure 1 shows the average monthly miles driven per van for each van group with ±95% confidence interval lines. In June 2011, a route switch was initiated to balance the evaluation and provide data for both vehicle groups on both route types. Vehicles from each group were assigned routes previously assigned to the other group; the drivers kept their original route assignments but with a new vehicle. The area in orange denotes when the route switch took place between the groups, causing the mileage change from June into August 2011. Note that not only did the average miles per van swap, but the width of the 95% confidence interval lines swapped as well. The original diesel group routes had a wide range of daily miles driven while the hybrids were on routes with more tightly grouped daily miles.

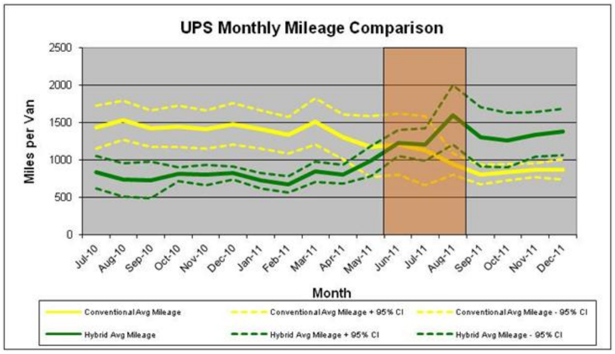


Figure 1. Hybrid vs. Conventional Mileage Comparison

In-Use Duty Cycle

Isaac Instruments DRU900/908 data logging devices with GPS antennas and J1939 controller area network bus (CANBUS) connections were deployed to the UPS fleet on two occasions. In total, 338 days of hybrid operation and 252 days of conventional operation on 8 vans from each group were documented. Comparing the routes driven by the two groups is difficult because of the disparity in the average daily miles driven. Initially, the conventional vans averaged 64 miles per day while the hybrids averaged only 43 miles per day. Figure 2 shows the average distance (as a percentage) that the vans with GPS loggers drove at different vehicle speeds.

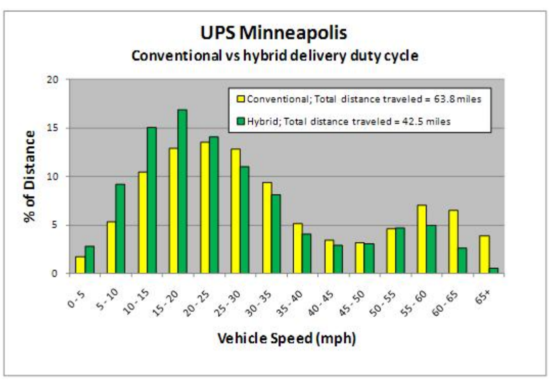


Figure 2. Percentage of Distance Travelled at Speeds.

The hybrids drove a greater percentage of their distance at slower speeds than the conventional vans; the conventional vans drove more of their miles operating at higher speeds. The greater percentage of miles driven by the hybrids at slower speeds is an indication of a more urban duty cycle. The lower percentage of miles driven at highway speeds is an indication of routes closer to the depot.

These statistics indicate that the hybrid vans were initially operating on very different route types (urban vs. rural) than the conventional vans. Because of these major differences, the study groups switched route assignments in June/July 2011. As of August 2011 the hybrid vans had assumed the drive characteristics of the conventional group and the conventional vans had assumed the drive characteristics of the hybrid group. The hybrid fuel economy advantage discussed below will be compared while the groups were on the same routes rather than during the same time periods.

In-Use Fuel Economy Analysis

Fuel economy was analyzed for each route over similar calendar year time periods (August 1 through December 31 of both 2011 and 2012). Figure 3 compares the route assignment time periods.

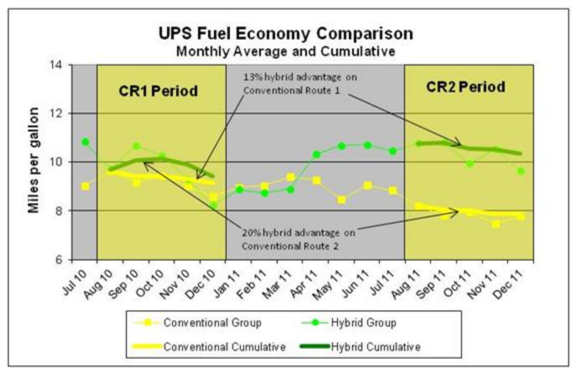


Figure 3. Route Based MPG Comparison.

Both study groups had lower mpg on Conventional Route 2 than on Conventional Route 1: 14% lower for the conventional vans and 9% lower for the hybrid vans, which confirms that the conventional group was on a less demanding duty cycle while the hybrids were on a more demanding one. Table 2 shows the group fuel economy comparison for the route switch. Also of note is that the hybrid advantage was 13% on the less kinetically intense, more highway-based route assignments (Conventional Route 1), matching well with the laboratory results on the Heavy Heavy-Duty Diesel Truck (HHDDT) cycle, while they achieved a 20% hybrid advantage on the more kinetically intense Conventional Route 2 assignments.

Table 2. Fuel Economy Comparison

	Conventional Route 1	Conventional Route 2	Effect of Higher KI* Route Assignment
Conventional	Aug thru Dec 2010	Aug thru Dec 2011	
Mileage	75,404	37,901	-50%
Fuel	8,233	4,822	-41%
Group MPG	9.2	7.9	-14%
MPG vehicle months	51	44	
Hybrid Group	Aug thru Dec 2011	Aug thru Dec 2010	
Mileage	62,991	32,149	-49%
Fuel	6,086	3,417	-44%
Group MPG	10.4	9.4	-9%
MPG vehicle months	46	39	
Hybrid Advantage	**13%**	**20%**	
t-test P value (cumulative mpg of individual vans in the group)	0.0015	0.1468	

In-Use Maintenance Cost Analysis

This cost category includes the costs for parts and for labor at an artificial rate of $50 per hour; it does not include warranty costs. Table 3 shows total and propulsion-related maintenance costs for the two study groups.

Table 3. Maintenance Cost

Study Group	Miles	Parts Cost	Labor Hours	Maintenance Cost	Cost per Mile ($/mile)	Cost per Day ($/day)
Hybrid total	198,220	$12,703	613	$43,367	$0.219	$10.90
Hybrid propulsion-related	198,220	$2,779	237	$14,651	$0.074	$3.68
Conventional total	242,957	$17,934	458	$40,835	$0.168	$9.80
Conventional propulsion-related	242,957	$2,336	156	$10,124	$0.042	$2.43

In-Use Reliability

UPS records instances in which a vehicle is not available to load in the morning as scheduled. Figure 4 shows the monthly and cumulative uptime for each group as a percentage of the total available delivery days.

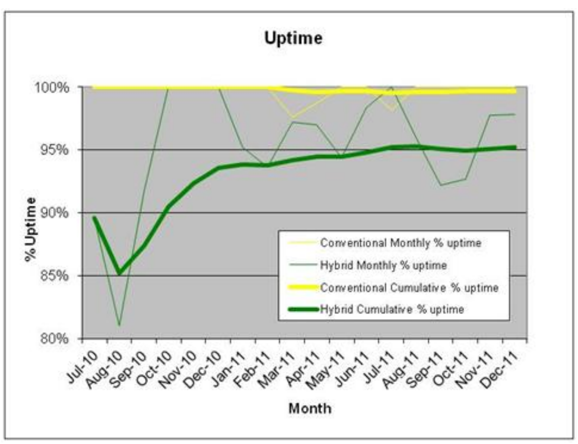


Figure 4. Monthly and Cumulative Uptime

Laboratory Fuel Economy and Emissions Testing

Two UPS delivery vehicles were tested on the chassis dynamometer at NREL's Renewable Fuels and Lubricants (ReFUEL) Research Laboratory.

All fuel economy and emissions results are averaged over four test runs of each cycle. Fuel economy results for the vans are shown in Table 4. The hybrid vans showed a 13%–36% improvement in fuel economy over the conventional vans on the tested duty cycle.

Table 4. Fuel Economy Comparison

Fuel Economy	NYC Comp	HTUF4	HHDDT
Conventional P100D (mpg)	6.8	7.5	9.6
Hybrid P100H (mpg)	8.8	10.1	10.8
Hybrid Advantage (%)	**29%**	**36%**	**13%**
t-test P value	0.0001	0.0000	0.0002

Ton-mi./gal fuel economy results for the vans are shown in Table 5. The hybrid vans showed a 21%–45% improvement in fuel economy over the conventional vans on the tested duty cycles.

Table 5. Freight Efficiency Comparison

Ton Fuel Economy	NYC Comp	HTUF4	HHDDT
Conventional P100D (ton-mi./gal)	51.1	56.2	72.0
Hybrid P100H (ton-mi./gal)	70.9	81.6	87.2
Hybrid Advantage (%)	**39%**	**45%**	**21%**
t-test P value	0.0000	0.0000	0.0001

Emissions results for oxides of nitrogen (NOx) are shown in Table 6. NOx emissions increased with the hybrid on all cycles, and the results were statistically significant.

Table 6. Emissions Comparison

NOx Emissions	NYC Comp	HTUF4	HHDDT
Conventional P100D (g/mile)	6.8	5.2	3.2
Hybrid P100H (g/mile)	8.2	6.6	4.8
Hybrid Increase (%)	**21%**	**28%**	**49%**
t-test P value	0.0001	0.0001	0.0000

Figure 5 shows a comparison of laboratory results to the corrected in-use vehicle days and vehicle averages. The vehicle days show the wide daily variation in fuel economy while the vehicle averages generally fall in line with the laboratory testing results—higher-kinetic intensity (KI) drive cycles result in lower fuel economy. In total, 338 days of hybrid van operation and 252 days of conventional van operation on 8 vans from each group were documented and are displayed in this figure.

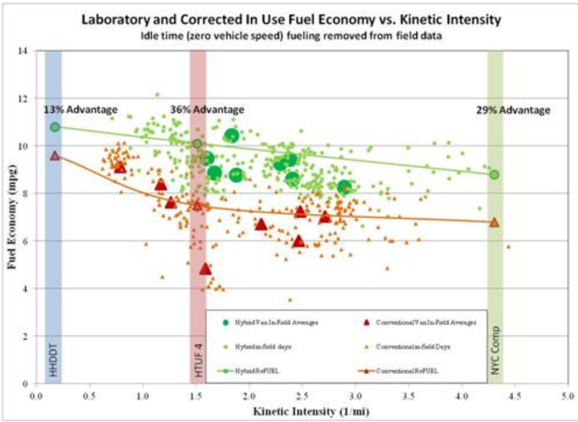


Figure 5. Laboratory vs. In-Use Fuel Economy

Conclusions

- Cumulative miles per van for the hybrids were 33% less than the conventional group during the 18-month study. The hybrid group accumulated miles at a slower rate than the conventional group during the 13 months of the original route assignments, but at a faster rate than the conventional group for the 5 months after the route switch.
- Fuel economy before and after the route switch during equal five-month periods from different years on a route assignment was considered.
- "Conventional," lower-KI route analysis: Fuel economy of the hybrid group on the original conventional route assignments over 5 months was 10.4 mpg, or 13% greater than the 9.2 mpg of the conventional group on those routes a year earlier.
- "Hybrid," higher-KI route analysis: Fuel economy of the hybrid group on the original hybrid route assignments over five months was 9.4 mpg, or 20% greater than the 7.9 mpg of the conventional group on those routes a year later.
- The difference in hybrid advantage in fuel economy was as expected. The hybrids demonstrated a greater advantage on more urban, low speed, high stops-per-mile route assignments and lower advantage on route assignments with a longer highway leg and less dense delivery zones.
- Total maintenance cost per mile was 30% higher for the hybrids, but was not statistically significant (P value = 0.1128). However, this was only 11% more when considered on a cost-per-delivery-day basis.
- Propulsion-related maintenance cost per mile was 77% higher for the hybrids (P value = 0.0278). However, this was only 52% more when considered on a cost-per-delivery-day basis.
- Fuel costs per mile (assuming $3.58/gal) for the hybrids were 11% less than those for the conventional vans (P value = 0.0034).
- Total operating costs per mile (assuming $3.58/gal) for the hybrids were not found to be statistically significant (P value = 0.9677).
- The hybrid group had a cumulative uptime of 92.5% compared to the conventional group uptime of 99.7%.
- Laboratory testing demonstrated a 13%–36% increase in fuel economy for the hybrid.
- Laboratory testing demonstrated a 21%–45% increase in ton-mi/gal for the hybrid.
- Laboratory testing demonstrated an increase in NOx emissions of 21%–49% for the hybrid.

2. Coca-Cola Miami 13-Month Study

This project represents a collaborative opportunity for NREL and Coca-Cola Refreshments (CCR) to evaluate the field performance, fuel economy, and emissions performance of two Class 8 propulsion technologies. This report discusses a 13-month in-use evaluation of 5 MY 2010 Kenworth T370 tractors with Eaton hybrid electric systems that were placed in service at CCR's facility in Miami, Florida, and 5 MY 2009 Freightliner M2106 conventional tractors at the same Miami facility. Both of these Class 8 technologies are currently being utilized by CCR in a similar manner in commercial service. Chosen for its pairing of hybrid and conventional tractors in one location and unbiased, random delivery route assignments, the Miami, Florida CCR fleet was the source of vehicles and data for this evaluation. Additional tractor details are given in Table 7.

Table 7. Vehicle Descriptions

Vehicle Information	HEV Tractor	Conventional Tractor
Chassis manufacturer/model	Kenworth T370	Freightliner M2106
Chassis model year	2010	2009
Engine manufacturer/model	PACCAR PX-6 280	Cummins ISC-285
Engine displacement (L)	6.7	8.3
EPA emissions certification (2007) NO_x (family emissions limit) CO (family emissions limit)	 1.95 g/bhp-hr 19.4 g/bhp-hr	 1.25 g/bhp-hr 19.4 g/bhp-hr
CARB emissions certification	2008 (Clean Idle)	2008 (Clean Idle)
Engine ratings Max. horsepower Max. torque	 280 HP @ 2,300 RPM 660 lb-ft @ 1,600 RPM	 285 HP @ 2,000 RPM 800 lb-ft @ 1,300 RPM
Fuel capacity	56 gallons	80 gallons
Transmission manufacturer/model	Eaton Fuller UltraShift Automated manual	Eaton Fuller T-14607 Manual 7-speed
Rear axle gear ratio	5.38:1	3.58:1

Truck Use

The hybrid group accumulated 27% fewer miles than the diesel group during the study, even though the hybrids were driving a comparable number of miles per day. The discrepancy primarily stems from down time experienced by two hybrid trucks during the first six months of the study. Figure 6 shows group average daily miles, average days per month, and cumulative group miles.

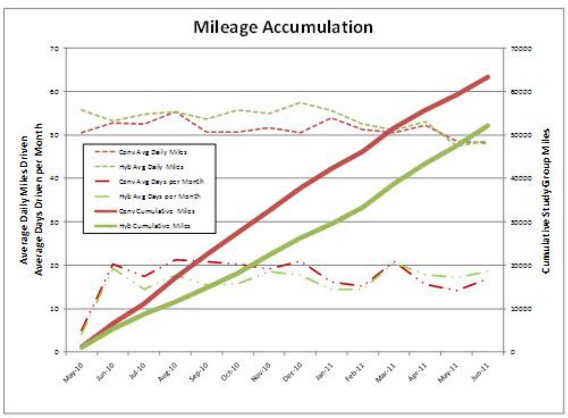


Figure 6. Vehicle Mileage Accumulation

Truck In-Use Duty Cycle

NREL implemented two data logging periods for this study, one summer and one winter, for a total of four weeks of data to analyze the duty cycle of the fleet.

The WVU City duty cycle represents "city" or urban driving commonly performed by medium- and heavy-duty commercial trucks. The CILCC duty cycle is a composite duty cycle developed to represent typical delivery truck driving characteristics. The California Air Resources Board (CARB) HHDDT duty cycle is a composite duty cycle developed to represent medium- and heavy-duty commercial vehicles. Figure 7 illustrates how the HHDDT, CILCC, and WVU City cycles compare to the observed daily in-use fleet data. The selected cycles bracket the range of collected fleet data well on these and other metrics.

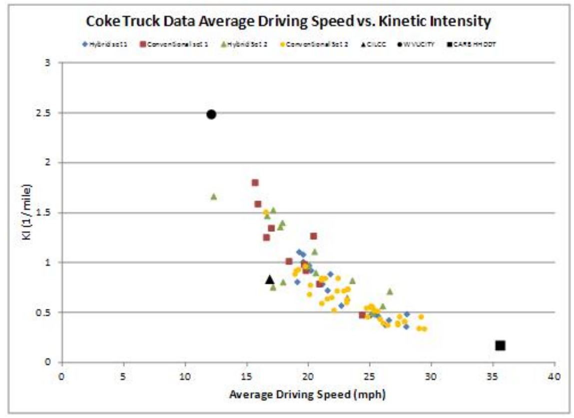


Figure 7. Driving Characterization

In-Use Fuel Economy Results

Table 8 shows mileage and fuel use according to ECM trip records for the 13-month period from May 22, 2010, through June 30, 2011, along with the resulting fuel economy for each group. Overall, for the 13-month study period, the hybrid group fuel economy was 5.63 mpg, 13.7% better than the diesel group's 4.95 mpg, which is directly between the CILCC and HHDDT cycle laboratory results.

Table 8. Fuel Economy Comparison

Fuel Economy Comparison (May 2010 - June 2011)				
Tractor	Mileage Total	Fuel Used	$/mile	MPG
Conventional total	64,958	13,123	$0.68	4.95
Conventional average	12,992	2,625	$0.69	4.93
Hybrid total	47,444	8,430	$0.60	5.63
Hybrid average	9,489	1,686	$0.58	5.79
Hybrid advantage			12.0%	13.7%

Maintenance Cost Analysis

This cost category includes the costs for parts and for labor at an artificial rate of $50 per hour; it does not include warranty costs. The hybrid group's $0.14/mile maintenance costs were 51% less than the diesel group's $0.29/mile. Table 9 shows the cumulative operational costs for both groups. Based on the in-use fuel economy observed, hybrid fuel costs per mile were 12% less than for the diesels. As such, hybrid total cost of operation per mile was 24% less than the diesels.

Table 9. Maintenance Cost Comparison

	Group Miles	Maint. Materials Cost	Labor Hours	Total Maint. Costs*	Maint. $/mile	Fuel Gallons	Fuel $/Mile*	Total $/mile
Conventional	63,305	$6,926.03	231.1	$18,479.12	$0.29	13,123.1	$0.68	$0.97
Hybrid	52,100	$1,558.76	118.5	$7,483.54	$0.14	8,430.4	$0.60	$0.74
Hybrid % difference	-18%	-77%	-49%	-60%	-51%	-36%	-12%	-24%

Laboratory Fuel Economy and Emissions Results

The HEV demonstrated improved fuel economy on the two duty cycles with higher KI and lower average driving speed, achieving a 30.3% increase in fuel economy between the two tractors on the WVU City cycle, as seen in Table 10, and a 22% increase in fuel economy on the CILCC cycle. However, on the CARB HHDDT duty cycle, which has a higher average driving speed and a lower KI, the two tractors were statistically indistinguishable.

Table 10. Fuel Economy Comparison

Drive Cycle	HEV Fuel Economy (mpg)	Conventional Diesel Fuel Economy (mpg)	HEV Percent Increase (%)	P Value
WVU City	5.79	4.44	30.3%	0.0003
CILCC	7.55	6.18	22.2%	0.0001
CARB HHDDT	6.17	6.18	-0.13%*	0.69

The hybrid tractor demonstrated improved ton-mi/gal fuel economy (combined vehicle test weight, not solely cargo) on the two duty cycles with higher KI and lower average driving speed, achieving a 32.1% increase in ton fuel economy between the two tractors on the WVU City cycle, as shown in Table 11.

Table 11. Freight Efficiency Comparison

Drive Cycle	HEV Fuel Economy (ton-mi/gal)	Conventional Diesel Fuel Economy (ton-mi/gal)	HEV Percent Increase (%)	P Value
WVU City	99.24	75.13	32.1%	0.0003
CILCC	129.54	104.54	23.9%	0.0001
CARB HHDDT	105.78	104.49	1.23%	0.31

The emissions results were as expected for carbon monoxide (CO), total hydrocarbons (THC), and carbon dioxide (CO2). The HEV produced fewer of these emissions on each of the three selected duty cycles, as detailed in Table 12. However, NOx increased for the HEV over the conventional tractor for each of the tested duty cycles. For the HHDDT cycle, the HEV produced more than double the NOx emissions when compared to the conventional tractor. This is shown in Table 12 as a percent improvement in emissions for the hybrid over the conventional tractor (a negative number indicates a decrease in emissions and vice versa).

Table 12. Emissions Comparison

	HEV % Reduction							
Drive Cycle	NO_x	P Value	CO	P Value	THC	P Value	CO_2	P Value
WVU City	29.1%	1.7E-5	-3.6%*	0.75	-222.7%*	0.28	-23.3%	8.5E-6
CILCC	5.1%	8.8E-3	-62.3%	1.1E-6	-147.5%	1.4E-3	-18.1%	1.9E-9
CARB HHDDT	101.3%	8.5E-9	-31.3%*	7.7E-2	-141.9%	2.1E-4	0.2%*	0.85

Figure 8 compares the in-field daily fuel economy results collected from the two data logging events mentioned previously and in-field vehicle averages with the measured chassis dynamometer (ReFUEL) fuel economy results. Of note is how the field KI vehicle averages were predominantly between the HHDDT and CILCC KI numbers or just barely higher than the CILCC number. This helps explain why the field fuel economy results were less than those seen on the CILCC or the more intense WVU City laboratory tests. The in-use hybrid advantage of 13.7% falls between the laboratory results for HHDDT and CILCC. A hybrid advantage in the 25% range could be expected if routes are identified at other locations that are composed primarily of the high KI (> 1.5) days seen as the upper end of the in-use experience in Miami (the handful of in-field day points in the figure below around and above 1.5 KI).

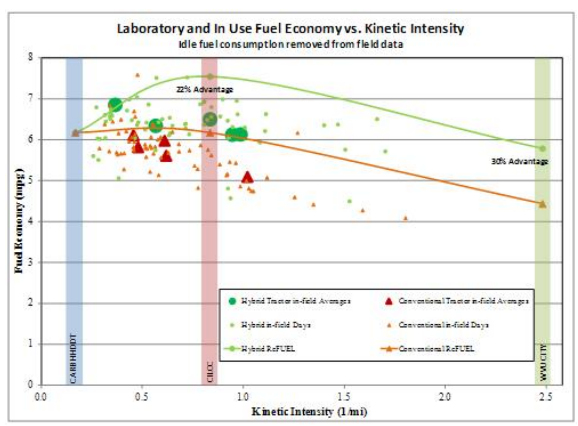


Figure 8. Laboratory vs. In-Use Fuel Economy.

Conclusions

- Route and drive cycle analysis showed that both study groups drove similar duty cycles with similar KI (0.95 vs. 0.69), average speed (20.6 vs. 24.3 mph), and stops per mile (1.9 vs. 1.5). Because of the similar usage of the vehicles, the groups were judged to provide a good comparison.
- During the study, the hybrid group accumulated 27% fewer miles than the diesel group even though the hybrids were driven a comparable number of miles per operational day. The discrepancy primarily stems from non-hybrid-related down-time experienced by two hybrid trucks during the first six months of the study.
- Laboratory dynamometer testing demonstrated a 0%–30% hybrid fuel economy improvement, depending on duty cycle, and up to a 32.1% improvement in ton-mi/gal.
- The 13-month field study demonstrated that the hybrid group had a 13.7% fuel economy improvement over the diesel group.
- Laboratory fuel economy and field fuel economy studies showed similar trends along the range of KI, average speed, and stops per mile. This means the vehicles could achieve higher in-field fuel economy results if they were used in a more urban location with drive cycle statistics closer to the WVU City cycle.
- Hybrid fuel costs per mile were 12% less than for the diesels.
- Hybrid vehicle total cost of operation per mile was 24% less than the cost of operation for the diesel group ($0.74 vs. $0.97/mile), which means the customer is realizing real savings with the hybrids.
- CCR is actively evaluating the fleet-wide hybrid and conventional performance, and all the specification options that affect that performance including engine size, transmission type, and rear axle gear ratios.

3. FedEx Ontario Six-Month Fleet Study

The focus of this study is to determine the fuel economy and emissions performance of Eaton hybrid-equipped Class 7 delivery trucks compared to conventional diesel delivery trucks. In addition to quantifying the fuel economy improvements, route characterization will identify the best route types to select for both the hybrid and conventional vehicles to maximize fuel savings. This study focuses on driving routes and does not investigate driving style or driver performance.

This study will involve a total of 20 FedEx vehicles by the end of testing. One of the tested vehicles is shown in Figure 9. Phase 1 consisted of a 2-week route identification study that included 11 conventional vehicles and 1 hybrid vehicle in the Ontario, California fleet that were instrumented with engine controller and GPS recorders. Phase 1 has been completed. For Phase 2, an additional five hybrid vehicles were brought in from another FedEx depot, making a total of six hybrid vehicles in the Ontario fleet. See Table 13 for vehicle information. Fuel consumption, route information, tire and brake wear, and vehicle maintenance are now being monitored for a period of 6 months, scheduled to end in December 2012. Two vehicles in the fleet, one hybrid and one conventional, will continue to log continuous ECM and GPS data during Phase 2. Phase 3 of testing will involve vehicle chassis testing of one hybrid and one conventional vehicle at NREL's ReFUEL laboratory.

Figure 9. FedEx Box Truck. NREL PIX # 22259.

Table 13. Vehicle Descriptions

Vehicle Information	HEV Truck	Conventional Truck
Chassis Manufacturer/Model	Freightliner M2-106	Freightliner M2-106
Chassis Model Year	2010	2010 or 2011
Weight (lbs)	32,000 GVWR – Class 7	32,000 GVWR – Class 7
Payload (lbs)	13,000	13,000
Engine Manufacturer/Model	Cummins ISB-200	Cummins ISB-220
Engine Displacement (L)	6.7	6.7
EPA Emissions Certification	2010	2010

Vehicle Usage and Chassis Testing Plan

Both a hybrid and a conventional diesel vehicle will be tested over three drive cycles at NREL on the heavy-duty chassis dynamometer. Fuel consumption, gaseous emissions, and particulate emissions data will be collected. Testing is scheduled to occur in October 2012. Three chassis dynamometer drive cycles were selected following the analysis of the Ontario FedEx routes from Phase 1 of the study. The criterion of drive cycle selection included how close the cycle simulated actual fleet routes and how the cycles might reflect fuel consumption for conventional and hybrid vehicles. The cycles chosen are CARB HHDDT (minimum hybrid advantage), NYC Comp (maximum hybrid advantage), and HTUF 6 (median hybrid advantage).

Figure 10 shows the resulting in-motion fuel economy (not including idling) plotted against the KI of the route driven that day. It is apparent that fuel economy goes up as KI decreases. Also note that the fuel economy for the one hybrid vehicle is generally higher than the conventional vehicles even at lower KIs. Generally speaking, hybrids will show greater fuel economy benefit over conventional vehicles as KI increases, so as we test both vehicles on the chassis dynamometer we would expect to see a large improvement in fuel economy for the hybrid vehicles.

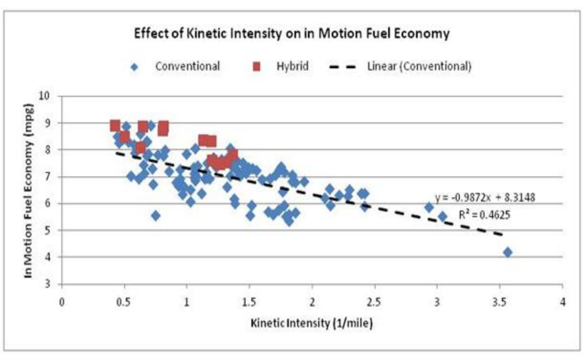


Figure 10. Driving Behavior vs. Fuel Economy.

Conclusions

- Fleet driving route data logging was successfully completed. The routes were analyzed and compared against drive cycles to properly select drive cycles that will be used in the chassis dynamometer testing in October 2012.
- The six-month evaluation involving six hybrid and six conventional vehicles is currently underway and will be completed by the end of 2012. Fuel consumption, route information, tire and brake wear, and vehicle maintenance are being recorded.

4. Verizon Class 3-4 Bucket Truck & Service Van Fleet Study

Verizon fleets in Long Island, New York and Los Angeles, California were instrumented with data loggers for two weeks as part of an effort to analyze hybrid vehicle options. To fully understand vehicle and PTO options, approximately ten service vans and ten light aerial trucks were instrumented in each location to capture GPS, OBDII, and boom operation sensor information for duty cycle analysis.

Table 14 lists the types of vehicles being studied.

Table 14. Project Instrumentation List

Make/Model	Configuration	Long Island	Los Angeles
2005 CHVRL C4500	Light aerial truck		2
2006 Ford F350	Light aerial truck	2	1
2007 CHVRL G2500	Service van		7
2008 CHVRL G2500	Service van		1
2008 Ford F350	Light aerial truck	6	6
2009 CHVRL G2500	Service van		2
2011 CHVRL G2500	Service van	9	
2012 Ford F350	Light aerial truck	2	

While data collection is still underway in California, initial basic analysis of the New York data shows that the vehicles are not being driven a standard amount every day. Instead, daily miles driven vary widely without correlation to other metrics. Further analysis is in process and will continue after final data from California is received. Figure 11 shows daily miles driven by the bucket trucks and vans as compared to the kinetic intensity of the drive cycle for the day.

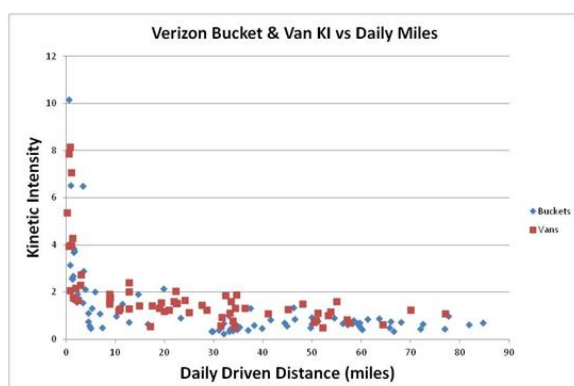


Figure 11. Driving Characteristics.

FY 2012 Overall Observations and Conclusions

- Reliability: Medium- and heavy-duty hybrid vehicles perform vocational functions as necessary, but are slightly less available due to early model changes and HEV-related updates throughout the study periods (~95%–96% uptime for HEVs, 99% uptime for conventional is typical). Uptime percentage has improved as a function of time.
- Operational Cost: High variability in sampling resulted in some studies not having statistically significant total overall cost savings (not significant at the 95% confidence level) and one study showing a 24% reduction in overall operating cost.
- In-Use Fuel Economy: Observed group-to-group comparisons of vehicles operating in similar operation showed in-service fuel economy improved 14%-23% in the field for the HEVs. Significant differences in mpg improvements were observed due to assigned routes/duty cycles.
- Laboratory Fuel Economy: Testing in the laboratory, based on usage patterns observed in the field, resulted in HEV improvements of 0%–36% when calculating mpg, and up to 45% improvement in ton-mi/gal measurements. This range of possible improvements in the laboratory versus the in-field averages suggests the importance of placing the vehicles on the correct routes to maximize return on investment for fleets.

III.N.3. Products

The following publications were a result of the work completed in FY 2012 under this project:

1. Lammert, M.; Walkowicz, K. (2012). Eighteen-Month Final Evaluation of UPS Second Generation Diesel Hybrid-Electric Delivery Vans. 47 pp.; NREL Report No. TP-5400-55658
2. Walkowicz, K.; Lammert, M.; Curran, P. (2012). Coca-Cola Refreshments Class 8 Diesel Electric Hybrid Tractor Evaluation: 13-Month Final Report. 48 pp.; NREL Report No. TP-5400-53502
3. Lammert, M.; Walkowicz, K. (2012). Thirty-Six Month Evaluation of UPS Diesel Hybrid-Electric Delivery Vans. 32 pp.; NREL Report No. TP-5400-53503
4. Walkowicz, K. (2012). In-Use Performance Results of Medium Duty Electric Vehicles (Presentation). NREL (National Renewable Energy Laboratory). 18 pp.; NREL Report No. PR-5400-55986
5. Lammert, M; Walkowicz, K; Duran, A; Sindler, P (2012). Measured Laboratory and In-Use Fuel Economy Observed over Targeted Drive Cycles for Comparable Hybrid and Conventional Package Delivery Vehicles. SAE 2012 Commercial Vehicle Engineering Congress; 2012-01-2049

III.O. Fleet DNA – Common Drive-Cycle Database

Principal Investigator: Kevin Walkowicz
National Renewable Energy Laboratory
Center for Transportation Technologies and Systems
15013 Denver West Parkway
Golden, CO 80401
Phone: (303) 275-4492; Email: Kevin.Walkowicz@nrel.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.O.1. Abstract

Objectives

This effort, which is funded by the U.S. Department of Energy's Vehicle Technologies Program within its Vehicle & Systems Simulation and Testing Activities, will:

- Collect, filter, 'cleanse,' and locate existing medium-duty (MD) and heavy-duty (HD) data from the National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), Federal Transit Administration, California Air Resources Board (CARB), and others for inclusion in a central database
- Create dedicated server space for each vocation
- Modify existing light-duty web interface with the Transportation Secure Data Center to create MD/HD portal
- Review and assess ORNL and NREL drive-cycle tools and create initial functionality for web interface
- Provide summary statistics for each vocation data set.

Approach

The National Renewable Energy Laboratory, in partnership with Oak Ridge National Laboratory, will design the Fleet DNA project as a vocationally grouped repository of medium- and heavy-duty commercial fleet transportation data to enhance user understanding of the operational characteristics of medium- and heavy-duty vehicles. The primary goal is to accelerate the evolution of advanced vehicle development while supporting the strategic deployment of market-ready technologies that reduce costs, fuel consumption, and emissions. The specific approach for this project includes the following elements:

- Design a portal that offers access to easy-to-interpret data summaries and graphical data outputs based on real-world operational information
- Perform basic data analysis to provide insight into vehicle/fleet operation and allow for comparison among multiple fleets and geographic locations
- Ensure sufficient data quality for comparison; the summaries generated via the Fleet DNA database will be built on thousands of data points of operation per vocation
- Focus initial efforts on the vehicles, fleets, and vocations that consume the most fuel in the United States
- Process results to obscure proprietary/private information; post results on an NREL website for public review.

Major Accomplishments

- All hardware and software necessary to input, filter, store, and access data have been assembled and validated
- Five terabytes of vehicle data—including 80,208,155 individual data points representing 288 vehicles from eight data providers—have been collected, analyzed, and stored
- Project partners—including the National Truck Equipment Association, CARB, ORNL, and the South Coast Air Quality Management District—have been engaged and will be contributing additional data in FY 2013
- A portal that provides access to summarized information has been completed and will be available to the public by the end of Calendar Year 2012
- Researchers explored interactive avenues for custom on-demand data visualization and statistical analysis.

Future Activities

- Continue with web integration and deployment
  - Provide interactive dataset and result examples
  - Generate on-demand data reports
  - Automate drive-cycle generation to provide on-demand generation from selected datasets
- Collect additional vehicle data
  - Gather data from additional fleets to enhance the depth of existing data
  - Recruit additional research partners to enrich the Fleet DNA database with additional datasets(UMTRI, WVU, CALSTART, etc.)
- Continue the development of the National Elevation Dataset's elevation repair and prediction algorithms
- Explore integration of tools like FASTSim and Autonomie for vehicle modeling using data sets
- Expand on standard global positioning system (GPS) signal collection with additional information sources such as J1939 CAN bus signals
- Add fuel consumption, engine, and powertrain data to the database
- Optimize processing routines and data organization to improve calculation speed and reduce computational overhead

III.O.2. Technical Discussion

Approach

The Fleet DNA database features transportation data captured during past and ongoing fleet evaluation and research projects completed under the Advanced Vehicle Testing Activity program. In addition to leveraging existing DOE-funded data-capture efforts to provide source data, Fleet DNA has also received contributions to the project in the form of additional source data provided through a network of cooperating partners. Building on existing relationships and through the establishment of new cooperative agreements, Fleet DNA has enlisted a wide range of partners from industry, government, and academia/research, as shown in Table 1.

Table 1. Fleet DNA Partners

Project Partner	Status
California Air Resources Board	Regulator
CALSTART	Industry/Research
Clean Cities National Clean Fleet Partnership	Government/Industry
National Truck Equipment Association	Industry
Oak Ridge National Laboratory	Government
South Coast Air Quality Management District	Regulator
Zonar Systems	Industry

As part of the Fleet DNA project summary outputs, a wide range of statistics for each vehicle vocation and/or vehicle type of interest will be compiled and made publically available. Additional detailed data and specialized analysis summaries will be accessible to partners who contribute data or provide additional support. Example data sets produced by Fleet DNA will contain information such as aggregated route distance, average speed, maximum acceleration, stops per mile, load and grade statistics, and many other drive cycle metrics along with comparisons to standard industry test cycles. Users will be able to produce customized datasets using the Drive-Cycle Rapid Investigation, Visualization, and Evaluation (DRIVE) tool—which will be integrated with Fleet DNA—and then use the data for vehicle testing and/or vehicle simulation and modeling.

Data Processing

The Fleet DNA database is operated through a combination of a postgreSQL database linked with QGIS visualization software and Python scripting language. In linking a structured database platform such as postgreSQL with QGIS, users of Fleet DNA can quickly perform geospatial evaluations of field data and visual route information with a simple database query. Data analysis and filtration are performed using the Python computer scripting language. Python was chosen as the primary means of calculation for its speed and ability to interlink between both the SQL database and QGIS, creating a network of interlinked software that provides easy data access and visualization. Additionally, all three software system used as part of the Fleet DNA project are free open-source software (FOSS) systems, which allows for large scale, low/no cost deployment, scaling, or replication.

The fundamental components recorded in all projects stored in Fleet DNA include a unique vehicle identifier, a latitude and longitude coordinate pair, a timestamp, and vehicle speed. These fundamental components are specific to a vehicle in time and space, and each vehicle is unique to an individual data provider. Fleet DNA utilizes this hierarchy to convert raw data sets to a standard format as the data move through the system. Standard processing routines handle all data uniformly, with the routine adapted to differences in file formats and sampling rates. The end result is a system that loads, filters, sequences, and produces extensive amounts of data regarding vehicle performance using multiple temporal scales.

The structure of the Fleet DNA process can be understood as performing three separate operations:

1. Load and normalize raw files from a mapped file directory into the database
2. Filter and sequence the normalized raw data
3. Generate and output results to the support application/data warehouse.

The Python program developed to manage the flow of data through a PostgreSQL/GIS database relies on the unique identifier for each data provider and each vehicle. The data provider identifier is an integer the program uses to call in the appropriate interpreter and locate the file storage area where the data provider's raw data files are stored. The vehicle identifier is used to organize, track, and move the data through each of the steps. Each vehicle maintains a reference to the data provider through the original vehicle ID assigned by the data provider.

As an initial step in the data-analysis process, each data provider is given a specific folder on the NREL data-storage server. The data provider uses this folder to submit its raw files to NREL through secure FTP transfer. The database monitors these folders, and identifies when new data have been added by a data provider. If new data are identified, then a Python-based data-loader script operates on each new dataset to load the new data into the database. Currently, this process is initiated manually as needed; however, data uploads to the database will be automated in the future once additional data quality checks and file continuity checks have been added to the data-loading process. The raw data housed in the data files are converted into a standard vehicle ID, latitude, longitude, timestamp, and speed column format using the interpreter program written to handle the data provider's file format.

Data Filtration

When employing a GPS data logger, as with any other data-acquisition system, a number of errors can creep into the raw data samples. For the GPS logging device, the primary concerns regarding data quality are sudden signal loss, data spikes, and zero speed drift observed when a vehicle is motionless. To account for these issues and to improve the quality of data used in NREL studies, a common GPS data-processing method was developed using a series of logic-based data filters. To date, the common data-processing approach consists of six distinct filters ordered in an iteratively optimized series. The general filtration process is outlined as follows:

1. Remove outlying high/low speed values
2. Fix speed drift when vehicle is stopped
3. Repair false data readings
4. Amend gaps in data
5. Remove outlying acceleration values
6. Perform additional smoothing to remove noise and prepare for testing/simulation.

Each filter in the process records and tracks the number of data points that are altered, and a total percentage of data that has been "cleaned" can be calculated. In ongoing testing and evaluation, on average less than 1% of the data sampled required one of these filtering steps, which is what one would expect assuming a Gaussian normal data distribution with a six-sigma usable range.

Results

At the time of this report, data have not yet been posted to the Fleet DNA website, but the following sections discuss the types of results and approach that will be included with each data set.

Drive Cycle Analysis and Statistics

The Fleet DNA project incorporates and expands on the existing statistical analysis capabilities found in NREL's DRIVE tool, with the ability to supply more than 200 unique drive-cycle metrics on the microtrip, trip, and day timescales. In addition to generating more than 200 metrics, users are able to produce informative graphics and visuals for data exploration, with the capability of downloading underlying public summary statistics for supplementary analysis. Figures 1 and 2 highlight visualizations generated using some of the data housed in Fleet DNA, with Figure 1 providing a cross-vocation statistical comparison and Figure 2 exploring vocation-specific metric distributions.

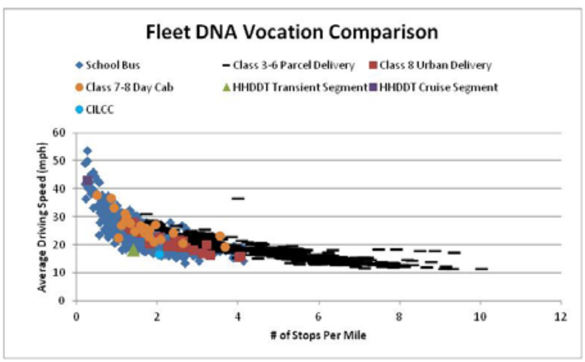


Figure 1. Sample Fleet DNA Vocational Comparison Output.

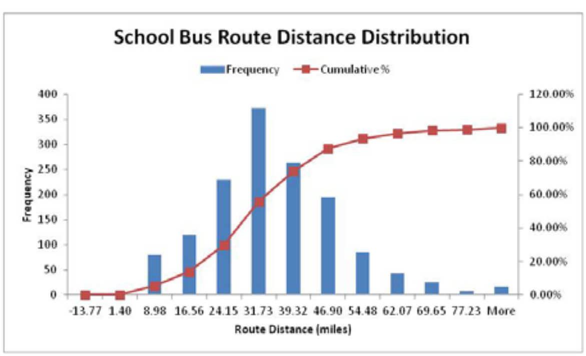


Figure 2. Sample Route Distance Characterization.

Route Visualization

In addition to providing a platform for drive-cycle metric visualization, exploration, and comparison, Fleet DNA also affords users the unique opportunity to visualize vehicle routes and operation. The ability to quickly determine typical vehicle route operation based on geospatial inspection increases analysis speed and improves results through the rejection of outliers. An example of the power of this capability can be found in Figure 3, which details the U.S. locations where Fleet DNA has currently captured data. With a cursory look at the map, one can quickly identify five states spread across the country—California, Arizona, Colorado, Florida, and Minnesota—as sources of data. If, after uploading data, the user expected data in only four of the five states shown on the map, the outlying data could quickly and easily be identified, quarantined, and examined in greater detail while being removed from the global dataset.

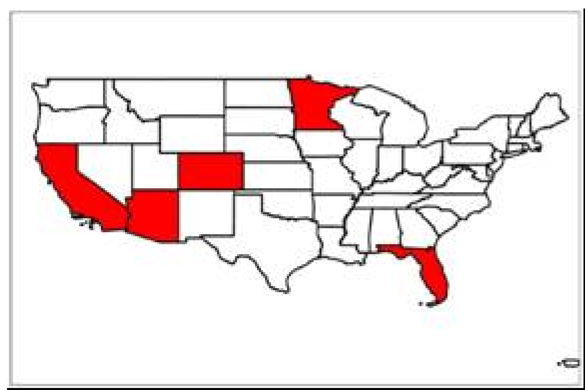


Figure 3. U.S. Data Collection Locations.

In addition to providing a quick synopsis of data collection as well as acting as a platform for data rejection, route visualization via Fleet DNA can also be used as a quality-control tool when applied to data filtration. As shown in Figures 4 and 5, we can see the dramatic effect that data filtration has on GPS data stored in the Fleet DNA database. If researchers were to simply examine speed-time traces in two-dimensional space, they may miss the additional information provided by adding geospatial orientation. It is obvious when comparing the two figures that one has data quality problems and the other does not.

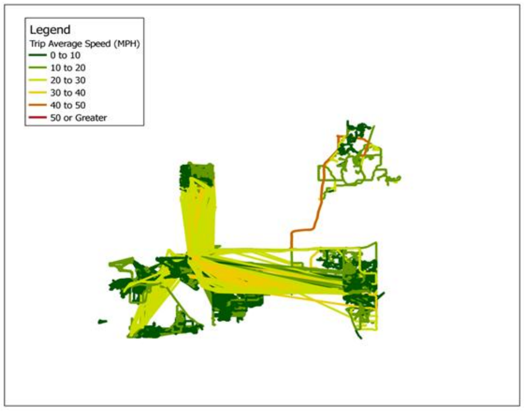


Figure 4. Trip Speed Visualization of Raw Data.

Figure 5. Trip Speed Visualization of Filtered Data.

Summary & Conclusions

As of the end of FY 2012, the primary analytical and technical challenges facing the Fleet DNA project have been addressed. These challenges—including development of the database structure, file input/output, process structure, and data visualization—are now undergoing continued refinement.

Additional work will be completed in FY 2013 to overcome the following issues:

1. Integrating and developing cross vocation databases that consist of mixed vehicle sizes and applications. This will require adapting the data visualization routines to work with mixed data sets and adjusting the data filtration and analysis routines for the variations between medium- and heavy-duty vehicles.
2. Technical challenges remain in the area of web deployment, particularly as it relates to user data upload and download.
3. Some technical barriers remain regarding the integration of the National Elevation Dataset into the Fleet DNA database as an independent data layer or schema. Given its substantial size (3 TB), questions remain regarding how to efficiently and quickly access this large data set for use with fleet-scale analysis. Efforts in FY 2013 will determine if it is possible to get on-demand results when querying data of this size.

III.O.3. Products

Publications

1. Walkowicz, K.; Duran, A. *Telecom Fleet Vehicles: Using Data-Focused Tools and Other Capabilities to Assess and Enable Lower Vehicle Energy Use*. NREL Report No. CP-5400-56299.
2. Duran, A.; Earleywine, M. *GPS Data Filtration Method for Drive Cycle Analysis Applications.* NREL Report No. CP-5400-53865.
3. Duran, A. *Vehicle Drive Cycles and Their Role in the Evaluation of Advanced Vehicle Technologies.* Online Presentation at SAE 2012 School Bus Powertrain Innovation Symposium. March 2012.
4. *Overview of the Fleet DNA Project.* NREL Fact Sheet. NREL Report No. FS-5400-52683.

Tools & Data

1. Fleet 1Drive-Cycle, Rapid Investigation, Visualization and Evaluation Tool (DRIVE), Copyrighted 2011. Tool created to analyze large sets of drive-cycle data.
2. Fleet DNA Database. Created to input, filter, and analyze large amounts of vocational vehicle-use data.

III.P. MD PHEV/EV Data Collection and Reporting

Principal Investigator: Kevin Walkowicz
National Renewable Energy Laboratory
Center for Transportation Technologies and Systems
15013 Denver West Parkway
Golden, CO 80401
Phone: (303) 275-44492; Email: Kevin.Walkowicz@nrel.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

III.P.1. Abstract

Objectives

This effort, which is funded by the U.S. Department of Energy's (DOE's) Vehicle Technologies Program (VTP) within the Vehicle & Systems Simulation and Testing Activities (VSST), will:

- Utilize data collected from ARRA demonstration projects. Data from up to electric vehicles (EVs) and plug-in hybrid vehicles (PHEVs) entering fleets in FY 2011–FY 2013 will be collected and analyzed.
- Record more than 25 parameters, recorded each second from each vehicle. Drive cycle information will be used in coordination with other DOE laboratories to further refine medium-duty (MD) vehicle R&D activities. Motor, power electronics, and battery performance will also be monitored and recorded for use in DOE-sponsored R&D.
- Compile all data from these MD electric drive vehicles to directly support VTP's goals of developing and deploying plug-in EVs. Collection, storage, and analysis of vehicle data transmitted from each original equipment manufacturer (OEM) will take place via the NREL Commercial Fleet Data Center (CFDC).
- Securely deliver detailed reports of vehicle performance to the DOE. Additional results, processed to obscure proprietary/private information, will be posted on the NREL website quarterly for public review.

Approach

- Securely collect, store, and analyze vehicle data transmitted from MD and heavy-duty plug-in EVs and equipment being deployed/developed as a part of DOE-funded activities (under the ARRA Transportation Electrification Awards and MD PHEV school bus Technology Acceleration and Deployment Activity Award).
- Report data and progress of the data collection effort as well as analyzed vehicle/equipment performance data to the DOE and the general public.
- Provide for secure storage of data on 30-TB capacity storage arrays.
- Create initial data processing routines to easily analyze data sets as they become available as well as provide quality checking and filtering.
- Provide data analysis and reporting of initial ARRA vehicles expected to deploy in FY 2012 (expected to be at the 10%–20% levels of total).
- Create data sheets and on-line access for DOE managers and full monitoring of vehicles (four specific vehicle types)
- Obtain more than 25 parameters, recorded each second from each vehicle, store at NREL.
- Use drive cycle information in coordination with other DOE laboratories to further refine MD vehicle R&D activities. Motor, power electronics, and battery performance will also be monitored and recorded.
- Additional results, processed to obscure proprietary/private information, will be posted on an NREL website quarterly for public review.

Major Accomplishments

- Smith Electric Vehicles: Developed data analysis and reports for the Smith "Newton." Two quarterly reports and one cumulative report were published on the NREL website detailing the performance of 187 vehicles that were transmitting data as of April 30, 2012. These reports cover October 2011 – December 2011 and January 2012 – March 2012. The cumulative report covered October 2011 – April 2012.
- Navistar: Developed data analysis and reports for the Navistar "e-Star." Battery data transmission began in July. The first Navistar quarterly report covering August–September will be posted in October 2012. This shortened data collection period will cover field data collected on more than 60 vehicles. The following report will cover October 2012 – December 2012.
- Cascade Sierra Solutions: Finalized a nondisclosure agreement and data transfer plan, and developed a quarterly report template. Automated analysis and reporting routines are well under way and ready for validation with additional OEM discussions.

Future Activities

- Analysis will continue on all four vehicle data sets to improve data quality and fidelity of the results. Quarterly reports will continue to be published. Additional analyses will be added, including:
  - Power train thermal performance
  - Battery thermal performance/efficiency
  - Battery degradation
  - Fleet charging effects to the grid.
- Efforts will include processing drive cycle data for public consumption and incorporating it with Fleet DNA, and coordinating with other projects within the VTP.
- PHEV analysis capabilities will be added to the toolkit and, when applicable, publicly available data will be shared with Clean Cities to provide guidance to more fleets interested in HEVs.

III.P.2. Technical Discussion

Approach

Data recorded (typically via controller area network bus onboard the vehicle) is collected by the onboard data acquisition systems and transmitted wirelessly to the OEM or third-party telemetry provider data warehouse. From there, raw data files are uploaded to NREL secure FTP sites as shown in Figure 1.

Automated software checks the FTP sites every morning for new files and stores them locally (with nearly 30 TB of capacity) in NREL's CFDC.

The data is then converted to more useful formats, analyzed, and processed into reports delivered to DOE and the public website.

Within the CFDC, the data is investigated throughout a series of steps. While raw data is never deleted, if some of it is found to be corrupt or unusable, it is quarantined for closer inspection.

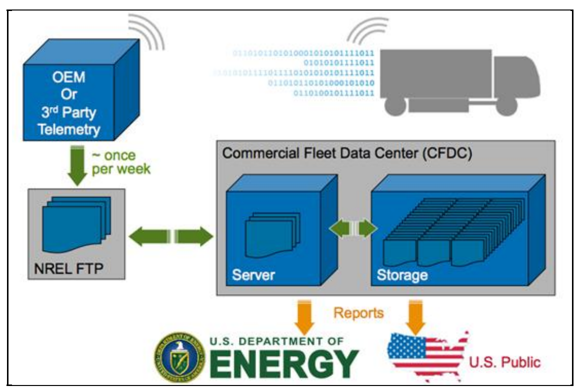


Figure 1. Data Transfer Network Topology.

The central portion of the analysis takes place after the second-by-second data have been aligned with local time stamps and separated into driving and charging modes, as shown in Figure 2. The major interest of this program is how effective these new electrified drive systems can be in reducing oil consumption and fuel costs for commercial fleets.

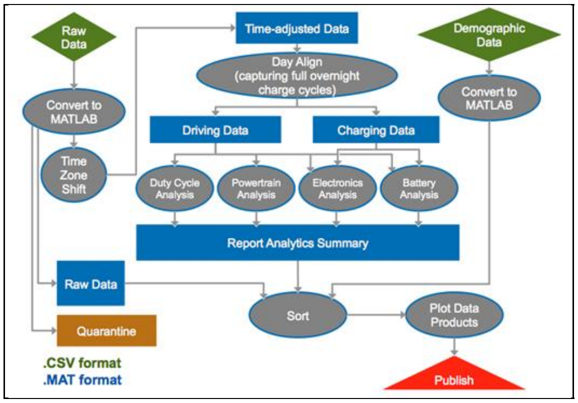


Figure 2. Data Processing Methodology.

Throughout the analysis process, routines correlate the data with local demographic data to provide information about the markets in which these vehicles are used. Additional routines sort the data and produce dozens of individual metrics to produce charts and reports.

Results

Smith Data Collection, Analysis, and Reporting

The October 2011–April 2012 data for the Smith Newton Deployment Program is summarized below. During this period, the focus was on data collection for the first-generation Smith Newton (Figure 3).

- Number of vehicles reporting: 187
- Number of vehicle days driven: 7,996
- Number of operational cities: 83
- Total distance travelled: 249,670 miles.

Figure 3. Smith Newton, NREL PIX #17631.

Smith Newton Vehicle and Component Specifications

Quality data collection on the first-generation Smith Newton began in October 2011. In May 2012, Smith released a second generation Newton with an upgraded battery and powertrain. The data collected and analyzed in this report is for the first-generation Newton. Although two battery sizes are offered, the data reported in this timeframe was from vehicles with 80 kWh battery packs. Vehicle and component specifications are given in Table 1.

Table 1. Smith Newton 1st Generation Specifications

GVW	22–27K lbs.
Drag Coefficient	~0.5
Charging Standards	J1772 or 3-phase
Onboard Charger Power	5–6 kW
Battery Capacity	80 kWh
Inverter Efficiency	94%
Motor	
Peak Motor Power	134 kW
Efficiency	90%

In the first-generation Newton, a charger sends a direct current into the battery. The battery current is fed into an inverter, where it is converted to alternating current for the electric motor. The electric motor drives a single reduction gear transmission that rotates the drive wheels.

Table 2 shows the advertised performance of the first generation Newton. The 120 kWh configuration is thought to be the basis for the 150 mile advertised range.

Table 2. Smith Newton Advertised Performance

Top Speed	50 mph
Advertised Range	Up to 150 miles

Smith Newton Deployment and Data Collection Quantity

Deployment of Smith's first generation EV began in November 2010, but higher quantity ramp-up began in early 2011. As of April 30, 2012, we are collecting data on 187 vehicles. Figure 4 shows new vehicle deployment by month where vehicle deployment is identified as the month in which data collection started for a given vehicle ID. The cumulative line plot includes vehicles deployed before October 2011. Eighty vehicles were deployed before we formally started data analysis for the quarterly reports.

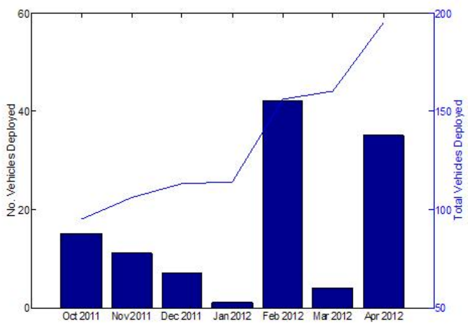


Figure 4. ARRA Newton Fleet Vehicle Deployment.

The number of files that are processed each month is increasing. Figure 5 illustrates this trend. We reported a decline in data for January and March, and missing data for May and June. The Smith engineering team reviewed their processing code and found an error. This error resulted in missing data segments and an energy imbalance in our processing. At the time of this report, the Fleet Testing and Evaluation team is reprocessing the data including the missing data segments using the Fleet Analysis Toolkit.

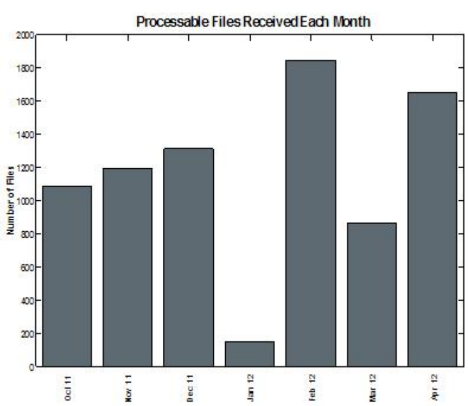


Figure 5. Processed Files by Month.

Smith Newton Data Analysis Results

The analysis presented in this section is based on data collected from October 1, 2011, through April 30, 2012. NREL's composite data products cover four main topical areas: national fleet composition, duty cycle analysis, energy analysis, and vehicle-to-grid integration.

National Fleet Composition

Figure 6 shows that 43% of the ARRA-funded Smith Newton fleet is deployed in California. Texas, Oregon, and Indiana distantly follow with 8%, 7%, and 6 % of the nationwide fleet.

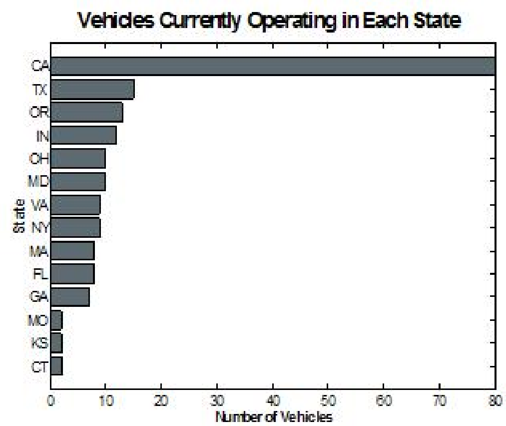


Figure 6. Vehicles By State.

Figure 7 illustrates where these vehicles are used. Roughly 40% of the total distance traveled was covered in California.

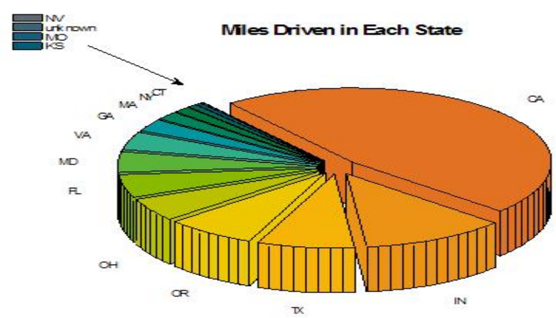


Figure 7. Miles Driven by State.

Duty Cycle Analysis

Smith vehicle driving metrics are also being calculated to understand vehicle usage and performance. Some basic drive cycle statistics include:

- Average number of stops/day: 66.4
- Average number of stops/mi: 2.6
- Maximum driving speed: 47.4 mph
- Average driving speed: 20.6 mph.

The size of the battery pack does not appear to be range limiting. The average daily driving distance (Figure 8) and average distance between recharges (Figure 9) is less than the pack's estimated range. Figure 10 shows the average fuel economy (gasoline gallon equivalent) observed as compared to driving aggressiveness (a measure of acceleration, deceleration, and speed).

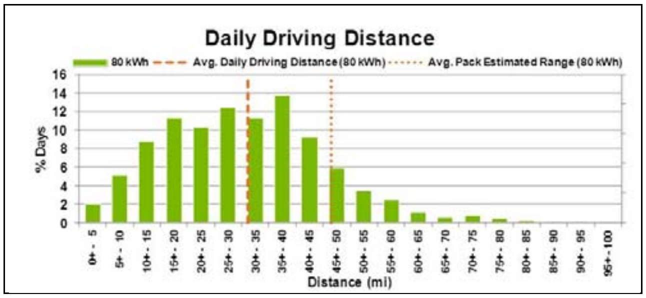


Figure 8. Daily Driving Distances.

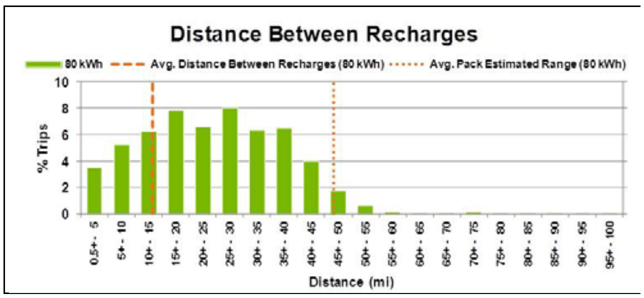


Figure 9. Distance Between Recharges.

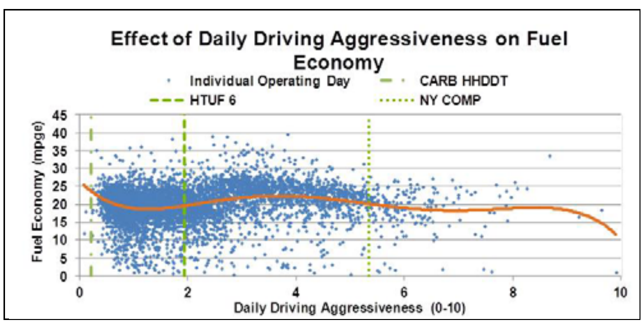


Figure 10. Fuel Economy vs. Daily Driving Aggressiveness.

Energy Analysis

In this section, the energy use these vehicles are seeing in the field is explored and furthermore what that translates to in terms of operating costs when compared to a baseline diesel vehicle.

In Figure 11, a point represents the average energy per mile used to travel a daily distance. The majority of the daily routes used 1 to 2 kWh of energy per mile with an average usage of 1.7 kWh observed. Figure 12 breaks up the two-dimensional space into bins and then counts the number of occurrences in each bin.

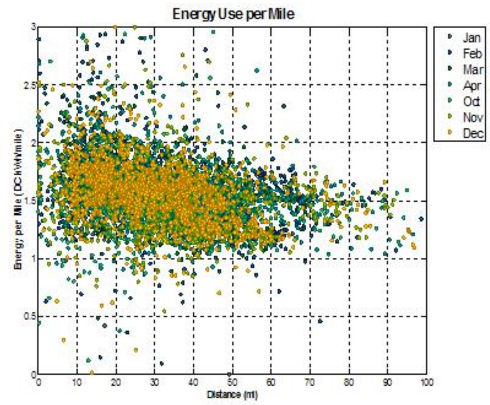


Figure 11. Energy Use Per Mile.

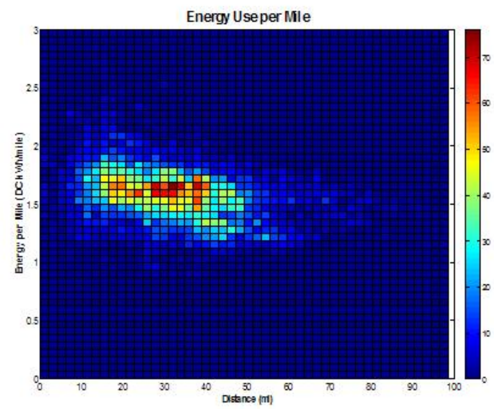


Figure 12. Density Plot of Energy Use Per Mile.

Despite the energy use per mile results, the EV is still cheaper to operate on a fuel cost-per-mile basis when compared to a conventional diesel baseline. NREL used vehicle specification and performance data from a conventional UPS vehicle tested at the Renewable Fuels and Lubricants research laboratory (ReFUEL) to create a conventional diesel model. The model was simulated on all of the field drive cycles collected for the Smith Newton vehicle. These data are shown in Figure 13. Since the payload mass for the vehicles run in the field is unknown, the conventional model was run at empty, industry average, and maximum payload. The electric vehicle is cheaper on a cost per mile basis even for the empty conventional vehicle. Table 3 lists average trip fuel cost per mile for the electric and conventional vehicle scenarios.

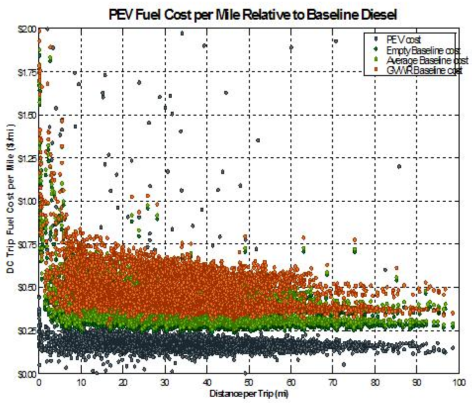


Figure 13. EV and Baseline Diesel Cost per Mile.

Table 3. Cost per Mile Summary

Configuration	Average DC Trip Fuel Cost per Mile
PEV	$0.26
Conventional, No Payload	$0.40
Conventional, Average Payload	$0.43
Conventional, GVW	$0.52

Vehicle-to-Grid Integration

NREL is also evaluating how an electric MD fleet would impact the local utility grid. Figure 14 shows the distribution of times when these vehicles are plugged in. Ten percent of the time these vehicles are plugged in between 5 p.m. – 6 p.m. This coincides with peak electrical demand.

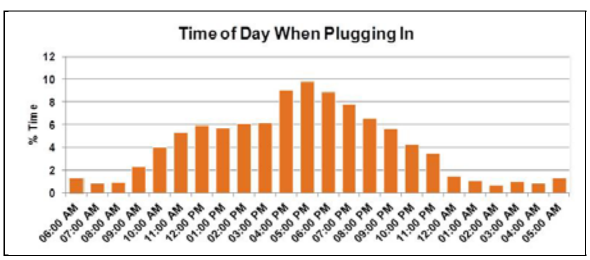


Figure 14. Time of Day when Plugging In.

Figure 15 and Figure 16 show the distribution of local times at which these vehicles are driving and charging. The charging mode is initiated when a vehicle is plugged in and is not completed until a vehicle is keyed on and the driving mode is started. In general, these vehicles are being used between 6 a.m. and 6 p.m. and are being charged between 12 p.m. and 5 a.m. NREL plans to evaluate the grid impacts of these vehicles in a future study.

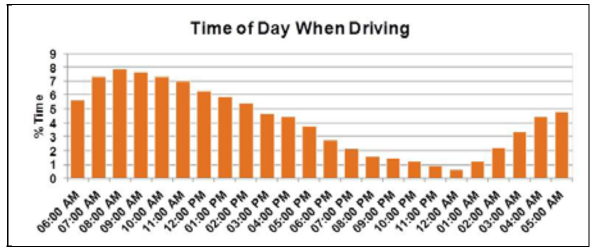


Figure 15. Time of Day when Driving

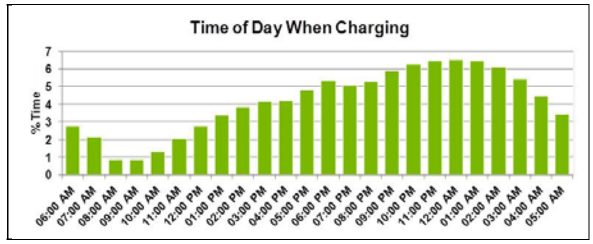


Figure 16. Time of Day when Charging

The results of our analysis are summarized in four-page quarterly reports available on the Fleet Test and Evaluation team's section of the NREL website. The practice is to publish the quarterly data along with a cumulative report covering the data collection period in its entirety. Two quarterly reports and one cumulative report have been published on the NREL website. The reports detail the performance of the 187 vehicles transmitting data as of April 30, 2012. The quarterly reports cover October 2011 – December 2011 and January 2012 – March 2012. The cumulative report covered the period from October 2011 through April 2012.

Navistar Data Collection

Navistar EVs (eStar) began deployment and data transmission in 2011 (Figure 18). Navistar began providing quality battery data, which is necessary to calculate energy use data, in mid-July. The data has not yet been processed or published. For this report, we focus on duty cycle data collected in August 2012. We are in the process of modifying existing coding to accommodate Navistar's data conventions for energy flow. Energy data will be published in an August 2012 – September 2012 quarterly report planned for October.

Figure 17. Navistar eStar NREL PIX #18624.

The Navistar eStar Deployment Program preliminary data for August 2012 is summarized below.

- Number of vehicles reporting: 63
- Number of vehicle days driven: 412
- Number of operational cities: 25
- Total distance travelled: 5,102 miles.

This data is the focus of this report. Vehicle specifications and data collection and analysis are defined and evaluated in the following sections.

Vehicle and Component Specifications

Navistar eStar vehicle details and performance are as follows in Tables 4 and 5:

Table 4. eStar Vehicle Specifications

GVW	12,122 lbs.
Charging Standards	J1772
Battery Capacity	80 kWh
Motor Power	70 kW

Table 5. Advertised Performance

Top Speed	50 mph
Advertised Range	Up to 100 miles

Data Analysis

The analysis presented in this section is based on data collected as of August 2012. Navistar vehicle driving metrics enable understanding of vehicle usage and performance. Some basic drive cycle statistics include:

- Average number of stops/day: 36.7
- Average number of stops/mi: 9.8
- Maximum driving speed: 49.5mph
- Average driving speed: 20.7 mph.

We expect to be able to include energy data in the August – September 2012 quarterly report.

Cascade Sierra Solutions

In FY 2012, the Fleet Testing and Evaluation team finalized a nondisclosure agreement with Cascade Sierra Solutions (CSS) to collect data from long-haul trucks using shorepower at ARRA-funded truck stop electrification sites around the country. Trucks with drivers that are participating in the study have idle-reduction equipment installed that was purchased with rebates through the ARRA.

Technology

Several anti-idle technologies were rebated:

- Auxiliary power units/generator sets
- Battery air conditioning systems
- Thermal storage systems, evaporative coolers
- Trailer transport refrigeration units
- Straight truck cold plate and refrigeration systems
- Plug-in adapter kits.

Status

Beginning in October 2012, CSS will be uploading vehicle information from the rebate application that is required for the ARRA rebates as well as truck stop electrification site usage data (transmitted during truck stop electrification events) to an NREL FTP site. Data uploaded to this site will be automatically downloaded to the Fleet Testing and Evaluation Team's Commercial Fleet Data Server for storage and analysis. The team is currently designing data products that will use the submitted data to track truck stop electrification usage information. The overall goal of the analysis will be to track usage patterns and locations, and identify factors which enable or disable usage of the electrified truck stops. Tables 6 and 7 show the parameters which will be collected from the rebate form as well as from the electrification site.

The vehicle information and truck stop electrification site load data will also be used to quantify the popularity of each rebated technology in the ARRA sample fleet and the

Table 6. Rebate Application Data

Parameter	Units
Vehicle Profile	Type
Engine Make	Name
Engine Model	Model #
Engine Year	Certification Year
Annual fuel consumption	Gallons per year
Idle hours	Hours per year
Percent of time spent idling	%
TRU	YES/NO
Vocation detail	Type of duty cycle
Route they drive	Location

Table 7. ShorePower Data being Received

Parameter	Units	Acquisition Frequency	Comments
Vehicle ID	NA	NA	Remote Device ID Links to Vehicle
Timestamp	YY/MM/DD/HH/MM/SS	1Hz	None
AC current	Amps	1Hz	None
AC voltage	Volts	1Hz	None
GPS latitude	Degrees	1Hz	Station location
GPS longitude	Degrees	1Hz	Station location
Ambient temperature	Celsius	1H	

gallons of diesel saved and kilograms of greenhouse gas emissions avoided. To date 2,360 membership IDs have been mailed to participants (this corresponds to the number of trucks with idle-reduction equipment installed), and 10 truck stop electrification sites have opened as a result of these funds. It is anticipated that the first summary report will be ready for publication by November 2012.

Summary & Conclusions

Vehicle Data

- Over 180 Smith Electric Vehicle "Newtons" and 60 Navistar "eStars" have been deployed and are transmitting data directly to NREL for analysis.
- Over 8,408 days of operation of the Smith and Navistar vehicles have been captured and analyzed, which contain 254,772 miles of operation and 18,947 charge events.
- Analysis of the data has shown charging patterns and energy usage patterns that can be used for future planning and deployment of EVs in fleets.
- Analysis of driving characteristics versus energy use is illustrating the variation in vehicle efficiency and its dependence on route type and driving style.

Reporting

- The first quarterly reports for Navistar eStar will cover August through September 2012.
- Smith EV data has been analyzed, and quarterly reports have been published for October 2011 through April 2012. A cumulative analysis report has also been published for this time period.
- Smith quarterly reports for this calendar year will be retroactively updated to include the missing data segments.
- Future Smith quarterly reports will be modified to include second-generation Newton data.
- Additional sites in FY 2013 will include the SCAQMD / EPRI vehicles as well as Class 8 truck stop electrification (from Cascade Sierra).

III.P.3. Products

Publications

1. Walkowicz, K.; Ramroth, L.; Duran, A.; Rosen, B. (2012). *MD PHEV/EV ARRA Project Data Collection and Reporting* (Presentation). NREL (National Renewable Energy Laboratory). 21 pp.; NREL Report No. PR-5400-53878.
2. *Smith Newton Vehicle Performance Evaluation* (Brochure). NREL (National Renewable Energy Laboratory). (2012). 4 pp.; NREL Report No. BR-5400-54345; DOE/GO-102012-3589

Tools & Data

1. **Drive-cycle, Rapid Investigation, Visualization and Evaluation Tool (DRIVE)**, Copyrighted 2011. Tool created to analyze large sets of drive cycle data.2.
2. **Fleet Analysis Toolkit (FAT GUI).** Created/modified to input, filter, analyze and visualize large sets of vehicle performance data.

III.Q. Medium Truck Duty Cycle (MTDC)

Principal Investigator: Gary Capps
Oak Ridge National Laboratory (ORNL)
National Transportation Research Center
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1285; Fax: (865) 946-1381; Email: cappsgj@ornl.gov

Gratis Fleet Partner: Fountain City Wrecker Service
President: Joel Smith
Phone: (865) 688-0212; Email: fcwreckerservice@bellsouth.net

Gratis Fleet Partner: The H. T. Hackney Company
Director of Transportation: Ed Meyer
Phone: (865) 546-1291; Email: ed.meyer@hthackney.com

Gratis Fleet Partner: Knox Area Transit
General Manager: Cynthia McGinnis
Phone: (865) 215-7824; Email: cmcginnis@cityofknoxville.org

Gratis Fleet Partner: Knoxville Utilities Board
Fleet Supervisor: Chris Wilson
Phone: (865) 558-2408; Email: Chris.Wilson@kub.org

Federal Agency Partner: Federal Motor Carrier Safety Administration
General Engineer: Chris Flanigan
Phone: (865) 558-2408; Email: chris.flanigan@dot.gov

DOE Technology Development Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

III.Q.1. Abstract

Objective

- To collect and analyze real-world heavy- and medium-truck duty cycle (HTDC, MTDC) and performance data on four (4) types of vocational vehicles. This objective is further delineated as:
  - Provide a source of real-world medium-truck performance data that can be utilized by DOE for making decisions related to future technology research investments.
  - Provide a baseline of data that can be utilized to gauge 21CTP technology advancements.
  - Provide a national source of real-world data for the medium-truck research community.
  - Potentially provide data germane to Environment Protection Agency's goal of collecting emissions data from medium trucks in quantifiable driving environments.
  - Potentially provide data germane to the U.S. Department of Transportation (DOT) Federal Motor Carrier Safety Administration's (FMCSA's) goal of collecting vehicle, driver and carrier data in real-time during normal vocational operation.

Approach

- Identify relevant performance measures (e.g., location, speed, fuel consumption, gear, grade, time-of day, congestion, idling, weather, weight, etc.). Note: no emissions data is currently being collected.

- Design/test a data acquisition system to collect identified performance measures (i.e., field hardened and tested, able to interface with the test vehicle's on-board databus and other sensors, communicates data wirelessly/daily/securely).
- Find fleets willing to participate without direct funding (i.e., gratis partnerships). Incentives for partners include: better introspective data to improve fuel efficiencies, public exposure, and public goodwill.
- Instrument and "shake-down" test vehicles; i.e., six test vehicles per year in two vocations per year over two years
- Manage data in a cost effective and secure manner (e.g., automatic quality assurance programs to look for data that is out-of-range, missing data, etc.).
- Develop specialized data manipulation and analysis software; e.g., the prototype real-world-based duty-cycle generation tool – Duty Cycle Generation Tool (DCGenT) will generate duty cycles of user specified duration based on user-selected duty cycle characteristics (e.g., grade, payload, type of roadway, weather, time-of-day, etc.).
- Outreach to other agencies/programs for cost leveraging. This project facilitated a DOE/DOT partnership agreement for the collection of brake and tire performance data. DOT provided funding for all sensors and labor associated with their brake and tire interests and by doing this in conjunction with DOE's MTDC efforts reduced the amount of funding required to conduct this research. The benefit to DOE is that the brake and tire performance data adds to the DOE's data store of medium-truck performance data; already the largest known data store of medium-truck performance data from real-world operating environments in the world.

Major Accomplishments

- Data collection and analysis completed on Part 2 vehicles (towing and recovery and utility).
- DCGenT completed with user's guide
- Transportation, Analysis, Modeling, and, Simulation application developed to select and analyze data from a list of parameters or geospatially
- The MTDC final report encompassing Part 1 (transit bus and local delivery) and Part 2 of the project was completed

Future Activities (proposed)

- Develop a MTDC and HTDC public website for summarized and analyzed data
- Broaden the data collection suite to include aerodynamics, parasitic energy losses, rolling resistance measures, and emissions
- Broaden the data collection efforts to include duty cycle data for heavy- and medium-truck hybrids
- Complete the DCGenT with the capability of estimating energy demand including truck-based energy demands involving real-world event such as idling, coasting, and congestion

III.Q.2. Technical Discussion

Background

This Medium Truck Duty Cycle (MTDC) project is a critical element in DOE's vision for improved heavy vehicle energy efficiency and is unique in that there is no other existing national database of characteristic duty cycles for medium trucks collecting data from Class 6, Class 7 and Class 8 vehicles. It involves the collection of real-world data on medium trucks for various situational characteristics (rural/urban, freeway/arterial, congested/free-flowing, good/bad weather, etc.) and looks at the unique nature of medium trucks' drive cycles (stop-and-go delivery, power takeoff, idle time, short-radius trips). This research provides a rich source of data that can contribute to the development of new tools for fuel efficiency and modeling, provide DOE a sound basis upon which to make technology investment decisions, and provide a national archive of real-world-based medium-truck operational data to support energy efficiency research.

Introduction

The MTDC project involved a two-part field operational test (FOT). For the Part-1 FOT, three vehicles each from two vocations (urban transit and dry-box delivery) were instrumented for the collection of one year of operational data. The Part-2 FOT involved the towing and recovery and utility vocations for a second year of data collection. Examples of the vehicles used in the FOT are shown in Figures 1 through 4.

Figure 1. Part 1; Class 7 Transit Bus

Figure 2. Part 1; Class 7 Local Deliver Truck

Figure 3. Part 2; Class 8 Bucket Truck

Figure 4. Part 12; Class 6 Flat-Bed Recovery Vehicle

Approach

In order to collect the duty cycle and safety-related data, ORNL developed a data acquisition system (DAS) that was placed on each test vehicle. Each signal recorded in this FOT was collected by means of one of the instruments incorporated into each DAS. Other signals were obtained directly from the vehicle's J1939 and J1708 data buses. A VBOX II Lite collected information available from a Global Positioning System (GPS) including speed, acceleration, and spatial location information at a rate of 5 Hz for the Part 1 FOT. For the Part 2 FOT, this information was obtained from DAS-based GPS instrumentation. The Air-Weigh LoadMaxx, a self-weighing system which determines the vehicle's gross weight by means of pressure transducers, was used to collect vehicle payload information for the combination, urban transit, and towing and recovery vehicles. A cellular modem, the Raven X EVDO V4221, facilitated the communication between the eDAQ-lite (the data collection engine of the system) and the user. The modem functioned as a wireless gateway, allowing data retrievals and system checks to be performed remotely. Also, in partnership with FMCSA, two additional safety sensors were installed on the combination vehicles: the MGM e-Stroke brake monitoring system and the Tire SafeGuard tire pressure monitoring system. All of these sensors posted data to the J1939 data bus, enabling these signals to be read without any additional DAS interface hardware. Seventy-three signals from the various deployed sensors and from the available vehicle systems were collected. Because of the differences in vehicle data buses (J1939 and J1708), not all desired signals were available for all test vehicles.

ORNL developed a data-retrieval and archiving system that accessed the vehicles automatically over the air and downloaded the collected information that was resident on the on-board DAS. Each day the system e-mailed a summary of the data downloaded from each vehicle to the ORNL researchers, highlighting any sensors that showed a percentage of error above a pre-defined threshold.

A list of the data channels gathered in the MTDC effort is provided in Table 1.

Table 1. MTDC Data Channels

No.	Description
1	Total Vehicle Distance
2	Road Speed Limit Status (On/Off)
3	Wheel-Based Vehicle Speed/Road Speed
4	Front Axle Speed
5	Engine Speed
6	Current Gear
7	Selected Gear
8	Actual Gear Ratio
9	Output Shaft Speed
10	Transmission Selected Range
11	Transmission Current Range
12	Engine Oil Temperature
13	Intake Manifold Temperature
14	Engine Coolant Temperature
15	Boost Pressure
16	Fuel Rate
17	Instantaneous Fuel Economy
18	Actual Engine - Percent Torque
19	Percent Accelerator Pedal Position
20	Percent Load at Current Speed
21	Driver's Demand Engine - Percent Torque
22	Nominal Friction Percent Torque
23	Brake Switch
24	Clutch Switch
25	Cruise Control Accelerate Switch
26	Cruise Control Active
27	Cruise Control Coast Switch
28	Cruise Control Enable Switch
29	Cruise Control Resume Switch
30	Cruise Control Set Switch
31	Cruise Control Set Speed
32	Power Takeoff Governor/Status Flags
33	Power Takeoff Set Speed
34	Total Power Takeoff Hours
35	Battery Voltage
36	Fan Drive State
37	AC High Pressure Fans Switch
38	Barometric Pressure
39	Latitude
40	Longitude
41	Altitude
42	Vertical Velocity
43	Velocity over Ground
44	Longitudinal Acceleration
45	Lateral Acceleration
46	Heading
47	Satellites
48	Time UTC
49	Distance
50	Steer Axle Weight
51	Drive Axle Weight
52	Wiper Switch Position (On/Off)
53	Brake Actuator Status - Left Front
54	Brake Actuator Status - Right Front
55	Brake Actuator Status - Left Rear
56	Brake Actuator Status - Right Rear
57	Lining Status - Left Front
58	Lining Status - Right Front
59	Lining Status - Left Rear
60	Lining Status - Right Rear
61	Brake Application Pressure
62	Tire Pressure - Left Front
63	Tire Pressure - Right Front
64	Tire Pressure - Left Rear Outside
65	Tire Pressure - Left Rear Inside
66	Tire Pressure - Right Rear Inside
67	Tire Pressure - Right Rear Outside
68	Tire Temperature - Left Front
69	Tire Temperature - Right Front
70	Tire Temperature - Left Rear Outside
71	Tire Temperature - Left Rear Inside
72	Tire Temperature - Right Rear Inside
73	Tire Temperature - Right Rear Outside

Results

Over the length of the data collection effort (approximately 28 months for Parts 1 and 2 of the MTDC FOTs combined), over 70 channels of data were collected at a rate of 5 Hz. The data gathered in this project included information such as instantaneous fuel rate, engine speed, gear ratio, vehicle speed, and other information read from the vehicle's data bus; and spatial information (latitude, longitude, and altitude, etc.) acquired from a GPS device. Additional devices were mounted on nine of the 12 participating vehicles in order to collect weight information. These devices were mounted on the tractor of the three combination trucks, the buses, and the towing and recovery trucks.

During the one-year data collection period for the Part 1 MTDC FOT, the six participating vehicles logged over 105,000 miles (45,400 for the combination trucks and 59,400 for the transit buses) and consumed over 17,000 gallons of fuel (6,000 for the combination trucks and 11,300 for the transit buses), while conducting business in the East Tennessee area. In Part 2 of the MTDC FOT, the utility vehicles and towing and recovery trucks traveled 88,000 miles (18,000 miles for former and 70,000 for the latter), and consumed 13,000 gallons of fuel (5,000 and 8,000, for the utility vehicles and towing and recovery trucks, respectively).

Overall, the MTDC project collected 320 GB of uncompressed data (190 GB for Part 1 of the MTDC FOT and 130 GB for Part 2 of the MTDC FOT).

Conclusions

For the combination trucks, the largest proportion of idling time and fuel consumed while idling corresponded to idling intervals lasting 0-5 minutes (i.e., intervals involving traffic congestion and delay at traffic signals). The transit buses also spent most of their idling time in congestion and bus dwelling stops (0-5 minute idling interval). However, unlike the combination trucks, the transit buses spent about a fifth of their idling time in intervals larger than 4 hours. In the case of the utility vehicles, the largest proportion of idling time and idling fuel consumed corresponded to idling intervals lasting 15-60 minutes, while for the towing and recovery trucks the 5-15-minute interval had the largest percentage of idling time and fuel consumed while idling. The overall and moving fuel efficiencies ranged greatly across vocations, from as low as 3.6 mpg overall for the utility vehicles to 9.7 mpg at speed for the towing and recovery trucks.

One very important variable affecting the fuel efficiency of any vehicle is its payload level. The collected and post-processed data indicated that on average, the combination trucks weighed 27,700-29,000 lb (GVW), the buses 23,000-23,800 lb, and the towing and recovery vehicles 17,000-33,000 lb. The utility vehicles were not instrumented with weight sensors since they do not experience significant variations in weight during their vocational activities. To generate the distribution of fuel efficiency under the payload levels described above, 10-mile segments were considered for which the fuel efficiency was computed and counted as one observation. Overall, the fuel efficiency was found to decrease as the payload increased for the combination and the towing and recovery trucks, as expected. In the case of the transit buses, the relationship between fuel efficiency and vehicle weight was not as expected, but rather fuel efficiency tended to increase with increases in payload. This phenomenon is due to several factors, including idling while empty and having a larger number of passengers on highway routes.

The data collected in this project was also used to investigate two aspects of routing: (1) the variability that may exist in duty cycles that are generated by the same vocation and that follow the same route; and (2) the effect of route optimization on fuel savings. The measures used in this analysis indicated that the highway duty cycles presented a higher variability than the surface street duty cycles, which was largely attributed to the variability in traffic conditions. In the majority of the cases studied, a duty cycle of the original sequence of stops with route optimization was found to be better than the original routing in both of the measures considered (including travel time and fuel savings); optimization of both routing and stop sequencing led to even better performance.

III.Q.3. Products

Publication

1. Medium Truck Duty Cycle Data from Real-World Driving Environments: Project Interim Report

Patents

None

Tools & Data

Several software tools were developed to aid in the overall effort (data collection and data extraction). Additionally, tools were developed as deliverables for the project to aid stakeholders in the use of the data

1. Data Bus Analysis Utility – An internal use tool developed to analyze the data bus of a given potential host vehicle.
2. Wireless Data Download Tool – An internal use tool developed to automate the downloading of vehicle data during the data collection period.
3. Data Quicklook Tool – An internal use tool developed to allow researchers to iew and plot collected to verify that data was in range and that the DAS and sensors were working properly.
4. Data Extractor and Analysis Tool – An internal tool use tool developed to allow data to be extracted from the data base for manipulation in a timely manner and with all spatial components present.
5. Transportation, Analysis, Modeling and Simulation Tool – An internal and external use web-based application which allows the user to filter the data based upon user defined criteria. The user can view the filtered data as a grid, a chart, or spatially in a map. The user determines which data elements are displayed in the grid and chart. The spatial interface can display one or more days' worth of data for each test vehicle. The HTDC and MTDC data are accessed separately using this tool.
6. MTDC Duty Cycle Generation Tool (MTDC DCGenT) - An internal use suite of programs designed to generate duty cycles of a practical length for modeling or testing purposes from measured driving data. Large sets of test data can be "compressed" using this tool, which allows researchers to use collected data to perform vehicle simulations and analyses in a more efficient manner. With the DCGenT, researchers can now create synthetic duty cycles that represent entire days, weeks, or months of data, which will allow more efficiency in data analyses.

.

III.R. Vehicle Systems Integration (VSI) Laboratory

Principal Investigator: David E. Smith
Oak Ridge National Laboratory
National Transportation Research Center
2370 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1324; Email: smithde@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

III.R.1. Abstract

Objective

- Establish a dedicated light and heavy-duty powertrain integration research laboratory to support DOE VT Hybrid Electric Systems research. The facility would be located at the National Transportation Research Center (NTRC) and consist of a hardware-in-the-loop based powertrain integration facility suited to characterize component behaviors exposed to real-world operating conditions in a vehicle systems context, or subsystem interactions based on various advanced powertrain architectures.

Approach

- Enable system-level research that integrates the best of advanced combustion, electric drive, controls, and fuels within applicable emissions constraints. ORNL has made numerous contributions within all these individual technology areas.
- Establish a dedicated propulsion test facility to support prototype component and subsystems integration R&D with an emphasis on transient, HIL testing capabilities.
  - VSI Powertrain Test Cell – the main test cell within VSI capable of testing engine plus transmission of vehicles from light duty up to heavy duty Class 8 powertrains
  - VSI Component Test Cell – the smaller test cell capable of testing individual components (engines, electric machines, energy storage systems, etc.)

Major Accomplishments

- Twin 500 kW powertrain dynamometer test system procured and installed
- 400 kW battery emulation system procured, expected delivery March 2013
- Building infrastructure construction completed

Future Activities

- Baseline and full system commissioning of VSI Powertrain Test Cell
- Installation and commissioning of 400 kW battery emulation system
- Procurement, installation, and commissioning of high speed dynamometer for VSI Component Test Cell

III.R.2. Technical Discussion

Background

ORNL has extensive transportation-related laboratories in support of the DOE's Vehicle Technology Program (VTP). Many of these facilities directly or indirectly support the Vehicle Systems subprogram. As mentioned previously, ORNL currently and historically supports the DOE on multi-cylinder and vehicle applications of diesel combustion, lean burn gasoline combustion, and low temperature combustion processes, and performs principal research for the DOE on emission controls, thermal energy recovery, alternative fuels, transportation materials, and advanced power electronics and electric machinery. The existence and availability of these resources and corresponding expertise in a common location with the VSI Laboratory offers a unique opportunity for addressing not only component-level but also vehicle-level system integration challenges. Expertise in close proximity is of critical importance to operate specialized instrumentation, diagnose complicated prototype equipment, and perform non-standard experiments. The proposed VSI research program will make use of the collocation of diverse expertise, personnel, instrumentation, and hardware resources to perform detailed system and component characterizations that will more efficiently expedite promising technologies toward the marketplace.

Introduction

The modeling/analysis and experimental expertise of the ORNL AVS will form the basis of the VSI laboratory. The vision is a flexible engine-system transient dynamometer laboratory for the rapid characterization of transportation technologies from subcomponent and systems perspective under conditions consistent with realistic on-road operation. The VSI laboratory is necessary to expose the powertrain system to operational conditions consistent with transient drive cycles allowing for the identification of issues related to technology performance, drivability, and noise-vibration-harshness (NVH). This laboratory will be modular by design allowing for minimal downtime to reconfigure the powertrain and supporting components such as aftertreatment and thermal energy recovery systems. Open powertrain control architecture will provide full flexibility for developing vehicle management strategies to balance advanced transportation technologies for optimal efficiency and lowest emissions. A graphical representation of the vision for VSI is shown in Figure 1.

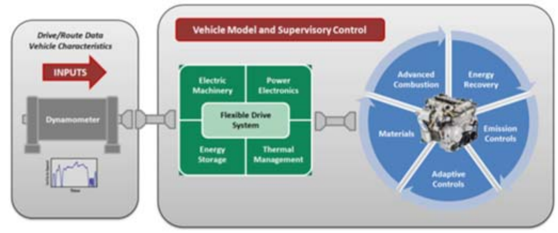


Figure 1. High level representation of VSI concept.

The VSI laboratory will be instrumented to provide emissions and performance data for use in the development and evaluation of engine, exhaust emissions aftertreatment, and thermal energy recovery models under steady-state and transient duty cycle conditions. The ability to exercise transient operation in a well-instrumented and controlled environment is essential to the development of more accurate analytical tools and identifying potential issues which typically are not evident in steady-state technology evaluations.

The VSI laboratory will also be well suited for characterizing and developing high power electric traction drive technologies such as those necessary for plug-in hybrid-electric and fuel cell powertrain applications. This laboratory allows for transient evaluations of advanced power electronics and electric machinery subcomponents, which provide extremely valuable information on subcomponent performance and unprecedented assessment of not only subcomponents but also the entire system to better understand possible synergies or operational issues. Subsystem interactions and potential issues are difficult to identify through modeling or quasi-static evaluations and often require the development and implementation of the full powertrain system for a vehicle chassis dynamometer evaluation.

Approach

The Vehicle Systems Integration laboratory provides a test facility for evaluating components, subsystems, and full powertrain systems from both a steady state and transient perspective. Hardware-in-the-loop principles will be utilized to emulate sub-system components that are not physically available for test.

The VSI Laboratory is comprised of two (2) distinct test cells. The Powertrain Test Cell features a powertrain dynamometer test system (PDTS) that allows complete flexibility for testing a host of various subsystems and powertrains. A few examples of the flexibility of the Powertrain Test Cell are shown in Figure 2. Highlights of the PDTS for the Powertrain Test Cell are summarized below:

- Twin 500 kW (nominal) dynamometers capable of absorbing 3000 N*m each.
- Combining gearbox to connect both dynamometers together to allow torque absorption of ~15,000 N*m
- Emissions measurement system (2 complete sets)
- Battery emulation system capable of providing 400 kW DC power. This system can provide up to 800 V, ±600 A. This unit can be used as a simple DC power source, or can emulate any energy storage system through SIMULINK based models.

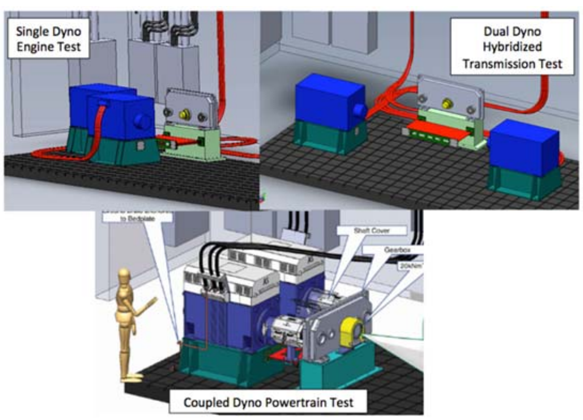


Figure 2. Variations of VSI Powertrain Test Cell capabilities.

The VSI Component Test Cell provides a facility to test individual components in both steady state and transient applications, such as:

- APEEM system level benchmarking and prototype verification/validation
- Fuels, engines, and emissions (and aftertreatment) sub-system level benchmarking and prototype verification/validation
- Energy storage benchmarking (battery HIL capability)

The VSI Component Test Cell features a single, 250 kW dynamometer capable of rotational speeds up to 12,000 RPM. The high speed capability allows testing of modern electric machines commonly found in electric and hybrid electric powertrains. The VSI Component Test Cell is also serviced by the VSI Powertrain Test Cell battery emulation system to enable electric machine and energy storage system testing. With these capabilities, the VSI Component Test Cell allows for enhanced component level benchmarking, with the following vision:

- Maintain current test regimen for static performance/efficiency mapping
- Include "standard" duty or drive cycle HIL based simulations to understand transient phenomena and "real world" operating points for components and systems
- Possibly include a standard group of powertrain architectures to exercise the component in (BEV, PHEV, HEV, etc.)
- Co-funded effort between DOE VSST and other program area (APEEM, ACEC, etc.)
  - Respective program area responsible for "standard" or static testing (no change from current)
  - Vehicle Systems provides funding for test cell use, HIL setup and execution

Results

The focus for FY 2012 has been to set up and commissioning of the VSI Powertrain Test Cell. The current configuration of the VSI Powertrain Test Cell is shown in Figure 3. Accomplishment highlights for FY 2012 include:

- Twin 500 kW powertrain dynamometer test system procured and installed
- 400 kW battery emulation system procured, expected delivery March 2013
- Building infrastructure construction completed

The VSI facility will have baseline commissioning (engine only) completed in November 2012, with full system commissioning including both dynamometers, gearbox, and battery emulation system complete in April 2013. The VSI Component Test Cell will be commissioned at the end of FY2013.

Figure 3. Current configuration of VSI Powertrain Test Cell arranged for engine-in-the-loop testing.

Conclusions

The Vehicle Systems Integration laboratory supports DOE goals by pulling together core ORNL competencies to provide a synergistic approach to vehicle systems research. The facility is well underway to being fully operational. The facility enables steady state and transient, HIL based work for light and heavy-duty components, systems, and powertrains in a controlled laboratory environment. The VSI Powertrain Test Cell offers the capability for light duty through heavy-duty power-pack testing, and provides a mechanism for test procedure and standards development (J2711) of the same. The VSI Component Test Cell will enhance the benchmarking and prototype verification/validation capabilities through the ability to evaluate components in emulated system environments decrease time to market of components developed for electrified powertrains.

IV. MODELING AND SIMULATION

LIGHT DUTY MODELING AND SIMULATION

IV.A. Autonomie Maintenance

Principal Investigator: Shane Halbach, Aymeric Rousseau, Phil Sharer
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-2853; Email: shalbach@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

IV.A.1. Abstract

Objective

- Enhance and maintain Autonomie as needed to support DOE, the user community, and hardware-in-loop/rapid control prototyping (HIL/RCP) projects

Approach

- Use the feedback from Autonomie users to implement new features
- Enhance Autonomie capabilities to support DOE studies

Major Accomplishments

- Imported test data into Autonomie
- Enhanced data analysis features (data set comparisons, windowing, new plot types, and user defined plots)
- Added “Work in Simulink” feature to better support developers
- Added “Look Ahead” driver model and process
- Added distance-based driver model and process
- Added new engine thermal models
- Added new cycles (e.g., European certification cycle with imposed gear) and procedures (e.g., European PHEV procedure) and distributed computing

Future Activities

- Continue to enhance Autonomie to support DOE and technical transfer

IV.A.2. Technical Discussion

Background

Autonomie is a plug-and-play powertrain and vehicle model architecture and development environment to support the rapid evaluation of new powertrain/propulsion technologies for improving fuel economy through virtual design and analysis in a mathematical-based simulation environment. Autonomie is open architecture to support the rapid integration and analysis of powertrain/propulsion systems and technologies. This allows rapid technology sorting and evaluation of fuel economy under dynamic/transient testing conditions.

Introduction

To better support the U.S. Department of Energy (DOE) and its users, several new features have been implemented in Autonomie. Some of the most significant accomplishments are described below.

Approach

There are always more ideas for new Autonomie features and enhancements than time to actually implement them. Feedback on which items to prioritize and include is collected in several ways.

First, users of Autonomie register suggestions for improving the software or models through our online issue tracking system at autonomie.net. Second, direct interaction with partners and sponsors while working on shared projects also contributes to collecting new requirements. Finally, feedback is obtained internally while working on DOE studies, since new development is often required to complete those studies.

Results

The software has been modified in three main categories: the user interface, the models (plant and controls), and standard processes.

User Interface

Import Test Data

Autonomie has been enhanced to allow users to import and analyze component and vehicle test data. There are three main use cases for this new feature.

First, users can quickly format and import raw data for use with Autonomie's data analysis functionality. An example might be a first-cut quality check on raw test data.

Second, users can perform more complicated analysis. Signals can optionally be selected, excluded, or renamed, or the units can be converted (see Figure 1). Additional post-processing can be selected to calculate missing information, such as wheel speed from vehicle speed, power, energy efficiencies, etc. An example of this usage might be a more in-depth analysis of test data.

Finally, users can import data to validate models. In this case, all of the above actions can be applied to the imported data, and the data can be used for detailed comparison and correlation to an Autonomie vehicle model.

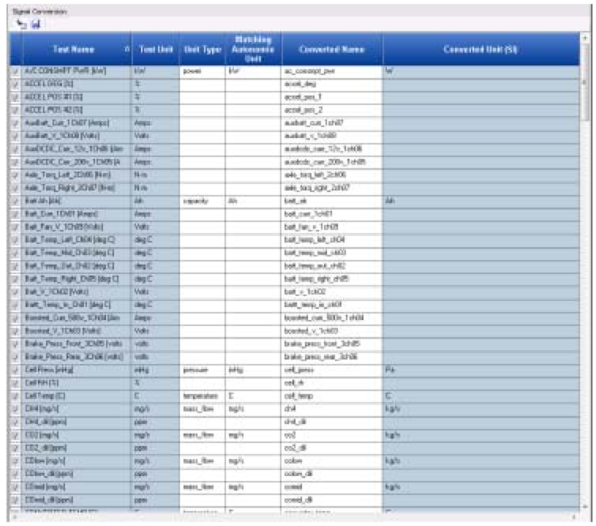


Figure 1. Signal Name and Unit Conversion in Autonomie.

At any level of analysis, all the selections can be saved and reused later. In addition, Autonomie now includes pre-built data adaptors for converting test data from standard formats (i.e., xlsx, txt…). Users can also provide their own custom formatters. Examples of vehicle test data imports have been provided as well.

Enhanced Data Analysis Features

Complementary to the import data feature, the data analysis in Autonomie has been enhanced in several key ways.

Data Set Comparisons

Autonomie has made it even easier to compare multiple data sets (test to test, test to simulation, or simulation to simulation). New plots have been provided for comparison and correlation of signals, as well as comparison of look-up tables, with just a few clicks, as shown in Figure 2.

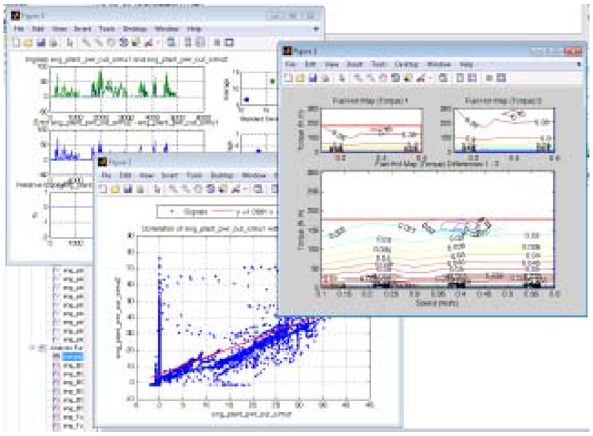


Figure 2. New Data Comparison Plots.

Advanced Plotting

Additional plotting functionalities have been provided for analysis. In addition to the regular signal plots, new plot types can be created with a simple drag-and-drop in the graphical user interface, such as column and pie charts and distribution graphs as shown in Figure 3. New signals can be computed directly from the signal plots. Additional MATLAB plots have been included for quick signal operations, such as derivation, integration, signal distribution, and non-zero signal distribution.

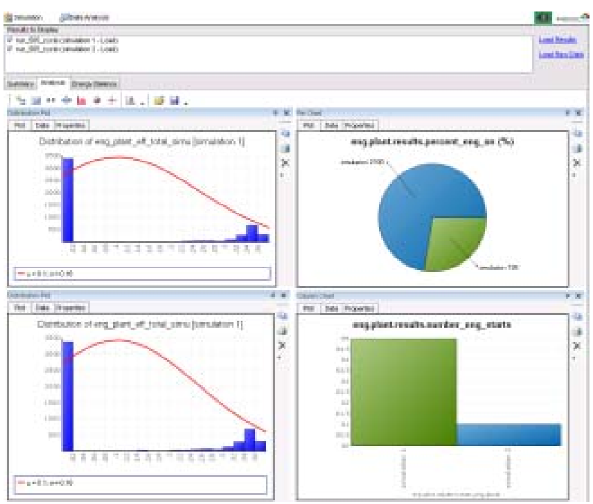


Figure 3. New Drag-and-Drop Plots.

User Defined Plots

Autonomie now features a new system for user defined plots. Users define any MATLAB ".m file" for analyzing data (it needn't be restricted to plots) and run the Autonomie Import Wizard. The new analysis file is matched to an existing file (model, initialization, process, etc.), and is available whenever that file is selected by double clicking an icon in the user interface. This system is completely plug-and-play and allows users to easily and seamlessly harness the power of MATLAB for reusable data analysis functions.

Windowing

Autonomie now features the ability to zoom in on a specific window for data analysis. The window is selected via a simple drag operation on a special plot, as shown in Figure 4. The post-processing is re-run on the selected time interval, and the user interface is updated to display the new results. In this way, any calculation (power, energy, efficiency, etc.) can be focused on specific areas of interest, such as transient conditions and steady-state or "hills" of a drive cycle.

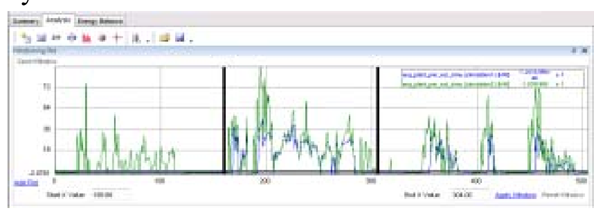


Figure 4. Example of Windowing.

"Work in Simulink" Feature

Many users move in and out between the Autonomie environment and the Simulink environment, especially during model development. These users might work days or even weeks in MATLAB before coming back to Autonomie. A fast-track user interface has been developed to set up and initialize the MATLAB environment and prepare it for development work. Depending on the user's selections, Autonomie can open the appropriate version of MATLAB, set up the path, open a model, initialize it, prepare the workspace, and run additional setup scripts.

Additional Features

There are many additional user interface features, such as:

- Ability to enforce minimum/maximum values of parameters
- Faster load times
- Upgrades to parametric study process (including units, vehicle weight, default values, and range checking)

Models

"Look Ahead" Driver

Until now, driver models that used PI (proportional-integral) controllers computed pedal position according to the difference between actual vehicle speed and target speed. While this feedback model worked well in most cases, steep grades and sharp accelerations could cause vehicles to miss the target.

The new Autonomie "look-ahead" driver model looks at the target speed and grade coming ahead to compute pedal position (and gear demand for manual transmissions), leading to better target speed following and smoother acceleration demand (Figure 5).

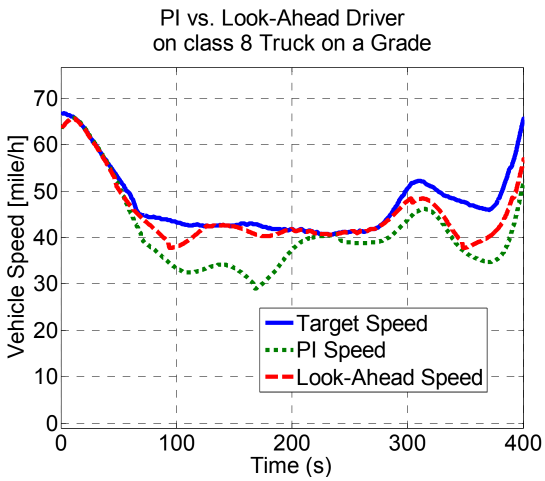


Figure 5. Output from look-ahead driver model.

Distance-Based Driver Model

Previously, the drive cycles in Autonomie were primarily time-based. However, some applications require cycles that are distance-based, such as line-haul applications. Autonomie now provides a default driver to work with these types of cycles.

New Engine Thermal Models

Thermal models add another dimension of complexity that can lead to more accurate results and better predictive capabilities. Two new engine thermal models have been provided with Autonomie: one developed in Simulink, and one developed with AMESim, a high-fidelity modeling tool.

Additional Features

There are many additional modeling features, such as:

- Updated reference vehicles
- Added component and vehicle cost and net present value calculations

Processes

New Cycles and Procedures

Several new cycles and procedures have been added to Autonomie, including:

- The European certification cycle with imposed gear
- The European plug-in hybrid vehicle procedure
- A distance-based process that works with the new distance-based driver model.

Additionally, new process modifiers have been provided to improve the speed of simulation runs by distributing the runs across hardware. These include the ability to distribute a run across multiple cores of a single computer, or to distribute a run on a distributed computing farm.

Additional Features

There are many additional process and model building features, such as:

- Model Advisor Rules for checking imported models for common mistakes
- Support for MathWorks versions R2010a to R2012b

Conclusions

The latest version of Autonomie includes numerous new features that were developed on the basis of feedback from DOE and the user community.

IV.A.3. Product

1. A new version of Autonomie ("Autonomie 2013") will be released in April 2013.

IV.B. Simulation Runs to Support GPRA

Principal Investigators: Ayman Moawad, Namdoo Kim, Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-2849; Email: amoawad@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email:david.anderson@ee.doc.gov

IV.B.1. Abstract

Objective

- Simulate multiple vehicle platforms, configurations, and time frames to provide fuel economy data for analysis in support of the Government Performance and Results Act (GPRA).

Approach

- Validate component and vehicle assumptions with DOE national laboratories and US Drive Tech Teams.
- Use automatic component sizing to run the study.

Major Accomplishments

- Simulated and sized more than 2,000 vehicles for light-duty applications.
- Simulated new vehicles when assumptions or platforms were revised or when additional configurations or time frames were requested.

Future Activities

- Continue to provide analytical data to support GPRA in 2013.

IV.B.2. Technical Discussion

Background

Through the Office of Planning, Budget, and Analysis, DOE's Office of Energy Efficiency and Renewable Energy (EERE) provides estimates of program benefits in its annual Congressional Budget Request. The Government Performance and Results Act (GPRA) of 1993 provides the basis for assessing the performance of federally funded programs. Often referred to as "GPRA Benefits Estimates," these estimates represent one piece of EERE's GPRA implementation efforts—documenting some of the economic, environmental, and security benefits (or outcomes) that result from achieving program goals.

Introduction

Autonomie was used to evaluate the fuel economy of numerous vehicle configurations (including conventional, hybrid electric vehicles [HEVs], plug-in HEVs [PHEVs], and electric), component technologies (gasoline, diesel, and compressed natural gas [CNG], as well as fuel cells), and time frames (2012, 2015, 2020, 2030, and 2045). The uncertainty of each technology is taken into account by assigning probability values for each assumption.

Approach

To evaluate the fuel efficiency benefits of advanced vehicles, the vehicles are designed on the basis of component assumptions. The fuel efficiency is then simulated using the Urban Dynamometer Driving Schedule (UDDS) and

Highway Fuel Economy Test (HWFET). The vehicle costs are calculated from the component sizing. Both cost and fuel efficiency are then used to define the market penetration of each technology to finally estimate the amount of fuel saved. The process is highlighted in Figure 1. This report focuses on the first phase of the project: fuel efficiency and cost.

Figure 1. Process to Evaluate Fuel Efficiency of Advanced-Technology Vehicles.

To properly assess the benefits of future technologies, the following options were considered, as shown in Figure 2:

- Different vehicle classes: compact car, midsize car, small sport utility vehicle (SUV), medium SUV, pickup truck.
- Four time frames: 2012, 2015, 2020, 2030, and 2045.
- Five powertrain configurations: conventional, HEV, PHEV, fuel-cell HEV, and electric vehicle.
- Four fuels: gasoline, diesel, CNG, and ethanol.

Overall, more than 2,000 vehicles were defined and simulated in Autonomie. The current study includes micro hybrids as they are introduced to substitute for conventional vehicles, starting in 2030 (medium-uncertainty case). This study does not focus on emissions.

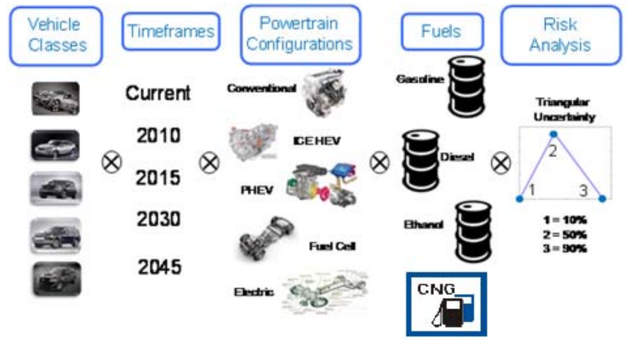


Figure 2. Vehicle Classes, Time Frames, Configurations, and Fuels Considered

To address uncertainties, a triangular distribution approach (low, medium, and high uncertainty) was employed, as shown in Figure 3. For each component, assumptions (e.g., regarding efficiency and power density) were made, and three separate values were defined to represent the (1) 90th percentile, (2) 50th percentile, and (3) 10th percentile. A 90% probability means that the technology has a 90% chance of being available at the time considered. For each vehicle considered, the cost assumptions also follow the triangular uncertainty. However, each set of assumptions is used for each vehicle, and the most efficient components are not automatically the least-expensive ones. As a result, for each vehicle considered, we simulated three options for fuel efficiency. Each of these three options also has three values representing the cost uncertainties.

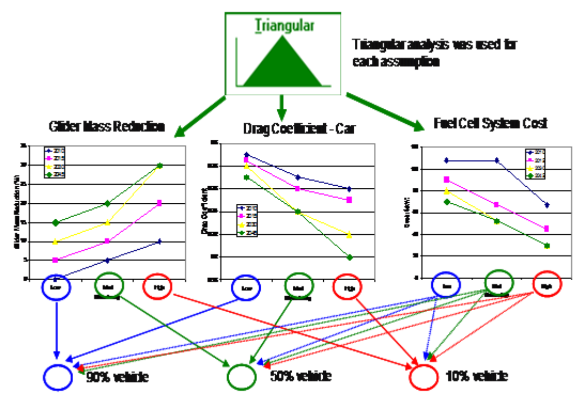


Figure 3. Uncertainty Process

Vehicle Technology Projections

The assumptions described below have been defined on the basis of inputs from experts and the US Drive targets (when available).

Engines

Several state-of-the-art internal combustion engines (ICEs) were selected as the baseline for the fuels considered: gasoline (spark ignition or SI), diesel (compression ignition or CI), ethanol (E85), and CNG. The engines used for reference conventional vehicles were provided by automotive car manufacturers. The proprietary engine data used for HEVs and PHEVs are based on Atkinson cycles.Table 1 shows the engines selected as a baseline for the study.

Table 1. Engines Selected

Fuel	Displacement	Peak Power
SI (Conv)	1.8	99
CI	1.9	110
CNG	1.5	112
E85	2.2	106

Fuel-Cell Systems

Figure 4 shows the evolution of the fuel-cell system peak efficiencies. The peak fuel-cell efficiency is assumed to be at 60% currently, and it will increase to 69% by 2045.

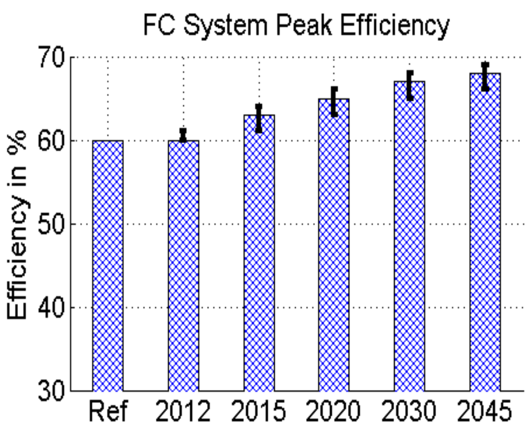


Figure 4. Fuel-cell System Efficiency

CNG Storage Systems

As in the case of the fuel-cell systems, all the assumptions used for NG storage were based on values provided by DOE. Overall, the volumetric capacity dramatically increases (doubles) between the reference case and 2045, going from 0.24 kg NG/kg to 0.538 kg NG/kg. The percentage of NG used in the tank also increases over time, with a value of 83% from the reference case to the 2020 high case and a constant value of 90% for 2030 and 2045.

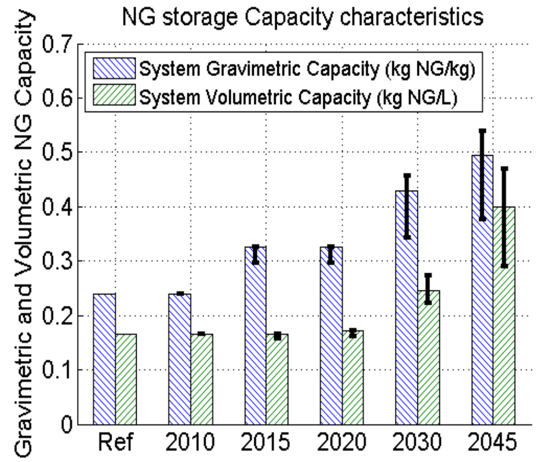


Figure 5. Hydrogen Storage Capacity in Terms of Hydrogen Quantity

Electric Machines

Two different electric machines will be used as references in this study:

- The power-split vehicles (similar to the Toyota Camry hybrid) run with a permanent-magnet electric machine that has a peak power of 105 kW and a peak efficiency of 95%.
- The series-configuration (fuel-cell) and electric vehicles use an induction electric machine with a peak power of 72 kW and a peak efficiency of 95%.

Energy Storage System

The battery used for the HEV reference case is a NiMH battery. It is assumed that this technology is the most likely to be used until 2015 for the low-uncertainty case. The model used is similar to the one found in the Toyota Prius. Both medium- and high-uncertainty cases use a lithium ion battery technology. For PHEV applications, all the vehicles are run with a lithium ion battery from Argonne.

After a long period of time, batteries lose some of their power and energy capacity. To be able to maintain the same performance at the end of life (EOL) compared to the beginning of life, an oversize factor is applied while sizing the batteries for both power and energy. These factors are supposed to represent the percentage of power and energy that will not be provided by the battery at the EOL compared to the initial power and energy given by the manufacturer. The oversize factor is decreased over time to reflect an improvement in the ability of batteries to uniformly deliver the same performance throughout their life cycles.

Vehicles

As previously discussed, five vehicles classes were considered, as listed in Table 2.

Table 2. Characteristics of Different Light-Duty Vehicle Classes

Vehicle Class	Glider Mass (Ref) (kg)	Frontal Area (Ref) (m^2)	Tire	Wheel Radius (m)
Compact Car	820	2.331	P195/65/R15	0.317
Midsize car	990	2.2	P195/65/R15	0.317
Small SUV	1000	2.52	P225/75/R15	0.35925
Midsize SUV	1260	2.88	P235/70/R16	0.367
Pickup	1500	3.21	P255/65/R17	0.38165

Because of the improvements in material, the glider mass is expected to significantly decrease over time. Although the frontal area is expected to differ from one vehicle configuration to another (i.e., the electrical components will require different cooling capabilities), the reduction values were considered constant across the technologies.

Vehicle Powertrain Assumptions

All the vehicles have been sized to meet the same requirements:

- 0–60 mph in 9 sec +/-0.1
- Maximum grade of 6% at 65 mph at gross vehicle weight
- Maximum vehicle speed of >160 km/h

For all cases, the engine or fuel-cell powers are sized to complete the grade without any assistance from the battery. For HEVs, the battery was sized to recuperate the entire braking energy during the UDDS drive cycle. For the PHEV case, the battery's power is defined as its ability to follow the UDDS in electric mode for the 10- and 20-mile cases and the US06 schedule for the 30- and 40-mile cases, while its energy is calculated to follow the UDDS for a specific distance regardless of distance.

Input mode power-split configurations, similar to those used in the Toyota Camry, were selected for all HEV applications and PHEVs with low battery energies. Series configurations were used for PHEVs with high battery energies (e.g., 30 miles and up in electric mode on the UDDS). The series fuel-cell configurations use a two-gear transmission to allow them to achieve the maximum vehicle speed requirement.

Results

The vehicles were simulated on both the UDDS and HWFET drive cycles. The fuel consumption values and ratios presented below are based on unadjusted values.

Evolution of HEV vs. Conventional Vehicle

The comparisons between power-split HEVs and conventional gasoline vehicles (same year, same case) in Figure 6 show that the ratios increase slightly for all fuel cases.

The advances in component technology will not significantly benefit HEVs. Conventional vehicles tend to improve quickly and catch up to HEVs, as the ratio gets closer to 1 by 2045.

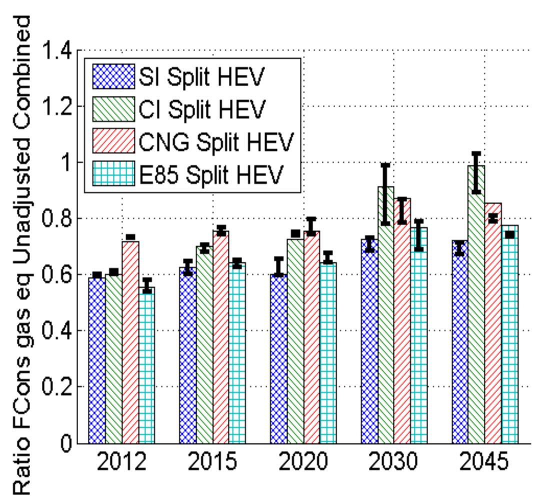


Figure 6. Ratio of Fuel Consumption (Gasoline Equivalent, Unadjusted, Combined) in Comparison to a Conventional Gasoline Vehicle (Same Year, Same Case), for Midsize Vehicles

Figure 7 shows the vehicle cost ratio between HEVs and conventional vehicles. As expected, HEVs remain more expensive than conventional vehicles, but the difference significantly decreases because costs associated with the battery and electric machine fall faster than those for conventional engines.

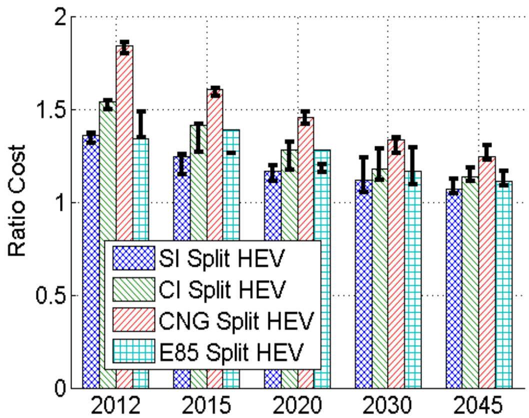


Figure 7. Ratio of Vehicle Cost in Comparison to a Conventional Gasoline Vehicle of the Same Year

Evolution of HEV vs. Fuel Cell

Figure 8 shows the fuel consumption comparison between HEVs and fuel-cell HEVs for the midsize-car case. First, note that the technology for fuel-cell vehicles will continue to provide better fuel efficiency than the technology for HEVs, with ratios above 1. However, the ratios vary over time, depending upon the fuel considered. The ratio for the diesel HEV increases over time because most improvements considered for the engine occur at low power and consequently do not significantly impact the fuel efficiency in hybrid operating mode.

Because of the larger improvements considered for the gasoline engine, the gasoline power-split technology shows the best improvement in fuel consumption in comparison to the fuel-cell technology. Both CNG and ethanol HEVs follow the same trend.

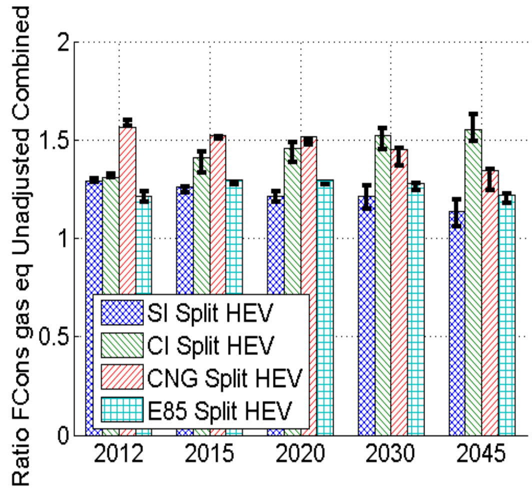


Figure 8. Ratio of Fuel Consumption (Gasoline Equivalent, Unadjusted, Combined) in Comparison to a Fuel-Cell HEV (Same Year, Same Case) for Midsize Vehicles

Figure 9 shows the vehicle cost comparison between HEVs and fuel-cell HEVs. Note that the cost advantages for conventional, diesel, and E85-fueled vehicles are expected to decrease over time, while CNG-fueled vehicles will remain more expensive over time.

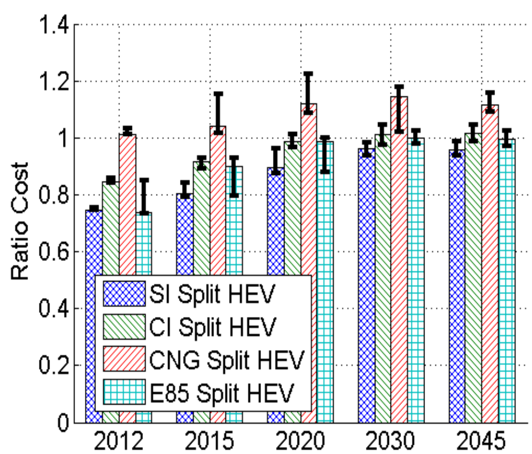


Figure 9. Ratio of Vehicle Cost in Comparison to a Fuel-cell HEV Vehicle of the Same Year

Evolution of PHEVs

Figure 10 shows that the fuel-consumption evolution for power-split PHEVs and extended-range electric vehicles (EREVs) is similar to that for power-split HEVs with gasoline engines.

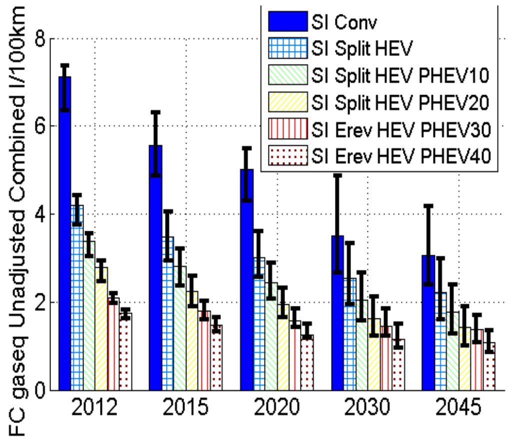


Figure 10. Fuel Consumption Evolution for PHEVs (Gasoline Engine, Midsize Car)

Table 3 shows and confirms that the gasoline-engine PHEVs' improvement ranges from 22% to 67% as for the HEV powertrain.[Not clear what this phrase means.]

Table 3. Fuel Consumption of PHEVs (Gasoline Engine, Midsize Vehicle)

	Ref	Low	High	Percentage	
				Low	High
Conv.	7.36	2.38	4.17	67.6%	43.3%
HEV	4.43	1.59	2.97	64.1%	32.9%
PHEV10	3.56	1.28	2.39	64%	32.8%
PHEV20	2.92	1.00	1.90	65.7%	34.9%
PHEV30	2.18	1.07	1.70	50.9%	22%
PHEV40	1.83	0.84	1.35	54.1%	26.2%

As shown in Figure 11, electric consumption tends to decrease over time for all PHEV ranges; however, it can be seen that electric consumption is almost twice as high for EREVs as for power-split PHEVs. This is due to the configuration itself, in addition to the fact that they are being sized on US06 drive cycles.

Figure 12 shows that there is a linear relationship between vehicle mass and electric consumption: the bigger the vehicle, the higher the electrical consumption. One can estimate that for every 200-kg decrease in mass, there is a 50-Wh/mile decrease in electric consumption.

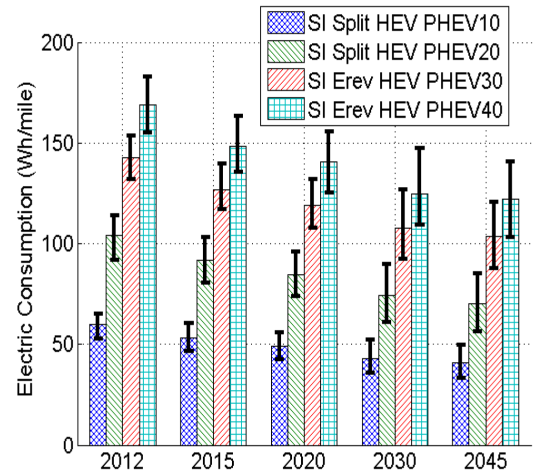


Figure 11. Electric Consumption for PHEVs (Gasoline Engine, Midsize Car)

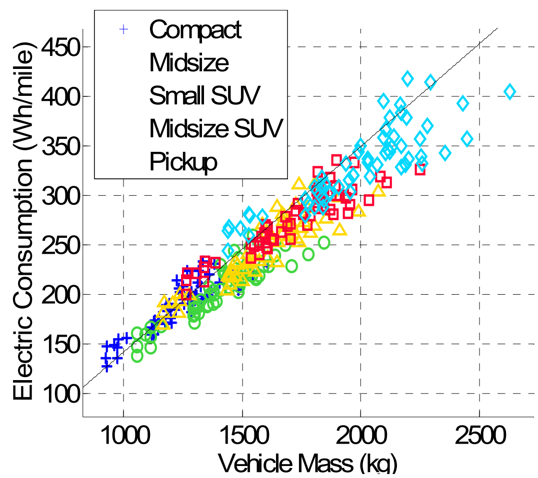


Figure 12. Electric Consumption in Charge Depleting +Charge Sustaining Mode for Gasoline-powered Split PHEVs.

Trade-off between Fuel Efficiency and Cost

Figure 13 shows similar trends in cost vs. fuel consumption for HEVs independently of ICE technology. The overall trend is decreasing, which means lower fuel consumption and lower cost. Gasoline and ethanol HEVs offer the best trade-offs over time.

Figure 14 shows a comparison of all the powertrains, considering gasoline fuel only. The main conclusion is that conventional vehicles are more likely to improve in fuel efficiency than in cost, whereas the higher the electrification level, the more the improvement focuses on cost. For example, the incremental cost for the PHEV40 decreases from $17,070 to $3,526 between 2010 and 2045, whereas the incremental cost for the conventional gasoline vehicle increases from $0 to $1921 over the same period.

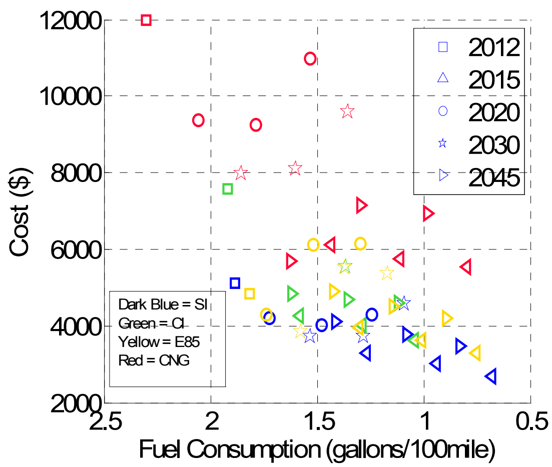


Figure 13. Incremental Cost vs. Fuel Consumption for Midsize HEVs

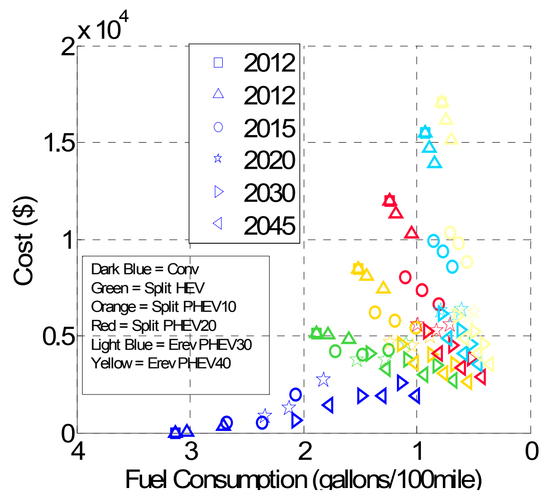


Figure 14. Incremental Cost (in Comparison to the Manufacturing Cost for the Reference Conventional-Gasoline Vehicle) as a Function of Fuel Consumption for Gasoline Vehicles

Figure 15 shows the trade-offs between fuel consumption and cost for all powertrains and fuels compared to the conventional-gasoline reference. Overall, the vehicles on the bottom right would provide the best fuel consumption for the least additional cost. All years, all cases, and all fuels are presented.

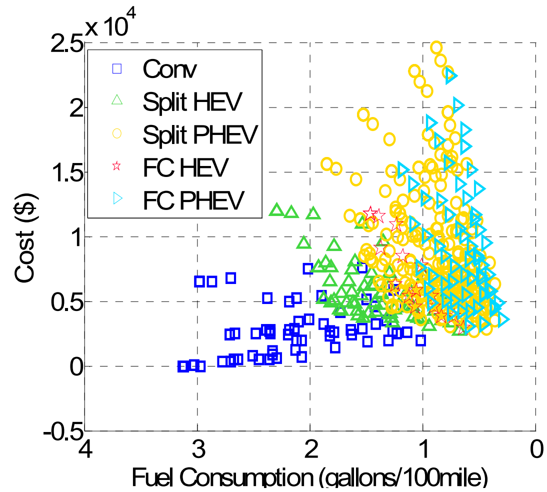


Figure 15. Incremental Cost (in Comparison to the Reference Conventional-Gasoline Vehicle) as a Function of Fuel Consumption for All Powertrains.

Conclusions

More than 2000 vehicles were simulated for different time frames (up to 2045), powertrain configurations, and component technologies. Both their fuel economy and cost were assessed to estimate the potential of each technology. Each vehicle was associated with a triangular uncertainty. The simulations highlighted several points:

- From a fuel-efficiency perspective, HEVs maintain a relatively constant ratio compared to their conventional-vehicle counterparts. Although advances in component technology will not significantly benefit HEVs, conventional vehicles tend to improve quickly. However, the cost of electrification is expected to be reduced in the future, favoring the technology's market penetration.
- Ethanol vehicles will offer the best cost/fuel-consumption ratio among the conventional powertrains in the near future, driving the interest in bio-fuel development. On the other hand, gasoline improvements will be significant as well.
- Fuel-cell HEVs have the potential to reduce fuel consumption.
- CNG shows good fuel-efficiency improvements over time, but its cost remains noncompetitive, mainly because of its high fuel tank cost.

IV.C. Fuel Efficiency of CNG Light Duty Vehicles

Principal Investigator: Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-7261; Email: arousseau@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

IV.C.1. Abstract

Objective

- Evaluate the fuel efficiency benefits of CNG compared to gasoline, on the basis of the current state of the art, for a wide variety of powertrain configurations.

Approach

- Gather state-of-the-art engine data for both gasoline and CNG from the same OEM for fair comparison.
- Select the powertrain configurations to be studied.
- Design vehicles for each powertrain selected, with and without CNG engine resizing.
- Simulate the vehicles on the U.S. standard drive cycles.
- Analyze results.

Major Accomplishments

- Demonstrated the impact on vehicle performance of a CNG engine when using the same block as gasoline fuel.
- Demonstrated the gasoline-equivalent fuel consumption benefits with and without engine resizing.
- Showed the potential of electrification to reduce the gasoline-equivalent fuel consumption penalty from CNG.

Future Activities

- Evaluate the fuel efficiency impact of CNG on medium- and heavy-duty vehicles.
- Adjust vehicle level control to improve fuel economy for CNG vehicles.
- Perform a cost-benefit analysis based on realistic driving conditions.

IV.C.2. Technical Discussion

Background

According to the Natural Gas Vehicles for America, there are now over 120,000 vehicles in the United States that run on compressed natural gas (CNG). Around the world, there are now more than 8.7 million natural gas vehicles. In addition, vehicle electrification is seen as an effective way to improve vehicle fuel efficiency.

Introduction

This study evaluates the benefits of CNG compared to gasoline, on the basis of the current state of the art, for a wide variety of powertrain configurations, including conventional, Start-Stop System, Mild Hybrid, Pre-transmission Full HEV, Single Mode Power Split, Single Mode Power Split with 10-mi All-Electric Range (AER), and the Voltec Extended-Range Electric Vehicle (E-Rev) with 40-mi AER. State-of-the-art engine maps for both gasoline and CNG, generated from the same engine, were used for the simulation. The impact of switching from gasoline to CNG without any engine resizing was analyzed. Then all the CNG vehicles were sized to meet the same Vehicle Technical Specifications or VTSs (i.e., performance, grade, . . .) as the gasoline vehicles. The fuel efficiency impacts of the different fuels were then compared.

Approach

Powertrain Configurations

For the study, seven different powertrain configurations for mid-size vehicles have been chosen. The selected configurations are as follows:

- Conventional
- Conventional with a Start & Stop system with assist (Micro Hybrid)
- Mild Hybrid
- Pre-transmission parallel for HEV
- Power-Split for HEV
- Power-Split for Plug-in HEV with 10-mi AER
- E-Rev with 40-mi AER

Engine Comparison

To allow a fair comparison of the gasoline and CNG fuels, two proprietary maps of the **same** engine operating on gasoline and CNG, respectively, have been provided by an OEM representing the state-of-the-art technologies. Figure 1 shows the difference in peak power between the two fuels.

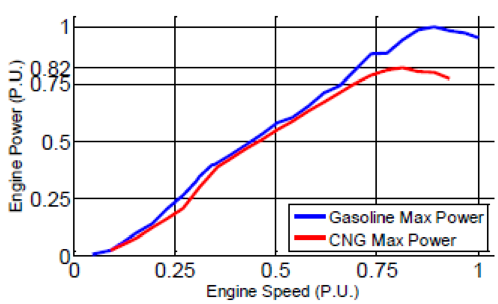


Figure 1. Engine Peak Power Comparison

As a consequence, a loss of performance is expected when using CNG fuel. To be able to provide a fair comparison of the fuels, two cases will be studied for fuel efficiency impact:

- Without any engine resizing (i.e., vehicle performances will be different), and
- With CNG engine resizing (i.e., same vehicle performances).

Vehicle Sizing

Methodology

When sized, the vehicles have to meet certain VTSs.

- For conventional vehicles:
  - Maximum time for acceleration (0 to 60 mph) = 9 sec,
  - Maximum time for passing (50 to 80 mph) = 9 sec, and
  - Vehicles are sized to ascend a 6% grade at 65 mph at Gross Vehicle Weight.
- For Full HEVs, in addition:
  - Minimum engine peak power is 70% of maximum between requirements for acceleration and grade performance, and
  - Regenerative power is captured on the UDDS cycle.
- For PHEVs, in addition:
  - The vehicle must be able to run the following cycle in electric mode: UDDS for the PHEV10 and US06 for the E-Rev.

Automated vehicle sizing algorithms are used to rigorously define the characteristics (i.e., power, energy, weight, . . .) of each component of the vehicle to provide consistent results.

CNG Tank

All the vehicles were sized to provide the same range on the combined drive cycle. Since the weight of the CNG tank depends on its capacity, publicly available information was used as an input to the simulation. Figure 2 shows the tank capacity/weight relationship that was used.

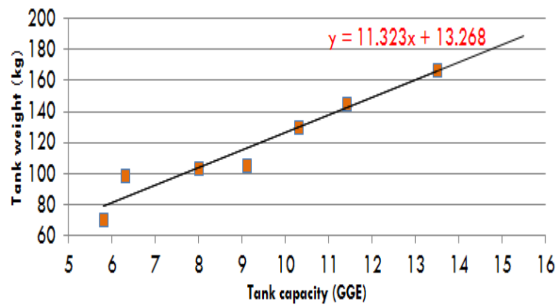


Figure 2. CNG Tank Weight as a Function of Capacity

Driving Cycles

The UDDS and HWFET driving cycles were used to perform the simulations. All the results are based on the assumption of hot conditions.

Results

Vehicle Sizing

As previously discussed, in addition to the gasoline vehicles (Case1), two cases for the CNG vehicle have been simulated:

- without any engine resizing (Case 2), and
- with CNG engine resizing (Case 3).

The CNG vehicles are heavier, mainly because of the tank. The difference between the two CNG cases (Figure 3) is due to the engine weight. Indeed, the engine has a lower power density when it uses CNG and therefore will be heavier when the peak power is the same as for gasoline.

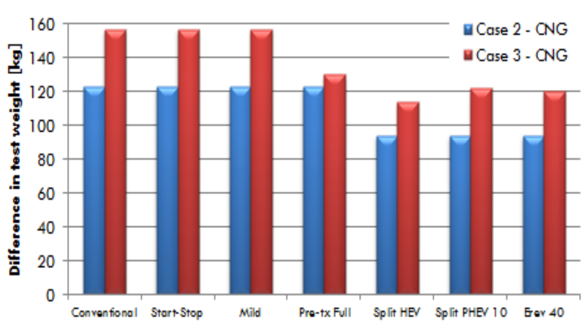


Figure 3. CNG Vehicle Test Weight Difference Compared to the Gasoline Conventional Vehicle (Case 1).

When using CNG with the same engine technology as the gasoline vehicle, there will be a loss of power, as summarized in Figure 4.

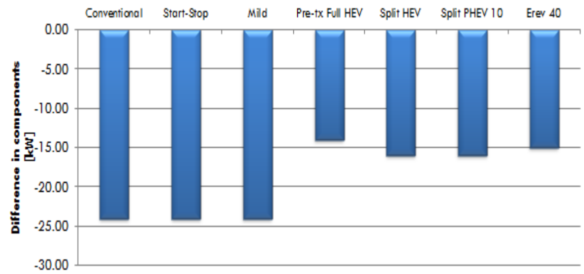


Figure 4. Engine Power Difference Required to Meet the Same VTSs

Without resizing, this extra weight and loss of power will inevitably lead to a loss of performance for the non-resized CNG vehicles compared to the gasoline vehicles, as summarized in Figure 5.

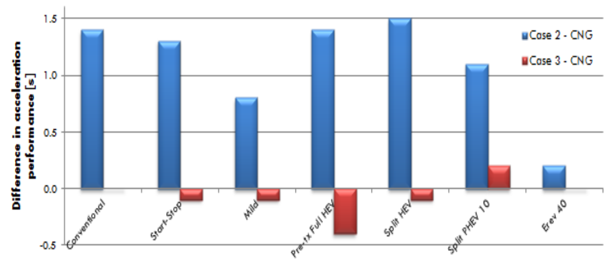


Figure 5. Performance Differences for Case 2 and Case 3 Vehicles Compared to Case 1 Vehicles

Vehicle Efficiency

Figures 6 and 7 show the gasoline-equivalent fuel consumption values of the different powertrain configurations considered.

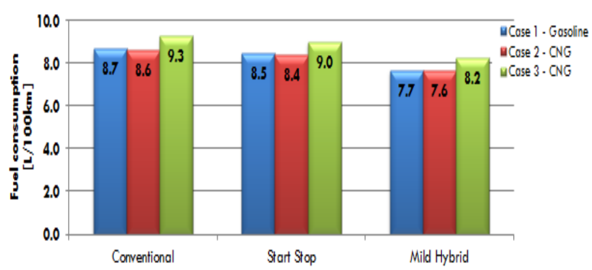


Figure 6. Fuel Consumption of Conventional and Mild HEVs

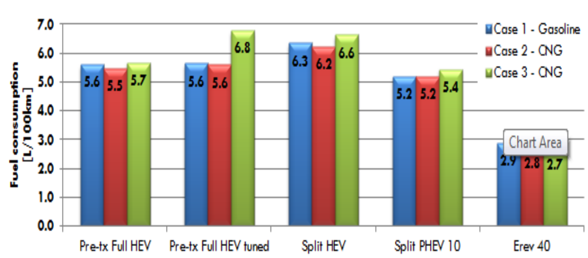


Figure 7. Fuel Consumption of Full HEVs and PHEVs

Despite the difference in test weights, the gasoline-equivalent fuel consumption of each configuration of each case is comparable, mostly for high hybridization degrees.

Figure 8 shows the CNG percent gasoline-equivalent fuel saving compared to the gasoline-fueled engine of the same configuration. The results show that the resized CNG vehicles will consume in the range of 1.8% to 6.9% more fuel, except for the pre-transmission tuned engine, which will consume 21.4% more fuel than its gasoline counterpart. The non-resized E-Rev will achieve 3.4% in fuel savings compared to its gasoline counterpart despite not having been resized. This result is due to the higher peak efficiency of the engine when it uses CNG. This higher efficiency also benefits the non-resized E-Rev engine, which exhibits 7% in fuel savings. Moreover, the sizing revealed no drastic differences between the two engine powers (86 kW for gasoline and 91 kW for the non-resized case).

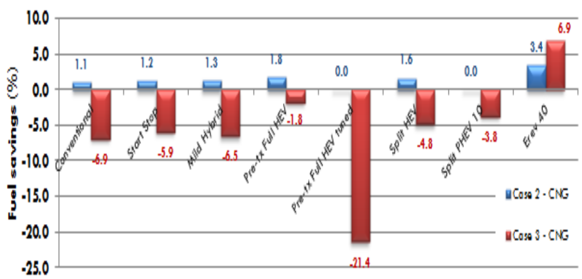


Figure 8. CNG Percent Gasoline-equivalent Fuel Saving Compared to Gasoline with the Same Engine Configuration

Further analysis shows that hybridization enables the engine to operate at higher average efficiency, as shown in Figure 9.

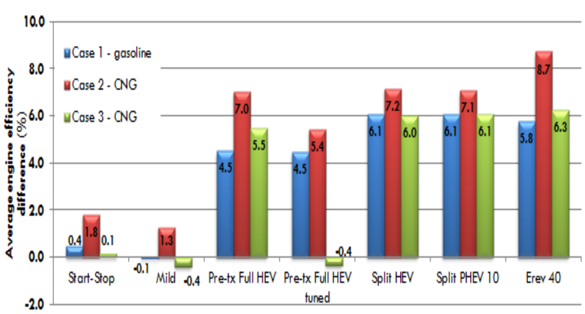


Figure 9. Average Engine Efficiency Differences Compared to the Gasoline Conventional Vehicle

Conclusions

The objectives of the study were to quantify the impact of using CNG fuel compared to gasoline on the vehicle efficiency for different levels of hybridization. Seven powertrain configurations for midsize vehicles were considered, including conventional micro and mild HEV, full HEV, and two PHEVs. The vehicles have been defined to represent the potential of current or near-term technologies. Two engine maps of the same engine technology using CNG and gasoline, respectively, were provided by an OEM to allow a fair comparison.

In addition to the gasoline reference case, two additional options were considered: one where the CNG engines were not resized to meet the same VTSs as the gasoline vehicle, and one where the vehicles had the same VTSs.

The following conclusions can be drawn from the study on the basis of the methodology and the assumptions considered:

- When the engine is not resized, CNG vehicles show a significant loss in performance (from 0.7 to 1.5 sec for acceleration from 0 to 60 mph), but fuel economy is only slightly affected (up to a 2% benefit).
- When the CNG engine is resized to meet the same VTSs as the gasoline vehicles, the fuel consumption penalty ranges from 0 to 7%.
- Hybridization appears to have the potential to lower the fuel consumption penalty of CNG vehicles.

IV.C.3. Product

Publication

1. ANL, "Fuel Efficiency Analysis of CNG Light Duty Vehicles," Presentation to DOE, June 2012.

IV.D. GM Volt Vehicle Validation

Principal Investigators: Namdoo Kim, Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-7261; Email: arousseau@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

IV.D.1. Abstract

Objective

- Develop the complete vehicle thermal management system for an electric-drive vehicle (PHEV).

Approach

- Validate with liquid coolant experimental data at the vehicle level.
- Create an integrated model of engine, cabin, electric machine and transmission in Autonomie.
- Validate the thermal behavior of each thermal system or component, and the fuel economy of the vehicle, under various vehicle driving conditions by using Argonne's Advanced Powertrain Research Facility (APRF).

Major Accomplishments

- Developed a new methodology for Energy Management System (EMS) plug-and-play architecture.
- Developed GM Volt battery thermal management system (TMS) for liquid cooling.
- Validated the TMS with APRF experimental data.
- Developed a control strategy for the GM Volt vehicle, including temperature, based on testing results.

Future Activities

- Complete the vehicle thermal validation of both the Toyota Prius and the GM Volt.
- Develop vehicle-level thermal management control strategies to optimize the energy efficiency of the system with the goal of minimizing fuel and electrical consumption.

IV.D.2. Technical Discussion

Background

An Energy Management System (EMS) is critical in improving fuel consumption and achieving good vehicle performance under real driving conditions. Appropriate modeling for predicting the energy behavior of vehicle powertrains helps in improving design and developing optimal controls. EMSs provide improved vehicle energy efficiency and component performance, but in order to contain costs and eliminate redundancies, redesigned components and system integration are required. As vehicles become electrified, there is a need for shifts in the design paradigms for energy management. These require not only the development of innovative technologies for individual components, but also a superior level of understanding of vehicle energy loops and their integration.

Introduction

This study describes the creation of efficient architecture designs of vehicle thermal management systems (VTMSs) for plug-in hybrid electric vehicles (PHEVs). The objective is to develop guidelines and methodologies for the architecture design of the VTMS for PHEVs, which are used to improve the performance of the VTMS and the fuel economy of the vehicle. For the numerical simulations, a comprehensive model of the VTMS for PHEVs which can predict the thermal response of the VTMS during transient operations is being developed. The comprehensive VTMS model consists of the vehicle cooling system model and climate control system model. A vehicle powertrain model for PHEVs is also being developed to simulate the operating conditions of the powertrain components, because the VTMS components interact with the powertrain components. Finally, the VTMS model and the vehicle powertrain model are being integrated to predict the thermal response of the VTMS and the fuel economy of the vehicle under various vehicle driving conditions.

Approach

All energy management models will be developed and validated by automotive manufacturers and Argonne National Laboratory. Battery manufacturers and automotive manufacturers will provide component data (including engine, transmission, electric machines, battery, driveline, and vehicle) for validation and debugging purpose. If the data are not provided by the OEM, ANL will use the internal public data.

Results

Electric Machine Thermal Model

The proposed thermal model of a permanent-magnet synchronous motor (PMSM) is based on the geometry of the components of the PMSM, as shown in Figure 1. Thermal energy stored in a structure is modeled as a thermal capacitance. The thermal model is represented as the equivalent thermal circuit of the motor. The thermal circuit can be constructed directly in Simulink using Simscape, as shown in Figure 2.

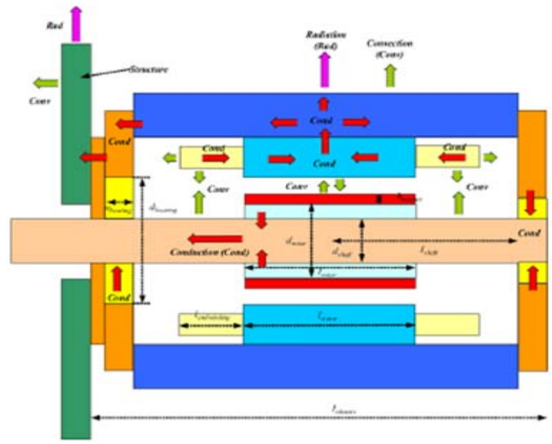


Figure 1. Heat flow diagram of PMSM

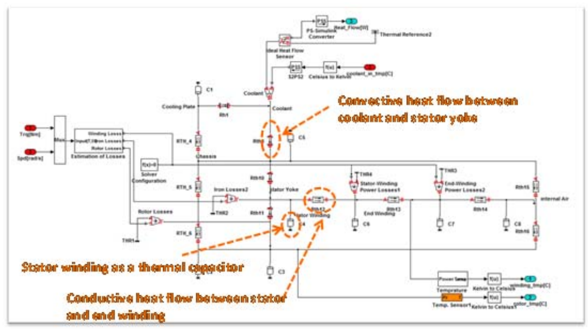


Figure 2. Thermal equivalent network representing a PMSM

The thermal model of the PMSM is based on the following:

- Equations for the power losses of iron, winding, and rotor were obtained from the literature. Assumptions were made in order to simplify the model.
- After the PMSM power losses were estimated, the PMSM thermal model was developed. Mass and positive constant convection and conduction coefficient parameters were chosen carefully.

Transmission Thermal Model

The thermal system of the transmission is cooled by the transmission oil. As a starting point for configuring the cooling system architecture, a transmission thermal model is designed for the PHEV by adding a cooling circuit for electric components to the transmission cooling system, as shown in Figure 3.

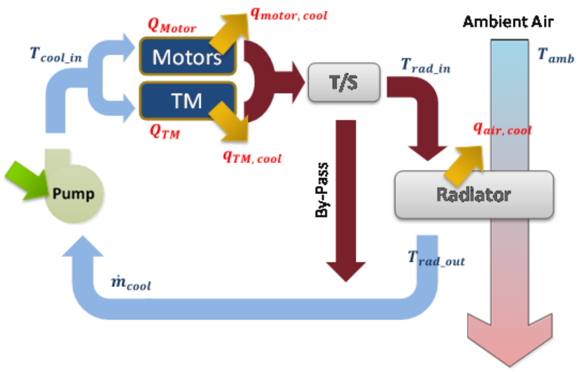


Figure 3. Schematic of cooling system architecture

The lumped thermal mass model is used for the temperature calculation of all heat-source components. In this model, the average temperature of a component is calculated from the balance of heat generation by the component, heat transfer to the coolant, and heat transfer to the ambient air.

Figure 4 shows an example of simulation results for the transmission thermal model on the UDDS cycle at an ambient temperature of 22°C.

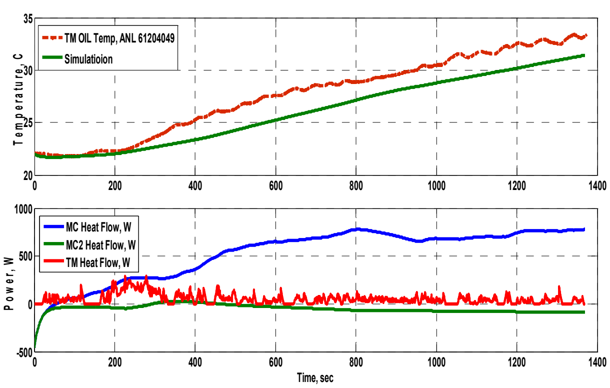


Figure 4. Transmission oil temperature and heat flow.

Engine Thermal Model

The primary goal of this work was to develop a basic response surface model (RSM) and a physics-based thermal model (PBTM) to understand the impact of engine heat transfer on the fuel consumption. The RSM method in this work uses engine torque and speed data to predict fuel consumption.

Response surface model (RSM)

The RSM explores the relationships between several process variables and one or more response variables. The main idea of RSMs is to use a sequence of designed experiments to obtain an optimal response. This model is only an approximation, but is useful because such a model is easy to estimate and apply, even when little is known about the process.

In this work, an RSM was used for predicting fuel consumption and temperature on the basis of laboratory test data. The initial approach was based on fitting multivariate quadratic surfaces to the data and then analyzing where these simple surfaces fail to produce accurate predictions. (See Figure 5.)

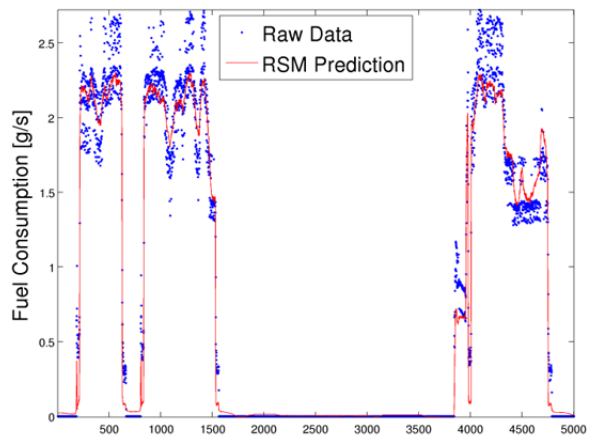


Figure 5. Sample RSM showing prediction of fuel consumption.

Physics-based thermal model (PBTM)

The useful work (brake work) from an engine depends, among other factors, on the heat lost to the engine walls and coolant. The heat lost from the engine wall depends on the temperature of the engine wall and the gas temperature in the engine. The engine wall temperature, in turn, depends on the heat flux from the hot gases in the combustion chamber on the engine side and the coolant conditions on the coolant side of the engine wall. The heat flux to the engine walls from the gases in the combustion chamber is thus also highly transient, producing temperature transients in a thin layer of the engine wall adjacent to the hot gases. The temperature oscillations of the engine wall affect engine performance and hence there is a need to develop a thermal model to model engine heat loss. On the basis of the discussion above, to compute the heat lost from the engine, one needs to compute the temporal variation of the hot engine gases and the engine wall temperature. The development of the thermal model thus has two components, namely, determination of the temporal variation of the gas temperature in the engine and computation of the engine wall temperature.

Figure 6 shows the temporal variation of the gas-side wall temperature. It is seen that in about 8 to 10 seconds the wall temperature reaches a quasi-steady state with an oscillation of about 20-25°C.

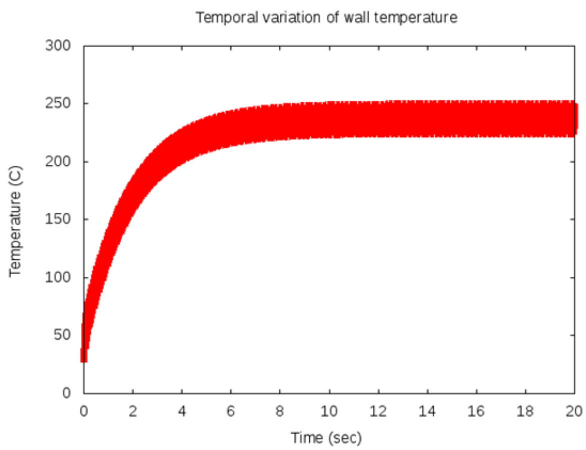


Figure 6. Temporal variation of wall temperature.

Battery Thermal Model

In the case of PHEVs, the battery pack generates considerable heat as a part of the powertrain; therefore, the climate control system includes a battery thermal management system, which controls the temperature of the battery pack. Thus, the climate control system of PHEVs consumes more power compared with that of conventional vehicles. In addition, battery thermal management is important in PHEVs because battery temperature influences the availability of discharge power (for start-up and acceleration), energy, and charge acceptance during energy recovery from regenerative braking. These affect vehicle drivability and fuel economy. Thus, the battery thermal management system is critical for the performance of the vehicle and the durability of the battery pack.

In this study, an active cooling–liquid circulation system is considered because of the high heat load from the large battery pack. The heating method of the battery pack is also considered, as shown in Figure 7.

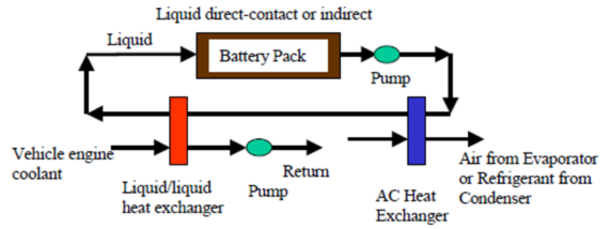


Figure 7. Active cooling and heating–liquid circulation

The simulation results for the temperature of the battery module, the voltage, and the SOC of the battery are compared with the testing results under 18°C ambient temperature in Figure 8. The simulation results closely reproduce the testing results.

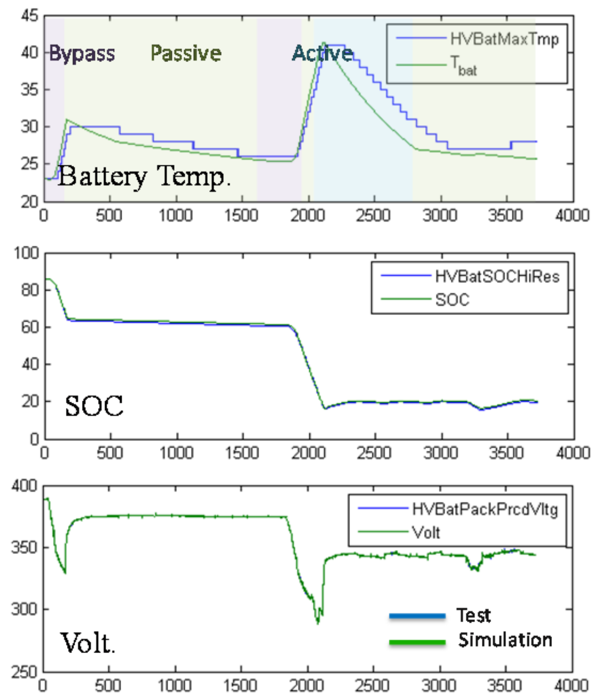


Figure 8. The simulation results and testing results under 18°C ambient temperature

Vehicle Model

The thermal models for each component are integrated in a forward-looking simulator, Autonomie. The vehicle control model is also deployed and validated with the testing data under ambient temperature.

Simulation is done using the UDDS driving schedule and the simulation results are compared with the testing results. First, the vehicle speed, engine speed, and engine torque on the UDDS cycle are compared with the testing results (Figure 9).

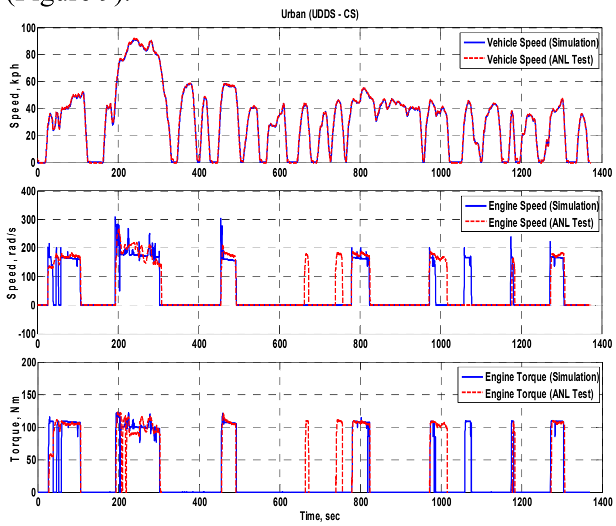


Figure 9. The simulation results and testing results for the engine on the UDDS cycle

In Figure 10, the SOC obtained from simulation on the UDDS cycle is matched well with the testing results at the first 200 seconds, since the controller tends to maintain the engine turned on to warm up the engine, and so the simulation results show an increase in the SOC at the starting of the engine. The simulations of the battery temperature and battery coolant temperature are also well matched with the testing results under ambient temperature.

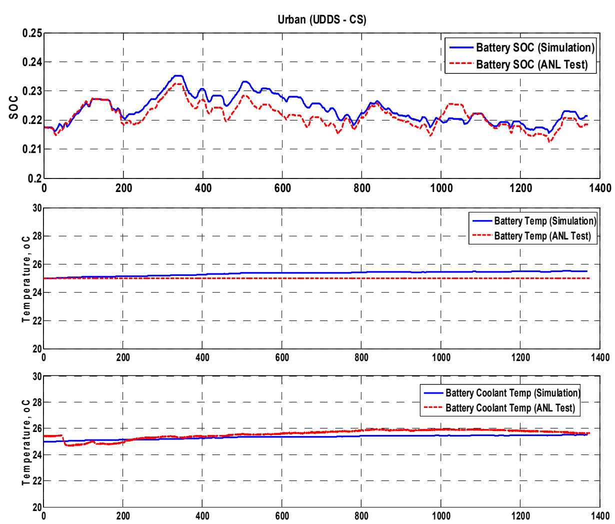


Figure 10. The simulation results and testing results for the battery on the UDDS cycle

Conclusions

- The thermal models for the engine, battery, electric machine and transmission were integrated in Autonomie. The battery model was validated with liquid coolant experimental data at the vehicle level.
- A control strategy for the GM Volt was updated on the basis of testing results from the APRF under ambient temperature. A supervisory controller for the model was deployed in Autonomie.
- Comparison between the measured and simulated engine and electric machine torque and speed showed good correlation. However, some discrepancies remain regarding the component efficiency, most likely due to uncertainties in component data combined with the control strategy

  Validation under different conditions is in progress to understand the system and update the supervisory controller.

IV.D.3. Products

Publications

1. Kim, N., Rousseau, A., Rask, E., “Toyota Prius MY2010 Validation,” Presentation to U.S.DOE, September 2011.
2. Kim, N., Rousseau, A., Rask, E., “Autonomie Model Validation with Test Data for 2010 Toyota Prius”, SAE World Congress, 2012-01-1040.
3. Kim, N., Kwon, J, Rousseau, A., “Trade-off between Multi-mode Powertrain Complexity and Fuel Consumption,” EVS25, Shenzhen, China, November 2010.

.

IV.E. HEV Vehicle Level Control Development under Various Thermal Conditions

Principal Investigator: Aymeric Rousseau (Project Leader), Namwook Kim
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-7261; Email: arousseau@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

IV.E.1. Abstract

Objective

- Analyze the control behavior under various thermal conditions.

Approach

- Test a real-world vehicle at different thermal conditions.
- Analyze the test results and find control parameters that determine the control behaviors.

Major Accomplishments

- Designed control logics that realize real-world behavior at different thermal conditions.
- Found temperature thresholds to turn off the engine, control the engine speed, and limit the battery power on braking modes.

Future Activities

- Integrate the controller with thermal component models and validate the models with the test results.

IV.E.2. Technical Discussion

Background

The control of real-world vehicles should be designed to be capable of managing the temperature of the components in appropriate ranges. For instance, engine coolant is needed to cool the engine down because it generates a lot of heat that cannot be spontaneously rejected by the ambient air. On the other hand, it is necessary to heat the engine when it becomes too cold because engine efficiency is very low if the temperature is too low. Likewise, battery operation could be also affected by the component temperature. To realize the effect of the component in the controllers, we tested the real-world Prius (model year 2010 [MY10]) according to different thermal conditions and analyzed the control behavior on the basis of the test results.

Introduction

According to the request of those performing thermal analysis in vehicle simulation, thermal component models for Autonomie are under development, so that the additional power or energy affected by thermal conditions is estimated through simulation techniques. For instance, the engine fuel consumption can be estimated by a Response Surface Model (RSM) when the engine temperature is one of the input variables of the model, as shown in Figure 1.

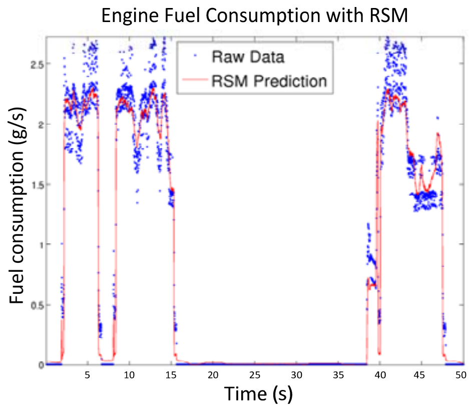


Figure 1. Fuel consumption is estimated based on a response surface model where the engine temperature is used as one of the input variables of the model.

Even though we have thermal models that appropriately predict performance, we still need the controller that reproduces the real-world behavior of the vehicle component accurately according to the thermal conditions. For instance, engine on/off could be controlled based on the engine temperature, or battery power also could be limited by the component temperature. To reproduce these control behaviors, we analyzed the test results of the Prius MY10 obtained from the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (Argonne).

Approach

Argonne has systematic processes to conduct vehicle tests, and the testing procedures are classified by two levels.

- Level 1: test the overall performance of the vehicle based on signals that are easy to access.
- Level 2: test with more signals obtained by attached devices to measure the additional signals.

For instance, the torque and speed sensor are mounted between the engine output axis and the transmission input axis for the Level 2 test. To analyze the control behavior for the thermal conditions, the results from the Level 2 test are used in this study. Further, the APRF was renovated to be able to benchmark a vehicle's behavior according to different ambient temperatures, as shown in Figure 2; and the test results from the new facility will be available for following studies.

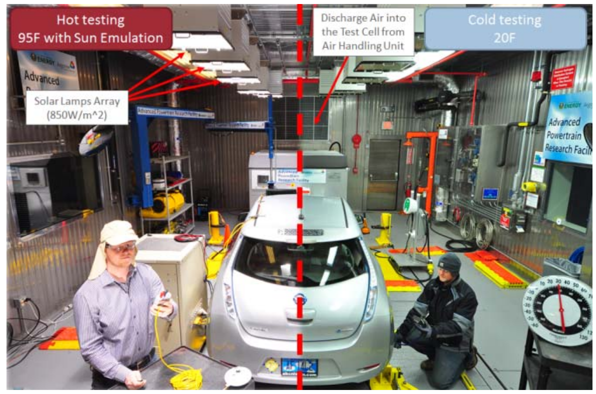


Figure 2. The thermal chamber in the APRF is able to control the ambient temperature from 20F to 95F.

With different starting engine temperatures, the vehicle is tested on various driving schedules, as shown in Figure 3.

	Cycle	Cycle length(s)	Engine starting temp (°C)		Cycle	Cycle length(s)	Engine starting temp (°C)
1	Accels_merge	258.1	72.5 - 92	14	UDDS_prep_merge	1372.9	70 - 87.5
2	Cycle_505_2_merge	1019.5	75 - 88.5	15	UDDScs_merge	1372.9	22.5 - 78.5
3	Hwy_01_merge	764.9	88.5 - 88.5	16	UDDShs_01_merge	1372.9	66 - 85.5
4	Hwy_02_merge	764.9	88.5 - 88.5	17	UDDShs_02_merge	1372.9	69 - 86
5	JC08_01_merge	1204.9	55 - 85	18	UDDShs_03_merge	1372.9	74.5 - 87.5
6	JC08_02_merge	1204.9	68 - 88	19	US06_01_merge	599	78.5 - 90
7	LA92_01_merge	1431.5	46.5 - 90.5	20	US06_02_merge	598.9	92.5 - 89
8	LA92_02_merge	1433.9	74.5 - 90.5	21	SS_0pct_Grade	549.6	80 - 89
9	NEDC_01_merge	1164.9	70 - 88.5	22	SS_0p5pct_Grade	549.6	84.5 - 89.5
10	NEDC_02_merge	1164.9	77 - 88.5	23	SS_1pct_Grade	549.6	89.5 - 89.5
11	NYCC_merge	607.6	23 - 57.5	24	SS_2pct_Grade	549.6	88 - 90
12	SC03_01_merge	599.9	45 - 77	25	SS_4pct_Grade	549.6	90.5 - 89.5
13	SC03_02_merge	599.9	63 - 84.5	26	Long_SS_Warmups	1800	24 - 89.5

Figure 3. A list of test cycles and starting thermal conditions for the Prius MY10

Focusing on the engine control, we analyzed how the engine temperature impacts on the engine on/off control, and we also analyzed the effect of the battery temperature on the power limitation of the battery.

Results

Engine Control According to Temperature

To analyze the engine control behavior according to the engine temperature, three test cases are introduced in this study. The three test results are obtained on the first 350 seconds on the Urban Dynamometer Driving Schedule (UDDS), although they have different starting engine temperatures: 22ºC, 69ºC, and 88ºC. Figure 4 shows that the vehicle successfully runs on the cycle regardless of the starting temperature.

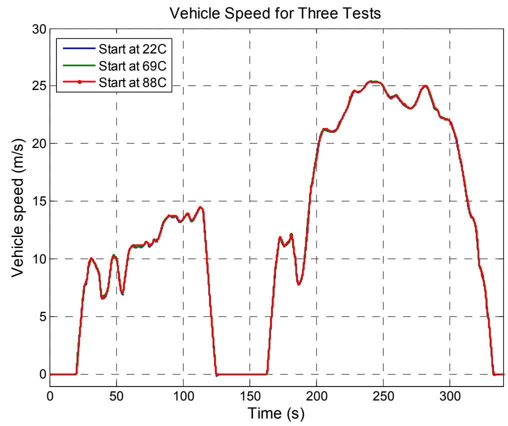


Figure 4. Vehicle speed for three selected tests. All of the test driving cases run well on UDDS.

According to the starting temperature, the engine temperatures show different variations, as shown in Figure 5.

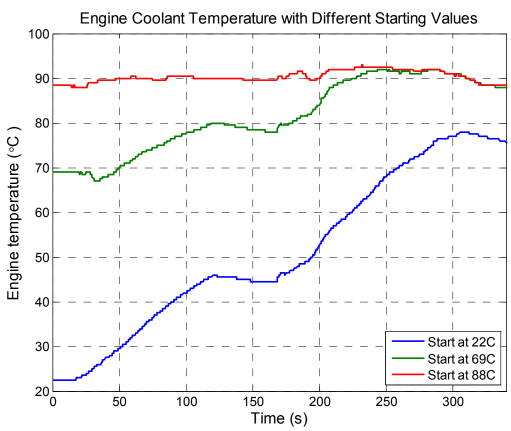


Figure 5. Temperature variations of the engine according to the starting temperatures. The output temperature of the engine coolant is measured and is assumed to be the engine temperature.

The main results of the analysis are that the engine operation differs according to engine temperature, as shown in Figure 6. In the figure, the engine is only fully turned off when the engine temperature is high enough. If the temperature is low, the engine is not turned off but, instead, remains on idle.

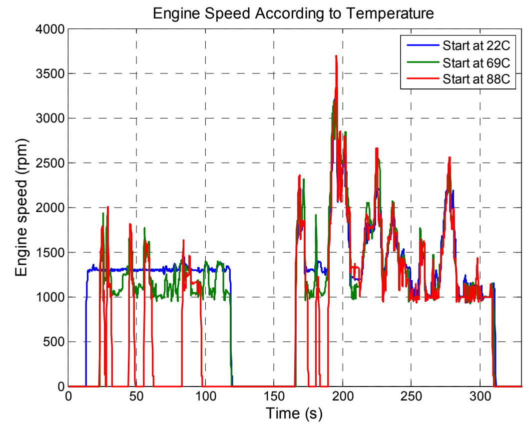


Figure 6. Engine operating speed according to the starting temperature.

Although the engine is not turned off, it behaves differently according to the temperature. In Figure 7, the engine that started at 22ºC does not produce power to launch the vehicle, whereas it produces power after it reaches the 60-second (s) mark, which means that the engine is only operating for warming up the engine, and the motor provides all propulsion power under low temperature (i.e., 35ºC).

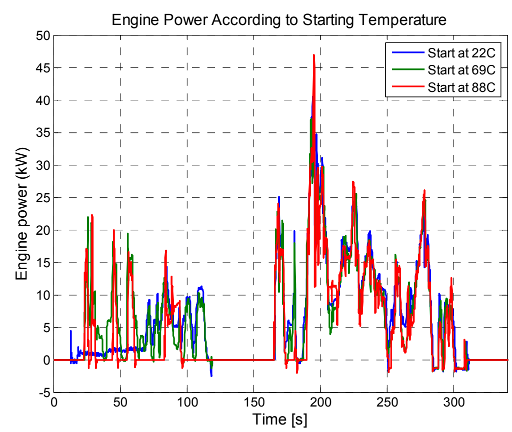


Figure 7. In starting at 22ºC, the engine does not provide power to drive the vehicle until 60 s, which means that the motor provides all power needed to run the vehicle.

Further, the results show that the engine is not turned off until the engine temperature reaches a very high temperature, such as 80ºC, and, in the middle temperatures from 35ºC to 80ºC, it produces the desired power if needed and remains on idle if the power is not needed (Figure 8).

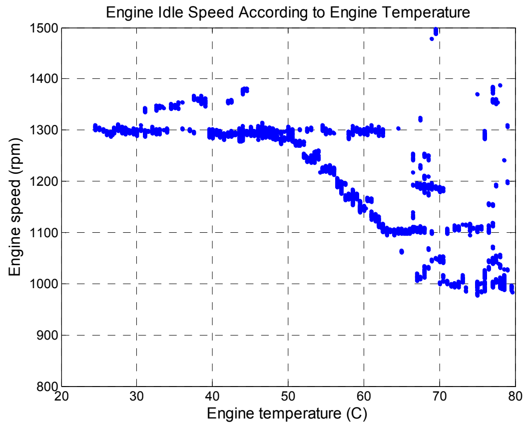


Figure 8. The engine speed is also controlled by the engine temperature when the engine is not hot enough.

On the other hand, the engine speed decreases when the engine temperature increases even if the engine is under the idle state. By targeting higher-than-normal idle speed, this control helps the engine rapidly increase the temperature when the engine is too cold.

According to the analyzed results, a controller as shown in Figure 9 is designed and applied to the Prius MY10 in Autonomie.

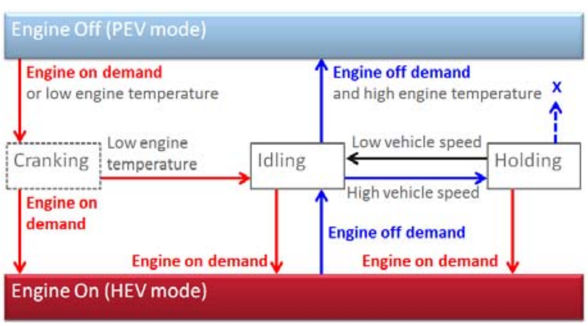


Figure 9. Engine controller that realizes the engine on/off according to the engine temperature.

Battery Power Limitation According to the Temperature

The battery for the Prius MY10 has a maximum power close to 30 kW during charging modes. Figure 10 shows the motor power according to the battery temperature when the electrical braking is limited and the mechanical braking supports the electrical braking to slow down the vehicle.

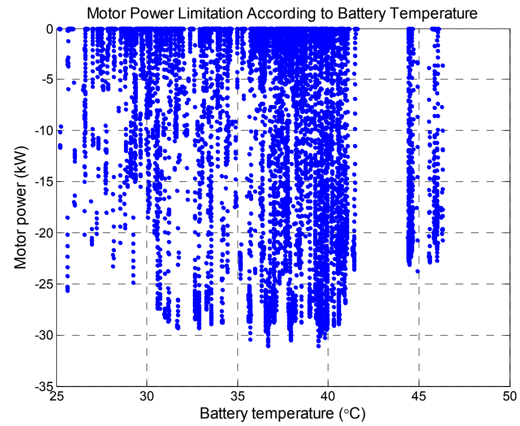


Figure 10. Motor power on braking modes when the motor power is limited by the battery power.

The motor power could be limited by safety issues or other control issues. However, we found that the maximum power of the motor is also limited by the battery temperature, as shown in Figure 10.

Conclusions

By analyzing results obtained from testing the Prius MY10, we can observe the following findings:

Engine Control

- In low engine temperature, the engine stays on idle speed.
- In middle-range temperatures, the engine produces desired power or remains on idle.
- In high temperature, the engine is turned off if it is not needed to propel the vehicle.
- If the engine is on idle, the engine target speed is controlled according to the temperature.

Regeneration Control

- The motor power is limited by the battery temperature.

On the basis of these results, we designed the engine control logic that realizes the control behavior. The controller will be applied to the thermal vehicle model and will be validated with the test data after all thermal components are developed and integrated into Autonomie.

IV.E.3. Products

Publications

1. Kim, N., A. Rousseau, and E. Rask, "Vehicle-level Control Analysis of 2010 Toyota Prius Based on Test Data," IMechE Part D: *J. Automobile Engineering*, in print, 2012 doi:10.1177/0954407012445955.
2. Kim, N., and A. Rousseau, "Autonomie Model Validation with Test Data for 2010 Toyota Prius," in *Proc. SAE World Congress*, Detroit, Mich., 2012, 2012-01-1040.

IV.F. Fuel Consumption Benefits of Advanced Engine Technologies

Principal Investigator: Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-2853; Email: arousseau@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

IV.F.1. Abstract

Objective

- Evaluate the fuel displacement potential of several advanced engine technologies for different powertrain configurations — ranging from conventional powertrains to those of hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs).

Approach

- Develop engine data sets representing different incremental technologies based on the same baseline using a high-fidelity engine plant model.
- Select the different powertrain configurations.
- Size the vehicles to meet the same technical specifications.
- Run the simulations.
- Analyze the benefits of each engine technology for the different powertrains.

Major Accomplishments

- Six engine technologies have been developed using high-fidelity plant models based on the same baseline.

Future Activities

- Define the vehicles and perform the simulations.
- Write report.

IV.F.2. Technical Discussion

Background

Because of to the increasingly stringent Corporate Average Fuel Economy (CAFE) regulations, car manufacturers are aggressively looking for technologies to minimize fuel consumption. One of the main targets for improvements remains the internal combustion engine (ICE). Despite numerous improvements to the ICE over past decades, still more technology options are currently being considered for a wide range of powertrain applications.

Introduction

The objective of the study is to evaluate the fuel displacement potential of several advanced engine technologies for different powertrain configurations — ranging from conventional powertrains to those of HEVs and PHEVs.

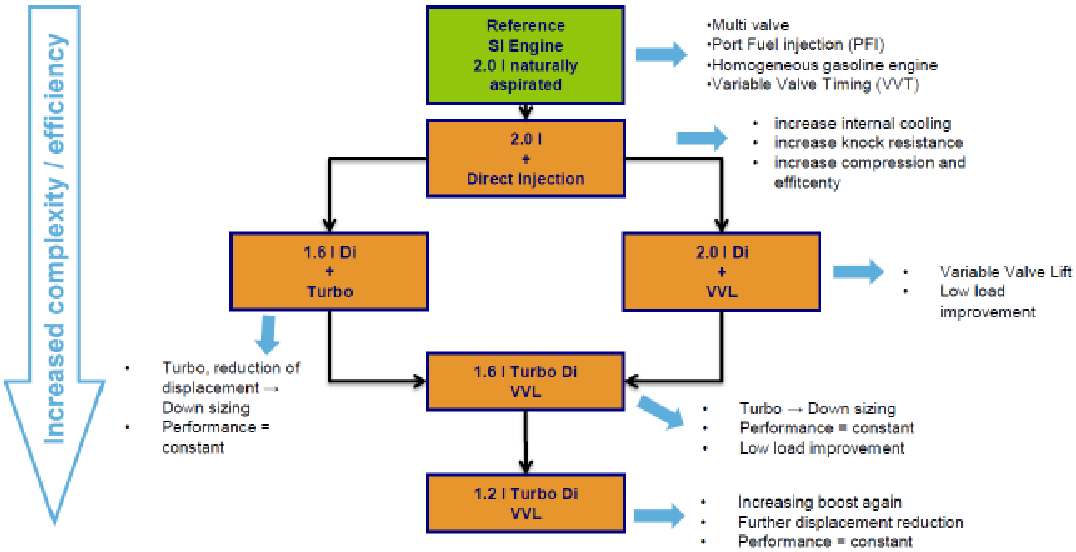


Figure 1. Engine Technologies Considered.

Approach

The first step of the simulation work is to create brake-specific fuel consumption (BSFC) maps of six engines equipped with several advanced technologies (see Figure 1). Two existing engine models, which have been tuned and validated with measurements, are used as the starting point for all investigations. Use of the combustion model helps in understanding the impact of the selected technologies on the in-cylinder combustion.

For the engine simulation work, the following prerequisites are assumed:

- Only steady-state data are required.
- Results of simulation are required for warmed-up engines.
- One variant of low-load technology is used in this study.
- Engines are designed for gasoline fuel.
- A downsized Turbo engine is part of the investigation.
- The low-load improvements used in the simulation are also applicable for idling.
- The idle speed will have the same value for all variants.

The start point for the investigation is a state-of-the-art, 4-cylinder, 2.0-L gasoline engine. The engine is equipped with port fuel injection (PFI), 4-valve technology, homogenous combustion, and variable valve train timing. Comparable variants of this engine are built by adding these technologies:

- Direct fuel injection (DI)
- Variable valve lift technology (VVL)
- Downsizing

Once the engine maps are generated, the following powertrain configurations were selected:

- Conventional
- Micro HEV
- Mild HEV
- Pre-transmission HEV
- Pre-transmission PHEV
- Voltec PHEV

As previous studies have demonstrated the impact of advanced transmission technologies on the fuel displacement potential of engines, several transmissions will be considered as well.

All of the vehicles will be sized to meet the same technical specifications, including performance and gradability.

Results

The six engine maps have been successfully developed using high-fidelity engine models. The baseline engine model was validated using test data.

Using a generic process, the engine initialization files have been created in Autonomie. Then, using default conventional vehicle models, preliminary simulation results show that the fuel consumption rates we obtained are within the range of values found in the literature.

Conclusions

The six engine maps have been developed successfully using high-fidelity engine models. Each set of data has been developed using incremental technologies, an approach that is critical to providing a fair comparison. The data have been implemented into Autonomie. Future work will include vehicle sizing, as well as running the simulations.

IV.F.3. Products

Publications -None

Patents -None

Tools & Data - None

IV.G. Optimal Energy Management of a PHEV Using Destination Information, GPS, and Traffic Estimation

Principal Investigator: Dominik Karbowski, Sylvain Pagerit, Daeheung Lee, Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: 1-(630) 252-5362; Email: dkarbowski@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: david.anderson@ee.doc.gov

IV.G.1. Abstract

Objective

- Assess the fuel consumption benefit of an optimal energy management of a plug-in hybrid vehicle (PHEV) using destination information, global positioning system (GPS), and traffic estimation.

Approach

- Understand the type of data on future trips that can be made available to a car controller.
- Link Autonomie to a GIS tool that provides that type of data on a desktop computer.
- Process data from the GIS to make it usable for future trip predictions.
- Generate a target speed for the vehicle on future trips using the GIS tool.
- Develop high-level energy management strategies that take advantage of the information about the future trip.
- Perform vehicle simulations using conventional control strategy and "trip-based" strategy.
  Analyze results.

Major Accomplishments

- Developed a partnership with NAVTEQ, a leading provider of digital maps.
- Developed a plug-in for the Advanced Driver Assistance Systems-Research Platform (ADAS-RP), a NAVTEQ GIS tool that is able to send information on a trip defined in ADAS-RP to a readable format for Autonomie.
- Created algorithms that interpret the information provided for each link of the trip to create a speed target.
- Created a distance-based driver that allows analysts to run a simulation using that speed target.
- Created an optimal controller that results in lower energy consumption compared to a classic control strategy.

Future Activities

- Evaluate the real-world validity of the speed targets generated from ADAS RP information.
- Create a process where the simulated trip (a model for the actual trip) is different from the horizon trip. This activity is intended to represent the real-world scenario in which predicted and actual trips may be close but will never fully match.
- Use an optimal controller on routes defined by the user and evaluate the fuel consumption benefit.
- Using recorded real-world trips, evaluate the potential real-world benefit(s) of this technology.
- Create an integrated, user-friendly process in Autonomie.

IV.G.2. Technical Discussion

Background

Most research on vehicle energy efficiency relies on predefined drive cycles as benchmark tests. Although this approach provides repeatable results and allows for easy comparisons, it ignores the relationships between the driver, the vehicle controller, and the environment.

Future route prediction is a promising research topic because such data are essential inputs for optimal controllers for PHEVs. Dynamic programming and the Pontryagin minimization principle (PMP) are the two main control theory techniques used for advanced powertrains. Both require full knowledge of the trip profile ahead to compute the optimal control law. Some heuristically optimized controls also rely on trip prediction.

This research aims to assess how well optimal control will perform if it is fed the type of input data that realistically can be available in the real world.

Approach

Linkage between Autonomie and ADAS-RP

ADAS-RP (Advanced Driver Assistance Systems-Research Platform) is a software framework developed by NAVTEQ. It is used to develop prototypes of applications that use positioning and maps for a wide range of applications, from eco-routing to headlamp orientation in turns.

In a typical utilization, the user can select a starting point and destination on a map integrated in the graphical user interface (GUI). The internal map engine then computes the most likely route, and it is possible to see the attributes of each link.

An Autonomie plug-in for ADAS-RP was created and is displayed as a tab in the ADAS-RP GUI. From that tab, the user can export the cycle, which saves relevant data in a comma-separated file (CSV).

The user then switches to the Autonomie GUI. After defining the vehicle to simulate, he/she chooses an "ADAS-RP" to process and selects the CSV file corresponding to the trip to be simulated.

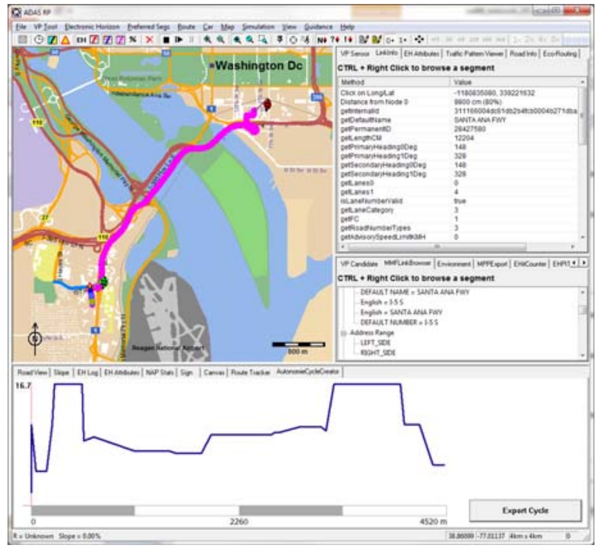


Figure 1. Screenshot of ADAS-RP, in the top left corner, a map shows the itinerary selected by the user. Along the bottom is the plug-in to export to Autonomie.

From Raw Link Data to Target Speed

The data produced by ADAS-RP contain a lot of useful information about the road travelled. The most important is speed, which comes from various signals, depending on the level of details contained in the map. Speed limit and traffic pattern speed (i.e., estimated average speed based on historical data) are also very important factors. Another important piece of information concerns the locations of stop signs and traffic lights. However, stop times are not provided and need to be estimated. The traffic pattern speed is also an average speed and already "includes" those stop times.

The first step in the raw data processing is to estimate the stop times at stop signs and intersections. This is accomplished by having a traffic light model to predict the waiting time (if any) and an adjustment factor for heavily congested links.

The second step is to estimate the actual speed from traffic pattern speed, adjusting for stops along the way and speed changes. It is assumed that the trip is composed of a continuous succession of constant accelerations, constant speeds, and constant decelerations, as seen in Figure 2.

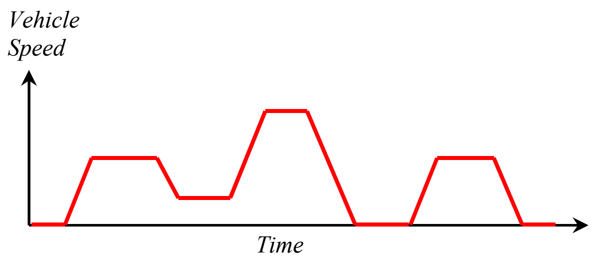


Figure 2. Example of speed profile

Whenever a stop is planned, an algorithm computes the target speed so that the average speed on the link matches the traffic pattern speed after the inclusion of constant speed, acceleration, and stop subsections. Figure 3 shows those two speeds in an example trip.

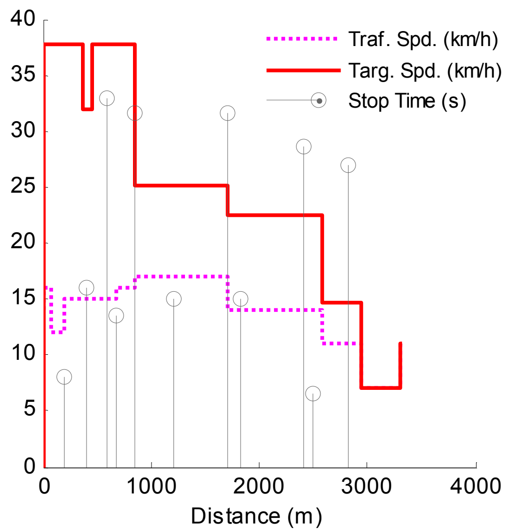


Figure 3. Traffic speed (from ADAS-RP), target speed, and durations of stops for a sample trip.

The third step is to compute the final driver speed demand for use in simulation by adding speed transitions at discontinuities, for example, when the target speed changes or when the vehicle needs to stop.

Following all of those steps, the driver speed demand can be fed to a distance-based driver in any vehicle in Autonomie. Figure 4 shows an example of simulation. It clearly illustrates the differences between the traffic speed from ADAS-RP, the target speed that does not include stops, and the final driver speed demand that includes stops and all speed transitions.

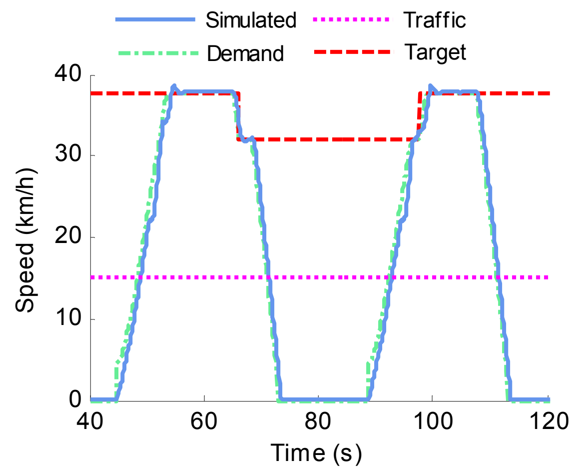


Figure 4. Speed changes, decelerations, accelerations, and stops in simulation.

PHEV Energy Management Optimization

An optimal controller for PHEV was developed using the Pontryagin minimization principle. The vehicle considered is a one-mode, power-split (2012 Prius PHEV). The state of the system is S, the battery state of charge (SOC). Once the battery power P_{bat} is given, there is only one way to operate the engine that minimizes the fuel consumption $\dot{m}_f$:

$$\dot{m}_f = g(P_{bat}, S)$$

The battery power therefore appears as the command variable for the system. The state follows a dynamic equation linking it to the command variable:

$$\dot{S} = f(P_{bat}, S)$$

Finally, the optimization problem is to minimize the fuel rate, with constraints on S and P_{bat}, as well as initial and final conditions for the SOC:

$$\min_{P_{bat}}\left(\int_0^T g(P_{bat}, S)dt\right)$$

The Hamiltonian of the system is:

$$H = g(P_{bat}, S) + p(t)f(P_{bat}, S)\,,$$

where p is the co-state and follows the co-state equation:

$$\dot{p}(t) = -p(t)\frac{\partial f}{\partial S}$$

In the case of hybrid electric vehicles (HEVs), f does not vary very much in the function of the SOC, so we can assume that the co-state is constant. As a result, the optimal command is the one that at each time step minimizes the Hamiltonian:

$$P_{bat}^{*} = \underset{P_{bat}}{\operatorname{argmin}}\left((P_{bat}, S) + p_0 f(P_{bat}, S)\right)$$

The challenge is to find the co-state that results in the target SOC at the end of the trip. Several techniques were tested. One called "shooting method" consists in running simulations with a broad range of co-states, eventually finding the right co-state. This method, although it is accurate, is computationally intensive. A faster way to estimate the co-state is to predict the battery energy that is going to be recuperated during the cycle. This value can then be used to compute the effective SOC drop, $\Delta SOC_{drv,eff}$. The co-state is then proportional to the effective drop in SOC. Figure 5 illustrates how it is computed.

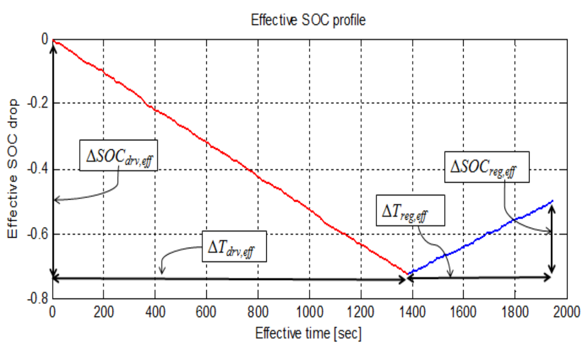


Figure 5. Computation of the effective drop in SOC

Results

Simulation of Trips Defined by the User

We successfully demonstrated the interoperability between ADAS-RP and Autonomie. Several trips were built and simulated on both conventional and HEV vehicles. Figure 6 shows the rates of fuel consumption for both vehicles on those trips.

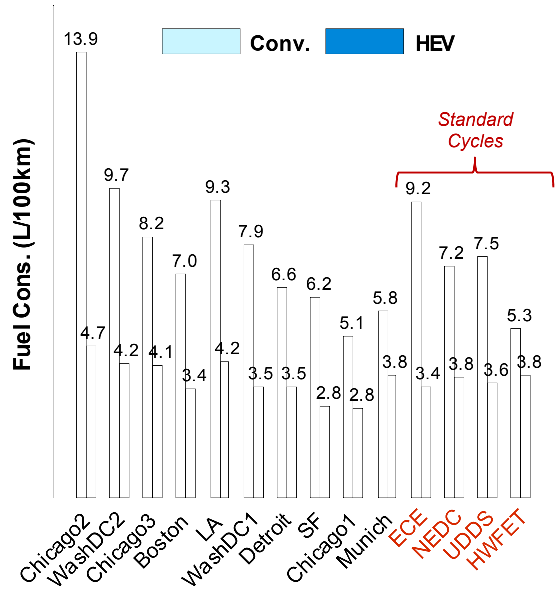


Figure 6. Rates of fuel consumption of conventional vehicle and HEVs in selected real-world itineraries and standard cycles

In addition to providing the speed target, the tool also provides a high grade of accuracy. Control strategies can then be tested on trips with elevation changes, which can have significant impacts on fuel consumption. For example, Figure 7 illustrates a trip in the San Francisco Bay area and the SOC profile of an HEV performing that trip.

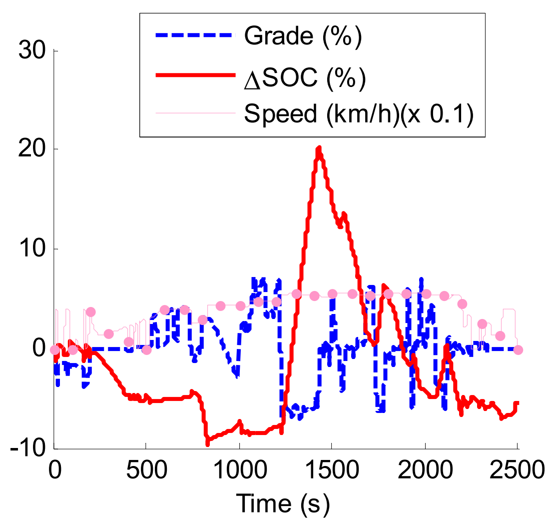


Figure 7. Battery SOC* and grade on a San Francisco Bay area itinerary where *ΔSOC = SOC – SOC(t=0)

Optimal Control

The optimal controller was tested on standard cycles and led to non-negligible fuel savings, as shown in Table 1.

Table 1. Comparison of fuel use using a classic PHEV control and another that is trip-based.

Control Method for PHEVs	Fuel Use	Fuel Economy	Final SOC	Fuel Savings
CD+CS Mode	758 g	139 mpg	26.37%	Reference
Prediction-based PMP Control	695 g	152 mpg	26.25%	+9.1%

Conclusions

A process was created to generate a speed schedule including grade and stops anywhere in the United States. This process relies on NAVTEQ's ADAS-RP for the trip definition and geographical information and on Argonne's Autonomie for vehicle simulation.

A PHEV control using trip information was implemented, and it showed promising results on standard cycles. That control will be compared to a standard PHEV control, and the benefits of trip-based control will be quantified by using information obtained from real-word trips.

This study will demonstrate that trip information can be used successfully to improve PHEVs' energy efficiency and thus their success.

In addition, the map-based speed target generation will have numerous side applications, such as green routing, fleet fuel consumption estimation, selection of optimal powertrains for specific routes, etc.

IV.G.3. Products

Publications

1. Karbowski, D., S. Pagerit, and A. Calkins, Energy Consumption Prediction of a Vehicle along a User-Specified Real-World Trip, EVS 26, Los Angeles, Calif., May 2012.
2. Lee D., S.W. Cha, A. Rousseau, N. Kim, Optimal Control Strategy for PHEVs Using Prediction of Future Driving Schedule, EVS 26, Los Angeles, Calif., May 2012.
3. Karbowski D., S. Pagerit, Optimal Energy Management of a PHEV Using Trip Information, 2012 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review, May 15, 2012.

Tools and Data

1. Linkage between ADAS-RP and Autonomie.

IV.H. Impact of Worldwide Test Procedures on Advanced Technology Fuel Efficiency

Principal Investigator: Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-7261; Email: arousseau@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov

IV.H.1. Abstract

Objective

- The objective of the study is to evaluate the impact of the current and future worldwide test procedure on the energy consumption benefits of advanced technologies

Approach

- Select a large number of advanced powertrain technologies
- Size the vehicles to meet similar Vehicle Technical Specifications
- Simulate each vehicles on the different standard drive cycles
- Evaluate the benefits of each technology

Major Accomplishments

- Highlighted significant discrepancies related to the fuel and electrical consumptions of the powertrains for the drive cycles considered
- Conventional and series fuel-cell HEVs favor high speed with little idling, while power-split HEVs offer higher fuel benefits on low-speed cycles.
- BEVs are not significantly impacted by the drive cycle.
- When looking at the current market share of the technologies worldwide, there appears to be a correlation with the current drive cycles.

Future Activities

- Considering that a new WLTC drive cycle will be adopted soon, future studies will need to analyze its impact on future technology shares

IV.H.2. Technical Discussion

Background

In an effort to reduce the dependence of transportation on fossil oil, a great number of alternative automobile technologies have been proposed. These technologies include start-stop systems, hybrid and plug-in hybrid vehicles, full electric vehicles, and fuel cell vehicles. Some have already been introduced to the market, while others await further technological development.

To meet future government regulations, such as Corporate Average Fuel Economy (CAFE) in the United States and CO2 in Europe, the assessment of vehicle fuel consumption is critical. Different standard test procedures have been developed to evaluate vehicle performance. The U.S. Environmental Protection Agency uses the two-cycle procedure based on the Urban

Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET). Similarly, Europe relies on the New European Driving Cycle (NEDC), and Japan uses JC08. Vehicle energy consumption varies from cycle to cycle due to the different driving conditions that are represented.

Introduction

This study focuses on the assessment of the performance of various powertrain technologies on the different standard test cycles, in terms of fuel and electrical consumption. The results of this study are then related to the car sales in different regions of the world, in an attempt to examine some choices made by carmakers.

Approach

By using Autonomie, different powertrain configurations and component technologies were selected to represent 2015 technologies for three risk levels. These models are simulated on worldwide test cycles. The fuel consumption results simulated are then compared and related to drive cycle parameters, including mean speed, stop time, stop frequency, and so forth. In addition, the levelized cost of driving is calculated on several scenarios. Finally, the fuel consumption results are related to worldwide car sales data in an attempt to determine a correlation between them.

Powertrain Configurations

The vehicles simulated cover a variety of powertrain technologies, including:

- Conventional midsize 2wd SI (conv)
- Conventional midsize 2wd CI
- Split 2wd HEV SI (HEV)
- Split 2wd PHEV 10 (PHEV10)
- GM Volt 2wd EREV (PHEV40)
- Series midsize Fuel Cell HEV (FC HEV or FCV)
- Electric fixed-gear 100 (BEV FG 100)
- Electric fixed-gear 300 (BEV FG 300)
- Electric AMT 2-speed 100 (BEV AMT 100)
- Electric AMT 2-speed 300 (BEV AMT 300)

Vehicle Sizing

When sized, the vehicles must meet certain vehicle technical specifications:

- For conventional vehicles:
  - Minimum time for an acceleration (0 to 60 mph) is 9 seconds,
  - Minimum time for a passing (50 to 80 mph) is 9 seconds, and
  - Vehicles are sized to perform at a 6% grade at 65 mph at gross vehicle weight.
- For full hybrid electric vehicles (HEVs), in addition:
  - Minimum engine peak power is 70% of maximum between requirements from acceleration and grade performances, and
  - Regenerative power is captured on the UDDS cycle.
- For plug-in hybrid electric vehicles (PHEVs), in addition:
  - Vehicles must be able to run the UDDS cycle in electric mode for the PHEV10 and the US06 cycle for the E-Rev.

Automated vehicle sizing algorithms are used to rigorously define the characteristics (i.e., power, energy, and weight) of each component of the vehicle to provide consistent results.

Driving Cycles

Currently, countries and organizations have developed their own standard test cycles, such as UDDS and HWFET in the United States, NEDC in Europe, and Japan1015 and the new JC08 in Japan. In addition, a new cycle, called Worldwide Harmonized Light-Duty Driving Test Cycle (WLTC), is now under development. The objective is to adopt a single driving cycle worldwide to provide a consistent set of vehicle fuel and electrical consumption values to customers and regulators. Figure 1 shows the main characteristics of each drive cycles considered.

		JC08	UDDS	NEDC	WLTC	HWFE
Max accel.	m/s^2	1.69	1.48	1.07	1.88	1.43
Mean accel.	m/s^2	0.43	0.50	0.59	0.41	0.19
Max decel.	m/s^2	1.22	1.48	1.43	1.52	1.48
Max speed	mph	50.70	56.70	74.60	81.60	59.9
Mean speed	mph	15.21	19.66	20.95	28.85	48.4
Mean running speed	mph	21.55	24.14	27.77	33.06	48.5
Distance	miles	5.09	7.48	6.87	14.43	10.2
Stop frequency	per miles	2.17	2.28	1.90	0.56	0.10
Stop time pct.		29.65%	18.85%	24.83%	13.00%	0.52
Cruising time pct.		0.58%	6.77%	38.51%	0.49%	16.60
Accel. time pct.		36.13%	39.71%	20.91%	44.03%	44.18
Decel. time pct.		33.64%	34.67%	15.75%	42.48%	38.69

Figure 1. Standard Drive Cycle Parameters All the fuel and electrical consumption adjustments (i.e., unadjusted to adjusted for the United States, as well as specific processes such as PHEV utility weighting factors for the United States or Europe) have been used in the study.

Results

Drive Cycle Results

Figure 2 shows the fuel consumption ratio of micro, mild, and full HEVs compared to their respective conventional vehicles. The highest benefits are achieved on the JC08 cycle, followed by the NEDC. The U.S. Combined Cycle and WLTC offer similar levels of savings.

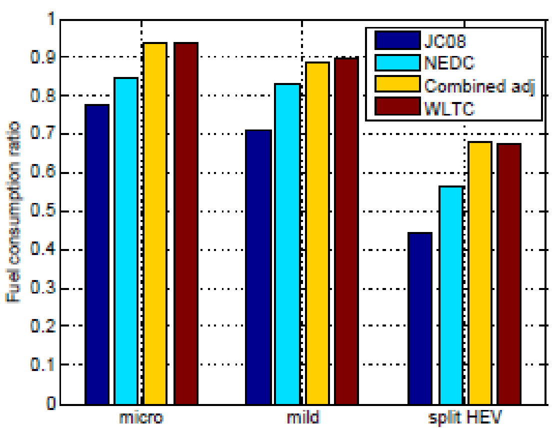


Figure 2. Fuel Consumption Ratio of Micro, Mild, and Full HEVs Compared to Their Respective Conventional Vehicles.

Table 1 provides the fuel consumption ratio for a sample of powertrain configurations compared to the Combined drive cycle. Results show that, while the WLTC and the Combined drive cycle show similar benefits for the different configurations, both the JC08 and the NEDC are much more favorable to electrification than other cycles.

Table 1. Fuel Consumption Ratio Compared to the Combined Drive Cycle

	JC08	NEDC	Combined	WLTC
Conv	0.97	0.85	1.00	0.80
Micro HEV	0.80	0.77	1.00	0.80
Mild HEV	0.78	0.79	1.00	0.80
Split HEV	0.63	0.70	1.00	0.79

Origins of Fuel Savings

Fuel savings are achieved through different advanced technologies. Each benefit is influenced by cycles in different ways. This study analyzed the impact of several parameters, including

- Idle consumption,
- Regenerative brake benefits,
- Efficiency of powertrain components, and
- Engine ON/OFF events.

However, only the idle consumption and the component efficiencies will be presented

Idle Consumption

Figure 3 shows the portion of fuel consumed during idling for the different drive cycles considered. The fuel savings of micro-hybrids are realized almost solely by removing the idle consumption. As such, their benefits on the new WLTC will certainly be lower than for the current JC08 cycle in Japan, thereby potentially influencing the penetration of the technology in the market.

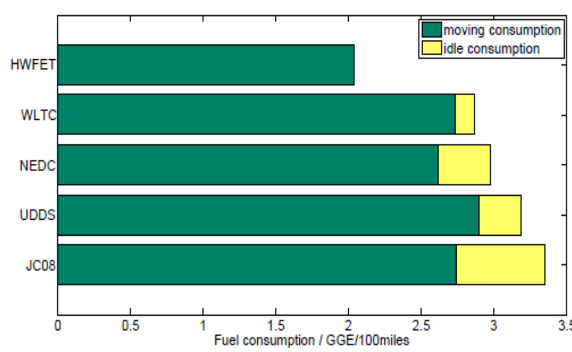


Figure 3. Idle Consumption of Conventional Vehicles.

Engine Efficiency

Figure 4 shows the average engine efficiency of the powertrain considered over the different standard drive cycles. It is well known that the average engine efficiency of conventional vehicles in urban driving conditions is lower than that achieved under high-speed conditions. One potential benefit of hybridization is to increase the average engine efficiency by decoupling its speed from the vehicle speed. With a higher average cycle speed (i.e., WLTC) the benefits of hybridization for the low-speed cycles (i.e., JC08 or UDDS) would significantly decrease. As a result, the technology would not appear as attractive to car companies striving to meet their CO2 requirements.

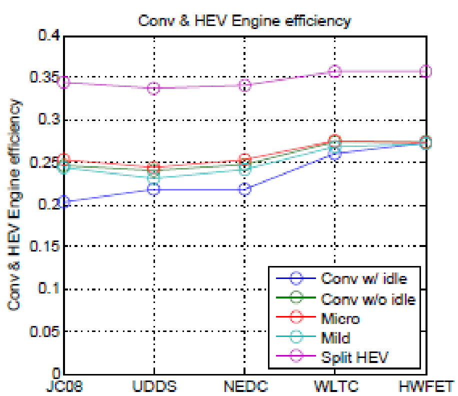


Figure 4. Average Engine Efficiency over Different Cycles.

Economic Analysis

The levelized cost of driving was used as a metric to evaluate the benefits of different technologies. The 2015 U.S. Department of Energy (DOE) cost targets for each component technology were used to assess manufacturing costs.

While the vehicle costs are maintained constant across all drive cycles, the fuel prices are varied per region by using the factors shown in Figure 5.

	Gasoline	Electricity
France	×2.2	×1.7
Germany	×2.2	×3.2
Japan	×2.0	×2.0

Figure 5. Adjustment for International Fuel Price.

Figure 6 shows one example of results when assuming the adjusted fuel price for a 3-year payback. The HEV, PHEV10, and battery electric vehicle 100 (BEV100) are able to recover the additional cost for a 3-year analysis period assumption. The PHEV40 also is able to rival the cost of conventional vehicles when considering the high-case scenario. A BEV with a 300-mile range, however, will not provide an acceptable return on investment.

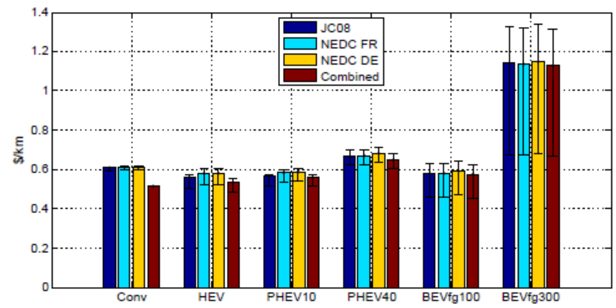


Figure 6. Levelized Cost: 3-Year Payback.

Impact of Standard Cycles on Market Shares

The market of alternative vehicle technologies is disparate throughout the world. For example, among the commercialized models, the full hybrid is much more popular in the United States than in Europe. Statistics for 2010 indicate that HEVs constituted 3.9% of the total sales, while in the European Union the share was 0.6%. Conversely, start-stop systems have penetrated well in the European market, but there are few in the United States. In Japan, the sales of full HEVs have significantly increased in the past two years. Although numerous factors influence customer choices, our analysis indicates that the preference for the standard drive cycle is of critical importance. Indeed, HEVs show much higher benefits on the JC08 than on other cycles, partially explaining the volume of sales in Japan. Micro and mild HEVs demonstrate very good gains on the NEDC and the benefits of full HEVs are not as large, partially explaining the technology choices in Europe.

Following the analysis, one might expect a change of technology in the near future with the introduction of the WLTC as a replacement for some — if not all — standard cycles. For example, since the WTLC is not as favorable as the JC08, will it affect the market penetration of full HEVs in Japan?

Conclusions

The objective of this study was to evaluate the fuel and electrical consumption performance of several alternative powertrain technologies on standard test procedures, including JC08, NEDC, U. S. Combined, and WLTC. Several powertrain configurations were considered, including conventional micro and mild HEVs, full HEVs, PHEVs, BEVs, and fuel-cell hybrid electric vehicles (FCHEVs). The vehicles were defined to represent the potential of near-term technologies.

The simulation results showed significant discrepancies related to the fuel and electrical consumptions of the powertrains for the drive cycles considered. Conventional and series fuel-cell HEVs favor high speed with little idling, while power-split HEVs offer higher fuel benefits on low-speed cycles. On the contrary, BEVs are not significantly impacted by the drive cycle. To understand these differences, we examined a selected number of vehicle parameters, including idle consumption, efficiency of the propelling unit, benefits of regenerative braking, and ICE ON/OFF events. Through an economic analysis, the study indicated that several powertrain configurations would be cost effective based on the 2015 DOE cost target, with the exception of the PHEV40 and the BEV300. Finally, when looking at the current market share of the technologies worldwide, there appears to be a correlation with the current drive cycles. Considering that a new WLTC drive cycle will be adopted soon, future studies will need to analyze its impact on future technology shares.

IV.H.3. Products

Publications -None

Patents -None

Tools & Data - None

IV.I. Light Vehicle HVAC Model Development and Validation

Principal Investigator: Jason A. Lustbader
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401- 3305
Phone: (303) 275-4443; Email: Jason.Lustbader@nrel.gov

DOE Program Manager: David Anderson and Lee Slezak
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

IV.I.1. Abstract

Objective

- Develop analysis tools to assess the impact of technologies that reduce the thermal load, improve the climate control efficiency, and reduce vehicle fuel consumption.
- Develop an open source, accurate and transient air conditioning (A/C) model using the Matlab/Simulink environment for co-simulation with Autonomie.
- Connect climate control, cabin thermal, and vehicle-level models to assess the impacts of advanced thermal management technologies on fuel use and range.
- Expand capabilities of Autonomie to include A/C loads in fuel economy simulations.

Approach

- Develop a flexible, open source, transient A/C model based on first principles that simulates A/C performance and generates mechanical or electrical loads.
- Validate A/C components and system performance with bench data.
- Demonstrate co-simulation of A/C system with Autonomie, and Release A/C model plug-in for Autonomie.

Major Accomplishments

- Developed a transient A/C model based on first principles that simulates A/C performance and generates mechanical or electrical loads.
- The line model was enhanced to improve robustness and the heat transfer correlations were improved.
- The model was extensively validated to data provided by Visteon.
- Delivered standalone model to Visteon and GM.
- Integration into Autonomie was demonstrated and A/C models delivered to Argonne National Laboratory.
- First public release of open source A/C model.

Future Activities

- Alternative models of expansion devices will be developed and applied to investigate control strategies.
- Simplified solution options will be developed for more rapid, less detailed analysis, with a focus on vehicle co-simulation with Autonomie.
- A reasonable default A/C model will be built for class 8 heavy-duty vehicles.
- NREL will also work with Argonne National Laboratory's Advanced Powertrain Research Facility (APRF) to conduct vehicle-level A/C system performance validation.
- An updated A/C system model version will be released.

IV.I.2. Technical Discussion

Background

When operated, the A/C system is the largest auxiliary load on a vehicle. A/C loads account for more than 5% of the fuel used annually for light-duty vehicles in the United States [1]. A/C loads can have a significant impact on electric vehicle (EV), plug-in hybrid electric vehicle (PHEV), and hybrid electric vehicle (HEV) performance. Mitsubishi reports that the range of the i-MiEV can be reduced by as much as 50% on the Japan 10–15 cycle when the A/C is operating [2]. The advanced powertrain research facility at Argonne National Laboratory has reported a nearly 20% reduction in range in the Nissan Leaf operating on the UDDS cycle [3]. HEVs have 22% lower fuel economy with the A/C on [4]. Increased cooling demands from the battery thermal management system in an EV may impact the A/C system. Air conditioning in heavy-duty vehicles also uses significant fuel in both down-the-road and idle conditions. A flexible, open source analysis tool is needed to assess the A/C system impact on advanced vehicles. Industry has expressed a need for both a standalone A/C system model as well as an A/C model that can co-simulate with a vehicle simulator such as Autonomie. This model expands the capability of Autonomie to address industry needs.

Introduction

The A/C system contains complex flow, thermodynamics, and heat transfer. On the refrigerant-side, the flow is transient and both compressible and two phase. Calculating refrigerant properties near the phase transitions can also be computationally difficult.

Air flow through the condenser can vary widely, depending on vehicle speed and condenser fan speed. Heat is transferred from the refrigerant through the oil film and to the metal heat exchanger surface, then from the heat exchanger surface to the air.

Simulation of air flow through the evaporator must account for condensation of water vapor from the humid air stream. The result is that the mass flow of air through the evaporator is constantly changing. The latent heat of water vapor condensation can account for a significant portion of the evaporator heat load. Heat is transferred from the air through the layer of condensed water on the heat exchanger surface to the metal of the heat exchanger, then through the oil film to the refrigerant.

A cabin model is also needed to provide a realistic load on the evaporator. The cabin model must consider all the major pathways of heat transfer into the cabin, including solar and convective loads from the environment, heat from the engine compartment, and sensible and latent heat loads in the air stream.

Approach

Matlab/Simulink was chosen as the platform to develop the model. Using this platform has several advantages. Autonomie is also built on Simulink, which will facilitate integration of the model into Autonomie. Matlab/Simulink is widely used in industry, so the standalone, open source version of the A/C model can be widely distributed.

The A/C system simulation uses control volume simulation blocks and line simulation blocks. Conservation of mass and energy is implemented in the zero-dimensional control volume blocks. Conservation of mass, momentum, and energy are implemented in the one-dimensional line simulation blocks. The mathematical description is shown in Figure 1. All refrigerant thermodynamic and material properties are determined from two-dimensional tables based on specific internal energy and density. The receiver/dryer and headers are modeled with the control volume blocks. The heat exchanger elements are modeled with the line simulation blocks. Condensation of water from air is accounted for in the evaporator model.

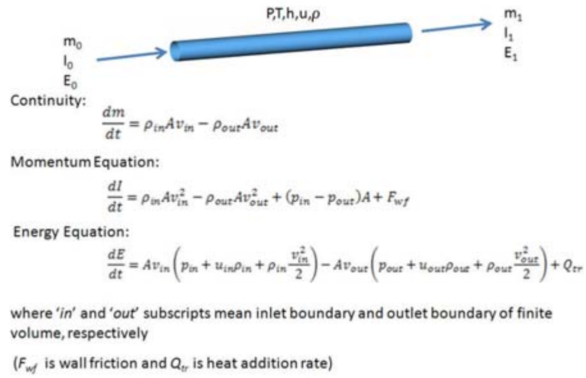


Figure 1. Conservation equations solved in refrigerant lines.

Heat transfer correlations are needed to account for the heat transfer from the air to the tube wall and from the tube wall to the refrigerant. The process is illustrated in Figure 2.

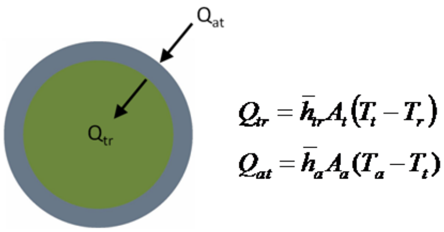


Figure 2. Tube to refrigerant and air to tube heat transfer schematic.

Separate heat transfer correlations are used for the air to tube heat transfer (Q_{at}) and from the tube wall to the refrigerant (Q_{tr}). The heat transfer correlation for the air to tube wall heat transfer (h_a) is based on the Chang and Wang [5] correlation for heat transfer in compact heat exchangers with louvered fins. The heat transfer correlation for the tube wall to refrigerant (h_{tr}) is based on the Chen [6] correlation and the Dittus-Boelter [7] correlation.

A schematic illustrating how the condenser model is built up from line blocks is shown in Figure 3. This condenser has four passes. Each pass consists of several flat tubes connected to a common header. The model assumes equal flow per flat tube, so the flow in each pass is a multiple of the flow in a single flat tube. Each flat tube in the condenser has several parallel channels. The refrigerant flows in the parallel channels are also assumed equal, so the flat tube refrigerant flow can be modeled as a multiple of the flow in a single channel. A single channel is then divided into a number of lengthwise segments, and each segment is modeled as described in Figure 1.

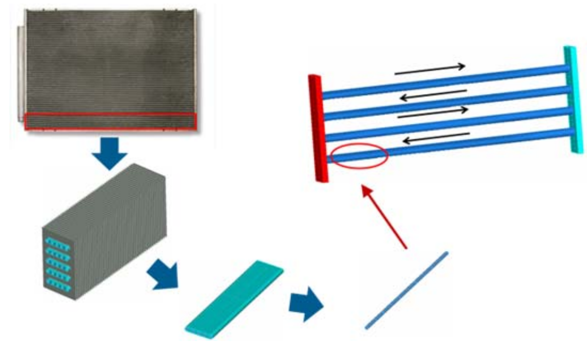


Figure 3. Condenser model schematic.

At the outlet of the condenser a single volume element is used to model the receiver-dryer component.

The thermostatic expansion valve (TXV) shown in Figure 4a is modeled as a two-phase equilibrium orifice flow model. A proportional with integral (PI) controller is used to adjust the orifice opening to maintain a set superheat at the outlet of the evaporator. This approach does not include the dynamics of the mechanical bellows, spring, and plunger in a TXV, but it does capture the performance of the refrigerant flow needed to maintain a set refrigerant superheat at the evaporator outlet. A recently developed, more detailed version of the model calculates the valve flow area opening based on the static balance of forces on the moving valve stem, and calculates the delayed response of the bulb temperature to change in evaporator exit temperature based on a user-input characteristic time.

The evaporator was modeled similarly to the condenser. In the evaporator model, the condensation of water vapor on the exterior of the tubes is also accounted for. The suction line leading from the evaporator to the compressor was not modeled. However, the refrigerant vapor pressure drop in the suction line and the effect on refrigerant properties were included.

The compressor shown in Figure 4b was modeled using a compressor map or lookup table. Both volumetric efficiency and isentropic efficiency as a function of compressor rpm and pressure ratio were used to evaluate refrigerant flow and compressor power. An electrically driven version of the compressor model was also developed. The electrical compressor is not dependent on engine speed, so controls had to be developed to adjust the compressor speed based on cooling demand.

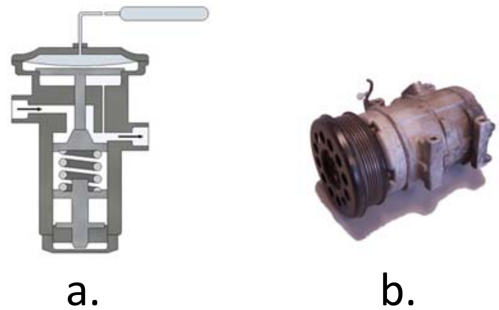


Figure 4. a. Thermostatic expansion valve, b. Compressor.

A cabin model was developed last year for incorporation with the A/C model [8]. The model is a lumped thermal mass with inputs for the thermal loads (Figure 5). This year the model was enhanced by splitting the thermal mass into interior (seat, console, instrument panel, etc.) and exterior (roof, doors, etc.) masses.

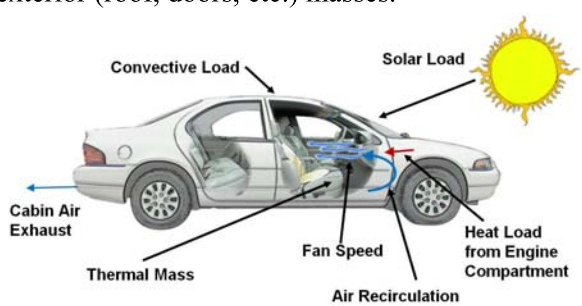


Figure 5. Vehicle cabin thermal parameters.

A schematic illustrating the integration of the A/C and cabin model with Autonomie is shown in Figure 6. The blue and green lines indicate the information flow between the A/C model and the cabin model. The black lines show the information flow to and from Autonomie.

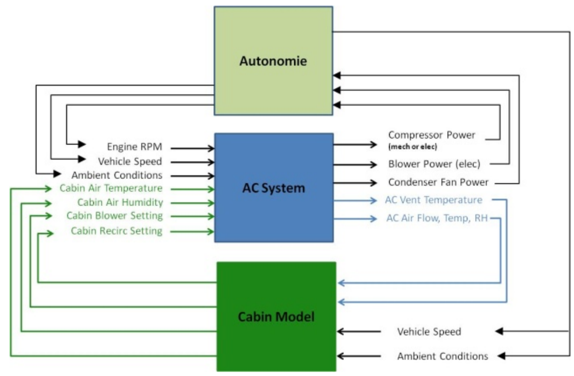


Figure 6. System integration schematic

A dead band temperature control and high- and low-limit pressure controls were implemented in the mechanical compressor A/C model. A more sophisticated PI controller for the compressor was implemented in the electric A/C model.

Results

Validation

In FY 2011 the A/C model was evaluated for functionality. In FY 2012 the model was extensively validated against data sets provided by Visteon. The data sets represented various conditions, including vehicle speed from idle to 60 mph, several blower speed settings, ambient conditions, and condenser airflow rates. The measured and calculated refrigerant flow rates for 22 conditions are shown in Figure 7. The results show very good comparison to measurements. The average error between simulation and measurements is 1.7%. The data have been non-dimensionalized to preserve confidentiality.

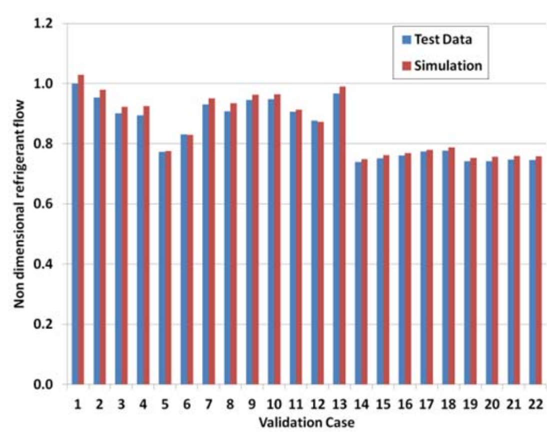


Figure 7. Non-dimensional refrigerant flow rate.

The measured and calculated heat transfer from the condenser for the 22 conditions in the data set is shown in Figure 8, and the comparison of evaporator heat transfer is shown in Figure 9. The data in Figures 8 and 9 have been non-dimensionalized to preserve confidentiality. The average error between the measured data and the simulation results is 1.9% for the condenser and 2.7% for the evaporator.

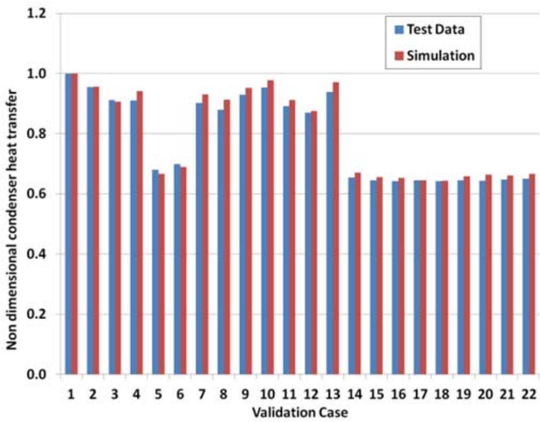


Figure 8. Non-dimensional heat transfer from condenser.

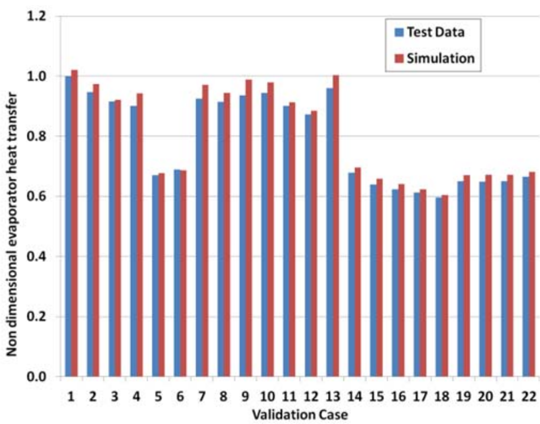


Figure 9. Non-dimensional heat transfer from evaporator.

The results show that the model can correctly predict heat transfer from the heat exchangers.

Figure 10 shows the comparison of evaporator outlet air temperature. The average error between measured data and simulation results was 1.8% for the evaporator air outlet temperature.

Figure 10. Evaporator air outlet temperature.

The results show that the model can correctly predict the performance of this complex, multi-pass heat exchanger.

Figure 11 shows the complete thermodynamic cycle on a P-h diagram. This figure is representative of the results obtained for each of the 22 points and shows that the model correctly predicts the thermodynamics of the refrigeration cycle.

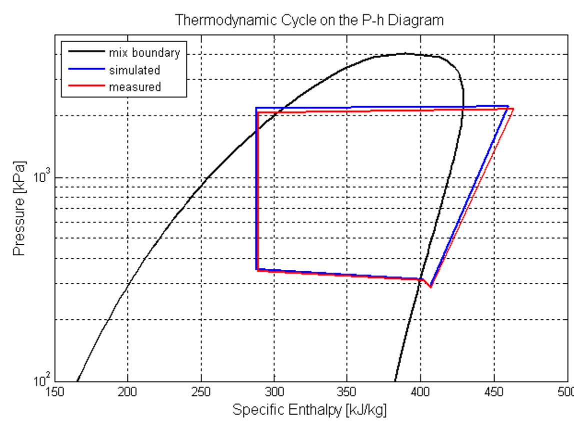


Figure 11. Thermodynamic cycle.

Autonomie Integration

The integration of the NREL A/C model into Autonomie is illustrated in Figures 12 through14. The upper-level Simulink block diagram of the A/C model is shown in Figure 12, and the Simulink diagram of the A/C model and cabin model is shown in Figure 13. Figure 14 shows the component level of the A/C Simulink model.

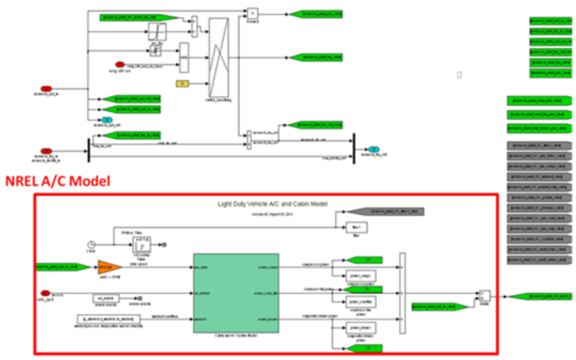


Figure 12. Top level of the Simulink A/C model.

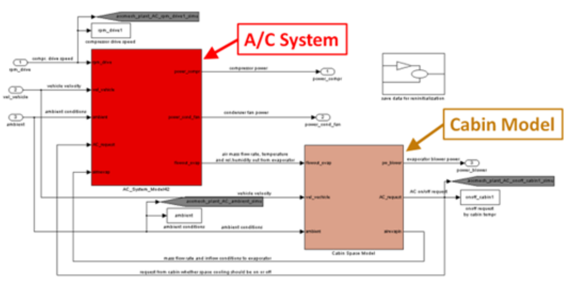


Figure 13. A/C system and Cabin model

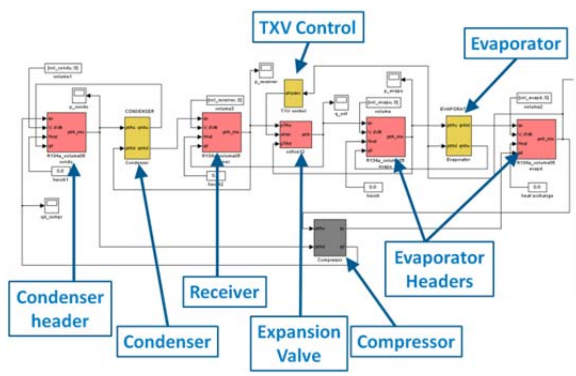


Figure 14. Component level A/C system block diagram.

The A/C model was co-simulated in Autonomie using a default midsized automobile on the SC03 drive cycle. Figure 15 shows engine and compressor speed in rpm. The compressor follows the engine rpm. The compressor power, and condenser and evaporator heat transfer dynamics all follow the rapidly changing compressor speed. Note that the compressor begins to cycle at approximately 90 seconds (as indicated by the vertical dashed line) because the cabin temperature has reached its set point.

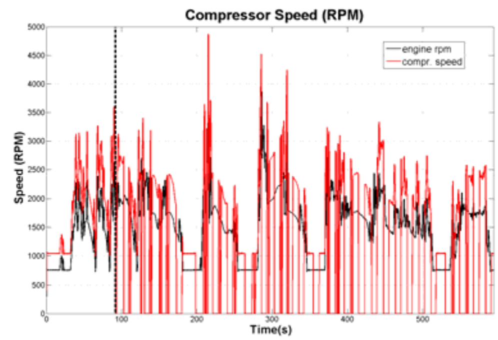


Figure 15. Engine and compressor speed.

Figure 16 shows the compressor power requirement and the condenser and evaporator heat transfer. This model uses a mechanically driven compressor, so the compressor power and heat transfer are affected by the rapidly changing engine rpm as well as the cycling of the compressor.

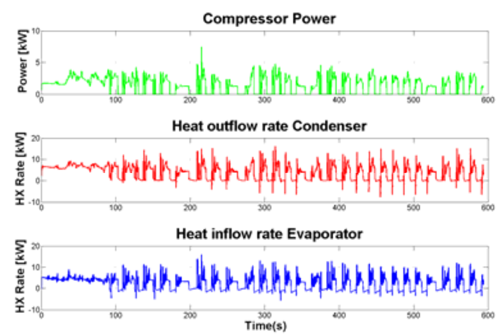


Figure 16. Heat transfer and compressor power.

Figure 17 shows the cabin air temperature and the dead band control signal. The dead band control switches the compressor off when the cabin temperature falls below the "target offset" temperature and switches the compressor back on when the temperature rises above the target temperature. The model cycles the compressor capturing the behavior that occurs in an actual automotive A/C system.

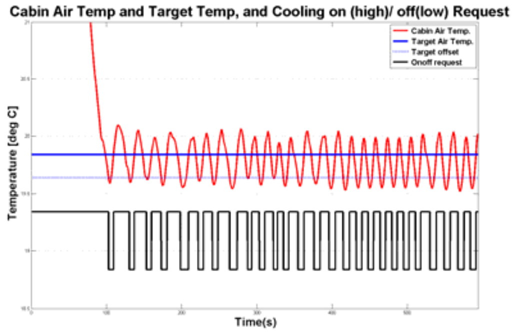


Figure 17. Cabin air temperature, control signal, and control upper and lower limits.

The simulation results show that the use of A/C results in a reduction in fuel economy of 14.7 percent, with an A/C COP of approximately 2.

Conclusions

A Matlab/Simulink model of a light-duty vehicle HVAC system was developed. The system is built up from components. The components were developed using a one-dimensional finite volume basic line building block. The line building block was enhanced to improve robustness and speed. The heat transfer correlations used in the model were enhanced. The model was extensively validated to component and system data provided by Visteon. The model results were within 2 percent of the test data. A version of the model was also developed that uses an electrically driven compressor.

The model was co-simulated in Autonomie using a default midsized automobile over the SC03 drive cycle. The results show a 14.7% increase in fuel consumption with A/C on.

A standalone version of the A/C model was released to key industry partners. The standalone model as well as the Autonomie integrated model was released to the public in September.

References

1. Rugh et al., 2004, Earth Technologies Forum/Mobile Air Conditioning Summit.
2. Umezu et al., 2010, SAE Automotive Refrigerant & System Efficiency Symposium.
3. ANL APRF data, EV Everywhere Workshop presentation, Lee Slezak, September 13, 2012.
4. NREL, Vehicle Technologies Program 2007 annual report, p145.
5. Chang, Y.J., and Wang, C.C., "A Generalized Heat Transfer Correlation for Louver Fin Geometry," *Int. J. Heat Mass Transfer*, Vol. 40, No. 3, pp. 533-544, 1997.
6. Chen, J.C. (1966). "A Correlation for Boiling Heat Transfer of Saturated Fluids in Convective Flow," *Ind. Eng. Chem. Process Ses. Dev.,* Vol. 5, No. 3, pp. 322-329.
7. F. W. Dittus and L. M. K. Boelter, "Heat Transfer in Automobile Radiators of the Tubular Type," *Publications in Engineering*, Vol. 2, p, 443, University of California, Berkeley (1930).
8. 2011 NREL annual report to DOE, "LDV HVAC Model Development and Validation," VSST Vehicle Simulation and Modeling.

IV.I.3. Products

Publication

1. Paper offered for SAE congress 2013.

Patent

1. Software Copyright CoolSim.

Tools & Data

1. NREL's open source HVAC model, CoolSim, has been released in standalone and Autonomie software plug-in versions

.

IV.J. Advanced LD Engine Systems and Emissions Control Modeling and Analysis

Principal Investigator: Zhiming Gao (PI) and Stuart Daw (Co-PI)
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Boulevard, Room K-04
Knoxville, TN 37932-6472
Phone: (865) 946-1339; Email: gaoz@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

IV.J.1. Abstract

Objective

- Develop component models that accurately reflect the driving performance, cost, fuel savings, and environmental benefits of advanced combustion engines and after treatment components as they could potentially be used in leading-edge light-duty (LD) hybrid electric and plug-in hybrid electric vehicles (HEVs and PHEVs).
- Apply the above component models to help the Department of Energy (DOE) identify the highest HEV and PHEV R&D priorities for reducing U.S. dependence on imported fuels while achieving regulated pollutant emission levels.

Approach

- Develop, refine and validate low-order, physically consistent computational models for emissions control devices including three-way catalysts (TWCs), diesel oxidation catalysts (DOCs), hydrocarbon (HC) trap, lean NOx traps (LNTs), diesel particulate filters (DPFs), selective catalytic reduction reactors (SCRs), and other advanced catalyst technologies that accurately simulate LD HEV and PHEV performance under realistic steady-state and transient vehicle operation.
- Develop, refine and validate low-order, physically consistent computational models capable of simulating the power out and exhaust characteristics of advanced diesel and spark-ignition engines operating in both conventional and high efficiency clean combustion (HECC) modes.
- Develop and validate appropriate strategies for combined simulation of engine, after treatment, battery, and exhaust heat recovery components in order to accurately account for and compare their integrated system performance in HEV and PHEV powertrains.
- Translate the above models and strategies into a form compatible with direct utilization in available vehicle systems simulation software.
- Leverage the above activities as much as possible through inclusion of experimental engine and after treatment data and models generated by other DOE activities.

Major Accomplishments

- Developed a partitioned engine map with combined reactivity controlled compression ignition (RCCI) and conventional diesel combustion (CDC) capability and made preliminary estimates for the hot-start drive cycle fuel economy and emissions reduction potential of RCCI in a LD conventional vehicle.
- Implemented 2.0-L BMW direct injection spark ignition (DISI) gasoline engine map accounting for lean and rich modes into Autonomie and carried out comparative fuel economy and emissions control with DISI gasoline engines versus stoichiometric gasoline engines in a LD HEV with appreciate nitrogen oxides (NOx) after treatment device.
- Refined and implemented various lean exhaust after treatment components (including DOC, DPF, LNT, and SCR) combinations for both conventional and hybrid vehicles into Autonomie.

- Continued calibration and refinement for both diesel and gasoline HEV/PHEV Autonomie simulations to improve the effect of cold ambient conditions and optimal control system on fuel consumption and emission reduction.
- Published cold-start emissions control in hybrid vehicles with a passive hydrocarbon (HC) and NOx Adsorber, (Proc. IMechE Part D: J. Automobile Engineering, 2012, 226(10), 1396-1407).
- Received final acceptance of invited publication on the impact of premixed charge compression ignition on the comparative fuel economy and emissions of LD conventional and hybrid diesel vehicles, (Proc. IMechE Part D: J. Automobile Engineering, 2012, in press).

Future Activities

- Based on current budget projections, this task is being deactivated in FY 2013. Some aspects of the models developed here will be adapted and utilized in studies of heavy-duty hybrid power trains in a related task that is providing support to a CRADA with Meritor.

IV.J.2. Technical Discussion

Background

Accurate predictions of the fuel efficiency and environmental impact of advanced vehicle propulsion and emissions control technologies are vital for making informed decisions about the optimal use of R&D resources and DOE programmatic priorities. One of key modeling tools available for making such simulations is the Autonomie software platforms developed by Argonne National Laboratory (ANL) for DOE. However, the usefulness of vehicle drive-cycle simulations critically depends on the accuracy of the individual component models used to simulate the fuel efficiency and emissions performance of the engine and after treatment systems. In some cases of leading-edge technology, such as with engines utilizing high efficiency clean combustion and lean exhaust particulate and NOx controls, the availability of appropriate component models or the data needed to construct them is very limited.

Oak Ridge National Laboratory (ORNL) is specifically tasked with providing data and models that enable hybrid vehicle systems simulations that include advanced combustion engines and emissions controls. ORNL has carried out many experimental measurements of emissions and fuel efficiency for advanced diesel and lean-burn gasoline engines and their associated emission control components. These data have been transformed into maps and low-order transient models that explicitly support vehicle performance simulations in vehicle simulation software such as Autonomie. Significantly, this activity supports DOE's mission of addressing vehicle energy efficiency and conservation, energy security, global climate change in transportation, and related environmental impacts.

Introduction

In FY 2012, we collaborated with partners at ORNL, ANL, Pacific Northwest National Laboratory (PNNL), and industry and universities to continue development of advanced transient combustion engine and after treatment component models. These models were then used to generate updated simulations of emissions and fuel economy for HEVs and PHEVs powered by both stoichiometric and lean-burn engines. We concentrated our effort this year in the following specific areas:

- Generation of a dual-mode engine map with RCCI over a wide speed and load range in a 2.0-L, 4-cylinder diesel engine specifically designed for a mid-size sedan.
- Refinement and validation of 2.0-L BMW DISI gasoline engine maps for lean and rich combustion modes.
- Simulation of the impact of RCCI on the fuel economy and emissions reduction potential in a LD conventional vehicle over transient driving cycles for comparison with RCCI in LD HEVs.
- Comparison of the fuel economy and emissions for LD conventional vehicles and HEVs powered by DISI gasoline engines versus stoichiometric gasoline engines.

- Complete implementation of all possible combinations of current lean exhaust after treatment components in Autonomie including diesel oxidation catalysts (DOCs), diesel particulate filters (DPFs), lean NOx traps (LNTs), urea selective catalytic reduction (SCR), and passive hydrocarbon (HC) traps.
- Continued calibration and refinement of engine and after treatment component models to account for the effect of cold ambient conditions on performance.
- Documentation of ORNL's DOC, SCR, DPF, and HC trap models in journal publications.

Approach

Simulations of advanced hybrid vehicles require computationally efficient and physically accurate models for the various types of engines and after treatment devices that might be employed to maximize the overall vehicle energy efficiency and assess the effects of both advanced combustion modes (such as RCCI and DISI) and lean exhaust after treatment devices (such as innovative DPF, LNT, and SCR) for removing NOx and particulate matter (PM).

Thus, as much as possible, we simplify the complex internal processes in after treatment devices to account for the dominant physics while maintaining reasonable execution speeds. For example, there are no cross-flow (i.e., radial) spatial gradients accounted for, and kinetics are defined as global rather than elementary reactions. Nevertheless, this approach appears to do a good job of accounting for the strong coupling of after-treatment devices with both upstream and downstream components.

Due to the even greater complexity of engines, our approach for transient engine modeling relies on a very coarse representation of internal engine heat transfer and highly simplified assumptions about how engine-out species change as the engine heats up. The result is expressed in the form of an experimentally parameterized transient correction term that is applied to steady-state or pseudo-steady-state engine-dynamometer data.

Our engine and device control strategies used to date are highly simplified and typically based on previously published studies or strategies used in public proof-of-principle demonstrations at national laboratories. These strategies are typically not optimal and frequently rely on sensor technology that may be ideal or at least not yet commercial. Our intention is to address general questions about trends rather than assess specific designs.

Results

Engine Mapping and Advanced Combustion. RCCI is one of the most recent developments in advanced engine combustion now being exploited to increase fuel efficiency. Typically, in RCCI both gasoline and diesel fuel are injected in a compression ignition engine. We are collaborating with ORNL researchers who are making experimental measurements of RCCI on a 1.9-L GM diesel engine. Currently, RCCI can only be enabled within a limited portion of the engine operating range. Thus we developed a partitioned engine map with combined RCCI and conventional diesel combustion capability in a similar fashion to what has been done earlier for PCCI. Figure 1 illustrates the current version dual-mode engine map for the GM engine.

As an initial benchmark, we used the map in Figure 1 to make preliminary simulations of the hot-start drive-cycle fuel economy and emissions of an RCCI-capable LD conventional diesel vehicle operating over the Urban Dynamic Driving Schedule (UDDS), the Highway Fuel Economy Driving Test Schedule (HWFET), and the EPA US06 cycle. These simulations indicate that the HWFET cycle would be most affected by utilization of RCCI, potentially decreasing fuel consumption, engine-out NOx emissions, and engine-out particulate emissions by up to 15%, 21%, and 68%, respectively. However, engine-out CO and HC emissions were also predicted to increase significantly.

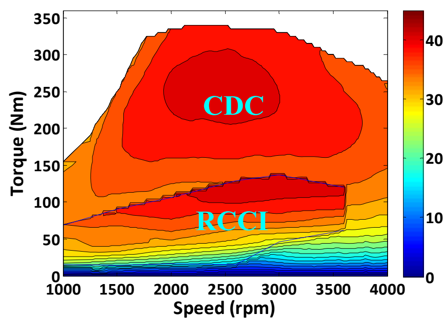


Figure 1. A partitioned 1.9-L GM diesel engine efficiency map with combined RCCI and conventional diesel combustion capability

Another likely effect from RCCI would be a dramatic reduction in exhaust temperature. As depicted in Figure 2, our preliminary simulations indicated that engine-out exhaust temperature could be below 200°C for a significant fraction of the UDDS cycle. This highlights a recent concern among engine manufacturers that some advanced combustion modes may drop exhaust temperature to levels where current after treatment catalysts cannot perform sufficiently well to meet current or proposed emission regulations. Although we have not yet simulated the impact of RCCI in diesel HEVs, we expect that emissions control for the low temperature exhaust will be a significant issue during frequent engine restarts.

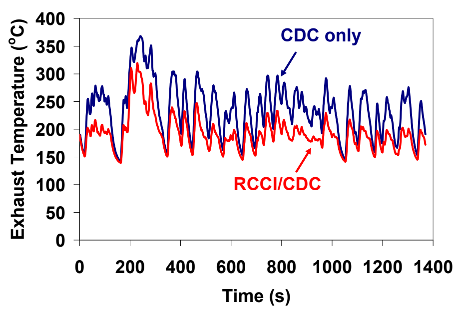


Figure 2. Comparison of simulated engine-out exhaust temperature for a conventional medium-size passenger vehicle operating over a UDDS cycle with either conventional diesel combustion (CDC) or dual mode (CDC/RCCI) combustion.

We continued to refine maps for the BMW series 120i 2.0-L DISI gasoline engine using recent chassis dynamometer measurements made at ORNL over the UDDS and HWFET cycles. It appears that the BMW engine controller commands stoichiometric fueling for more than 150s after cold start to heat up the engine and after treatment catalysts before switching to lean operation. We included this constraint in updated simulations along with a stoichiometric gasoline engine map developed from the 2.0-L Saab Biopower engine. Utilizing the Saab stoichiometric map is an interim measure until more stoichiometric BMW data become available. Even with this rough approximation, our simulations of the BMW over the UDDS and HWFET cycles have been able to match the measured cumulative fuel consumption within 3%. Simulated engine-out emissions of NOx, CO, and HCs differed at most by 0.6, 1, and 0.6 g/mile from the measurements.

Component Models Development. We developed a reduced-order three-way-catalyst (TWC) model to facilitate very rapid simulations of multiple cases, while still accounting for detailed thermal balances and conversion efficiencies for key species. The reduced-order model consists of conversion maps for CO, HCs and NOx created from our dynamic 1-D TWC model as a function of catalyst temperature and space velocity. Catalyst temperature is determined from a 0-D TWC heat balance. While such models are not as effective for handling complex reaction transients and large TWC temperature gradients, they can be useful for rapid, high-level studies of engine and after treatment parameters and identification of promising control strategies. Once promising trends are identified, more precise studies can be done with more detailed TWC models. Figure 3 compares predicted TWC temperatures from this simple model with measurements from the Saab Biopower vehicle over a UDDS driving cycle.

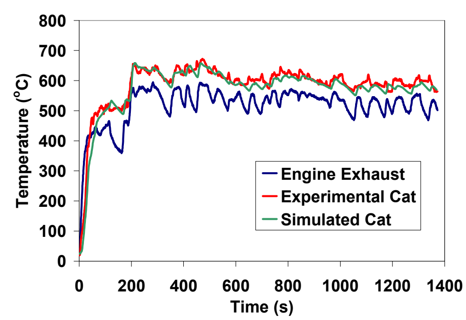


Figure 3. Comparison of simple TWC model temperature predictions with measurements from the Saab Biopower flex-fuel vehicle over a UDDS driving cycle

System Integration in Hybrid Vehicle Simulations. Cold starting and intermittent operation are major concerns in meeting HEV and PHEV emissions and fuel consumption targets. Besides refining and calibrating HEV/PHEV system models, we continued to refine a discretized engine heat transfer model. The model explicitly accounts for thermal interactions among the engine block, coolant, and radiator, and it has been calibrated with chassis dynamometer data supplied by ANL for a G3 Prius gasoline HEV operating over a UDDS cycle beginning with a 20°C cold start. Figure 4(a) compares the experimental and simulated fuel consumption for the 20°C case. The experimental overall fuel economy was 62.4 mpg compared to 64.6 for our simulation. Figure 4(b) illustrates the agreement among the measured and predicted engine coolant temperatures.

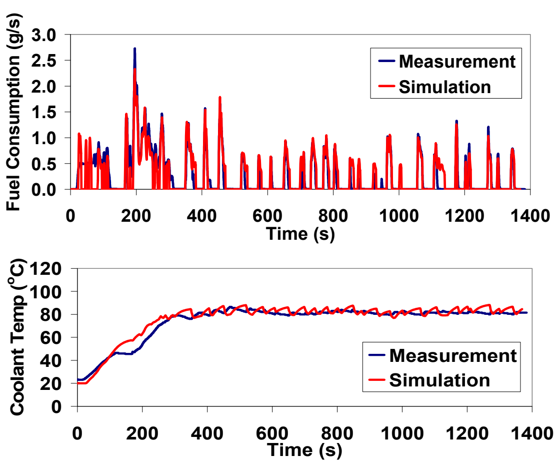


Figure 4. Comparison between predicted and measured fuel consumption and coolant temperature for the HEV Prius with a cold start at 20°C.

We also studied the potential benefits of using a DISI gasoline engine in HEVs using the engine maps described above. Since DISI engines run lean, we included a TWC and LNT in the DISI hybrid vehicle to compare with a conventional gasoline HEV using TWC emissions control. When the fuel penalty for the LNT operation is discounted, the predicted fuel economy advantage for the DISI HEV was approximately 13% in the UDDS cycle, 11% in the HWFET cycle, and 9% in the US06 cycle. The reasons behind this difference are illustrated in Figure 5, where the brake thermal efficiencies of the two engines and their fuel-to-air equivalence ratios are compared. We emphasize, however, that the LNT regeneration adds a significant fuel penalty that must be accounted for. In the UDDS driving cycle for example, the DISI LNT requires an additional 2.1% fuel to be injected in order to achieve similar NOx tailpipe levels to the stoichiometric HEV.

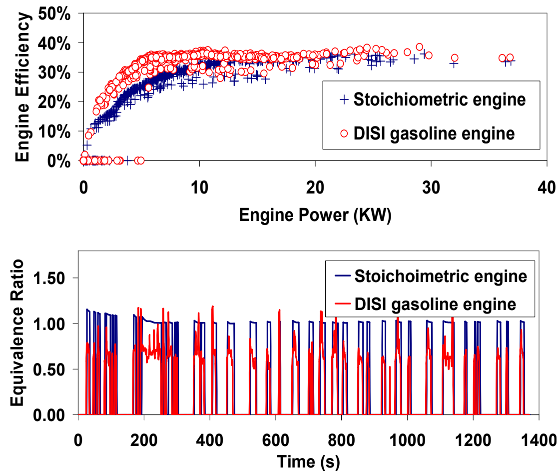


Figure 5. Comparison of the simulated brake efficiency and equivalence ratio of the DISI and stoichiometric gasoline engines operating in the reference LD hybrid vehicle over a UDDS cycle.

Conclusions

- A partitioned engine map with RCCI capability has been developed to support studies of the fuel economy and emissions benefits of RCCI in conventional and hybrid LD vehicles.
- Preliminary simulations indicate that a conventional RCCI-enabled LD diesel vehicle can achieve decreased fuel consumption of up to 15%, lower engine-out NOx by 21%, and reduced engine-out particulate by 68% in the HWFET cycle. Potential benefits for diesel HEVs have not yet been estimated, but emissions control may become limiting due to the expected low exhaust temperatures.
- Updated fuel consumption, emissions, and temperature maps for a LD DISI gasoline engine have been demonstrated to compare reasonably well with engine-out chassis dynamometer measurements from the BMW 2.0-L series 120i vehicle.

- Preliminary simulations of an HEV powered by a DISI gasoline engine indicate that it could have more than a 10% boost in fuel economy compared to conventional gasoline HEVs. However, lean NOx emissions control using an LNT catalyst could reduce the potential DISI fuel savings by about 2%.
- A coarse-grained TWC model based on detailed thermal balances and catalyst efficiency performance maps has been developed for rapid exploration of HEV control and powertrain configuration options.
- Engine heat transfer component models accounting for HEV/PHEV cold starting and intermittent operation have been further refined to account for a range of cold-starting conditions.
- Based on current budget projections, activities in this project will be suspended in FY 2013 until further directions are given by DOE project managers. As much as possible, the engine and after treatment simulation tools developed to date will be utilized for HD HEV studies in support of ongoing CRADA activities.

IV.J.3. Products

Publications

1. Z. Gao, C.S. Daw, R.M. Wagner, K.D. Edwards, D.E. Smith, Simulating the Impact of Premixed Charge Compression Ignition on Light-Duty Diesel Fuel Economy and Emissions of Particulates and NOx, Journal of Automobile Engineering, in press, 2012 (Invited publication).
2. Z. Gao, M.-Y. Kim, J.-S. Choi, C.S. Daw, J.E. Parks II, D.E. Smith, Cold-Start Emissions Control in Hybrid Vehicles Equipped with a Passive Hydrocarbon and NOx Adsorber, Journal of Automobile Engineering, 226(10), 1396-1407, 2012.
3. Z. Gao, C.S. Daw, V.K. Chakravarthy, Simulation of Catalytic Oxidation and Selective catalytic NOx Reduction in Lean-Exhaust Hybrid Vehicles, SAE paper 2012-01-1304.
4. Z. Gao, C.S. Daw, R.M. Wagner, Simulating Study of Premixed Charge Compression Ignition on Light-Duty Diesel Fuel Economy and Emissions Control, Spring Technical Meeting of the Central States Section of the Combustion Institute, Dayton, Ohio, April 22-24, 2012.
5. Z. Gao, C.S. Daw, M.-Y. Kim, J.-S. Choi, J.E. Parks II, D.E. Smith, Cold-Start Emissions Control in Hybrid Vehicles Equipped with a Passive Adsorber for Hydrocarbons and NOx, DOE-DEER Conference, October 16-19, 2012.
6. S. Curran, Z. Gao, R.M. Wagner, Light-Duty Reactivity Controlled Compression Ignition Drive Cycle Fuel Economy and Emissions Estimates, DOE-DEER Conference, October 16-19, 2012.
7. C.S. Daw, Z. Gao, Advanced Heavy-Duty Engine Systems and Emissions Control Modeling and Analysis, U.S. DOE Hydrogen Program and Vehicle Technologies Program, Annual Merit Review and Peer Evaluation Meeting, Washington DC, May 14, 2012.
8. Z. Gao, C.S. Daw, Advanced Light-Duty Engine Systems and Emissions Control Modeling and Analysis, U.S. DOE Hydrogen Program and Vehicle Technologies Program, Annual Merit Review and Peer Evaluation Meeting, Washington DC, May 14, 2012.
9. Z. Gao, C.S. Daw, K.D. Edwards, S. Sluder, R.M. Wagner, Effect of Premixed Charge Compression Ignition on Vehicle Fuel Economy and Emissions Reduction over Transient Driving Cycles, DOE-DEER Conference, October 3-6, 2011.
10. Z. Gao, C.S. Daw, J.A. Pihl, M. Devarakonda, Evaluation of 2010 Urea-SCR Technology for Hybrid Vehicles using PSAT System Simulations, DOE-DEER Conference, October 3-6, 2011.

Patents

None

Tools & Data

1. After treatment device and engine component models described above and summarized in the cited publications [1-10].

IV.K. Autonomous Intelligent Electric Vehicles

Principal Investigator: Andreas Malikopoulos
Oak Ridge National Laboratory
National Transportation Research Center (NTRC, Bld. II)
2370 Cherahala Boulevard
Knoxville, TN 37932-6472
Phone: (865) 946-1529; Email: andreas@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

IV.K.1. Abstract

Objective

- Develop the control learning algorithms for making a hybrid propulsion system into an *intelligent system* capable of learning its optimal operation in real time while the driver is driving the vehicle.
- Quantify the maximum possible fuel economy that a driver can achieve with respect to his/her driving and commuting habits in a hybrid vehicle.

Approach

- Consider hybrid propulsion systems as cooperative multi-agent systems in which each subsystem, i.e., engine, motor, generator, and battery, are treated as intelligent agents. The agents attempt through their interaction to jointly maximize common utilities, i.e., fuel economy, emissions, and efficiency.
- Establish the *instantaneous equilibrium operating point* of hybrid propulsion systems that assure maximization of their overall efficiency.

Major Accomplishments

- Completed an extensive literature review of more than 120 archival publications covering key state-of-the-art power management control algorithms.
- Developed the control algorithms that allow a hybrid propulsion system to operate at the *instantaneous equilibrium operating point* and reported the results in a paper submitted in the 2013 IEEE Conference on Decision and Control. Implemented the control algorithms into Autonomie software platform.
- Evaluated the efficiency of the algorithms in a series hybrid propulsion system demonstrating up to 7% fuel economy improvement and reported the results in a paper submitted in the 2013 American Control Conference.
- Evaluated the efficiency of the algorithms in a parallel hybrid propulsion system and reported the results in a paper submitted in the *7th IFAC Symposium on Advances in Automotive Control*.

Future Activities

- In FY 2013, we plan to develop the learning control algorithms that allow a hybrid propulsion system to learn to operate at the *instantaneous equilibrium operating point* for each different driver.

IV.K.2. Technical Discussion

Background

The necessity for environmentally conscious vehicle designs, in conjunction with increasing concerns regarding U.S. dependency on foreign oil and climate change, has led to significant investment in enhancing the propulsion portfolio with new technologies. Among the promising technologies are hybrid electric vehicles (HEVs), which have shown the potential to achieve greater fuel economy than vehicles powered only by internal combustion (IC) engines. The main advantage of HEVs is the existence of two individual subsystems, thermal (IC engine) and electrical (motor, generator, and battery), that can power the vehicle either separately or in combination. Recently, PEVs—the US Department of Energy (DOE) defines both plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles (EVs) as PEVs—have attracted considerable attention due to their potential to increase fuel economy and reduce emissions. PEVs are hybrid vehicles with rechargeable batteries that can be restored to full charge by connecting a plug to an external electric wall socket, and thus they share some of the characteristics of both HEVs and EVs. They are especially appealing in situations where daily commuting is over short distances (about 60% of US passenger vehicles travel less than 30 miles each day). The high costs associated with the batteries and concerns with battery range and predictability have been significant barriers to extensive market penetration of PEVs. Under the average mix of electricity sources in the United States, PEVs can be driven with lower operating costs and fewer greenhouse gas (GHG) emissions per mile when powered by electricity rather than by gasoline.

These hybrid propulsion systems have the potential to reduce petroleum consumption and GHG emissions by means of sophisticated supervisory power management control algorithms. The latter is of great importance in both HEVs and PEVs as it determines how to split the power demanded by the driver between the thermal and electrical subsystems to improve fuel economy and reduce emissions. The overarching goal of this task is to develop an intelligent supervisory controller combining and stochastic control algorithms that will learn to optimize fuel economy and emission in advanced hybrid propulsion systems.

Introduction

Widespread use of alternative hybrid powertrains is currently inevitable, and many opportunities for substantial progress remain. HEVs and PEVs have attracted considerable attention due to their potential to reduce petroleum consumption and greenhouse gas emissions in the transportation sector. This capability is mainly attributed to (a) the potential for downsizing the engine, (b) the potential for recovering energy during braking and thus recharging the energy storage unit, and (c) the ability to minimize the operation of the engine in inefficient brake specific fuel consumption (BSFC) regimes.

A significant amount of research has been focused on power management control algorithms that employ deterministic and stochastic dynamic programming to derive offline the optimal control policy with respect to a given driving cycle or family of driving cycles. These methods, however, can be efficient only for those driving cycles for which they have been derived. Recent research has focused on developing real-time power management algorithms and intelligent energy management systems for HEVs. One common approach is to exploit a fuzzy clustering criterion that combined with a genetic algorithm can achieve better results, both in terms of a reduced computational effort and an improved efficiency of the control system over various driving cycles. Another more simplified approach is to develop a set of fuzzy logic control rules based on the driver's commands, the SOC of the battery, and the motor/generator speed to effectively split the power between the thermal and electrical paths. The underlying scheme of the fuzzy rules is to optimize the operational efficiency of all components, considered as one system. Once again, though, these algorithms can be efficient in minimizing fuel consumption and emissions only for the given driving cycles for which they have been designed due to the inherent assumption of average efficiencies of the subsystems restricting the efficiency of these algorithms. These recent developments and future trends in the modeling, design, control, and optimization of energy storage systems for hybrid propulsion systems have been presented in the literature with a detailed review and classification of current control strategies. Other recent research has focused on optimal operation of the motor, generator, and battery in HEVs and PEVs, another issue critical to deeper market penetration of EVs.

Although the aforementioned power management algorithms can be efficient in minimizing fuel consumption and emissions for a given driving cycle, state-of-the-art power management control algorithms cannot guarantee continuous optimum operation of the powertrain system on any different driving cycle. However, to fully exploit the potential benefit in fuel economy and emissions in hybrid propulsion systems, it is important to guarantee continuously efficient cooperation of all subsystems and components for any different driver. The research objective in this project is to develop the control learning algorithms that can make the hybrid propulsion systems into intelligent systems with the aim of realizing continuously their optimal operating point, defined as an instantaneous equilibrium operating point, for all subsystems, e.g., engine, motor, generator, battery, etc., with respect to any different driver.

In the first year of the project, the control algorithms were developed that allow a hybrid propulsion system to operate at the *instantaneous equilibrium operating point* that assures maximization of the overall efficiency in a hybrid propulsion system. In the second year of the project, it is intended to develop the learning control algorithms that allow a hybrid propulsion system to learn to operate at this *instantaneous equilibrium operating point* for each different driver.

Approach

The research hypothesis here is that the solution of a self-learning stochastic control problem formulation can efficiently address the problem of optimizing the overall efficiency of a hybrid propulsion system in terms of fuel economy. In previous research, we developed the theoretical framework and algorithms for making the engine of a vehicle learn its optimal operation in real time while the driver is driving the vehicle. Through this approach, the engine progressively perceives the driver's driving style and eventually learns to operate in a manner that optimizes specified performance criteria (e.g., fuel economy, emissions, or engine acceleration). The engine's ability to learn its optimum operation is not limited, however, to a particular driving style. The engine can learn to operate optimally for different drivers, identified, for example, through their car keys.

The approach adapted here extends this framework by developing a power management control algorithm that can make HEVs and PEVs learn to continuously optimize their overall efficiency with respect to fuel economy and emissions. HEVs and PEVs are considered as cooperative multi-agent systems in which the subsystems (i.e., IC engine, motor, generator, and battery) will be treated as autonomous intelligent agents. The agents will attempt through their interaction to jointly maximize overall HEV/PEV operation. Consequently, the supervisory power management controller will allow the HEV/PEV to learn how to improve its performance over time in stochastic environments. In this framework, the HEV/PEV interacts with driver and obtains information enabling it to improve its future performance; namely, optimizing the specific performance criteria while satisfying the system's physical constraints.

Computational intelligence, or rationality, can be achieved by modeling the HEV/PEV and its interaction with its environment (the driver) through actions, perceptions, and associated costs (or rewards). A widely adopted paradigm for modeling this interaction is the completely observable Markov decision process (MDP). The problem is formulated as sequential decision making under uncertainly where an intelligent system is faced with the task to select those control actions in several time steps (decision epochs) to achieve long-term goals efficiently. Sequential decision models are mathematical abstractions representing situations in which decisions must be made in several stages while incurring a certain cost at each stage. MDP in our formulation comprises (1) a decision maker (supervisory power management controller), (2) HEV/PEV states, (3) control actions, (4) a transition probability matrix (driver), (5) a transition cost matrix (HEV/PEV overall efficiency), and (6) an optimization criterion (e.g., maximize fuel economy and minimize emissions.) The evolution of the HEV/PEV occurs at each of a sequence of stages $t = 0, 1, \ldots$, and it is portrayed by the sequence of the random variables X_t and U_t corresponding to the HEV/PEV state and controller's action. The PEV state is a vector corresponding to various variables (e.g., vehicle speed, battery temperature, SOC). The controller's action is a vector corresponding to engine torque, motor/generator torque, and battery power and coolant temperature. At each stage, the controller observes the system's state $X_t = i \in \boldsymbol{S}$, and executes an action U_t, from the feasible set of actions at this state. At the next stage, *t*, the system transits to the state $X_{t+1} = j \in \boldsymbol{S}$ imposed by the conditional probability $P(X_{t+1} = j \mid X_t = i, U_t = \mu_i)$ of the transition probability matrix, and a cost $k(X_t = i, U_t = \mu_i) = k(i, \mu_i)$ is incurred. After the transition to the next state has occurred, a new action is selected, and the process is repeated. We are concerned with deriving an optimal control policy π (i.e., a sequence of control actions U_t) to minimize the long-run average cost per unit time.

The optimal solution of this problem is a control policy that endows a stationary probability distribution yielding higher probability at the states with low cost and lower probability at the states with high cost. This policy is defined as an equilibrium control policy [2]. However, achieving the equilibrium control policy might not be feasible at some given states. Therefore, avoiding operating the propulsion system at those states is important. To address this problem, the controller needs to avoid these control actions that increase the likelihood of operating the system at those undesirable states. The ultimate goal of the controller is to learn the optimal control policy corresponding to the driver's driving style that makes the HEV/PEV perform optimally with respect to fuel economy and GHG emissions. A key aspect of the stochastic control problem is that decisions are not viewed in isolation. Consequently, the controller should select those values that balance the desire to minimize the cost function of the HEV/PEV operating point against the desire to avoid future operating points where high cost is inevitable.

Results

To validate the effectiveness of the power management control algorithm, we employed Autonomie. A vehicle model from Autonomie's database representing a series HEV configuration was used in this study. In the series HEV configuration considered here and illustrated in Figure 1, the motor provides all the power demanded by the driver. Thus we can operate the engine at any desired combination of engine torque and speed. The objective of the centralized controller is to maintain the SOC of the battery within a given range while operating the engine efficiently. So the optimal control policy of the controller is a sequence of the optimal engine power at each instant of time corresponding to the engine's current speed. To operate the engine under the condition designated by the centralized controller, a PID controller regulates the engine torque through the generator as shown in Figure 2. The sequence of the engine's optimal power is converted to electrical power through the generator and goes to the battery.

The equilibrium control policy can be achieved, if the engine is operated at the speed range ensuring higher probability to the engine speed with lower BSFC values and lower probability to the engine speed with higher BSFC values. However, the centralized controller needs to maintain the battery's SOC close to the target value (65% in this case). To achieve both objectives, we establish a one-on-one correlation between SOC and the optimal engine power range. In particular, the controller is set up to command the engine to provide the power corresponding to the minimum optimal value in the range of the engine power, whenever SOC is equal to 65% (target SOC) and gradually increase as SOC drops below 65% all the way down to the minimum allowable SOC value (60% in this case), as illustrated in Figure 3. Consequently, this map provides the engine power, indicated as P_{SOC} in the plot to emphasize the connection with the current SOC. Whenever the battery SOC is at 65%, the engine operates at its minimum possible bsfc value and gradually increases to the value corresponding to the maximum value.

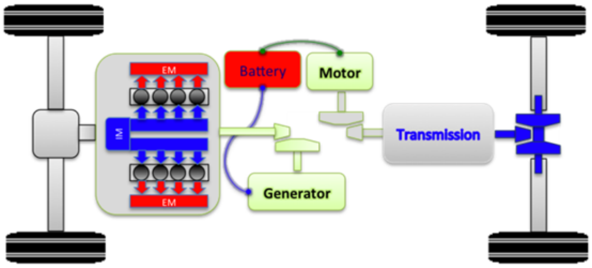


Figure 1. The series HEV configuration.

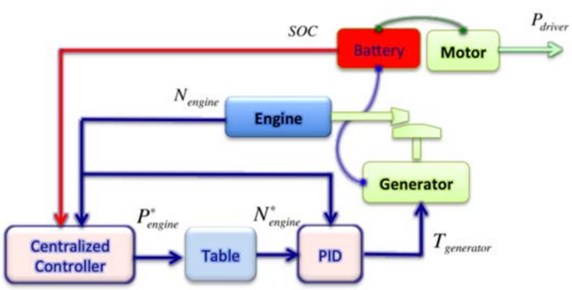


Figure 2. The centralized control scheme.

To ensure that the probability distribution of the engine speed is correlated to the values specified by the equilibrium control policy, we impose the condition that the P_{SOC} must meet the engine power imposed by the probability distribution of the equilibrium control policy. In particular, we assign a given probability to each state (engine speed), and then we correlate the engine power to this stationary probability distribution as illustrated in Figure 4. Although the centralized controller needs to maintain the battery's SOC within the target value as indicated by P_{SOC}, engine should be operated optimally. So, at each instant of time, the value of the engine power provided by the map in Figure 3, P_{SOC}, is constrained by the value P_β provided in Figure 4.

To validate the effectiveness of the equilibrium control policy, we compared it to a thermostat-type controller as the latter has been considered an optimal controller for series HEVs in the literature. The thermostat-type controller was also set up to operate the engine within the maximum and minimum value of the engine power. Both HEVs, the one having the thermostat-type controller and the one with centralized controller using the equilibrium control policy, were run over the same driving cycle.

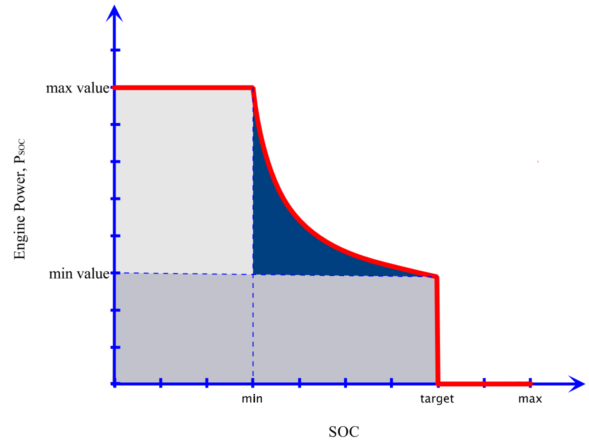


Figure 3. Engine power with respect to the state of charge of the battery.

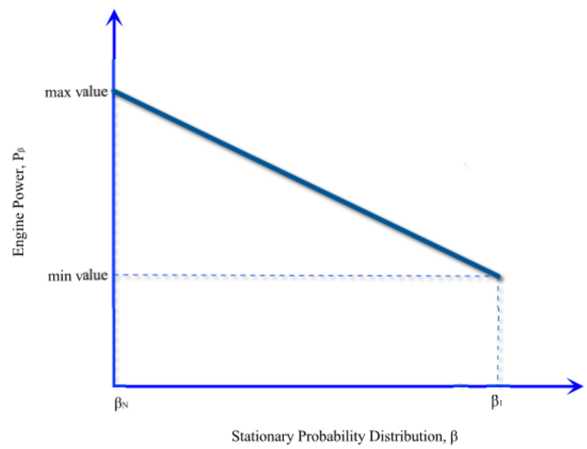


Figure 4. Engine power with respect to the stationary probability distribution.

The inherent algorithm in Autonomie called dichotomy was used to compare the simulation results. The algorithm runs the HEV model over the same driving cycle for multiple times and then provides results corresponding to the same initial and final SOC, as illustrated in Figure 5. Although the thermostat-type controller operates the vehicle by varying the battery SOC from 60% to 65% and also operates the engine at its most efficient BSFC regimes, the centralized controller is set up to maintain SOC at 65%, which corresponds to the engine speed with the lower BSFC values.

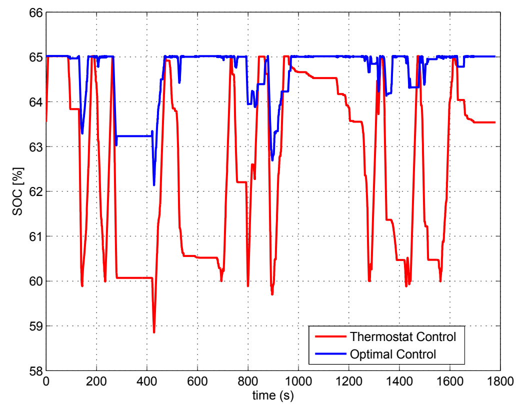


Figure 5. State of charge of the battery for hybrid electric vehicles with the thermostat-type controller and the centralized controller employing the equilibrium control policy.

As the SOC drops below the target value, the controller increases the engine power taking values from the feasible set with the intention to yield the stationary probability distribution and cost function corresponding to the equilibrium control policy. As a result, a 6.6% fuel consumption improvement was achieved, as shown in Figure 6.

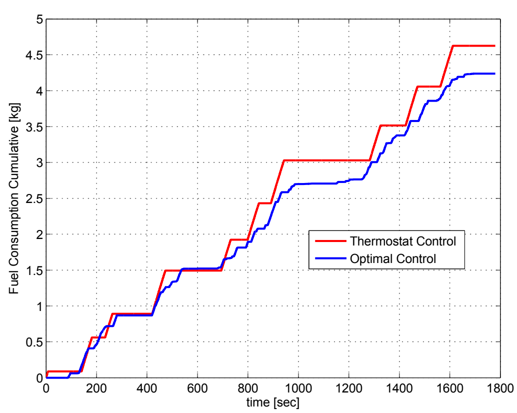


Figure 6. Cumulative fuel consumption for hybrid electric vehicles with the thermostat-type controller and the centralized controller using the equilibrium control policy.

Conclusions

- Identified the instantaneous equilibrium operating point of hybrid propulsion systems that assure maximization of their overall efficiency;
- Developed the control algorithms that can achieve in real time the instantaneous equilibrium operating point;
- The effectiveness of the centralized controller was validated through simulation in various hybrid propulsion systems demonstrating up to 7% fuel economy improvement compared to the state-of-the-art power management control algorithms.

IV.K.3. Products

Publications

1. Malikopoulos, A.A., “Pareto Efficient Power Management Control for Hybrid Electric Vehicles,” *Proceedings of 7th IFAC Symposium on Advances in Automotive Control. (submitted)*
2. Malikopoulos, A.A., “Stochastic Optimal Control for Series Hybrid Electric Vehicles,” *Proceedings of 2013 American Control Conference. (in review)*
3. Malikopoulos, A.A., Charalambous, C.D. and Tzortzis, I., “Dual Constrained Optimization of Markov Chains Subject to Total Variation Distance Uncertainty,” *Proceedings of 2013 Conference on Decision and Control. (submitted)*
4. Malikopoulos, A.A., ECO-Driving Panel: From Habits to Research, ORNL Earth Day Lunch and Learn Seminar, Oak Ridge, TN, April 16, 2012.
5. Malikopoulos, A.A., Stochastic Optimal Control for Advanced Propulsion Systems, 2012 DOE Crosscut Workshop on Lean Emissions Reduction Simulation, University of Michigan, Dearborn, MI, April 30- May 2, 2012.
6. Malikopoulos, A.A., Autonomous Intelligent Plug-In Hybrid Electric Vehicles, DOE Hydrogen and Vehicle Technologies Program Annual Merit Review and Peer Evaluation, Washington D.C., May 14, 2012.
7. Malikopoulos, A.A., Self-Learning Control for Advanced Propulsion Systems, Cummins Inc., Columbus, IN, May 23, 2012.

IV.L. Fuel Consumption Benefit of Low-Temperature, Compression-Ignited Engine for a Conventional Vehicle

Principal Investigator: Philippe Abiven, Aymeric Rousseau, Steve Ciatti
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-7261; Email: pabiven@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: david.anderson@ee.doc.gov

IV.L.1. Abstract

Objective

- Assess the fuel consumption benefit of a low-temperature, compression-ignited engine for a conventional vehicle compared to existing spark-ignited engine technologies

Approach

- Collect test points for a low temperature combustion (LTC) engine and generate complete LTC engine map
- Select additional engine technologies for comparison, including port fuel injected (PFI) and spark-ignited direct injection (SIDI)
- Build test vehicles with the same vehicle technical specifications, optimize vehicle level controls to perform fair analysis, perform vehicle system simulations, and analyze results

Major Accomplishments

- Developed a generic process to generate an engine map from test points based on interpolations and extrapolations
- Compared vehicles using LTC, PFI, and SIDI technologies, demonstrating the potential for the LTC engine to provide up to 18% fuel consumption benefit

Future Activities

- Evaluate impact of baseline engine selection
- Evaluate impact of transmission and final drive ratio selection
- Evaluate impact of shifting algorithm
- Look at the benefits of LTC engine for electric drive vehicles
- Measure fuel rate and emissions on the test bench for selected vehicles

IV.L.2. Technical Discussion

Background

Compression-ignited (CI) engines are widely used all over the world due to their high efficiency. However, one of the main challenges of CI engines is the continuously increasing cost and complexity of the after-treatment system due to stringent environmental regulations. The objective of this project is to use CI engines running on gasoline fuel to maintain the high efficiency while producing lower engine emissions.

Introduction

Thanks to the progress in advanced combustion control by Argonne National Laboratory, a low-temperature combustion (LTC) engine was developed and tested to assess its fuel consumption potential over spark-ignited engines.

Approach

A map of the LTC engine was created from 29 test points. Light-duty midsize vehicles were simulated in Autonomie to compare the LTC engine to port fuel injected (PFI) and spark-ignited direct injection (SIDI) technologies. All vehicles were sized to meet the same vehicle technical specifications. Outside of the engine, all the component and vehicle assumptions were maintained except for the transmission and shifting strategy, which was tailored to each engine.

LTC Engine Map

The baseline engine used to develop the new LTC control is the 1.9 L GM.

Test Points

The Autonomie engine model uses a grid of equally spaced points for engine speed and engine torque to determine the fuel rate.

To represent the most frequent operating conditions of the LTC engine, several conventional vehicles were simulated on standard drive cycles to select 29 representative steady-state test points. However, these test points do not fit exactly in the grid, so the engine map had to be completed using interpolation and extrapolation methods. Figure 1 shows the grid and the location of the test points.

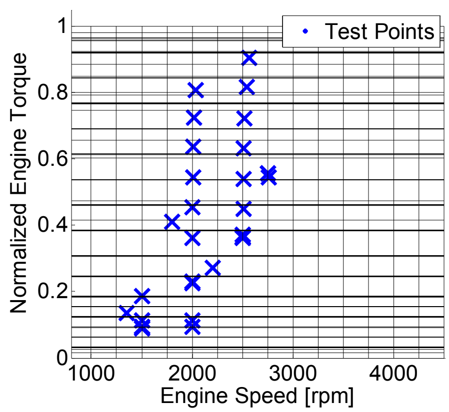


Figure 1. LTC Engine Fuel Rate Test Points.

Engine Map Generation

A portion of the engine map is created by applying an interpolation function to the remaining points.

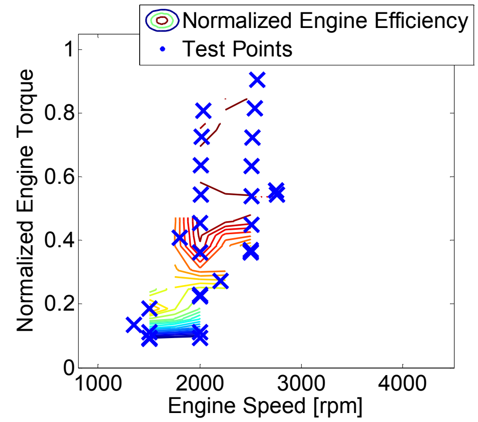


Figure 2. LTC Engine Map Based on Test Points.

For each engine speed considered, one now must define engine efficiency and fuel rate values for the entire range of torques considered. To do so, we consider the lines representing engine efficiency as a function of torque at constant speed: $\eta_{LTC,S}(T)$, where s is the engine speed, and T is the engine torque. As indicated in Figure 2, we assume that the lines should have the same shape for the LTC engine as for a diesel engine. The rate of change of the efficiency lines from a diesel engine is used to complete the partial lines of the LTC engine. The first section of the LTC engine map based on the speed range selected during testing was then created.

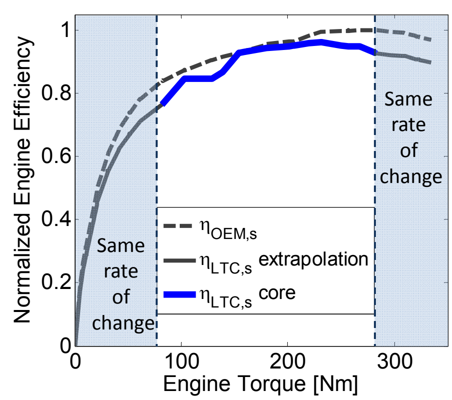


Figure 3. Extrapolation of Map Core for a Defined Engine Speed Value.

During the second phase, the fuel rate/efficiency curves were created for the remaining engine speeds. We assumed that all the lines have the same shape as the line at the top of the range. The ratio applied to compute values above the top range line comes from a map for an original equipment manufacturer (OEM) diesel engine. Consider speed s, which is above the range top speed s_{top}. The efficiency line of the LTC engine at speed s is:

$$\eta_{LTC,s} = \frac{max(\eta_{OEM,s})}{max\left(\eta_{OEM,s_{top}}\right)} \times \eta_{LTC,s_{top}}$$

Figure 4 shows the OEM diesel and LTC efficiency lines at speeds s and s_{top} for $s > s_{top}$.

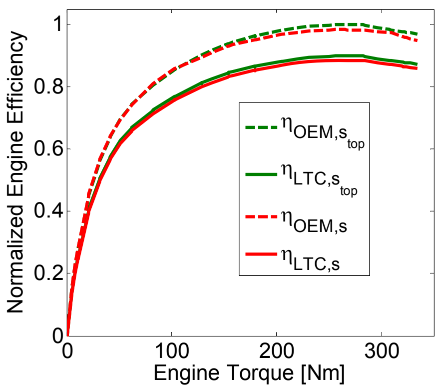


Figure 4. Extrapolation of Engine Map from One Speed Value to Another.

Similarly, if s is below the range:

$$\eta_{LTC,s} = \frac{max(\eta_{OEM,s})}{max(\eta_{OEM,s_{bottom}})} \times \eta_{LTC,s_{bottom}}$$

The complete Willans plot of the LTC engine, representing the fuel rate as a function of torque at various speeds, is consistent with that of other engines (Figure 5).

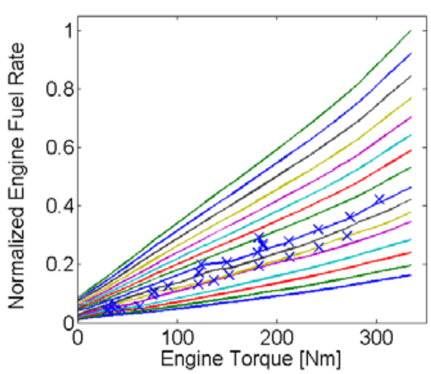


Figure 5. LTC Engine Willans Plot (curves, other engines; crosses, our results).

Simulation Assumptions

A light duty midsize vehicle was selected for the simulations. All powertrain components and specifications were the same, except:

- Engine
- Gearbox
- Final drive
- Vehicle weight

Transmission

Using the same gearbox and final drive ratios with the LTC engine as with the spark-ignited engines would have led to an imbalanced comparison since they have different speed ranges. The differences are shown in Tables 1 and 2.

Table 1. Gearbox ratios

LTC	SIDI & PFI
4.15	4.04
2.37	2.37
1.56	1.56
1.16	1.16
0.86	0.85
0.69	0.67

Table 2. Final drive ratios.

LTC	SIDI & PFI
4.15	4.04

Engine Sizing

To ensure a fair comparison, engine maps were linearly scaled so that vehicles achieve the same vehicle technical specification, which is 0-60 mph in 9 seconds. Because the maximum torque curves of the three engines are very different (Figure 6), so is their scaled power (Table 3).

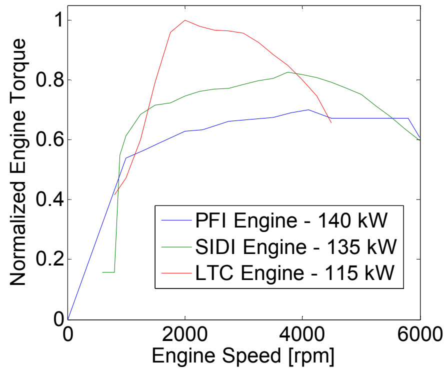


Figure 6. Maximum Torque Curves.

Table 3. Scaled Engine Power

	LTC	SIDI	PFI
Engine Power Max (kW)	115	135	140

Vehicle Test Weight

To account for the difference in engine weight between SI and CI technologies, the vehicle test weight for SI engines was set to 3,200 lb, compared with 3,310 lb for CI engines.

Drive Cycles

The Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) drive cycles were simulated for the three engine technologies. A weighting of 55% UDDS and 45% HWFET was used to determine the combined drive cycle benefits. All the simulations were performed with the assumption of hot conditions.

Results

Fuel Consumption

In terms of fuel consumption (Table 4), the LTC engine brings an 18% improvement over the PFI engine on the combined drive cycle, 7% over the SIDI engine. For reference, the fuel economy results are presented in Table 5.

Table 4. Fuel Consumption Results (L/100 km)

	PFI	SIDI	LTC Engine
UDDS	9.7	8.5	8
HWFET	6.7	6	5.6
Combined	8.4	7.4	6.9
Improvement over PFI (%)		**11**	**18**
Improvement over SIDI (%)			**7**

Table 5. Fuel Economy Results (mpg)

	PFI	SIDI	LTC Engine
UDDS	24.2	27.6	29.6
HFWET	35.2	38.9	42.4
Combined (mpg)	28.2	31.7	34.2
Improvement over PFI (%)		**13**	**21**
Improvement over SIDI (%)			**8**

Transmission Impact

On the UDDS and HWFET cycles, the SIDI engine operates at higher speed than the LTC engine because the transmission ratios of the LTC are lower (compare Figure 7 and Figure 8). However, the shape of the PFI engine map leads the shifting logic to operate more often in 5th gear on the UDDS cycle. Indeed, the algorithm that computes the shifting logic uses engine-dependent parameters, such as idle speed and maximum speed. Thus, even though all other parameters were kept the same for all engines, the shifting logic was different for the PFI than the SIDI. As a consequence, the PFI engine operates at lower speed than the LTC engine on the UDDS cycle (compare Figure 8 and Figure 9). However, on the HWFET cycle all vehicles are in 5th gear; as a result, because of its higher ratio, the PFI engine operates at higher speed than the LTC engine.

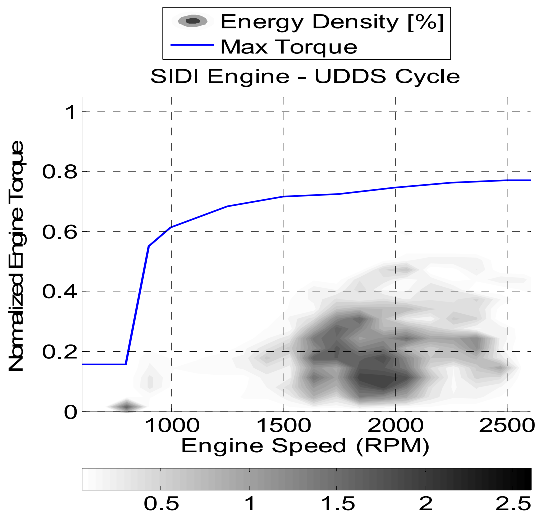


Figure 7. SIDI Engine Density on UDDS Cycle.

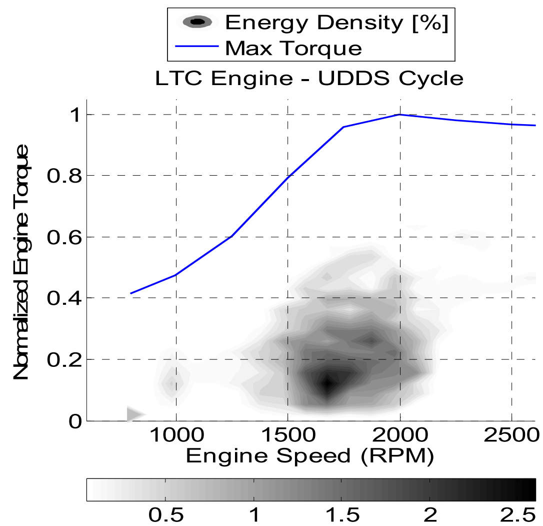


Figure 9. LTC Engine Density on UDDS Cycle.

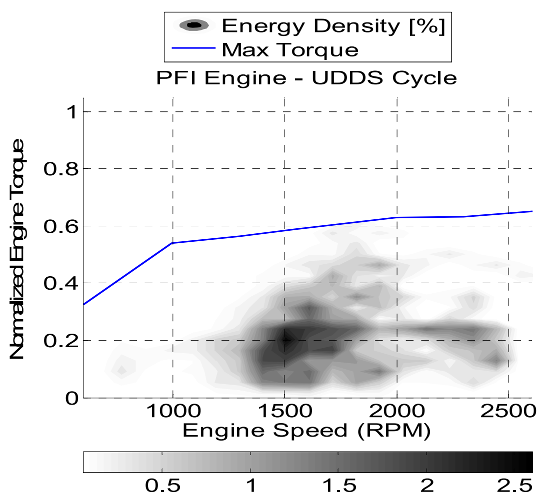


Figure 8. PFI Engine Density on UDDS Cycle.

Conclusions

A complete engine map was developed for an LTC engine. The fuel consumption benefits of the technology were then compared to those for the PFI and SIDI engines.

The results showed that the LTC engine has the potential to provide significant fuel consumption improvement over existing SI technologies: an 18% increase compared to PFI and 7% compared to SIDI.

Since these fuel consumption benefits are only valid for the assumptions considered (e.g., reference engines, transmission, shifting algorithm, and drive cycles), the impact of the assumptions on the results will be evaluated in the second phase of the project.

IV.L.3. Product

Publication

1. Abiven, P., “Fuel Consumption Benefit of Low Temperature Combustion Engine for Conventional Vehicle,” DOE Vehicle Technologies Program, Washington, DC, August 2012.

IV.M. Crosscutting Support Activities (VSATT, LEESS and TSDC)

Principal Investigator: Jeffrey Gonder
National Renewable Energy Laboratory (NREL)
15013 Denver West Parkway, MS 1634
Golden, CO 80401
Phone: (303) 275-4462; Email: jeff.gonder@nrel.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: david.anderson@ee.doe.gov

IV.M.1. Abstract

Objective

- Support three crosscutting activities:
  - NREL's participation in the U.S. DRIVE Vehicle Systems Analysis Technical Team (VSATT).
  - The combined effort with DOE Energy Storage to analyze full-HEV performance using a lower-energy energy storage system (LEESS). Maintaining high fuel economy with a smaller, less costly and/or higher performing ESS would improve the overall cost/benefit, market penetration and aggregate fuel savings of HEVs.
  - Partnership with the U.S. Department of Transportation (DOT) on operating the Transportation Secure Data Center (TSDC).

Approach

- Apply analysis tools, give feedback to and receive input from other national lab and automaker participants in VSATT on studies of pre-competitive interest to advance commercialization of vehicle efficiency technologies.
- Work with industry partners to develop a test platform for in-vehicle evaluation of LEESS devices.
- Securely archive GPS data sets in the TSDC, process the data for advanced vehicle analyses, post cleansed data for public download, and make spatial data accessible to approved users through a controlled interface.

Major Accomplishments

- Delivered multiple presentations at the request of VSATT OEM participants (see Products section); educated the group on pertinent research findings and received recommendations for next steps.
- Obtained Ford Fusion HEV and designed LEESS conversion/test platform.
  - Executed CRADA with Ford to support the conversion, and an NDA and Bailment Agreement with JSR Micro to obtain the initial lithium-ion capacitor (LIC) modules to test.
  - Developed detailed understanding of the production battery system, and approach to use components from a salvaged battery along with dSpace equipment to implement the conversion.
- Doubled the number of TSDC datasets available and surpassed 130 registered users.

Future Activities

- Continue supporting VSATT and participate in the more formal project review process starting in FY 2013.
- Conduct comparison testing of the Fusion HEV operating on the production battery as compared to the LIC modules, and later in FY 2013 implement and evaluate a Nesscap-provided LEESS.
- Add TSDC data sets and support lab and other researchers making use of the data for advanced vehicle analyses.

IV.M.2. Technical Discussion

Background

This task encompasses three different crosscutting activities: (1.) Support for NREL's participation in the Vehicle Systems Analysis Technical Team (VSATT), (2.) Continued cost-share support with the DOE Energy Storage program for the hybrid electric vehicle (HEV) lower-energy energy storage system (LEESS) analysis and test platform development activity, and (3.) Participation in the Transportation Secure Data Center (TSDC), which is primarily funded by the U.S. Department of Transportation (DOT) Federal Highway Administration (FHWA).

VSATT is one of several technical teams participating in the U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) program. NREL provides on-going support for VSATT as requested by the co-chair with DOE approval. NREL's role focuses on the application of analysis tools (e.g., via simulation, trade-off analysis, and optimization), and support for component model development, calibration, and validation.

For the TSDC project, DOT has provided the primary funding to maintain the data center and perform data processing that supports travel activity, spatial and other transportation-focused analyses. The DOE contribution via this task enables further data processing focused on supporting vehicle fuel use and energy analyses.

Example outputs from the VSATT- and TSDC-supporting activities will be given in the following section titled "Products." The remainder of this Technical Discussion section will focus on highlights from the LEESS support activity.

Introduction

Automakers have been mass producing HEVs for well over a decade, and the technology has proven to be very effective at reducing per-vehicle fuel use. However, the incremental cost of HEVs such as the Toyota Prius or Ford Fusion Hybrid remains several thousand dollars higher than the cost of comparable conventional vehicles, which has limited HEV market penetration. The battery energy storage device is typically the component with the greatest contribution toward this cost increment, so significant cost reductions and/or performance improvements to the energy storage system (ESS) can correspondingly improve the vehicle-level cost vs. benefit relationship. Such an improvement would, in turn, lead to larger HEV market penetration and greater aggregate fuel savings.

In recognition of these potential benefits, the United States Advanced Battery Consortium (USABC) asked NREL to collaborate with its Workgroup and analyze the trade-offs between vehicle fuel economy and reducing the decade-old minimum energy requirement for power-assist HEVs. NREL's analysis showed that significant fuel savings could still be delivered from an ESS with much lower energy storage than the previous targets, which prompted USABC to issue the new set of LEESS targets and issue a request for proposals to support their development. In order to validate the fuel savings and performance of an HEV using such a LEESS device, this jointly-funded activity has designed a test platform in which alternate energy storage devices can be installed and evaluated in an operating vehicle.

Table 1. USABC LEESS Device Requirements

End of Life Characteristics	Unit	Target Value	
2s / 10s Discharge Pulse Power	kW	55	20
2s / 10s Regen Pulse Power	kW	40	30
Discharge Requirement Energy	Wh	56	
Regen Requirement Energy	Wh	83	
Maximum Current	A	300	
Energy over which Both Requirements are Met	Wh	26	
Energy Window for Vehicle Use	Wh	165	
Energy Efficiency	%	95	
Cycle-Life	Cycles	300,000 (HEV)	
Cold-Cranking Power at -30ºC (after 30-day stand at 30^{o}C)	kW	5	
Calendar Life	Years	15	
Maximum System Weight	kg	20	
Maximum System Volume	Liter	16	
Maximum Operating Voltage	Vdc	≤400	
Minimum Operating Voltage	Vdc	≥0.55 V_{max}	
Unassisted Operating Temperature Range	ºC	-30 to +52	
30^o -52^o	%	100	
0^o	%	50	
-10^o	%	30	
-20^o	%	15	
-30^o	%	10	
Survival Temperature Range	ºC	-46 to +66	
Selling Price/System @ 100k/yr)	$	400	

Approach

In fiscal years 2009-2010 (FY 2009-2010) General Motors (GM) supported NREL through a funds-in Cooperative Research and Development Agreement (CRADA) to convert a Saturn Vue belt alternator starter mild HEV to operate on ultracapacitor modules instead of the production 42 V nickel-metal hydride (NiMH) batteries. That effort demonstrated that the mild HEV was able to achieve just as high fuel economy using the ultracapacitors as using the production batteries. For this effort, NREL sought to establish a similar automaker collaboration in order to facilitate a robust conversion of a full-HEV (with a larger motor and battery than a mild HEV) to operate on alternative LEESS devices.

NREL also engaged with device developers to confirm their ability and interest to provide LEESS modules for evaluation in the converted vehicle. The automaker and device developer interactions began in FY 2011, and came to fruition during FY 2012 in the form of several contractual agreements.

Results

The first agreement to be completed was a CRADA with Ford, which was executed in April, 2012. NREL and Ford agreed upon the model year 2012 Fusion Hybrid as a good platform for the project, and the acquired research vehicle is shown in Figure 1.

Figure 1. Ford Fusion Hybrid Test Platform at NREL.

Designing the conversion required first understanding the construction of the production High Voltage Traction Battery (HVTB) and its integration with the rest of the vehicle. Important components of the HVTB include the high-voltage Bussed Electrical Center (BEC), the Battery Pack Sensor Module (BPSM) and the Battery Energy Control Module (BECM). The BEC acts as an interface between the high-voltage output of the HVTB and the vehicle's electric motor, air conditioning compressor, and DC/DC converter. The BPSM measures the voltage and temperature of the NiMH cells and communicates with the BECM, which manages the charging/discharging of the battery and also communicates with the other vehicle control modules over the High Speed Controller Area Network (HS-CAN) bus. Figure 2 shows a schematic of the HVTB including these components, and a photo of the HVTB in the vehicle, which mounts between the rear seat and the trunk area.

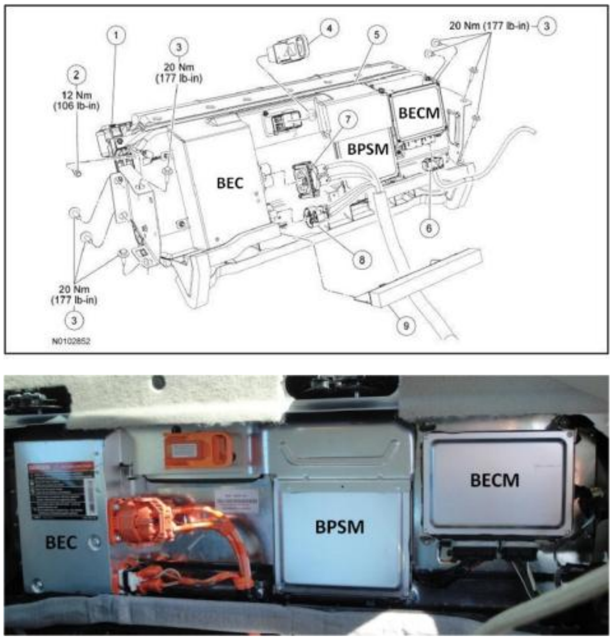


Figure 2. Schematic and Photo of the Fusion Hybrid's High-Voltage Traction Battery (HVTB).

NREL elected to implement the conversion with the production HVTB still installed and the option of operating the vehicle either with the original battery or with the alternative LEESS under test. This arrangement helps retain drive-ability even if something is not working properly with the replacement system, and allows direct A-to-B comparisons with the vehicle alternately operated using each ESS. In order to implement this configuration, NREL acquired a second HVTB and disconnected the BEC, BPSM, BECM, cell sense leads, and various wiring harnesses so that they could be used with the alternative LEESS under test.

Figure 3 shows a picture of these disconnected components, and Figure 4 shows a schematic of their connections within the replacement system and to the vehicle. The dSpace component represented in the schematic is a dSpace MicroAutoBox (MABx), which is used to intercept certain CAN signals pertaining to the BECM's calculations for the production NiMH battery (state of charge, power capability, etc.) and to replace them with corresponding calculations for the alternate LEESS under test. The MABx will also record data during the testing.

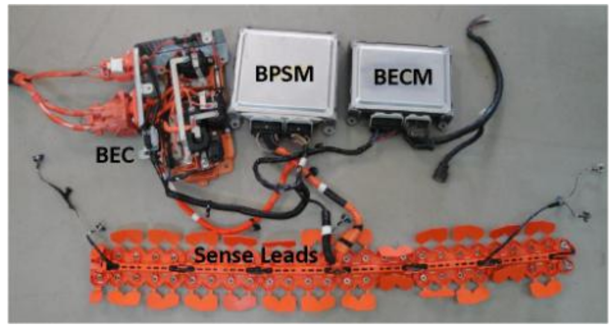


Figure 3. Replacement Interface Components for Use with the Alternate LEESS.

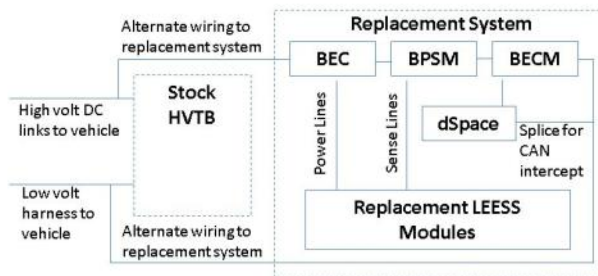


Figure 4. Schematic of Connections between Replacement Components and the Vehicle.

Additional project results obtained during FY 2012 include execution of an agreement with JSR Micro, Inc. to provide (at their expense) lithium-ion capacitor (LIC) modules as the first LEESS device to evaluate in the vehicle, along with proprietary information about the modules to support their integration and testing. The LICs are asymmetric electrochemical energy storage devices possessing one electrode with battery-type characteristics (lithiated graphite) and one with ultracapacitor-type characteristics (carbon).

Figure 5 shows a picture of the JSR Micro LIC modules that recently arrived at NREL. These modules will initially be cycled in a laboratory environmental chamber to verify their performance and to obtain calibration data for the state estimator model in the MABx. By providing this model continuous current and voltage measurements from the LIC pack, it can keep track of variables such as the instantaneous state of charge and power capability of the pack, which need to be reported to the overall vehicle controller over the HS-CAN.

Figure 5. Photo of the JSR Micro LIC Modules.

Conclusions

Alternate HEV storage systems such as the LIC modules described above have the potential for improved life, superior cold temperature performance, and reduced cost relative to traditional battery storage systems. If such LEESS devices can also be shown to maintain high HEV fuel savings, then future HEVs designed with these devices could have an increased value proposition relative to conventional vehicles, thus resulting in greater HEV market penetration and aggregate fuel savings. The vehicle test platform developed through this project will help to validate the in-vehicle performance capability of alternate LEESS devices and to identify unforeseen issues.

This report describes the collaboration agreements established and the test vehicle design completed in FY 2012. During the continuation of this project in FY 2013, NREL will evaluate the test vehicle's operation using the LEESS devices from JSR Micro and other developers. Nesscap Energy, Inc. intends to provide the second system to test and has begun the process to execute a CRADA with NREL for this purpose. The Nesscap system will consist of ultracapacitor modules that are believed to satisfy the design requirements of a replacement for the Fusion Hybrid battery. The test vehicle will thus provide a reusable platform for evaluating alternate HEV ESS options, including those under development by the USABC LEESS contract awardees, when they become available.

Testing on the various LEESS options is expected to be completed in FY 2013 or perhaps FY 2014, pending device availability. Other possible future work on this topic could include evaluating the potential offered by LEESS devices with more extensive vehicle modification, such as by increasing the motor size to leverage a higher-power capability ESS.

IV.M.3. Products

This section lists work products from the VSATT and TSDC support activities, as well as from the LEESS evaluation effort.

Publications

VSATT related (NREL presentations given at VSATT meetings):

1. Gonder, J., Earleywine, M., and Sparks, W., "Analyzing Vehicle Fuel Saving Opportunities through Intelligent Driver Feedback." Invited presentation at the January 2012 VSATT meeting, Southfield, MI.
2. Brooker, A., Wu, H., Earleywine, M., and Gonder, J., "Evaluation of the Costs, Benefits and Feasibility of Electric Roadway Technologies and Travel Scenarios." Invited presentation at the February 2012 VSATT meeting, Southfield, MI.
3. Gonder, J., Brooker, A., Earleywine, M., Wang, L., and Pesaran, A., "Advanced HEV/PHEV Concepts – Project Overview." Invited presentation at the February 2012 VSATT meeting, Southfield, MI.

TSDC related (sample of 2012 publications using TSDC data for vehicle energy analyses):

1. Lin, Z., Dong, J., Liu, C., and Greene, D., "PHEV Energy Use Estimation: Validating the Gamma Distribution for Representing the Random Daily Driving Distance." Presented at the Transportation Research Board's 91st Annual Meeting, January 2012.
2. Gonder, J., Earleywine, M., and Sparks, W., "Analyzing Vehicle Fuel Saving Opportunities through Intelligent Driver Feedback." Society of Automotive Engineers 2012 World Congress, 2012-01-0494.
3. Smith, K., Neubauer, J., Earleywine, M., Wood, E., and Pesaran, A., "Comparison of Plug-In Hybrid Electric Vehicle Battery Life across Geographies and Drive-Cycles." Society of Automotive Engineers 2012 World Congress, 12PFL-0731.

4. Wood, E., Neubauer, J., Brooker, A., Gonder, J., and Smith, K., "Variability of Battery Wear in Light Duty Plug-In Electric Vehicles Subject to Ambient Temperature, Vehicle Design and Consumer Usage." 2012 Electric Vehicle Symposium, EVS26-3240298.
5. Khan, M., and Kockelman, K., "Predicting the Market Potential of Plug-In Electric Vehicles Using Multiday GPS Data." Journal of Energy Policy, Vol. 46, July 2012.
6. Neubauer, J., Brooker, A., Wood, E., "Sensitivity of Battery Electric Vehicle Economics to Drive Patterns, Electric Range, and Charge Strategies." Journal of Power Sources. Vol. 209, July 2012; pp. 269-277; NREL Report No. JA-5400-52964.

LEESS related:

1. Gonder, J., Ireland, J., and Pesaran, A., "Development and Operation of a Test Platform to Evaluate Lower-Energy Energy Storage Alternatives for Full-Hybrid Vehicles." Submitted to the SAE Hybrid and Electric Vehicles Technology Symposium, February 2013, Anaheim, CA.

Tools & Data

1. TSDC website: nrel.gov/vehiclesandfuels/secure_transportation_data.html
2. LEESS effort: The test vehicle serves as a reusable tool for evaluating multiple alternative energy storage devices.

HEAVY DUTY MODELING AND SIMULATION

IV.N. CoolCab Truck Thermal Load & Idle Reduction

Principal Investigator: Jason A. Lustbader
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
Phone: (303) 275-4443; Email: Jason.Lustbader@nrel.gov

DOE Program Manager: David Anderson and Lee Slezak
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

IV.N.1. Abstract

Objectives

- Demonstrate at least a 30% reduction in long-haul truck idle climate control loads with a 3-year or better payback period by 2015.
- Collaborate with industry partners in the development and application of commercially viable climate control solutions targeted at minimizing long-haul truck rest period idling.
- Reduce the 838 million gallons of fuel used annually for rest period idling to increase national energy security and sustainability.

Approach

- Evaluate commercially available and advanced technologies using a three-phase approach consisting of baseline testing and model development, thermal load reduction, and idle reduction.
- Implement cost-effective and readily modified cab sections as representative replacement test bucks for full trucks in the evaluation of idle load reduction technologies.
- Quantify the effects of thermal load reduction technologies such as films, paints, or radiant barriers and idle reduction technologies using engine-off soak and daytime rest period air conditioning (A/C) test procedures.

Major Accomplishments

- Demonstrated a 20.8% reduction in daily electric A/C system energy consumption in Colorado outside environment test conditions when switching from a black colored cab to white.
- A 16.7% reduction in A/C battery capacity and weight reduction of 22 kg (48lb) was achieved at little or no additional cost through the selection of cab paint color.
- Demonstrated a 31.1% of maximum possible interior air temperature reduction during peak solar loading soak conditions when switching from a black colored cab to white.
- Demonstrated a 21.8% of maximum possible sleeper air temperature reduction during peak solar loading soak conditions using all privacy curtains.

Future Activities

- Further evaluation of commercially available advanced thermal management and idle reduction technologies such as advanced paints, films, glazing materials, glazing treatments, and insulation.
- Research innovative technologies that may include air distribution, zonal control, comfort based control, and active ventilation systems.
- Development of test methodology for direct quantification of cab climate conditioning energy demands.
- Implement tools for quantifying the impacts of climate control solutions on fuel use and payback period.

IV.N.2. Technical Discussion

Background

Cab climate conditioning is one of the primary reasons for operating the main engine in a long-haul truck during driver rest periods. In the United States, long-haul trucks (trucks that travel more than 500 miles per day) use 838 million gallons of fuel annually for rest period idling [1]. Including workday idling, over 2 billion gallons of fuel are used annually for truck idling [2]. By reducing thermal loads and improving the efficiency of climate control systems, there is a great opportunity to reduce fuel use and emissions associated with idling. Enhancing the thermal performance of cab/sleepers will enable smaller, lighter, and more cost-effective idle reduction solutions. In addition, if the fuel savings from new technologies provide a one- to three-year payback period, fleet owners will be economically motivated to incorporate them. Therefore, financial incentives provide a pathway to rapid adoption of effective thermal load and idle reduction solutions.

Introduction

The U.S. Department of Energy's National Renewable Energy Laboratory's (NREL's) CoolCab project is researching efficient thermal management systems to maintain cab occupant comfort without the need for engine idling. The CoolCab project uses a system-level approach that addresses thermal loads, designs for occupant thermal comfort, and maximizes equipment efficiency. In order to advance the goals of the CoolCab project and the broader goals of increased national energy security and sustainability, the CoolCab team works closely with industry partners to develop and apply commercially viable solutions to reduce national fuel use and industry costs.

Approach

NREL is closely collaborating with original equipment manufacturers (OEMs) and suppliers to develop and implement a strategic approach capable of producing commercially viable results to enable idle reduction systems. This strategic, three-phased approach was developed to evaluate commercially available and advanced vehicle thermal management and idle reduction technologies. The three phases, illustrated in Figure 1, are: Baseline Testing and Model Development, Thermal Load Reduction, and Idle Reduction. Each phase features applications of NREL's suite of thermal testing and analysis tools.

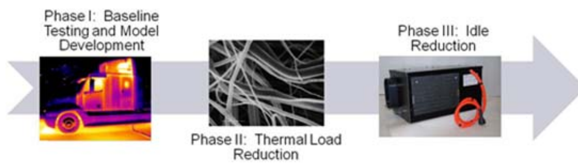


Figure 1. NREL's three-phase approach

In Phase I, Baseline Testing and Model Development, thermal data are collected on a test vehicle and on a control vehicle simultaneously. Several days of data are collected for each test procedure under varying weather conditions. These data are used to calibrate the control vehicle to represent an unmodified, baseline test vehicle. Once the control vehicle is calibrated to predict the performance of the test vehicle, validation tests are conducted. Validation data are collected with the control and test vehicles under unmodified, baseline conditions. Calibration coefficients are applied to the control vehicle validation data, and the results are used to confirm the accuracy of the calibration. After calibration verification, the test vehicle is modified with technologies for Phase II evaluation. Baseline performance data of the test vehicles is also used for the development and validation of CoolCalc [3] models.

In Phase II, Thermal Load Reduction, CoolCalc parametric studies are used as a screening tool for potential thermal load reduction technologies. Reductions in cab/sleeper thermal loads are quantified through experimental investigation of selected commercial and advanced technologies identified from CoolCalc modeling.

In Phase III, Idle Reduction, the most promising of the evaluated technologies are researched further by closely collaborating with industry partners and their suppliers to design and evaluate cab thermal packages that improve thermal performance, reduce climate control loads, and enable market penetration of idle reduction systems. In this phase, vehicles are equipped with commercial and advanced cab thermal management packages coupled with an idle reduction system. NREL experimentally characterizes the impact of these technologies on idle loads. CoolCalc analysis and vehicle simulations are also used to characterize the reduction in idle loads and fuel consumption over a wide range of use and environmental conditions.

In order to experimentally characterize the impacts of the technologies being studied, thermal test procedures are conducted in each phase of the project. Throughout the project, the following test procedures are used for technology evaluation: thermal soak, overall heat transfer (UA), daytime rest period A/C, infiltration rate, and infrared imaging. For the technology evaluation in FY 2012, thermal soak and daytime rest period A/C testing were utilized.

For FY 2012, application of the CoolCalc analysis tool applied to a Volvo cab model identified a reduction in the truck cab rise over ambient temperature by as much as 35.9% through the application of films, paints, or radiant barriers to the exterior opaque surfaces. In addition, experimental results in previous work by Rugh and Farrington [4] on light-duty vehicles showed that a reflective roof film reduced breath air temperature by 12% of the maximum possible temperature reduction and determined that a theoretical maximum of 28% was possible with treatment of all opaque surfaces. Work done by Levinson et al. on light-duty vehicles showed a 4°C–6°C reduction in cabin air temperature with a silver car compared to a black car [5]. It was expected that application of films, paints, or radiant barriers to the exterior opaque surfaces of heavy-duty vehicles would have a larger impact on thermal load reduction due to the increased ratio of opaque to glazing surface areas compared to light-duty vehicles. Experimental tests were completed to quantify the impacts on thermal and idle load reduction.

The test program was conducted at NREL's Vehicle Testing and Integration Facility, shown in Figure 2, during the months of May through October. The facility is located in Golden, Colorado, at an elevation of 5,997 feet at latitude 39.7 N and longitude 105.1 W. The experimental setup included an NREL-owned test truck and two cab test "bucks." Both bucks were the cab section from a representative truck in current production provided by Volvo Trucks North America. One buck was utilized as the control buck, while the other was experimentally modified. For the study, bucks were utilized in place of complete vehicles because they provided a representative and cost-effective model that was adaptable for test configurations and evaluation of potential thermal and idle load reduction technologies.

For the experimental setup, the modified truck, test buck and control buck were oriented facing south and separated by a distance of 25 feet to maximize solar loading and minimize shadowing effects. To keep the buck firewalls from receiving direct solar loads, a firewall shade cloth was implemented on both the control and test bucks. In each vehicle, five curtains were available for use depending on the test being conducted. The curtains available were the privacy, cab skylight, sleeper, and two bunk window curtains.

Figure 2. NREL's Vehicle Testing and Integration Facility.

A National Instruments SCXI data acquisition system was used to record measurements at a sampling frequency of 1.0 Hz, which was averaged over one-minute intervals. Among the three vehicles, a total of 140 calibrated type K thermocouples were utilized. An isothermal bath and reference probe were used for thermocouple calibration, achieving a U_{95} uncertainty of

±0.32°C in accordance with ASME standards [6]. Air temperature sensors were equipped with a double concentric cylindrical radiation shield to prevent errors due to direct solar radiation.

Weather data were collected from both NREL's Solar Radiation Research Laboratory and the Vehicle Testing and Integration Facility weather station, which together feature more than 160 instruments dedicated to high-quality measurements of solar radiation and other meteorological parameters.

Thermal soak tests were conducted to evaluate the impact of technologies in an engine-off solar loading condition. This test procedure was used to characterize technology impacts on interior air temperatures in a test truck or buck ($\overline{T}_{modified}$) compared to interior air temperatures in the baseline buck ($\overline{T}_{baseline}$). During summer operation with passive vehicle thermal load reduction technologies, the best possible steady-state performance is to reduce the interior temperature to ambient temperature. The percent of maximum possible temperature reduction (β) was developed to describe this maximum possible reduction in interior air temperature rise above ambient ($\overline{T}_{ambient}$), as described in equation 1. A β value of 0% indicates that the technology under evaluation did not change the rise over ambient temperature, while a β value of 100% indicates the technology reduced the interior air temperature in the modified vehicle to equal the temperature of ambient air in the environment.

$$\beta = \frac{\overline{T}_{baseline} - \overline{T}_{modified}}{\overline{T}_{baseline} - \overline{T}_{ambient}} \cdot 100\% \qquad (1)$$

For the evaluation of β, the interior air temperature was determined as a volume weighted average of the combined sleeper and cab air temperatures. The average interior cab air temperature was calculated by averaging six type K thermocouples with four located in accordance with the American Trucking Association Technology Maintenance Council's recommended practice RP422A [7], as shown in Figure 3A. Similarly, average sleeper air temperature was calculated by averaging eight type K thermocouples with six located in accordance with RP422A. The addition of two thermocouples located in both the cab and sleeper air spaces improved the accuracy of the average air temperature by more accurately capturing the air temperature distribution, illustrated in Figure 3B. During testing, it was determined that the two temperature measurements made in the cab footwell air space were exposed to occasional direct solar radiation. Due to the increased variability that would occur in the calculation of average interior air temperature, these two measurements were omitted from the calculation.

For the thermal soak testing, data were collected for a time interval from 6:00 a.m. to 4:00 p.m. MDT. During baseline thermal soak measurements, all privacy curtains were removed. The thermal soak performance of the bucks in their baseline conditions were used to characterize and calibrate the inherent differences between the two bucks and between the control buck and the test truck. Calibration was accomplished by collecting four days of baseline data and generating a time-of-day dependent correction factor between the control buck and test buck and between the control buck and test truck. Solar load intensity peaked at approximately 1:00 p.m. daily during thermal soak testing. In addition, peak differential temperatures were found to occur within the 12:00 p.m. to 2:00 p.m. MDT time interval corresponding to this peak solar load. Therefore, interior air and ambient temperatures from 12:00 p.m. to 2:00 p.m. MDT were used for the calculation of β.

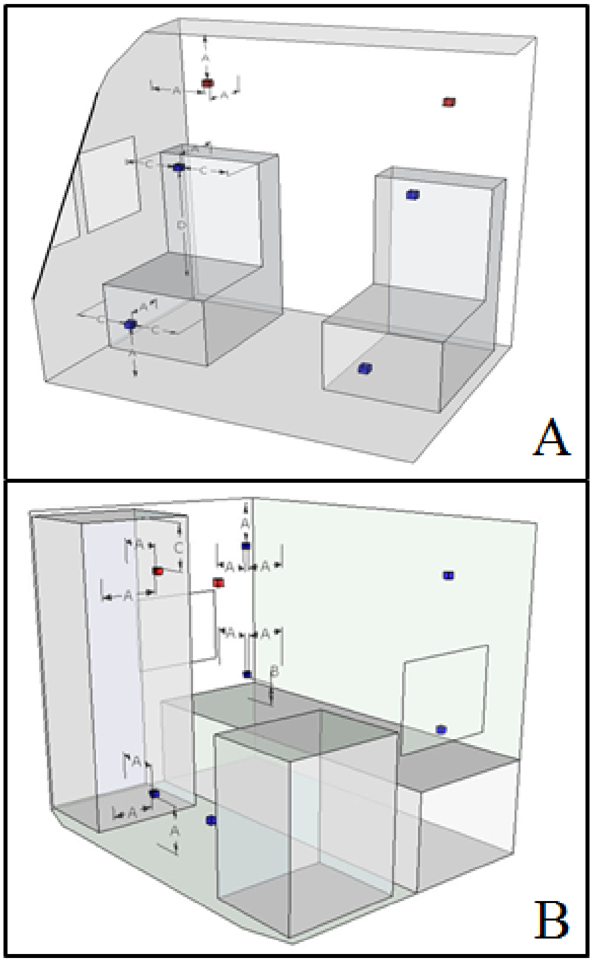


Figure 3. Cab (A) and Sleeper (B) thermocouple locations, dimension A = 12", B = 6", C = 18", blue – TMC standard [5], red – NREL added.

Daytime rest period A/C tests were conducted to characterize thermal management technology impacts on an electric no idle A/C system. A 2,050 W (7,000 BTU/hr) Dometic electric A/C system [5] was installed in the sleeper compartment of each vehicle. For A/C experimentation, all five curtains were utilized on the control buck, test buck, and test truck. All curtains were employed to match the expected standard configuration during a rest period operation. The test period was defined as A/C system first-on to last-off to quantify the daily A/C energy consumption.

A/C electrical power consumption was measured using a Load Controls Incorporated model UPC adjustable capacity power sensor. The power sensor was calibrated to ±15 W. A/C systems were controlled to a target sleeper air temperature of 22.2°C (72°F) or increased to 26.7°C (80°F) if a configuration was expected to exceed the A/C capacity at the lower target temperature. Calibration of the modified buck's A/C system was performed by collecting four days of baseline data. A clear solar day with insignificant cloud cover was required for data to qualify as a baseline test day.

Results

Phase I research focused on the installation, instrumentation, and baseline testing of the two bucks supplied by Volvo Trucks and the NREL-owned test truck. To confirm the bucks were accurate representations of a complete truck, average sleeper and cab air temperatures were compared between the control buck and test truck baseline data. The average air temperature between the control buck and test truck differed by less than 7°C for the cab air space and 5°C for the sleeper air space. The temperature differences observed may be largely explained by differences in manufacturer, geometry, and components. The temperature difference between the buck and truck prior to calibration was highly repeatable with a standard error of less than ± 0.17°C. For the test buck and control buck, cab air temperature agreed to within 1.6°C and sleeper air temperature was within 0.9°C prior to calibration.

After calibrating the modified buck and test truck with the control buck, calibration accuracy was checked using validation test data. Thermal soak calibration was shown to be within ±0.4°C for the test cab and within ± 0.6°C for the test truck between the peak solar loading time of 12:00 and 2:00 p.m. The results of the calibration applied to a validation dataset for the test truck sleeper air temperature is shown in Figure 4. For the validation dataset, sleeper air temperature prediction agreed to within ±0.4°C for the test truck and ±0.2°C for the test buck.

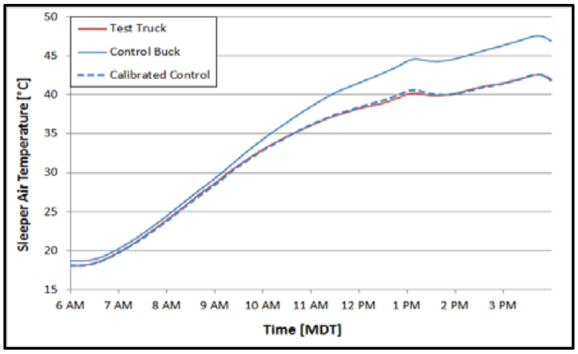


Figure 4. Average sleeper interior air temperature validation day

Baseline A/C testing of the test and control bucks showed repeatable differences between the two configurations. The calibration curve for A/C baseline testing is shown in Figure 5, which includes both calibration days and additional test days. The additional test days were collected but are excluded from the calibration dataset because the solar load throughout these days was not consistent due to partially cloudy weather. The additional test days confirm the strong linear correlation between the two test configurations. The additional test data also indicate that the correlation between test and control buck A/C power consumption is somewhat insensitive to minor solar load variations.

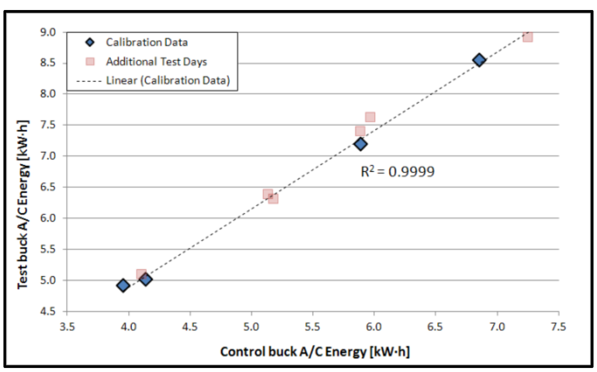


Figure 5. Daily A/C energy calibration data for test and control bucks.

Phase II research focused on the identification and quantification of thermal load reduction strategies. To study the effect of paint on cab air temperatures in thermal soak conditions, black OEM paint was provided through partnership with PPG Industries. The radiative properties of both baseline and black paint were quantified experimentally. Paint properties are given in Table 1. The test buck was painted black and compared to the calibrated white control buck as shown in Figure 6.

Table 1. Solar-weighted optical properties of paint test samples

Buck model	Control	Test	Test
Color	White	White	Black
Reflectance, %	64.2	62.2	4.7
Absorptance, %	35.8	37.8	95.3
Emissivity	0.948	0.953	0.951

Figure 6. Cab experimental configurations: Test buck painted white (left) and painted black (right)

Thermal soak testing of the black and white opaque exterior surfaces showed an average buck air temperature difference of 8.1°C during peak solar load. The temperature difference equates to a percent of maximum temperature reduction, $\beta = 31.1\%$. Figure 7 shows the average buck air temperature for black and white opaque surfaces. Thermal soak testing of additional opaque surface treatments is currently in progress.

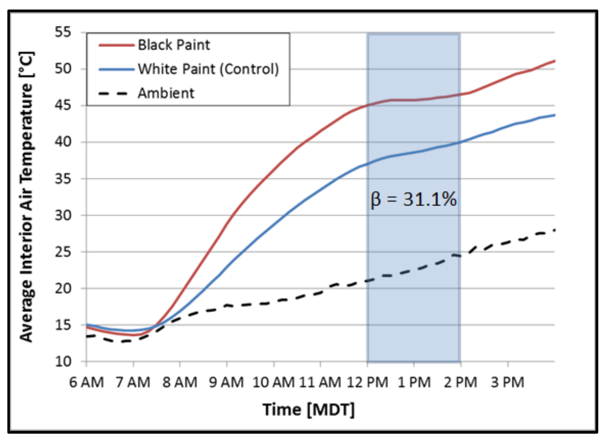


Figure 7. Thermal soak results with black and white opaque surfaces for test buck

Thermal soak testing was completed on the test truck in order to quantify the effects of OEM privacy curtains on the average sleeper air temperature. As outlined in the Approach section, all curtains were used for testing. During the peak solar load from 12:00 to 2:00 p.m., a maximum sleeper air temperature reduction of

2.4°C was measured when using all five OEM curtains on the test truck. During this time, the percent of maximum possible temperature reduction, β = 21.8%, was obtained. Figure 8 shows the average sleeper air temperature and ambient temperature for both curtains open and closed configurations. Additional test configurations to further characterize the cab thermal system for the test truck are in progress.

Phase III focused on the quantification of idle load reduction strategies through collaboration with industry partners. NREL collaborated with Volvo Trucks North America, PPG Industries, and Dometic Environmental Corporation to evaluate the effect of paint on thermal load. Black OEM paint was supplied by PPG Industries and was combined with Dometic Environmental Corporation's A/C system to quantify the impact of paint color on A/C power use in the test cab sleeper air space during engine-off daytime test conditions.

.

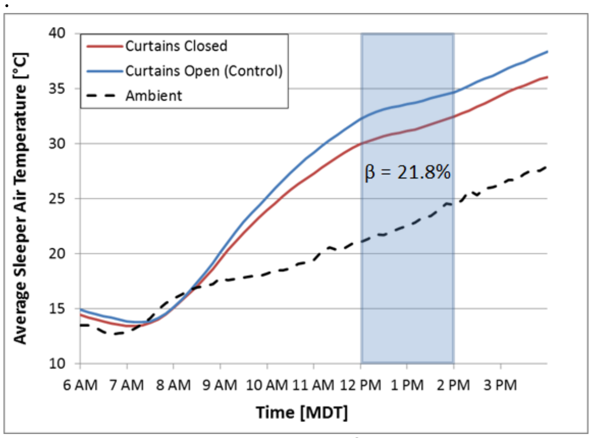


Figure 8. Thermal soak results for curtains opened and closed configurations for test truck.

During evaluation of the black test buck, the A/C target temperature was 26.7°C (80°F) for both the test buck and control buck, as discussed in the Approach section. Hourly average A/C power consumption (Figure 9) shows consistent reduction in A/C electrical energy loads throughout daytime operation. The average daily A/C power consumption decreased 20.8% switching from black to white paint. The decrease corresponds to a 1,001 W·h battery energy savings over the daytime test period. The standard battery-powered A/C system uses four 1,500 W·h lead-acid batteries, weighing a total of 132 kg (291 lb). A 1,001 W·h daily energy savings corresponds to a 16.7% reduction in battery capacity and 22 kg (48 lb) reduction in weight. Daytime rest period A/C testing of additional opaque surface treatments is currently in progress.

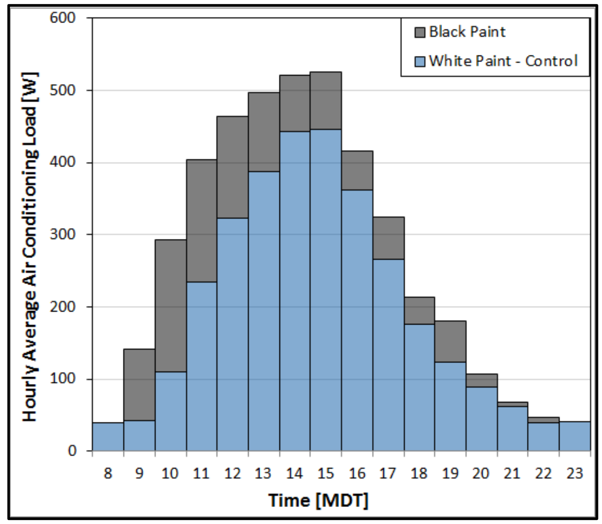


Figure 9. Hourly average test cab A/C power consumption for black and white opaque exterior surfaces.

Conclusions

Long-haul sleeper daily electrical A/C loads were reduced by as much as 20.8% by switching from black to white paint. An electrical energy saving of 1,001 W·h was achieved during a daytime rest period while operating an A/C system under ambient conditions in Golden, Colorado. The electrical energy savings corresponds to a 16.7% reduction in A/C battery capacity and 22 kg (48 lb) weight reduction. Savings in battery capacity lead to lower purchase price and operating costs of idle reduction systems. The savings were realized with a change in paint color, which adds little to no additional cost. Although large savings were realized by using white paint compared to black, other factors such as brand recognition and aesthetics factor into the choice of paint color for heavy-duty trucks. For this reason, additional testing is in progress to characterize advanced paint colors that are dark in the visible spectrum but thermally behave similar to white paint. Future work is planned to model the impact of these technologies over a wide range of use and operating conditions.

In addition to idle load reductions, a sleeper air temperature reduction of 21.8% of maximum possible was realized during engine-off thermal soak testing by applying all vehicle curtains. This result provides insight to the effectiveness of privacy curtains in long-haul vehicles. Additional testing is in progress to fully characterize the impact and value that OEM curtains have on truck idle loads.

Working closely with industry partners and applying both modeling and testing tools, NREL has shown that systematically combining vehicle thermal management and idle reduction technologies can reduce climate control loads needed for long-haul truck rest period idling. This can reduce cost, weight, and volume of idle reduction systems, improving payback period and increasing economic motivation for fleet owners and operators to consider idle reduction systems. Increasing idle reduction system effectiveness and adoption rates will help reduce the 838 million gallons used annually in the United States for long-haul truck rest period idling and potentially reduce truck operation costs.

IV.N.3. Products

Publication

1. Lustbader J., Venson, T. "Application of Sleeper Cab Thermal Management Technologies to Reduce Idle Climate Control Loads in Long-Haul Trucks," SAE Commercial Vehicle Engineering Congress, Rosemont, IL, October 2-3, 2012, Paper Number 2012-01-2052

References

1. Stodolsky, F., Gaines, L., Vyas, A. *Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks.* Argonne National Laboratory, ANL/ESD-43, June 2000.
2. Gaines, L., Vyas, A., Anderson, J., "Estimation of Fuel Use by Idling Commercial Trucks," 85th Annual Meeting of the Transportation Research Board, Washington, D.C., January 22–26, 2006, Paper No. 06-2567.
3. Lustbader, J., Rugh, J., Rister, B., Venson, T. "CoolCalc: A Long-Haul Tuck Thermal Load Estimation Tool," SAE World Congress, Detroit, MI, April 12-14, 2011, Paper Number 2011-01-0656.
4. Rugh, J., Farrington, R. *Vehicle Ancillary Load Reduction Project Close-Out Report*, National Renewable Energy Laboratory, NREL/TP-540-42454, January 2008.
5. Levinson, R., Pan, H., Ban-Weiss, G., Rosado, P., Paolini, R., Akbari, H. "Potential benefits of solar reflective car shells: Cooler cabins, fuel savings and emissions," *Applied Energy*, 2011, 88, 4343-4357.
6. Dieck, R.H., Steele, W.G., Osolsobe, G. *Test Uncertainty.* ASME PTC 19.1-2005. New York, NY. American Society of Mechanical Engineers. 2005.
7. *Battery Based HVAC*, dometictruck.com/bb-hvac.php, accessed on 7/5/2012.

Tools & Data

1. CoolCalc rapid HVAC load estimation tool version 2.0.0. Only available to industry and laboratory partners at this time.

Acknowledgments

- Co-author: Cory Kreutzer (NREL)
- Additional thanks to: John Rugh, Matt Jeffers, Jon Cosgrove, Matthew Gray (NREL)
- Special thanks to: Our industry partners Volvo Trucks, PPG Industries, and Dometic Corporation's Environmental Division.

IV.O. CoolCalc HVAC Tool

Principal Investigator: Jason A. Lustbader
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
Phone: (303) 275-4443; Email: Jason.Lustbader@nrel.gov

DOE Program Managers: David Anderson and Lee Slezak
Phone: (202) 287-5688; Email: David.Anderson@ee.doe.gov
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

IV.O.1. Abstract

Objectives

- Demonstrate at least a 30% reduction in long-haul truck idle climate control loads with a three-year or better payback period by 2015
- Help industry overcome barriers to the adoption of market-viable and efficient thermal management systems that keep the cab comfortable without the need for engine idling
- Investigate opportunities to reduce truck cab thermal loads through modeling and simulation to reduce the 838 million gallons of fuel used for truck rest period idling

Approach

- Develop analytical tools to evaluate the impact of technologies that reduce thermal loads, improve climate control efficiency, and reduce vehicle fuel consumption
- Work closely with industry partners to evaluate and improve modeling and analysis tools that are relevant and beneficial to both original equipment manufacturers and suppliers
- Use validated CoolCalc models to identify promising technologies for further investigation with outdoor testing
- Utilize CoolCalc simulations to extend test results to a wide variety of climate and time-use conditions to more thoroughly evaluate technology performance and estimate fuel savings

Major Accomplishments

- Validated model of Volvo test buck to within 0.89°C of sleeper air temperature at peak solar load
- Applied Volvo model to guide CoolCab outdoor testing, predicting average interior air temperature reductions of:
  - 7.3°C (β=35.9%) from black to white paint
  - 2.8°C (β=15.6%) from blue to an estimated solar-reflective blue paint
- Developed and incorporated vehicle-specific interior convection models
- Improved functionality and reliability; released latest version to industry partners for evaluation

Future Activities

- Improve and apply CoolCalc's rapid parametric analysis tools to help industry estimate design impacts on fuel use and payback period across a broad range of weather and operating conditions
- Continue validation of CoolCalc models, including heavy-duty vehicle heating and cooling systems
- Begin development, validation, and application of medium- and light-duty vehicle models
- Improve integration of CoolCalc with NREL's air conditioning model (CoolSim) and with Autonomie

IV.O.2. Technical Discussion

Background

Heating and air conditioning are two of the primary reasons for long-haul truck main engine operation when the vehicle is parked. In the United States, trucks that travel more than 500 miles per day use 838 million gallons of fuel annually for rest period idling [1]. Including workday idling, over 2 billion gallons of fuel are used annually for truck idling [2]. By reducing thermal loads and improving efficiency, there is a great opportunity to reduce the fuel used and emissions created by idling. Enhancing the thermal performance of cab/sleepers will enable cost-effective idle reduction solutions. If the fuel savings from new technologies can provide a one- to three-year payback period, fleet owners will be economically motivated to incorporate them. This provides a pathway to rapid adoption of effective thermal and idle load reduction solutions.

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory's (NREL's) CoolCab project is researching efficient thermal management strategies that keep the vehicle occupants comfortable without the need for engine idling. To achieve this goal, NREL is developing tools and test methods to assess idle reduction technologies. The heavy-duty truck industry needs a high-level analysis tool to predict thermal loads, evaluate load-reduction technologies, and calculate their impact on climate control fuel use.

To meet this need, NREL has developed CoolCalc, a software tool to assist industry in reducing climate control loads for heavy-duty vehicles (HDV). CoolCalc is enables rapid exploration of idle reduction design options for a range of climates.

Introduction

CoolCalc is an easy-to-use simplified physics-based HVAC load estimation tool that requires no meshing, has flexible geometry, excludes unnecessary detail, and is less time-intensive than more detailed computer-aided engineering (CAE) modeling approaches. For these reasons, it is ideally suited for performing rapid trade-off studies, estimating technology impacts, and sizing preliminary HVAC designs. CoolCalc complements more detailed and expensive CAE tools by first exploring the design space to identify promising technologies and specific parameters that require deeper investigation.

CoolCalc, described in more detail in [3], was originally built on NREL's OpenStudio platform as a plug-in extension for Google's SketchUp three-dimensional design software (now owned by Trimble), and has been adapted to better suit the transportation industry. DOE's EnergyPlus software (developed for building energy modeling) is used as the heat transfer solver for CoolCalc.

CoolCalc is filling an important role in the CoolCab project's suite of experimental and analytical tools, as well as equipping industry partners with a valuable and cost-effective research and design tool.

Approach

The goals of the CoolCab research project are to reduce thermal loads, improve occupant thermal comfort, and maximize equipment efficiency to eliminate the need for rest period engine idling. To accomplish these goals, NREL is closely collaborating with original equipment manufacturers (OEMs) and suppliers to develop and implement commercially viable thermal management solutions.

The CoolCab project employs a strategic, three-phase approach to evaluating commercially available and advanced vehicle thermal management and idle-reduction technologies. The three phases are (I) baseline characterization and model development, (II) thermal performance enhancement, and (III) idle reduction. Each phase features applications of NREL's suite of thermal testing and analysis tools. CoolCalc is applied throughout the entire research process to complement the evaluation of idle-reduction strategies through outdoor testing and more detailed CAE modeling.

In Phase I, CoolCalc models of the test vehicles are built, starting from computer-aided design (CAD) models and other information provided by OEMs and suppliers. The models are validated against test data collected at NREL's Vehicle

Testing and Integration Facility (VTIF). Local weather data logged at the VTIF's new weather station are fed into the CoolCalc simulation to ensure that the model behaves similarly to the test vehicle under the same weather conditions.

CoolCalc is leveraged in Phase II to identify opportunities to reduce thermal loads via rapid simulation of technologies and thermal management strategies. Top candidates from the parametric simulations are selected for further investigation through outdoor testing.

Testing results from Phase II serve as a launching point for CoolCalc simulations to analyze performance and estimate fuel use savings across a wide variety of weather and time-use distributions. For each set of conditions, CoolCalc supplies thermal loads to CoolCab's air-conditioning (A/C) model, which calculates required compressor power. The model is then coupled with Autonomie to predict fuel use for the weather and use conditions. This fulfills the end goal of providing decision makers with the necessary information to adopt solutions that reduce or prevent engine idling and save fuel.

Results

COOLCALC IMPROVEMENTS AND NEW FEATURES

Many enhancements were made to the CoolCalc HVAC load estimation tool to improve functionality and usability:

- Several minor and major bugs were corrected, and a CoolCalc bug tracker was developed to report software issues and to suggest new features. The bug tracker was only used internally, but will be available to the public in future CoolCalc releases.
- CoolCalc source code was restructured to a "project-based" format, permitting the use of more modular components and building a strong foundation for future model improvements. This change also gives users more control over individual portions of CoolCalc models while still allowing importing and exporting of EnergyPlus input file format.
- The graphical user interface (GUI) of the Object Browser was expanded to include dynamically generated interfaces for all available EnergyPlus objects. An exclusion list was developed to hide all objects that do not apply to vehicle modeling. When available, EnergyPlus Class and Field notes are displayed to the user.
- A Parametric Variables GUI was developed that enables users to define multiple values for individual model parameters. The GUI allows simulations to be run parametrically. For example, all defined values of a material property such as insulation thickness can be programmatically evaluated. The parametric variables can be implemented at the field level and, in the future, at the object level, providing greater flexibility to the model for parametric analyses. This feature also applies to weather files, which can be grouped (for example, by geographic region) and defined as a single parametric variable.
- The overall model development process was extended beyond vehicle geometry and basic component definitions to incorporate a more flexible vehicle climate control system setup. The user can now more easily add a default HVAC system to a vehicle model and modify system settings through a graphical interface, as shown in Figure 1.

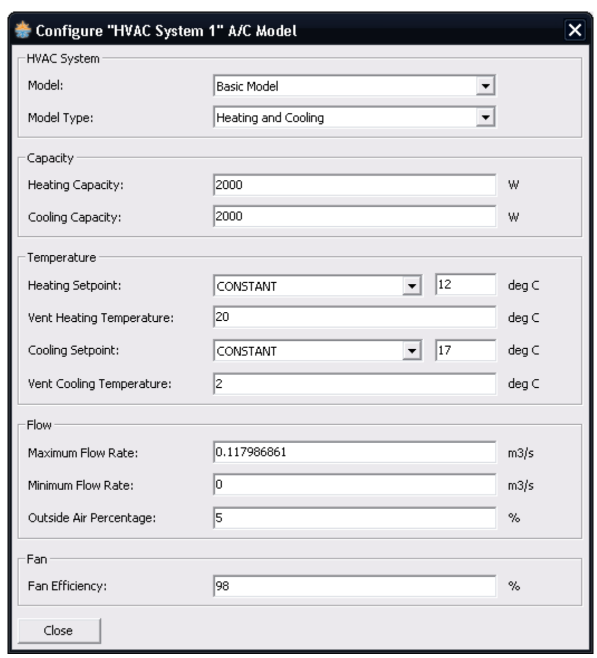


Figure 1. CoolCalc HVAC system GUI.

- The Run Simulation GUI was overhauled to provide much greater simulation control. With the new GUI, the user can select which design days to evaluate, which output variables to report, and which output files to create and display upon simulation completion. The user can also create and select multiple simulation periods (opposed to only one, previously) when using weather files. The Run Simulation GUI displays all parametric variables defined in the model, including weather files. The GUI also allows the user to configure variable combinations for simulation up to a full factorial analysis. Sequential simulations are automatically executed, saving user setup time and allowing simulations to be run unattended.
- Documentation of code was improved. HTML documentation of the classes and a diagram of the general system architecture were added. This improved code readability and facilitates future development.

The CoolCalc user guide will be updated to reflect all of the recent improvements, and expanded to include sections for troubleshooting common errors and for advanced users. The latest version of CoolCalc was released to industry partners in September.

VEHICLE INTERIOR CONVECTION MODELS

An important component of any vehicle thermal model is the convection model used for the interior surfaces. The EnergyPlus heat transfer coefficient model is appropriate for the natural convection under soak conditions. Interior forced convection that occurs when using vehicle HVAC systems is not properly captured by the default convection models available in EnergyPlus. To improve the accuracy of forced convection modeling on interior surfaces, vehicle-specific convection correlations have been implemented in CoolCalc. Leveraging previous computational fluid dynamics (CFD) simulations of vehicles, these correlations were developed to relate the interior surface convection coefficients to the HVAC air exchange rate of the vehicle. Correlations were developed for heavy- and light-duty models, for four primary surface types: ceiling, floor, walls, and windows. For the HDV correlations, CFD simulations were conducted with air flow rates varying between 0.005 and 0.119 m^3/s, and the resulting convection coefficient data were fitted with a third-order polynomial curve, as shown in Figure 2.

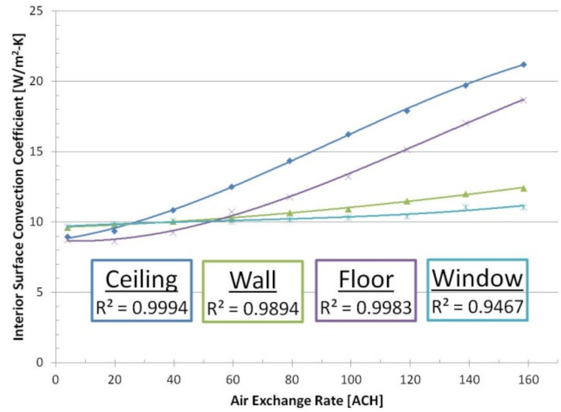


Figure 2. HDV interior surface convection correlations.

In future work, these convection correlations will continue to be refined, validated and extended to a variety of different vehicles and air-distribution configurations.

VOLVO COOLCALC MODEL VALIDATION

A CoolCalc model of a Volvo test “buck” (shown in Figure 3, below) was built from CAD files of the vehicle geometry and other vehicle information supplied by Volvo, as well as information collected at NREL. When information was not available, model parameters were defined to most closely match the configuration of the actual Volvo test bucks (Figure 4) undergoing thermal testing at the VTIF. Test bucks were used in place of complete vehicles to reduce cost and improve adaptability.

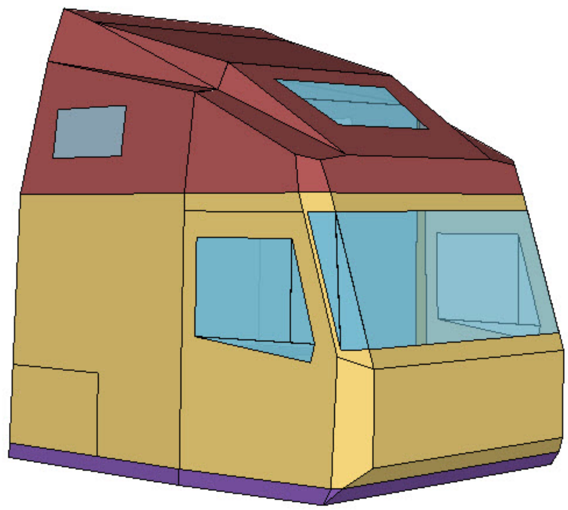


Figure 3. CoolCalc model of a Volvo test buck.

Figure 4. Volvo test bucks at NREL's VTIF.

A custom weather file was created from data collected at NREL's VTIF and Solar Radiation Research Laboratory weather stations. The Volvo model simulation used the same south-facing orientation, thermal soak configuration, and weather conditions experienced by the test bucks. The model was then validated against experimental thermal soak test data to verify its accuracy.

Comparison of the model and experimental results for three consecutive days (Figure 5) shows close agreement in trends and peak air temperatures for a variety of weather conditions. The maximum difference between experimental and model average sleeper air temperature during the hours of peak solar load (11 a.m. – 1 p.m. MST) was 0.89°C. Exterior surface temperature comparisons, shown in Figure 6, between model and test results demonstrate that the model accurately captures the effect of solar position.

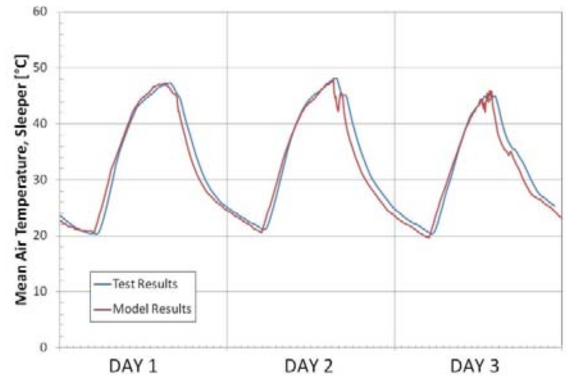


Figure 5. Volvo test buck CoolCalc model validation – sleeper compartment mean air temperatures

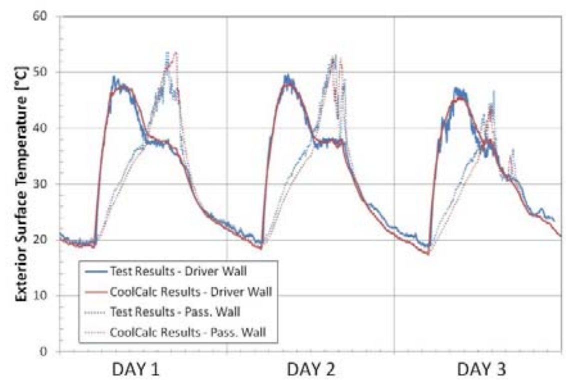


Figure 6. Volvo test buck CoolCalc model validation – exterior side wall temperatures.

COOLCALC ABSORPTIVITY STUDY

After validating the model with test data, the CoolCalc model of the Volvo test buck was used to identify opportunities to reduce long-haul truck thermal loads and help guide testing efforts. The FY 2012 focus was on the solar envelope of the vehicle, including opaque and glazing surfaces. A CoolCalc analysis was performed to evaluate the impact of different vehicle paints, including those with solar-reflective properties. PPG supplied samples of traditional (OEM) paints to support CoolCab research activities. Samples of black, white, and blue paint were tested at NREL to determine their solar spectral properties, which are shown in Table 1. Properties for solar-reflective (SR) blue paint were estimated from [4] and are also listed in Table 1. These four paints were applied to the validated CoolCalc model to evaluate the impact of surface absorptivity on the thermal load of the vehicle.

Table 1. Solar-weighted optical properties of paint test samples

Paint Color	*Absorptance [%]*	*Emissivity*
White	37.2	0.953
Black	95.3	0.951
Blue	88.0	0.951
SR Blue	65.0*	0.950*
*estimated value		

Figure 7 shows the predicted interior air temperatures from each of the simulations. The percentage of maximum possible temperature reduction, β, (described in more detail in the CoolCab section of this report) was calculated from the average air temperatures during the peak solar time of day (11 a.m. – 1 p.m. MST). The model predicts β = 35.9% changing from black to white paint, and β = 14.6% from blue to solar-reflective blue paint. These estimates predict the potential impact of paint properties on engine-off thermal soak air temperature reduction for heavy-duty trucks.

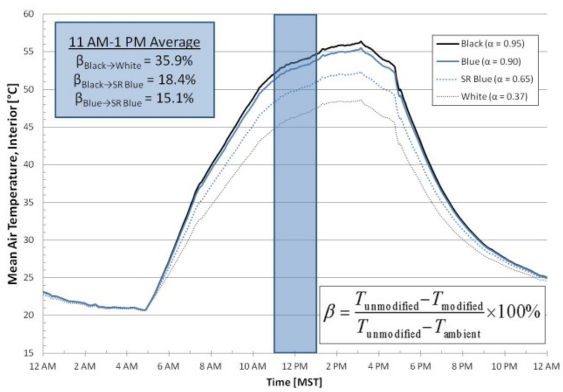


Figure 7. CoolCalc surface absorptivity study.

CoolCalc will continue to be used in conjunction with outdoor testing to estimate the impact of polycarbonate and chromogenic (switchable) glazings.

Conclusions

The CoolCalc model predicted an interior air temperature reduction of 7.3°C changing from black to white paint at peak solar load. This corresponds to β = 35.9%, which is a measure of the maximum temperature reduction possible. These results are in good agreement with CoolCab test results provided in the CoolCab section of this annual report. Switching from blue to the estimated solar-reflective blue, an air temperature reduction of 2.8°C was predicted, with β = 15.6%.

CoolCalc's recent improvements have added significant modeling capability and made the modeling environment much easier to use. Reducing the user learning curve allows for much quicker adoption and implementation of the tool by industry partners.

CoolCalc continues to be used effectively to guide testing efforts through preliminary technology performance evaluation. Methods and tools are currently being developed to improve CoolCab vehicle fuel use estimation through testing and the application of CoolCalc modeling. The next step is to apply CoolCalc across a wide variety of weather and time-use conditions. Quantifying fuel savings and payback periods is vital to the adoption and implementation of idle-reduction solutions in long-haul truck fleets.

CoolCalc was used to assist partners on both DOE- and industry-funded projects, including Volvo Trucks, Daimler Trucks, E-A-R Thermal Acoustic Systems, PPG Industries, Oshkosh, and The Aerospace Corporation. By working with industry partners to develop and apply commercially viable solutions to reduce idling fuel use, both national energy security and sustainability will be improved.

IV.O.3. Products

Tools & Data

CoolCalc version 2.0.0 is currently available to industry and laboratory partners.

1. CoolCalc 2.0.0 – long-haul truck thermal load estimation tool

References

1. Stodolsky, F., Gaines, L., Vyas, A. *Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks.* Argonne National Laboratory, ANL/ESD-43, June 2000.
2. Gaines, L., Vyas, A., Anderson, J., "Estimation of Fuel Use by Idling Commercial Trucks," 85th Annual Meeting of the Transportation Research Board, Washington, D.C., January 22–26, 2006, Paper No. 06-2567.
3. Lustbader, J., Rugh, J., Rister, B., Venson, T. "CoolCalc: A Long-Haul Tuck Thermal Load Estimation Tool," SAE World Congress, Detroit, MI, April 12-14, 2011, Paper Number 2011-01-0656.
4. Levinson, R., Pan, H., Ban-Weiss, G., Rosado, P., Paolini, R., Akbari, H. "Potential benefits of solar reflective car shells: Cooler cabins, fuel savings and emission reductions," *Applied Energy*, 2011, 88, 4343-43

Acknowledgements

- Co-author: Matthew Jeffers (NREL)
- Additional thanks to: John Rugh, Cory Kreutzer, Jon Cosgrove, John Langewisch, Ryan Langewisch, Matthew Gray, and Brent Griffith (NREL)
- Special thanks to our industry partners: Volvo Trucks, Daimler Trucks, Oshkosh, E-A-R Thermal Acoustic Systems, PPG Industries, and The Aerospace Corporation

IV.P. Advanced HD Engine Systems and Emissions Control Modeling and Analysis

Principal Investigator: Stuart Daw (PI) and Zhiming Gao (co-PI)
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Boulevard, Room L-04
Knoxville, TN 37932-6472
Phone: (865) 946-1341; Email: dawcs@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

IV.P.1. Abstract

Objective

- Develop powertrain component models that can accurately reflect and optimize the overall fuel efficiency and emissions control of advanced medium (MD) and heavy-duty (HD) hybrid powertrain systems powered by current and leading-edge combustion engines with exhaust aftertreatment over transient driving conditions.
- Collaborate with an industry CRADA partner to help the Department of Energy (DOE) identify the highest hybrid HD powertrain R&D priorities for reducing U.S. dependence on imported fuels through overcoming technical barriers that limit HD vehicle cost and energy efficiency.

Approach

- Utilize and refine physically consistent computational models for emissions control devices including diesel oxidation catalysts (DOCs), lean NOx traps (LNTs), diesel particulate filters (DPFs), selective catalytic reduction reactors (SCRs), and other advanced catalyst technologies to accurately simulate and optimize HD hybrid vehicle emissions control under transient vehicle operation.
- Refine and validate low-order, physically consistent computational models for simulating power and exhaust characteristics of advanced diesel and alternative fuel engines operating in advanced combustion modes.
- Develop appropriate strategies for combined simulation of engine, aftertreatment, battery, and exhaust heat recovery components to accurately account for the integrated system performance in HD hybrid powertrains.
- Identify and compare the potential cost and energy benefits of alternative fuels and exhaust heat recovery technologies and develop associated simulation models for MD and HD trucks.
- Leverage the above activities as much as possible through inclusion of experimental engine and aftertreatment data and models generated by other DOE activities.

Major Accomplishments

- Developed a 2007 certified 15-L HD engine map and utilized it to make preliminary simulations of transient fuel consumption and cumulative engine-out emissions for comparison with chassis dynamometer measurements at West Virginia University of a conventional HD tractor.
- Refined the ORNL urea-SCR model for diesel NOx emissions control based on experimental measurements of a commercial chabazite Cu-zeolite SCR catalyst (presently sold on medium-duty vehicles) according to the CLEERS transient SCR characterization protocol.
- Demonstrated simulation of a HD hybrid truck powered by a 2007 emissions compliant 15-L diesel engine with fully integrated aftertreatment train consisted of DOC, catalyzed DPF, and SCR over multiple city and highway driving cycles.
- Demonstrated simulation of the comparative fuel economy and cost differential for Class8 HD trucks fueled by conventional diesel versus natural gas over city and freeway-dominated driving cycles.

Future Activities

- Utilize ORNL dynamometer measurements for a 2010-certified, 15L heavy-duty diesel engine to develop and refine steady-state engine maps (including fuel consumption, exhaust temperature, and emissions) for simulating class 8 long-haul diesel trucks operating over various drive cycles.
- Continue refining diesel exhaust aftertreatment models based on the most recent laboratory and chassis dynamometer measurements for emerging commercial catalysts and emission control devices.
- Collaborate with industry partners to identify and compare the potential fuel economy and emissions reduction benefits associated with the leading candidate MD and HD hybridization configurations over city and highway driving cycles.
- Continue investigating alternative management strategies for engines, aftertreatment devices, batteries, and exhaust heat recovery and compare the integrated performance in MD and HD hybrid powertrains.

IV.P.2. Technical Discussion

Background

U.S. highway petroleum consumption is nearly 12 million barrels per day, more than 24% of which goes to HD trucks. Thus, HD truck hybridization can play a vital role in improving fuel economy, greenhouse gases reduction, and reducing dependence on imported oil. Typically lean-burn diesel engines achieve a significant fuel efficiency advantage over stoichiometrically fueled engines. This is one of the reasons why current HD trucks are overwhelmingly powered by diesel engines. However, HD diesel hybrid truck design and optimization require accurate engine and lean exhaust emissions control device models. More efficient engines in the future will produce exhaust temperatures that are too cool for existing emissions control technology. This requires the development of appropriate engine models accounting for innovative combustion modes and new catalysts and aftertreatment system components and configurations.

Oak Ridge National Laboratory (ORNL) supports DOE's vehicle systems analysis and technology efforts by providing data, sub-models, and model validation for advanced engines and emissions control systems. Experimental generation and modeling of performance and emissions for both engines and emissions control devices is an area of notable strength at ORNL and one in which ORNL can provide a complementary contribution to the DOE Vehicle Systems Subprogram. These data have been transformed into maps and physically consistent computational models that explicitly support vehicle performance simulations in vehicle simulation software such as Autonomie. Significantly, the activity supports DOE in the mission of addressing vehicle energy efficiency and conservation, energy security, global climate change in transportation, and related environmental impacts.

Introduction

In FY 2012, we collaborated with ORNL colleagues, other national labs, and industry partners to generate and utilize computational models for investigating the implementation of electric hybridization in medium and heavy duty trucks without having a negative environmental impact. We concentrated our effort this year in the following specific areas:

- Generation of a 2007 certified 15-L HD engine map accounting for fuel consumption and exhaust emissions and temperature under transient conditions.
- Definition and calibration of model components for a conventional HD powertrain with a 2007 certified 15-L HD engine as a reference for hybrid HD truck simulations in support of the Meritor CRADA.
- Refinement of ORNL's urea-SCR NOx control model based on the most recent experimental measurements of a commercial chabazite Cu-zeolite catalyst.
- Simulation of a HD hybrid truck powered by a 15-L diesel engine with fully integrated aftertreatment train consisted of DOC, catalyzed DPF, and SCR.

- Assessment of the comparative fuel economy and emissions performance of HD conventional and hybrid diesel trucks under city and highway driving conditions.
- Assessment of the comparative fuel economy and costs of natural gas fuel versus diesel in Class-8 HD trucks operating over city and highway driving cycles.

Presentations on the above have been submitted to the 92nd Transportation Research Board Annual Meeting and the 2012 Directions in Engine Efficiency and Emissions (DEER) Conference. In addition, journal manuscripts documenting the major findings from the conventional versus hybrid HD truck comparisons are under preparation.

Approach

Simulations of advanced MD and HD hybrid vehicles require computationally efficient and physically accurate models for the engines and aftertreatment devices that might be employed to maximize the overall vehicle energy efficiency and assess the effects of advanced combustion modes and lean exhaust aftertreatment.

Because of the inherent complexity of aftertreatment devices, we focus on lower-order models that account for the dominant physics and chemistry while maintaining reasonable execution speeds. For example, there are no cross-flow (i.e., radial) spatial gradients accounted for, and kinetics are defined as global rather than elementary reactions. Nevertheless, this approach appears to do a good job of accounting for the strong coupling of after-treatment devices with both upstream and downstream components.

Our approach for transient engine modeling relies on a coarse representation of internal engine heat transfer and highly simplified assumptions about how engine-out species change as the engine heats up. The result is expressed in the form of an experimentally parameterized transient correction term that is applied to steady-state or pseudo-steady-state engine-dynamometer data.

The engine and aftertreatment device control strategies used to date are highly simplified and typically based on previously published studies or strategies used in proof-of-principle demonstrations at national labs. These strategies are typically not optimal and often rely on sensor technology that may be ideal or not yet commercial. Our intention is to address general questions rather than specific designs.

Results

Engine Mapping. This year we implemented steady-state maps for a 2007 certified HD 15-L engine in Autonomie, with corrections to account for transient operation. The original data used to generate the steady-state maps are from a proprietary source, so we are using it as a development placeholder until data are available from ORNL measurements of a 2010 certified engine, which will be fully public.

Figure 1 illustrates the non-dimensional engine-out NOx emissions and exhaust temperature trends from the current steady-state engine maps. The transient map predictions were validated against chassis dynamometer measurements made at West Virginia University (WVU) for an 18,750 kg Class 8, 2004 10-speed manual Volvo truck powered by a 2005 Cummins ISX 475 diesel engine. The WVU measurements were made for two different drive cycles, designated as UDDS Truck and ORNL4LS, which represent city and highway driving conditions, respectively. Both transient and cumulative fuel consumption predictions by the corrected steady-state maps showed good agreement with the measurements. For the UDDS Truck cycle the predicted and measured cumulative fuel consumptions were 4.55 mpg and 4.63 mpg, respectively, and for the ORNL4LS cycle they were 6.26 mpg and 6.10 mpg, respectively. Predicted and measured cumulative engine-out emissions were also similarly close.

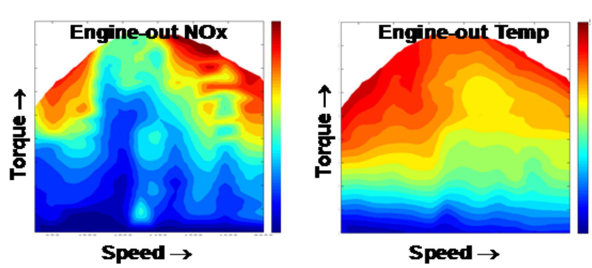
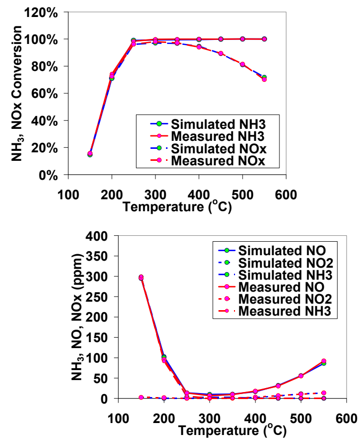


Figure 1. Non-dimensional depictions of the steady-state engine-out NOx and exhaust temperature trends for the 2007 certified HD 15-L engine

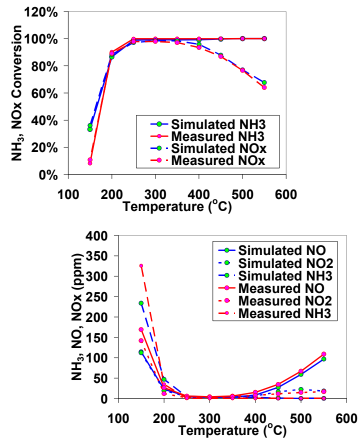
Earlier this summer ORNL obtained a 15-L, 2010 certified HD engine (along with complete aftertreatment train) as part of the Meritor CRADA. With access to this engine and aftertreatment components, we have been able to obtain the detailed configuration information needed to implement HD simulations for this basic powertrain. Dynamometer measurements of this engine are now underway in the Vertical Systems Integration (VSI) lab at ORNL. The dynamometer results will be used to generate updated engine maps and associated transient corrections for refined comparative simulations of conventional and hybrid HD trucks.

Component Models Development. Urea-SCR is the leading technology for removing NOx from HD diesel engine exhaust. We have refined and calibrated our NH_3-SCR aftertreatment model for simulating HD truck NOx control in order to reflect the most recent developments in this rapidly evolving technology. In our refined SCR model, the three main global catalytic reactions, known as the standard reaction between NH_3 and NO, the fast reaction between NH_3 with NO and NO_2, and the NH_3-NO_2 reaction, are allowed to occur in both the gas and catalyst phases. The updated model also accounts for NH_3 storage effects (NH_3 adsorption and desorption), as well as NH_3 oxidation and NO oxidation. NH_3 oxidation occurs in both adsorbed and gaseous states. With these assumptions, the predicted NO and NO_2 species are able to better capture experimental lab measurements a wide range of temperature variation and space velocities.

Figure 2 illustrates example comparisons of the SCR model predictions for steady-state NOx conversion and NH_3/NO/NO_2 species in the product gas as measured by the ORNL CLEERS SCR protocol for the most recently obtained chabazite catalyst as a function of temperature at 60,000 1/hr space velocity. Figure 2a depicts the predicted and measured performance for a urea dosing condition of NH_3/NO_x=1.0 and all inlet NOx as NO. Figure 2b depicts the relative performance for a urea dosing condition of NH_3/NO_x=1.0 and half of the inlet NOx as NO_2.



(2.a) NO/NO_x=1.0



(2.b) NO/NO_x=0.5

Figure 2. Comparison of measured and predicted NOx conversion and SCR-out NH_3/NO/NO_2 species over the chabazite SCR catalyst with variations in temperature and inlet NOx composition at a space velocity of 60,000 1/hr.

System Integration and Vehicle Simulations. We have developed a class 8 HD hybrid truck simulation based on a pre-transmission parallel configuration with a single motor between the clutch and gearbox. As a benchmark, we also simulated a conventional Class 8 HD truck with the same 15-L diesel engine and 10-speed manual transmission. To account for emissions controls, an integrated aftertreatment train system consisting of a DOC, a catalyzed DPF, and urea-based SCR were developed for both trucks.

So far our simulations have included three different heavy duty driving cycles without significant grades: the UDDS Truck; the city-suburban heavy vehicle route cycle (CSHVR); and the heavy heavy-duty diesel truck cycle (HHDDT65). UDDS Truck and CSHVR represent city driving conditions while

HHDDT65 stands for a freeway-dominant driving condition. We also studied the effects of two non-urban cycles: the freeway-dominant heavy duty truck (FDHDT) A and B drive cycles (which include significant grades). The FDHDT A, covers 196.4 miles in 3.72 hours, and the FDHDT B spans 262.7 miles in 5.29 hours.

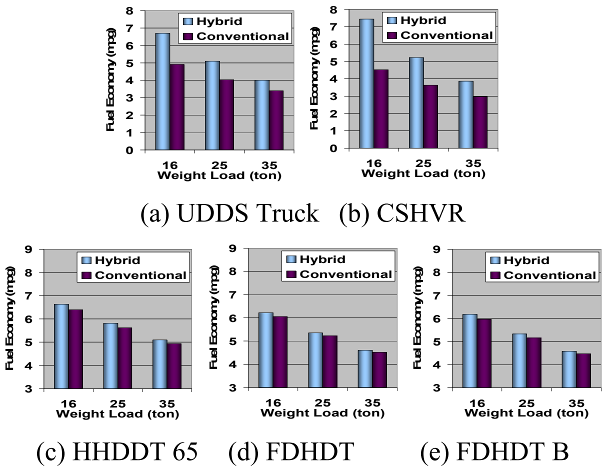


Figure 3. Hybridization impact on fuel consumption for HD trucks with different loads operating over city and freeway-dominant driving conditions. An additional 400kg was included to account for the added weight of the battery, electric motor and control system in the hybrid truck.

Figure 3 compares the relative fuel economies of the hybrid and conventional trucks operating at different loads for each of the above drive cycles. The results indicate that hybridization (without engine downsizing) can significantly boost HD truck fuel economy over city driving conditions (see Figures (a)-(b)), but offers less potential benefit for freeway-dominant driving conditions (see Figures (c)-(e)). One reason for the difference appears to be that the cycle-averaged engine efficiency for conventional HD trucks is significantly lower under city driving conditions than under highway conditions. Perhaps because of the lower baseline fuel economy and engine efficiency in the city, HD hybridization appears to have more potential beneficial in an urban context. As noted above, we have not included the effect of engine downsizing in our simulation studies to date. Downsizing could conceivably improve the benefits of hybridization.

Simulated tailpipe emissions from hybrid and conventional trucks were also compared over each drive cycle. For city driving, hybridization can reduce tailpipe emissions. However, for freeway driving, there is almost no difference between the hybrid and conventional truck emissions. This might be due to the particular hybridization configuration used, so future consideration of other configurations should have high priority. The results also indicate that it may be possible to passively regenerate the DPF in both hybrid and conventional trucks operating over freeway-dominant drive cycles (see Figure 4). This is due to exhaust temperatures that were sufficiently high for sufficiently long to initiate oxidation of accumulated particulate. Passive regeneration is beneficial in that it reduces the fuel penalty associated with DPF operation.

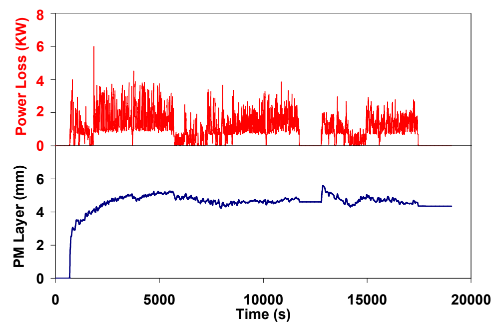


Figure 4. Estimated DPF particulate inventory for a hybrid truck operating over the FDHDT B drive cycle. The model predicts that passive regeneration will lead to a stable layer that does not require active regeneration.

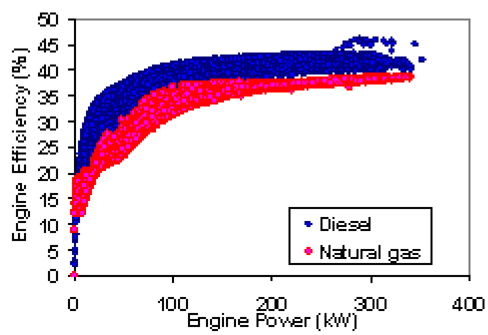


Figure 5. Comparison of diesel and compressed natural gas (CNG) engine efficiencies over a freeway-dominant driving cycle.

We also conducted a preliminary comparison of fuel consumption and cost for compressed natural gas as an alternative fuel in Class 8 HD trucks. Even though the inherent energy efficiency of spark-ignited natural gas engines is typically lower than for diesels (see Figure 5), natural gas engines can lower CO_2 emissions due to less fuel carbon. This reduced CO_2 footprint for natural gas might be further increased by the development of innovative natural gas combustion technologies that can improve the inherent fuel efficiency of natural gas engines.

Hybridization of both diesel and natural gas trucks can reduce fuel consumption in city and freeway driving conditions, but there is a likely to be a considerable differential in payback time for the two different duty cycles. Our initial results indicate that urban natural gas HD hybrids may be able to achieve a relatively quick payback from fuel savings, but the payback period for highway operated HD natural gas hybrids is likely to be significantly longer.

Conclusions

- Transient capable maps for a 2007 certified 15-L HD engine have been implemented in Autonomie to estimate fuel economy and emissions reduction in both conventional and hybrid HD trucks.
- ORNL's urea-SCR model for diesel NOx control has been updated and validated with experimental measurements from a commercial Cu-zeolite SCR catalyst.
- We have successfully simulated the fuel economy and emissions from a HD hybrid truck powered by 15-L diesel engine and outfitted with fully integrated aftertreatment train consisted of DOC, catalyzed DPF, and SCR and operated over multiple drive cycles.
- Simulations indicate that even without engine downsizing, hybridization can significantly boost HD truck fuel economy over city driving conditions, but the benefit is less for freeway-dominant driving.
- Our simulations also confirm that hybridization can reduce tailpipe emissions for city driving cycles, but for freeway-dominant driving, there is only a very modest emission control benefit.
- Passive regeneration of catalyzed DPFs may be possible for both hybrid and conventional HD trucks in freeway driving due to higher exhaust temperatures.
- A preliminary study of fuel economy and cost saving of natural gas as alternative fuel in Class-8 HD trucks shows gas can lower CO_2 emissions and have a short payback period in both city and freeway-dominated driving.
- Hybridization of natural gas HD trucks is more likely to be feasible for urban driving.

IV.P.3. Products

Publications

1. Z. Gao, C.S. Daw, V.K. Chakravarthy, Simulation of Catalytic Oxidation and Selective catalytic NOx Reduction in Lean-Exhaust Hybrid Vehicles, SAE paper 2012-01-1304, 2012.
2. **Z. Gao,** T.J. LaClair, C.S. Daw, D.E. Smith, Fuel Consumption and Cost Saving of Natural Gas as Alternative Fuel in Class 8 Heavy-Duty Trucks, submitted to the 92nd Transportation Research Board Annual Meeting, 2013.
3. Z. Gao, D.E. Smith, C.S. Daw, T.J. LaClair, J.A. Pihl, Fuel Economy and Emissions Reduction of HD Hybrid Truck over Transient Driving Cycle and Interstate Road, DOE-DEER Conference, October 16-19, 2012.
4. C.S. Daw, **Z. Gao,** Advanced Heavy-Duty Engine Systems and Emissions Control Modeling and Analysis, U.S. DOE Hydrogen Program and Vehicle Technologies Program, Annual Merit Review and Peer Evaluation Meeting, Washington DC, May 14, 2012.
5. Z. Gao, C.S. Daw, K.D. Edwards, S. Sluder, R.M. Wagner, Effect of Premixed Charge Compression Ignition on Vehicle Fuel Economy and Emissions Reduction over Transient Driving Cycles, DOE-DEER Conference, October 3-6, 2011.

Patents

None

Tools & Data

1. HD Vehicle component models described above and summarized in the cited publications [1-5].

IV.Q. Hydraulic Hybrid Vehicle Fuel Consumption Potential

Principal Investigators: Aymeric Rousseau (Project Leader) and Namwook Kim
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL60439-4815
Phone: (630) 252-7261; Email: arousseau@anl.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: david.anderson@ee.doc.gov

IV.Q.1. Abstract

Objective

- Assess the fuel displacement potential of parcel-delivery-truck Class 6 hydraulic hybrid vehicles (HHVs) for different applications and powertrain configurations in comparison with both conventional vehicles and hybrid electric vehicles (HEVs).
- Evaluate the potential of HHVs for extended-range electric vehicles (EREVs).

Approach

- Develop a vehicle model for a hydraulic hybrid system based on component models provided by the U.S. EPA.
- Run simulations to evaluate the system performance.
- Compare benefits with other alternatives.

Major Accomplishments

- Developed a series HHV and a parallel HHV vehicle models for Class 6 trucks
- Developed a model of an EREV using a hydraulic system.
- Assessed the fuel consumption for conventional vehicles, HEVs, HHVs, and EREVs according to powertrain configurations.
- Evaluated the impact of hybrid technology based on a hydraulic system.

Future Activities

- Compare different technologies from a cost benefit point of view

IV.Q.2. Technical Discussion

In order to reduce fuel consumption, companies have been looking at hybridizing vehicles. Two main hybridization options have been considered: electric and hydraulic hybrids. Because of light duty vehicle operating conditions and the high energy density of batteries, electric hybrids are being used for light duty vehicles. However, companies are still evaluating both hybridization options for both medium and heavy duty vehicles. Trucks generally demand very large regenerative power and frequent stop-and-go. In that situation, hydraulic systems could have an advantage over electric drive system as the hydraulic motor and accumulator can handle high power with small volume capacity.

The hydraulic motors can achieve higher efficiency than electric motors during regenerative braking, since they can operate efficiently at high torque demand. Due to their high round trip efficiencies, hydraulic systems should be reevaluated as a secondary power source to determine how this technology could impact the range of electric heavy-duty vehicles

Background

Hydraulic systems have several advantages compared with electric systems, including.

- High capacity (compact design),
- High efficiency in a specific operating condition, and
- Low cost.

Their drawbacks include:

- Late response for control, and
- Generally low efficiency (leakage).

Considering these points, hydraulic systems cannot achieve the expected performance if the system is not well designed and precisely controlled. In this study, the performance of hydraulic hybrid vehicles (HHVs) is compared with the performances of other candidates, such as conventional and hybrid electric vehicles (HEVs).

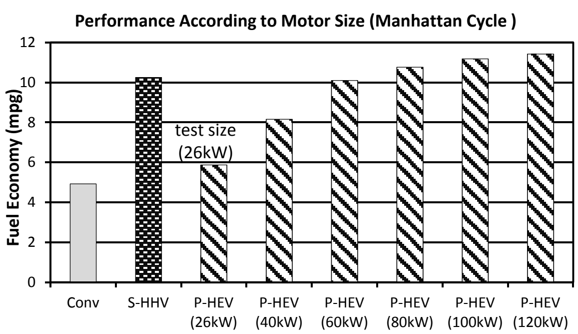


Figure 1. Fuel Economy of a Parallel Hybrid Hydraulic Vehicle According to Motor Size.

Vehicle test results from the U.S. Environmental Protection Agency (EPA) and the national Renewable Energy laboratory (NREL) indicate that for the vehicles considered, the series HHV demonstrated better performance than a conventional vehicle or a parallel HEV (the first three bars in Figure 1). These results were reproduced in simulation, based on the component characteristics of the vehicles tested. However, our simulation results also showed that the parallel HEV could achieve better fuel efficiency using different component sizes for the HEV. This analysis confirms that this study requires appropriate component design and control.

Introduction

Most energy losses in the hydraulic system are caused by two components: the hydraulic motor and the accumulator. Leakage and friction of fluid or mechanical components cause the loss. Thermal energy loss between the accumulator and the fluid also affects the system efficiency. An example of the hydraulic system is shown in Figure 2.

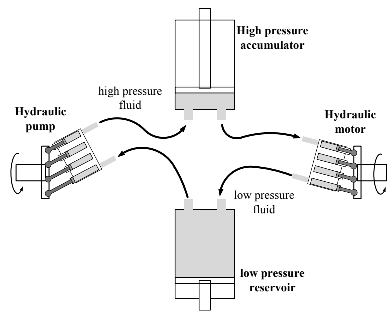


Figure 2. Example Schematic of a Hydraulic System Used in a Series Hydraulic Hybrid System.

Simply, the fluid in the high-pressure accumulator flows into the low-pressure reservoir. At that point, the pressure is converted to the mechanical torque that propels the hydraulic motor.

Approach

Comparative Study for Class 6 Trucks

For the comparative study of Class 6 trucks, we simulated five vehicles:

- Conventional
- Series hydraulic hybrid (S-HHV)
- Parallel hydraulic hybrid (P-HHV)
- Series hybrid electric (S-HEV)
- Parallel hybrid electric (P-HEV)

All vehicles have the aerodynamic and tire losses. However, they are sized to have similar performance. The fuel economies for the five vehicles are evaluated on six different cycles, including:

- Manhattan Bus Cycle
- New York Truck Cycle
- Combined International Local and Commuter Cycle (CILCC)

- City-Suburban Heavy Vehicle Route
- Urban Dynamometer Driving Schedule (UDDS)
- Central Business District (CBD)

The conventional vehicle used in this study has an automatic transmission, and the gear shifting ratio is controlled to maximize the fuel economy. Figure 3 depicts a configuration of a conventional vehicle.

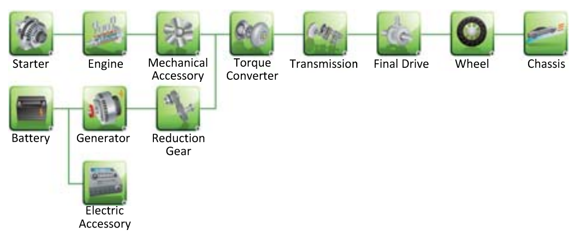


Figure 3. Configuration of a Conventional Vehicle.

The S-HHV shown in Figure 4 is designed to disconnect the engine from the vehicle if needed, so the engine is able to operate at an optimal operating area.

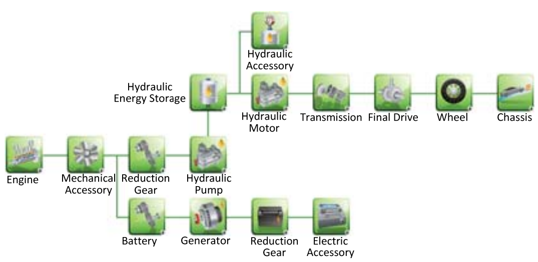


Figure 4. Configuration of a Series Hydraulic Hybrid Vehicle.

The configuration of a P-HHV is displayed in Figure 5. The hydraulic motor can perform as a pump, so the braking energy is recuperated at the hydraulic accumulator.

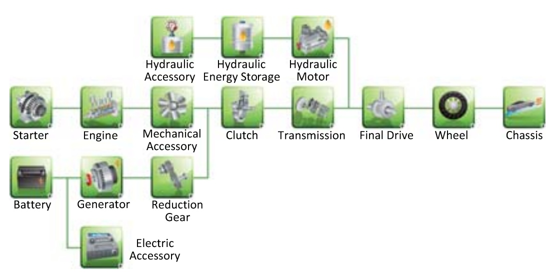


Figure 5. Configuration of a Parallel Hydraulic Hybrid Vehicle

For the S-HEV displayed in Figure 6, a traction motor is connected to the wheel with a two-speed transmission, and a generator is connected to the engine with a reduction gear.

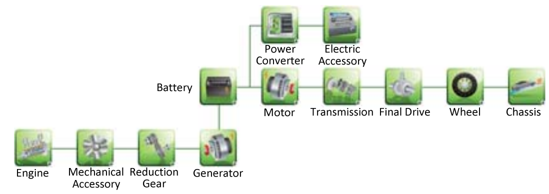


Figure 6. Configuration of a Series Hybrid Electric Vehicle.

The configuration for a P-HEV is shown in Figure 7. Whereas the post-transmission type is selected for the P-HHV, the pre-transmission type is selected for the P-HEV.

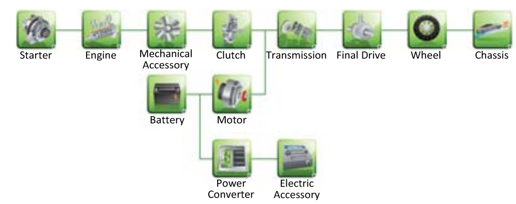


Figure 7. Configuration of a Parallel Hybrid Electric Vehicle.

Comparative Study for EREVs

While the same cycles are used in the comparative study for Class 6 trucks, we evaluated the performance of extended-range electric vehicles (EREVs) when the hydraulic system is applied to extend the driving range. Figure 8 depicts a configuration of an EREV.

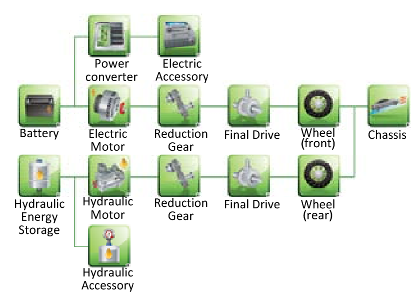


Figure 8. Configuration of an Extended-Range Electric Vehicle.

The configuration is compared with a battery electric vehicle (BEV). For both the BEV and EREV, an 80-kWh battery is designed based on a delivery truck from Navistar eStar. The hydraulic system in the EREV is primarily used to save regenerative energy from the braking situation and to provide power at the launch of the vehicle.

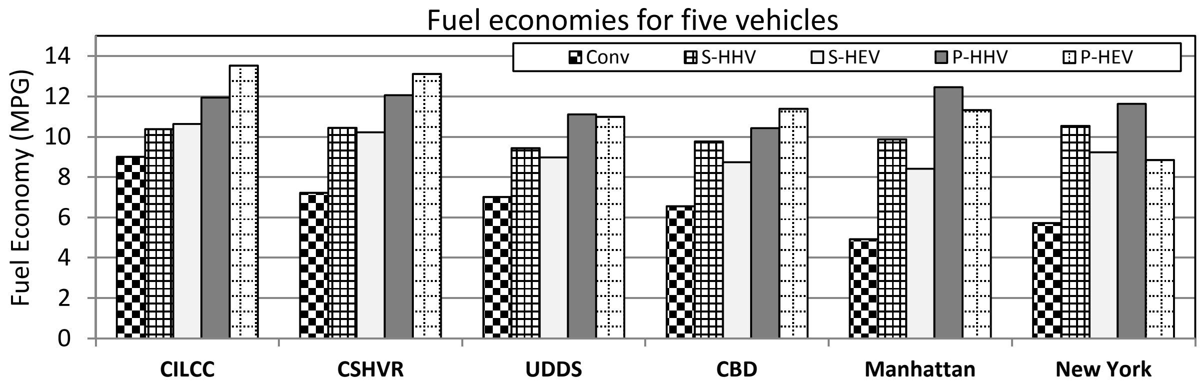


Figure 9. Simulation Results for Fuel Economies (Note: The HHVs are better than HEVs at aggressive cycles, and parallel configurations are generally better than series configurations.).

Results

Simulation results are obtained for Class 6 trucks according to the configurations and for EREV application.

Comparative Study for Class 6 Trucks

The simulation results for the six different cycles are shown in Figure 9. Vehicles are simulated on 10 repeated cycles to reduce the effect of the unbalanced storage energy. Based on the results, we observe that:

- Parallel configurations offer higher fuel economy than series configurations in most cases.
- The S-HHV shows better fuel economies than the S-HEV at most cycles up to 17%.
- The P-HHV vs. P-HEV shows mixed results.
- HHVs provide higher benefits if the driving cycle allow more opportunities to recuperate energy from braking.

The advantages of HHVs come from the increased opportunities to recuperate energy from the braking of the vehicles.

Comparative Study for EREVs

For the EREVs application, the hydraulic system shows mixed results, as presented in Figure 10. Our results show that:

- Because of the hydraulic system, the EREV is heavier than the EV by 5.5%.
- The benefit range of the EREV is from -2.7% to 14%.
- The benefit highly depends on the driving cycles.

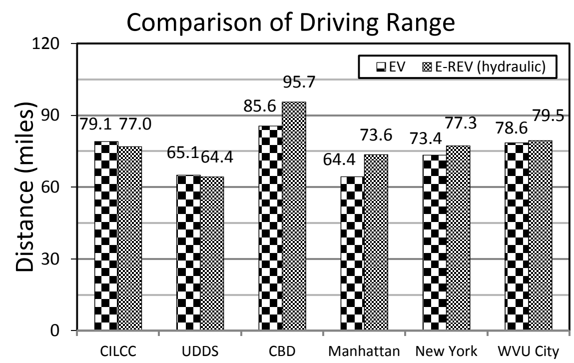


Figure 10. Comparison of the Driving Range between an Electric Vehicle and an Extended-Range Electric Vehicle.

Conclusions

In conclusion, HHVs can lead to higher benefits than HEVs if the vehicles are driven on cycles that offer large opportunities to recuperate braking energy. Therefore, the HHV can have benefit when:

- The vehicle is very heavy, so the regenerating energy is more important than the driving resistance.
- The driving cycles have many stops or braking situations.

This conclusion indicates that HHVs could be very favorable for specific cases.

IV.Q.3. Products

Autonomie Vehicle Models for HHVs.

Publication

1. Kim, Namwook and Aymeric Rousseau, "A Comparative Study for Class 6 Truck for Hydraulic Hybrid Systems," SAE World Congress, submitted.

IV.R. Medium-Duty Electric Drive Vehicle Simulation and Analysis

Principal Investigator: Jeffrey Gonder
National Renewable Energy Laboratory (NREL)
15013 Denver West Parkway, MS 1634
Golden, CO 80401
Phone: (303) 275-4462; Email: jeff.gonder@nrel.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: david.anderson@ee.doe.gov

IV.R.1. Abstract

Objective

- Expand on an FY 2011 study and evaluate the petroleum reduction and cost implications of different parcel delivery plug-in hybrid electric vehicle (PHEV) designs relative to a conventional diesel vehicle.

Approach

- Coordinate across multiple Vehicle Systems Simulation and Testing (VSST) focus areas.
  - Refine/validate models using chassis dynamometer test data collected at NREL's Renewable Fuels and Lubricants (ReFUEL) Laboratory.
  - Enhance cycle selection procedure in partnership with NREL's Fleet Test and Evaluation team—analyzing vehicle performance over hundreds of in-use driving profiles compiled from commercial parcel delivery vehicles during real-world operation.
- Evaluate a large matrix of different vehicle designs, drive cycles and daily travel distances using the Future Automotive System Technology Simulator (FASTSim), including engine downsizing cases.
  - Rapidly calculate performance, fuel economy and cost for each scenario, taking into account use-case-specific battery wear and the corresponding battery sizing implications.
- For given fuel price, discount rate and service life assumptions, calculate the maximum tolerated battery cost per kilowatt-hour (kWh) for each scenario's lifetime fuel savings to offset the incremental vehicle capital cost.

Major Accomplishments

- Demonstrated that lifetime fuel savings from vehicle electrification could be as high as 20,000 gallons of diesel for a single vehicle, but that daily travel distance, drive cycle, and battery price play critical roles in determining whether fuel savings can offset the incremental cost for a particular PHEV.
- Identified that high cycle kinetic intensity and long driving distances improve payback potential, but that few real-world profiles simultaneously possess both of these characteristics.
- Highlighted several plausible payback scenarios, such as a 12.5-kWh PHEV configuration operated for 60 miles per day on a cycle similar to the HTUF 4 with battery cost at or below $700/kWh (and fuel at $3.23/gal).

Future Activities

- Publish a paper on the project at the 2013 SAE World Congress.

IV.R.2. Technical Discussion

Introduction

Commercial vehicles consume a significant amount of petroleum and emit a large amount of greenhouse-gas emissions. Fortunately, medium-duty vehicles in the parcel delivery vocation are ideal candidates for electric drivetrains because they often share the following characteristics:

- Daily driving routes that return to a central depot, facilitating overnight charging
- Stop-and-go drive cycles that allow for energy capture from regenerative braking
- A buyer that more heavily values the bottom line over other factors
- Fuel savings that can multiply across an entire for-hire/private fleet.

This FY 2012 investigation adds significant enhancements to the analysis conducted in FY 2011, including updates to the stock drive cycle selection approach that better capture the range of field drive cycles, and identification of the battery cost-per-kilowatt-hour (kWh) break-even point for achieving payback relative to the baseline conventional vehicle.

Approach

Completing this study involved collaboration between multiple focus areas supported by the Vehicle Systems Simulation and Testing (VSST) activity within the U.S. Department of Energy (DOE) Vehicle Technologies Program. As described below, these included modeling, simulation and system optimization conducted by NREL's Vehicle Systems Analysis team, in-field vehicle evaluations by NREL's Fleet Test and Evaluation team, and chassis dynamometer vehicle testing by NREL's Renewable Fuels and Lubricants (ReFUEL) Laboratory. In this analysis, battery life, cost, and fuel consumption tradeoffs are compared for two different diesel powertrain configurations: conventional and plug-in hybrid electric vehicle (PHEV).

This section describes the approaches to conventional and hybrid vehicle model development and validation, development of the PHEV model, field data framing the analysis, and the development of the design and cost matrix.

Conventional and Hybrid Model Development and Validation

The models for this analysis were developed in the Future Automotive Systems Technology Simulator (FASTSim) using basic component specifications, engine-specific efficiency data when available, drive-train-specific accessory loads, and comparison to the second-by-second data from the ReFUEL laboratory testing.

The ReFUEL laboratory collected data from two parcel delivery vehicles owned and operated by United Parcel Service (UPS), which were transported to the ReFUEL laboratory for fuel economy and emissions testing on the chassis dynamometer. Both the conventional and hybrid diesel vehicles used the same 149-kW engine. The hybrid-electric van was equipped with a parallel-hybrid system from Eaton. The ReFUEL laboratory tested the vehicles on three cycles—the New York Composite Cycle (NYComp), the Heavy Heavy-Duty Diesel Truck (HHDDT), and the HTUF 4 (developed by the Hybrid Truck Users Forum).

Table 1 summarizes the cycles used in the dynamometer testing, and Table 2 details specific vehicle and component specifications for each of the two drivetrains.

Table 1. Cycles Used for ReFUEL Testing

Configuration	Fuel	Cycles
Conventional/Hybrid	Diesel	NYComp, HTUF 4, HHDDT

Table 2. General Vehicle/Component-Level Specifications

	Conventional Diesel	Diesel Hybrid
Test Weight GVWR	6,813 kg 10,433 kg	7,303 kg 10,433 kg
Coefficient of Drag Frontal Area	0.5 7.80 m^2	0.5 7.80 m^2
Wheel rolling resistance	0.01	0.01
Battery Energy		1.8 kWh
Engine power	149 kW	149 kW
Motor power		26 kW
Accessory Load	10 kW	4 kW

Figure 1 shows good agreement between the models' fuel consumption predictions and the measurements that were recorded at the ReFUEL laboratory. The discrepancies between the modeled and the experimentally measured values are slightly higher for the hybrid than for the conventional vehicle, but in all cases the disagreement is less than 10%.

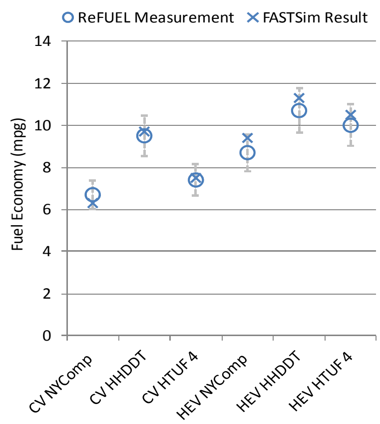


Figure 1. Validation of conventional and hybrid vehicle models.

Development of the Plug-In Hybrid Model

A PHEV version of the model was developed based on the hybrid-diesel template.

To make the PHEVs comparable, the Vehicle Systems Analysis team applied similar vehicle-specific parameters and matched the engine power to that of the diesel hybrid and conventional vehicles (149 kW) for one set of simulations. In order to evaluate the additional fuel savings potential from engine downsizing, a second set of simulations was run with the engine power decreased by 20% to 120 kW. It should be noted, however, that fleet managers interviewed as part of this study articulated minimum vehicle performance criteria (i.e., acceleration and continuous grade-climbing capability) that suggests any appreciable engine downsizing may result in unacceptable vehicle performance.

The mass of the PHEVs is based on the mass of the diesel hybrid with an appropriate adjustment for the additional battery capacity. Battery power was matched to motor power through motor efficiency. In a previous PHEV parcel delivery study, the Vehicle Systems Analysis team used 2.5 kWh for the battery energy. This is the starting point for the additional battery energy used in this analysis.

Field Data Framing the Analysis

Leveraging concurrent DOE-sponsored fleet evaluation activities with data from UPS and FedEx, the top two for-hire carriers, the NREL Fleet Test and Evaluation team is building a fleet data center of field drive cycle and performance data. A subset of this data was chosen because it was recorded using ISAAC loggers and appeared to have the best data quality of the group. For this subset, over a month of drive cycle data was collected for 11 vehicles instrumented with Global-Positioning System (GPS)-enabled data loggers. This data was the basis of the FY 2011 analysis, in which the Vehicle Systems Analysis team used a frequency distribution of kinetic intensity and daily distance traveled to guide the selection of stock cycles and driving distances used in the analysis [1].

For this year's analysis, the Vehicle Systems Analysis team includes fuel consumption in the stock cycle selection approach. This approach involved an enhancement to FASTSim and ultimately the addition of a drive cycle to the design matrix.

The Vehicle Systems Analysis team worked with the Fleet Test and Evaluation team to simulate fuel consumption on the conventional real-world drive cycles collected in this data subset. The Vehicle Systems Analysis team customized FASTSim to run field cycles of excessive duration in batches. The simulated fuel consumption was then compared to the field-measured fuel consumption and plotted alongside the stock cycles selected for last year's analysis.

In Figure 2, there is good agreement between the simulated real-world fuel consumption and the fuel consumption collected in the field. The payload mass for the data collected in the field was unavailable. The simulated points were run at an industry-provided average payload.

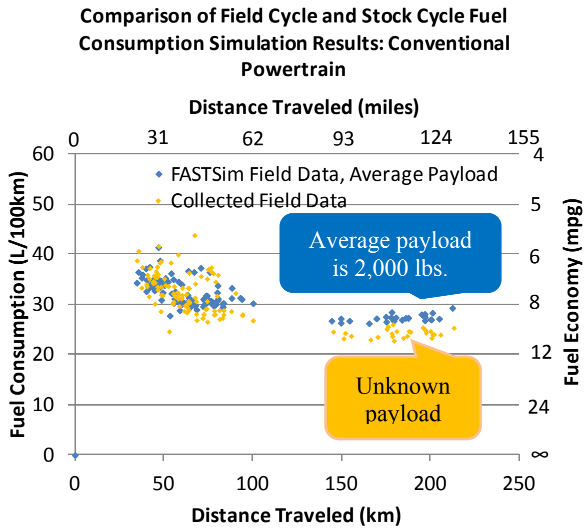


Figure 2. Enhancement to FASTSim allowed simulation of every real-world cycle.

Figure 3 plots HTUF4, the heavy-duty Urban Dynamometer Driving Schedule (UDDS HD), and the Orange County Bus (OC Bus) fuel consumption as a function of distance. The NYComp cycle was added to cover those field cycles that went shorter distances and experienced higher fuel consumption. Figure 4 plots fuel consumption against stops per mile. The NYComp cycle also captures those vehicles experiencing daily routes with higher stops per mile, which appears to correlate with the higher fuel consumption data points not captured by the other standard cycles.

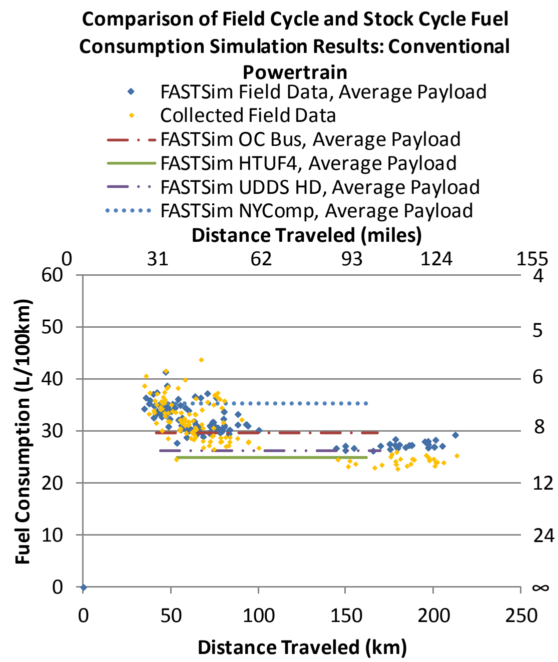


Figure 3. Addition of NYComp cycle captures full range of fuel consumption.

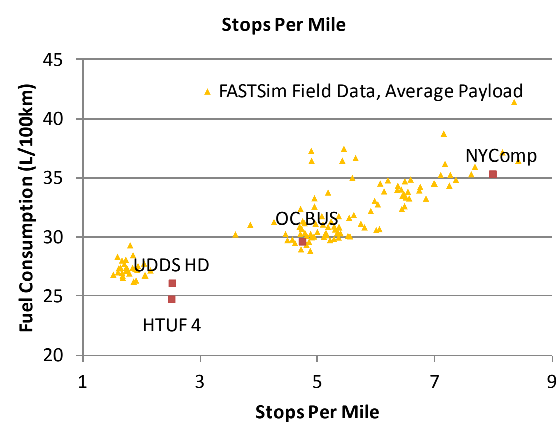


Figure 4. Addition of NYComp cycle captures full range of stops per mile.

Development of the Design and Cost Matrix

Figure 3 and Figure 4 lead to the development of the design matrix in Table 3. It should be noted that the additional battery capacity array is of varied step size. There is a finer resolution at lower battery capacities (i.e., 12.5 kWh, 22.5 kWh, 42.5 kWh, and 62.5 kWh), because it is expected that the battery capacity is a key cost driver in the total cost of ownership. To be consistent with commercially available battery offerings, the power-to-energy ratio is set at a floor of 1.125. The battery power was held constant at 30 kW unless the power-to-energy ratio fell below the 1.125 limit. If the ratio fell below this limit, the battery power was increased to compensate. Based on last year's results showing little impact from variable motor size, the motor power was held constant in this year's analysis at a level matched to the 30 kW battery power.

Two cost scenarios were developed to represent a fair range of costs (Table 4). Current and future fuel and electricity costs are yearly highs for 2011 and 2030, respectively [2]. Long-term battery cost-per-kWh is cited from the United States Advanced Battery Consortium (USABC) Goals for Advanced Batteries for EVs [3].

Table 3. Design Matrix for PHEVs

Drive cycles	UDDS HD, HTUF 4, OC Bus, NYComp
Daily distance traveled	40, 80, 120, 160 km
Additional battery capacity	10, 20, 40, 60 kWh
Battery power	MAX (30 kW, Capacity×P/E)
Battery power-to-energy ratio	1.125[10]

Table 4. Cost Matrix

Scenario	Battery Cost	Diesel Fuel Cost	Electricity Cost
Current	$700/kWh	$0.85/L ($3.23/gal)	$0.11/kWh
Future	$100/kWh	$1.37/L ($5.19/gal)	$0.11/kWh

Table 5 lists additional assumptions used in the analysis. Note for the battery that FASTSim assumes a base packaging cost plus a cost-per-kWh and cost-per-kW, so the simplified battery cost assumptions from Table 4 were manipulated into this form for the analysis.

Table 5. Additional Assumptions

Vehicle life (years)	15
Battery cost	$22/kW × (kW) + scenario $/kWh * (kWh) + $680
Motor and controller cost	$21.7/kW + $425
Markup factor	1.5
Discount rate	8%
Charger efficiency	0.9

Results

This section presents analytical results for the specified range of vehicle configuration, usage, and economic scenarios.

Lifetime Cost Analysis

Two different methods compare costs: a fuel savings comparison, and a relative comparison with the baseline diesel conventional. The relative comparison subtracts the discounted lifetime fuel costs for the baseline diesel conventional from the comparable lifetime energy and incremental capital costs of the PHEV version (including battery and motor, fuel, and electricity). Lastly, the fuel savings comparison allows us to determine how many liters of diesel fuel were saved by the PHEV diesel when compared to the diesel conventional.

Vehicle Nomenclature

Column charts have several dimensions. Along the x axis, the results fall into four groups of increasing distance driven. For each distance driven, there are four levels of battery energy. For each battery energy level, there are four cycles that increase in kinetic intensity. It should be noted that the +40 and +60 kWh scenarios resulted in a battery power-to-energy ratio of less than 1.125. For these cases, the battery power was increased and the motor power is matched to the original 30-kW battery power.

Fuel Use Savings from Drivetrain Electrification

Adding an electric drivetrain saves fuel. Figure 5 plots lifetime fuel savings in liters. As expected the longer the distance traveled, the greater the fuel savings. For each distance and battery

[10] Smith Newton battery

capacity combination fuel savings also increases with kinetic intensity.

When Are PHEVs Cost Effective?

Figure 6 and Figure 8 show the difference between the PHEV lifetime cost and the diesel conventional lifetime cost where the PHEV lifetime cost, is composed of upfront battery and motor costs, liquid fuel cost, electricity cost, and a battery replacement cost as applicable; and the diesel conventional lifetime cost is comprised of the cost of liquid fuel. A positive value indicates that the PHEV is more expensive.

Assuming $700/kWh battery costs and $3.23/gal fuel costs, Figure 6 shows that only a few of the PHEV options pay off. The 12.5 kWh battery PHEV configuration recoups the additional battery and motor cost when it can accumulate fuel savings over 50 miles (80 kilometers) on the higher kinetically-intense cycles. When the vehicles travel longer distances per day, more PHEV configurations pay off. However, as indicated by the density plot in Figure 7, few real-world drive cycles coincide with the conditions that result in payback under the current cost assumptions (i.e., long distance driving at high kinetic intensity).

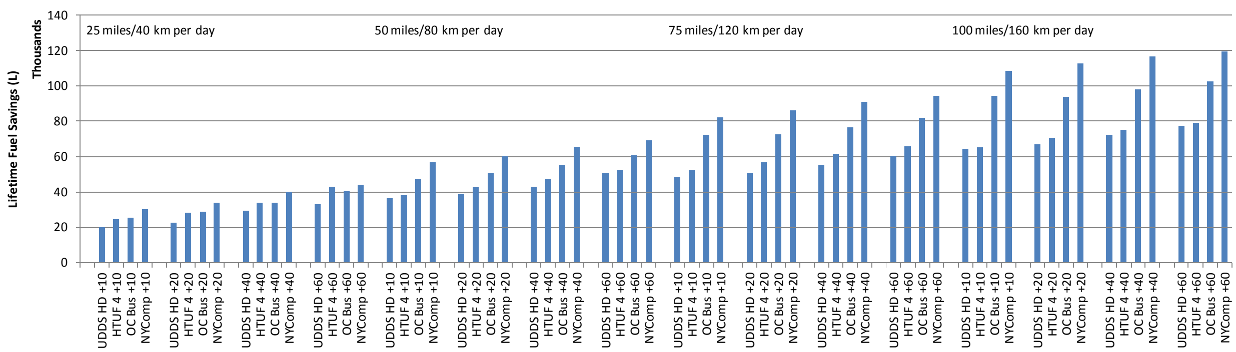


Figure 5. Lifetime fuel savings: Diesel PHEV.

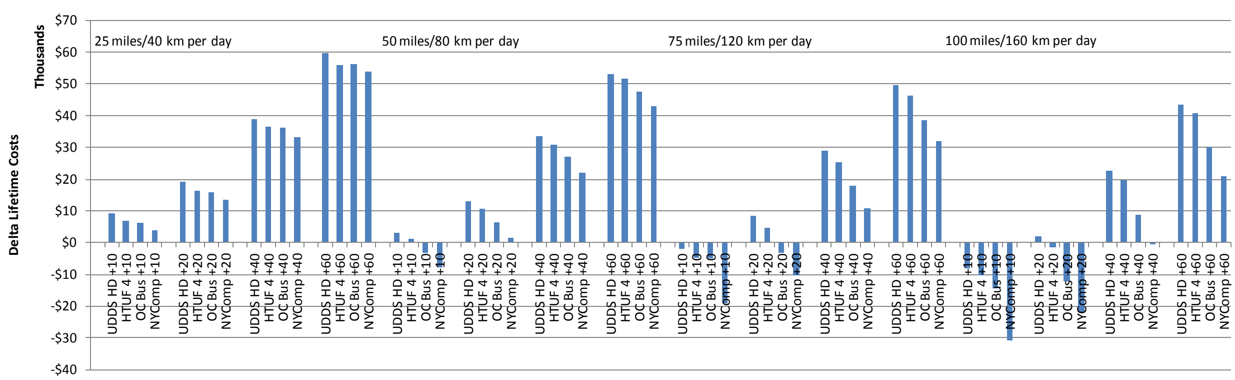


Figure 6. Incremental lifetime cost: Diesel PHEV, current scenario.

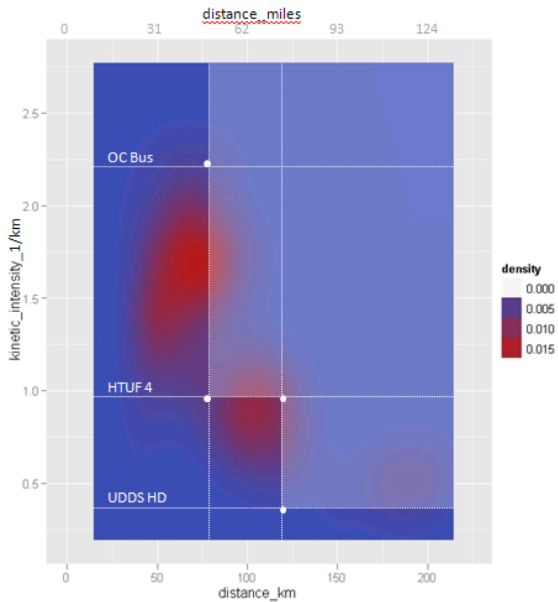


Figure 7. Density plot of real-world drive cycles relative to their travel distance and kinetic intensity. (Note that relatively few cycles fall into the shaded area, which corresponds with cost-effective usage scenarios for a 12.5-kWh diesel plug-in hybrid with no battery replacement under the current cost treatment.).

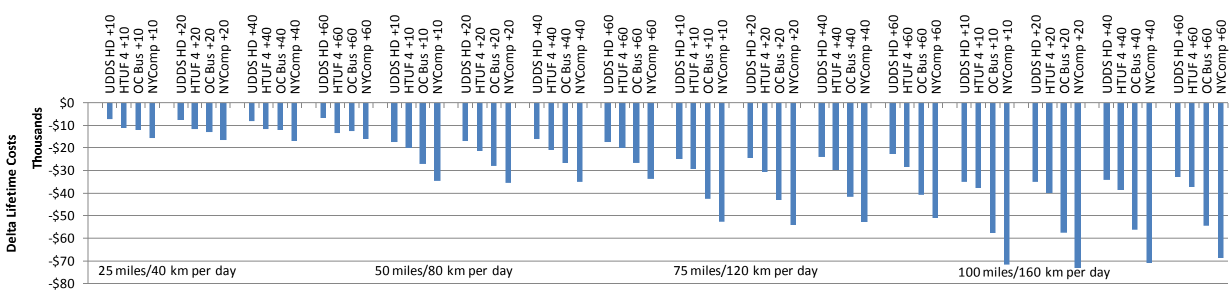


Figure 8. Incremental cost: Diesel PHEV, future scenario.

Assuming $100/kWh battery costs and $5.19/gal fuel costs, the simulated usage patterns paid off the incremental cost of the PHEV in accumulated lifetime fuel savings. Figure 8 shows that of those configurations simulated on the NYComp drive cycle over 100 miles the 22.5-kWh battery pack was the configuration that provided the most savings.

Break-Even Point Analysis

To evaluate the break-even point, we assume current fuel costs and solve for the battery cost per kWh that would make PHEVs economical in these usage patterns. Figure 9 and Figure 10 plot the break-even cost per kWh against daily distance traveled for the current cost scenario.

In Figure 9, the lower the battery capacity the higher the cost per kWh tolerated to break even. In other words, a smaller battery allows for more money to be spent on the battery cost per kWh for any given usage pattern.

The bold dashed line at $700/kWh marks the current scenario cost per kWh. At this cost, the 12.5-kWh battery, 149-kW engine configuration pays back at 60 miles traveled on the HTUF 4 cycle, and the 22.5-kWh configuration pays back at 93 miles traveled.

The dashed lines in Figure 9 represent break-even cost curves for the downsized engine scenario. In general, downsizing results in a higher tolerated cost per kWh break-even point due to the higher fuel savings. Downsizing the engine on the 12.5-kWh configuration, HTUF 4 usage scenario increased battery use and resulted in a battery replacement for the 12.5-kWh pack around 100 miles traveled. The battery replacement required for this scenario results in a lower cost per kWh break-even point at 100 miles traveled.

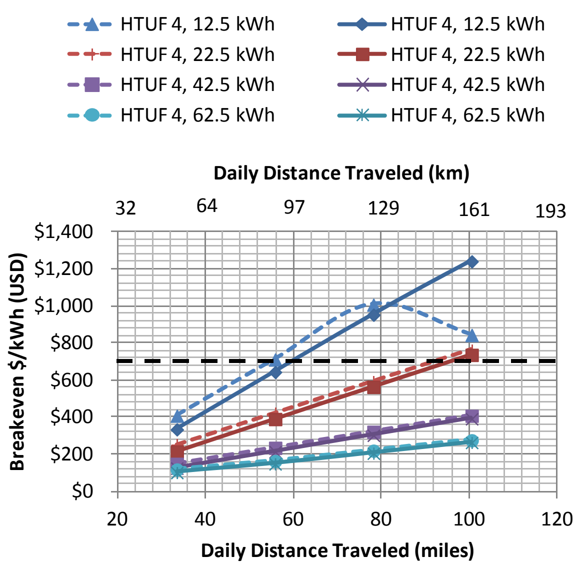


Figure 9. Impact of engine downsizing on the break-even point.

In Figure 10, the drive cycles listed in the legend are in order of increasing kinetic intensity. The higher the cycle's kinetic intensity, the higher the battery cost per kWh that is tolerated.

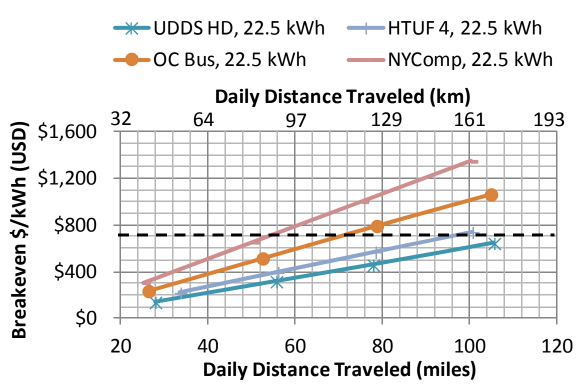


Figure 10. Impact of kinetic intensity on break-even point: 149-kW engine, current scenario.

Conclusions

Electrification of the conventional diesel parcel delivery truck powertrain could result in lifetime fuel savings as high as 20,000 gallons (75,000 liters) for a single vehicle, but may not be economical, depending on battery costs, the daily distance traveled, and the drive cycle kinetic intensity. The Vehicle Systems Analysis team identified the battery cost per kWh break-even point at which these vehicles become cost-effective under different scenarios. The longer the daily distance traveled, the more kinetically intense the cycle, and the higher the reference fuel cost, the higher the battery cost per kWh that could be tolerated. With battery cost at $700/kWh and diesel fuel at $3.23/gal, the 12.5-kWh plug-in configuration run on the HTUF 4 cycle for 60 miles per day pays back relative to the baseline conventional configuration over the vehicle's 15-year life.

References

1. Robb A. Barnitt, Aaron D. Brooker, and Laurie Ramroth. Model-based analysis of electric drive options for medium-duty parcel delivery vehicles. Preprint. Conference Paper NREL/CP-5400-49253. December 2010. Available online at nrel.gov/docs/fy11osti/49253.pdf.
2. U.S. Energy Information Administration, Annual Energy Outlook 2011, Table 20, Energy Prices by Sector and Source, United States, Reference Case. Current 2011, Future 2030. eia.gov/forecasts/aeo/topic_prices.cfm Direct Link eia.gov/oiaf/aeo/tablebrowser/aeo_query_server/?event=ehExcel.getFile&study=AEO2011&region=1-0&cases=ref2011-d020911a&table=3-AEO2011&yearFilter=0
3. United States Council for Automotive Research LLC. Electrochemical Energy Storage Tech Team. Energy Storage System Goals. USABC Goals for Advanced Batteries for EVs. uscar.org/guest/view_team.php?teams_id=11

IV.R.3. Products

Publications

1. Ramroth, L., Gonder, J. and Brooker, A. "Medium-Duty Electric Drive Vehicle Simulation and Analysis." Proceedings of the 26th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exposition (EVS-26), May 2012.
2. Ramroth, L., Gonder, J. and Brooker, A. "Assessing the Battery Cost at which Plug-In Hybrid Medium-Duty Parcel Delivery Vehicles Become Cost-Effective." Paper abstract accepted for publication at the 2013 SAE World Congress and Exhibition.

Tools & Data

1. ReFUEL Laboratory test data (Matthew.Thornton@nrel.gov)
2. FASTSim: Available from nrel.gov/vehiclesandfuels/vsa/fastsim.html (Aaron.Brooker@nrel.gov)
3. FleetDNA field data (Kevin.Walkowicz@nrel.gov)

V. COMPONENTS/SYSTEMS EVALUATIONS

V.A. Improved Cold Temperature Thermal Modeling and Strategy Development

Principal Investigator: Forrest Jehlik
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
(630) 252-6403; fjehlik@anl.gov

DOE Program Manager: Lee Slezak
(202) 586-2335; lee.slezak@ee.doe.gov

V.A.1. Abstract

Objective

The objective of this project is to investigate and quantify the fuel consumption losses in both conventional and advanced powertrains as a function of ambient temperature and to evaluate the potential of minimizing the losses through waste heat utilization.

Approach

- Develop a thermally instrumented vehicle mule for conducting tests and research
- Develop and utilize a vehicle powertrain fluid thermal conditioning cart to condition oil and coolant under a variety of ambient conditions to characterize efficiency losses due to viscosity and heat transfer
- Characterize waste energy available, post catalyst, to determine the amount of available energy to minimize fuel consumption under various thermal conditions
- Determine the efficiency increase potential through waste heat utilization

Major Accomplishments

- Completed Ford Fusion thermal mule instrumentation (minus the engine torque sensor)
- Completed and commissioned thermal conditioning cart
- Completed preliminary matrix of varied ambient temperature test cycles

Future Activities

- Design, fabricate, and install engine torque sensor system in vehicle
- Complete testing matrix with cold, intermediate, and hot temperatures
- Include creature comfort testing with cold and hot temperatures
- Accurately measure exhaust flow (validate current estimations) to determine total exhaust availability
- Predict and model total potential efficiency gains for engine utilizing exhaust availability
- Determine transmission efficiency losses as a function of thermal state
- Predict and model total potential efficiency gains for transmission utilizing exhaust availability

V.A.2. Technical Discussion

Internal combustion engines power nearly the entire U.S. fleet of personal transportation and nearly that whole fleet is fueled by petroleum. Typically, the standard is for over 70% of the total energy in the fuel to be discarded through heat transfer or through the exhaust as waste enthalpy. Methods to enable us to harness that heat could have a significant impact on increasing powertrain efficiency. The focus of this work is to investigate the potential of using waste exhaust heat to decrease powertrain lubrication viscosity under real-world ambient conditions, thereby greatly improving vehicle system efficiency in real-world driving conditions.

The vehicle thermal test mule and thermal conditioning cart used in this project are shown in Figure 1. For these preliminary tests, only engine oil was conditioned through the cart (coolant was excluded). Tests were conducted at 20°F and 72°F ambient conditions over a variety of drive cycles. The initial goal of testing was to determine levels of inefficiency associated with cold operation (increased oil viscosity/heat transfer) and to determine if sufficient energy exists in the exhaust stream to serve as a heat transfer medium.

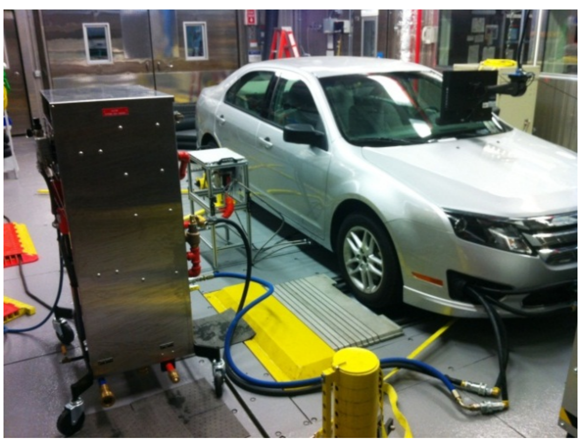


Figure 1. 2011 Ford Fusion thermal test mule and thermal conditioning cart (on left). Hoses from front grill of Fusion are engine oil inlet and outlet from the oil pan.

Background

Under real-world driving conditions, ambient temperature variations have a significant impact on fuel consumption (independent of drive cycle intensity). Research conducted at the Argonne National Laboratory (Argonne) Advanced Powertrain Research Facility (APRF) has shown variations in fuel consumption of advanced powertrains on the order of 40%, depending upon the ambient conditions. This does not include creature comfort effects. Figure 2 displays an example of this dramatic of fuel consumption on a Gen-2 Toyota Prius.

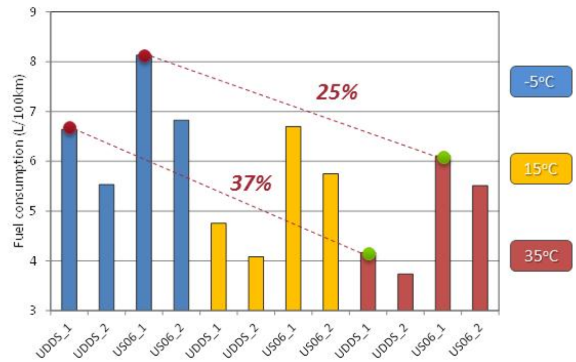


Figure 2. Effects of ambient temperature on fuel consumption. Gen-2 Toyota Prius results shown. Temperatures on right are test cell temperatures held constant during testing. Back-to-back urban dynamometer driving schedule (UDDS) and US06 cycle fuel consumption results shown.

Annual ambient conditions vary greatly, depending upon the region one lives in. These variations in temperature greatly affect fuel consumption, as shown in Figure 3. By understanding the physical mechanisms of these losses and by researching the potential methods of reducing these losses, significant national fuel efficiency increases might be realized.

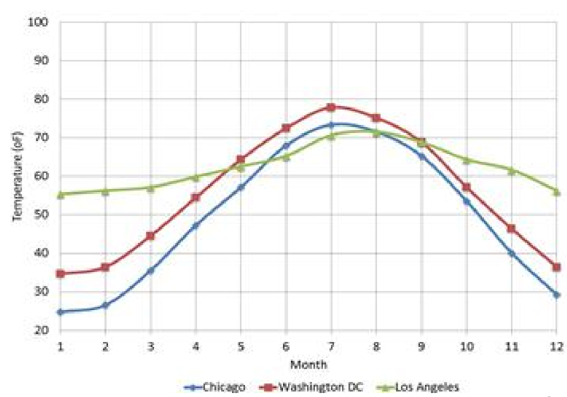


Figure 3. National seasonal temperature variations for select cities: Chicago, IL; Washington D.C.; and Los Angeles, CA.

Although much effort is being applied to advancing powertrain hybridization and electrification, systems to minimize efficiency losses of these powertrains from thermal effects are either uncommon or non-existent. These thermal effects have a dramatic impact on annual fuel consumption — nationally — as seasons change.

Introduction

A critical part of the U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy (EERE) plan is to develop and support technologies that displace petroleum usage. A portion of that work entails researching and benchmarking advanced powertrains, understanding their energy paths and usage, and researching methodologies to address any powertrain inefficiencies that are identified.

Considering the rapid advancement of advanced powertrain technologies today (hybrids, plug-in hybrids, electric vehicles), market penetration still remains very low with the vast majority of transportation coming from fossil-fuel-powered, internal combustion (IC) engines. To meet the goals established by the DOE, significant benefits will be realized by addressing technologies that can serve to increase the efficiency of the IC engine (whether in a standard or in a hybridized configuration).

This work focuses on the losses associated with any powertrain that utilizes an IC engine as a function of the ambient effects on efficiency. Since large efficiency variations are observed in testing, it logically follows that understanding the losses in efficiency can lead to developing proposed solutions.

Approach

The first step in understanding the ambient effects of the vehicle systems involved methodologies that predicted the fuel consumptions of IC engines as a function of the operational temperatures. Testing work was completed on a number of vehicles and a methodology was developed.

The second step involved estimating the powertrain temperature from its usage history. As a first step, a lumped capacitance technique was applied and the results were published. Finally, exhaustive research on the energy usage and waste from a vehicle needed to be analyzed.

By developing a vehicle thermal testing mule and a thermal conditioning cart, a sufficient matrix of tests and varied conditions could be conducted, and the potential to increase efficiency under varied ambient conditions could be understood.

A.2 Mobile Thermal Testing Cart

A mobile fluid thermal conditioning cart was designed and procured that controls the engine coolant and the oil temperature, by using a steady supply of lab facility cooling water. Additionally, heat may be added utilizing a 1.5-kW oil heater and a 3-kW coolant heater that run on 440-V AC three-phase power. The cart is shown in Figure 4.

Figure 4. Mobile Thermal Testing Cart.

The engine coolant heat exchanger is a tube-and-shell construction sized to regulate the engine coolant temperature between 180º and 220ºF and includes the 3-kW coolant heater installed in series with the heat exchanger. The heater has its own manually set thermostat. The coolant circuit includes a small pump and by-pass loop to push coolant from the heater through the system while it is in a standby mode. The by-pass loop and pump are controlled by an on/off switch from the control room.

The oil cooler is also a tube-and-shell heat exchanger. It is sized to remove 45 HP of heat and to control the oil temperature from 180º to

230ºF. In series with the heat exchanger is an inline 1.5-kW oil heater that runs on 440-V AC three-phase power. The heater has its own manually adjustable thermostat. This system has a separate oil pump to push the oil through the cooling system and back into the oil pans.

The engine coolant outlet temperature is monitored by thermocouples fitted to the expansion tank and the return coolant line. This provides the input signals to the self-contained temperature feedback controller. Controlling the exiting cooling water from the heat exchanger controls the return engine coolant temperature. The oil system has a similar process.

A.2 Ford Fusion Thermal Testing Mule

A standard four-cylinder, six-speed automatic 2011 model Ford Fusion was purchased and instrumented to conduct detailed thermal research and analysis. Over 30 thermocouples were located on the vehicle to analyze energy flows at critical nodes along the powertrain. In addition, the vehicle was instrumented with flow measurement devices to enable the ability to calculate enthalpy where appropriate. Figure 5 shows the test vehicle on the dynamometer at Argonne's facility.

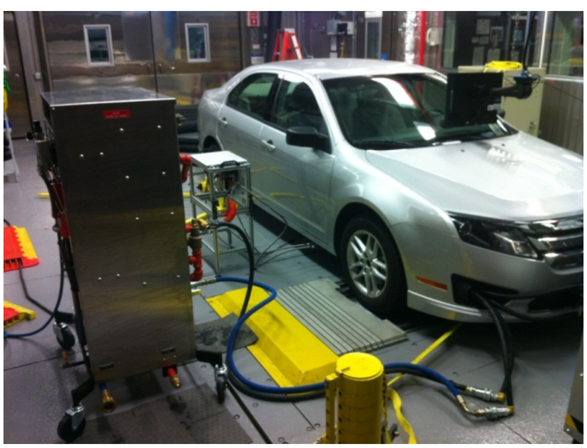


Figure 5. 2011 Ford Fusion thermal testing mule. Thermal Testing Cart shown in the lower left hand corner.

Results

A series of back-to-back UDDS cycles were completed at -7^{o}C, 15^{o}C, and 22^{o}C. Fuel consumption was compared to determine the overall consumption at each temperature and the increase in efficiency as the powertrain warmed. Over the standard cycle, there was a 21% increase in fuel consumption at -7^{o}C compared with 22^{o}C. Additionally, as the vehicle fuel consumption stabilized at each temperature, the -7^{o}C fuel consumption was still nearly 4% more than the consumption at 22^{o}C. This is shown in Figure 6.

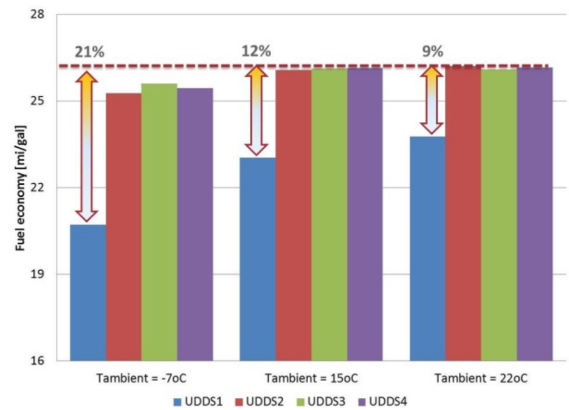


Figure 6. Ford Fusion thermal testing mule fuel consumption as a function of ambient temperature, Four back-to-back UDDS cycle.

Idle fuel consumption was shown to increase 50% at cold temperatures as the powertrain temperature stabilized. This effect may be reflected in fuel consumption variations for hybrid powertrains as the time of inoperability and loading may generate insufficient heat to reach higher efficiency states. Results are shown in Figure 7.

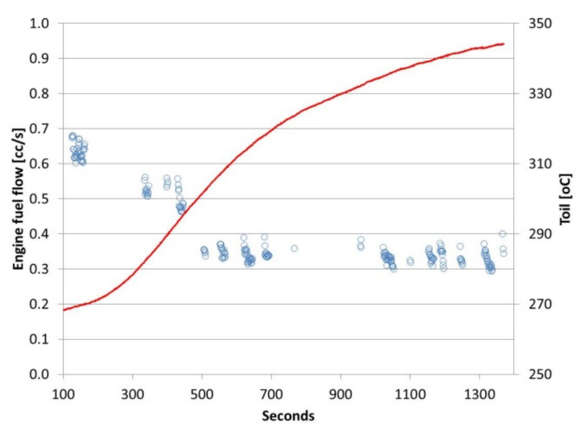


Figure 7. Ford Fusion thermal testing mule, idle fuel consumption, oil temperature dependency.

Preliminary tests with the thermal conditioning cart were conducted to calculate the difference in fuel consumption for identical drive cycles that were maintaining different oil temperatures. Test cell temperature for the tests was maintained at both 70^{o}F and 20^{o}F. The thermal testing cart was then used to heat or cool the oil to a higher or a lower value. Results are shown in Figures 8 and 9.

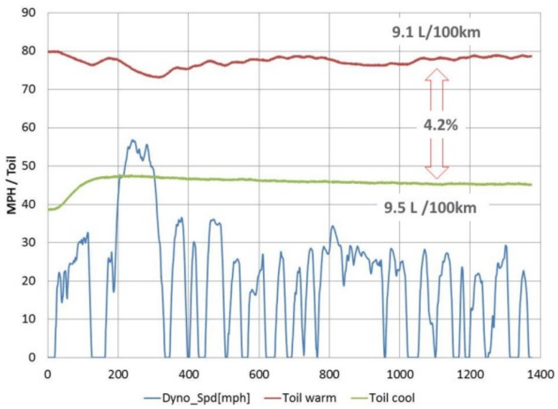


Figure 8. 2011 Ford Fusion UDDS drive cycle fuel consumption, engine oil temperature variable. Test cell maintained at 70°F.

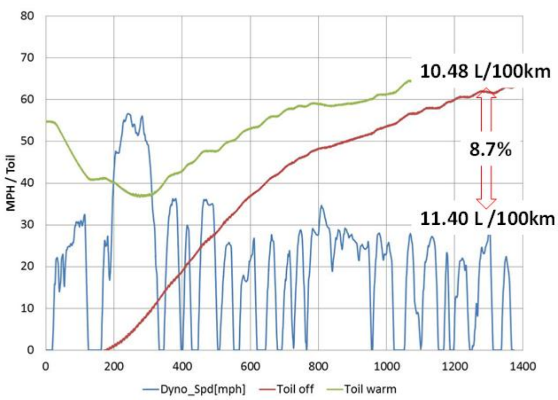


Figure 9. Ford Fusion UDDS drive cycle fuel consumption, engine oil temperature variable. Test cell maintained at 20°F.

From these results, it can be seen that the fuel consumption for identical cycles varies considerably with modest changes in the oil temperature. For 20^{o}F tests, fuel consumption decreased nearly 9% over the cycle, with median oil temperature averaging only 20^{o}F warmer. For the test cell maintained at 70^{o}F, average oil temperatures just over 30^{o}F increased efficiency over 4%. Note that for cold and hot testing, oil temperatures that result in maximum efficiency had not been achieved in the test cell and that the benefits would be even larger for higher temperatures (to be tested at a later date).

Finally, an analysis was conducted to estimate the amount of power and energy available in the exhaust that can be utilized to heat lubricating fluids within the engine and transmission — or perhaps coolant — as well as the amount of additional energy required to heat the oil to low viscosity and, thus, lower friction conditions. The results are shown in Figure 10. Note that an additional ~900 kJ is required to heat the oil to near ideal conditions in ambient conditions of 22^{o}F for a UDDS cycle. This energy is calculated as the additional energy above what is already being used to heat the oil through the engine operation to greatly reduce the viscosity.

Analysis was then conducted to determine the integrated amount of energy available in the exhaust stream, past the catalytic convertor. This was done to estimate if sufficient energy is present for the potential use of heating the engine lubricating fluids to their optimum temperatures.

In Figure 10, note that at an ambient temperature of 20^{o}F, after approximately 200 seconds of the UDDS cycle, the integrated energy that passes through the exhaust is greater than the calculated amount of energy required to increase the oil temperature to an optimal temperature. This finding indicates that there would be sufficient thermal energy present in the exhaust stream to theoretically heat the engine oil to the optimum temperature to reduce friction and increase engine efficiency. However, a follow-on project would be necessary to design and develop a heat exchanger that could be practically applied to accomplish this on a vehicle.

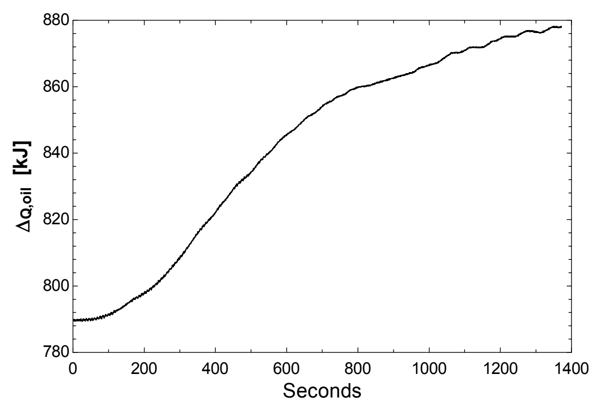


Figure 10. Energy required to heat oil to 362 K (near optimal conditions). UDDS cycle at 22°F.

By using the engine data collected during the tests, an engine fueling map as a function of the oil temperature was developed for a variety of ambient temperatures. The fueling maps at an oil temperature of 270 and 370 K are shown in Figures 11 and 12, respectively. From these results, it can be seen that the fueling rate is greatly reduced at higher oil temperatures for a given load. Comparing the modeled fueling rates of oil temperatures fixed at 340 and 370 K, even at a 30-degree difference in temperature, there is a significant decrease in required fuel at a given load for the increased temperature. This is shown in Figure 13. By combining these results, it is estimated that a 10% increase in efficiency may potentially be realized.

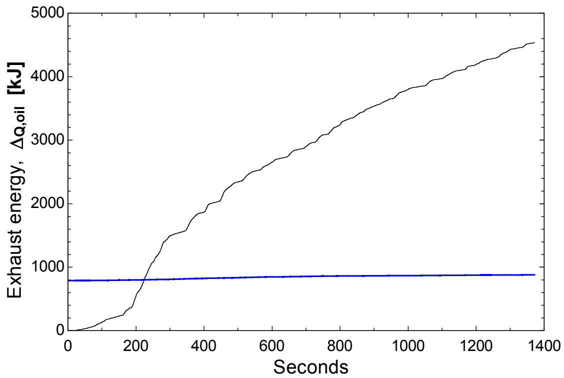


Figure 11. Integrated exhaust energy available, post catalytic convertor. Blue line denotes energy required to get oil temperature to near optimal conditions (362 K).

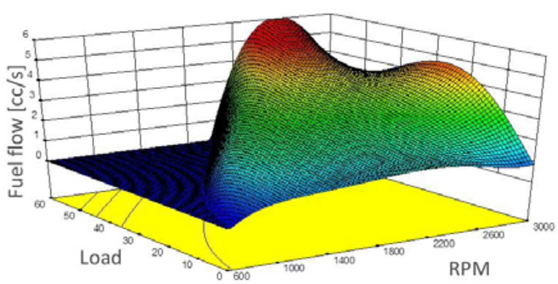


Figure 12. Ford Fusion engine fueling map, results shown with oil temperature at 270 K.

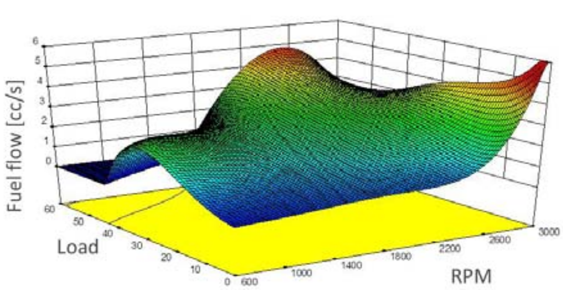


Figure 13. Ford Fusion engine fueling map, results shown with oil temperature at 370 K.

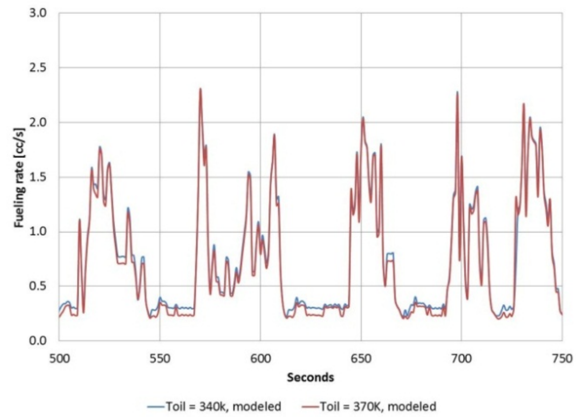


Figure 14. Ford Fusion engine fueling map, results shown with oil temperature at 340 K and 370 K for a UDDS cycle between 500 and 750 seconds.

Conclusions

For conventional powertrains, cold ambient temperatures have a marked impact on decreasing vehicle efficiency. This impact is exacerbated at lower engine loads in which less energy is available to increase the temperature of the engine lubricating fluids and, thus, decrease viscous losses. These effects are magnified by hybrid powertrains in which the engine operation is not constant, allowing for cooling cycles to occur.

Preliminary estimations suggest that sufficient energy exists — post catalyst — in the exhaust stream to be utilized as a heating medium for the powertrain lubrication system. The quality (availability) of this energy source is not understood. The total impact on potential fuel consumption savings has not yet been determined; however, the results of this thermal study show promise.

V.A.3. Products

Publications

1. "PHEV Energy Management Strategies at Cold Temperatures with Battery Temperature Rise and Engine Efficiency Improvement Considerations", Shidore, Neeraj, S., Jehlik, F., Rask, E., SAE Journal of Engines Vol. 4, Detroit, SAE 2011-01-0872

2. "Development of Variable Temperature Brake Specific Fuel Consumption Engine Maps", Jehlik, F., Rask, E., SAE Powertrain Fuels and Lube Conference, San Diego, SAE 2010-01-2181

3. "Simplified Methodology for Modeling Cold Temperature Effects on Engine Efficiency for Hybrid and Plug-in Hybrid Vehicles", Jehlik, F., Rask, E., Christenson, M., SAE Powertrain Fuels and Lube Conference, San Diego, SAE 2010-01-2213

4. "Methodology and Analysis of Determining Plug-In Hybrid Engine Thermal State and Resulting Efficiency", Jehlik, F., SAE World Congress, Detroit, Mi., SAE 2009-01-1308

V.B. AVTA EDAB (Battery Mule) Project

Principal Investigator: James Francfort
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2209
Phone: (208) 526-6787; Email: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

V.B.1. Abstract

Objective

- Test a variety of advanced energy storage systems (ESSs) that are at or near commercialization in on-road, real-world operation and to quantify the ESS capabilities, limitations, and performance fade over the life of the ESS.

Approach

- Idaho National Laboratory and ECOtality N.A. collaborated with the Oak Ridge National Laboratory to develop an on-road testbed for testing advanced ESSs for the Electric Drive Advanced Battery (EDAB) project.

Major Accomplishments

- The base test platform is a Colorado pickup and it was converted by AVL to a series hybrid electric vehicle by mating a UQM 145 kW motor/generator to the stock 5.3 L, V8 engine to form an auxiliary power unit (APU), removing the stock driveshaft, introducing a second UQM 145 kW motor/generator as the drive motor, and inserting a custom-built driveshaft assembly.
- Procurement, installation and testing of an Enerdel lithium ion battery in the EDAB vehicle.
- Test the Enerdel battery in an operations mode mimicking the battery demands of a Nissan Leaf .
- Benchmarking capacity fade, and changes in calculated discharge resistance, discharge power capability, charge resistance and charge power capability.

Future Activities

- Continue benchmarking the Enerdel battery until end of life criteria (23% decrease in capacity) while continuing to perform periodic battery testing
- Select and install the next traction battery for testing.

V.B.2. Technical Discussion

Background

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA) is part of DOE's Vehicle Technologies Program (VTP), which is within DOE's Office of Energy Efficiency and Renewable Energy (EERE). The AVTA is the only activity tasked by DOE to conduct field evaluations of vehicle technologies that use advanced technology systems and subsystems in light-duty vehicles to reduce petroleum consumption. A secondary benefit is the reduction in exhaust emissions.

Most of these advanced technologies include the use of electric drive propulsion, advanced energy storage, and advanced charging infrastructure systems. However, other vehicle technologies that employ advanced designs, control systems, or other technologies with production potential and significant petroleum reduction potential, are also considered viable candidates for testing by the ATVA.

The AVTA light-duty activities are conducted by the Idaho National Laboratory (INL) for DOE. INL has responsibility for the AVTA's execution, direction, management, and reporting; as well as data collection, analysis and test reporting. INL is supported in this role by ECOtality North America (ECOtality), which has a competitively awarded contract that is managed by DOE's National Energy Technology Laboratory (NETL).

Energy storage system (ESS) technology is rapidly improving, and methods for evaluating the developments must be devised for both laboratory and on-road conditions. Laboratory testing of ESS is a fairly mature process, but it is difficult to capture the unpredictability and randomness of the on-road conditions that traction batteries are required to perform within. The testing method and equipment must provide for accurate and precise data capture but accomplish this while driving on the road. The test results elucidate the performance of the ESS and also areas where there are limitations.

Introduction

The INL and ECOtality have collaborated with the Oak Ridge National Laboratory to develop an on-road testbed for testing advanced ESSs for the Electric Drive Advanced Battery (EDAB) project. The project objective is to be able to test a variety of advanced ESSs that are at or near commercialization in on-road, real-world operation and to quantify the ESS capabilities, limitations, and performance fade over the life of the ESS.

Approach

Performance of each ESS is measured by the following metrics:

- Discharge rate
- Capacity
- Charge rate
- Durability
- Reliability
- Lifetime
- Temperature resilience.

The performance is measured under both controlled and real-world conditions, and the project results will inform the research community and automotive original equipment manufacturers (OEMs) on the state of the art of ESSs for PHEVs and BEVs. The data and findings from this project have also been made available to support U.S. DOE modeling and energy storage development efforts.

The first ESS selected for testing is the EnerDel Type I EV lithium-ion chemistry with a mixed-oxide cathode and amorphous hard carbon anode. The pack has 384 cells (96 in series, four strings in parallel), and each cell has a maximum voltage (at 100% state of charge (SOC)) of 4.1 V and a rated capacity of 17.5 Ah (at a C/3 rate). The pack has a maximum voltage of 393.6 V, a nominal voltage of 345.6 V, and a rated capacity and energy of 70 Ah and 23 kWh, respectively. The ESS is a sealed unit, meaning that there is no thermal management system (TMS), and cooling can be done only by either passive radiation or forced air on the enclosure. The ESS uses controller area network (CAN) communications. This EnerDel ESS is designed for a small EV.

The base test platform is a Colorado pickup truck and it was converted into a series hybrid electric vehicle by mating a UQM 145 kW motor/generator to the stock 5.3 L, V8 engine to form an auxiliary power unit (APU), removing the stock driveshaft, introducing a second UQM 145 kW motor/generator as the drive motor, and inserting a custom-built driveshaft assembly. The power electronics, including the motor controllers, DC/DC converters, and on-board charger, and ESS cooling fans were located in the bed of the truck, along with the ESS. The motor/generator configuration is shown in Figure 1. The components in the figure, from left to right, are the motor controllers of the drive motor and generator, the drive motor, and the generator on the right.

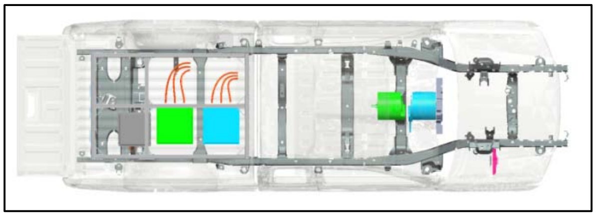


Figure 1. Locations of the drive motor, generator, and motor controller units. The front of the truck is to the right.

The Hybrid Controller is overlaid on top of the base vehicle controls, and the Hybrid Controller manages the driver requests and translates these requests into control of the various vehicle subsystems and components. The driver acceleration and braking requests are also sent via CAN to the High Level System Controller (HLSC). The HLSC contains the physical characteristic algorithms that determine the demand on the ESS based on the algorithms and on the information provided by the battery management system (BMS) on the battery SOC, temperature, maximum available charge and discharge current. Once the ESS demand is determined, the value is sent back to the Hybrid Controller, and the amount of drive power or mechanical braking that must be made up by the APU and friction brakes, respectively, is determined.

A picture of the EDAB testbed with the bed shell cover removed is shown below in Figure 2. The picture shows how the ESS is mounted on a configurable rail system for ease and flexibility of system mounting.

Figure 2. The vehicle bed with ESS under test (bed shell cover is removed).

Results

The first ESS to be tested with the mule vehicle is a 23 kWh pack designed for all-electric small passenger car applications. Even though the ESS under test was not designed for a Nissan Leaf, this vehicle platform was chosen as the emulated vehicle because its pack size and cooling principles are similar to the test ESS. Moreover, Nissan Leaf characterization data is available from other DOE projects to validate the project models and algorithms.

Physical characteristics emulation algorithms were first tuned off-line using Autonomie™ software as the simulation environment. The final tuning and validation phase was performed on a chassis rolls dynamometer (Figure 3). Within that controlled environment, the pick-up truck mule vehicle completed UDDS, HFET and US06 drive cycles. Its ESS energy usage was compared to data collected on the chassis roll dynamometer for the Nissan Leaf. The mule vehicle ESS energy consumption was within 5% of the actual Nissan Leaf consumption when driving the Urban Dynamometer Drive Schedule (UDDS) cycle, and was within 1% on the HFET cycle, shown in Figure 4. No Leaf data were available for US06 cycle ESS energy benchmarking.

Figure 3. Tuning and validation testing.

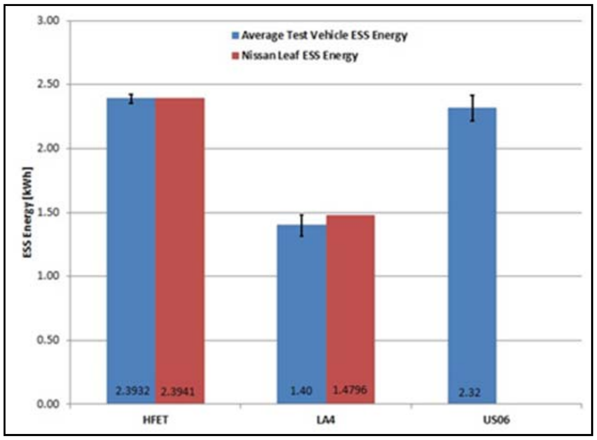


Figure 4. Physical characteristics emulation validation.

In order to confirm that the ESS current and power were consistent with usage monitored in the Nissan Leaf, current histograms and power traces were compared as well. Both show good correlation between the test vehicle and the actual vehicle, as shown in Figures 5 and 6.

With this calibration phase completed on chassis rolls, weight emulation algorithms have demonstrated that they allow the heavier Colorado pickup truck to emulate ESS energy flow as if it were a lighter Nissan Leaf, over both urban or highway driving conditions.

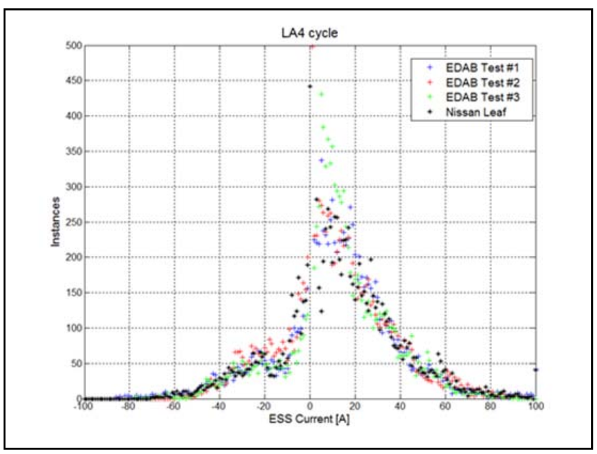


Figure 5. Histogram of ESS current usage for the Nissan Leaf and mule vehicle while driving UDDS drive cycles.

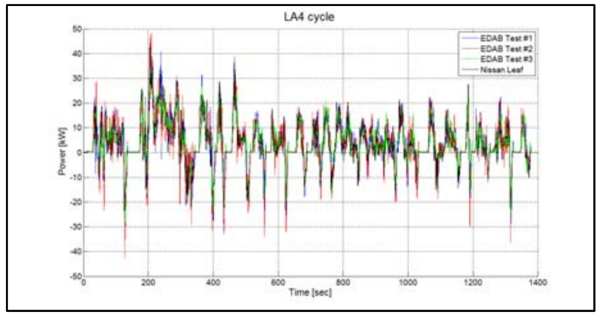


Figure 6. ESS power traces for the Nissan Leaf and mule vehicle while driving the UDDS drive cycles.

The Static Capacity test results are shown in Table 1. Laboratory testing has shown a 15.4% decrease in static capacity from the rated value over the first 115 days of testing.

Table 1. Static capacity testing results

Testing Date	Days into test	Measured Discharge Capacity (Ah)	% of rated capacity
2/29/2012 (BOT)	0	63.15	90.2%
4/9/2012	39	62.72	89.6%
5/16/2012	76	60.58	86.5%
6/24/2012	115	59.21	84.6%

The calculated EVPC resistances and power capabilities are depicted in Figures 7 to 10. As can be seen in both charge and discharge, resistances have increased while both charge and discharge power capabilities have decreased from the BOT results. For example, the discharge resistance at 50% SOC has increased from 120 mΩ to 136 mΩ over the same on-road operation. This is a 14.5% increase in resistance. Due to the fluctuation in the calculated charge and discharge power values from the EVPC testing, no determination can be made as to an estimated time until the ESS can no longer perform the power needed to drive the vehicle.

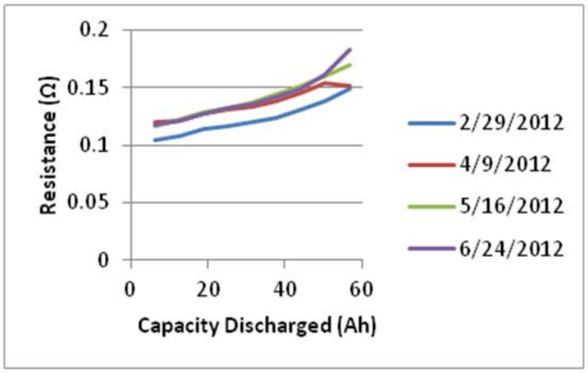


Figure 7. EVPC calculated discharge resistance

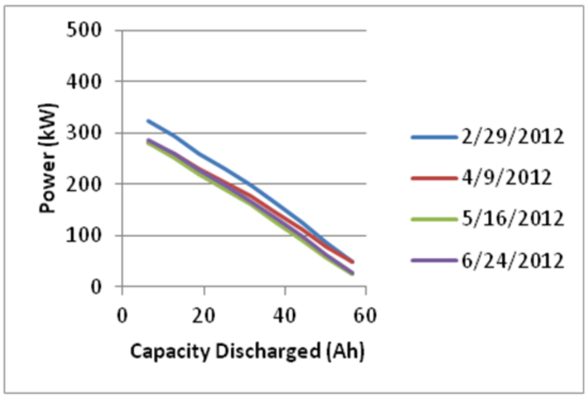


Figure 8. EVPC calculated discharge power capability

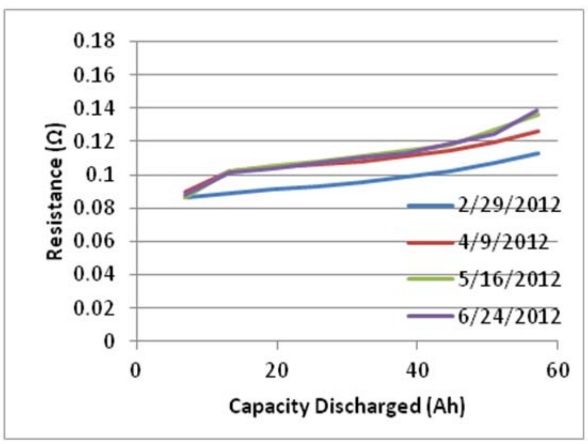


Figure 9. EVPC calculated charge resistance

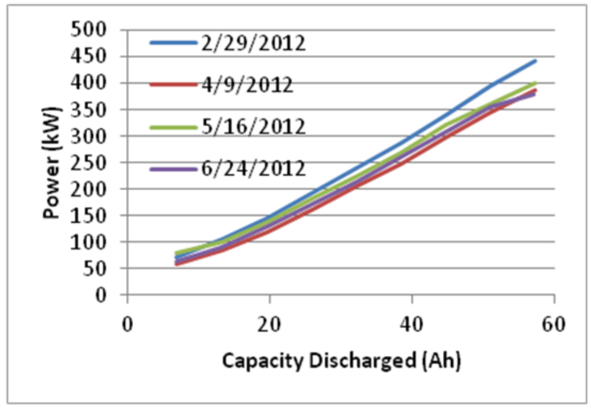


Figure 10. EVPC calculated charge power capability

After completion of the initial reference performance test (RPT) at the ESS beginning of life (BOL), on-road operation of the EDAB platform with the EnerDel Type 1 EV pack commenced. The on-road operation is intended to utilize the pack in a manner that is representative of typical BEV operation during both driving and charging. The on-road operation consists of driving and charging between 50 to 100 miles and 2 to 3 charge events per day which is within the bounds of driving and charging of a typical BEV driver. The driving is a mix of approximately 50% city and 50% highway driving miles on public roads during typical driving times. The charging consists solely of Level 2 charging that is initiated following driving events. These driving and charging patterns provide appropriate and representative operation of the ESS for thermal cycling and energy throughput.

To date, the EDAB testbed has accumulated 5,103 miles of on-road results with the EnerDel Type 1 EV pack. A total of 9,645 Ah throughput (into and out of the pack) has been measured through on-road driving and charging as well as the reference performance testing. As per the design of the high level controls system, the ESS is operating at a representative energy consumption of a typical small four-door BEV. The energy consumption to date is 235 DC Wh/mi. Table 2 shows the summary results of the on-road testing from the EDAB platform during the on-road testing of the EnerDel Type 1 EV pack.

Table 2. Summary of on-road driving and charging results.

On-Road miles driven	5,103.3 miles
City / Hwy percent of miles driven	51% / 49%
Amp Hours throughput lifetime during on-road driving and charging	9,645 Ah
Average on-road energy consumption	235 DC Wh/mi

The on-road driving typically starts with a full state of charge since most of the charge events are long enough in duration to allow for a full recharge of the ESS. Since each drive event was typically 40 to 50 miles in length, the SOC at the end of the drive is typically between 10% and 50% SOC. This variance is due to driving distance, driving style, accessory utilization and other factors. Figure 11 shows a histogram of the ESS SOC at the beginning and end of each trip.

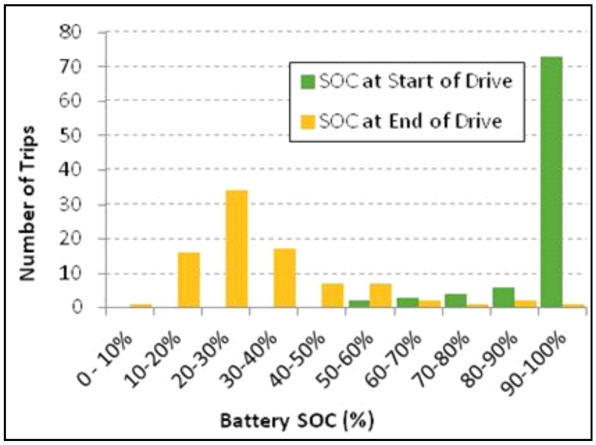


Figure 11. Initial and final SOC from on-road driving trips.

To characterize the utilization of the ESS during on-road operation, the Ah throughput was analyzed with respect to both ESS current and ESS mean battery cell temperature. Figure 12 shows the typical current draw during propulsion is between 30 and 60 amps (less than C1 rate). The AC Level 2 charging occurs between 0 and 10 A, which accounts for a majority of the negative amp hours into the pack. Although the amount of regenerative braking amp hour throughput is small, it is notable that nearly all of the charging amp hours occur at currents less than 30 A (less than C/2 rate).

Figure 13 shows the typical operating temperature of the ESS is between 30 to 38 degrees Celsius with bounds at 48 and 22 degrees. This upper temperature bound is primarily due to the ESS BMS dictating current limitation as ESS temperature increases.

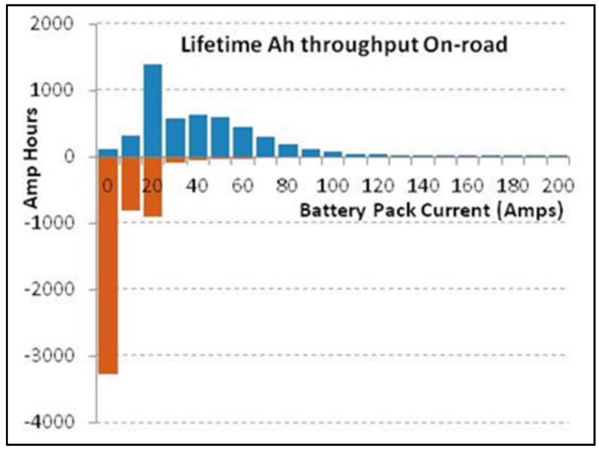


Figure 12. Amp-hour throughput as a function of ESS current during on-road operation.

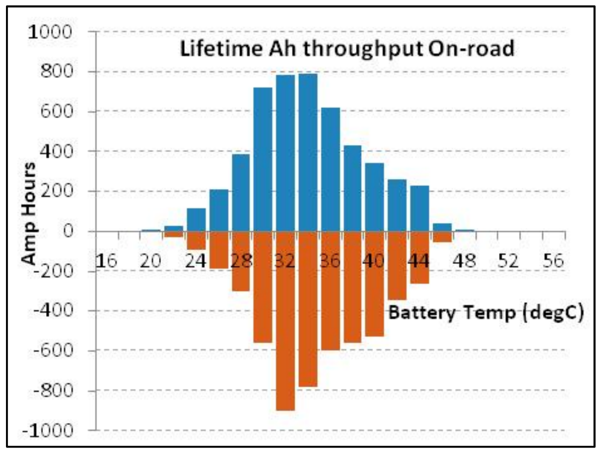


Figure 13. Amp-hour throughput as a function of mean ESS cell temperature during on-road operation

Conclusions

After 5,100 miles of on-road operation of the ESS, capacity has decreased from 63.2 Ah to 59.2 Ah as shown in Table 3. This is a decrease of 6.25% in measured capacity. The change in capacity appears to be linear with respect to Ah throughput. If the rate of change of capacity remains constant, the end of life criteria (23% decrease in capacity) will occur shortly after 20,000 miles of on-road operation.

Summary of on-road driving and charging results:

Table 3. Summary of On-Road Driving & Charging Results.

Measured ESS capacity prior to commencing on-road driving	63.2 Ah
Measured ESS capacity at current miles accumulated	59.2 Ah
Measured ESS discharge resistance at 50% SOC prior to commencing on-road	120 mΩ
Measured ESS discharge resistance at 50% SOC at current miles accumulated	136 mΩ

On-road driving and charging will continue until the end of life (EOL) criteria is reached, which is a reduction in capacity of 23% or an increase in discharge resistance of 30%. Once EOL is reached, the ESS will be removed from the test platform and transferred to a partner National Laboratory for use in testing secondary life ESS applications.

V.B.3. Products

Publication

1. Two status reports have been published for project to date statues. They can be accessed at: avt.inel.gov/pdf/energystorage/BattMule030512thru051712.pdf and avt.inel.gov/pdf/energystorage/BattMule030512thru062412.pdf

V.C. PHEV Advanced Series Gen-set Development/Demonstration Activity

Principal Investigator: Paul H. Chambon
Oak Ridge National Laboratory (ORNL)
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1428; Email: chambonph@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

V.C.1. Abstract

Objective

- The objective of this project is to integrate ORNL advancements in vehicle technologies to properly design, size and simulate an advanced series hybrid (HEV/PHEV) gen-set. This project integrates two of the core strengths of ORNL – advanced combustion with emissions after-treatment technologies and advanced power electronics and electric machines. The goal is to design a "best effort" gen-set drawing on advanced, high risk technologies currently under development in each respective program activity at ORNL or by their partners.

Approach

- Perform a literature search of existing gen-set technologies
- Create a decision matrix to identify suitable technologies and application
- Down-select engine/fuel, generator motor and power electronics technologies
- Perform simulation study to evaluate benefits of various engine/fuel –traction motor combination

Major Accomplishments

- The literature searched was completed. It highlights the recent renewed interest in APUs for PHEV applications
- Relevant engine and electric machine technologies were listed and weighted in a decision matrix to down select which ones should be considered in the simulation study
- A simulation study was performed to quantify the efficiency of various APU combinations at the vehicle level. It points towards alternative fuel and advanced combustion for engine technologies and induction machines for generators.
- Engine and motor manufacturing partners were contacted regarding opportunities for simulation and hardware evaluation

Future Activities

- Pursue partners to proceed with hardware integration of both IC engine and electric machine
- Refine simulation based on actual data from potential partners
- Finalize component selection and sourcing based on technical merit and partnerships

V.C.2. Technical Discussion

Background

Series HEV and PHEVs present a unique configuration where a gen-set (engine-generator set, also referred to as Auxiliary Power Units (APU)) is used to recharge the Energy Storage System (ESS) and can be decoupled from the propulsion drivetrain, operating the gen-set for optimum energy efficiency. As such, gen-sets provide unique opportunities for component sizing and combustion operating regimes. Decoupling the IC engine from the variable load requirements of typical vehicle drive cycle, allows for the consideration/optimization of a wide range of technologies and key components: internal combustion engine, exhaust after-treatment, electric machine and power electronics.

Introduction

This project will draw from the extensive experience in power electronics and electric machinery from the Power Electronics and Electrical Power Systems Research Center as well as the broad knowledge in advanced combustion and emissions after-treatment through the Fuels, Engines, and Emissions Research Center, both centers being part of transportation section of ORNL. The emphasis will be placed on technologies currently under development in each respective center. It will attempt to focus on a modular gen-set that could have multiple applications outside of a vehicle, which would reduce cost based on high volume production.

This project will investigate several advanced technologies for each key component considering several aspects in its selection process such as efficiency, cost, strategic benefits (rare earth / non rare earth) and complementarity of the engine and motor technology.

Approach

A literature search will be performed to obtain the state of the art technology status for gen-sets aimed at PHEV applications.

A decision matrix will be developed to list various technology candidates and requirements both on the combustion engine side and the electric machinery side. Weighting factors will be applied to emphasize the key features for our PHEV application. The resulting scores will be used to down-select a limited number of technologies/ components to be evaluated via simulation.

Autonomie models for each gen-set component will be developed and evaluated at the vehicle level to quantify resulting gen-set combination efficiency. That will provide an additional selection criterion when recommending which technology to proceed with during the hardware demonstration phase of this project.

Results

Literature search

Gen-sets have seen a renewed interest recently, especially in the transportation sector and Electric Range Extended Vehicles (EREV) in particular. This is due to the high costs of Energy Storage Systems (ESS) and the “range anxiety” syndrome of Battery Electric Vehicles (BEV) owners who fear that their vehicle does not have enough energy stored in its ESS to complete some out-of-the-ordinary commutes. Yet adding battery capacity is not always a feasible option because of cost and weight. Therefore, using a small gen-set to recharge the battery offers a viable alternative to a larger, heavier and costly ESS, while potentially exceeding customer expectations with regards to vehicle range. Figure 1 shows a graphical representation which highlights the benefits of a gen-set architecture: reducing BEV ESS size from 100mile range to 40 mile range will reduce the vehicle cost dramatically. Some of those savings can be invested in an APU which can increase the EREV vehicle range past the original BEV 100mile range. This is particularly true for todays’ ESS costs (red trace) but will remain true with 2020 target costs for batteries (blue trace).

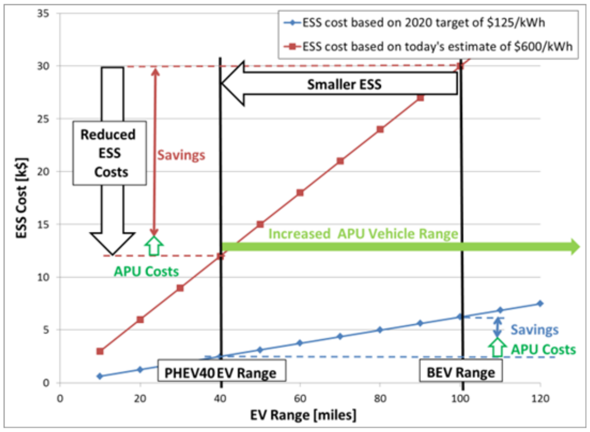


Figure 1. Trade-off between APU costs and ESS size depending on range and ESS cost.

Most APUs identified during that search use a conventional gasoline 4-stroke small displacement (less than 1.2l) engine whose power output is less than 35kW. See Table 1 for results. There are some variations on the number of cylinders (from one to three) and configurations (V-twin and in-line) but the technology level remains low: all engines are port fuel injected. That choice of technology indicates that the emphasis has so far been placed on cost rather than efficiency, even though no paper proposes any cost figure for their APU to confirm the affordability of their product.

Table 1. Non-exhaustive list of APU

	Power	Technology	Displacement	Cylinder	Generator
Lotus	35kW	4 stroke, PFI	1200cc	3	Not specified
FEV-Pierburg	30kW	4 stroke, PFI	800cc	2	Permanent magnet
Mahle	30kW	4 stroke, PFI	900cc	2	Axial flux generator
Getrag	14kW	4 stroke, PFI	1000cc	3	Not specified
Polaris	22kW	4 stroke, PFI	325cc	1	Not specified
AVL	15kW	Wankel	254cc	1	Permanent magnet
FEV	18kW	Wankel	295cc	1	Not specified
AIXRO	15kW	Wankel	294cc	1	Permanent magnet

As shown in table 1, Wankel engines are being investigated too because of their high power density though emissions can be a concern.

Most engines run on gasoline (except for the Lotus APU which is said to be capable of ethanol and methanol). Fuels do not seem to have been investigated or optimized for those APUs.

There are some more advanced engine concepts that are advertised in the literature, such as Opposed Piston Opposed Cylinder (OPOC) engines, as well as turbines, but it is difficult to gauge their readiness because of the lack of tangible results.

It has to be noted that all of those APUs are concepts or technology demonstrators at best, but none have made it to production.

The generator technology is, most of the time, not specified in the papers. When it is, it is said to be permanent magnet machines, but no additional details are provided (such as interior magnet vs. exterior magnet design). The inverter technology and control methodology are never mentioned.

The main takeaways from that literature search are that there is a definite renewed interest for APUs for range extender applications but that the emphasis is on small displacement low technology (presumably low cost) engines. Engine efficiency and electric machine technology do not seem to be high priority factors.

Technology down-selection

For the purpose of this project, we want to emphasize technologies that ORNL's Fuel Engines and Emissions Research Center as well as Power electronics and Electric Machinery Research Centers have prior experience with. Therefore turbines, OPOC engines and Wankel engines will not be considered.

A matrix was created to prioritize engine technologies identified so far. Each engine type got assigned score with respect to four criteria: advanced technology, suitability of the technology for an APU application, alignment with prior and current engine research projects at ORNL, and cost (See table 2). The final overall score confirmed some of the down selection performed so far. Wankel engines and turbines can be ruled out. The study should focus on advanced combustion and alternative fuels.

Table 2. Engine selection matrix.

Criteria	Technology Prospect	Suitability for APU application	Alignment with ORNL Engine programs	Affordability	Total
Gasoline PFI	1	8	6	10	**25**
Gasoline GDI	5	8	8	5	**26**
Gasoline HCCI	9	10	10	4	**33**
Diesel	4	6	8	3	**21**
PCCI	7	10	10	3	**30**
RCCI	10	10	10	2	**32**
Ethanol PFI	4	8	8	10	**30**
Wankel	5	9	1	6	**21**
Turbine	8	5	1	1	**15**

The simulation study will focus its investigation on the following engine types:

- Gasoline Port Fuel Injected (PFI)
- Gasoline Stoichiometric Direct Injection (GDI)
- Ethanol Direct Injection (EDI)
- Gasoline Homogenous Charge Compression Ignition (HCCI)
- Diesel
- Reactivity Controlled Compression Ignition (RCCI)

No available dataset was complete enough to build reliable models for ethanol PFI and PCCI engine. PCCI technology characterization performed at ORNL focused on 5 modal test points that are not sufficient to build a look up table. Still that combustion work showed that PCCI efficiency is very close to conventional direct injection Diesel but can reduce NOx and PM emissions.

For electric machinery, fewer technologies are available, so a selection matrix was not necessary. The following four types will be simulated:

- Interior Permanent Magnet machine
- Field Wound machine
- Induction machine
- Switched reluctance machine

Simulation Study

If not already in existence, new Autonomie models were created for engines and electric machines identified in the previous phase of the project. Those models are based on steady state characterizations performed by FEERC and PEEMRC during previously completed DOE projects (see Figure 2 and 3 for examples of engine and e-machine efficiency tables).

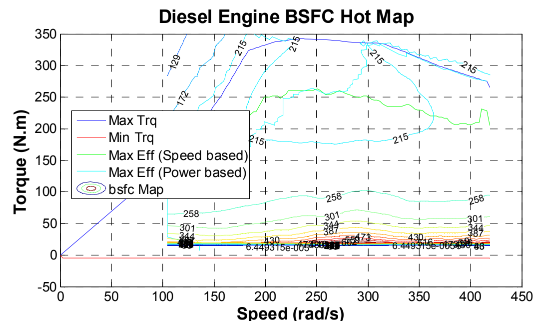


Figure 2. BSFC table for diesel engine.

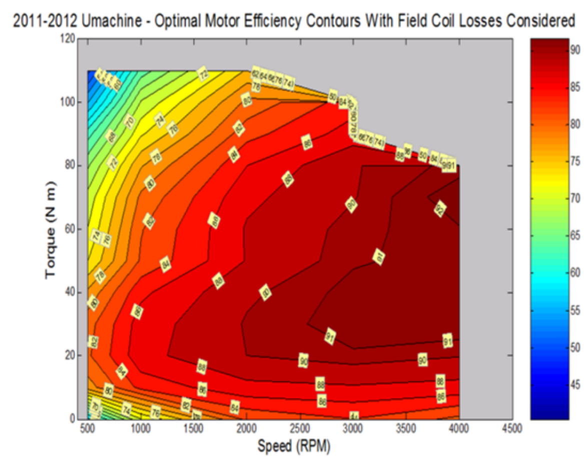


Figure 3. Efficiency characteristic of ORNL Novel Flux Coupling machine without Permanent Magnets.

The gen-set efficiency is evaluated in the context of a series PHEV the size of a Nissan Leaf over three different drive-cycles (UDDS, HWFET and US06). The gen-set is managed by the hybrid powertrain supervisory controller. It implements thermostatic control strategies: the engine can only be on or off based on the battery state of charge, and when activated, the engine operates at its peak efficiency conditions. All drive cycles are performed when the vehicle is in Charge Sustaining mode so that the gen-set comes on and off regularly. By nature, thermostatic control is not charge balanced, so a correction factor is applied during post processing to compensate for state of charge discrepancies.

The size of electric machines and engines was standardized to equate 30kW, which reflects the average size of APUs identified in the literature search. Preliminary simulations were performed to confirm that this power level is suitable to sustain vehicle operation. Figure 2 shows how the ESS state of charge (green trace) can be maintained on a US06 cycle while in charge sustaining mode, with the engine generating 25kW of mechanical power, even though power demands for traction purposes might be as high as 60kW. Table 3 shows engine power levels for steady state speed operation and various road grades while in charge sustaining mode. A steady 30kW APU output is sufficient to maintain ESS energy levels while driving 70mph on a flat surface or 60mph on a 2% grade.

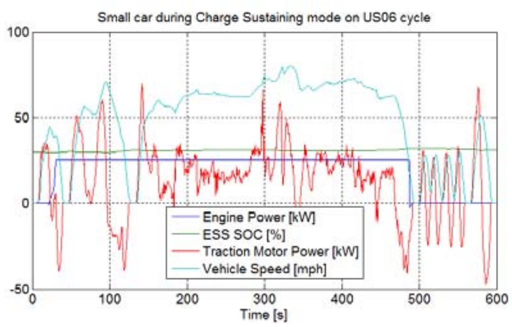


Figure 4. Series PHEV power requirements on US06 cycle while in charge sustaining mode.

Table 3. Steady state engine power requirements in charge sustaining mode

Vehicle speed [mph]	Grade [%]	Engine Power [kW]
60	0	18.7
70	0	26.0
80	0	36.3
60	2	28.9
60	4	39.2
60	6	50.0

All gen-set combinations of the six engine technologies and 4 electric machine technologies were tested over the three drive cycles (UDDS, HWFET and US06). Fuel economy results were normalized by converting them to gasoline equivalent and charge balancing the ESS state of charge over each cycle in order to compare all fuels (gasoline, ethanol and diesel) without biasing results based on fuel energy content or hybrid operation.

For a given e-machine technology, HCCI proved to be the most efficient ahead of RCCI, Diesel, ethanol, PFI gasoline and GDI. It has to be noted that the PFI engine is an Atkinson cycle engine representative of the Prius engine, hence its high fuel economy. See Figure 5 for engine technology comparison when generator is an interior permanent magnet machine.

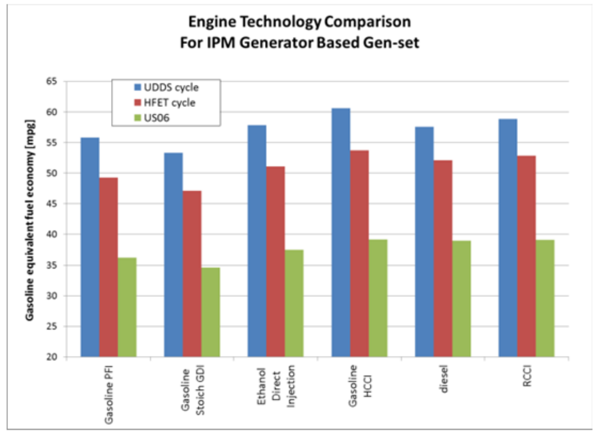


Figure 5. Comparison of engine technologies.

For a given engine technology, interior permanent magnet generator demonstrated the most fuel economy ahead of induction machine and wound field and switched reluctance machines. See Figure 6 for generator technology comparison when engine is a PFI gasoline engine.

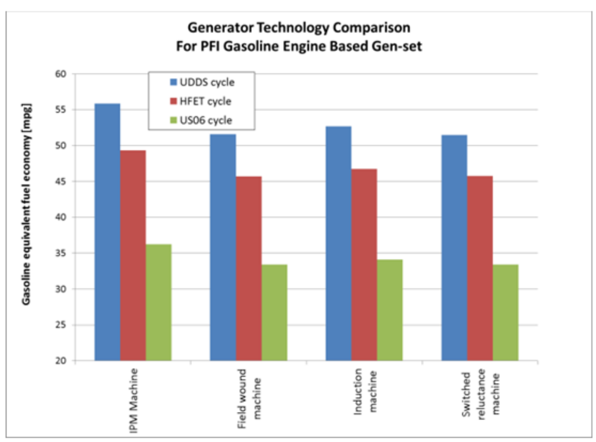


Figure 6. Comparison of electric machine technologies.

Based on those results, the project should investigate alternative fuels such as ethanol and advanced combustion, such as HCCI for engine technology, and induction machines for generators. Other technologies demonstrated high efficiency such as Diesel and RCCI engines, or permanent magnet generators. Those technologies are not preferred for this application because of other criteria such as after-treatment requirements for diesel, dual fuel and associated complexity for RCCI, and use of rare earth materials for permanent magnet machines.

Conclusions

A literature search showed that there is a renewed interest for APUs for range extender applications. But cost seems to be more of a factor than efficiency when it comes to engine technology, selection since most engines are gasoline port fuel injected. Generator technology is not often described but permanent magnet machines are most often used. Engine and generator technologies were down selected to six engine types and four generator types to conduct a simulation study that yielded vehicle fuel economy for various engine-generator combinations. Out of those technologies, alternative fuels such as ethanol and advanced combustion such as HCCI are the most promising on the engine side, and induction type machines offer the best non-rare earth efficiency for generators. Therefore the project should focus on those technologies to proceed with a hardware phase.

V.C.3. Products

Publication – None

Patents – None

Tools & Data - None

V.D. PHEV Engine Control and Energy Management Strategy

Principal Investigator: Paul H. Chambon
Oak Ridge National Laboratory (ORNL)
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1428; Email: chambonph@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

V.D.1. Abstract

Objective

- Investigate novel engine control strategies targeted at rapid engine/catalyst warming for the purpose of mitigating tailpipe emissions from plug-in hybrid electric vehicles (PHEV) exposed to multiple engine cold start events.
- Validate and optimize hybrid supervisory control techniques developed during previous and on-going research projects by integrating them into the vehicle level control system and complementing them with the modified engine control strategies in order to further reduce emissions during both cold start and engine re-starts.

Approach

- Optimize engine cold start strategies on stand-alone engine
  - Implement best in class engine control strategies in open source controller
  - Improve/optimize strategies to reduce cold start emissions
- Engine-In-the-Loop (EIL) system testing
  - Develop EIL platform suitable for PHEV emulation
  - Port Autonomie™ model into EIL platform
  - Commission and validate EIL system on test cell
- Optimize plug-in hybrid supervisory strategies and engine control strategies as a system in order to reduce tailpipe emissions on the EIL test stand
  - Integrate and improve hybrid supervisory control strategies from previous ANL-ORNL simulation-only study
  - Concurrently optimize both control strategies (engine and hybrid) as a system

Major Accomplishments

- Optimized cranked and motored cold start strategies on stand-alone engine
- Commissioned Engine-In-the-Loop on test cell, therefore allowing the emulation of a virtual vehicle while having actual engine and after-treatment measurements
- Optimized powertrain emissions as a system by coordinating engine control strategies and vehicle supervisory strategies

Future Activities

- FY 2012 is the final year of this project

V.D.2. Technical Discussion

Background

Plug-in hybrid electric vehicle (PHEV) technologies have the potential for considerable petroleum consumption reductions, at the expense of increased tailpipe emissions due to multiple "cold" start events and improper use of the engine for PHEV specific operation. PHEVs operate predominantly as electric vehicles (EVs) with intermittent assist from the engine during high power demands. As a consequence, the engine can be subjected to multiple cold start events. These cold start events have a significant impact on the tailpipe emissions due to degraded catalyst performance and starting the engine under less than ideal conditions. On current conventional vehicles as well as hybrid electric vehicles (HEVs), the first cold start of the engine dictates whether or not the vehicle will pass federal emissions tests. PHEV operation compounds this problem due to infrequent, multiple engine cold starts.

Previous research had focused on the design of a vehicle supervisory control system for a pre-transmission parallel PHEV powertrain architecture. Engine cold start events were aggressively addressed by only modifying vehicle supervisory strategies while retaining the base engine control strategies which were intended for a conventional (non-hybrid) powertrain. This led to enhanced pre-warming and energy-based engine warming algorithms that provide substantial reductions in tailpipe emissions over the baseline supervisory control strategy. Yet the system was not thoroughly optimized due to the lack of access to engine control strategies.

During FY 2011, an open calibration engine controller for a GM Ecotec LNF 2.0l Gasoline Turbocharged Direct Injection engine was obtained thanks to the support of Robert Bosch LLC. That controller allows control strategies to be modified and calibration to be tuned differently from the production settings, so that they can be optimized for our hybrid application. The LNF engine and its open controller were commissioned on an engine test cell at ORNL. A literature search was performed to identify key engine cold start control parameters. Their impact on engine-out emissions was characterized with the LNF engine on a test stand using the Bosch engine controller to calibrate them.

Introduction

This project expands the work performed so far on hybrid vehicle supervisory strategies to include engine control strategies in order to proceed with a system approach of the powertrain control strategies optimization rather than independent component optimization.

Gasoline direct injection engines with variable valve timing, such as the one identified for this project, offer more degrees of freedom to optimize cold start emissions than port fuel injected engines. Their operating envelope will also vary in the case of a hybrid powertrain compared to a conventional powertrain. Therefore engine control strategies should be calibrated first to make the most of those added degrees of freedom specific to the GDI technology and second, to take advantage of the operating conditions specific to hybrid powertrain.

This project will focus on adapting the conventional engine calibration to a hybrid powertrain application as well as optimizing cold start engine strategies. Then cold start emissions will be targeted by jointly optimizing both vehicle supervisory strategies and engine control strategies.

Approach

The LNF engine and its Bosch open controller that was benchmarked during FY 2011, has been moved out from the ORNL facility and commissioned at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility, so that it can be integrated with the Hardware-In-the-Loop system there. This will, in turn, allow emulating a virtual hybrid vehicle and test cold start emissions for that vehicle configuration.

That testcell was upgraded with a new data acquisition system from DyneSystems based on National Instruments hardware and software, it is integrated with the dyno controller and capable of thermocouples and analog inputs. The testcell was also fitted with a new 2-channel 5-gas emissions bench analyzer from California Analytical Instruments for pre and post catalyst emissions characterization. Those pieces of equipment were commissioned only after the engine-only testing phase. Prior to their installation, a portable emissions measurement system from Sensors Inc, a SEMTEC DS, was used. Thermocouples were also fitted to the exhaust system to measure pre-catalyst temperature as well as catalyst brick temperatures (See Figure 1), thereby allowing to characterize the thermal behavior during a cold start.

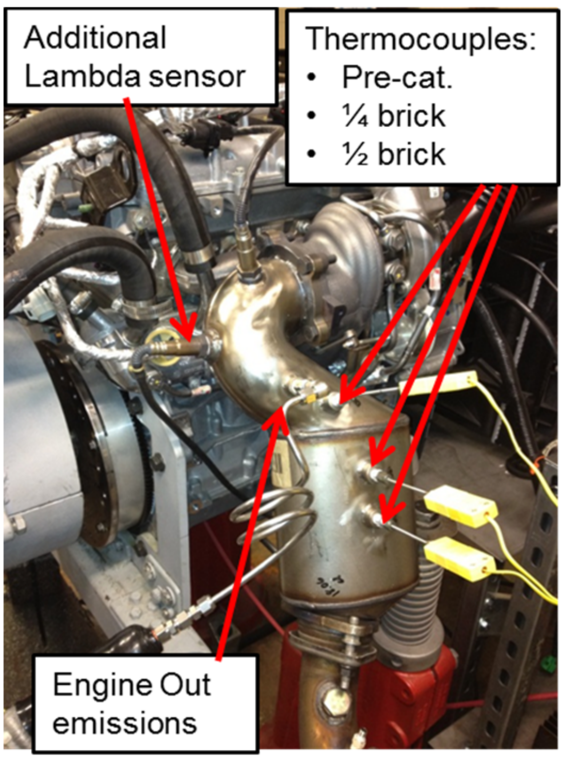


Figure 1. Exhaust and after-treatment instrumentation.

In order to ensure that cold start behavior is representative of the in-vehicle installation, the engine was fitted with its production air intake and exhaust system, as well the production coolant loop including thermostat and radiator. The heater core loop was modified to be used as a means to provide external cooling between runs so that, after a true cold that can happen only once a day, subsequent pseudo cold starts can be performed. Pseudo cold starts are defined when the engine coolant has cooled down to 25 degC between tests and the exhaust and catalyst brick temperature has returned to ambient temperature too.

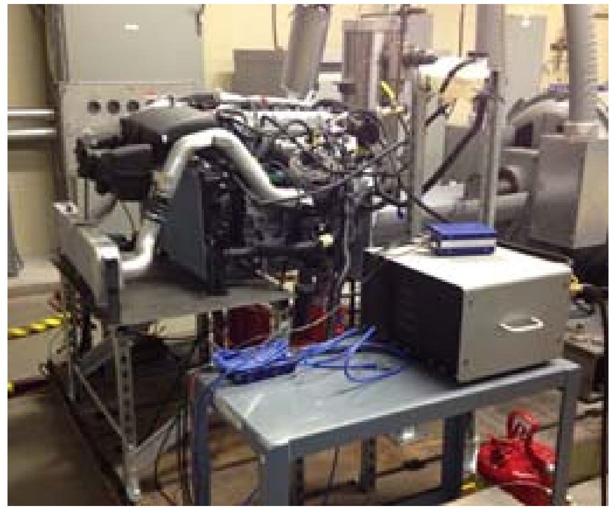


Figure 2. Ecotec LAF engine commissioned at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility.

The literature search performed prior in this project had identified a few key features to speed up catalyst warm-up on a gasoline direct injection engine: elevated idle speed, elevated idle load, dual injection (early injection during the intake stroke and late injection during the compression stroke), extremely retarded spark timing, limited start enrichment and lean operation during post start, elevated fuel rail pressure, retarded exhaust cam timing and high pressure compression stroke injection cranking (stratified cranking). All those features are currently in–use on the Bosch ECU except for stratified cranking.

The engine-only testing phase of that project will characterize the effect of that additional feature (stratified cranking). Then the effort will focus on optimizing the engine operation and calibration envelope to make the most of the properties of the series PHEV powertrain architecture, where the electric generator can supplement the engine. For instance, the engine can be motored up to various speeds by the hybrid drive generator. So the effects of motored starts compared to starter motor starts will be quantified, as well as the effects of different idle speed during catalyst warm-up. Another operating mode specific to series hybrid is that the engine does not need to generate torque early on after being fired since the engine is decoupled from the wheels. So the generator can be used to smooth out engine operation, allowing the generator to push the operating envelope of the engine. Two examples of different operating conditions whose effects have been characterized are increased idle load and idle speed as well as additional spark retard during warm-up.

A Hardware-in-the-loop platform was fully commissioned on the University of Tennessee testcell to run as an engine-in-the-loop configuration of a virtual plug-in hybrid vehicle. The real engine and after-treatment are physically installed on the test stand while a real time computer runs a virtual model of hybrid powertrain and vehicle implemented with Autonomie™. It also runs a virtual drive cycle and model of a driver. The real time platform is interfaced to the dynamometer controller and engine controller over analog and digital inputs and outputs (see Figure 3).

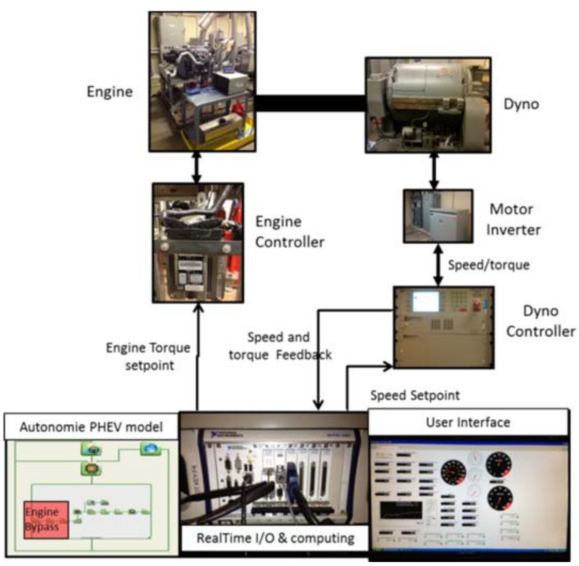


Figure 3. Diagram of Engine-In-the-Loop configuration.

This set-up enables the evaluation of an actual engine behavior for a specific virtual vehicle configuration providing the flexibility to change virtual powertrain configurations and test conditions of virtual test environment, as well as offering the accuracy of real engine and after-treatment measurements. This set-up is therefore critical to optimizing the vehicle as a system by coordinating both engine control strategies and hybrid supervisory control strategies.

Results

ENGINE-ONLY OPTIMIZATION

Comparison of starter motor starts and motored starts

A starter motor start is defined as a conventional start where the engine is decoupled from the dynamometer, and the starter motor is used to crank the engine. By contrast, a motored start is when the engine is coupled to an electric machine powerful enough to motor up the engine to an elevated idle speed. For evaluation purposes, the engine is coupled to the dynamometer and motored up to the elevated idle speed of 1400rpm but fired once engine speed exceeds 1100rpm. This method has the benefit of removing a highly transient phase when engine is cold and therefore has the potential to reduce tailpipe emissions.

The dynamometer maximum ramp up rate was limited to 500rpm/s due to its large inertia. This is much slower than would be achievable by a properly sized machine in a series PHEV configuration. Yet, test results showed that motored starts with delayed injection showed a 12% improvement of engine out total hydrocarbon emissions over a conventional cold start, whereas the reduction reaches 38% on stratified starts. See Figure 4 for instantaneous results in the case of homogenous injection during cranking.

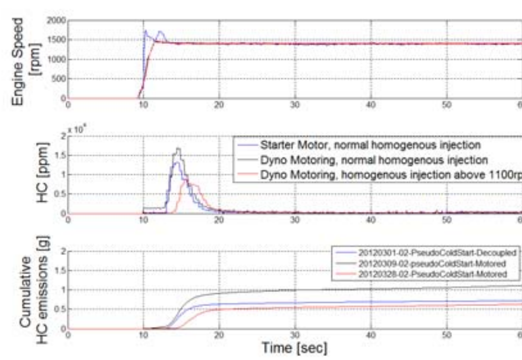


Figure 4. Starter motor starts versus motored starts.

Effect of stratified cranking

Stratified cranking is defined as high pressure late compression stroke injection during engine start. That injection mode was performed both for starter motor starts, as well as motored starts.

In both cases, it did not affect the engine out thermal behavior: post turbo temperature rise time was within half a second of each other which is about the test-to-test variability. Both injection strategies demonstrated a reduction in total hydrocarbon: 53% when motoring and 34% when cranking with a starter motor. Figure 4 shows a trace of injection timing, total hydrocarbons and post turbo temperatures when cranking the engine with a starter motor.

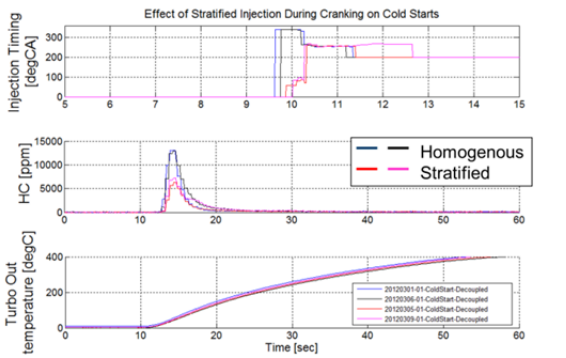


Figure 5. Injection timing, total hydrocarbons and post-turbo temperature for homogenous and stratified cranking when cranking the engine with a starter motor.

Effect of elevated idle load

In order to speed up catalyst warm-up, the idle speed and load were increased. The expectation is that more hot gases going through the catalyst will speed up its warm-up.

For those tests, only one gas analyzer was available. It was used to sample engine out emissions. Different cold start strategies are compared my measuring the time it takes for the temperature at the front of the catalyst brick (2inches inside the brick) to reach 350deg which is considered the light off temperature. Emissions are integrated up to that point to estimate what would go past the catalyst as it would be inefficient before light off.

Controlling idle speed alone is not enough because the ECU regulates airflow down to the same level regardless of the idle speed. So there was no impact on catalyst warm-up, though it did generate lower NO levels.

Idle load level was increased by 10, 20 and 30%, while maintaining idle speed at 1400rpm and keeping all other cold start calibration parameters unchanged too. It resulted in faster catalyst light off (as much as 32%) without any hydrocarbon penalty but it yielded higher NO emissions (see Figure 6)

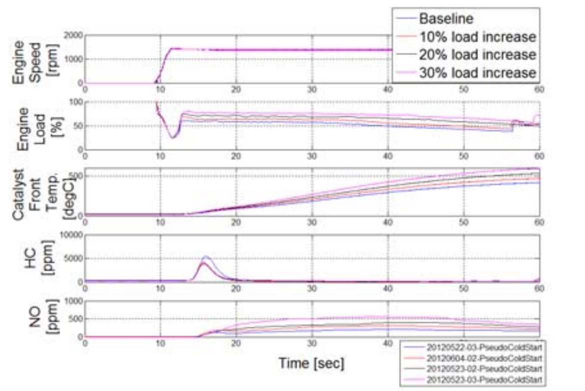


Figure 6. Effect of higher idle load on catalyst warm-up.

Elevated idle loads were tested at different idle speeds (1400, 1700 and 2000rpm) on pseudo cold starts conditions and as well as true cold starts.

For all speeds, increasing idle load yields:

- Faster catalyst warm-up
- Comparable HC emissions
- Larger NO emissions

NO emissions increase can be offset by operating at higher speeds, but higher speeds yields higher HC too.

The optimum point is measured to be 1700rpm and 20% increased idle load, where catalyst warm-up is 22% faster, hydrocarbons emissions are 27% smaller and Nitrogen Oxide emissions are comparable to baseline. See Figure 7, 8 and 9

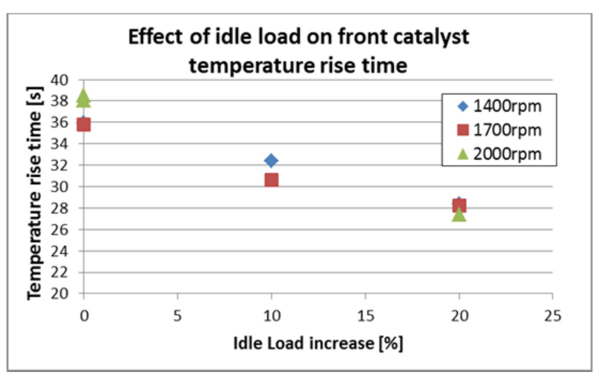


Figure 7. Effect of higher idle load and speed on catalyst warm-up.

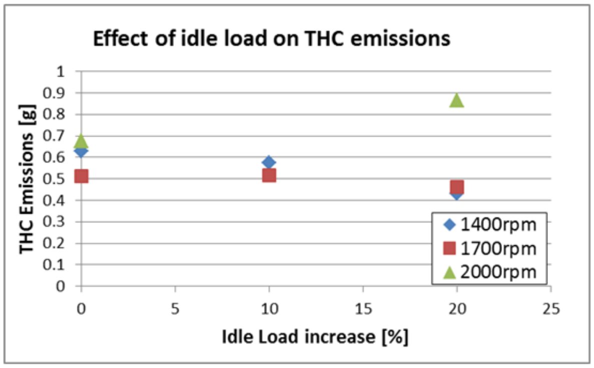


Figure 8. Effect of higher idle load and speed on Total Hydrocarbon engine out emissions.

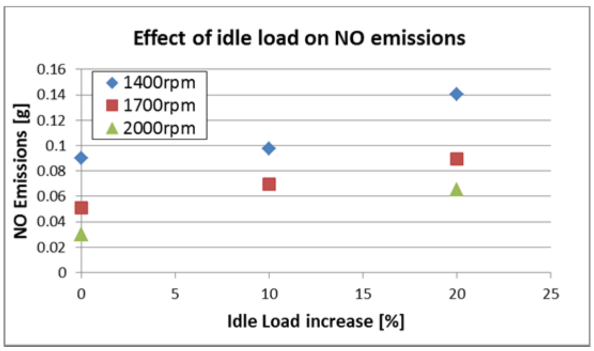


Figure 9. Effect of higher idle load and speed on Nitrogen Oxide engine out emissions.

Effect of additional spark retard

The following tests evaluate the benefits of retarding spark even more during catalyst heating mode to increase exhaust heat and speed up catalyst light off.

Baseline calibration runs about 20deg spark retard in HSP mode during catalyst heating mode at 1400rpm. The calibration is modified to further retard spark timing (3, 6 and 12 deg). All other parameters (such as load, injection mode and timing) are left unchanged. Increasing spark retard did heat up the catalyst faster (as much as 13%) without any hydrocarbon penalty and slightly higher NO emissions.

Several levels of spark retard were tested at different idle speeds (1400, 1700 and 2000rpm) on pseudo cold starts. For all speeds, increasing spark retard yields faster catalyst warm-ups. HC emissions trend higher at 1700rpm, trend lower at 1400rpm and deteriorate drastically when increasing spark retards past 6deg at 2000rpm. NO emissions tend to trend higher with spark retard. The optimum setpoint was measured at 1700rpm where it speeds up catalyst heating (up to 12% faster) without affecting emissions. See Figure 10.

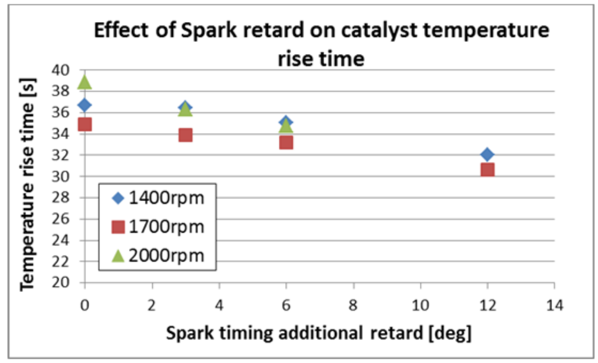


Figure 10. Effect of additional spark timing retard on catalyst warm-up.

Additional tests were carried out by combining increased idle load and spark retard during catalyst heating mode. They showed that that phase can be shortened by 25-30% from 35-36seconds to 25seconds (See Figure 11).1400rpm maintains HC levels but worsen NO whereas 1700rpm maintains NO (relative to production calibration) and worsen HC. The selection of optimal idle speed will therefore be determined based on cycle emissions whether the emphasis is on NO or HC reduction for that platform.

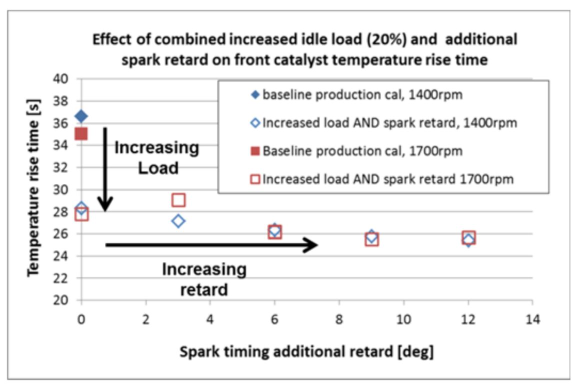


Figure 11. Effect of combining increased idle load and additional spark timing retard on catalyst warm-up.

SYSTEM LEVEL OPTIMIZATION

Series PHEV configuration offers great opportunity to optimize engine warm-ups because the engine is decoupled from the driver demand. But gains obtained by optimizing stand-alone engine strategies can be negated by poor coordination with hybrid supervisory strategies. Hybrid powertrain cold start emissions can be further improved over conventional load-following strategies by designing supervisory control strategies that make the most of the flexibility of series plug-in hybrid configuration by considering the engine warm-up and transient conditions restrictions.

Coordination strategies were tested over the first 505seconds of a UDDS cycle since this is sufficient to warm up the engine and its after-treatment and longer tests would only dilute the effect of a cold start. The virtual series PHEV model emulates hybrid strategies entering charge sustaining mode at the beginning of the second hill of that cycle. From that point on, the engine is started so that the generator can recharge the battery. Supervisory strategies are essentially load-following strategies with consideration for warm-up conditions and re-starts. The engine power can be modulated but the engine speed is selected accordingly so that power is obtained at its peak efficiency. Power requests are only authorized above a minimum threshold so that the engine does not have to operate at low speed, low load, and inefficient regions.

Table 1. Hydrocarbon emissions over 505 cycle depending on coordination strategies between engine and hybrid strategies.

Test condition	Engine out HC accumulation [g]	Improvement [%]
Baseline, no warm-up standard 200rpm injection	10.76	NA
No warm-up. Injection above 1100rpm	6.05	-44%
Idle Warm-up only. Injection above 1100rpm	3.21	-70%
Low load warm-up. Injection above 1100rpm	5.14	-52%
Idle warm up then low load warm-up . Injection above 1100rpm	3.65	-66%

Table 1 shows engine out emissions of several coordination strategies. The baseline case corresponds to hybrid strategies ignoring engine warm-up requirements: engine is fired at low cranking speeds, power requests are passed on to the engine without any filtering even if engine is cold, so the engine is considered as if it were in a conventional powertrain application. The second case still does not implement a warm-up and can request full torque from the cold engine but the engine is motored up to speed and fired only above 1100rpm. That yields a 44% improvement in engine out hydrocarbon emissions over the 505 cycle. The "idle warm-up only" test implements strategies that monitor the warm-up and let the engine complete that phase without requesting any other load until catalyst has reached its light off temperature. Subsequent transients are also filtered. That provided a 70% improvement in engine out emissions. Figure 12, shows temperature, emissions and speed traces for the baseline ("un-coordinated") algorithm and the idle warm-up ("coordinated") algorithm.

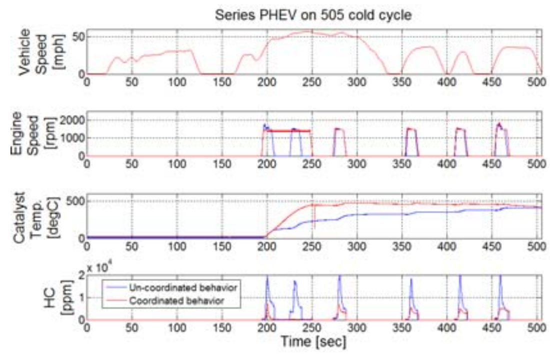


Figure 12. Warm-up behavior comparison between uncoordinated strategies and idle warm-up coordinated strategies.

A fourth configuration applied a small load of 15kW ("low load warm-up"), instead of warming the engine by idling. HC Emissions were much worse when warming up under load than idling, this resulted in 60% larger HC emissions over the cycle, and it did not speed up the catalyst warm-up (see Figure 13). Trying to combine idle load and low load warm-up (5th configuration in Table1), by sequencing them, only generated more engine out HC emissions without helping tailpipe emissions since light-off temperature was achieved during the idle phase.

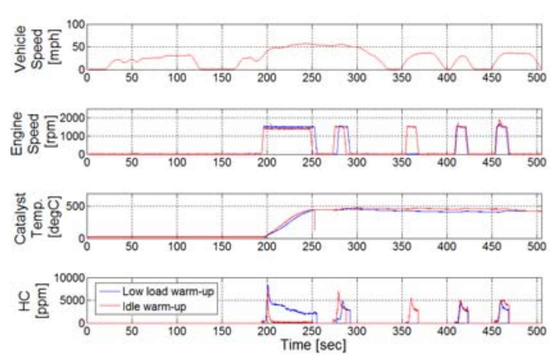


Figure 13. Warm-up behavior comparison low load warm-up and idle warm-up strategies

Conclusions

An engine was commissioned on a testcell at the University of Tennessee, with its production in-vehicle hardware configuration (included cooling loop) but with calibration and bypass authority over its cold start behavior to optimize it for conditions specific to a series PHEV configuration.

First, engine-only optimization was performed. It was shown that, using an electric machine to motor up the engine and having the engine injecting only above 1100rpm does help HC emissions by 13% compared to a conventional cranking start with a starter motor. Stratified cranking tests were performed. Combined with motored starts, they can improve HC emissions by 22%. Increasing idle load by 20% at 1700rpm can reduce the catalyst heating phase by 25% with comparable HC and NO emissions. Additional spark timing retard can also heat up the catalyst up to 12% faster. Finally, combining elevated speed, elevated load and additional spark retard can yield 25-30% faster catalyst heating phase but trade off on emissions will determine optimum operation conditions when tested on actual vehicle for specific drive cycle.

The second phase of the project looked at coordinating engine only and hybrid supervsiory strategies to ensure that the gains obtained by calibrated the engine appropriately are not negated by poorly designed hybrid supervisory startegies. It showed that, using the same engine control strategies, HC emissions can be reduced by as much as 70% with proper coordination compared to hybrid strategies commanding the engine without consideration for cold starts.

V.D.3. Products

Publications

1. "PHEV Cold Start Emissions Management", SAE technical paper, 13PFL-0868, World Congress 2013
2. "PHEV Engine Cold Start Emissions Management", DEER Conference Oct 18, 2012

V.E. The Meritor Dual Mode Hybrid Powertrain (CRADA)

Principal Investigator: David E. Smith
Oak Ridge National Laboratory
National Transportation Research Center
2370 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1324; Email: smithde@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

V.E.1. Abstract

Objective

- Explore the potential of systems optimization through model based design of their Dual Mode Hybrid Powertrain (DMHP) and alternative parallel powertrain designed for Class 8 long haul trucks

Approach

- Combine model-based design with experimental verification/validation to develop fuel efficient Class 8 heavy duty trucks
- Utilize the ORNL Vehicle Systems Integration (VSI) laboratory for advanced powertrain controls development and optimization

Major Accomplishments

- Developed robust vehicle systems model for DMHP and corresponding supervisory controls architecture and baseline strategy
- Optimized supervisory controls for series and parallel operation of the DMHP over a variety of duty cycles relevant to Class 8 line haul applications
- Completed Alternative Technology Analysis which includes a wide variety of advanced powertrain architectures for Class 8 trucks

Future Activities

- Baseline engine testing mapping (Cummins ISX 15 liter)
- Engine-in-the-loop testing (DMHP and alternative)
- Powertrain-in-the-loop testing (DMHP)
- Supervisory controls development to support vehicle build, including controller rapid controls prototyping and hardware-in-the-loop testing
- On-road vehicle testing of alternative powertrain

V.E.2. Technical Discussion

Background

Hybrid powertrains are of considerable interest because of potential reductions in fuel consumption, criteria pollutants and green house gas emissions. Parallel hybrids have been applied to light and medium duty trucks, where urban driving cycles are prevalent, while series hybrids have been successfully used for other applications like transit and school buses. Unfortunately, hybridization of the Class 8, HD powertrain is inherently challenging due the expected long-haul driving requirements and limited opportunities for regenerative braking. Meritor has conceived and demonstrated a transformational Dual Mode Hybrid Powertrain (DMHP) technology developed specifically for the needs and function of Class 8 line haul trucks. The DMHP system enables a new paradigm in powertrain operational efficiency in the Class 8 truck segment. It decouples the connection between the engine operating point and the truck road load demands over a broad operating range through an innovative hybrid design. The DMHP operation choices include running in full series, full parallel and engine-off modes. The DMHP offers the opportunity for an engine to operate in a narrow range, thus providing a strategy for maximized fuel economy and minimized emissions. Further, it is expected that transient torque and power wheel demands are handled in whole or part by the electric system, thus reducing the frequency and intensity of engine transients and further improving the fuel economy and emissions. Fuel consumption and emissions have been further reduced through the elimination of overnight hoteling and idling at stops. Finally, based on the unique operating profile of an engine integrated into our hybrid powertrain, a transformational HD truck engine design concept next can emerge.

Recent research activities by the Contractor have yielded significant data in real-life speed and load profiles of Class 8, long haul trucks. In addition, preliminary simulations of the DMHP carried out by the Contractor reveal significant optimization opportunities of the DMHP by applying systematic simulation and controls approaches. An improved understanding of the complex interactions offered by the on-board engine, energy storing system, and electric machines is necessary for the development of control methodologies and practical implementation. We will continue to further this understanding through detailed experimentation and modeling, drawing on and expanding the Contractor's core competency in basic engine R&D and advanced controls. This knowledge will be used to develop, implement, and evaluate control strategies on an actual DMHP using the Participant's components and subsystems. Our initial focus will be on optimization of DMHP utilizing a "stock" diesel engine that is commercially available in the market place. A new DMHP-specific engine design concept will be pursued at a later phase of this CRADA.

Introduction

The successful implementation of DMHP will require a thorough technical understanding of the complex interactions between various energy sources and energy consumption components, for various operating modes of HD, Class 8 on-highway trucks. Further, the Contractor has been developing and applying methods for the analysis, interpretation, and control of dynamic engine phenomena in single- and multi-cylinder engines for over fifteen years. The Participant has extensive knowledge and experience in DMHP components and subsystems. A partnership involving these knowledge bases is key to overcoming the critical barriers associated with the realistic implementation of DMHP and enabling a measurable progress in applying hybrid powertrain in the next generation of HD truck transportation systems. The Contractor and Participant have collaborated on a preliminary investigation that warrants much deeper R&D efforts.

Approach

The project is broken down into two (2) distinct components. Model based design will be thoroughly utilized to understand the complexity of the proposed DMHP system, and to synthesize a detailed supervisory control model and architecture. Experimental testing in the ORNL VSI laboratory will be utilized to validate control algorithms and to further understand impacts on the operation of the DMHP due to thermal transients, NVH, and emissions.

Model Based Design and Development

Simulation Model and Control Algorithm Development

The Contractor in partnership with the Participant will develop a comprehensive DMHP simulation strategy. ORNL will develop and update a robust DMHP vehicle simulation model for the study and discovery of potential operating scenarios of the total system, major components such as the engine and battery pack, and synergistic interactions under simulated load cycles. The focus of the model development will be to create a structured supervisory control model for the DMHP such that Meritor can utilize for rapid controls prototyping and production code development.

Note: All models will be refined for steady-state and transient operation as experimental data becomes available during the course of this activity.

DMHP System Optimization Studies

The Contractor will carry out a comprehensive optimization analysis of the DMHP control system, using rigorous optimization methods. System variants, optimization criteria, optimization parameters, and constraints shall be considered.

Alternative Technology Evaluation

A comprehensive comparison of alternative technologies shall be conducted to assess current and proposed DMHP concepts as well as other relevant Class 8 line haul hybrid powertrain systems. The alternative technologies considered shall possibly include different energy sources (engines, etc.) Competitive and /or promising technologies may be examined.

Hardware and Experimental Testing

The Contractor will utilize expert engine dynamometer testing, the new hybrid powertrain laboratory facility and/or mule trucks to validate the virtual (simulation) tasks, provide experimental data for future simulation and develop methodologies and control strategies for DMHP operation. Testing of SIL, HIL and Rapid Prototyping of engine systems have been a well-recognized expertise of the Contractor. This will be applied and further extended to advanced hybrid powertrains.

DMHP System Development and Baseline

The Participant in partnership with the Contractor will construct and baseline a DMHP in support of this activity. The DMHP setup will be located at the Participant facility.

Engine Acquisition, Installation, and Mapping

The Contractor in coordination with the Participant will acquire a representative HD engine and dynamometer compatible controller and wiring harness. In addition, necessary hardware and software will be identified and developed as necessary to support installation of the engine for dynamometer testing. After installation, a baseline will be performed on the engine to develop a performance/emissions map to support modeling efforts.

DMHP Simulated and Full System Dynamometer Testing

The Contractor in coordination with the Participant will develop and test a simulated DMHP on the HD engine acquired in the previous task. This will include the use of a hardware-in-the-loop and advanced control methodologies. The next step will include the Participant delivering a complete DMHP unit and associated components to the Contractor. The DMHP system will be installed on the new hybrid HD dynamometer test stand for full system hardware testing.

On-Road Testing in a HD Class 8 Truck

Meritor will deliver a prototype, Class 8 truck equipped with an advanced hybrid powertrain. In addition to supervisory controls development and physical implementation, ORNL will develop a test plan and install the necessary data acquisition and instrumentation on the mule test vehicle. The integrated powertrain will then be transferred to a fleet vehicle in order to observe normal fleet operation over the road in realistic conditions. Information, such as vehicle loading, duty cycle, component physical conditions, etc. will be obtained through this study that can be transferred back to both the vehicle simulation model and the experimental full system test facility.

Results

Model Development

The project revolves around utilization of a robust vehicle level model to develop the necessary control strategies for successful DMHP operation. Figure 1 shows the Autonomie block diagram that represents the second and third generation of the Meritor DMHP. This powertrain architecture model was constructed with a high degree of flexibility such that exploration of various operating mode and mechanical parameters could easily be achieved.

In addition the DMHP model shown in Figure 1, a conventional vehicle model was developed to serve as a basis for comparison for fuel economy results.

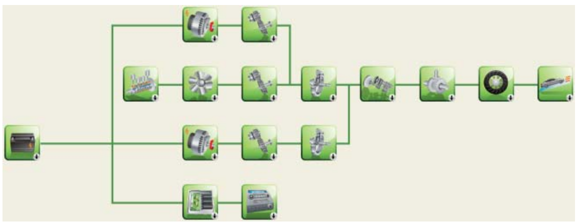


Figure 1. Autonomie block diagram for Gen2/Gen 3 DMHP model.

As part of the model development phase of the project, a supervisory control architecture was created and populated for use with the Meritor DMHP. A schematic representation is shown in Figure 2. The supervisory control system was segregated into various control processes such that development of each could be performed in parallel.

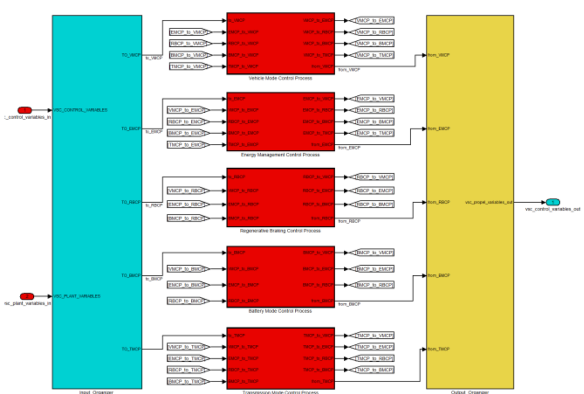


Figure 2. Supervisory control strategy architecture for DMHP.

Supervisory Controls Optimization

An equilibrium control policy was implemented in the supervisory controller of the heavy-duty DMHP. This powertrain configuration can operate both in a series and parallel mode. The series mode is intended for low vehicle speed profiles while the parallel mode is intended for highway driving. To demonstrate the potential benefits in fuel economy the vehicle was simulated in each mode separately.

In the series mode, the DMHP models with the baseline supervisory controller and with the one employing the equilibrium control policy were run over the same driving cycle for multiple times to achieve the same initial and final SOC, as illustrated in Figure 3. The model with the controller employing the equilibrium control policy exhibited a 5% improvement in fuel economy as shown in Figure 4.

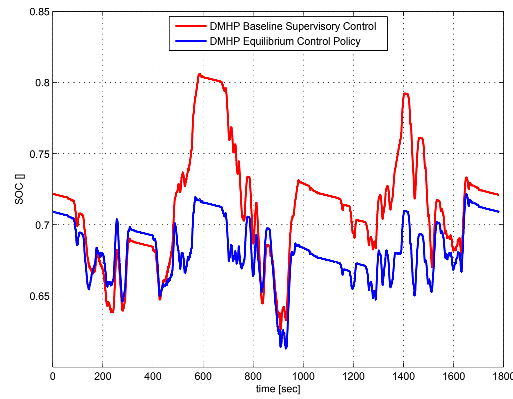


Figure 3. State of charge of the battery for DMHP in series mode with the baseline controller and the centralized controller employing the equilibrium control policy.

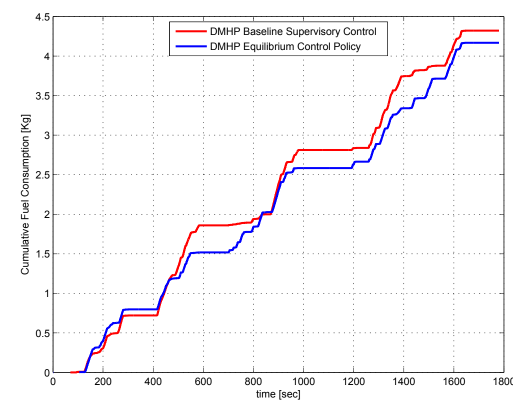


Figure 4. Cumulative fuel consumption for DMHP in series mode with the baseline controller and the centralized controller employing the equilibrium control policy.

In the parallel mode, the DMHP models were run over a highway driving cycle. Although, in this driving cycle, DMHP is at steady-state operation (visiting the same states), the system achieved a 1% fuel economy improvement with the supervisory controller using the equilibrium control policy. Figure 5 and Figure 6 show the SOC variation and cumulative fuel consumption.

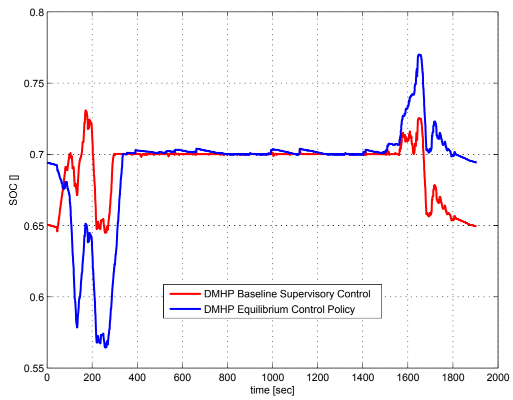


Figure 5. State of charge of the battery for DMHP in parallel mode with the baseline controller and the centralized controller employing the equilibrium control policy.

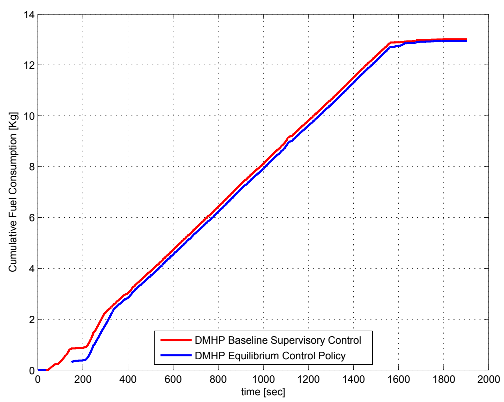


Figure 6. Cumulative fuel consumption for DMHP in parallel mode with the baseline controller and the centralized controller employing the equilibrium control policy.

Alternative Technology Analysis

The Autonomie model and corresponding supervisory control system was utilized as a basis for comparison to other advanced powertrain concepts for the Alternative Technology Analysis. Table 1 outlines the array of powertrains that were analyzed as part of this study. The purpose of this study was to better understand how the DMHP concept compares to both currently available and future powertrains in this vocation.

Table 1. Alternative Technology Analysis powertrain matrix

Case	Concept	ESS			Motor		Accessories & Operation
		Nominal Voltage	Approx. Capacity	Rationale	Size	Rationale	
1	Mild Parallel Pre-Transmission HEV	350 V	5 kWh, 150 kW	Min Regen. Energy Capacity	60 kW	Idle start/stop functionality & industry benchmark.	5.2/0.3 kW Mechanical/Electrical accessories, ENGINE ALWAYS ON.
2							1.0/3.0 kW Mechanical/Electrical accessories, ANTI-IDLE OPERATION.
3	Moderate Parallel Pre-Transmission HEV				130 kW	Max out battery regen power capacity.	5.2/0.3 kW Mechanical/Electrical accessories, ENGINE ALWAYS ON.
4							1.0/3.0 kW Mechanical/Electrical accessories, ANTI-IDLE OPERATION.
5	Mild Parallel Post Transmission (Alternative Design)	350 V	5 kWh, 150 kW	Min Regen. Energy Capacity	60 kW	Same as Mild Pre-Transmission Benchmark (case 1).	5.2/0.3 kW Mechanical/Electrical accessories, ENGINE ALWAYS ON.
6	Meritor Dual Mode, Gen 2.1	700 V	20 kWh, 400+ kW	Minimum Full Hotel Energy Capacity	360 kW	Vehicle performance requirements.	1.0/3.0 kW Mechanical/Electrical accessories ENGINE OFF & ANTI-IDLE OPERATION.
7	Meritor Dual Mode, Gen 3						
8			10 kWh, 300 kW	Cost Effective Hotel Energy Capacity			

Table 2 outlines the respective drive cycles that were used to exercise the models for the study. The matrix is comprised of standard cycles (CSHVR, HD-UDDS, HHDDT65) that represent urban and short haul over the road operation, and "real world" cycles derived from the ORNL Heavy Truck Duty Cycle (HTDC) database that represent regional and line haul on-highway operation. The "real world" cycles were derived from actual vehicles traversing local roads and interstate routes that include grade information. The inclusion of grade in the line haul simulations proved to be very important when considering the mass of these vehicles and the regenerative braking possibilities.

Table 2. Alternative Technology Analysis Drive Cycle Summary

Drive Cycle	Description	GCVW		
		FULL LOAD* 36,287 kg (80.0k lb)	HALF LOAD* 25,990 kg (57.3k lb)	OTHER
CSHVR	WVU transient (milder) City/Suburban Heavy Vehicle Route	X	X	
HD-UDDS	EPA Heavy Duty Urban Dynamometer Driving Schedule (aggressive, "Cycle D")	X	X	
HHDDT65	CARB Heavy Heavy Duty Diesel Truck, 5th Mode (~65 mph cruising)	X	X	
HDTC_NASHVILLE_ KNOXVILLE	ORNL "Real World" cycle. I40 Nashville to Knoxville long haul hilly route w/grade data.			35,411 kg (78,066 lb)
HDTC_STARKVILLE_ DANVILLE	ORNL "Real World" cycle. I65 Starkville to Danville long haul relatively flat route w/grade data.			33,884 kg (74,700 lb)

• "Empty" GCVW = 15,694 kg (34.6k lb). Max payload = 20,593 kg (45.4k lb = 80k - 34.6k lb).

The Meritor DMHP was compared to a host of currently available technology, dominated by pre-transmission parallel HEVs. As shown in Figure 7, the DMHP proved to be superior in terms of fuel economy improvement for urban cycles, however, this is due mainly to the high degree of hybridization of the DMHP compared to mild pre-transmission variants currently available. For "real world" line haul applications, the DMHP offered smaller, but significant, gains in fuel economy. In addition, it was observed that the alternative post-transmission parallel HEV was on par or slightly better (in "real world" simulations with no accessory electrification benefits) than its pre-transmission counterpart.

One of the most significant factors affecting the fuel economy of these heavy-duty vehicles is ability to capture kinetic energy through braking (regenerative braking). The DMHP has the ability to capture more energy due for two (2) reasons. The first simply is there is no significant number of transmission shifting events for the DMHP (none for urban operation).

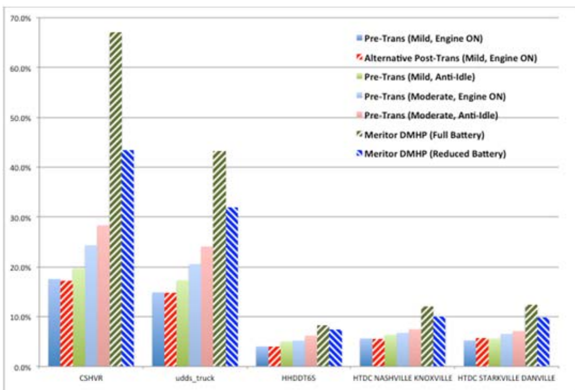


Figure 7. Economy improvement of DMHP compared to currently available technologies.

The regenerative braking capability of the pre-transmission HEV is frequently interrupted due to gear shifting, where the DMHP can smoothly absorb braking energy with no losses due to shifting. The second reason is that the powertrain is architected such that the speed of the electric machine is not confined to operate at lower speeds, thus having the ability to reach peak power more often. This is shown in Figure 8 where the regenerative braking capability of the pre-transmission variant is limited due to speed limitations imposed by the engine/transmission.

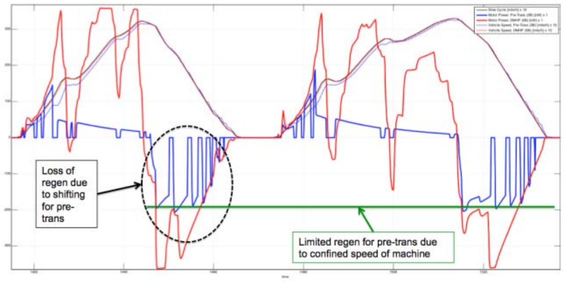


Figure 8. Regenerative braking comparison for DMHP and pre-transmission HEV.

Conclusions

The Meritor DMHP CRADA has progressed with the development of a robust powertrain model in Autonomie, as well as a structured supervisory control model. The baseline control laws were optimized for both series and parallel operation, with modest gains in simulated fuel economy achieved. Finally, an alternative technology analysis was performed to understand the benefits of the DMHP powertrain over currently available technologies. The simulation results indicate that the DMHP offers significant benefits over currently available technologies.

V.E.3. Products

Publications

1. Malikopoulos, A.A., The Meritor Dual Mode Hybrid Powertrain (DMHP): Opportunities and Potential for Systems Optimization (CRADA), DOE Hydrogen and Vehicle Technologies Program Annual Merit Review and Peer Evaluation, Washington D.C., May 15, 2012.
2. Malikopoulos, A.A., "The Meritor Dual Mode Hybrid Powertrain (DMHP): Optimal Control Algorithms," Annual presentation, September 2012.

V.F. Impact of Battery Management on Fuel Efficiency Validity

Principal Investigator: Eric Rask
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-3110; Email: erask@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

V.F.1. Abstract

Objective

- This work can be considered as a suite of different analyses — all revolving around issues related to net energy change (NEC) correction and its strengths/issues for use as a test procedure metric to ensure charge-corrected behavior. Issues for investigation include understanding generalized NEC versus fueling trends for both light-duty and medium-duty/heavy-duty (MD/HD) vehicles, improving battery behavior estimation to attain better energy calculations, and upgrading metrics for both test completion and battery "energy" definition.

Approach

- Leverage existing light-duty vehicle testing data to observe fuel consumption (FC) versus NEC trends for recently tested vehicles.
- Use high-fidelity battery information collected during vehicle testing to evaluate battery metrics and usage for robustness issues related to NEC trends.
- Perform simulations by using Autonomie to evaluate NEC trends for an MD/HD application.

Major Accomplishments

- Assessed several recent vehicles for FC versus NEC, and determined that current trends are similar to those observed previously.
- Performed a preliminary investigation of state of energy versus state of charge relative to the implications for vehicle testing and energy consumption estimation.
- Developed a correction factor for battery system voltage estimation during NEC calculation.
- Evaluated a wide range of MD/HD vehicles across a range of NEC values to assess the robustness of NEC correction for those types of vehicles.
- By using simulation results, adjusted the NEC procedure to better handle nonlinear FC versus NEC relationships.

Future Activities

- Continue data collection for state-of-the-art vehicles in terms of ensuring continued test procedure robustness.
- Conduct additional analysis and testing to evaluate these issues at hot and cold ambient temperatures to determine if sensitivities are greater.

V.F.2. Technical Discussion

Background

This work seeks to better understand sensitivities and robustness issues related to utilizing a fuel consumption (FC) versus net energy change (NEC) correction line to estimate charge-sustaining fuel consumption for a variety of hybrid vehicles. During charge-sustaining fuel economy testing, a vehicle may display both charge gaining and charge reducing operation. However, the most robust way to compare vehicles is to provide an energy-neutral consumption point that equates to no energy change in the battery relative to the powertrain. Figure 1 shows a basic NEC correction line. The green points represent the battery throughput and corresponding fuel consumption for a given test. While these tests may or may not be charge sustaining, a linear estimation of the zero NEC point can be created by using a least-squares regression. This point is illustrated in the Figure by the yellow star. While this type of correction has many positives, it is important to assess the limitations and challenges of these correction-based methods to understand their robustness and key issues leading to improved test validity.

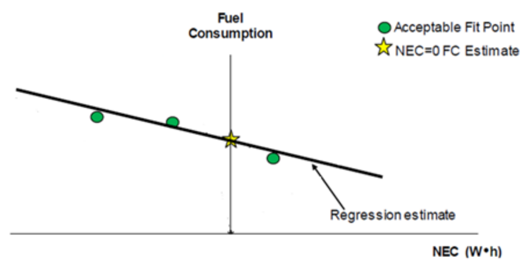


Figure 1. Example Net Energy Change Correction Line

Introduction

This work can be considered as a suite of different analyses — all revolving around issues related to NEC correction and its strengths/issues for use as a test procedure metric to ensure charge-corrected behavior. Issues for investigation include understanding generalized NEC versus fueling trends for both light-duty and medium-duty/heavy-duty (MD/HD) vehicles, improving battery behavior estimation to attain better energy calculations, and upgrading metrics for both test completion and battery "energy" definition.

Results

The following sections review some of the noteworthy findings related to this evaluation effort.

Evaluation of NEC Trends for Recent Vehicles

As discussed in the Introduction, recent vehicles have shown increased cycle-to-cycle NEC values. There are multiple reasons for this behavior. However, two of the major issues relate to increased electric vehicle (EV) operation/capability and larger battery packs, where SOC and NEC are harder to accurately track and retain the 1% of fuel energy tolerance. Figure 2 illustrates some of these issues for the Chevrolet Volt. This figure shows the fuel and energy consumption for a variety of drive cycles overlaid with the current 1% of fuel energy tolerances. As can be seen on the graph, several cycles fall outside the tolerance band, and even those within the band are near the edges.

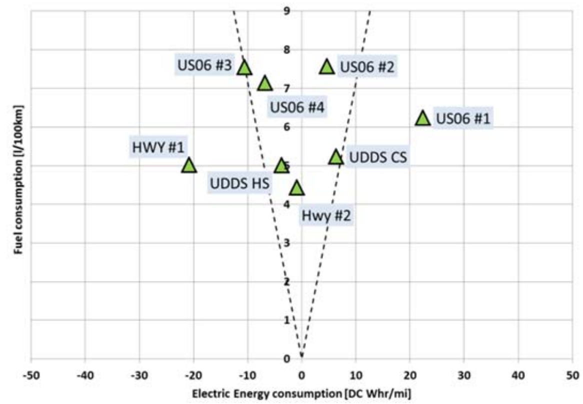


Figure 2. Chevrolet Volt Fuel Consumption versus Electric Energy Consumption

In order to evaluate the impact of NEC on fuel consumption for these more electrified vehicles, analysis was performed across a range of vehicles and drive cycles to investigate the "value" of battery energy. Figure 3 depicts some example results for the Toyota Prius, Hyundai Sonata, and Chevrolet Volt. From these data, the Urban Dynamometer Driving Schedule (UDDS) NEC tolerance can be calculated to correspond to roughly an 8% change in fuel consumption between the upper and lower boundaries of the tolerance band. Although some differences do exist, recent vehicles with more EV capability (Sonata and Volt) show fairly similar trends as compared to other vehicles tested.

Lastly, some additional issues and sensitivities that do not appear to be directly related to NEC can be observed for some of the Prius-based results. Two sets of results are highlighted in Figure 3, where the results are not as expected relative to the observed FC versus NEC trends.

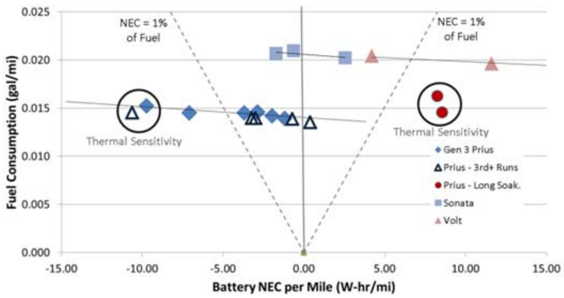


Figure 3. Fuel Consumption versus Net Energy Change for Selected Vehicles

These issues are of particular importance, since there is some discussion regarding a movement toward an NEC correction-based fuel economy certification that would allow for a scatter of operating points to be provided, as opposed to real-time testing. These sensitivities highlight some of these issues. In the case of Figure 3, the highlighted runs in red (right side) were soaked at ambient temperature for a slightly longer time compared to the previous tests, thus resulting in different vehicle behavior. The open triangles (left) are the third and later runs, which are slightly warmer as compared to the earlier runs and thus show slightly different behavior and FC versus NEC trends. Figure 4 shows the oil temperatures for the long soak and normal soak testing. Despite the very different fuel consumption and NEC values, the oil temperature does not indicate a significant departure in terms of operating temperature. Without the analysis of NEC trends, this behavior might have been missed, thereby resulting in the inclusion of incorrect data in an NEC correction regression.

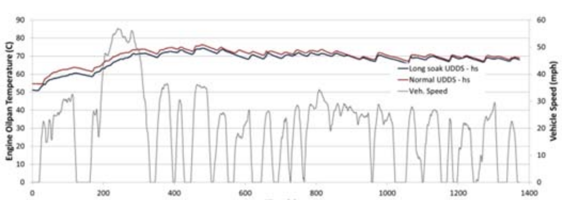


Figure 4. Engine Oil Temperature for Longer and Normal Soak Times.

Figure 5 shows the fueling rate for the two soak conditions during the initial portion of the UDDS cycle. The clearly different fueling rates indicate that the longer soak case has entered into warm-up operation, as evidenced by the steady fueling rate during the initial operating section. As would be expected, this behavior dramatically impacts both NEC and fuel consumption, thus mirroring the observed NEC trend issues.

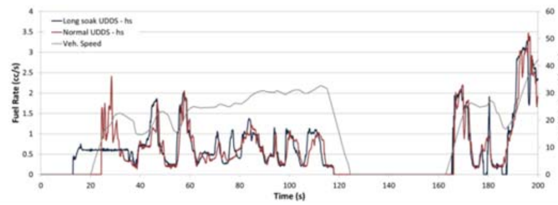


Figure 5. FFuel Rate for Longer and Normal Soak Times during the Initial UDDS Segment

While these differences may seem obvious, it is very important to understand the limitations of NEC-based trending and fuel consumption estimation. Since NEC trending will likely become an important part of hybrid vehicle fuel economy testing, these insights are valuable for improving the robustness of how vehicles are tested.

Investigation of State of Charge versus State of Energy

In a related piece of research, the differences between state of charge (SOC) and state of energy (SOE) were researched in relation to their importance to vehicle testing and EV/plug-in hybrid electric vehicle (PHEV) range and energy consumption determination. While SOC is frequently used to understand the energy removed from a battery pack, it is not necessarily the best signal for a particular situation. On a simplified level, SOC seeks to account for the current that has flowed into/out of the battery. While this value is important from a battery-centric perspective, the energy available from a battery may also be of importance. With this in mind, SOE seeks to estimate the energy remaining in the pack as opposed to the current. (Note: Some SOC algorithms in essence make these calculations, but they are not necessary the same thing.) Since energy is being used for SOE, the voltage at which current is used becomes an important part of the calculation. For example, the same amount of current removed from the battery will result in two different energy values, which may or may not be comprehended by SOC alone. Figure 6 depicts the battery terminal voltage for a series of back-to-back charge-depleting runs. From this figure, it is clear that the battery voltage is changing significantly over the course of the testing. This illustrates one occasion where energy information is useful to understand the energy available in the battery pack and to determine how much has been used.

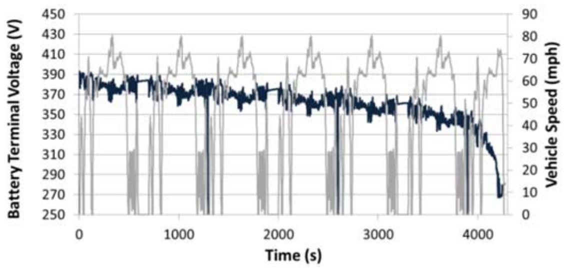


Figure 6. Battery Voltage during Back-to-Back Charge-Depleting Runs.

Figure 7 compares a simplified SOC versus SOE estimated for the previously shown depleting runs. While both quantities start and end with the same value, SOC and SOE begin to differ as more battery energy is used. This is logical because as more energy is removed from the battery, the open circuit voltage is lowered and thus more current is required for an equivalent amount of power. Once the battery is exhausted, energy and current again match. Figure 8 shows the ratio of SOE to SOC and, as discussed, they can be seen to increasingly differ as the battery is discharged. Moreover, there is a fairly significant difference once the battery is near its minimum capability.

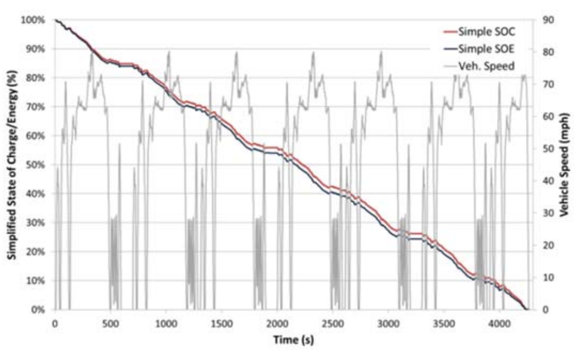


Figure 7. Simplified SOC versus Simplified SOE during US06 Operation.

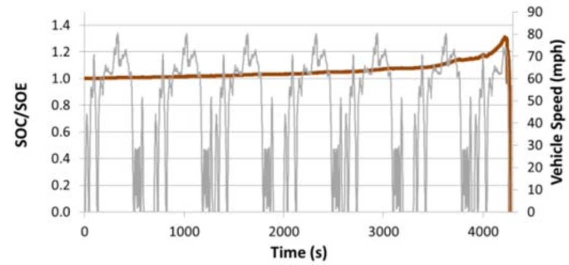


Figure 8. Comparison of Basic SOC to SOE Estimate.

This work does not seek to directly create an SOE algorithm. However, the aim is to understand these issues and how they relate to the validity of HEV/PHEV/BEV testing and analysis to improve the robustness of the testing procedures.

Correction Factor for Battery System Voltage Estimation

In another effort to better understand and correct issues relating to the robustness of NEC calculations, and thus vehicle energy economy calculations and procedures, a battery correction factor was investigated to assist in standards development robustness over a range of different battery chemistries and usage scenarios. As mentioned in the previous section, many original equipment manufacturers (OEMs) and regulatory agencies are looking into NEC correction-based charge-sustaining fuel consumption calculations. To ensure that these procedures are robust to a variety of vehicle usage scenarios, it is important to correctly calculate the battery energy used during a particular drive cycle. Equation 1 shows the basic form of the calculation for NEC. This quantity multiplies the total integrated current from the battery during a test by a "system" voltage to calculate NEC in terms of energy. As shown in Figure 6, voltage may change significantly over the course of battery depletion (and may show similar behavior for an 'off-on' charge-sustaining-type hybrid control strategy). With this issue in mind, a procedure was developed to estimate system voltage on a per-cycle basis to better comprehend changes in system voltage. The initial procedure to estimate system voltage was to simply average the beginning and end voltage of a particular cycle, but some issues arose with this technique.

$$\text{Net Energy Change} = \left((A \bullet h)_{final} - (A \bullet h)_{initial}\right) * V_{system}$$

Equation 2. Net Energy Change Calculation

The largest issue with the basic averaging method is that batteries may take significant time to "settle" following usage. This settling may skew the NEC calculations if not properly accounted for in the testing/procedure. Figure 9 shows this battery settling phenomenon. The battery voltage shown in green slowly reduces in voltage, even as the vehicle is at a standstill. Clearly, the voltage calculation will then depend on the time at which the measurement is taken and thus will result in a less robust NEC estimate.

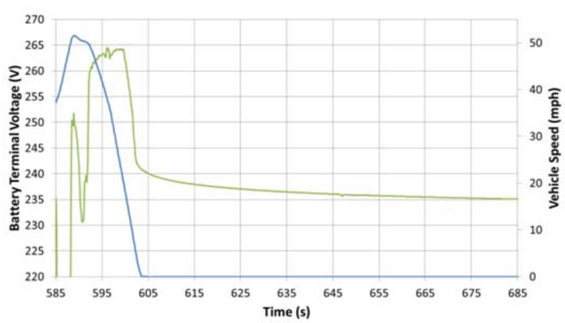


Figure 9. Battery Settling Observed during Vehicle Testing.

One solution to this problem is to simply wait for the settling to occur. However, this would be an extreme burden for vehicle testing that may require many back-to-back runs for NEC stabilization. Moreover, this settling time will vary between chemistries, so a robust solution is somewhat difficult. In order to solve these problems, a battery circuit model approach was developed that can be used to estimate system voltage for a particular run. The developed method utilizes the United States Advanced Battery Consortium (USABC) battery circuit model (shown in Figure 10) to create a parameter estimate for a given cycle, which then can be used as the system voltage in Equation 1. The developed method was shown to be much more robust, and it reduced the NEC calculation error by roughly 4% for a case using a Toyota Prius. Further, it is expected to return similar or better results for other vehicles and battery types.

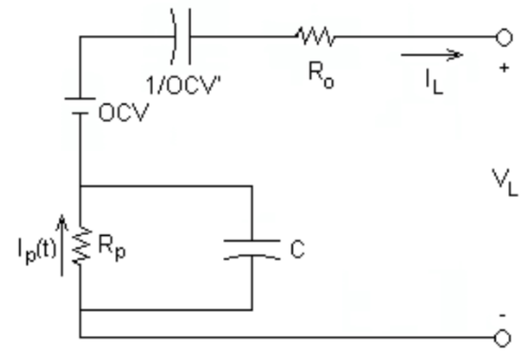


Figure 10. USABC Battery Circuit Model.

MD/HD Vehicle NEC Impact Simulation Study

As mentioned in the introduction, one of the major efforts of this work was to evaluate NEC trends for MD/HD vehicles. While a significant amount of real-world and testing data are available for light-duty vehicles, minimal data are available to evaluate NEC trends and issues for these larger vehicles. While it is expected that similar trends should apply, it is important to evaluate these vehicles, since they often will have much different degrees of hybridization and may also use a dramatically different control strategy relative to a light-duty hybrid. With these issues in mind, a simulation study was done in Autonomie to assess NEC-related fuel consumption trends for several classes of MD/HD vehicles. Figure 11 provides a simple illustration of the simulation test plan. Several classes of vehicles were simulated over multiple drive cycles with varying amounts of NEC. This information will allow the NEC trends to be evaluated for a variety of vehicle classes and drive cycles. Additionally, both diesel and gasoline engines were evaluated to observe if any differences occurred between the two engine types relative to NEC trends.

Figure 11. MD/HD Simulation Test Plan Overview.

Figure 12 shows some sample results from the simulation study. It can be seen that the NEC trend lines do appear to have a similar shape relative to the light-duty NEC trends.

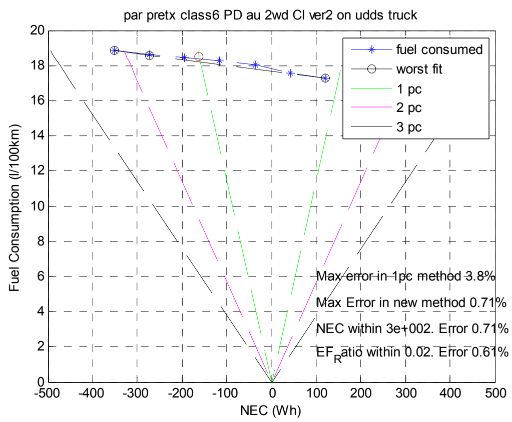


Figure 12. Example Simulation Results.

In addition to these basic NEC versus FC tests, some additional simulation runs were conducted. This effort included a nonlinearity in the overall control strategy that was used to test how robust a proposed NEC correction procedure was for MD/HD vehicles. More specifically, control boundaries were introduced to evaluate the procedures and to observe how far in error predictions might be if dramatic FC versus NEC behavior was estimated by using nonlinear trends. Figure 13 shows some example results from this section of the project. In this figure, the nonlinearities can clearly be observed for two of the selected cycles, whereas the other two tests are still fairly linear.

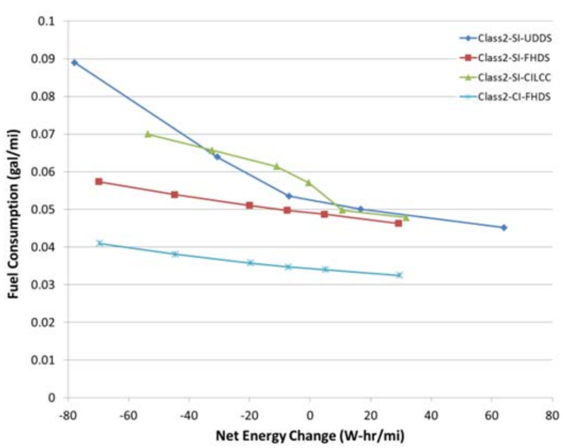


Figure 13. Class 2B Net Energy Change versus Fuel Consumption Results with Included Control Nonlinearity.

Figure 14 illustrates the worst-case possibility when using a linear NEC fit procedure with a nonlinear trend. Depending on the test points achieved during testing, the estimated trend may not comprehend the nonlinearities and thus over predict or under predict the actual behavior. In contrast, the red line in Figure 14 indicates more typical linear behavior. Table 1 displays some of the errors associated with this extreme evaluation case.

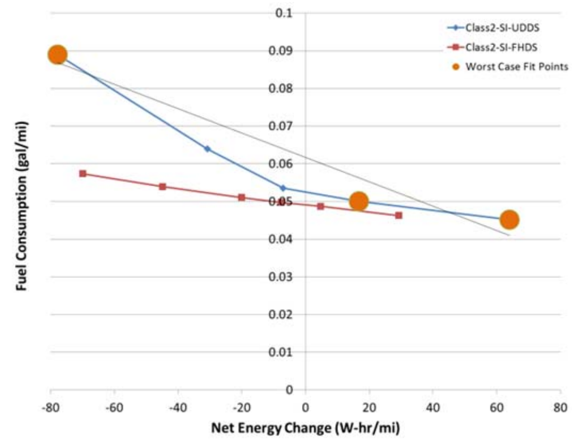


Figure 14. Worst Case and Standard Case Linear Fit Illustration.

Table 1. Summary of Worst-Case Errors for the Nonlinear Evaluation Case

Class 2b	Max Estimated Fuel Consumption Error
UDDS	18%
FHDS	-1%
CLICC	6%
Class 6	Max Estimated Fuel Consumption Error
UDDS	4%
FHDS	1%
CLICC	-1%

Conclusions

While the introduced nonlinearities are likely a worst-case and unlikely scenario, this work was insightful for revealing the degree of possible error associated with missing nonlinearities in the FC versus NEC trend. With these issues in mind, a new criterion was included to avoid these issues and thus improve the robustness of the test procedure. The new criterion adds a check to ensure that all (3+) points used to generate the fit line are within a certain percentage window. This new step minimizes the impact of nonlinearities and makes the test procedure much more robust.

V.F.3. Product

Publication

1. Multiple presentations were delivered to the SAE J2711 (MD/HD Vehicle Testing Standards) working group.

VI. CODES AND STANDARDS

VI.A. HEV, PHEV, EV Test Standard Development and Validation

Principal Investigator: Michael Duoba
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-6398; Email: mduoba@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

VI.A.1. Abstract

Objectives

- Provide guidance and develop and validate test procedures for the Society of Automotive Engineers (SAE) J1634 (battery electric vehicle [BEV] dynamometer test procedures).
- Serve on both the Hybrid Technical Standards Committee and the Light-Duty Vehicle Performance and Economy Measure Committee of the SAE.
- Provide U.S. representation for ISO TC22-SC21-WG2 (test procedures for electrified vehicles).
- Organize and run the SAE J2711 task force that is rewriting the medium-duty (MD) and heavy-duty (HD) vehicle dynamometer test procedures applicable to MD/HD hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and BEVs.

Approach

- Complete an analysis of the Nissan Leaf testing conducted at the end of last FY to validate the last revision of J1634 on the chassis dynamometer. Analyze a host of relevant details before SAE Committee balloting.
- Assist in developing new 4WD chassis dynamometer test procedures for worldwide adoption.
- Write the USA Annex for ISO 23274-1: "Hybrid-electric road vehicles — Exhaust emissions and fuel consumption measurements — Part 1: Non-externally chargeable vehicles."
- Run SAE J2711 meetings, and rewrite the draft for task force review.

Major Accomplishments

- The Nissan Leaf test results provided validation that the new J1634 "short-cut" testing procedures do indeed produce accurate results.
- A new J1634 testing sequence was devised to mitigate possible errors due to regenerative braking effects at the beginning of the test.
- The J1634 procedures were thoroughly vetted, and the equations were validated. The document was sent to ballot.
- The ISO 23274-1 was sent to ballot with the new USA Annex document.
- A new draft of J2711 was written and is under review by the task force members.

Future Activities

- The J2711 procedures will be rewritten after addressing comments received from the task force reviewers.
- The J2951 (dynamometer driver quality metrics) will be revised to include additional parameters.
- Now two years after publication, J1711 (HEV/PHEV test procedures) will undergo review. A decision will be made as to whether it should be revised. Special attention may be given for hot and cold test conditions (a new lab capability).

- Now two years after publication, J2841 (Utility Factor Analysis for PHEVs based upon 2001 U.S. Department of Transportation [DOT] data) also will undergo review. A decision will be made as to whether it should be updated and revised with the new 2008/2009 DOT data.

VI.A.2. Technical Discussion

Background

The SAE has been involved in standards development for almost 100 years. Vehicle technology is currently undergoing many radical changes. The U.S. Department of Energy (DOE) anticipates that these new technologies will provide pathways to achieve our current objectives to reduce petroleum usage in the transportation sector. In order to ensure that these new technologies do not stumble as they are introduced to the public, they must be properly and accurately evaluated by using robust analytical testing techniques. Argonne National Laboratory has been testing advanced vehicles for nearly two decades, and this expertise has been utilized to provide leadership and guidance for SAE committees involved in many vehicle testing areas.

Introduction

In 2006, Argonne staff was recognized by industry to be the best choice to chair the HEV/PHEV test procedure. Argonne staff, acting as objective arbiters impartial to specific technologies, used state-of-the-art testing facilities to help guide testing practices, especially for new and quickly advancing vehicle technology. Since the SAE J1711 Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles was completed, Argonne has continued its efforts to invent and test out new testing approaches for BEVs and heavy-duty vehicles. Argonne has provided input and test data for several other task forces and the ISO committees where critical advanced vehicle testing was involved.

Approach

Many of the existing testing programs at Argonne are heavily leveraged by the test-procedure development activity. The ongoing benchmarking effort through the Advanced Vehicle Testing Activity has allowed Argonne access to many advanced vehicles over the course of the last decade.

Argonne's vehicle researchers participate in regular task force meetings. They also take part in dedicated meetings with individual original equipment manufacturer (OEM) development engineers and testing staff, U.S. Environmental Protection Agency (EPA) testing staff, and California Air Resources Board (CARB) testing staff.

Results

1. BEV Test Procedure (SAE J1634)

The results from Argonne testing of the Nissan Leaf showed that a multi-cycle test does provide enough information to calculate the energy consumption and range for two or more types of cycles, all tested on the same day. The approach tested was:

1. Run two city cycles.
2. Run one highway cycle.
3. Run steady-speed cycle for *x* time or *y* miles.
4. Run one highway cycle.
5. Run two city cycles ending with less than 15% capacity (or range) left in the battery.
6. Run the steady-state cycle until the vehicle can no longer maintain the steady-speed target.

Analysis and further discussions led to a decision to change the test to:

1. Run one city cycle.
2. Run one highway cycle.
3. Run one city cycle.
4. Run steady-speed cycle for *x* time or *y* miles.
5. Run one city cycle.
6. Run one highway cycle.
7. Run one city cycle ending with less than 15% capacity (or range) left in the battery.
8. Run the steady-state cycle until the vehicle can no longer maintain the steady-speed target.

This revised test is now the final test configuration. It is arranged on a single time plot and shown in Figure 1:

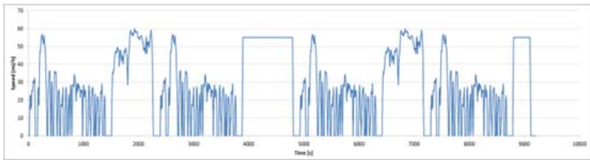


Figure 1. SAE J1634 Multi-Cycle Test Sequence

The effects of full charge initially limit regenerative ("regen") braking. The reordered procedure prevents the possibility of any residual regen limitation affecting the second city cycle in the sequence. The first cycle is weighted for first cycle effects, but the second cycle is assumed to be running without regen limitations. Also, the highway cycle is not much affected by regen limitations, so the reorder should be more robust in terms of matching the old procedure results.

After many months of meetings and fine-tuning the document, the revised J1634 was sent to ballot in June 2012. The final Motor Vehicle Council ballot should be finished in early October 2012.

2. U.S. Representation for ISO TC22-SC21-WG2

The work group ISO TC22-SC21-WG2 is responsible for test procedure standards for electrified vehicles. Over the past year, ISO 23274-1, entitled "Hybrid-electric road vehicles — Exhaust emissions and fuel consumption measurements — Part 1: Non-externally chargeable vehicles," has undergone revisions by the committee. The document is comprised of a general procedure with several annex documents that apply to the individual member countries. Argonne staff revised the USA Annex of ISO 23274-1 to reflect up-to-date methodologies utilized by Argonne, EPA, and CARB in testing HEVs. The revisions were well-received and included in the document for a May 2012 ballot.

3. Heavy-Duty/Medium- Duty Chassis Dynamometer Test Procedures (SAE J2711)

Argonne staff hosts regular meetings of the J2711 task force. Members include a diverse set of representatives from many truck manufacturers. The meetings cover a considerable amount of information regarding general hybrid testing concepts, since many of the task force experts are not experienced in hybrid powertrain designs. During the course of the meetings and discussions, several consensus decisions were made over the last year.

The procedure is applicable to the HEV and PHEV, but the BEV is still under consideration. The procedure is being written so as to be generic of drive cycle, to the extent that specific drive cycles are not within the recommendations.

In order to have more repeatable results while allowing for more operating strategy design flexibility, a consensus decision was reached to apply an energy correction procedure when calculating all charge-sustaining fuel consumption results. A minimum of three tests is required for energy corrections. Refer to Figure 2.

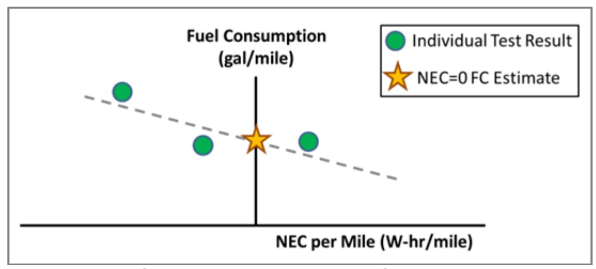


Figure 2. SAE J2711 Net Energy Change vs. Fuel Consumption Plot.

The results are to be given in gal/ton-mile or gal/1,000 ton-mile. Electric consumption will be in kWh/ton-mile or kWh/1000 ton-mile. Other features, such as "End of Test Criterion" and the several "Charge-Depleting Range" definitions, are carried over from J1711.

Conclusions

This FY is summarized by a ramping down of the BEV test procedure and a ramping up of others to meet the needs of updating outdated test procedures or developing new ones. The list of production PHEVs and BEVs is rapidly growing, and the new test procedures will meet the needs of regulators in the United States and throughout the world.

Argonne, under the auspices of the Vehicle Technologies Program at DOE, is uniquely positioned to conduct cutting-edge research on test procedure development. Argonne has a state-of-the-art testing facility, experienced staff, and working-level relationships with industry to discuss the science of the test measurements and development of the procedures outside of the regulatory arena. An objective of DOE is to properly evaluate new technologies that will reflect real-world petroleum and emissions savings. This approach — to maintain a center of excellence for test procedure development now and in the future — will provide robust support for this country's smooth transition to new and more efficient transportation technologies.

VI.A.3. Products

Publications

1. "Annex C" ISO 23274-1, "Hybrid-Electric Road Vehicles — Exhaust Emissions and Fuel Consumption Measurements — Part 1: Non-externally Chargeable Vehicles," written for the ISO work group (currently part of ISO 23274-1).
2. SAE J1634 "Battery Electric Vehicle Energy Consumption and Range Test Procedure," finished and sent to ballot (available from SAE International).
3. Duoba, M., "*Evaluating Plug-In Vehicles (PHEV & BEV) Using Standard Dynamometer Protocols*," 6th U.S.–China Electric Vehicles and Battery Technology Workshop, Boston, MA, August 22–24, 2012.
4. Duoba, M., "*Evaluating Plug-In Vehicles (Plug-in Hybrid and Battery Electric Vehicles) Using Standard Dynamometer Protocols*," 26^{th} International Electric Vehicle Symposium, Los Angeles, CA, May 6–9, 2012.
5. Duoba, M., "*Design of an On-Road PHEV Fuel Economy Testing Methodology with Built-In Utility Factor Distance Weighting*," SAE Congress, Detroit, MI, April 24–26, 2012.
6. Duoba, M., "*Test Results of Plug-In Electric Vehicles According to SAE Standard Testing Practices*," 2012 SAE Hybrid Vehicle Technology Symposium, San Diego, CA, February 22, 2012.
7. Duoba, M., "*Standards Update J1634 — Nissan Leaf Testing*," update to DOE, Washington, DC, November 17, 2012.

Tools & Data

Test procedure development is a data-intensive process. Large data sets are generated, and summary results are in need of analysis.

1. A large set of Nissan Leaf data was taken, analyzed, and distributed to J1634 task force representatives. Unlike the other sets of BEV data shared within the group, this set was not normalized or otherwise obfuscated to hide protected data or hardware. The vehicle was a production model purchased and owned by a partner supplier and tested at Argonne's Advanced Powertrain Research Facility. This allowed open and free discussions of the relative merits and limitations of the test options considered during the last stages of J1634 developement.
2. Several in-house tools were developed to calculate SAE J1634 summary results from the raw laboratory data. Some of these tools are executed at run-time. Others are post-processing code or spreadsheets that allow repeatable analysis and error-free communication of results across the many task force partners.

VI.B. Evaluation and Adaptation of 5-Cycle Fuel Economy Testing and Calculations for HEVs and PHEVs

Principal Investigator: Michael Duoba
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-6398; Email: mduoba@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

VI.B.1. Abstract

Objectives

- Investigate how new HEV and PHEV operation fits into the structure of EPA's new "5-Cycle" adjustments.
- Quantify errors due to segmentation of test cycles for "5-Cycle" implementation with and without corrections for charge-balance.
- Identify what types of PHEV operation and what test cycles are most troublesome with "5-Cycle" compatibility.
- Provide guidance to assessment researchers who want to determine "on-road" fuel and energy consumption of future modeled HEVs and PHEVs.

Approach

- Test Gen 3 Prius on chassis dynamometer on various test cycles and test cycle segments.
- Because the "5-Cycle" equations require input from test cycle phases, calculate errors by using phase segments with and without correcting for battery state-of-charge.
- For PHEVs, look at existing data from dynamometer and fleet testing with knowledge of control strategies to determine the response of varying PHEV designs on increased aggressiveness, hot temperature operation (with (A/C), and cold temperatures (with heating).
- Compare "5-Cycle" and "2-Cycle" adjustments for electric-only operation by using dynamometer data.

Major Accomplishments

- Repeatedly tested UDDS, Highway, and US06 cycles and their individual phases to find charge-balanced results for both the cycles and their individual phases.
- Applied the "5-Cycle" equations to electric-only operation and compared the results to the EPA "30% Rule" simplified approach.
- Defined a prescribed approach for assessment researchers to adjust modeled PHEV and BEV consumption rates to reflect real-world usage based upon direction from the 5-Cycle equations.

Future Activities

- Finish testing the Volt to further investigate "5-Cycle" equation robustness for electric operation.
- Test the Toyota Prius "PHV" and the Ford C-Max "Energi" blended plug-in hybrids to answer key questions about the fractional amounts of electric compared to gasoline when adjusting blended test results for PHEVs.
- Collaborate with other national laboratories collecting in-field data to find if either 5-Cycle, 2-Cycle, or a more simplified approach provides on-road prediction of fuel and electric energy consumption.

VI.B.2. Technical Discussion

Background

Since the mid-1970s, the U.S. Environmental Protection Agency (EPA) has tested passenger vehicles to verify compliance with emissions regulations and assign fuel economy ratings. The testing methods consist of driving vehicles on a chassis dynamometer through prescribed drive cycles, which are traces of velocity vs. time. The Federal Test Procedure (FTP) is based upon a city drive cycle called the Urban Driving Dynamometer Cycle (UDDS). This cycle and the federal highway cycle have been the benchmarks for vehicle testing and vehicle simulation studies for decades. EPA has employed adjustment factors to represent additional fuel use to do more aggressive driving and incorporate other real-world parameters, such as hot and cold weather driving. Before 2008, the adjustment factors were static percentage factors that reduce the MPG results: 10% for City and 22% for the highway.

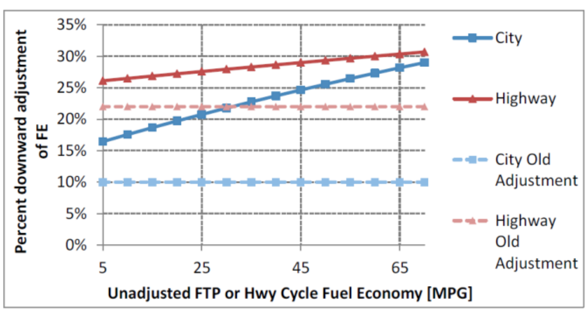


Figure 1. Post-2008 "2-Cycle" Adjustments Compared to Pre-2008 Adjustments.

Starting in model year 2008, EPA began applying a revised adjustment that is expected to be more accurate than the old adjustment method. The new adjustment has two approaches, both of which attempt to find similar results. The first method relies on the same two cycles ("2-Cycle" method) used in the old adjustment, but it is not a static factor — it is an equation valid from 5 to 80 MPG (see Figure 1 for adjustment comparison).

Phased-in from 2008 to 2012 is a more complex adjustment that employs other cycles that finds extra fuel usage due to "real-world" effects in the SC03 test (A/C usage on hot summer day), US06 (aggressive driving), and Cold FTP (cold-weather losses). By drawing upon data from five cycles, a more accurate characterization of each specific vehicle can be found. This "5-Cycle" method was derived by using conventional vehicles. Its application to HEVs and PHEVs is complicated by the changes in battery energy that were not fully considered in the development of the equations.

Approach

The "5-Cycle" equations are very complex and convoluted. Figure 2 simplifies them by showing the constituent parts that make up the city and highway "5-Cycle" fuel economy calculations. The various phases of the five different tests have a different level of contribution to the total amount.

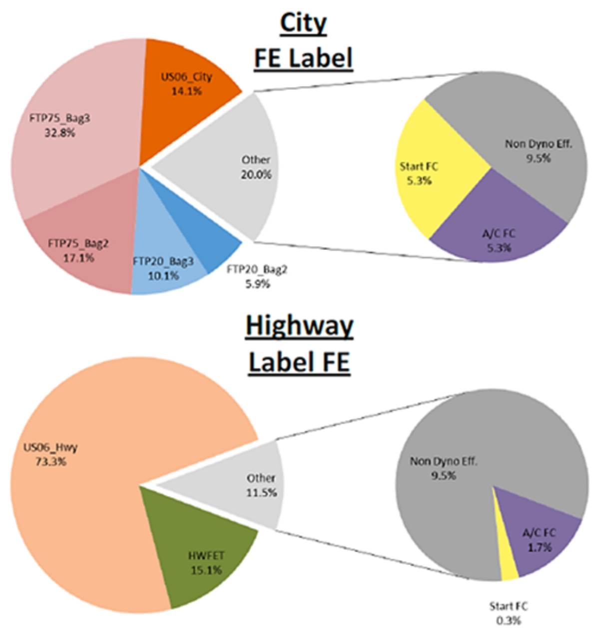


Figure 2. Post-2008 "5-Cycle" Adjustment Equations Analyzed for their Constituent Parts.

Approach for HEVs

This study examines the incompatibility problem between charge-balance and individual phase weighting. A 2010 Prius was used to investigate the magnitude of the issue.

The issue for HEVs is that although test results are charge-balanced for the entire test cycle, the individual phases are not, and this may cause overall errors in the final result.

Ever since the first issue of SAE J1711 in 1999, it is common practice to accept an HEV test result if the net change in battery energy was less than 1% of the fuel consumed in the test. However, if cycle results fall outside the 1% window, or if more accuracy within the 1% was desired, the practice of "State-of-Charge (SOC) Corrections" can be employed. Figure 3 illustrates the process for finding the charge-balanced fuel consumption result on the basis of several results that are not change-balanced. Several test results are needed for a robust correlation line that defines the "NEC=0" result.

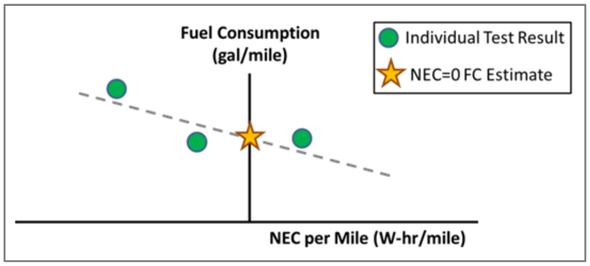


Figure 3. Graphical Depiction of Charge-Balance on a Plot of Fuel Consumption versus Net Energy Change (NEC).

Approach for PHEVs

The current approach for determining "5-Cycle" results for PHEVs is to use the HEV approach for charge-depleting behavior and the "2-Cycle" equations for charge-depleting behavior. The "2-Cycle" equations are used for electricity by converting Wh into gallons of gasoline (MPG-equivalent). However, the adjustments are capped at 30%, which is the highest MPG vehicle to which the equations have ever been applied. This study will look at electric-only charge-depleting operation encountered in PHEVs, like the Chevy Volt, to see if the "2-Cycle" approach is adequate.

For PHEVs that blend engine and electric propulsion during charge-depleting operation, the application of an adjustment may be the most challenging. The extra energy may come from the battery or fuel, thus making "2-Cycle predictions uncertain.

This study will investigate the "2-Cycle" and "5-Cycle" approaches for PHEV adjustment by using data from several vehicles.

Results

Results for HEVs

A full set of "5-Cycle" results for the 2010 Prius was not available at the time this analysis was written. This section will focus on the primary phases in the "5-Cycle" equations (UDDS, HWY, and US06) with the 2010 Prius.

The primary problem for HEVs is that whereas an entire test cycle may result in charge-balanced operation, the individual phases are certainly not. "5-Cycle" results will be made up of charge-imbalanced phase results. The magnitude of the imbalanced phases was investigated with a 2010 Prius. Charge-balanced US06, hot-start UDDS, and cold-start UDDS cycle results are shown in Figure 4. Note that the federal highway cycle does not have separate phases and is usually charge-balanced during testing.

As expected, the US06 phases are seen with the highest fuel consumption. Battery charge is taken out of the highway phase but returned during the city portions of the US06. The level of charge-imbalance in the city portion is just beyond 5% of fuel energy — a significant departure from charge-balanced operation. Data taken from phase 2 of the hot-start UDDS are even further from charge-balanced operation.

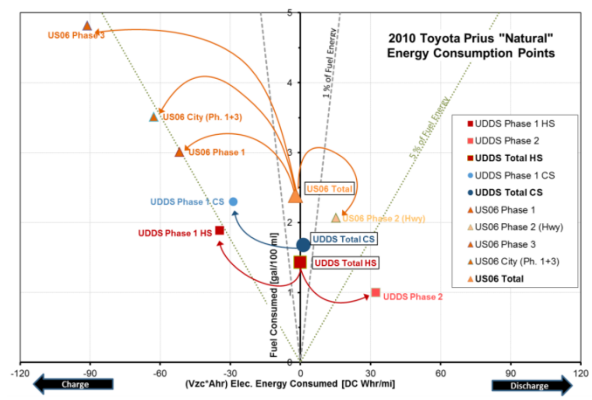


Figure 4. Location of Individual Cycle Phases on SOC-Correction Plot from Charge-Balanced Cycles.

The objective in the first set of experimental testing was to find individual charge-balanced phases. To do this, the vehicle was purposely started with SOC levels that were higher or lower than what would be encountered in normal testing (which usually includes running a prep cycle before the actual measured test cycle). Some amount of experimentation was required to find the right initial SOC to achieve the desired charge-balanced performance for each of the various individual phases. The results of all the test phases are shown in Figure 5.

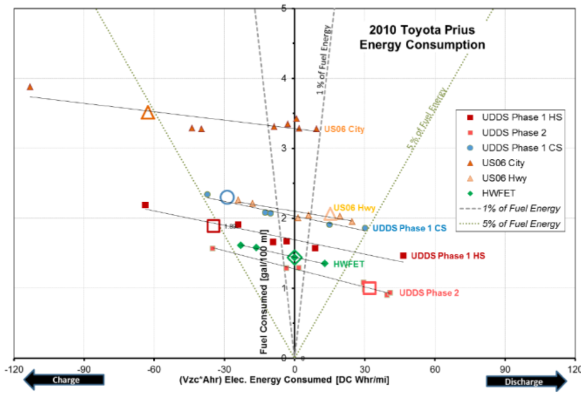


Figure 5. Individual Phase Results on SOC Correction Plot.

Although we do have results that are within the 1% window depicted on the SOC Correction plot, the most robust results come from correcting back to zero change in SOC. The results of the correction are shown in Table 1. Also shown in Table 1 are the degrees of error associated with using imbalanced phases compared to SOC-corrected results. The UDDS phases show considerable differences. The US06 cycle phases are also problematic. However, the highway phase of the US06 is heavily weighted in the "5-Cycle" equations (73.3%) but in the case of the 2010 Prius, error is a low -1%. The US06 city phase has a significant error (7%), but carries a reasonably low "5-Cycle" weight (14.1%), which therefore mitigates overall errors.

Table 1. SOC-Corrected Individual Phase Results

Cycle	Raw Slope [gal/100 mi per Wh/mi]	Inverse Unitless Slope [Elec Energy / Fuel Energy]	Intercept [gal/100 mi]	*Corrected* Phase MPG	Phase MPG of CS cycle	% Error from CS FC
UDDS Phase 1 Hot Start (HS)	-0.00687	-0.436	1.69	59.1	53.1	11%
UDDS Phase 2	-0.00858	-0.349	1.28	78.3	100.1	-22%
UDDS Phase 1 Cold Start (CS)	-0.00694	-0.431	2.03	49.2	43.5	13%
US06 City	-0.00399	-0.751	3.28	30.5	28.5	7%
US06 Hwy	-0.00660	-0.454	2.08	48.1	48.4	-1%
HWFET	-0.00743	-0.403	1.45	69.2	69.4	0%

Results for PHEVs

A full set of "5-Cycle" results was not available for the Chevy Volt; however, similar conclusions can be drawn for electric-only performance of a BEV. The full "5-Cycle" results of the Nissan Leaf will provide the trends required for studying charge-depleting operation for a PHEV with electric-only capability.

The Nissan Leaf was tested according to all five cycles. The results of all the tests are shown in Figure 6. As mentioned earlier, the proposed method for adjusting charge-depleting electric-only operation (for PHEVs and BEVs) is to use the "2-Cycle" method. Both the "2-Cycle" and the "5-Cycle" approach are also shown in Figure 6.

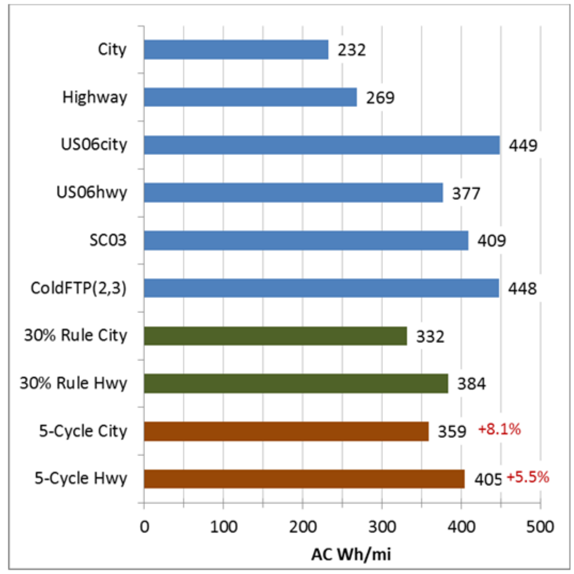


Figure 6. All-Electric Operation (Nissan Leaf) Adjusted by Using Both "30% Rule" ("2-Cycle" for MPGe>80) and "5-Cycle" Methods.

To better make observations of the electric-only results, conventional vehicle results (2004 Ford Focus) are shown in Figure 7 in the same fashion, except in units of gasoline consumption (gallons/mi).

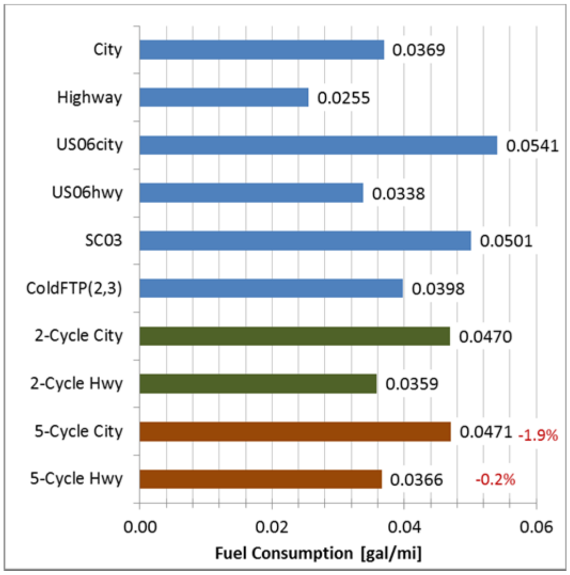


Figure 7. Conventional Vehicle (2004 Ford Focus) Adjusted Using Both "2-Cycle" and "5-Cycle" Methods.

Anyone who has spent time looking at the label fuel economy for conventional vehicles has made the observation that the city fuel consumption is higher than the highway fuel consumption (city MPG lower than highway MPG). One may immediately notice that for the electric-only consumption data, this disparity is reversed. The highway consumption is higher, but the gap between city and highway is perhaps not as pronounced. This trend is acknowledged in the new PHEV labeling, where only a single combined city and highway result is shown in an effort to reduce the overwhelming amount of information on the label.

Another important observation is made when considering high and cold operation. Whereas the conventional vehicle's SC03 result is only 35% higher than the city fuel consumption, the Leaf's electric-only SC03 consumption is 76% higher.

Cabin heating in a conventional vehicle utilizes free waste energy, but for electric-only operation, all of that energy comes from the battery. The consumption penalty of the Focus between the cold phases of the UDDS is only 8%, whereas for the Leaf, the consumption penalty is 92% higher.

Although the weights for the hot and cold operation are relatively small, the added consumption for the Leaf was considerable. The overall effect is that the "30% Rule" (the "2-Cycle" equations clipped at 30%) may not fully represent in-use operation in the manner that it was intended. The "5-Cycle" calculations for both city and highway of the conventional vehicle are within 2% of the "2-Cycle" calculations. However, the results of Leaf electric-only "5-Cycle" operation are 8.1% and 5.5% higher than those of the city and highway "2-Cycle" operation, respectively.

Results for Blended-Type PHEVs

Full "5-Cycle" results from a 2013 Toyota Prius are forthcoming. However, some preliminary testing and old testing and analysis of a converted Gen 2 Prius hybrid conducted a few years ago can be useful here.

For some studies, only a "2-Cycle" adjustment is possible; for example, simulations of various vehicle technologies currently do include off-temperature effects and HVAC loads. Some errors are shown in the previous section; however, for blended-type PHEVs, the fuel consumption uncertainty could be extremely high without some robust assumptions to guide the adjustment method.

Whereas we found uncertainty in the "30% Rule" adaptation of the "2-Cycle" method, consider Figure 8, which illustrates the two-dimensional uncertainty of blended PHEV charge-depleting adjustments. The green point on the "Fuel Consumption" axis represents the unadjusted charge-sustaining result. By means of "2-Cycle" or "5-Cycle" methods, assume that we find an adjusted point 33% higher. We would expect that the charge-depleting result will roughly fall in a parallel line of possibilities above the unadjusted line. However, the added energy for all of the adjusted ("off-cycle") effects have unknown origins. The additional energy could come entirely from the engine and fuel, in which case the adjusted depleting result is located at "A" (in Figure 8). Or, perhaps, all of the energy comes from the battery, in which case the adjustment is located at "C." Note that the different assumptions taken amount to an uncertainty as high as 300%.

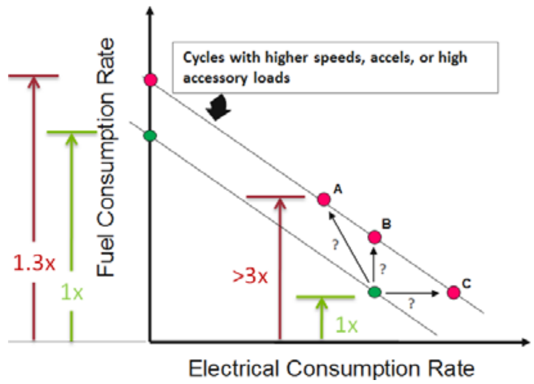


Figure 8. Uncertainty in Location of Adjusted Charge-Depleting Results for a Blended-Type PHEV.

Early in FY 2013, Argonne will have some comprehensive data from both the Toyota Prius "PHV" and Ford C-Max "Energi." These blended PHEVs bookend the blended PHEV space between the limited electric- operation Prius and the C-Max, which has higher power and is capable of higher-speed electric propulsion than the Prius.

For this study, we used earlier results from a study jointly done by Argonne and Idaho National Laboratories and preliminary 2013 Prius PHEV results. Figure 9 shows both dynamometer cycles and individual in-use driving trips from a Gen 2 Prius in the 2-dimensional space showing fuel versus electric consumption.

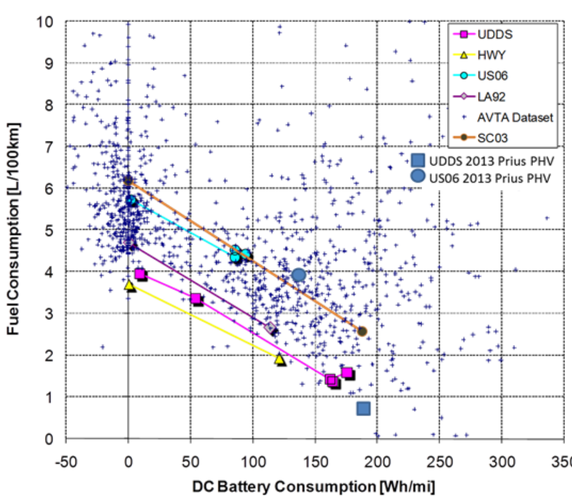


Figure 9. Two-Dimensional Plot of Fuel and Electricity Consumption for Cycles and In-Use Trips for a Gen 2 Prius Converted to PHEV Operation.

The data in Figure 9 show that more aggressive driving is biased toward additional fuel consumption, in comparison to added electricity consumption (both the US06 and the LA92 are aggressive cycles). High speeds and loads encountered in the US06 are mostly satisfied by the engine because the vehicle has limited electric capability. The electric capability is higher for the 2013 Prius "PHV," and preliminary data show that under the UDDS cycle, fuel consumption is lower and electricity consumption is higher. However, this added electric capability also contributes to a US06 result that is only slightly less up and over in the 2-dimensional space. Both vehicles show that US06 limited electric power and higher speeds move the adjustment point closer to point "A" in Figure 8.

Whereas higher loads and higher speeds push adjustment data points toward point "A," higher electric loads at similar speeds should vector toward point "C." Given that A/C in PHEVs will be powered electrically, this explains the SC03 results between "B" and "C." What remains to be seen is how blended PHEVs will handle cold operation. If, for example, the engine will be kept off and the battery is the source of heating, then the adjustment approaches point "C." If engine operation is higher, then the adjustment point moves closer to "B."

Conclusions

The "5-Cycle" equations were originally developed for conventional vehicles, and the analysis shows that there are limitations in their application for HEVs, PHEVs, and BEVs.

The study looked at individual HEV test phases to determine the extent to which the results could become out of balance. The results show that up to 20% error is possible. More data in the future of HEVs will provide a better look at the additional issues with hot and cold test phases.

For electric-only PHEV operation, a good set of data was analyzed to evaluate the validity of the "2-Cycle" approach compared to a full "5-Cycle" analysis. In labeling PHEVs, the effects of city versus highway and hot or cold versus ambient are all combined. This hides perhaps the most interesting trends for these new vehicles: (1) the fact that relative city-to-highway fuel consumption rates are reversed compared to those of conventional vehicles and (2) that cold and hot are the most significant factors to consider when predicting consumption rates. Perhaps this finding suggests that in order to properly convey consumption rates (or electric-only range), separate information for city and highway operation is not as necessary as comparing the hot and/or cold consumption rates with "ambient" temperature operation.

Making adjustments for blended PHEV operation is the most challenging task in analyzing the performance of advanced vehicles. The dynamics among maximum electric propulsion, cycle speeds, and HVAC loads are unpredictable.

On the basis of the trends observed from many tests, the preliminary conclusion is that if a researcher wants to make a "2-Cycle" adjustment in PHEV operation, the safest trend in the 2-dimensional space (depicted in Figure 8) is point "B." For the Prius, this projected outcome might not be fully accurate, but given what we know about the performance of the Ford C-Max "Energi," it is more likely that the US06 point will fall closer to point "B" because of the Ford's additional electric capacity.

VI.B.3. Product

Publication

1. Meyer, M., "*Understanding the Challenges in HEV 5-Cycle Fuel Economy Calculations Based on Dynamometer Test Data*," MS Thesis, Virginia Polytechnic Institute and State University, November 2011.

VI.C. International Cooperation

Principal Investigator: Keith Hardy
Argonne National Laboratory
9700 South Cass Avenue
Building 362, Office B-233
Argonne, IL 60439
Phone: (630) 816-7383; Email: khardy@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VI.C.1. Abstract

Objective

- Facilitate international cooperation to support harmonization of vehicle-grid interface standards and policy initiatives of the U.S. Government (USG) related to e-mobility.

Approach

- Identify opportunities for mutually beneficial cooperation with government and industry in Europe and Asia.
- Leverage activities of the DOE Vehicle Technologies (VT) Program as a basis for cooperation regarding:
  - Enabling technologies and standards development/verification related to electric vehicle (EV)-grid connectivity; 'EVs' includes battery electric and plug-in hybrid vehicles.
  - Information from the vehicle/infrastructure learning demonstration program.
- Implement activities within the framework of the following USG policy initiatives:
  - Work plan for advancing transatlantic e-mobility cooperation.
  - U.S.–German cooperation on e-mobility.
  - U.S.–China EV Initiative.

Major Accomplishments

- Reached an agreement between DOE and the European Commission to establish EV-Smart Grid Interoperability Centers at Argonne National Laboratory (Argonne) and the Joint Research Centre–Institute for Energy and Transport (JRC-IET) in Italy and the Netherlands.
- Developed successful proposals to participate in the German federal government's e-mobility showcase program.

Future Activities

- Coordinate the capabilities and projects of the EV-Smart Grid Interoperability Centers at Argonne and JRC-IET.
- Leverage Argonne's grid connectivity activity to support joint projects in Germany (Berlin and Baden-Württemberg) and Sweden (Gothenburg and Stockholm).
- Collaborate with European Commission regarding EV-grid connectivity and related smart city initiatives.
- Identify potential site(s) for an EV-Smart Grid Interoperability Center in China.

VI.C.2. Technical Discussion

Background

The International Cooperation task was initiated in 2009 to promote the introduction of EVs in the U.S. by identifying opportunities for cooperation in Europe and Asia that would address common barriers and benefit global automotive manufacturers and suppliers. The primary technical objectives are harmonized global standards and compatible/interoperable components for the EV-grid interface.

Initially focused on bilateral technology demonstration projects in Europe, the activity expanded to the European Commission in FY 2011, culminating in an agreement by the Transatlantic Economic Council on the "Work Plan for Advancing Transatlantic E-mobility Cooperation." The plan is aligned with DOE's objectives and Argonne's technical activities, that is, joint standardization and research initiatives related to e-mobility (smart grid communication methods, e-mobility pilot projects, and EV–smart grid interoperability).

Germany is the focal point for bilateral cooperation on e-mobility in Europe as established in the agreement between President Obama and Chancellor Merkel in FY 2011.

China is the focal point in Asia as established in the U.S.–China EV Initiative, an agreement between Presidents Obama and Hu in FY 2010.

Approach

The expertise and products produced through the DOE's VT Program are leveraged to support efforts to harmonize standards and minimize trade barriers as a means to accelerate global EV production and deployment. Examples include the following:

- Comparative analysis of demonstration projects in the U.S. and Europe will provide insight into customer expectations regarding EVs and the charging infrastructure (i.e., through DOE's EV Project and the European Commission's Green eMotion program).
- European versions of compact metrology and communication modules will be used in joint technology demonstration projects to evaluate, refine, and verify potential global EV standards.

Technical cooperation alone is not sufficient to establish and reinforce global alignment of standards and/or component compatibility across borders. Therefore, this activity is coordinated with USG diplomatic organizations that have the responsibility and experience required to facilitate interactions between key shareholders and/or decision-makers outside of the U.S.. In particular, DOE Policy & International Affairs, DOE representatives to the EU–U.S. Energy Council and the coordinators of the Transatlantic Economic Council (TEC) are briefed regularly. Interactions with the European Commission and EU member states are coordinated with, and often facilitated by, the U.S. Mission to the EU (in Brussels) and U.S. Commercial Service trade professionals in U.S. embassies (e.g., Berlin).

Through the utilization of similar diplomatic strategies and approaches, the USG supports the U.S.-China EV Initiative and cooperates with organizations supporting the EV development and standardization process in China (i.e., China Automotive Technology and Research Center [CATARC], China Automotive Engineering Research Institute [CAERI], Tsinghua University, etc.).

Results

Interoperability Centers in the United States and the EU

A major accomplishment in FY 2012 was the agreement reached between DOE and the European Commission establishing Argonne and JRC-IET as EV-Smart Grid Interoperability Centers to promote harmonization of standards and EV-grid connectivity (Figure 1).

In support of the harmonization objective, the centers will also address common test procedures and protocols for evaluating vehicles, batteries, and EV-grid compatibility/interoperability.

Initial funding has been allocated by the JRC to fabricate, equip, and staff the center in Italy that is expected to be initially operational in mid-2013.

Argonne's interoperability center will be fully operational in by the end of 2012. Development and/or verification of grid connectivity standards and enabling technologies have been ongoing for several years by utilizing experienced technical staff and the embedded controls/network lab. DOE allocated additional funds to equip adjacent high bay space, enabling vehicle-level development and testing with shared equipment and staff. The space has high-power electric service and a vehicle lift; a vehicle-sized radio frequency (RF) chamber for electromagnetic compatibility (EMC) testing is being installed. The space will also house the wireless charging test fixture currently being designed by Argonne.

Figure 1. Signing ceremony establishing the EV-Smart Grid Interoperability Centers at the Transatlantic Economic Council meeting in November 2011 (photo courtesy of the U.S. State Department). Seated: DOE Asst. Secretary David Sandalow (left) and Director-General of the JRC Dominique Ristori (right). Standing, left to right: European Commissioner for Energy Günther Oettinger, European Commissioner for Trade Karel De Gucht, and U.S. Deputy Asst. to the President and Deputy National Security Advisor for International Affairs Michael Froman.

Cooperation with Germany

In 2011, the German federal government announced a funding opportunity for e-mobility showcase projects to be awarded to several states. Project teams were expected to include automotive original equipment manufacturers (OEMs), suppliers, and utilities, among other participants, as well as international partners.

A well-timed speaking tour of Germany by the project PI (arranged by the U.S. State Department) resulted in requests from various hosts that Argonne researchers join several proposal teams; of particular interest was Argonne's experience with EV-grid connectivity standards and enabling technologies (e.g., compact metrology and communication). Because the projects directly support DOE objectives and the stated intent of U.S. and German OEMs to harmonize the charge coupler and communication methods, Argonne researchers agreed to participate. For the proposed work, the metrology and communication modules would be modified for the different voltage (3Ø, 200 VAC) and packaging standards (DIN [Deutsches Institut für Normung eV, the German Institute for Standardization] format). System integration with the OEMs and utilities would enable two-way communication between EVs and the charging infrastructure in a realistic local environment. The states of Berlin and Baden-Württemberg (Stuttgart) received awards, and project details will be determined in early FY 2013.

Cooperation with China

The vehicle roundtable of the U.S.-China Bilateral meeting, which took place in the summer of 2011, resulted in recommended actions in three topic areas:

- Shared technical information and experience from EV/infrastructure demonstrations.
- Harmonized global codes and standards (vehicles, connectors, and communication).
- Common vehicle benchmarking, evaluation, and test procedures.

Idaho National Laboratory (INL), the data manager for DOE's nationwide EV Project, had previously provided data collection parameters for EVs and electric vehicle supply equipment (EVSE) at U.S. sites. Presentations by Chinese participants during the 2011 bilateral meeting indicated that the data collection was being aligned accordingly, although EV demonstrations in China had focused on fleets (i.e., buses and taxis). The 2012 meeting showed some progress in private EVs (e.g., development of facilities to promote public exposure); however, the numbers are not statistically significant, and direct comparison to the U.S. program is not warranted at this time.

The National Institute of Standards and Technology (NIST) took the action to map U.S. and Chinese standards related to EVs and grid connectivity. Meetings were held with key organizations (e.g., CATARC) supporting the development of standards in China, and a draft standards cross-reference was developed in late 2011. The significant result of the 2012 meeting was the recommendation to explore the possibility of establishing an interoperability center in China to complement those in the U.S. and Europe. This center could be a catalyst for more meaningful cooperation on standards development and will be the subject of meetings in China in late 2012.

With respect to vehicle test procedures, Argonne (responsible for laboratory testing) and INL (responsible for field testing) have previously discussed procedures, data parameters, and the analytical process with CATARC and CAERI. Another significant result of the 2012 meeting was that plans were put in place for the test labs in the U.S. and China to conduct a portfolio of tests with the same EV to confirm compatible testing and analysis procedures.

Conclusions

Argonne has established working relationships and has facilitated cooperative activities that support the objectives of both the DOE and U.S. Government for global cooperation.

EV-Smart Grid Interoperability Centers should directly support harmonized standards and facilitate vehicle-grid compatibility — with the potential to shorten the standardization process and aid the deployment of EVs. Establishment of a center in China, and possibly in other Asian locations, should be considered.

Bilateral activities with industry and government (e.g., in Germany) reinforce harmonization efforts and present the opportunity to form working-level relationships that support long-term cooperation.

VI.C.3. Products

Publications - None.

Patents - None.

Tools & Data - None.

VI.D. Green Racing Initiative

Principal Investigator: Forrest Jehlik
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-6403; Email: fjehlik@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

VI.D.1. Abstract

Objective

Our objective is to use racing as a platform to educate the public about the acceptability of renewable fuels and the capabilities of advanced vehicle technologies through highly visible demonstrations of their performance. We will also demonstrate advanced technology coupled with renewable fuels in a race-car format to greatly reduce petroleum usage and greenhouse gas emissions by:

- Incentivizing vehicle manufacturers to develop, validate, and promote advanced technology relevant to production vehicles through racing.
- Increasing the use of renewable fuels in racing.
- Increasing the use of electric drive technologies in racing.

In addition, we will diversify the success of the Green Racing Initiative beyond sports cars to include other racing series, with even greater potential for wider participation and visibility, by:

- Utilizing results to support codes and standards development for racing series.
- Increasing the acceptance of "green racing" in the United States and internationally.

Approach

- Build and test technologies in a base race-car platform
- Demonstrate technologies on race tracks
- Publish results in technical and motorsports publications
- Present results at technical conferences and racing events
- Improve visibility and understanding of Green Challenge scores with the media and race fans
- Increase availability of second-generation biofuels
- Provide technical support for Project G.R.E.E.N sponsored by Circle Track Magazine

Major Accomplishments

- Integrated accessory hybrid lithium-ion (Li-ion) battery system into car
- Integrated electrified power steering, water pump, fuel pump, and engine control unit (ECU) system
- Instrumented vehicle with torque sensors and fuel flow meter
- Developed data acquisition system

Future Activities

- Replace failed Li-ion batteries (There was an issue with the battery management system that delayed testing.)
- Test vehicle on track
- Analyze and publish results
- Promote development of circle track race series by using renewable fuels and advanced technologies

VI.D.2. Technical Discussion

Phase 2 was broken into two separate segments: One for FY 2012 and the follow up proposed for FY 2013. The first segment focused on developing an accessory hybrid system on the circle track car. This entailed developing a chargeable Li-ion battery storage system on the vehicle that would power all of the accessories and traditionally engine-powered components, leaving the engine to make power. This allows the engine to operate more efficiently, and the data collected can be used to investigate such systems in fleet vehicle applications.

Electrification of the components included the water pump, the fuel pump, the ECU system, and the power steering pump. This allowed for removal of the alternator altogether, thereby reducing all of the parasitic drag typically associated with engines. Further, all of the vehicle accessories are powered by energy stored by on-board Li-ion batteries.

The final stage of the project (FY 2013) will involve converting the powertrain into a post-transmission hybrid with brake regeneration capability. The first stage electrifies the system and places a modest battery storage system on the vehicle, which facilitates brake regeneration development.

1. Water Pump

An electric water pump was sourced and replaced the production engine-driven unit. This unit flows 55 gallons per minute through stainless-steel hardware. Additionally, the electric powered unit allows for logic-based control to help optimize the engine operation temperature. Under normal use, the pump draws 12 amps and is mounted to the radiator, removing the production engine driven unit altogether (Figure 1).

Figure 1. Electric water pump, radiator mounted.

2. Electric Power Steering

The traditional hydraulic engine-driven power steering unit was replaced by a 14-pound adjustable electronic unit (Figure 2). This modification removes the engine's parasitic losses associated with turning, thereby increasing efficiency. Additionally, the electronic unit has adjustable feedback for the driver that can be dialed-in for various tracks, tires, and surfaces.

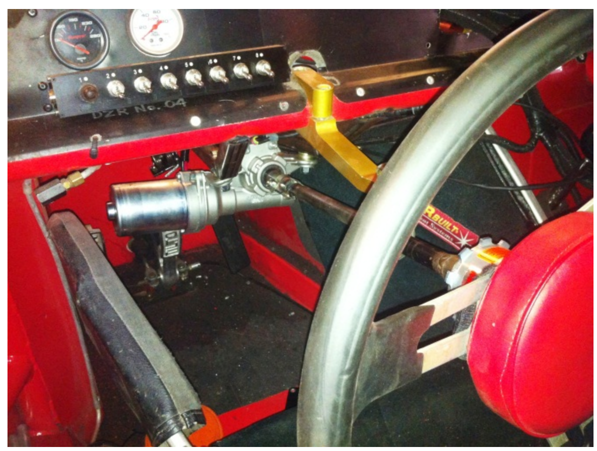


Figure 2. Electric power steering assist unit mounted under dash (replaces engine-driven hydraulic pump).

3. Instrumented Driveline

To determine the efficiency gains of removing the accessory loads, the driveshaft was instrumented with a calibrated torque-strain gage (Figures 3 and 4). By measuring both speed and torque, the total power coming from the transmission is calculated and compared with the power associated with and without engaging the accessory hybrid system. In utilizing the accurate fuel flow measurements, the total power into the system is calculated and the total efficiency is determined. This calculation allows the gain in efficiency and increase in power to be determined.

Figure 3. Drive-shaft-mounted torque sensor.

Figure 4. Torque sensor close-up. Note: System is remote powered via a 9V lithium ion battery.

4. Data Acquisition System

To determine the potential gains of the system, a data acquisition system was developed specifically for this project. Included in the system are very accurate fuel flow and drive shaft torque measurements. Controller area network (CAN) signals, as well as high-resolution accelerometer data, are collected from the ECU. Additionally, the Li-ion battery system has its own battery management system (BMS), in which accurate voltage, current, and state-of-charge data are collected to monitor the battery pack operation. This system allows for total determination of energy use, efficiency, and power gains. The data acquisition system components and location are shown in Figure 5.

Figure 5. Data acquisition, ECU, solid-state logic-based fuse system.

5. Energy Storage System

Energy storage for the accessory hybrid system comes from two Valence Technology lithium iron magnesium phosphate ($LiFeMgPO_4$) batteries, each of which contains 138 Ah (3.5 kWh total) of storage. Each battery contains its own battery management system, which regulates individual cell voltage and balancing. In addition, the system contains a CAN-based communication system that is used in the data acquisition system, to determine electrical energy utilization. The batteries have been mounted in the rear of the vehicle, forward of the rear differential housing on the driver's side of the vehicle, as shown in Figure 6.

Figure 6. Li-ion battery energy storage system, driver's side, forward of driveshaft (driver's side brake shown on lower right hand side of image).

Background

The Green Racing Initiative is a collaborative effort led by the U.S. Department of Energy (DOE), in partnership with the U.S. Environmental Protection Agency (EPA) and SAE International. The short track stock car initiative continued to develop the technical basis to prove that cost-effective engine and propulsion technology — based on renewable fuels with emissions control — was feasible. Through Argonne National Laboratory (Argonne), DOE provides technical assistance, instrumentation, and analysis for this project.

Introduction

In FY 12, the focus of the work centered on developing a two-stage hybrid system on a short track stock car, while integrating modern engine technology and renewable fuels to greatly reduce petroleum use and greenhouse gas emissions and yet increase performance in the field. The ultimate goal is to leverage the work so that various race series will integrate allowances for such technologies and raise public awareness of the benefits.

Approach

Motor sports are the only professional sports that can help attain critical national energy and environmental objectives. Such racing-based events can help achieve these objectives by directing the vast creativity and engineering talent, significant spending, and rapid developmental cycles in racing toward the use of technology and fuels that reduce our dependence on petroleum and lower the carbon footprint of vehicles — and yet still provide the entertainment and drama that has made racing one of the largest and most followed forms of sports around the world. Because of these unique attributes, racing is one of the biggest and best platforms for reaching a large audience with the message that, through advanced vehicle technologies and renewable fuels, we can maintain the personal mobility we want while moving toward the energy security and sustainability that we need.

Racing uses the crucible of competition to bring out the best in automotive technology — and the people who are willing to push the limits in using it — that touches a core cultural value that resonates with the public. The "living on the edge" with technology and danger is what adds to racing's interest, drama, and entertainment. Racing also inherently values efficiency, an attribute that underpins our national energy and environmental objectives. By building on this core value in racing, using its need for cutting-edge high-technology machinery — and adding renewable fuels and advanced technology as ways to achieve it — we have developed the Green Racing Initiative with our partners.

Results

The development of the accessory hybrid system and the data acquisition system were completed in August of 2012. However, a failure of the battery management system delayed testing until the first quarter of FY 13. Both batteries had to be shipped back to the producer, diagnosed, and repaired. Difficulty in shipping the Li-ion batteries and in diagnosing their failures greatly delayed the data acquisition portion of the project.

Conclusions

As a first step in the hybridization of a short track stock car, the goal is to show increased efficiency and petroleum displacement via electrification, which results in higher performance. Additionally, such technologies may have a place in certain fleet vehicles that Argonne has been studying (i.e., toll vehicles, police vehicles, etc.).

Test results from this Green Racing initiative will be the first step in our demonstration.

VI.D.3. Products

Publications

SAE Paper

1. "The Impact of Cellulosic Ethanol on the Performance and Emissions of a Circle Track Race Car," SAE 13PFL-1194, accepted SAE Congress 2013.

Circle Track Magazine

1. "Electrified! We amp up Project G.R.E.E.N.'s high voltage return with a new battery powered accessory system".

VI.E. Codes and Standards Support for Vehicle Electrification

Principal Investigator: Theodore Bohn
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (202) 488-2431; Email: tbohn@anl.gov

DOE Program Manager:
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VI.E.1. Abstract

Objectives

- Support the SAE standards committees related to connectivity and communication between plug-in vehicles and the charging infrastructure
  - Participate in the SAE standards definition and revision process
  - Utilize laboratory capabilities to evaluate, refine and verify proposed technologies and standards

Approach

- Focus on the EV charging-related standards activities that address the charge coupler/communication, Electric Vehicle Supply Equipment (EVSE), EV-EVSE-grid compatibility/interoperability and battery charging/handling.

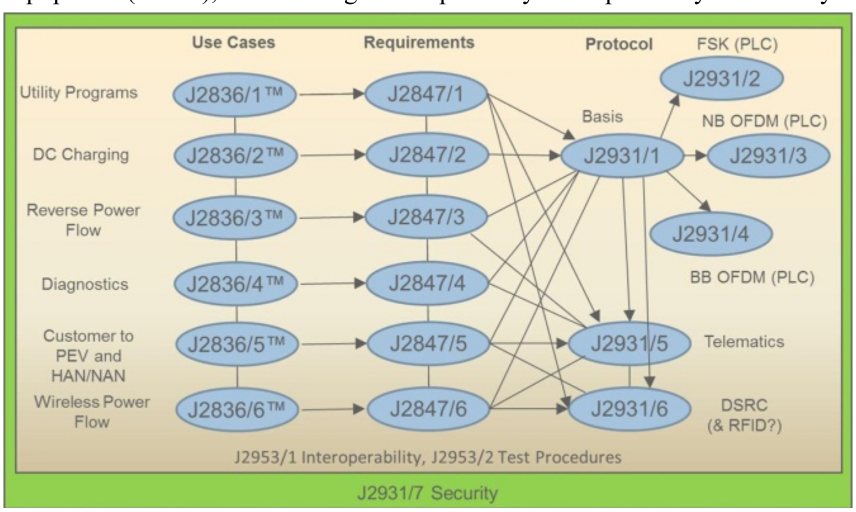


Figure 1. Inter-related SAE EV Charging Standards; Cyber Security Applicable to All.

- Address the largest gaps in technology-oriented application of the standards. Since some of the standards definition organizations (SDOs) require technology to be validated prior to being cited in the standard, ANL participates in both drafting standards and leveraging the embedded controls/network lab capabilities to verify component performance in an emulated system. For example, power line communication (PLC) controllers were tested to provide quantitative data to support publication of the standard for EV-EVSE communication-via-PLC.

Major Accomplishments

- Argonne contributed the following to the SAE standards process this year:
  - Supported UL certification of the SAE hybrid charge coupler (SAE J1772)

- Utilized laboratory test data and analysis to support fact-based deliberations in the SAE committees related to EV-grid communication (SAE J2836, J2847 and J2931); many of the standards were balloted this year with the aid of verification testing by Argonne (see Results section for timeline)
- Facilitated mutually agreed upon design criteria for the prototype test fixture for wireless EVSEs used to validate and further develop the seven sub-group activities of SAE J2954. These include alignment, foreign object detection, interoperability, health effects, communication protocols, testing methods, and frequency assignments. Most recently facilitated specifications for interoperability validation fixtures for bus and truck wireless charging standards.

- Worked closely with the ANSI EV Standards Panel to summarize current status of all EV charging/infrastructure/Smart Grid related standards, including gaps that need to be filled. ANSI published the draft gap analysis in April 2012.
- Initiated the physical layer task group within ISO15118-part 4-5, interoperability validation procedures for EV-EVSE charging communication.
- Worked with the Energy Information Standards consortium on energy services interface (ESI) standards related to Energy management systems in commercial and residential applications.
- Worked with the California Public Utilities Commission (CPUC) task force on sub-metering to create their mandated sub-metering roadmap as part of the low carbon fuel standard requirement to sub-meter ALL plug in vehicles to have an accounting of the non-petroleum miles traveled in California.

Future Activities

Maintain focus on near-term needs with long-term impact, i.e., direct support of SAE standards committees and global harmonization

- Charge coupler – verification testing – use cases, protocols and messaging
- Interoperability – Define laboratory test procedures for interoperability; verify with production-intent vehicles and EVSEs; provide input for SAE J2953 standard publication

  Design, develop, and deploy a standardized testing fixture with three-axis magnetic field probes and coil positioning systems to allow system-level performance on safety, alignment, and communication to be uniformly evaluated (SAE J2954).

VI.E.2. Technical Discussion

Background

Electric drive vehicles, including battery electric vehicles (EVs), and PHEVs have the potential to dramatically improve fuel economy and reduce greenhouse gas emissions compared with conventional technologies. These technologies require new infrastructure to become a significant part of the vehicle fleet. In the case of EVs and PHEVs, an electric charging infrastructure is needed in the form of charging stations, most often at home or at the workplace, but also in public parking locations. At present, few charging points are available. However, projects are under way to deploy new electric-drive vehicle charging infrastructure and to collect data to facilitate analyses of future needs.

While gasoline and diesel-fuel vehicles refill at a gas station, electric-drive vehicles recharge at a charging station. Three EV charging levels are currently under consideration and summarized in Figure 2. Level 1 charging uses a standard 120-volt (V), 15–20 amps (A) rated (12–16 A usable) circuit and is available in standard residential and commercial buildings. Level 2 charging uses a single-phase, 240-V, 20–80 A circuit and allows much shorter charge times. Level 3 charging — sometimes colloquially called "quick" or "fast" charging — uses a 480-V, three-phase circuit. Level 3 charging is available mainly in industrial areas, and it typically provides 60–150 kW of off-board charging power.

Figure 2. Depiction of the various charging levels.

Introduction

Meeting the Administration's goal of 1 million EVs on the road in the US by 2015 requires technical specifications for components and interfaces to be finalized as soon as possible, obviating the need for ratified standards. Otherwise the suppliers and OEMs that support the goal will be assuming the risks of fielding 'non-standard' products. Hence, a common objective of suppliers, OEMs, DOE and the national labs is to support the SAE committees as they define, refine and verify the standards that are focused on EVs.

This report summarizes current activities to demonstrate and deploy the electric recharging infrastructure, the communications challenges associated with EVSE, the potential impacts on the electric grid and distribution network, and government cooperation in developing industry-recognized EVSE standards.

The EV-grid interface has been defined, from a standards perspective, in terms of the charge coupler (the physical connector for power and communication, messaging and protocols), the EVSE (charging technology and power quality) and interoperability (EV-EVSE compatibility, communication and security). Substantial progress has been made in these standards in FY 2012, with direct contributions by Argonne.

Approach

Refinement and verification of standards requires hardware and software for testing and evaluation. Since components are not readily available for EV-grid connectivity, Argonne utilized its embedded controls/network lab and leveraged support contractors to develop components to fill the gaps – enabling lab testing and quantitative data to be provided to the SAE committees.

Argonne supports the short-term needs of SAE committees with technical expertise and quantitative assessment of proposed technical solutions and standards for connectivity and communication between EVs and the grid such as those identified in Figure 3.

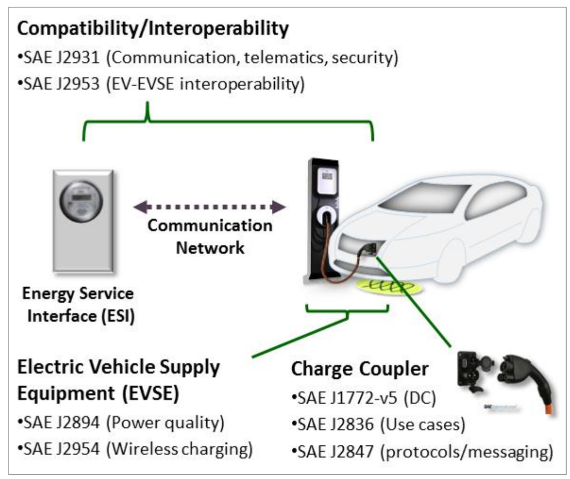


Figure 3. SAE standards committee support.

A key activity this year was the independent third-party benchmark comparisons of PLC candidate technologies for use in EV-EVSE smart-charging communication over existing connections. Unlike the dedicated pins and conductors required for other DC charging controls standards, the SAE-ISO/IEC standard for modulating over the existing pilot wire simplifies the connector design, thereby leading to reduced complexity by eliminating the insertion force assist mechanism.

Argonne engineers are leading the standards community in creating bona fide proof-of-concept systems for validating standards that complement previous electrical circuit simulations. Each of the SAE standards listed below relies, in a sequential manner (i.e., all are delayed until the communication system is validated), on quality results in a real-world context, such as that provided in the Argonne Advanced Powertrain Embedded Control Systems (APECS) laboratory.

The SAE standards are as follows:

- SAE J1772-DC (specification of the combination AC/DC single coupler solution; see Figure 4)
- SAE J2847/1-5 (communication messages – utility, DC charging, V2G, etc.)
- SAE J2931/1-4 (physical layer definitions, G3 PLC, HomePlug GreenPhy [HPGP], etc.)
- SAE J2953 (interoperability of EV charging systems with utility communications, gateways, EVSEs and EVs)
- SAE J2954 (wireless charging safety, performance, and interoperability)
- IEEE 802.11p (direct short-range communication for wireless charging).

Figure 4. Example of an SAE J1772 charge coupler connector for vehicle battery charging.

Defining Voluntary Standards

"Voluntary" standards (i.e., those not required by regulation[11]) address essentially all aspects of automobiles and are issued by several organizations around the world, such as the SAE in the United States, the ISO or IEC in Europe, and the Japan Automobile Research Institute (JARI) in Asia (see Figure 5). The electrical content of automobiles adheres to standards developed by the IEEE. As plug-in vehicles and EVSEs utilize the electric power grid, they are subject to standards established by Underwriters Laboratories (UL) and the fire and building safety standards set by the National Fire Protection Association (NFPA), including the National Electrical Code (NEC).

–

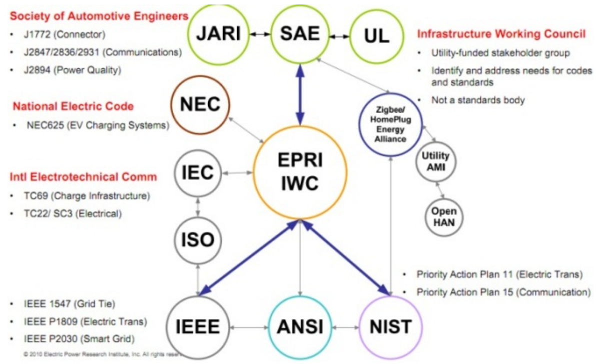


Figure 5. SDOs and others that influence EV charging standards (source: EPRI).

Codes and Standards Activities

Charge Coupler (SAE J1772, 2836, 2847)

The SAE hybrid coupler standard, enabling both ac and dc charging in the same connector, was published in October, 2012. This required the physical device to be certified prior to balloting and the communication technology to be characterized. ANL supported both aspects of the coupler; supporting UL certification and testing the communication technology/protocol options.

EVSE (SAE J1772, 2894, 2954)

In addition to Level 2 AC and DC EVSEs that have been deployed in recent years, interest has developed in Level 1 DC Level 1 charging (up to ~19 kW). Argonne initiated an assessment of proposed technical solutions and the impact on EV-grid communication requirements. DC Level 1 charging will be evaluated as part of a system assembled to verify EV-EVSE communication controllers that incorporates a production EV and EVSE.

DOE awarded development contracts for wireless EVSEs in FY 2012, which will result in hardware to be delivered to Argonne and Idaho National Laboratory (INL) for testing by the end of CY 2013. With input from the SAE J2954 wireless charging standards community Argonne will design, develop, and deploy a standardized testing fixture with three-axis magnetic field probes and coil positioning systems to allow system-level performance on safety, alignment,

[11] Although SAE J1772 is a voluntary standard, vehicles must comply in CA order to earn ZEV credit.

and communication to be uniformly evaluated. Argonne defined the requirements and developed a proof of concept test fixture in FY 2012.

Interoperability (SAE J2931, 2953)

Interoperability of EVs and EVSEs is generally viewed as a prerequisite for widespread adoption of EVs. Realization of this concept requires adherence to standards at the EV-grid interface. The key parameters and standards that define interoperability are being developed in the SAE J2953 committee; Argonne evaluated several combinations of individual components and messaging protocols in emulated EV-grid systems to support the committee in FY 2012.

The next steps are to support the draft of the SAE J2953 standard, develop standard test procedures and verify the standard with production-intent EVs, EVSEs and grid hardware … leading to a standard available for review and final publication by 2013/2014.

Results

Figure 6 shows a recently updated chart of the SAE EV charging standards development process. ANL played a key role in bringing these standards to the point of balloting, with validation. Many related standards are not shown here, such as those relating to cyber security that was also headed by ANL.

Conclusions

Argonne's expertise in connectivity and communication technology, combined with lab capabilities and resources for rapid prototyping components has been an important factor in the SAE standardization process and the adoption of key EV standards in FY 2012.

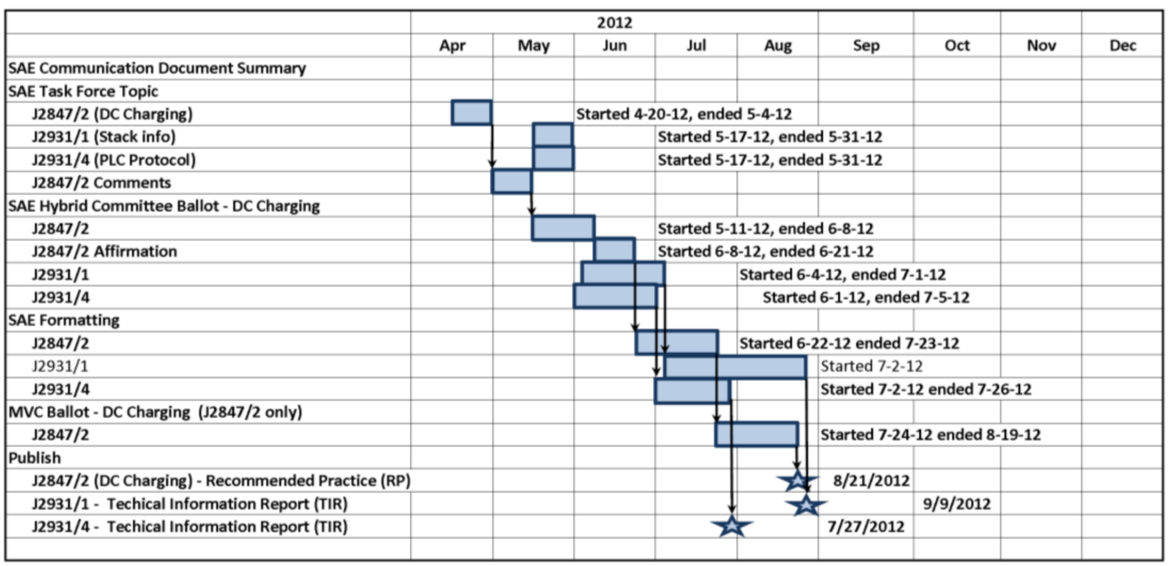


Figure 6. Standards development timeline (Source: R. Scholer, SAE standards committee chair)

VI.E.3. Products

Publications - None.

Patents - None.

Tools & Data - None.

VI.F. SAE Standards Development Support

Principal Investigator: Krishnan Gowri
Pacific Northwest National Laboratory
P.O. Box 999, MS-BSRC/377
Richland, WA 99354
Phone: (206) 528-3216; Email: Krishnan.gowri@pnnl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VI.F.1. Abstract

Objective

- PNNL provided technical support to SAE, ANSI and NIST electric vehicle standards working groups. PNNL actively contributed to the use case development, harmonization, and evaluation of the following SAE standards activities:
  - J2931/1 Electric vehicle to EVSE communication standard
  - J2847/3 Reverse energy power flow standard
  - J2847/5 Customer-to-vehicle standard
- PNNL tested and validated a set of potential technologies for meeting SAE communication requirements and provided recommendations for technology choices.

Approach

- Actively contribute to the development, review, and testing of SAE EV/EVSE communication standards
- PNNL participated and contributed to the ANSI Electric Vehicle Standards Panel working groups and NIST Smart Grid Interoperability Panel (SGIP) Vehicle-to-Grid domain working group on smart charging communications and related standards and roadmap development activities

Major Accomplishments

- SAE J2931/1 – PNNL performed and completed lab testing for three narrow-band communication technologies to assess adequacy for meeting SAE standards requirements. The outcome of the lab testing was a detailed presentation of test results used by the SAE committee to make their communication technology selection.
- SAE J2847/2 – PNNL researched existing standards and enhancements for implementers of the DC Charging communication message standard.
- SAE J2836/3 – PNNL ensured use cases incorporated grid reliability and utility oriented considerations, made committee presentations, and proposed alternative implementation methods to the development of the Reverse Energy Power Flow (Distributed Energy Resource) standard.
- SAE J2836/5 – PNNL prepared and presented use cases for adoption by the committee.

Future Activities

- SAE J2931/1 – Perform field testing of the SAE J2847/1 AC charging messages with home area network (HAN).
- SAE J2847/3 – Develop and test messages needed for the Distributed Energy Resource charging and discharging use cases.
- SAE J2847/5 – Develop and test messages needed for the Customer-to-Vehicle Communication standard.

VI.F.2. Technical Discussion

The interoperability between vehicles, charging stations and electric utilities is critical to the success of electric vehicle deployment. SAE, ISO and IEC are leading the standards development to define the communication architectures, protocols and messages.

Due to the large number of possible technologies and communication architectures, the SAE standard development includes 21 documents and the development process is delayed due to expanding scope and lack of research and test data related to development of these standards.

To expedite the standards development process DOE/EERE/VSST has been funding national laboratories (PNNL, ANL, ORNL and INL) to provide technical support for the SAE, ANSI, and NIST standards development process.

Background

There are three primary standards associated with the electric vehicle charging communications. The main communication standards development process is led by SAE. The standards pertain strictly to the communications between the electric vehicle and the charging station (EVSE).

SAE J1772 specifies the general physical, electrical, functional and performance requirements for conductive charging of PEVs (Plug-in Electric Vehicle) in North America, including the charging connector [1].

SAE J2836/1: documents the Use Cases describing the equipment and interactions to support grid-optimized AC or DC energy transfer for plug-in vehicles. These Use Cases enable Plug-In Vehicles to communicate with the utility so that the customer can take advantage of various incentive programs and charge their PEVs at times and rates to meet their needs [2].

SAE J2847/1: specifies the implementation of the information flow and messages [3]. J2847/1's primary purpose is grid-optimized energy transfer for Plug-In Electric Vehicles, and to ensure vehicle operators have sufficient energy for driving while enabling the delivery of that energy to vehicles in ways that minimize stress upon the grid. This can be accomplished, for example, by vehicle owners' voluntary participation in a utility controlled-charging program in return for incentives.

Communications pathway: There are several media and pathways for communications. SAE standards committees focused on using Power Line Carrier (PLC) as the primary medium using a wired communication path from the PEV to the electric vehicle supply equipment (EVSE) or charging station. PLC was selected as the primary medium since a direct association from the PEV to the utility can be obtained and is required by some utility programs for special rates or options. Within the EVSE to PEV electrical path, there are two physical layer communication options – the J1772 Control Pilot circuit or the mains (AC or DC power circuit). The Control Pilot circuit is a low voltage circuit used for communicating the maximum charge rate the EVSE can supply to the PEV.

J2931/1 Communications Testing

The SAE J2931/1 Test Plan [4] was completed by the J2931 committee in 2011. This plan includes a set of tests to evaluate potential Plug-in Electric Vehicle communications technologies in a laboratory environment. The evaluation criteria include requirements for utility/customer communications that support smart charging and support the use of off-board DC charging equipment. The completion of J2847/1 (Utility Messages) and J2847/2 (DC Charging Messages) enabled the J2931/1 digital communication requirements to be specified and a Test Plan to be developed to identify communication technology options for further development and testing.

Standards Development

SAE J2847/2 Recommended Practice

This document addressed recent major DC charging technology changes of electric vehicles, the grid, and information processing, including: (1) support for bidirectional energy transfer between vehicle and grid; (2) support for new local communications media (i.e., PLC, CAN, ZigBee, Wi-Fi) between vehicle and EVSE; and (3) synchronizing a major revision of SAE J1772 (Combo Connector).

SAE J2836/3 Information Report

The SAE Information Report J2836/3 provides use cases for using the stored energy in a Plug-in Electric Vehicle's (PEV) battery as a Distributed Energy Resource (DER) and how a PEV could serve the bulk grid, the distribution system, and a customer premises. This capability is often associated with an aggregator coordinating the power flow of many PEVs to provide frequency regulation for the bulk grid. A DER could also be used by a facility energy management system to offset facility loads during periods of peak demand. These are only two of many possible applications. J2836/3 also describes using active control of battery charging for grid purposes.

A primary requirement of J2836/3 committee's efforts was to insure that the architecture of the Reverse Energy flow standard will meet IEEE 1547, NEC, and UL 1741 and will be consistent with other standards.

SAE J2836/5 Information Report

The SAE Information Report J2836/5 establishes use cases for customer communications between Plug-In Electric Vehicles (PEV) and their customers. In essence, J2836/5 defines the key elements of the user interface considering:

- Communication paths (PLC, Wi-Fi, Telematics, ZigBee, etc.)
- Actors (EV, EVSE, EMS, EVSP, Utility).
- Customer Interaction points (dashboard, EVSE UI panel, Smartphone, Energy management devices).
- Locations (Work, home, parking garages, street, hotels, etc.)

Introduction

J2931/1 Communications Testing

Electric Power Research Institute (EPRI) led the J2931/1 Test Plan development and communication testing specified and approved by SAE to evaluate and select a PLC technology. The J2931/1 communication test plan was a three phase effort: (i) requirements development, (ii) communication performance testing, and (iii) selection of the communication technology that most effectively supports the requirements. EVSE and EV manufacturers jointly established communication performance requirements necessary to support charging of electric vehicles. The basic test configuration is shown in Figure 1 below.

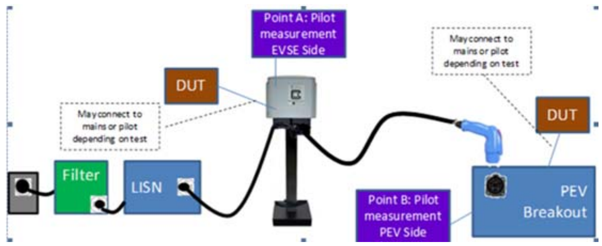


Figure 1. PLC Modules Test Configuration [4].

Standards Development

Vehicle-to-grid communication standards have been under development since 2009 and there are 21 documents currently being developed by the SAE Hybrid Committee. These address the communication messages, protocols and performance requirements for vehicle charging, reverse power flow, diagnostics and wireless charging. During the first three years, SAE has completed the use case development activities and initial versions of documents on messages for utility programs and digital communications. SAE is coordinating the standard development with ISO/IEC-15118 series of standards which parallel the J2836 and J2931 series of SAE documents. During FY 2012, the primary focus of PNNL is to support the finalization of DC charging messages, and use cases for reverse power flow and customer communications.

This progress report summarizes the testing related to selection of PLC technologies, describes SAE standards efforts completed in FY 2012, and identifies further SAE standards development needed to implement vehicle-to-grid communication.

PNNL actively participated and contributed to the reverse energy power flow and home area network requirements documents. PNNL developed use cases and data requirements supporting the development of J2836/3, J2847/3, J2836/5 and J2847/5. In addition, PNNL contributed to the ANSI Electric Vehicle Standards Panel working groups and NIST SGIP Vehicle-to-Grid domain working group on smart charging communications and related standards and roadmap development activities.

Approach

J2931/1 Communications Testing

At the recommendation of the SAE committee PNNL worked with the Electric Power Research Institute (EPRI), ANL and Grid Interaction Tech Team (GITT) members to develop performance requirements and test methods for selecting a PLC for vehicle-to-grid communication. PNNL obtained the necessary evaluation kits and conducted laboratory tests for narrow-band PLC technologies to identify a power line carrier communication technology would meet or exceed the performance requirements specified in SAE J2931/1, PLC Communication Test Plan [4]. Each lab had a different primary focus on testing performance, but two labs were involved in each technology's evaluation to provide verification of test results. Each lab independently developed testing configurations and performed lab testing to measure communication performance.

The test plan included control pilot impairment, throughput rate, and data latency tests. In addition, crosstalk, coexistence, interference, association, shared network, and distance measurements were made. The PNNL Mains and Control Pilot testing was performed using the schematic shown in Figure 2 below.

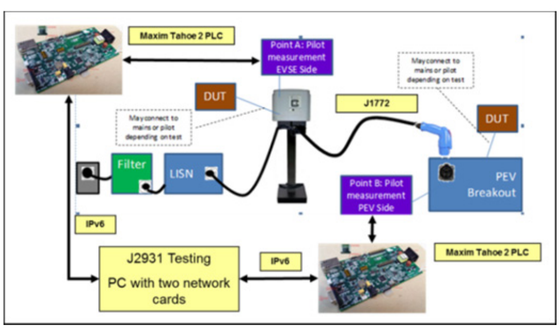


Figure 2. Typical J2931/1 Lab PLC Communication Testing Schematic.

EPRI and ANL both tested the HomePlug GreenPHY (HPGP) and Home Plug AV technology. ANL and PNNL tested the MAXIM G3 technology. PNNL tested the TI ODFM and Ariane Controls FSK technology. PNNL worked with the vendors to make needed hardware and firmware modifications to perform Control Pilot throughput, latency and control pilot impairment measurements independent of vendor supplied software measurements. The vendor evaluation boards required circuit changes to enable testing either mains or control pilot communication path.

Standards Development

SAE J2847/2, SAE J2836/3 and SAE J2836/5 Standards were developed by a team composed of Automobile OEMs, EVSE manufacturers, national lab representatives, and international members. The SAE J2836 standards focused on Use Case development and verifying compatibility of the proposed standard with existing standards. The J2847/2 standard development focused on required messages, message timing, and compatibility with international standards. PNNL team members contributed to use case preparation and research of existing standards, ensured use cases incorporated grid reliability and utility oriented considerations, made committee presentations, proposed alternative implementation methods, furnished detailed technical document review, and provided support to standard's team leader.

Results

J2931/1 Communications Testing

PNNL presented the J2931/1 lab communication results to the SAE membership on March 20-22, 2012. A summary of the PNNL test results is shown in Figure 3 below for each product tested.

Name	Latency	Error Rate	Throughput
Communication over AC Mains			
Echelon PL3170	193ms(1)	$17x10^{-6}$	1.9 Kbps
MAX 2990	37ms(1)	$< 1x10^{-6}$	33.4 Kbps
MAX 2992	17ms(1)	$< 1x10^{-6}$	28.5 Kbps
Communication over Control Pilot			
MAX 2992	37ms(1)	$< 1x10^{-6}$	27.5 Kbps
Ariane AC-CPM1	47.4ms(2)	----	39 Kbps
Maxim Tahoe 2	----	----	109 Kbps
TI Concerto	----	----	105 Kbps

(1) One-way latency (PNNL test plan)
(2) SAE 2931/1 latency (two-way)

Figure 3. PNNL Latency and Throughput Test Result Summary.

The SAE committee considered the EPRI, ANL, and PNNL testing results and then selected HPGP (analyzed by EPRI and ANL) as the communication technology meeting most of the requirements, though no technology completely met all performance requirements. Both Maxim Tahoe 2 and TI Concerto met the 100Kbps throughput requirement, but HPGP demonstrated the potential to provide a data throughput rate 10x better than the requirement, met the latency measurement performance, and met the control pilot impairment requirements. HPGP either met or showed the potential to meet the other requirements with further development. EMI testing was not performed. PNNL's contribution was in two areas – confirming ANL's narrow-band test results for the MAXIM Tahoe 2 technology and being the only test contributor for the Texas Instrument's Concerto and Ariane Control's products.

Standards Development

SAE J2847/2 Recommended Practice

A major revision to the Off-Board DC Energy Transfer Communication standard, SAE J2847/2 was completed and is going through the SAE committee review and approval process. The team made the J2847/2 messages and nomenclature more consistent with ISO/IEC 15118, DIN 70121, and the new version of SAE J1772 that includes the Combo Connector. PNNL researched existing standards and made corrections to J2847/2; proposed and implemented alternative methods for firmware developers to locate messages and message descriptions; and furnished detailed technical document review. In addition the timing diagrams and state diagrams were reviewed and updated to minimize implementation issues.

This document addressed major DC charging technology changes. The key changes were:

1. Signals and messages were specified that enable bidirectional energy transfer between vehicle and grid (V2G). The messages include protocol definitions, sequences, and session timing requirements for both the EVCC (EV Communication Controller) and SECC (Supply Equipment Communication Controller).
2. SEP2.0 is expected to provide a protocol that should enable translation between PLC communications between EV and EVSE to other local communications media (i.e. PLC, CAN, ZigBee, and Wi-Fi).
3. Messages and signals were implemented that recognize whether a J1772 AC, DC type 1, or DC Combo Connector is being used. This signal informs the vehicle of all energy transfer types supported by the EVSE. Since an EVSE may support multiple types of energy transfer (AC, DC type 1, or Combo) this signal allows a vehicle know all options of charging that are supported by the EVSE to determine if it is compatible and select the desired energy transfer type.

SAE J2836/3 Information Report

The SAE J2836/3 Information Report was completed and is going through the SAE committee review and approval process. J2836/3 added two additional use cases to those described in J2836/1 to enable the stored energy in a Plug-in Electric Vehicle's (PEV) battery to be used as a Distributed Energy Resource (DER). These two use cases (U6 - Basic Distributed Energy Resource and U7 – Advanced Distributed Energy Resource) would be the basis for developing communication requirements that would enable an aggregator to coordinate either the unidirectional or bidirectional power flow of many PEVs to provide frequency regulation for the bulk grid or offset facility loads during periods of peak demand.

The V2H, V2L and V2V applications require fundamentally different implementations than the V2G application. The V2H, V2L and V2V applications require that a vehicle inverter control system provides both frequency and voltage control since there are no other AC power sources supplying these loads. In addition, these applications would not use the J1772 cable and are off-grid applications and are outside the scope of J2836/3. The V2G application is significantly different because the energy from the vehicle is supplementing the grid energy and the grid is maintaining voltage and frequency control. In this case, the vehicle inverter needs only to maintain the battery current limits within specifications. The Basic Distributed Energy

Resource use case (U6) would provide bidirectional frequency regulation services to the bulk grid and is derived from IEC 61850 immediate functions (INV4). The Advanced Distributed Energy Resource use case (U7) is based on IEC 61850-90-7 and describes four-quadrant bidirectional power conversion. The bidirectional four-quadrant conversion enables volt and var support to the grid.

SAE J2836/5 Information Report

During FY 2012, PNNL prepared two use cases for vehicle charging at consumer private EVSE with basic charging and utility program based charging options. Several scenarios for each use case was developed and discussed with the committee. Further work is in progress for developing the basic charging use case. The progress of J2836/5 is coordinated with J3931/5 aimed at defining communication protocol for vehicle telematics to grid communication.

In addition to working with the SAE Hybrid Committee, PNNL participated in the NIST SGIP vehicle-to-grid domain expert working group (V2G DEWG) and the ANSI EVSP Communications Infrastructure working group. PNNL assisted V2G DEWG with initial version of documentation required for including SAE J2936/2, J2947/2 and J2931/1 in the SGIP catalog of standards. This submission is being reviewed and further work is underway to prepare the Standards Information Form (SIF) and these will be submitted for approval by the SGIP board during FY 2013. PNNL input for the ANSI EVSP roadmap for telematics and communication networks were reviewed and included in the Version 1.0 of the ANSI roadmap published in April 2012.

Conclusions

During FY 2012, the SAE J2931/1 Communications Testing was focused on the lab testing phase of the evaluation. The red circle in Figure 4 below shows the targeted extent of the lab testing in the overall system architecture of power flow and information flow.

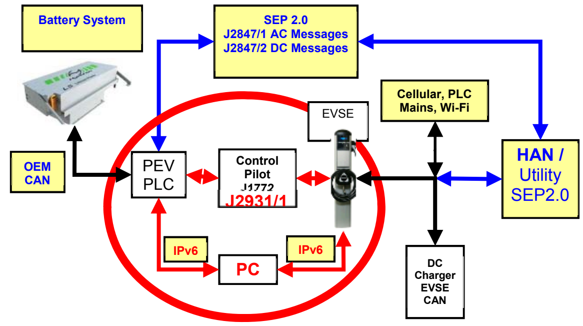


Figure 4. Lab PLC Testing.

During FY 2013, PNNL will undertake field testing of the J2931/1 standard and SAE J2847/1 messages. Field testing and demonstration of vehicle to utility AMI network will be conducted in partnership with EVSE manufacturers, utility partners to test end-to-end communication, and in collaboration with ANL. In addition, PNNL will continue to provide SAE standard development support for J2847/3 and J2847/5, once the J2836/3 and J2836/5 standards are completed.

VI.F.3. Products

NIST SGIP Vehicle-to-Grid domain working group on smart charging communications and related standards and roadmap development was supplied with four additional standards to add to SGIP catalog of standards.

1. SAE J2931/1
2. SAE J2847/2
3. SAE J2836/2
4. SAE J1772

Publication

1. Pratt RM, FK Tuffner, and K Gowri. 2011. Electric Vehicle Communication Standards Testing and Validation Phase I: SAE J2847/1; PNNL-20913, Pacific Northwest National Laboratory, Richland, WA.

Presentations

1. Pratt RM. 2011. "Grid-Friendly Charging and Communications." Presented by Rick Pratt (Invited Speaker) at UCLA Smart Grid Thought Leadership Forum, Los Angeles, CA on November 2, 2011. PNNL-SA-84282.
2. Gowri K, and RM Pratt. 2012. "J2931/1 Communication Testing Results." Presented

by Rick Pratt (Invited Speaker) at SAE J2931/1 Review Committee Meeting, Auburn Hills, MI on March 19-20, 2012.

3. Pratt RM, FK Tuffner, and K Gowri. 2012. "Testing and Validation of Electric Vehicle Communication Standards." Presented by Krishnan Gowri at Electric Vehicle Symposium (EVS26), Los Angeles, CA on May 8, 2012. PNNL-SA-87682.
4. Gowri K, and RM Pratt. 2012. "Vehicle-to-Grid Communication Standards Development Support." Presented by Krishnan Gowri (Invited Speaker) at DOE Office of Vehicle Technology - Annual Merit Review 2012, Washington, DC on May 14, 2012. PNNL-SA-86774.
5. Kintner-Meyer MCW, K Gowri, and RM Pratt. 2012. "Smart Grid Infrastructure Research Facility Network - PEV/Grid Integration." Presented by Rick Pratt (Invited Speaker) at SIRFN Task 2 Organizational Meeting, online conference, WA on August 15, 2012. PNNL-SA-90039.
6. Gowri, K., “Electric Vehicle Communication Standards: Why, How and When?”, Electric Vehicle Virtual Summit, Sept. 13, 2012, (Invited Panelist). smartgridobserver.com/shah-abstract-evvs9612.htm

Patents

1. 16464-E: “Grid Regulation Services for Energy Storage Devices Based on Grid Frequency,” U.S. Patent Application Nos. 12/755,260, filed on April 6, 2010, and 13/433,620 filed on April 10, 2012

(Note: This is a PNNL patent developed from prior year projects funded/cost-shared by Office of Electricity and Vehicle Technologies tasks related to smart charging and communication standards).

Tools & Data

1. PNNL has invested in the capability to perform J2931/1 field testing using the infrastructure made available by the PNNL
2. Lab Homes and an internal PNNL investment to install three charging stations on the Lab Homes. This field testing capability enables the 3 co-located charging stations to perform realistic interference, crosstalk, shared network, coexistence and association testing. Interfacing HPGP-based EVSE / PEV communications to the Lab Home Home Area Network will enable standards testing beyond the EVSE. This field testing site can be made available to OEMs for their off-site testing.
3. Vehicles are not available that have been equipped with J1772 Control Pilot HPGP communication capability, but the PNNL PRIUS can be retrofitted to add HPGP communication capability with two-way vehicle CAN bus communication that enables live parameters to be transferred during testing. The field testing plan includes using industry recognized tools such as GridTest’s Electric Vehicle Charger Test equipment to closely replicate a second or third PEV connected to adjacent charging stations.

References

1. SAE J1772 SAE Electric Vehicle and Plug-in Hybrid Electric Vehicle Conductive Charge Coupler. (Surface Vehicle Recommended Practice). SAE International, Warrendale, PA.
2. SAE J2836/1 Use Cases for Communication between Plug-in Vehicles and the Utility Grid. (Surface Vehicle Recommended Practice). SAE International, Warrendale, PA.
3. SAE J2847/1 Communication between Plug-in Vehicles and the Utility Grid. (Surface Vehicle Recommended Practice). SAE International, Warrendale, PA.
4. J2931/1 PLC Communication Test Plan, September 2011. Electric Power Research Institute, Palo Alto, CA.

VI.G. Grid Connectivity Support

Principal Investigator: Keith Hardy
Argonne National Laboratory
9700 South Cass Avenue
Building 362, Office B-233
Argonne, IL 60439
Phone: (630) 816-7383; Email: khardy@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VI.G.1. Abstract

Objectives

- Support the DOE Vehicle Technologies (VT) Program as the technical lead for technology and standards development/verification related to grid connectivity with electric and plug-in hybrid electric vehicles (EVs).
- Establish the technical capability to support an international EV-Smart Grid Interoperability Center at Argonne.
- Co-chair the US DRIVE partnership's Grid Interaction Technical Team (GITT).

Approach

- Participate in SAE committees related to EV-grid connectivity/communication and provide laboratory testing and evaluation of proposed standards and technical solutions, specifically on the committees related to the:
  - Charge coupler (SAE J1772, J2836, and J2847),
  - Electric Vehicle Supply Equipment (EVSE) (SAE J2894 and J2954), and
  - Compatibility/interoperability (SAE J2931 and J2953).
- Enhance laboratory facilities and testing capabilities to evaluate interoperability between EVs and the charging infrastructure and coordinate with the European Commission's Joint Research Centre–Institute for Energy and Transport (JRC-IET) to develop complementary EV-Smart Grid Interoperability Centers in the United States and Europe that will:
  - Supplement the embedded controls/network laboratory at Argonne with space and equipment to test EVs and EVSEs according to SAE standards for compatibility/interoperability.
  - Provide technical support to the JRC-IET plan to establish their interoperability centers.
- Coordinate with the DOE Office of Electricity Delivery and Energy Reliability (Office of Electricity [OE]) to:
  - Provide technical support for OE's low-cost charging infrastructure procurement.

Major Accomplishments

- Contributed to the SAE standardization process, including by:
  - Supporting Underwriters Laboratories (UL) certification of the SAE hybrid charge coupler (SAE J1772).
  - Providing laboratory test data and analysis to support fact-based deliberations in the SAE committees related to EV-grid communication (SAE J2836, J2847, and J2931).
  - Designing and fabricating a prototype test fixture for wireless EVSEs (SAE J2954).
- Designed/developed enabling technologies, including the following:
  - Third-generation revenue-grade sub-meter with EVSE-to-grid communication (EUMD-Rev3).
  - 'Auto-rem' power line communication (PLC) module for EV-EVSE messaging.
  - HomePlug® Green PHY (HPGP) PLC pilot-based communication controller for EVs and EVSEs.
- Demonstrated EV-to-EVSE-to-network-to-grid communication (SAE J1772, J2847, J2931, and J2953).

- Developed a working technology display of vehicle-to-smart grid communication and interoperability to support the annual Transatlantic Economic Council meeting and signing of the DOE-JRC agreement to establish complementary EV-Smart Grid Interoperability Centers at Argonne and JRC-IET.
- Acquired additional laboratory space and equipment to assess vehicle, EVSE, and energy service interface (ESI) compliance with interoperability standards.

Future Activities

- Maintain focus on near-term needs with long-term impact, that is, by providing direct support of SAE standards committees and global cooperation/harmonization for the following initiatives:
- Charge coupler; verification testing of use cases, protocols, and messaging.
- EVSE; fabrication of test fixture for wireless EVSEs and demonstrate associated wireless communication.
- Interoperability; Define laboratory test procedures for interoperability, verify with production-intent vehicles and EVSEs and provide input for the SAE J2953 standard publication.
- Enabling technologies; Fabricate and distribute limited copies of the EV-EVSE communication controller hardware and sub-meter/communication module to partners for joint testing/evaluation and harmonization.
- Interoperability Center; Complete modifications to laboratory space and installation of equipment for the EV-Smart Grid Interoperability Center (planned to be fully operational in early FY 2013).
- Support international initiatives; Leverage grid connectivity activities to promote joint development and verification of standards and provide technical guidance for complementary JRC-IET interoperability centers in Italy and the Netherlands.

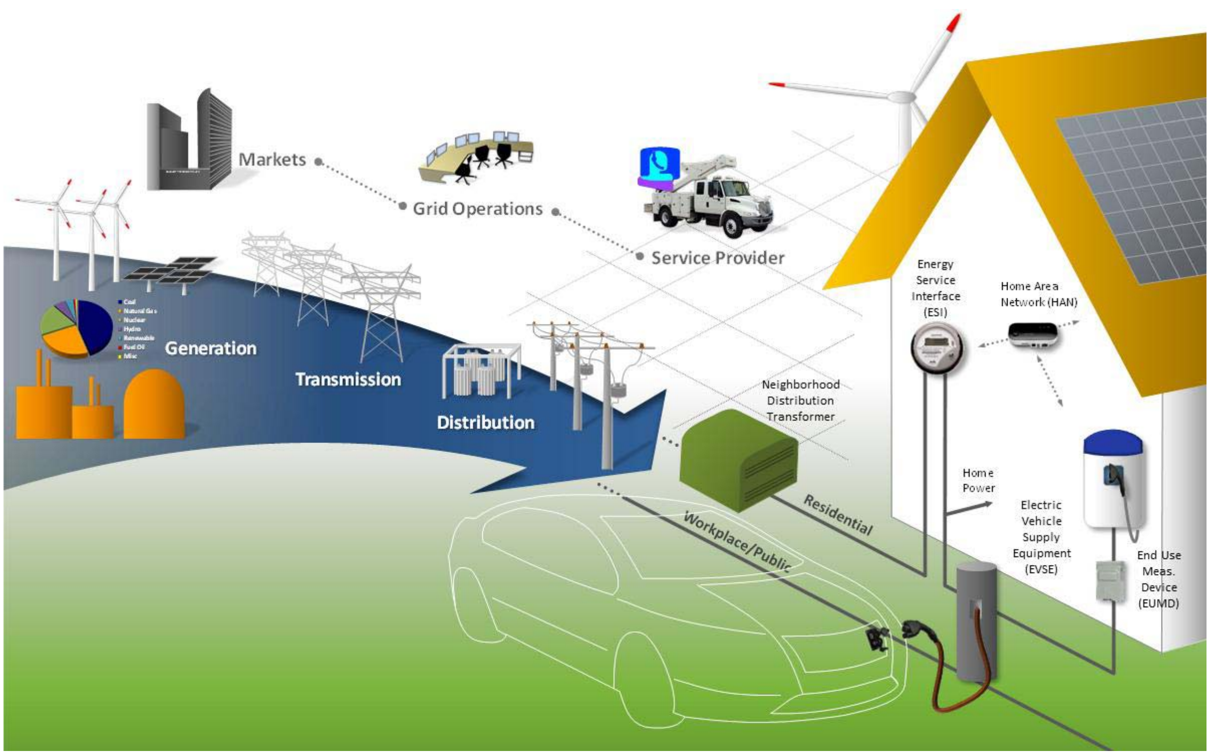


Figure 1. Electric vehicle charging infrastructure.

VI.G.2. Technical Discussion

Background

Meeting the Obama Administration's goal of having one million EVs on the road in the U.S. by 2015 requires finalizing specifications for components and interfaces as soon as possible, obviating the need for ratified standards. Otherwise suppliers and original equipment manufacturers (OEMs) will be assuming the risks of fielding 'nonstandard' products. Hence, a common objective of suppliers, OEMs, DOE, and the national laboratories is to support the SAE committees as they define, refine, and verify the standards that are focused on EVs.

The EV-grid interface has been defined, from a standards perspective, in terms of the charge coupler (the physical connector for power and communication, messaging, and protocols), the EVSE (charging technology and power quality), and interoperability (EV-EVSE compatibility, communication, and security) (Figure 2). Substantial progress has been made in these standards in FY 2012 with substantial contributions by Argonne.

Introduction

Argonne is the technical lead for technology development and/or standards verification related to EV-grid connectivity and co-chair of the Grid Interaction Technical Team (GITT), whose objective is to support a transition scenario to large scale grid-connected vehicle charging. The scope of the GITT is connectivity between light-duty EVs, the charging infrastructure, and the electric power grid (Figure 1). Argonne activities are aligned with the GITT, with substantial effort in refining and verifying EV-grid standards in direct support of the SAE committees related to the charge coupler, EVSE, and interoperability.

Refinement and verification of standards requires hardware and software for testing and evaluation. Because components are not readily available for EV-grid connectivity, Argonne utilized its embedded controls/network laboratory and leveraged support contractors to develop components to fill the gaps—enabling lab testing and quantitative data to be provided to the SAE committees.

Approach

Argonne supports the short-term needs of SAE committees with technical expertise and quantitative assessment of proposed technical solutions and standards for connectivity and communication between EVs and the grid. Further, Argonne collaborates with and supports the DOE Office of Electricity on activities related to the charging infrastructure.

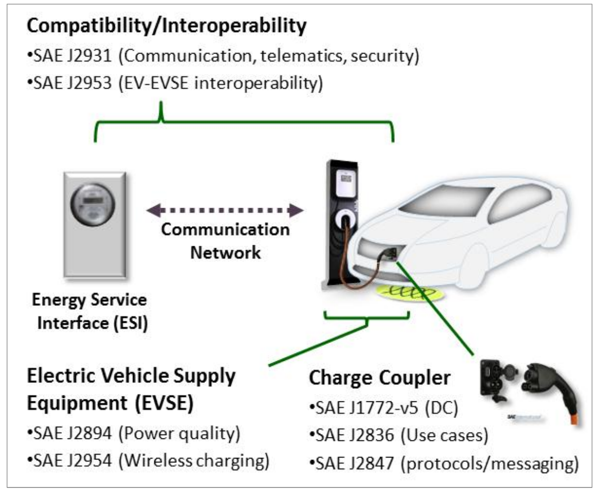


Figure 2. SAE standards committee support.

The activity has focused on developing realistic vehicle-grid communication systems and performing lab tests to provide as much data as possible to the committees in a timely manner. This approach necessitated development of enabling technologies, including compact metrology and communication modules and integration in emulated and real systems:

- EV-to-EVSE communication module.
- Third-generation sub-meter with integrated EVSE-to-grid communication.
- EV-EVSE communication controller (HPGP PLC pilot-based) for both the EV and EVSE.

In addition, the grid connectivity activity is leveraged to support DOE's international agreements in these areas:

- Expertise and laboratory facilities to support the EV-Smart Grid Interoperability Center.
- Compact metrology and communication components for application in joint projects to facilitate harmonized standards.

Standards Committee Support

Charge Coupler (SAE J1772, 2836, 2847)

The SAE hybrid coupler standard, enabling both AC and DC charging in the same connector, is expected to be adopted in October 2012. Obtaining this level of confidence in the proposed coupler required both certification of the physical device prior to balloting and adequate understanding of the communication technology. Argonne supported the UL certification as well as testing the communication technology/protocol options.

Argonne will assess the charge coupler in production-intent EVs with a variety of EVSEs as part of the development and verification of the SAE J2953 interoperability standards (FY 2013).

EVSE (SAE J1772, 2894, 2954)

A variety of AC Level 1 and Level 2 EVSEs (up to 6.6 kW and 19.2 kW, respectively) are being deployed by both the public and private sectors; far fewer DC Level 2 EVSEs (referred to as "fast chargers," typically 50 kW) have been deployed. Recent interest in DC Level 1 charging (up to ~19 kW) necessitated an assessment of proposed solutions and the impact on EV-grid communication requirements. Argonne will evaluate DC Level 1 charging as part of a system assembled to verify EV-EVSE communication controllers that incorporates a production EV and EVSE (see Figure 5 in the Enabling Technology Development section).

In addition to the development and deployment of AC and DC Level 2 EVSEs with conductive charging, DOE supported the effort to establish the SAE J2954 committee (nonconductive "wireless" charging) in FY 2011 and awarded development contracts in FY 2012. The contracts will result in hardware that will be delivered to Argonne and Idaho National Laboratory (INL) for testing by the end of 2013. In preparation for this effort, Argonne has defined the requirements for and is developing a prototype test fixture for wireless EVSEs, as well as exploring appropriate wireless communication. A proof-of-concept test fixture was constructed at Argonne at the end of FY 2012.

The next steps are addition of new controls, actuators, and data coordination. The test fixture design will be refined with the aid of the proof-of-concept wireless charging hardware developed by Oak Ridge National Laboratory (ORNL), and the final specification/design will be transferred to collaborating certification laboratories in FY 2013.

Interoperability (SAE J2931, 2953)

Interoperability—which in this case refers to the idea that any EV should be able to connect to any EVSE … anywhere … and communicate in a standard manner with the energy service provider—is generally viewed as a prerequisite for widespread adoption of EVs. Realization of this concept requires adherence to standards at the EV-grid interface. The key parameters and standards that define interoperability are being developed; Argonne has evaluated several combinations of individual components and messaging protocols in emulated EV-grid systems to support the committee's efforts.

The next steps are to support the draft of the SAE J2953 standard, develop test procedures, and verify the standard with production-intent EVs, EVSEs, and grid hardware, leading to a standard available for review and final publication by 2013/2014.

Enabling Technology Development

Argonne's support of interoperability standards has focused on technologies and methodologies for grid connectivity, including compact metrology to provide EV sub-metering and communication between the EV, EVSE, and ESI. Unfortunately, components were not available to make all of the linkages in the communication path, necessitating that Argonne design and develop prototype components.

Figure 3 shows Argonne's third-generation End Use Measurement Device (EUMD) module. The revenue-grade meter communicates EVSE energy use to the energy service provider via the ESI or Home Area Network (HAN). The compact unit, shown here configured for a standard AC power disconnect housing, has the potential to be an order of magnitude lower in cost compared to standard smart meters. In addition, the unit can be adapted for different communication protocols and locations (e.g., vehicle, EVSE, neighborhood transformer).

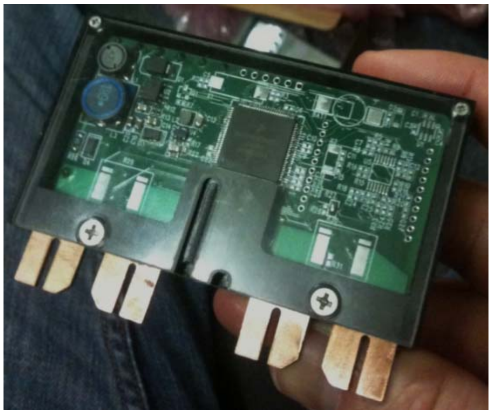


Figure 3. EUMD-Rev3 sub-meter with communication.

The fourth-generation EUMD will be updated (in collaboration with a supplier), and 100 evaluation units will be fabricated for evaluation by industry partners in FY 2013. Designed to support the communication standards, the EUMD-Rev4 will be based on a (production) system-on-chip (SOC) solution, custom cases, flux gate sensors, and Smart Energy Profile (SEP) 2.0 server connectivity.

Figure 4 shows the "Auto-rem" module Argonne designed for vehicle-to-EVSE communication. The unit has a controller area network (CAN) interface and PLC to transmit vehicle information.

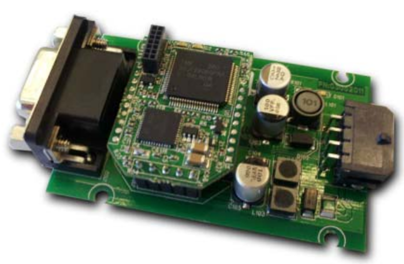


Figure 4. Auto-rem PLC module.

In 2011, the major German and American OEMs announced their intent to use a hybrid charge coupler and HPGP communication protocol in their EVs. As a result, the HPGP PLC pilot-based communication controller was designed to be used in both the EV and EVSE. Delayed delivery of the HPGP processor has pushed completion of the controllers into FY 2013. Upon completion, the functionality of the controller will be verified in a realistic laboratory testing (see the three-phase process in Figure 5) and deployed to industry partners for evaluation.

Figure 5. Test plan to verify EV-EVSE communication controllers, DC Levels 1 and 2 charging.

Support International Initiatives

EV-Smart Grid Interoperability Center

Argonne's interoperability center was initiated early in FY 2012 in an agreement between DOE and the European Commission's Joint Research Centre (see the International Cooperation task report) as a mechanism to promote U.S.-Europe cooperation on EV standards development and verification. Several laboratory spaces at Argonne are being updated and integrated to perform the necessary testing and evaluation:

- Embedded controls/network laboratory.
- Smart Home Lab with HANs, Advanced Metering Infrastructure (AMI), and SEP 2.0.
- High bay with vehicle lift, 200 kW/480 VAC power, and a vehicle–sized, climate-controlled radio frequency (RF) chamber.

Additional assets can be employed, as needed (e.g., the Advanced Powertrain Research Facility [APRF], with its component hardware-in-the-loop (HIL) capabilities, as well as vehicle testing in a controlled thermal environment).

The EV Charging Pilot Project, consisting of a network of EVSEs with communication located around the Argonne campus, can be utilized by for field studies in a limited-access environment.

Harmonization of Standards

Argonne, DOE, the European Commission, and some member States have discussed pilot projects to facilitate joint development and verification of grid connectivity standards, with the objective of shortening the standards development, verification, and adoption process.

The initial idea is to set up similar vehicle-grid test configurations (i.e., EVs, EVSEs, and utility interfaces) in the US and Europe with the cooperation of OEMs, suppliers, regional utilities, and international standards development organizations. European versions of the EUMD and communication modules (modified for 3Ø, 200 VAC) could be installed in the EVs and EVSEs. Similar use cases could be utilized, issues/differences could be identified, and proposals for resolution could be assessed jointly.

Results

Argonne contributed substantially to resolving the technical challenges of EV-grid this year:

- Design and development of proof-of-concept EV-grid communication systems identified the need for enabling technologies, supported fact-based deliberations in committee deliberations, and provided insight into the scope of assessing interoperability.
- Test requirements for wireless EVSEs were defined and a prototype test fixture was fabricated.

Argonne designed/developed key enabling technologies for EV-grid communication:

- Third-generation, revenue-grade sub-meter with EVSE-to-grid communication (EUMD-Rev3).
- "Auto-rem" PLC module for EV-EVSE messaging.
- HPGP PLC pilot-based communication controller for EVs and EVSEs.

.

Argonne's demonstrations of EV-smart grid connectivity and enabling technologies reinforced U.S. Government efforts to establish global cooperation in e-mobility and contributed to the agreement to establish EV-Smart Grid Interoperability Centers in the U.S. and Europe.

Conclusions

Argonne's grid connectivity activity directly addresses the technology gaps in the electric vehicle-grid interface and provides quantitative evaluations to support the SAE committees.

Argonne and support contractors successfully demonstrated joint development of rapid prototypes from a commercial perspective (e.g., the compact metrology and communication modules), assuring relevance and mutual benefit to DOE and industry.

The activities are well connected with industry and governments in the United States and internationally. Supplementing U.S. Government diplomatic efforts with demonstrations of practical technological innovation by Argonne contributed to a better understanding of the issues associated with EV-grid connectivity and the potential benefits of global harmonization.

Focusing on near-term needs with long-term impact has been an effective approach for the grid connectivity activity. Compatibility between EVs, EVSEs, and the grid is a pressing near-term issue, necessitating the development and verification of SAE J2953 (interoperability) standards as soon as possible. The EV-Smart Grid Interoperability Center is specifically designed to address the associated issues.

Argonne will continue to provide direct support to the SAE standardization process, including committee participation, development of enabling technologies, system integration, and laboratory testing.

In the interest of sustaining global cooperation on electro-mobility and to fulfill the objectives of the EV-Smart Grid Interoperability Centers, Argonne will continue its collaboration with Joint Research Centre-–Institute for Energy and Transport (JRC-IET) in Italy and the Netherlands

VI.H. Model Reusability

Principal Investigators: Chuck Folkerts (Project Leader), Larry Michaels, Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
Phone: (630) 252-7261; Email: cfolkerts@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.slezak@ee.doe.gov

VI.H.1. Abstract

Objectives

- Establish dynamic modeling and simulation standards
- Facilitate dynamic modeling and simulation of automotive systems
- Make dynamic models universally reusable using plug-and-play technology

Approach

- Define overall charter of committee
- Define, prioritize, and develop work plans for standards projects to enable plugability and playability of models
- Define charter and develop standards proposals for each major project
- Propose recommendations to the modeling and simulation community for each of the major projects considered
- Facilitate team review, revision, and refinement of recommendations to develop Society of Automotive Engineers (SAE) standards products

Major Accomplishments

- Produced draft of SAE Standard Recommended Practice J-2998 on Model Description Documentation (Task 1), currently in review and revision process
- Developed project charter and launched project on Model Architecture and Interfaces (Task 2)
- Defined vehicle system architectural partitioning (80% complete)

Future Activities

- Complete development of system architecture partitioning
- Address the remaining projects, starting with model interfaces
- Produce documents describing best practices and publish as SAE Standard Recommended Practices

VI.H.2. Technical Discussion

Introduction

The complexity of automotive systems (as used in passenger cars, heavy-duty trucks, military vehicles, and agricultural and construction equipment) is increasing at a rapid rate, as are competitive pressures to reduce product development cycle times. Development of these modern automotive systems requires highly coordinated collaboration between the disciplines of engineering and physics within organizations and among a network of original equipment manufacturers (OEMs), suppliers, research laboratories, and universities across the industry and around the globe. To keep up with technology changes and competitive pressures, these global teams need virtual engineering methods to enable responsive, cost-effective, and efficient collaborative development. To make global enterprise and cross-enterprise virtual engineering methods cost effective, efficient, and robust, automotive-industry-wide standards for virtual engineering of dynamic modeling and simulation are required.

Future development of automotive systems will continue to be driven by the same forces and trends that drive it today: continual improvements in fuel efficiency, quality and reliability, emissions performance, and safety and more value to the customer at a lower cost. To minimize costs and time, automotive systems will be developed by global teams collaborating across an industry network using virtual engineering processes and methods with minimal physical builds, which will be required only to confirm designs and performance. Virtual engineering of automotive systems will require dynamic modeling and simulation that integrates models from different companies and disciplines that have varying levels of abstraction (fidelity and complexity). Such models will enable global teams to engineer and develop automotive systems rapidly, efficiently, and effectively facilitate an integrated development process that seamlessly flows between all processes from research to production.

A committee of experts from industry, academia, and the national laboratories was formed to address these issues and requirements.

Objective

The objective of the committee is to establish modeling and simulation standards to facilitate dynamic modeling and simulation of automotive systems. These standards will facilitate integrated and multidisciplinary virtual engineering processes for highly coordinated and collaborative engineering work. SAE Standards, Recommended Practices, and Information Reports (standards) will be established and published to facilitate and promote the following:

1. Cost-effective, efficient, and robust model and data sharing and reuse;
2. Seamless modeling, simulation, and analysis workflows,
3. Virtual engineering processes,
4. Interoperability in modeling and simulation tools; and
5. Portability across simulation tools.

Scope

The committee will focus on developing standards for dynamic models and simulations that mathematically describe an automotive system's time-varying response and behavior and the interactions of subsystems and components. These standards will include processes, methods, performance metrics, and analyses related to dynamic modeling and simulation of automotive systems. The goals are to make models reusable and simulation results predictable and repeatable across engineering and physics disciplines, application tools, and the automotive industry.

Benefits

The established standards will improve the overall efficiency of development processes by providing a "common language" and a means for sharing and reusing data and mathematical simulation models of dynamic systems across engineering disciplines within companies and across the industry network. Hence, these standards will facilitate virtual engineering of automotive systems, resulting in optimized performance, improved process efficiency, and reduced development time and costs for the automotive industry and individual companies. Such process enhancements will accelerate the rate of development and adoption of new technologies, providing improvements in fuel economy, efficiency, and displacement.

Standards Projects Definition

After defining its charter, the committee identified four main standards-development projects (tasks).

1. Model Description Documentation Project
   - Define content of documentation necessary to decide whether a model is appropriate for a given task
   - Define model uses or applications for which the model is appropriate
   - Define what the model does, what principles, theories, and/or equations it is based on, what approximations or assumptions were made

    - Provide any verification and validation work (i.e., test data, reports)
2. Model Architecture and Interfaces Definition Documentation Project
    - Define model organizations for vehicle system and subsystems (i.e., input/output), including location of model controls in the architecture
    - Define conventions for naming, data types, units, etc.
    - Define how model parameters are set and their impact on interfaces (parameterization)
    - Define MIL, SIL, RCP and HIL interfaces to controls models
3. Model Data Dictionary Documentation Project
    - Define metadata required to support reuse of models between software applications by means of interoperability (e.g., co-simulation or wrapped-code) or porting of models between tools with repeatable results. The metadata include
        - Model classification type, version, creator, fidelity, accuracy, computational workload, tool version compatibility, and other model classification characteristics
        - Model interfaces (inputs, outputs, and buses), variables, parameters, and names and meanings of interfaces, variables, and parameters
4. Model Compatibility and Playability Requirements Documentation Project
    - Define model simulation requirements needed to make it function in the simulation of a system with repeatable results
    - Define precision of arithmetic, integration interval, integration type (fixed or variable), sampling interval required, ODE solvers required
    - Define metrics for computer resources requirements (e.g., ROM, RAM, disk space, computation time using standard benchmark tests)
    - Define task scheduling for models of control algorithms
    - Define model simulation initialization process or method for establishing initial conditions

Accomplishments

Model Description Documentation Project

The committee continued development of a standard for Model Description Documentation, a task that was started in FY 2011. The committee developed, reviewed, and refined the information required to document a model for seven use case applications. A documentation template was developed for each use case. Each template describes the information that is recommended to provide a user with sufficient data to apply a model for the specific use case. Approval for production of an SAE standard called 'Model Description Documentation Recommended Practice for Ground Vehicle System and Subsystem Simulation' was granted, and an SAE standard number (J-2998) was assigned. The draft of the standard is currently undergoing review and revision.

The goal of this project is to define standards for the documentation of finished (or production-ready) dynamic models. The standards will make models reusable by providing a clear, concise, and complete description of their capabilities, requirements, applications, and assumptions.

Dynamic modeling, as part of enterprise-wide and/or industry-wide engineering processes, requires different types of documentation to support different engineering functions for model development, application, management, and production. These functions require both unique and common information about a model. In addition, to protect intellectual property, different levels of documentation are required for engineering collaboration functions internally (i.e., within a company), externally (i.e., between companies), and globally (i.e., for internal and external work across national borders). Specifically, Model Description Documentation is needed for the following four categories of work.

1. Model users and simulation analysts from different disciplines apply models for various engineering tasks. For sharing and reusing existing models, they require a high-level

overview description to select an appropriate model with the capabilities, features, and performance required for their specific analysis purposes.

2. Model developers or producers (simulation modelers/developers/providers/suppliers) create new models or maintain, integrate, and modify existing models. To develop new models, they need to receive documentation that specifies the requirements for the model to enable performance of the intended analysis. They also need to provide documentation for users to understand and apply the models that they develop. In addition, to maintain, enhance, and continuously improve existing models, they require more detailed information about the physical principles, equations, assumptions, and approximations used.
3. Simulation model requestors are model users and simulation analysts who require new or improved models to perform specific engineering analysis functions for which models do not exist or are inadequate. To request new models or improved models, they need to supply or provide documentation that specifies the requirements for the model to enable performance of the intended analysis.
4. Modeling and simulation process management controllers require documentation to control the introduction, update, and removal of models from model libraries available for standard engineering analyses. These controllers ensure that the models are thoroughly tested, documented, and meet required performance measures before they are released for engineering work. To guarantee the quality of simulation results, they need information about model documentation, performance, verification, validation, change history, and theoretical basis.

The committee developed a list of the main content information recommended for model documentation for the different use case views. The outline of all of the main content includes, but is not limited to, the following major section headings:

1. Model Title (provide a name for the model)
2. High-Level Description of Model
3. Purpose/Applications/Usage
4. Features and Capabilities
5. Model Applicability and Limitations
6. External Interface Variables (or inputs and outputs)
7. Internal Variables
8. Parameters and Calibration Procedures
9. Model Architectural Structure
10. Detailed Functional Description
11. Implementation Requirements and Dependencies
12. Performance
13. Operating Instructions
14. Verification and Validation
15. Model Administrative Information

Model Architecture and Interfaces Project

The fundamental objective of this task is to establish modeling standards and conventions for the architectural structure and interfaces of dynamic ground vehicle simulation models.

One goal is to define (1) a standard vehicle system modeling architecture, (2) standard fundamental model building blocks that can be used to define any ground vehicle system, and (3) standard interfaces for the model building blocks. Another goal is to clarify the interaction among complex systems, subsystems, and components across disciplines to facilitate interdisciplinary understanding and collaboration. This task will (1) establish a basis for model plug ability and (2) define the standards required to establish fundamental model building blocks that can be reused and exchanged within and between organizations across the automotive ground vehicle industry.

The purpose and benefits of defining standards for architectural structure, interfaces, and implementation conventions for dynamical models are as follows:

1. Enable and facilitate exchange, reuse, and sharing of models across all disciplines of engineering and physics within organizations for enterprise-wide collaboration and across the industry (among OEMs, suppliers, research laboratories, government agencies, and universities) for inter-organizational collaboration.

2. Reduce or eliminate duplication of modeling work products by defining the boundaries and scope of models
3. Reduce the effort required to integrate models of all of the systems, subsystems, or components needed to create a functional system model for any ground vehicle
4. Make models of varying fidelity or abstraction rapidly connectable and functional in an overall system, subsystem, component, or mathematical function model (i.e., make models "pluggable and playable")
5. Reduce model development time and costs and improve model quality
6. Enable and facilitate management of large systems development projects through parallel development paths (i.e., decoupled development)

The committee has developed a model of the architectural structure for a ground vehicle system. The architecture is a hierarchical structure showing the interconnection of the fundamental subsystem building blocks. The architecture and subsystem partitioning has been validated against all known or proposed alternate vehicle and propulsion configurations for automotive, trucking, military, agricultural, mining, construction, and off-road equipment applications. A ground vehicle system architecture was proposed, modified, and refined through an extensive validation process that included the following propulsion alternatives: combustion engines, electrics (battery and fuel cell), hybrids (parallel and series) hydraulic hybrids (parallel and series), and flywheel hybrids; and the following chassis alternatives: front-wheel drive, rear-wheel drive, all-wheel drive, tractor trailer, and tandem or double-bottom trailers.

The results of this validation process demonstrated the any ground vehicle system can be described by the hierarchical model architecture structure shown in Figures 1 through 4. The first level of the hierarchy or top-level view of the model for a ground vehicle system is defined in Figure 1, which consists of six major subsystems. Figures 2 and 3 show some of the second level in the hierarchy, which defines the internal structure of the six major subsystems. In these figures, the Power Subsystem and the Chassis Subsystem Models reveal the architecture of their internal subsystems. Figure 4 shows an example of the third level of the hierarchy, where the internal subsystem architecture of the Trailer Subsystem (an internal subsystem of the Chassis Subsystem) is defined. Note that the Trailer Subsystem also includes a Trailer 2 Subsystem located on the far right, which would describe a fourth-level subsystem for a tandem trailer application.

The internal architecture of the Power Subsystem architecture is shown in Figure 2 as being composed of, at most, 11 subsystems. The internal architecture for the Chassis Subsystem is defined in Figure 3 and composed of, at most, 9 subsystems. Finally, the Trailer Subsystem internal architecture is defined in Figure 4 as being composed of seven subsystems. This layered approach to organizing models in a hierarchy can continue for each of the subsystems to reveal their internal subsystem architecture until the lowest subsystem level is reached; at that level, the internal architecture of each subsystem is composed of components. Each component will be described at the lowest level of the hierarchy by a mathematical model of its dynamic behavior.

This discussion demonstrates that complete definition of a ground vehicle system hierarchical model to the equation level would require several hundred models. So the scope of the current Model Architecture and Interfaces Project is limited to defining the architecture and interfaces for the top three levels, as described in Figures 1 through 4, to establish a standard for plugability of ground vehicle subsystems. After, the standards for architecture and interfaces for subsystems in the first three levels are defined, the focus of the standards development activity will shift to the development of standards for playability and portability of these models. The development of model architecture and interface standards for other lower-level subsystems and components is beyond the scope of the current effort. The intention of the current project is to lay a foundation for model reusability through standards that establish plugability and playability of dynamic models for ground vehicle systems; this foundational methodology can be extended to lower-level subsystems and components in the future.

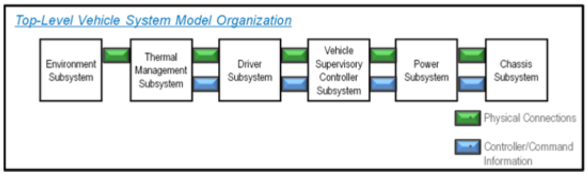


Figure 1. Top-Level Vehicle System Model Organization.

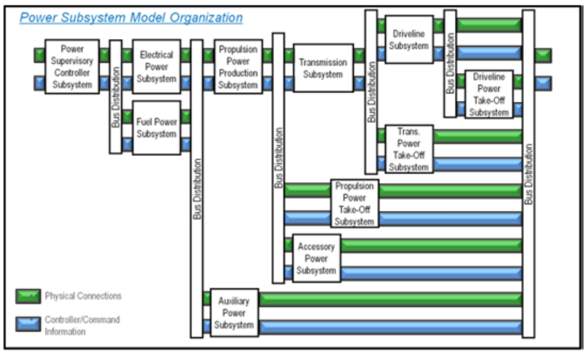


Figure 2. Power Subsystem Model Organization.

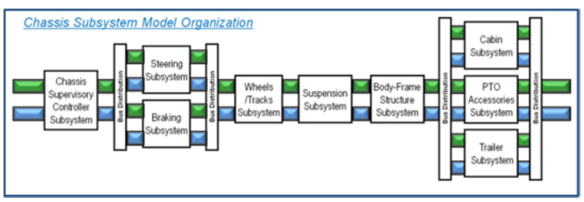


Figure 3. Chassis Subsystem Model Organization.

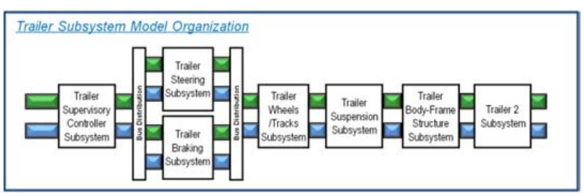


Figure 4. Trailer Subsystem Model Organization.

Conclusions

During this year, a draft for an SAE standard (J-2998) called "Model Description Documentation Recommended Practice" for Ground Vehicle System and Subsystem Simulation' was developed. The standard is currently undergoing review and revision in preparation for release early in calendar year 2013. A second major standards project was chartered and is under development for defining Model Architecture and Interfaces (Project 2). For this project, the definition of the system architecture structure and model partitioning of a vehicle system is fairly mature and ~80% complete. Next steps will be to finish the architecture definition and establish definitions for the interfaces of the architecture. Definition of model interfaces will lead to the third major standards project on the development of a definition for the Model Data Dictionary Interface Information, which will provide playability for models in any single modeling tool, but not across tools.

VI.H.3. Products

Publications - None.

Patents - None.

Tools & Data - None.

VI.I. Green Racing Technical Support

Principle Investigator: P.T. Jones
Oak Ridge National Laboratory
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1472; Email: Jonespt@ornl.gov

Technical Advisor: Bob Larsen
OboTech LLC
853 Merrill Way
Port Angeles, WA 98362
Phone: (360) 452-9700; Email:bob@obotech.com

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov:

VI.I.1. Abstract

Objective

- Incentivize vehicle manufacturers to develop, validate, and promote advanced technology relevant to production vehicles through motorsport participation.
- Increase the use of renewable fuels and petroleum alternatives in racing, and provide an avenue to introduce new fuels or bio-fuel blends.
- Increase the use of electric drive technologies in racing.
- Use racing as a platform to educate the public:
  - on the potential of renewable fuels and the concept of well to wheels fuel life cycle
  - on the performance and efficiency benefits and capabilities of advanced vehicle technologies.
- Diversify the success of the Green Racing Initiative beyond American Le Mans Series to include other racing series with the final goal of establishing advanced transportation technologies as a foundation for all motorsports.
- Gain automotive industry support in the validation of “green racing” in the United States and internationally.
- Maintain collaborative partnership with the U.S. Environmental Protection Agency (EPA) and SAE International.

Approach

- Work with the American Le Mans Series (ALMS) and its partners to strengthen its green racing program.
- Refine scoring system; make it easier to understand and distribute through media/outreach efforts the benefits of utilizing motorsports to advance transportation technologies.
- Increase outreach to teams to encourage renewable fuel use.
- Recommend HEV rules that create incentives for use.
- Increase availability of second-generation biofuels.
- Improve visibility and understanding of Green Challenge scores with media and race fans.

Major Accomplishments

- All of the full season GT class cars racing with the ALMS, with the exception of the new Lotus were running on biofuel (the lone team will be switching to E85 for 2013). The Chrysler SRT Viper returned running on E85!
- Provided guidance to ACO with regards to regulations for 2014 announced at 2012 Le Mans, which include fuel allocations and Hybridized powertrains for LMP1 category vehicles in 2014.
- HEVs from Audi and Toyota raced at Le Mans in 2012, with the AUDI HEVs taking win and second place.
- Nissan DeltaWing raced at the 24 hours of Le Mans and Petit Le Mans; where it finished in 6th position overall after starting from the back of the field as an unclassified car.
- Dyson Racing runs with Flybrid KERS at VIR and Petit Le Mans.
- 2012 Environmentally Friendly Vehicle Conference (Baltimore, MD) discussion panel moderated by Scott Atherton (ALMS CEO) and attended by Lee Slezak (DOE), Mark Kent (GM), Dr. Ulrich Baretzky (Audi), John Doonan (Mazda), Ben Bowlby (Delta Wing Designer) and Scott Clark (Michelin); all presenters paying high acclaim to utilization of motorsports as ultimate development arena for advanced transportation technologies.
- The ALMS, over the entire 2012 season on a distance-weighted basis, displaced over 37% of the petroleum typically used in racing with renewable fuels. GHG emissions were reduced by over 20%.
- Increased Green Challenge visibility on national and international television coverage and with teams and media.
- Refined the Green Challenge scoring system to make it more transparent by showing the results as the sum of three scoring elements: Clean Fast, and Efficient.
- Assembled Green Racing Protocol Committee for SAE J2880 Green Racing Protocol revision.
- Facilitated testing of the HySpy fuel flow meter at Sebring, Baltimore, and Petit LeMans. This highly accurate fuel flow meter is being considered as the primary method for implementing fuel allocation Green Racing strategy by the FIA, ACO, and ALMS.
- Engaged Regional SAE members at VIR for introduction to Green Racing.
- Transported and displayed the Green Racing Simulator (E85 CORVETTE HEV race car simulator) at five ALMS races and several additional events around the country.

Future Activities

- Obtain balloted approval of revised SAE J2880, the Green Racing Protocols, to reflect a new emphasis on electric drive technology; update definitions and life cycle analysis approaches to keep it current with evolving technology and the needs of racing.
- Work with new NASCAR/GRAND-AM and ALMS partnership to incorporate renewable fuels and advanced technology into racing into series in addition to ALMS.
- Support and incentivize the use of energy recovery technology in race cars, and identifying methods available to properly limit and/or record use of technologies to allow for performance balancing.
- Move towards a scoring system based on energy allocation, working with industry partners to develop fuel flow measurement technologies applicable in a racing vehicle.

VI.I.2. Technical Discussion

The Green Racing Initiative is a collaborative effort funded by DOE in partnership with the U.S. Environmental Protection Agency and SAE International. Oak Ridge National Laboratory (ORNL) coordinates the efforts of Green Racing (GR) in the sports car racing arena of motorsports for the DOE. FY 2012 was the fourth year of significant activity in this program signified by the third full season of the Green Challenge award in the American Le Mans Series. Through ORNL, DOE provides technical assistance, instrumentation, and analysis for this paradigm-shifting project. In FY 2012, the Green Racing initiative made major strides in taking advantage of the racing's huge potential for rapid technical development and the equally large potential to achieve DOE's objectives for public outreach. Additionally, major OEMs and sanctioning bodies came out in support of sustainable racing at a number of events this year.

Background

The Green Racing Initiative started in 2006 with a working group of industry, government and national lab representatives who sought to take advantage of the efforts and opportunities in motorsports to further develop advanced transportation technologies that could be applied to street vehicles. This effort focused on providing a proving ground for petroleum displacement and technology advancements in a competitive setting. Once the working group had built the foundation for GR, a set of protocols was approved through SAE and in 2008 the J2880 'Recommended Green Racing Protocols' were established.

The American Le Mans Series (ALMS) acknowledged these protocols and awarded the first Green Challenge Award in October 2008.

Figure 1. Corvette racing – the first recipient of the GT Class Green Challenge Award, proudly displays their fuel choice on the front bumper. Lessons learned when the racing program was running a GDI/E85 engine went into future GM production GDI vehicles.

The Green Challenge Award and the Michelin Green X Challenge soon became an integral part of ALMS racing, where Michelin awards the teams and the DOE EPA and SAE recognizes the manufacturers who perform best when evaluated using the Green Racing formula for competition. This formula takes into account measured performance and fuel consumption to determine a total score: Clean, Fast and Efficient terms are calculated in real time for each lap for each vehicle in the Prototype and GT categories.

Introduction

The 2011 racing season ended at the beginning of FY 2012 and went on record to show that sustainable motorsports activities advance both technology and performance, as the acquired speeds and efficiencies of the vehicles both increased. The 2012 season has been no different with the fiercest competition in the thirteen year history of the ALMS. Teams have applied new technologies and sanctioning bodies have confirmed future rules which incorporate sustainable practices and require advanced technologies for future racing vehicles. The Green Racing Initiative seeks to coordinate the strategies and guide motorsports requirements to optimize efforts within motorsports to highlight advances in transportation technologies.

Approach

Motorsports are the only professional sports that can directly help attain critical national energy and environmental objectives. Such racing-based events can help achieve these objectives by directing the vast creativity and engineering talent, significant spending, and rapid developmental cycles in racing toward the use of advanced transportation technologies and renewable/alternative fuels. These efforts reduce our dependence on petroleum and lower the carbon footprint of vehicles – and still provide the entertainment and drama that has made racing one of the most followed forms of sports around the world. Racing is one of the best platforms for reaching a large audience with the message that, through advanced vehicle technologies and renewable fuels, we can maintain the personal mobility and performance customers want while moving toward the energy security and sustainable transportation the country needs.

Racing brings out the best in automotive technology and places it in a demanding competitive environment allowing a technology showcase that resonates with the public. Racing also inherently values efficiency as successful teams operate in alignment with sanctioning body rules to optimize fuel use with other racing parameters, like distance between required tire changes. Efficiency and petroleum displacement are attributes that underpin our national energy and environmental objectives. Building on core values in racing and adding renewable fuels and advanced transportation technologies as ways to improve sustainability - we have developed the Green Racing Initiative with our partners.

Results

The 2012 racing season had a number of highlights in advancing transportation technologies through motorsports. Of particular interest was the inclusion of four hybridized racing vehicles on the starting grid of the 24 hours of Le Mans. Additionally, at Le Mans, in the new technologies class the fan favorite Nissan DeltaWing experimental vehicle raced competitively for the first time. Audi and Toyota each brought two hybridized LMP vehicles to the event, with the Audi's taking the pole and finishing in first and second place. Audi filled the podium with its R18 Ultra Diesel (non-hybrid) finishing third. Of equal importance to the future of motorsports, the Automobile Club de l'Ouest (ACO) announced that for 2014 the premiere Le Mans Prototype (LMP1) category vehicles could expand the size and type of energy recovery and have hybrid technologies as well as allowing a limited amount of energy (fuel) per lap depending on the level of hybrid technologies applied to each car. The ACO developed the rules in a manner to enhance efficiency and not performance. The rules will be remarkably open with regards to technologies allowing the factory teams to be innovative in creating and applying advanced technologies. This shift of motorsports to an energy allocation, rather than purely speed, represents a substantial change in the perspective of sanctioning bodies, and places a renewed relevance in the sport, as energy efficiency is something the manufacturers deal with in every vehicle they produce.

The Green Racing Initiative has become an integral part of the ALMS which maintains its claim as the global leader in green racing. The 2012 season continued the growth and acceptance of green racing activities in the series. The ALMS continues to search for opportunities to support alternatives to petroleum and announced in 2012 that it was partnering with Patrick Racing to demonstrate 2 LMPC cars running on LNG during the 2013 season. This announcement was supported by additional at track meetings with key project members and representation from the Green Racing Working Group (GRWG).

The 2012 ALMS season continued to offer alternative fuels for use by its competing teams. Every Green Challenge victory in the GT category was won by a car using advanced fuels. And in the LMP category, a significant showing of technology at Petit Le Mans occurred when the FlyBrid KERS-Isobutanol/Turbocharged 4 cylinder Mazda raced by Dyson Racing acquired maximum ALMS P1 points.

There was an important initial movement toward relevance in racing from the GRAND-AM series in the summer of 2012, with the announcement of its new GX class for alternative fuels and advanced technology applications in race cars. However, the September announcement that GRAND-AM and the ALMS would merge in 2014 trumped all previous news with regards to GR in the U.S. ALMS CEO Scott Atherton is committed to GR and the inclusion of the Green Racing Protocols in the new unified series.

In the GT, E85R dominated as the fuel of choice in this ultra-competitive category. All the top three finishers in all the races used E85R fuel. The GT class is based on cars that are on the road today and puts rival teams in door-to-door competition that may be the most competitive class in racing anywhere in the world. All the BMW, Corvette, Ferrari, and Porsche factory and most of the privately entered cars used this renewable fuel with great success. The wholesale movement to E85R was primarily motivated by the performance potential of this excellent fuel, but the message with respects to its upstream impact and its energy security and environmental advantages have provided an excellent outreach opportunity for DOE goals.

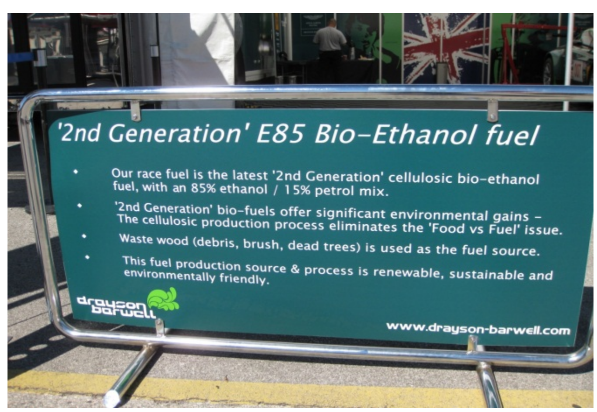


Figure 2. The Drayson racing team utilized this information board as a method of public education.

The Green Challenge scoring system accurately reflects each fuel's characteristics in terms of its greenhouse gas and oil replacement attributes without rewarding a team's selection of bio-fuels over conventional fuels. That makes this switch to renewable fuels at this level of motorsports all the more impressive and significant.

For the entire 2012 season and taking into account the total number of miles raced, 37.2% of the oil that would have been used before the Green Racing Initiative was begun was replaced by renewable and non-petroleum fuels. This noteworthy accomplishment demonstrates that these fuels are capable of outstanding performance, reliability, and capable of widespread use in street vehicles.

This year brought more visibility for DOE's involvement in the ALMS Green Challenge awards through a concerted effort of DOE, ORNL, and EPA staff in cooperation with ALMS media relations representatives. More television and radio time was devoted to Green Challenge scoring and explanations.

Figure 3. Regional SAE members receive racing 'GREEN' instructions at Virginia International Raceway.

At the inaugural race at Virginia International Raceway (VIR) the ALMS and GRWG combined to host a regional SAE meeting and Green Racing Introduction. Four teams and two Green Racing partners provided insight to the local professionals from the transportation industry.

Another first at the VIR race was the first LMP1 car to compete with a mechanical Kinetic Energy Recovery System (KERS). The Dyson Racing Mazda #16, which won the ALMS and Green Racing Championship in 2011 running a turbocharged 4 cylinder on isobutanol fuel, added the flywheel ESS system to the powertrain for the last two races of the year.

Figure 4. Flybrid system employed in #16 Dyson/Mazda at Petit Le Mans (photo by Eric Gilbert Motorsport.com)

"Without being able to race our hybrid systems in motorsport we would be much further behind in the technical development for our road car and bus hybrid systems." Tobias Knichel FlyBrid Commercial Manager and Racing Engineer. "The ALMS is the leader in green racing and the perfect series to showcase this technology," added Chris Dyson team owner.

Following on the success of the last years Green Racing Simulator (GRS), the mobile outreach simulator was deployed again this season for the Green Racing program. The GRS, developed by Argonne National Laboratory, incorporates a program that calculates the amount of regenerative braking energy captured and fuel used during two laps of simulated racing. This simulator was set up at five ALMS races in 2012, as well as other events. It served as a notable means of disseminating the DOE Green Racing's key message that the use of renewable fuels and hybrids can displace a substantial amount of imported petroleum.

Figure 5. Fans and professional racing drivers alike try their hand at the GRS. Tommy Milner of Corvette Racing puts the simulated E85/Hybrid Corvette to the test.

The GRS was a main attraction at several events throughout the season including sharing the spotlight with the DeltaWing at the 5th International Environmentally Friendly Vehicle Conference (EFVC) hosted in Baltimore, MD.

Figure 6. The GRS on the exhibit hall floor of the International Environmentally Friendly Vehicle Conference with the Nissan DeltaWing prior to opening of the event.

In addition to the GRS, some of the major stakeholders of Green Racing were on hand during the 2012 EFVC at the 'Race to Future Technology' panel discussion led by ALMS CEO Scott Atherton. On the panel were Lee Slezak (DOE), Mark Kent (GM), Dr. Ulrich Baretzky (Audi), John Doonan (Mazda), Ben Bowlby (DeltaWing Designer) and Scott Clark (Michelin); all presenters paying high acclaim to utilization of motorsports as ultimate development arena for advanced transportation technologies. Video of the event will be available on the EPA website.

Following the round of improvements that were made to the Green Challenge scoring system for last year's 2011 season, efforts continued to put results into a more easily understood format. The scores are comprised of three major components: Clean, Fast, and Efficient terms, each with significant impact on the overall scores. This change has been very well accepted by the media, as well as by the teams, as it provided a simple way to understand the elements that go into the score. The changes also improved the correlation between on-track performance and Green Challenge scores. At the end of every race, a summary of the results of the Green Challenge scores were produced that highlighted the comparative energy efficiency and average speeds of the competitors in MJ/km and km/hour, respectively. Updates to the well-to-wheel petroleum and greenhouse gas calculations using the latest GREET model release were made again this season. Of particular importance for next season some clean and biodiesel pathways will need to be revisited for GREET to ensure that all ALMS available fuels are accurately represented.

The DOE/EPA/SAE International's season-long Green Challenge awards were given to the vehicle manufacturers in the LMP and GT categories with the best Green Challenge Score for the season. For 2012, the winner in the Prototype category was Honda HPD for the P1 ARX-03 Honda run by Muscle Milk Petit Racing. And for GT category, General Motors earned the Green Challenge Championship award with Corvette Racing. Both teams also won their respective ALMS series championships, which validates the assumption that efficiency is a core attribute and focus area for motorsports.

Conclusions

Motorsports in FY 2012 reacted positively from efforts and developments in the Green Racing Initiative. Significant petroleum reduction was recorded by the ALMS in 2012 with nearly 40% displacement of petroleum when compared to a baseline of the 2005 series. Nearly all vehicles in GT class are running on E85 racing fuel, and the SRT Viper returned to the ALMS GT series running on E85. GRAND-AM, sports car series owned by NASCAR made provisions to allow for fuels other than gasoline to be used in competition, and the planned merger between the ALMS and GRAND-AM is ripe with opportunities to expand the recognition of Green Racing and sustainable transportation developments through motorsports.

Important accomplishments in incorporating energy recovery into world class sports car racing were showcased multiple times during the year. Two of the most significant events being the Audi Diesel HEV victory at the 24 hours of Le Mans and with the first factory-backed LMP1 (Dyson/Mazda Flybrid) taking maximum ALMS points at the 2012 Petit Le Mans.

The relationship between our partners at EPA and SAE International are strong and the future holds many opportunities for building acceptance of Green Racing principles as the working group moves forward with the revisions to the Green

Racing Protocol. The Green Racing Initiative continues to impact the future of motorsports in alignment with DOE's transportation goals.

VI.I.3. Products

Cooperative development of systems and performance information is provided by partners and contacts made through the Green Racing Innitiative.

Tools & Data

During FY 2012 and continuing in FY 2013, proprietary data and opportunities to be included in test/development were made available to the GRWG representatives. As these are projects in process reports will be generated in FY 2013.

1. SAE J2880 Green Racing Protocol revision.
2. HySpy fuel flow measuring systems ability to enable enforcement of energy allocation regulations.
3. Mazda SkyActiv-D engine PM data will be utilized for BioDiesel fuel selection for 2013 racing season and beyond.
4. FlyBird field data for braking energy values and component model verification.

VII. VEHICLE SYSTEMS OPTIMIZATION

AERODYNAMIC DRAG REDUCTION CLASS 8

VII.A. DOE Project on Heavy Vehicle Aerodynamic Drag

Project Principal Investigator: K. Salari
Co-Investigators: J. Ortega, Katie Lundquist, and Paul Urbanczyk
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94551-0808
Phone: (925) 424-4635; Email: salari1@llnl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

VII.A.1. Abstract

Objective

Class 8 tractor-trailers are responsible for 12-13% of the total US consumption of. At highway speeds, approximately 65% of the usable energy expenditure for a class 8 heavy vehicle is used to overcome aerodynamic drag. The project objective is to improve the fuel economy of class 8 tractor-trailers by at least 25% through the use of aerodynamic treatments. This presents 12% improvement in fuel economy at highway speeds, which translates to 3.2 billion gallons of diesel fuel saved per year and 28 million tons of CO_2 emission. The specific goals of this project include:

- Providing guidance to industry in improving the fuel economy of class 8 tractor-trailers through the use of aerodynamics
- Developing innovative aerodynamic designs/concepts for significant improvement in fuel economy that are operationally and economically sound
- Establishing a database of experimental, computational, and conceptual design information
- Demonstrating the potential of new aerodynamic designs for drag reduction

Approach

- Simulate and analyze the aerodynamic flow around heavy vehicles using advanced computational fluid dynamics (CFD) tools
- Produce an experimental database for code validation and better understanding of the flow physics
- Provide industry with design & performance guidance and insight into the flow physics around heavy vehicles from experiments and computations
- Investigate passive and active aerodynamic drag reduction concepts and devices (e.g., tail devices, tractor-trailer gap devices, and trailer underbody devices, etc.)
- Provide industry with conceptual designs for better aerodynamic bodies for the tractor and the trailer
- Demonstrate the fuel economy /performance of proposed aerodynamic treatments in wind tunnels and on the road

Major Accomplishments

- Collection of fuel economy data on over 80 tractor-trailers outfitted with aftermarket aerodynamic devices and wide-base single tires.

- Design of drag reduction devices for tanker-trailers.
- Journal submission of our full-scale wind tunnel report (*Fuel economy improvement of class 8 heavy vehicles through aerodynamic drag reduction: a full-scale wind tunnel study*) based upon data taken at NASA Ames, NFAC full-scale wind tunnel facility

Future Direction

- Continue with collecting and analyzing on the road fuel economy data from Frito-Lay and Spirit fleets for vehicles outfitted with aerodynamic drag reduction devices and wide-base single tires.
- Design and evaluate the aerodynamic performance of new trailer design and integrated heavy vehicle designs in a 1/8th scale wind tunnel test at the NASA Ames 7'×10' wind tunnel
- Design and evaluate the aerodynamic performance of new fairings for tanker trailers in a 1/8th scale wind tunnel at the NASA Ames 7'×10' wind tunnel
- Acquire aerodynamic force data and high-resolution velocimetry data of the flow field around the heavy vehicle through wind tunnel measurements made at NASA Ames
- Explore the benefits of tractor-trailer integration for improved fuel economy (geometry, flow, and thermal)
- Perform aerodynamic optimization of integrated vehicle designs

VII.A.2. Technical Discussion

For the FY 2012, the Heavy Vehicle Aerodynamic Drag Project achieved three major accomplishments.

The first is the collection of fuel economy data on over 80 tractor-trailers outfitted with aftermarket aerodynamic devices (Freightwing and ATDynamics) and wide-base single tires (Michelin) (Figures 1-2). We are presently collaborating with two fleets (Spirit and Frito Lay), which supply daily fuel economy data for both baseline and retrofitted vehicles. A basic analysis of statistical variance (ANOVA) with miles per gallon as a response and the device as a predictor is performed on various data sets that are separated either by vehicle, combined together across all vehicles, or filtered according to the average trip speed. A sample data subset from the Spirit fleet is shown in Table 1.

Freight Wing Skirts & ATD Boattail

Freight Wing Gap Fairing and Skirts

Figure 1. A Spirit trailer outfitted with Freightwing skirts and an ATDynamics (ATD) four-sided boattail..

Freight Wing Boattail

Michelin Single Wide Tires

Figure 2. Freightwing three-sided boattail and Michelin wide-base single tires.

Table 1. Sample fuel economy data from the Spirit fleet (ATD—ATDynamics, FW—Freightwing)

Date_start	Time_start	Date_end	Time_end	Fuel (gal)	Miles	MPG	MPH	Gal/Miles	Device
9/1/2011	0:00	9/1/2011	6:00	17.375	106.5	6.13	62.9	0.163	none
9/1/2011	6:00	9/1/2011	12:00	48.125	344	7.15	62.8	0.14	none
9/24/2011	6:00	9/24/2011	12:00	0.5	0.8	1.6	6.8	0.625	ATD
9/24/2011	18:00	9/25/2011	0:00	33.75	254.8	7.55	58	0.132	ATD
9/25/2011	0:00	9/25/2011	6:00	4.125	30.3	7.35	63.9	0.136	ATD
10/24/2011	6:00	10/24/2011	12:00	29.375	232.3	7.91	61.7	0.126	FW
10/24/2011	12:00	10/24/2011	18:00	35.625	307.5	8.63	60.1	0.116	FW
10/25/2011	0:00	10/25/2011	6:00	1.625	7.6	4.68	19.2	0.214	FW
10/25/2011	6:00	10/25/2011	12:00	24	211.1	8.8	53.8	0.114	FW

The second major accomplishment is the design of drag reduction devices for tanker-trailers. There are approximately 200,000 of these trailers in the United States, with about 60% utilized for the aluminum and petroleum product service, 15% for chemical transport, 15% for food-grade transport, and 10% for dry bulk transport.[1] On average, tanker-trailers operate at about 5 mpg.[2] Although these vehicles comprise a rather small portion of the United States heave vehicle fleet, we estimate that a 1% fuel economy improvement would yield approximately 31×10^6 gallons of fuel saved per year.

Our effort in reducing the aerodynamic drag of these vehicles is to utilize computational fluid dynamics simulations as a design tool. Figure 3 shows a baseline tanker-trailer that is outfitted with a gap fairing that has been previously developed by our research group. We have conducted simulations on this vehicle, which is subsequently retrofitted with a tanker boattail. The computational results (Figures 4-5) demonstrate that for a tanker-trailer traveling at 65 mph in a cross-wind, the gap fairing reduces the aerodynamic drag by about 26% and the boattail by another 4%.

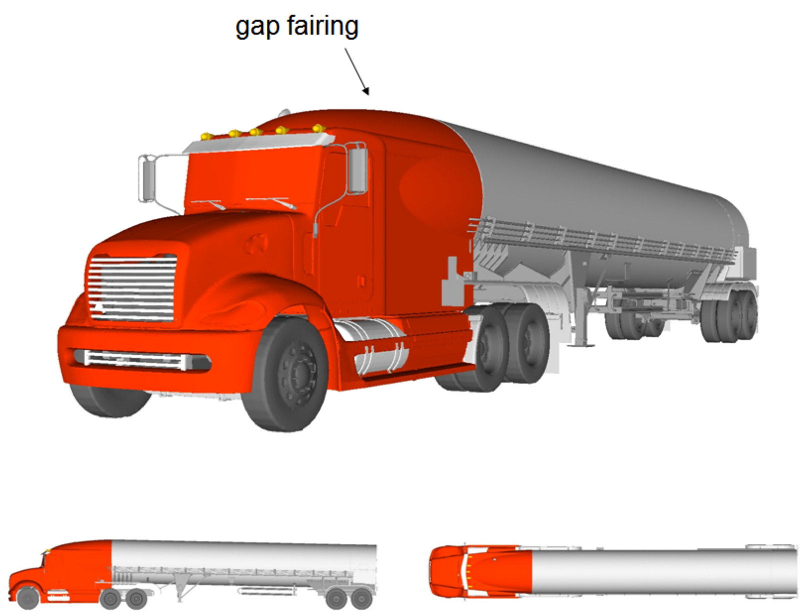


Figure 3. Baseline tanker-trailer vehicle that is outfitted with a gap fairing.

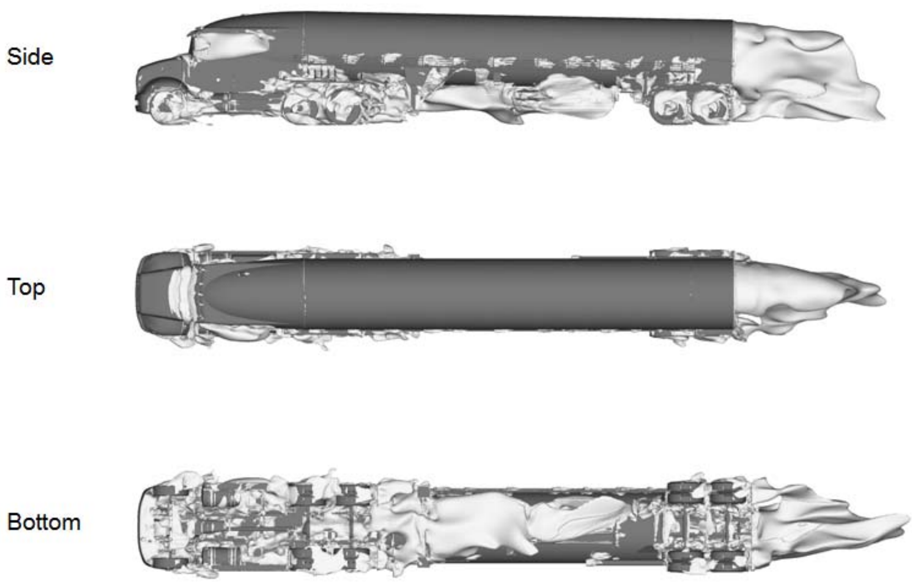


Figure 4. Regions of reversed flow for the baseline tanker-trailer with a gap fairing (computational fluid dynamics results).

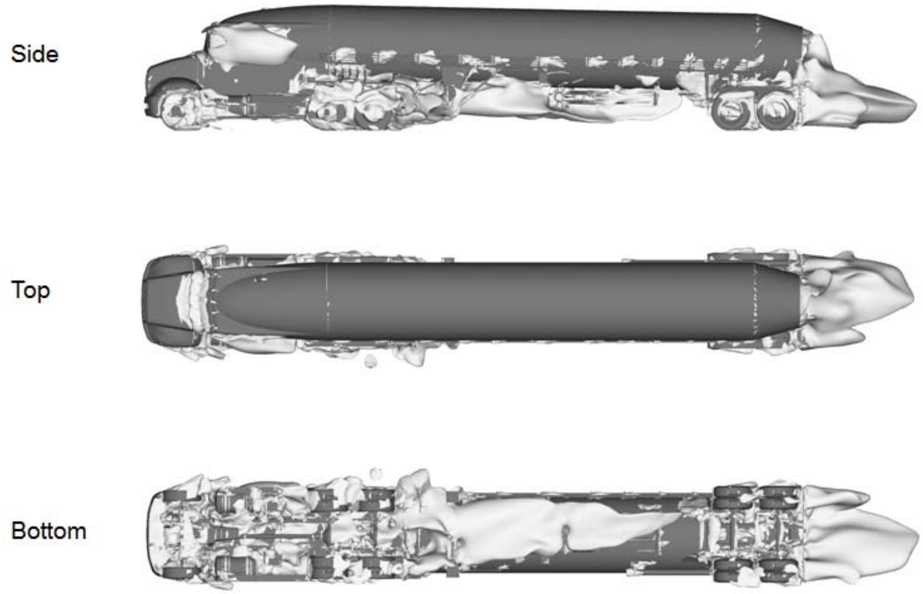


Figure 5. Regions of reversed flow for the baseline tanker-trailer with a gap fairing and a boattail (computational fluid dynamics results).

The final accomplishment for FY 2012 is the journal submission of our full-scale wind tunnel report (Fuel economy improvement of class 8 heavy vehicles through aerodynamic drag reduction: a full-scale wind tunnel study) based upon data taken at NASA Ames, NFAC full-scale wind tunnel facility. During this test, body-axis drag coefficient data is acquired by making drag force measurements on three full-scale tractor-trailer vehicles: a 2008 Navistar ProStar long sleeper (LS) tractor with a Wabash 16.2 m straight-frame (SF), dry freight trailer; a 2008 Navistar ProStar day-cab (DC) tractor with the SF trailer; and the DC tractor with a Kentucky Trailer 16.2 m drop-frame (DF), dry freight trailer (Figure 6). The gap between the tractor and trailer is set to 1.1 m for each baseline vehicle configuration and the trailer bogie on the SF trailer is positioned such that the midpoint between the trailer wheels is 3.7 m from the trailer base. The measurements are made within the NASA Ames 80×120 wind tunnel. Aside from a few select runs at speeds as low as 8.9 m/s (20 mph) and as high as 35.8 m/s (80 mph), the nominal tunnel speed is set to 25.9 m/s (58 mph). During each experimental run, the vehicle is yawed on the turntable through a range of angles to simulate varying cross-winds from which the wind-averaged drag coefficient can be calculated. For the majority of the runs, the yaw sweep ranges from -9° to +9° in 3° increments, though for a select number of runs, data is acquired from -15° to +15° in 3° increments.

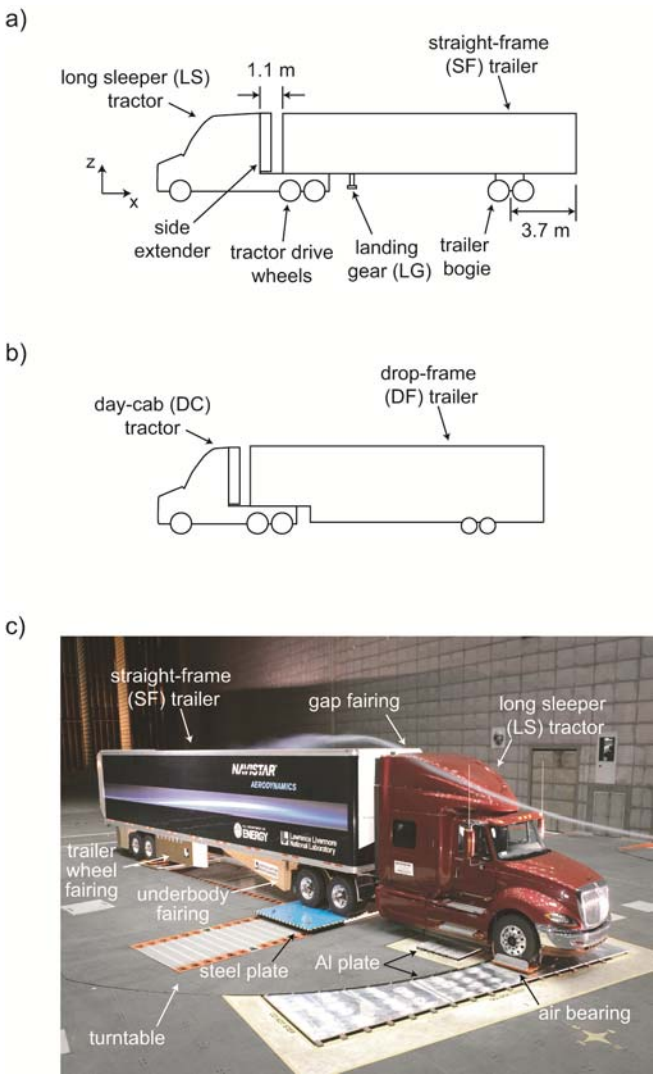


Figure 6. a) Long sleeper (LS) tractor and straight-frame (SF) trailer and b) day-cab (DC) tractor and drop-frame (DF). trailer configurations. c) LS/SF configuration mounted on the wind tunnel force balance.

The drag reduction characteristics are evaluated for devices that are installed in the tractor-trailer gap, trailer underbody, and trailer base. The three gap fairings (GP1, GP2, GP3), which attach to the front of the trailer, are comprised of curved plastic or aluminum plates that increase the radii of curvature of the front edge of the trailer sides and top (see Figure 6c). Other modifications to the tractor-trailer gap include reducing the distance between the back of the tractor to the front of the trailer from 1.1 m to 0.61 m, installing revised side extenders that flare slightly outboard in order to accommodate the smaller tractor-trailer gap on the LS tractor, and filling the gap between the DC side extenders and the trailer front with aluminum sheets. The devices installed on the trailer underbody are various trailer skirts (SK#) (Figure 7) and underbody fairings. Lastly, four boattails (BT) are installed on the trailer bases of various vehicle configurations (Figure 8).

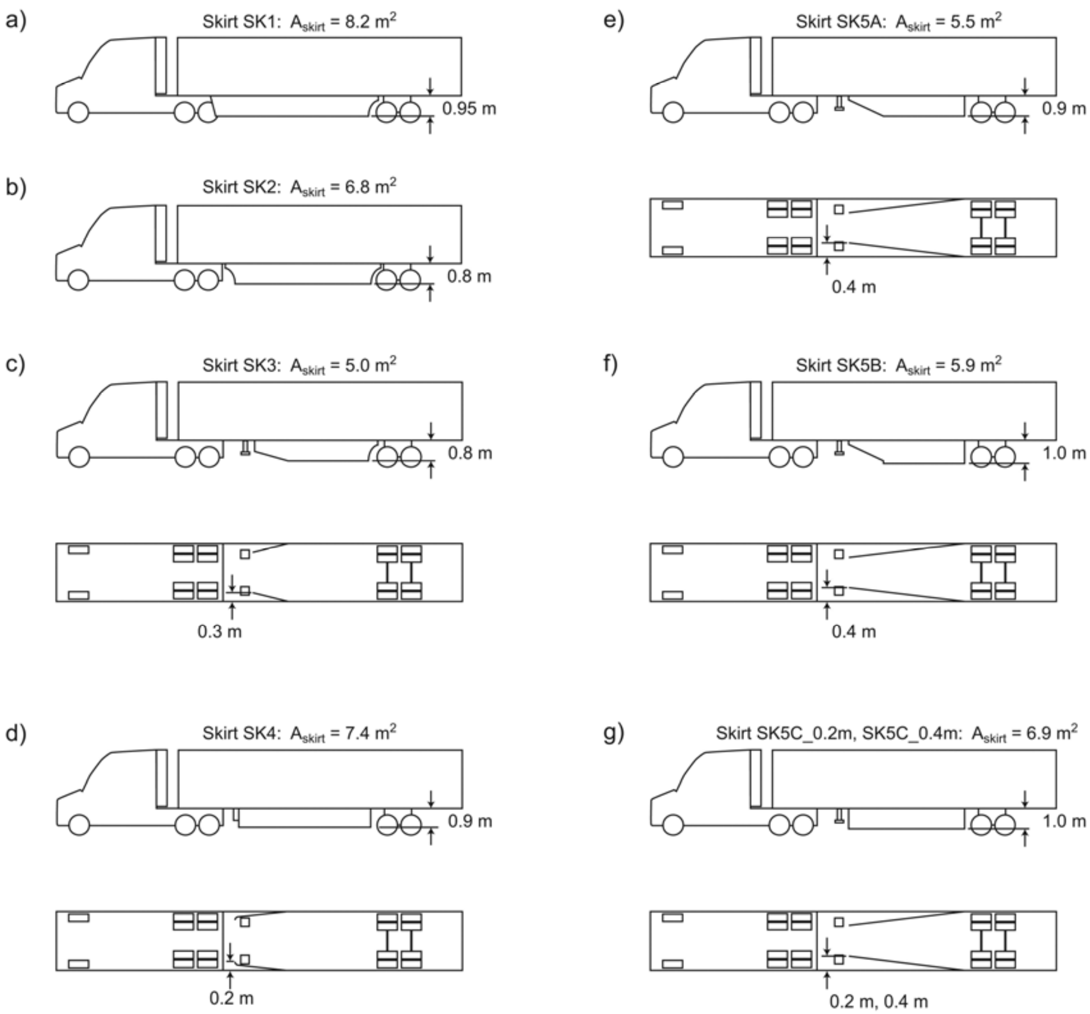


Figure 7. Trailer side skirts (SK). Askirt denotes the surface area of the trailer skirt.

The changes in the wind-averaged drag coefficient for all of the drag reduction devices on the LS/SF vehicle are plotted in Figure 9 (for additional details on the results for the other vehicle configurations, please refer to the original paper). The top performing individual devices are both trailer skirts (SK1–run 82; SK5C_0.2m–run74), each of which yields an estimated fuel savings of approximately 6000 L/2.012×10^8 m of highway mileage driven. The largest drag reduction in the wind-averaged drag coefficient (0.144) for the LS/SF configuration occurs for the simultaneous installation of the SK1 and TWSK1 skirts and the BT2 boattail along with a reduced tractor-trailer gap size of 0.61 m and the revised tractor side extenders. The resulting estimated fuel savings is approximately 14000 L /2.012×10^8 m of highway mileage driven. An even larger reduction in drag (0.150) occurs when the same skirts and boattail are installed on the DC/SF configuration with a 0.61 m tractor-trailer gap, which is completely covered on both the driver and passenger sides. In this case, the estimated fuel savings is calculated to be nearly 15000 L/2.012×10^8 m of highway mileage driven, which is the largest of the entire study.

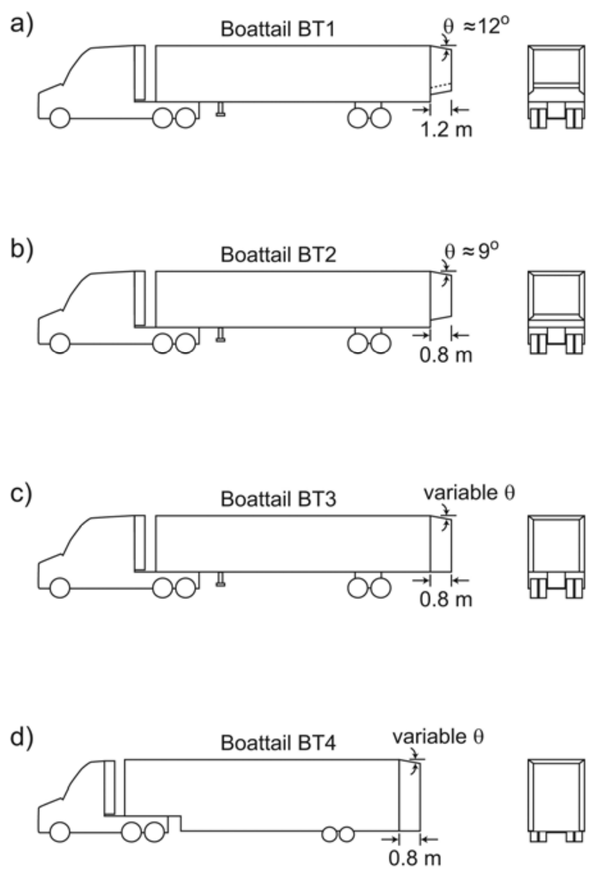


Figure 8. Trailer boattails (BT) for the a-c) straight-frame (SF) trailer and the d) drop-frame (DF) trailer. Boattails a-b) are 4-sided and c-d) are 3-sided.

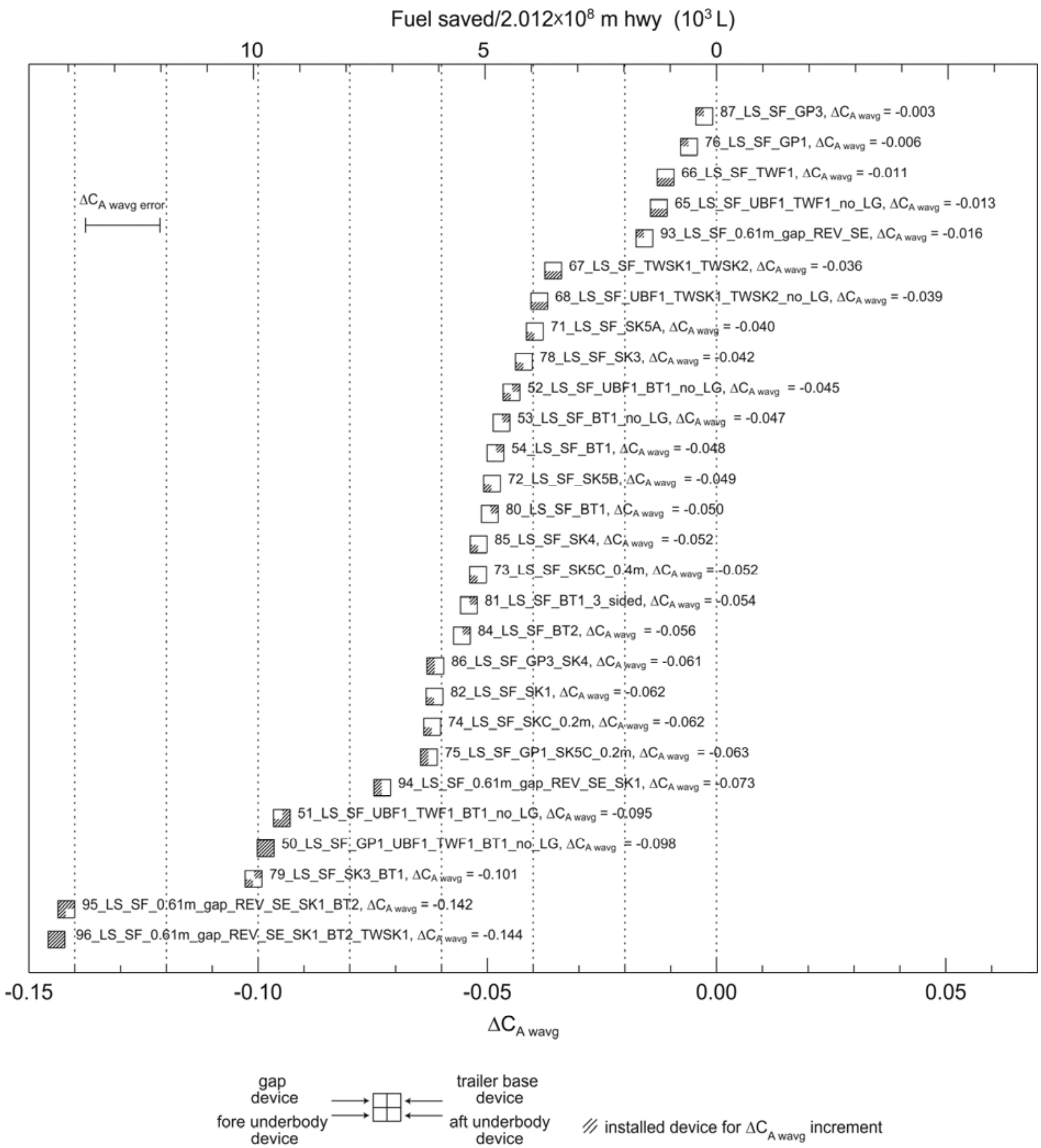


Figure 9. Reduction in the wind-averaged drag coefficient and the estimated highway fuel usage for the long-sleeper/straight-frame trailer (LS/SF) configuration relative to the baseline configuration.

Acknowledgments

- This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

References

1. National Tank Truck Association, tanktruck.org.

2. US Department of Transportation, Transportation Energy Data Book, Edition 26, 2007.

VII.A.3. Products

Publications - None.

Patents - None.

Tools & Data - None.

VEHICLE SYSTEM THERMAL CONTROL

VII.B. Thermal Control through Airside Evaporative Heat Removal

Principal Investigator: Dileep Singh
Coworkers: W. Yu, D. France, and D. Smith
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-5009; Email: dsingh@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VII.B.1. Abstract

Objective

- Explore possibilities of using evaporative cooling in radiator airside heat removal applications
- Determine potential radiator airside heat removal rate increases using evaporative cooling
- Determine potential radiator size reductions using evaporative cooling
- Optimize radiator evaporative fin designs

Approach

- Develop theoretical models for radiator airside evaporative cooling analyses
- Calculate airside heat removal rate increase, size reduction, and water usage for evaporative cooling radiators
- Optimize radiator evaporative fin designs using CFD simulations or experimental tests

Major Accomplishments

- 19% and 46% heat removal rate increases with 76-L/hr and 189-L/hr evaporative water flow rates
- 21% and 52% radiator width reductions with 76-L/hr and 189-L/hr evaporative water flow rates
- 22% radiator width reduction with less than 76 liters of water to traverse an extreme desert hill

Future Activities

- Investigate coating methods and materials to generate proper surface tension
- Experimentally measure the droplet thickness
- Experimentally verify the theoretical calculations using a small radiator
- Working with an OEM, assess the engineering feasibility and the cost-effectiveness of the technology

VII.B.2. Technical Discussion

Background

This project is aimed to explore the possibilities of reducing cooling system size and therefore aerodynamic drag on class 8 trucks by using evaporative cooling under extreme temperature, load, and grade conditions that would be encountered in the US.

Introduction

Aerodynamic drag is a major contributor to fuel consumption in class 8 trucks, especially at highway speeds. Aerodynamic drag, i.e. the resistance to truck's movement through the air, consists of two main components, pressure drag and shear drag. The shear drag for trucks is small compared to the pressure drag, and the basic shape of the truck imposes the pressure drag on the vehicle. Typically, a high-pressure zone is created in the front of the tractor due to the stagnation effect, and a low-pressure zone is created in the rear of the truck, both resulting in pressure drag. The frontal shape of the tractor is dictated in a large part by the radiator resulting in a large stagnation area. The method for reducing aerodynamic drag on trucks proposed in this study is to modify the frontal shape of the tractor by using a hybrid radiator-cooling system, a combination of conventional airside finned surface cooling and active evaporative water cooling.

Approach

Figure 1b shows the hybrid radiator compared to a conventional radiator of Figure 1a. The example hybrid radiator-cooling system shown in Figure 1b is similar to the conventional radiator with vertical coolant channels and fins between them on the air side. However, the channels have been extended beyond the fins on the downstream air side of the radiator. Liquid water flows downwards by gravity along the extended surfaces providing evaporative cooling to the engine coolant. In the case of the hybrid radiator, there is a liquid supply and distribution system not shown in Figure 1b.

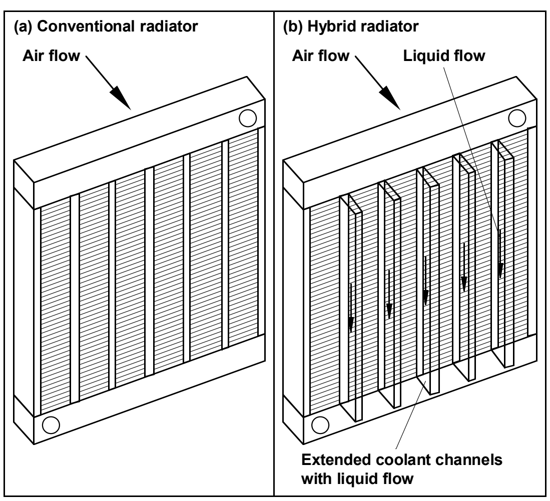


Figure 1. Hybrid Radiator System.

Figure 2 shows a top view of a section of the hybrid radiator. In this schematic, the extended channel surfaces are cooled by evaporating water flowing downwards by gravity into the plane of the figure. The combination of the conventional cooling from the finned surfaces and the evaporative cooling from the extended channel surfaces is the total heat transfer from the radiator to the atmosphere. Under the thermal design condition, both cooling mechanisms would be functioning. However, at most thermal loads below the design condition, only the conventional air-side finned surface cooling would be required. Thus, the active cooling of the water evaporation would be used only at or very near the thermal design condition.

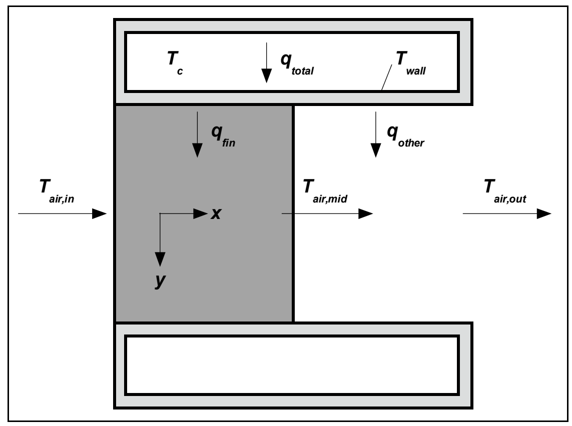


Figure 2. Top View of a Section of the Hybrid Radiator.

This limited use, of the active evaporative cooling component of the hybrid radiator-cooling system, is important because evaporative cooling requires a supply of water. Using evaporative cooling only at or very near the thermal design condition serves to optimize the parameters of reduced radiator size (or increased maximum radiator heat transfer) and minimized water use/transport.

Results

Heat Transfer Increases

Heat removal rates were calculated from the radiator of Figures 1 and 2 with a 221.8-kW heat rejection rate and the outside air temperature was fixed at 47 °C. The heat removal rate as a function of water consumption rate generated using falling liquid film evaporation is shown in Figure 3. It is noted that, at water consumption rates of 76 L/hr (20 gal/hr) and 189 L/hr (50 gal/hr), the total heat removal rate is increased by 42 kW and 102 kW, respectively, which is equivalent to the heat removal rate increase of

19% and 46%, respectively. A small part of this increase (~3 kW) is due to the increased surface area associated with the coolant channel extensions of the hybrid radiator design. The rest of the sizable increase in the heat removal rate is due to evaporative cooling. At both of these flow rates, the cooling water completely evaporated before reaching the bottom of the radiator.

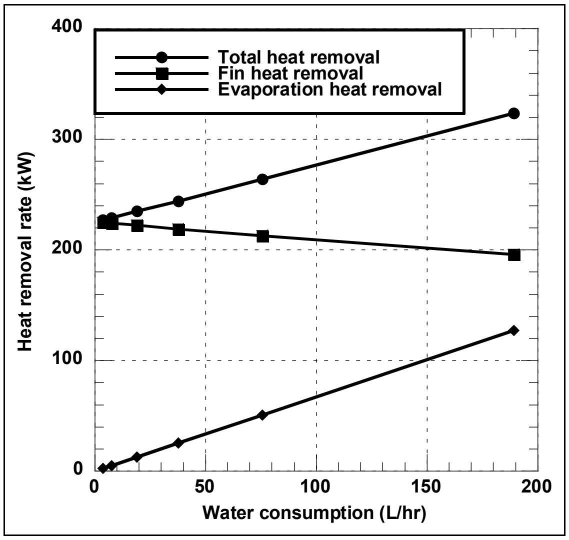


Figure 3. Increased Radiator Heat Transfer.

At a 76-L/hr (20-gal/hr) flow rate, the actual flow rate on each extended surface of the hybrid radiator is only 0.107 ml/s. At this low flow rate, the liquid film across the 20-mm radiator extension surface is only 0.11 mm thick and has a tendency to break up into rivulets or droplets such as streaks. It is because of this tendency that an analysis was performed with the evaporating liquid film replaced by evaporating discrete droplets falling downwards along the extended radiator channel surfaces. Such droplets have good potential to be maintained at the required thickness. For 100% evaporation of the droplets as they reach the bottom of the radiator, the amount of additional heat transfer using the droplets is similar to that using the falling film.

The droplet evaporation results showed that the thickness of the droplets from the radiator extension surfaces is the most important parameter governing both the evaporation rate of the droplets and the speed at which the droplets travel downward along the surfaces. Figure 4 shows the evaporation percentage for each droplet compared to the initial starting thickness of the droplet. Droplets with a small initial height (less than 0.2 mm) were able to stay on the surface until they completely evaporated. Thus, the droplet generation and contact angle with the radiator extension surface must produce initial drop thickness less than 0.2 mm for the most efficient operation of the hybrid radiator-cooling system. Such dimensions are well within current technology, and therefore the potential of evaporative cooling to increase heat transfer from the same sized radiator can be realized.

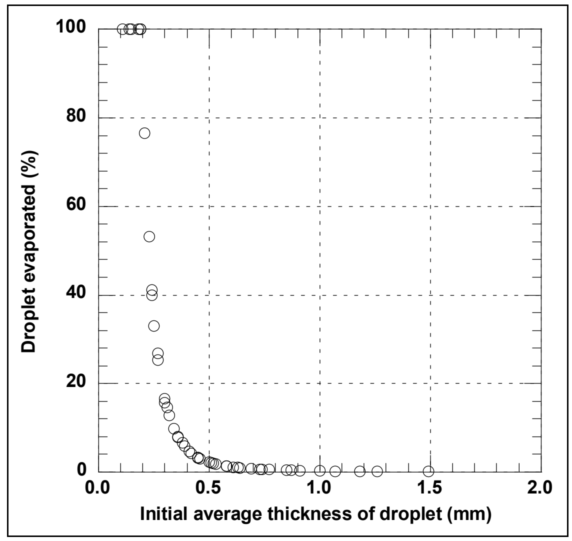


Figure 4. Droplet Evaporation.

Radiator Size Reductions

The results for the radiator width as a function of the water consumption rate, calculated from a thin falling film under the conditions of the engine speed of 1700 rpm with a 221.8-kW heat rejection rate and the outside air temperature of 47 °C, are shown in Figure 5. The original width of the radiator in this study was 988 mm. It is noted that, at water consumption rates of 76 L/hr (20 gal/hr) and 189 L/hr (50 gal/hr), the width could be reduced to 778 mm and 478 mm, respectively, which corresponds to radiator area decreases of 21% and 52%, respectively. In each case studied, the film was assumed to completely evaporate before reaching the bottom of the radiator. Using droplets instead of a film will give the same potential for area reduction as long as the droplets completely evaporate. It is also noteworthy to mention that if the frontal area of the tractor were modified, to account for the reduced radiator size that can be achieved by the hybrid cooling system, aerodynamic drag would also be reduced thereby increasing fuel efficiency.

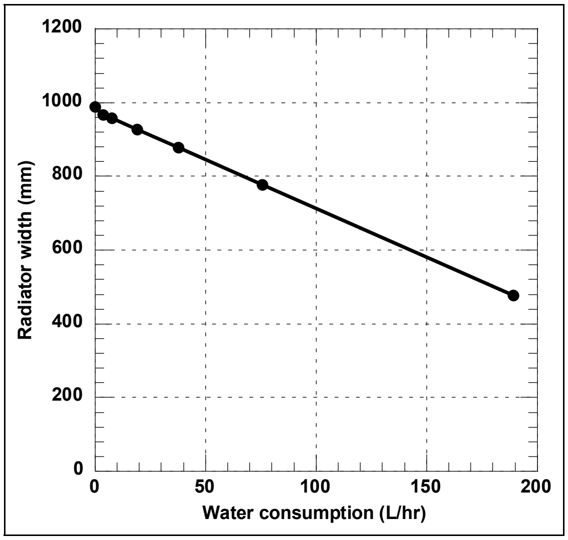


Figure 5. Reduced Radiator Size.

The design condition for truck and automobile radiators usually is the most severe condition possible: the highest air temperature and the steepest grade. Many vehicles may never encounter such conditions found at places such as Baker Grade in California or Union Pass in Arizona in a hot summer afternoon. A good potential utilization of evaporative cooling is to size the finned portion of the radiator for an alternative design condition corresponding to a steep grade away from the desert hills. Thus, water for evaporative cooling would be needed only when a vehicle travels through the desert hills under extremely hot conditions. An 11-kilometer (7-mile) stretch of land along Interstate Highway 24 near Monteagle, Tennessee is an example of a steep grade that could be used for the alternative design condition for the finned portion of the radiator. According to the typical meteorological year for Chattanooga, Tennessee near Monteagle, the highest temperature can reach 37 °C. If the radiator were sized at this location with the same coolant temperatures and heat transfer rates, then the radiator could be 22% smaller in width compared to the Baker grade design condition. Thus, on the majority of roads in the United States, the smaller radiator would be sufficient. Under conditions of 47 °C and constant full engine power for a long period of time, the water flow rate of approximately 76 L/hr (20 gal/hr) would be needed to remove the remainder of the heat. Since it takes less than one hour to traverse 40-kilometer (25-mile) Baker Grade and 48-kilometer (30-mile) Union Pass, the amount of water consumed would be less than 76 liters (20 gallons) for either of them with this example design modification.

Conclusions

Coolant radiators in trucks and automobiles were shown to be amenable to evaporative cooling. Using a hybrid truck radiator, 19% and 46% heat transfer increases were obtained with 76-L/hr (20-gal/hr) and 189-L/hr (50-gal/hr) water flow rates, respectively. These results were dependent on the establishment of water flow with small thickness from the radiator surfaces. It was found that such thickness could readily be obtained by using droplet flow with contact angle management.

An alternative to the heat transfer increase from an existing radiator with the addition of evaporative cooling is radiator size reduction. It was shown that, at the design heat load, the 76-L/hr (20-gal/hr) and 189-L/hr (50-gal/hr) water flow rates yield radiator area reductions of 21% and 52%, respectively.

A good potential utilization of evaporative cooling was considered wherein the finned portion of the radiator was designed to accommodate all driving conditions except for desert hills. In this case, water for evaporative cooling would only be needed when a vehicle travels through desert hills under extremely hot conditions. It was found that the radiator area could be reduced by 22% when only 76 liters (20 gallons) of water were used to traverse an extreme desert hill such as Baker grade.

VII.B.3. Products

Publications

1. D. S. Smith, D. M. France, W. Yu, and J. L. Routbort, Hybrid Radiator-Cooling System, ANL internal report.
2. D. M. France, D. S. Smith, W. Yu, Efficient, Active Radiator-Cooling System, submitted to the SAE Journal of Commercial Vehicles.

Patents

1. D. M. France, D. S. Smith, W. Yu, J. L. Routbort, Hybrid Radiator Cooling System, pending US patent

VII.C. ANL-Cummins CRADA: "Integrated External Aerodynamic and Underhood Thermal Analysis for Heavy Vehicles"

Principal Investigator: Tanju Sofu
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, Illinois 60439
Phone: (630) 252-9673; Email: tsofu@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VII.C.1. Abstract

Objective

- The main objective of this CRADA project is development of a predictive analytical capability to address unique heavy-vehicle underhood thermal design challenges while keeping the aerodynamic considerations in perspective.
- Optimal design of a vehicle thermal system is important for energy efficiency considerations. The analytical capability being developed as part of this project is aimed to help with the overall heavy-vehicle optimization through analysis of interdependent phenomena such as the underhood configurations, cooling system optimization, and vehicle external aerodynamics.

Approach

- The capability being developed will be used to fully characterize a heavy vehicle energy balance based on combined use of 1-D thermo-fluids system model for the engine and cooling system, and 3-D computational fluid dynamics (CFD) techniques for the underhood and external aerodynamics analyses.
- A network of 1-D representation of a Cummins ISX engine internal flow loops and the coolant system will be developed with *Flowmaster* software.
- CFD model of the underhood compartment and external aerodynamic configuration will be developed using *Fluent* or *Star-CCM+* commercial CFD software.
- Coupling of the CFD model with *Flowmaster* systems model will be achieved via a custom interface developed at ANL.

Major Accomplishments

- This project will formally start in FY2013, but ANL experience with heavy vehicle underhood thermal analysis and aerodynamics is based on a number of previous collaborations with various industrial partners including Caterpillar, Inc., Paccar Technology Center, and Cummins, Inc.
- In an earlier CRADA with Cummins, Argonne team developed a network of 1-D representation of a Cummins engine internal flow loops combined with a coolant system model and control module. The CFD modeling of the underhood compartment of a generic class-8 heavy vehicle, and its coupling with the 1-D systems model were also accomplished. During the current phase of the CRADA project, this experience will be extended to include vehicle aerodynamics and its influence on overall energy balance for the entire heavy vehicle system.

Future Activities

- The new CRADA agreement between ANL and Cummins, Inc. has been signed in September 2012 to start the implementation of an integrated underhood and external aerodynamics simulation for a prototypical heavy-vehicle configuration.
- Cummins team will identify a realistic heavy-vehicle configuration to be studied and provide technical information to help prepare the CFD models and test data for validation. Argonne team will lead the methods and model development, analysis, and validation efforts.

- The best practice guidelines to be established as a result of this study will be made available to the consortium of OEMs participating in the DOE program.

VII.C.2. Technical Discussion

Background

An optimal design of vehicle thermal system is important for energy efficiency since less than one-third of the total fuel energy provides useful mechanical work (remainder is lost through the exhaust system and heat rejection). Determination of accurate temperature distributions in and around the engine allows redesign of a heavy-vehicle underhood configuration and helps achieve fuel efficiencies through cooling system optimization. Specific issues related to emission control technologies needed to meet the new diesel engine emission requirements further highlight the need for a predictive analytical capability to address unique heavy-vehicle underhood thermal control challenges.

Engine makers like Cummins, Inc. work closely with OEM's for engine installation issues as well as cooling system optimizations. Fuel efficiency considerations also tie their work to external aerodynamics of different heavy vehicle designs. As a result, they need a comprehensive analytical capability to make C_D assessments for different design options in addition to their traditional focus on underhood thermal management.

Introduction

The new CRADA project between ANL and Cummins, signed in September 2012, will address the challenges with integrated underhood and aerodynamics analyses. This capability is expected to address specific issues related to emission control technologies needed to meet the new diesel engine emission requirements and increased electrification of the engine system. But optimal design of a vehicle thermal system is also important for energy efficiency considerations. Predicting the engine and component temperatures accurately speeds up underhood design cycle and helps achieve fuel efficiencies through cooling system optimizations and radiator size reduction.

A typical thermal-control challenge is to avoid component overheating due to tighter packaging. Since high temperatures can reduce component durability and life, the assessment of temperature distributions under the hood is an important element of a design cycle. In addition to the need to identify hot-spots, determining the temperature distributions under the hood is also critical to achieve fuel efficiencies through cooling system optimization and radiator size reduction. A predictive analytical capability can help to redesign an underhood configuration while keeping the aerodynamic considerations in perspective to meet energy efficiency and emissions reduction targets.

The objective of this new CRADA project between ANL and Cummins, Inc. is to provide a methodology to fully characterize thermal-flow conditions in the underhood compartment of a heavy vehicle based on combined use of thermo-fluids system models and computational fluid dynamics (CFD) techniques for both the underhood and external aerodynamics analyses. This methodology will help OEM's address design challenges related to emission control technologies needed to meet the new diesel engine emission requirements by providing a predictive capability to shorten component design and test cycles with a validated high-fidelity (but also a practical) simulation tool.

Approach

A This project will provide a methodology to fully characterize a heavy vehicle energy balance based on combined use of 1-D thermo-fluids system model for the engine and cooling system, and 3-D CFD techniques for the underhood and external aerodynamics analyses.

Although computationally intensive and expensive, CFD is the tool of choice for simulations of the entire vehicle in 3-D. When coupled with 1-D systems models to represent the engine and cooling system response, however, CFD can be used to simulate thermal-flow conditions in the underhood compartment.

Combined use of CFD and 1-D system models offers unique advantages: System model accounts for thermal energy balance and heat distribution inside the engine through 1-D network of flow loops, and CFD model can address multi-dimensional flow and heat transfer effects wherever needed (tight, but large volume under the hood with very complex geometry). The combined model only needs basic ambient conditions and component performance curves by exchanging data between 1-D and 3-D models.

In this collaboration, a network of 1-D representation of a Cummins ISX engine internal flow loops and the coolant system will be developed with *Flowmaster* based on the software preference of the industrial partner (Cummins, Inc.). This system model will be combined with a lumped-parameter approach to characterize thermal interactions between flow loops through the engine structure as major conduction paths to determine the engine and component surface temperatures. In other words, the system model will account for thermal energy balance by considering the heat generated from combustion to be transferred to various discrete component surfaces; cylinder head, valve cover, front cover, engine block, ECM, intake and exhaust manifolds etc. The surface temperatures obtained from the system model will then be used as the thermal boundary conditions for the CFD model.

CFD model of the underhood compartment and external aerodynamic configuration will be developed using *Fluent* or *Star-CCM+* commercial CFD softare. Coupling of the CFD model with *Flowmaster* systems model will be achieved via a custom interface developed at ANL during an earlier CRADA between Argonne and Cummins, Inc.

Results

Since the CRADA project agreement is finally signed in September 2012, there are no technical accomplishments to report yet. The project will formally kick-off in FY2013. So far, informally, the Cummins team has identified a truck configuration via participation of a foreign manufacturer, and ANL has developed a CFD model for a "proof-of-principle" aerodynamic analysis as shown in Figure 1.

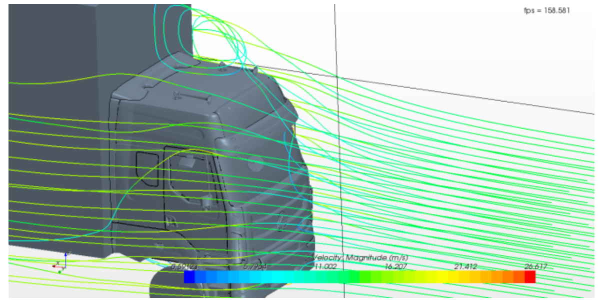


Figure 1.

The project will also rely on the technical work completed in an earlier CRADA project between ANL and Cummins team that was completed in earlier years.

As part of that work, Argonne team developed a network of 1-D representation of a Cummins engine internal flow loops combined with a coolant system model and control module. This thermo-fluids system model simplified the complex engine system by discretization based on known heat transfer paths under equilibrium conditions to predict the complete engine thermal system performance by analyzing the interactions of the engine with the coolant, oil, and ventilation air loops. The CFD modeling of the underhood compartment of a generic class-8 heavy vehicle, and its coupling with the 1-D systems model were also accomplished. The results of the coupled CFD and network flow models were compared with the test data from Cummins for validation and good agreement were achieved. A comparative study to assess various fan modeling options were also pursued to capture the influence of radiator fan.

On the aerodynamics analysis, Argonne has been involved in the analysis of a "Generic Conventional Truck-Trailer Model" (GCM) as part of a DOE-EERE Consortium supported with very high quality test data from high Reynolds number wind tunnel conducted at NASA's Ames laboratory. In addition to the integral drag force, these NASA tests provided detailed surface pressure measurements to validate CFD codes and turbulence models. The complex flow field behind the trailer and in the gap between the truck and trailer was also characterized via super-fine resolution LDV measurements. Argonne team predicted drag coefficient at zero yaw within 1% of value measured in 1/8th scale wind tunnel. The predictions were within 1-3% at small yaw angles and 5-7% at nominal yaw for models of similar size.

Additionally, the CRADA with PACCAR Tech Center involved aerodynamic analysis of a realistic truck-trailer configuration using test data from another university wind tunnel. The smaller scale projects such as the CRADA with Caterpillar on truck electrification and its impact on aerodynamics as well as collaborations with vendors that market add-on drag reduction devices provided a broad range of experience for Argonne team in terms of validation of commercial CFD tools in application to heavy vehicle aerodynamics.

All of these experiences will be leveraged for the current CRADA project between ANL and Cummins, Inc.

Conclusions

This effort will result in an improved modeling capability to more closely tie the overall energy efficiency considerations (including effects of aerodynamic gains/losses) to the issues related to cooling system optimizations. Industrial partner, Cummins, Inc, will identify a realistic heavy-vehicle configuration to be studied and provide technical information to help prepare the CFD models, and Argonne team will lead the methods development activities.

In the final stage, both the Argonne and Cummins teams will build the analytical models and conduct simulations to assess changes in aero-drag forces in response to cooling system design changes. Cummins will provide underhood test data from the experiments conducted in their vehicle integration facilities. Cummins, through partnership with one of their clients (an OEM or a fleet operator), will also conduct controlled road tests to evaluate fuel efficiency of various design options and add-on drag reduction devices.

The final product will be an experimentally validated analysis methodology for performing external aerodynamics simulations of realistic heavy vehicle geometries using commercial CFD software and system analysis tools. The best practice guidelines to be established as a result of this study will be made available to the consortium of OEMs participating in the DOE program. This new CRADA agreement between ANL and Cummins, Inc. will be completed in three years.

VII.C.3. Product

1. The new CRADA agreement between ANL and Cummins, Inc. has been signed in September 2012 to start the implementation of an integrated underhood and external aerodynamics simulation for a prototypical heavy-vehicle configuration. The project will formally kick-off in FY2013.

VII.D. CRADA with PACCAR – Experimental Investigation of Coolant Boiling in a Half-Heated Circular Tube

Principal Investigator: Dileep Singh
Coworkers: Wen Yu, David France, and Roger Smith
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-5009; Email: dsingh@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VII.D.1. Abstract

Objective

- Understand and quantify sub-cooled engine coolant boiling heat transfer in heavy duty trucks
- Experimentally determine sub-cooled flow boiling heat transfer rates and limits in the head region of heavy duty truck engines
- Develop predictive mathematical models for sub-cooled boiling heat transfer results
- Provide measurements and models for development/validation of heavy duty truck engine computer codes

Approach

- Design and fabricate an experimental test facility with the test section sized to the specification of a cooling channel in the head region of a heavy truck engine
- Experimentally determine sub-cooled boiling heat transfer rates and critical heat fluxes with water
- Experimentally determine sub-cooled boiling heat transfer rates and critical heat fluxes with 50/50 and 40/60 ethylene glycol/water mixtures

Major Accomplishments

- Completed the concept design, the technical design, and the fabrication of the experimental test facility and support systems
- Completed the LabVIEW-based data acquisition and test control hardware and software
- Completed the heat loss calibrations of the experimental test facility
- Completed single-phase convective heat transfer experiments and data reduction with three test fluids
- Completed low-flow-rate sub-cooled boiling heat transfer experiments and data reduction with three test fluids

Future Activities

- Perform sub-cooled boiling experiments and data analyses for three test fluids at higher flow-rates
- Develop experimental data-based predictive mathematical models for sub-cooled boiling heat transfer

VII.D.2. Technical Discussion

Background

Started in FY 2010 as a CRADA between Argonne National Laboratory and PACCAR Inc./DAF Trucks (PACCAR/DAF), this project aims to provide heat transfer and critical heat flux measurements and models of sub-cooled coolant boiling in the head region of heavy-duty truck engines for development and validation of heavy duty truck engine computer codes.

Introduction

Sub-cooled boiling is an important phenomenon that must be understood in order to design efficient diesel engine cooling systems. If the system fluid is at or below the critical heat flux (CHF), the cooling can be very efficient. However, if the system is allowed to go above the CHF, the system can become unstable. PACCAR/DAF is designing engines to take advantage of sub-cooled boiling heat transfer below the CHF, but the CHF and heat transfer rates have not been determined under realistic conditions. These experiments address this situation using a design specified by DAF. The data will be used in computational fluid dynamics models and designs by PACCAR/DAF, and could result in more efficient engines for heavy trucks. The objective of this project is to measure heat transfer rates during sub-cooled boiling of engine coolants in a geometry typical of valve bridge areas in heavy duty truck engines under various operating conditions.

Approach

The general approach for this project is to experimentally investigate sub-cooled boiling of water and ethylene glycol/water mixtures for heavy duty truck engine applications.

The test facility used in this investigation was designed and fabricated to study sub-cooled boiling heat transfer of flowing water and ethylene glycol/water mixtures at temperatures <200 ˚C and at pressures just above atmospheric. The experimental test facility shown schematically in Figure 1 is a closed-loop system with major components consisting of a pump, a flowmeter, two preheaters, an experimental test section, a heat exchanger (cooler), three power supplies, and a data acquisition system. The selected regenerative turbine pump (MTH Pumps, Model T31FAB) has the capability of pumping the testing fluids at the required liquid velocity range of <1.5 m/s (corresponding to the liquid volume flow rate range of $<8.4\times10^{-3}$ m^3/s) with enough head to accommodate the entire experimental facility including the test section, balance of piping, and throttling. The flowmeter (Endress + Hauser, Model Promag 10) was chosen to cover the required flow rate range with an uncertainty of <2%. The preheaters provide a means to set the inlet temperature of the test section at various desired levels. The preheaters and the test section are resistance-heated with controllable direct current power supplies (Sorensen Company, Model DCR 16-625T for the preheaters and Electronic Measurements, Inc., Model EMHP 40-450-D-11111-0933 for the test section). As shown in Figure 1, provisions are made to measure temperatures along the test section for calculating heat transfer coefficients. The outlet pressure, the inlet fluid temperature and the outlet fluid temperature of the test section are also measured. The estimated uncertainties in the measurements of pressure and temperature are ±3% and ±0.2˚C, respectively. As a safety precaution, the preheaters and the test section are provided with high-temperature limit interlocks to prevent them from overheating. After leaving the test section, the fluid is cooled in the heat exchanger (cooler) and returns to the pump to close the system loop.

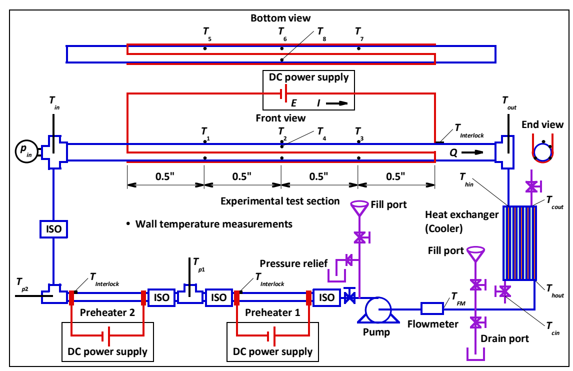


Figure 1. Schematic of PACCAR Heat Transfer Facility.

A data acquisition system consisting of a Dell computer (Model Optiplex GX270) and a Hewlett-Packard multiplexer (Model HP 75000) was assembled to record outputs from all sensors. A LabVIEW data acquisition program, which includes all calibration equations and conversions to desired engineering units, was written. Shown in Figure 2, the data acquisition system provides not only an on-screen display, of analog signals from all sensors and graphs of representative in-stream and wall-temperature measurements, but also a means of recording temperature measurements and pertinent information such as input power, mass flux, and inlet pressure for further data reduction.

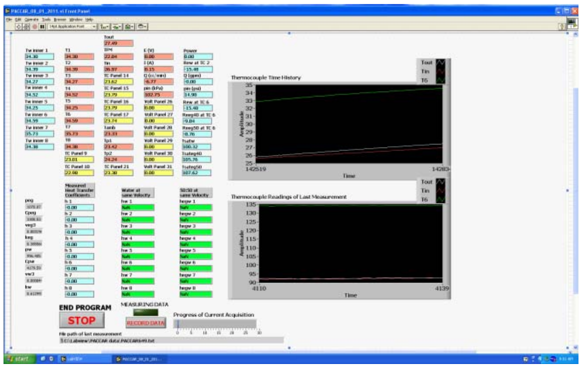


Figure 2. LabVIEW Data Acquisition Program.

An overview of the completely-fabricated PACCAR heat transfer test facility is shown graphically in Figure 3 before it was insulated.

Figure 3. Overview of PACCAR Heat Transfer Facility.

Results

Heat Loss Calibration

Although the experimental test section is well insulated thermally from the atmosphere to minimize heat loss to the environment, the heat loss is not negligible during flow boiling heat transfer experiments because of the relatively high driving temperatures. Therefore, heat loss experiments were performed for the experimental test section wall temperatures up to the boiling heat transfer conditions, and the heat loss was subsequently incorporated into the data reduction procedures for single-phase convective and two-phase sub-cooled boiling heat transfer data. The heat loss was characterized through a special series of experiments with no fluid in the experimental test section. Power was applied to the experimental test section to bring its wall temperature to a selected level. The heat loss rate q_{loss}, the input power required for maintaining the wall temperature at the selected value and calculated by the product of the voltage drop across the heating wire and the current through the heating wire ($q_{loss}=EI$), is related to the difference between the experimental test section wall temperature T_w and the ambient temperature $T_{ambient}$. Experimental results confirmed a linear dependence on this driving temperature difference. Then the heat loss rate was expressed approximately as $q_{loss}=c(T_w-T_{ambient})$ where the proportional constant c, which depends on the heat transfer coefficient and the heat transfer surface area between the experimental test section and ambient for this particular experimental apparatus, was determined from the heat loss experiments. Figure 4 shows the heat loss rate as a function of the driving temperature difference for the experimental test section. The test section heat loss is expected to be <1% of the applied input power to the experimental test section in all subsequent heat transfer tests.

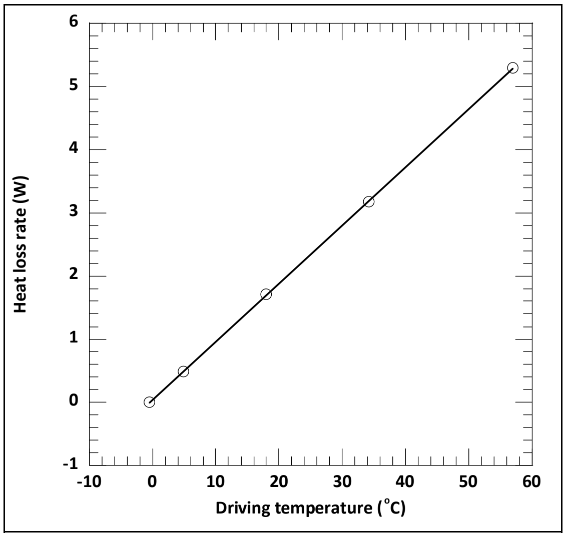


Figure 4. Heat loss calibration.

Single-Phase Heat Transfer Experiments

Investigations of heat transfer under the condition of heat supplied only to the bottom half surface of an experimental test section are very rare and none was found in the engineering literature. Therefore, to validate the test apparatus and to establish a base line, a series of single-phase heat transfer experiments was carried out before two-phase sub-cooled flow boiling experiments. For the single-phase heat transfer experiments, the system pressure was kept around atmosphere pressure similar to the two-phase sub-cooled flow boiling experiments. The single-phase heat transfer experiments were performed under the turbulent flow condition mirroring the flow region of the two-phase sub-cooled flow boiling experiments, and the liquid heat transfer coefficients were correlated as functions of the Reynolds number Re and the Prandtl number Pr by modifying the Dittus-Boelter equation. As shown in Figure 5, where the heat transfer coefficients are plotted, the experimental data are in good agreement with the values from the predictive equations with a mean deviation of <4%. Almost all experimental data are within ±5% of the predictions.

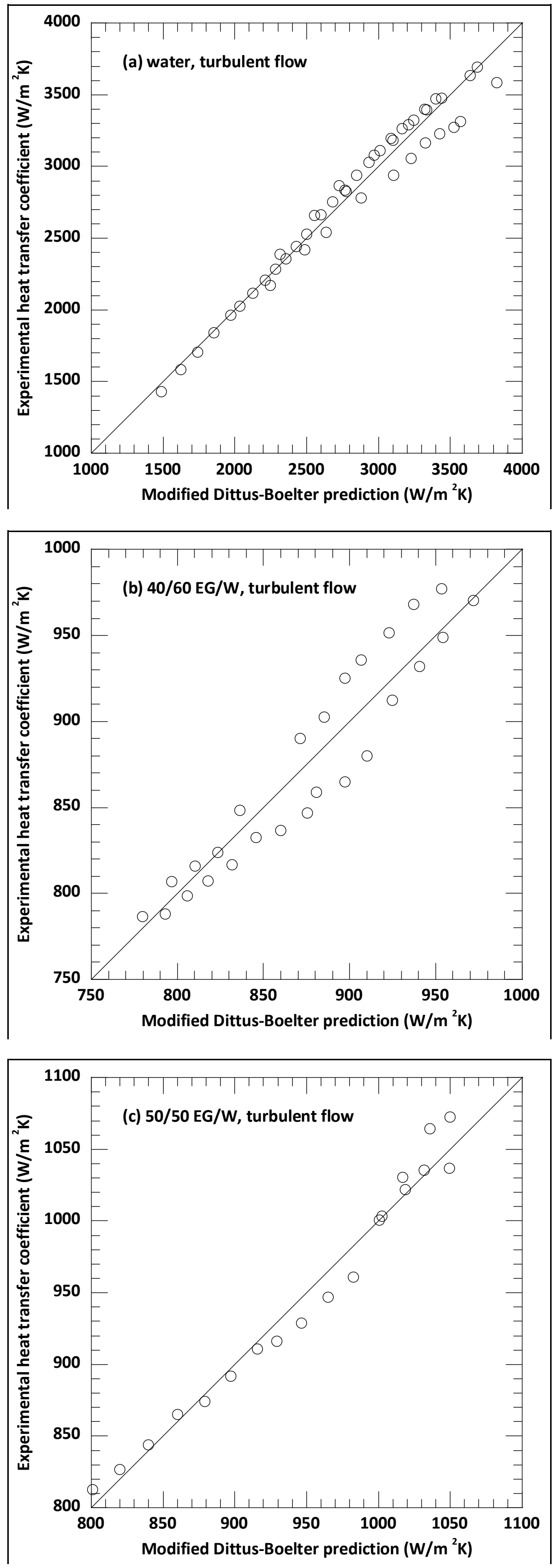


Figure 5. Turbulent Heat Transfer Coefficient Comparison.

In addition to the turbulent flow, single-phase heat transfer experiments were also performed under the laminar flow condition with ethylene glycol and water mixtures to establish a base line for the two-phase sub-cooled laminar flow boiling that occurred at the lowest flow velocity of ethylene glycol and water mixtures. The liquid heat transfer coefficients were correlated as functions of the Reynolds number Re and the Prandtl number Pr by modifying the Shah equation. As shown in Figure 6, where the heat transfer coefficients are plotted, the experimental data are in good agreement with the values form the predictive equations with a mean deviation of <2%. All experimental data are within ±5% of the predictions.

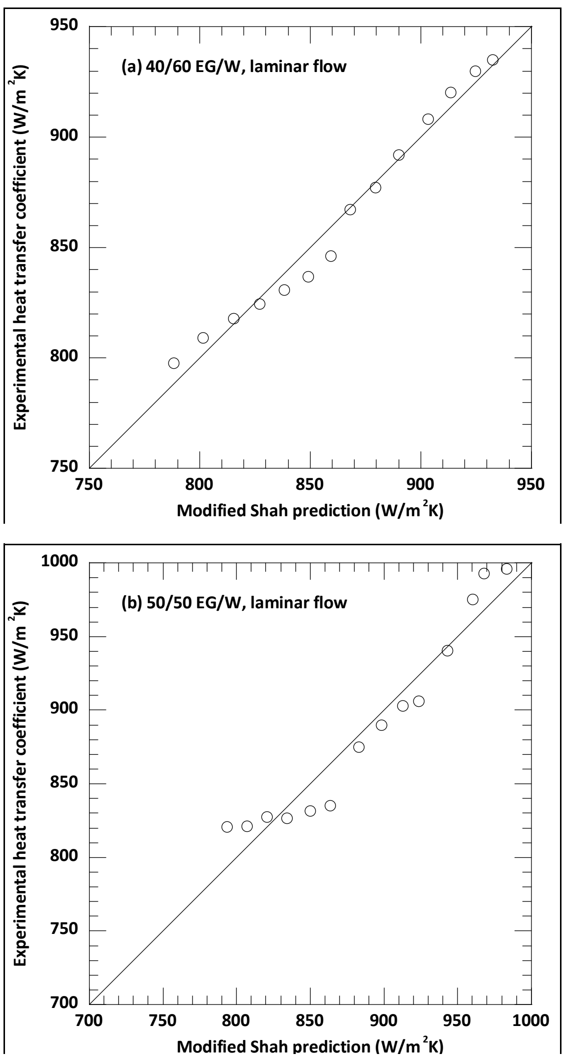


Figure 6. Laminar Heat Transfer Coefficient Comparison.

Two-Phase Sub-cooled Boiling Experiments

It is the object of this project to experimentally measure the heat-transfer coefficients of water and ethylene glycol/water mixtures in sub-cooled flow boiling with various flow rates and sub-cooling levels. A series of experiments have been performed for sub-cooled boiling of water, 40/60 ethylene glycol/water mixture, and 50/50 ethylene glycol/water mixture at a flow rate of 0.125 m/s and sub-cooling temperatures of 10, 15, 20, and 25 °C. Figure 7 shows the heat flux of these three test fluids as a function of the wall superheat for the four sub-cooling temperatures. Several trends can be seen from the boiling curves shown in Figure 7: (a) the boiling curves can generally be divided into the convection dominant region with the wall superheat smaller than approximately 12 °C and the boiling dominant region with the wall superheat larger than approximate 12 °C for water (with lower cut-off temperatures for mixtures); (b) at the same heat flux, the wall superheat for sub-cooled boiling with a smaller sub-cooling temperature is higher than that for sub-cooled boiling with a larger sub-cooling temperature; and (c) while they separate clearly in the convection dominant region for different sub-cooling temperatures, the boiling curves tend to merge together in the boiling dominant region indicating less of a sub-cooling temperature effect in this region. These trends have important influences on heat transfer rates, and therefore will be combined with results from high flow-rate sub-cooled boiling heat transfer experiments to form the basis for correlating sub-cooled boiling heat transfer coefficients.

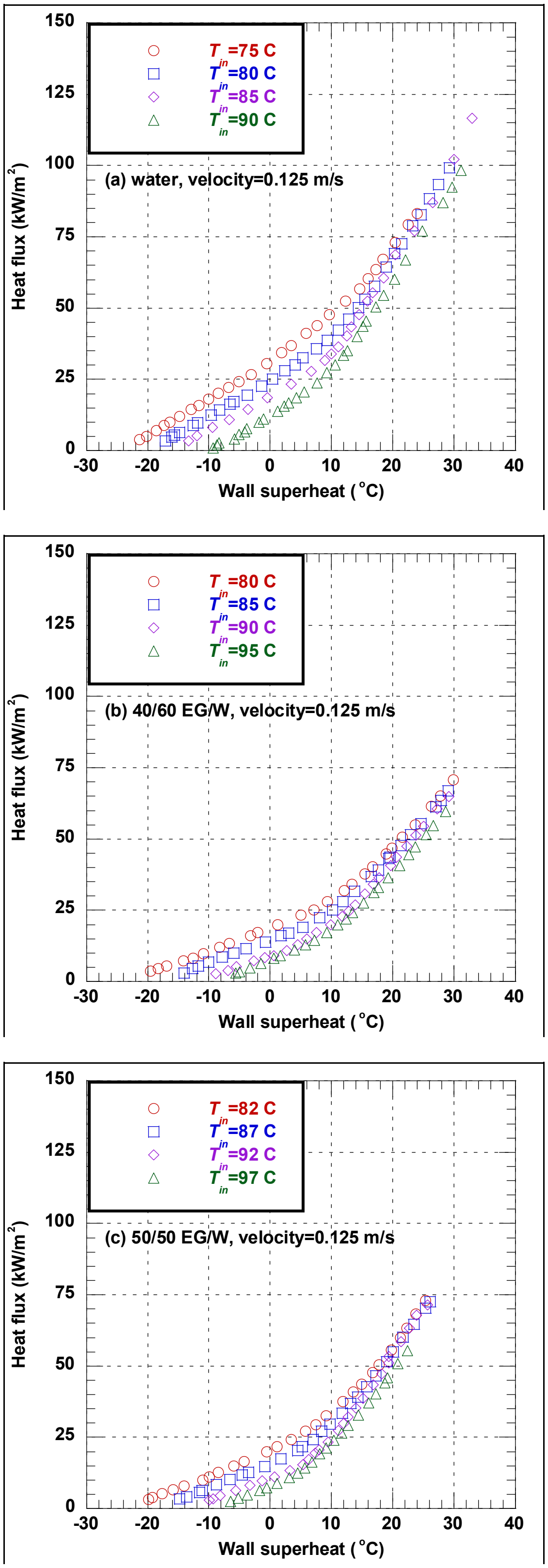


Figure 7. Sub-cooled Boiling Curves.

Conclusions

In summary, the design and fabrication of the PACCAR heat transfer test facility have been finished; the LabVIEW-based data acquisition and test control hardware and software have been established; the experiments and data reduction for single-phase convective heat transfer with three test fluids have been completed; and experiments for two-phase sub-cooled boiling with three test fluids have been performed at a low flow rate. The project is on schedule, and the future work will be focused on experiments and data reduction of two-phase sub-cooled boiling with water and ethylene glycol/water mixtures at higher flow rates.

VII.D.3. Products

Tools & Data

1. Experimental database and mathematical models for single-phase laminar flow and turbulent flow heat transfer of water and ethylene glycol/water mixtures.
2. Low-flowrate experimental database for two-phase sub-cooled boiling heat transfer of water and ethylene glycol/water mixtures.

VII.E. Development of Nanofluids for Cooling Power Electronics for HEVs

Principal Investigator: Dileep Singh
Coworkers: E. Timofeeva and W. Yu
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-5009; Email: dsingh@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VII.E.1. Abstract

Objective

- Perform an assessment of using nanofluids to cool power electronics used in hybrid electric vehicles.

Approach

- Using the data from a heat exchanger supplied by NREL, perform a heat transfer analysis to determine the magnitude of enhancement in the thermal properties of a nanofluid required to improve the cooling
- Develop nanoparticle/fluid formulations with the desired thermo-physical properties
- Experimentally establish the thermo-physical properties of the cooling fluids
- Evaluate the cooling fluids for heat transfer performance

Major Accomplishments

- Calculations have shown that for the designated heat exchanger (laminar flow) that an enhancement of between 50% and 100% in thermal conductivity could, without a significant increase in pumping power, eliminate one radiator in HEVs
- We have developed a graphite and grapheme based fluids having a >65% increase in thermal conductivity.

Future Activities

- Further develop and optimize the fluid thermal properties and viscosity effects
- Conduct long-term fouling experiments
- Conduct heat transfer experiments to establish the efficacy of the cooling fluids for power electronics cooling
- Seek industrial partner that can supply heat exchanger for testing heat transfer of nanofluids

VII.E.2. Technical Discussion

Background

Power electronic heat exchangers are varied within a particular vehicle, and they vary from vehicle to vehicle and manufacturer to manufacturer. A typical heat exchanger was used consistently in this study. The heat exchanger was the basis of recent research at NREL; results were supplied to ANL by NREL.

The heat exchanger used consists of composite materials starting with power semiconductors generating heat and ending with liquid coolant removing the heat in laminar flow. In between the heat generation and coolant are layers of materials: copper, aluminum, heat conducting grease, and Thermal Interface Material (TIM). The materials and layers were documented in references [1-2]. The baseline conditions, at or near which current power electronics operate, include: semiconductor heat flux of 100 W/cm^2 and junction temperature at the semiconductor surface in contact with the material layers of 150°C. The actual geometry of the material layers was taken from references [1-2].

In current hybrid electric vehicles, two cooling systems are used: a higher temperature system for cooling the gasoline engine and a lower temperature system for cooling the power electronics. A Department of Energy (DOE) goal is to eliminate the lower temperature system and to accomplish all cooling with a single higher temperature system. This would obviously reduce weight (thereby increasing fuel economy) and complexities. In this study, that higher temperature system was taken as a mixture of 50% ethylene glycol and 50% water by volume at an average temperature of 105°C.

Heat Transfer Analyses

Analyses were performed to estimate the effectiveness of the cooling that can be achieved with the 50/50 mixture of ethylene glycol and water at 105°C (base fluid) and with nanofluids specifically engineered for this application. The nanofluids consist of nanoscale solid particles suspended in the same base fluid that is currently used in hybrid vehicles, i.e. 50% ethylene glycol and 50% water. The analyses were multifaceted. First, properties of nanofluids were estimated that would be required to meet current heat flux and junction temperature conditions. Next, nanofluid properties were identified for conditions at or exceeding current parameter levels. These properties were identified for single- and double-sided cooling with and without TIMs. Finally, nanofluids were identified with potential for achieving those properties based on a research program with reasonable goals (based on the state of the art in the field).

In order to estimate requirements for nanofluids to meet and exceed current hybrid vehicle cooling requirements, a one-dimensional mathematical analysis of composite materials was made. One boundary condition was the power semiconductor junction temperature of 150°C. The other boundary condition was convective heat transfer to the laminar flow of a coolant at 105°C, which was taken either as a nanofluid or as the base fluid (50/50 ethylene glycol/water mixture). The resistance of the composite materials between the power semiconductors and the coolant was divided into two groups. The first was the resistance of the TIM taken as 100 mm^2K/W, and the second was the balance of the resistance in the composite determined from results presented in reference [1] for the case of no TIM in the composite. With these boundary conditions, the heat removal rate was calculated for various coolants. Alternatively, the first boundary condition was replaced by a heat flux of 100 W/cm^2, and the junction temperature was calculated for various coolants.

Calculations were made using the analysis described for the following parameters:

1. Single- or double-sided cooling
2. With TIM or without TIM
3. A nanofluid range defined by the ratio of the thermal conductivity of the nanofluid to that of the base fluid

Based on last year's effort on thermal analysis, the main conclusions was that to meet DOE's goal of eliminating the second radiator used for cooling power electronics can be achieved if the ratio of heat transfer (equal to the ratio of thermal conductivity in laminar flow) of the nanofluid to the base fluid is about 2 without the TIM in single-sided cooling. In double-sided cooling, the second radiator can be eliminated and the current standards of 100 W/cm^2 heat flux and/or 150°C junction temperature can be improved substantially with a thermal conductivity ratio of about 1.5 with or without the TIM. In this regards, various cooling fluids are being developed with enhanced thermal properties.

Approach

The general approach for this project is to use commercially available graphitic or graphene based nanoparticles and disperse them in base cooling fluid formulations to enhance the thermal performance. Subsequently, conduct thermal and mechanical characterizations on the fluid to assess their performance.

Results

Nanofluids with addition of carbon-based nanoparticles are the prospective cooling fluids for power electronics. Carbonaceous nanoparticles added to fluids have a high industrial interest for improving both lubrication and heat transfer properties. Multi-layered graphene nano-platelets (GnPs) with various plate diameters and thicknesses are being studied. Low cost of these graphitic nanomaterials (current cost \$100/lb and projected future cost of \$20/lb) makes them commercially feasible candidate as a heat transfer fluid additive. The GnPs have an interesting property of being large particles composed of several layers of graphene, as noted below in Figures 1 and 2. The multilayered graphene properties are anisotropic with a higher thermal conductivity along the hexagonal layers than the thermal conductivity perpendicular to the layered graphite structure as noted in Figure 1. Graphitic nanomaterials are typically hydrophobic, i.e., suspensions of them in water and water/ethylene glycol mixtures commonly used as heat transfer fluids in power electronics cooling would require use of surfactants. The approach we are exploring to achieve high performing nanofluids is to "functionalize" the GnP material with hydrophilic groups and make those nanoparticle miscible with water, ethylene glycol, propylene glycol, glycerin and their mixtures. ANL has received samples of multilayered graphene from XG Sciences for functionalization, and XG Sciences are seeking new applications for their material.

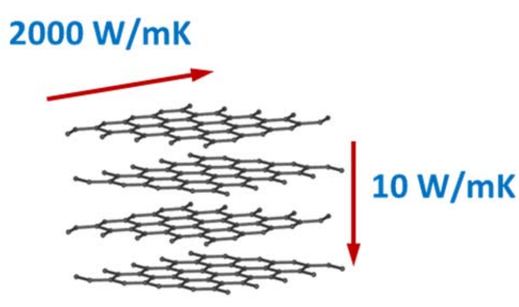


Figure 1. Schematic of multi-layered graphene structure.

As received GnP graphitic nanopowders have very poor suspension ability. The functionalization process that was employed is an oxidation of the GnP powder in a mixture of concentrated sulfuric and nitric acids (3:1 ratio). The process used was to mix 6 g of GnP to 50 ml of the acids mixture and stirred with a magnetic bar. Next the mixture was sonicated in a water bath 5 times for 30 minutes in each sonication, and magnetically stirred between sonications. A centrifuge was used to separate the nanoparticles and washed with de-ionized water until the pH was above 3. No surfactants were needed for the fluid stabilization after the functionalization process. For maximum stability the zeta potential was optimized with addition of sodium hydroxide and pH was 9-10 the optimum. The good stability in a fluid, water or ethylene glycol/water mixture seems to be that the graphene surface is covered in OH^-, COO^- and CO ionic groups that create the electrostatic charge that keeps the particles separated from each other due to repulsion and prevents particle agglomeration and settling.

Figure 3 shows the improvement in thermal conductivity of the f-GnP versus suspension of unmodified GnP without surfactants and compares the similar suspension of unmodified GnP that was stabilized with cationic (CTAB) and anionic (SDS) surfactants for comparison. One can see that the thermal conductivity of functionalized graphene improved significantly compared to the as-received nanoparticles, while addition of surfactants significantly degrades the thermal conductivity, even though the stability of suspension is improved.

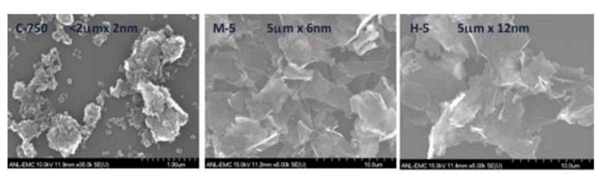


Figure 2. SEM micrographs of various graphene particle sizes.

Three grades of GnP were tested that varied in average particle diameter and thickness (number of single graphene layers per particle). The functionalization process was the same for all 3 grades, but the thermal properties of resulting nanofluids varied significantly (Figure 4). The particles with the highest number of graphene layers (thickness) showed highest increases in thermal conductivity.

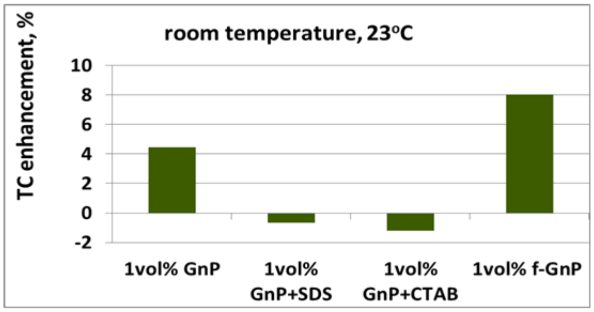


Figure 3. Thermal conductivity increase in water suspensions of multilayered graphene grade C-750.

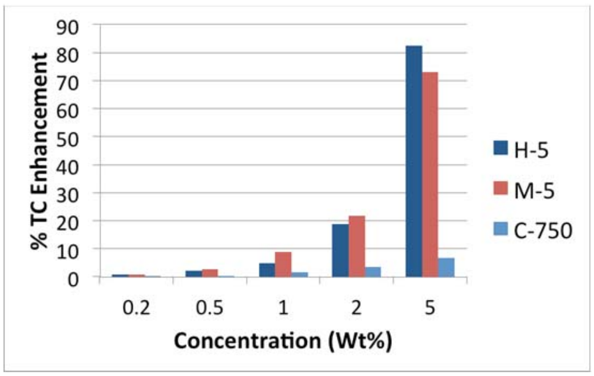


Figure 4. Comparison of thermal conductivity of f-GnP suspensions at the same concentration, but of different particle morphology (f-GnP grades).

Also the increase in thermal conductivity and viscosity was found to be temperature dependent, showing even higher heat transfer enhancements at elevated temperatures (Figure 5). On the other hand viscosity (Figure 6) decreases as a function of temperature, making nanofluid even more attractive for high temperature applications. Such increase in thermal conductivity with temperature is expected for disordered materials, where the heat conduction mechanism is the hopping of localized excitations.

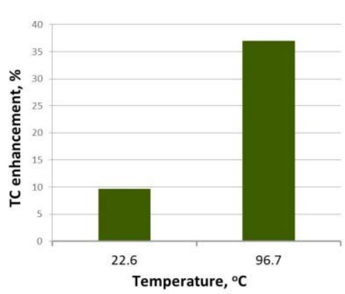


Figure 5. Thermal conductivity of 1 vol.% f-GnP-750/water suspensions as a function of temperature.

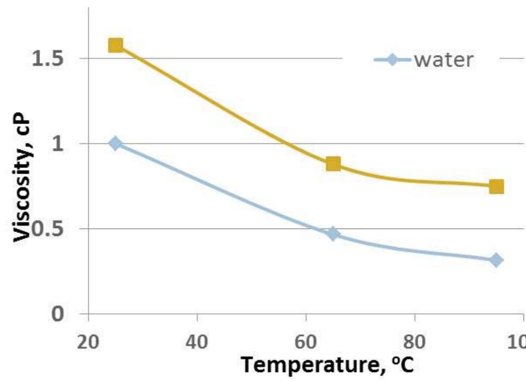


Figure 6. Viscosity of 1 vol.% f-GnP-750/water suspension (yellow) as a function of temperature.

Conclusions

Knowing the level of the thermal conductivity enhancements required for economically-interesting nanofluids in power electronics cooling, we would like to focus on developing a system that has viability in this regard, namely the nanofluids with non-noble metal nanoparticles or carbon available through simple chemical synthesis in a fluid containing 50/50 mixture of ethylene glycol and water.

Further investigation of f-GnP nanofluids will focus on viscosity, thermal conductivity of suspensions resulted from different oxidation times, fluid aging effects, abrasive effects, and Raman Spectroscopy characterization of nanoparticles on the oxidation state of graphene material and it's correlation to thermal properties that would allow better control of the nanofluid thermal properties in the future. Preliminary experiments to produce such nanofluids have been successful, but considerable work remains. In particular, the stabilization of the surface of nanoparticles, control over size, agglomeration, and concentration of nanoparticles, viscosity, possible erosion and clogging, and measurements of thermal properties would have to be investigated. However success, as expected, would assure the commercial viability of nanofluids.

The promising nanofluids will be used for tests in a heat transfer loop as described in the project plan.

VII.E.3. Products

Patent Application

1. D. Singh, et al., Heat Transfer Fluids with Enhanced Thermal Energy Storage and Thermophysical Properties, patent application filed.

References

1. M. O'Keefe and K. Bennion, A Comparison of Hybrid Electric Vehicle Power Electronics Cooling Options, 2007 IEEE Vehicle Power and Propulsion Systems Conference, Arlington, Texas, September 9-12, 2007.
2. K. Bennion and K. Kelly, Rapid Modeling of Power Electronics Thermal Management Technologies, 2009 IEEE Vehicle Power and Propulsion Systems Conference, Dearborn, Michigan, September 7-11, 2009.

FRICTION AND WEAR

VII.F. Development of High Power Density Driveline for Vehicle Efficiency Improvement

Principal Investigators: Oyelayo Ajayi, Cinta Lorenzo-Martin, Aaron Greco and George Fenske
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-9021; Fax: (630) 252-4798; Email: ajayi@anl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335, Email: Lee.Slezak@hq.doe.gov

VII.F.1. Abstract

Objective

- Achieve significant reduction in transportation vehicle weight and consequent fuel savings through size and weight reduction of driveline systems, such as transmission and axles.
- Develop materials, surface finishes, and lubricants to enable development of durable and reliable high-power-density (HPD) driveline systems that are smaller and lighter than current systems.
  - Increase wear scuffing and contact fatigue lives for HPD driveline to achieve up to 25% size reduction in gears and bearings

Approach

- Analyze planetary gear systems to establish materials, surface finishes, and lubricants that meet tribological performance requirements for a specific gearbox size reduction.
- Develop, integrate, and evaluate appropriate materials, surface finishes, and lubricants to reduce wear, scuffing, and contact fatigue of gears and bearings.
- Conduct comprehensive evaluation of tribological performance of integrated materials, surface finishes, and lubricants that can achieve up to 25% size reduction in driveline systems.

Major Accomplishments

- Completed preliminary analysis of the contact kinematics for specific size reduction in a simple planetary gearbox.
- Assessed the effect of new contact kinematics in terms of Hertzian contact stresses, effect of surface velocities of meshing gear teeth on wear, and scuffing and contact fatigue lives.
- Developed a bench-top test methodology for evaluating tribological performance under relevant contact kinematics.
- Identified potential synergy between thin-film coating and lubricant additives resulting in low friction under the boundary lubrication regime.

Future Activities

- Evaluate the baseline scuffing and contact fatigue performance of current materials, surface finishes, and lubricants.
- Develop new materials, surface finishes, and lubricants and evaluate their ability to meet new requirements for HPD drivelines.
- Conduct comprehensive evaluation of tribological performance of integrated materials, surface finishes, and lubricants.

VII.F.2. Technical Discussion

Introduction

One of the main goals, perhaps the ultimate goal, of the U.S. Department of Energy's Vehicle Technologies Program (DOE-VTP) is the dramatic reduction of the amount of petroleum oil used in transportation vehicles. This would reduce the nation's dependence on foreign oil, thereby enabling greater energy independence and homeland security. In addition, consumption of less oil in vehicles would reduce environment-degrading emissions, such as greenhouse gases and particulates. Such emissions have been associated with climate change and detrimental effects on human health.

Significant fuel savings can be achieved in all classes of transportation vehicle through weight reduction. Numerous analyses have shown that 2-5% reduction in fuel consumption is possible with a 10% reduction in automobile weight. Table 1 shows such a calculation for three classes of vehicles based on the New European Drive Cycle (NEDC) for both gasoline- and diesel-fueled internal combustion engines (ICEV-G and ICEV-D, respectively). Consequently, all original equipment manufacturers (OEMs) are adopting vehicle weight reduction as a prime approach to reduce fuel consumption.

Table 1. Calculated fuel saving in different classes of automotive vehicles

	NEDC ICEV-G	NEDC ICEV-D
Compact Class	-2.6 %	-3.5 %
Mid-Size Class	-1.9 %	-2.7 %
SUV	-2.4 %	-2.6 %

Weight reduction must be accomplished without sacrificing safety, reliability, and durability for a vehicle to gain public acceptance and market share. Figure 1 shows the weight distribution for a typical automobile, highlighting the systems and components that present an opportunity for weight reduction. The DOE-VTP currently has programs and projects devoted to weight reduction in vehicle structures and engines (light-weight materials program). The driveline system constitutes about 20% of a vehicle's weight, making it an excellent target for weight reduction. One route to reducing the size and weight of the driveline system without sacrificing performance, or compromising reliability and durability, is by increasing its power density.

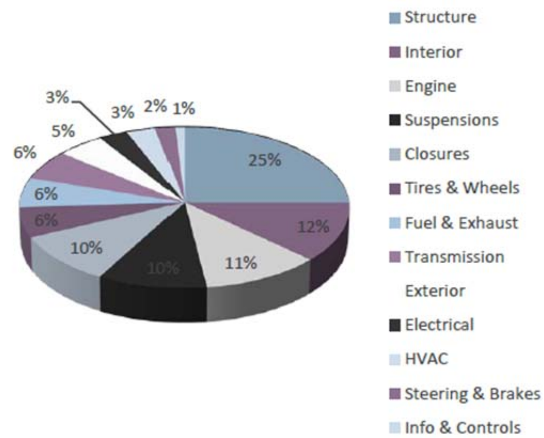


Figure 1. Typical vehicle weight distribution.

The ultimate objective of this project is the development of technologies that will enable OEMs and their suppliers to successfully develop smaller, lighter, and more efficient driveline system for transportation vehicles by increasing the power density without sacrificing reliability and durability. Such a system will result in significant vehicle weight reduction and concomitant increase in fuel savings. Furthermore, an HPD driveline may enable the downsizing of the powertrain system, resulting in further improvement in fuel savings.

Approach

Vehicle driveline systems such as transmission and axles consist of planetary gear systems and bearings to form a gearbox, as exemplified in Figure 2. Development of HPD gears and bearings would enable a size and weight reduction of the gearbox. Size reduction of the gears and bearings would increase the contact severity of the gear teeth and bearings, leading to reduction in wear, scuffing, and contact fatigue lives. To mitigate the tribologically induced reliability and durability issues expected in an HPD gearbox, materials, surface technologies, and lubricants have to be developed and integrated into the system – the focus of the present project.

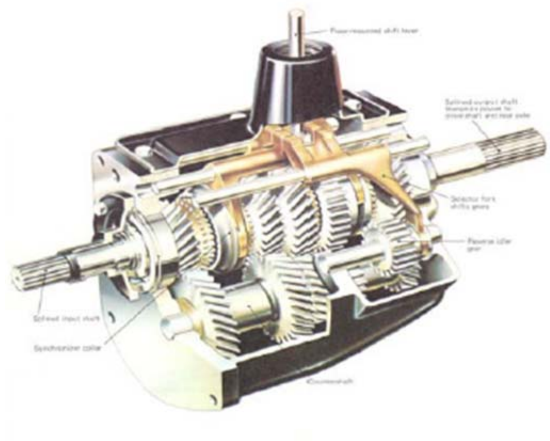


Figure 2. Example of an automotive transmission gearbox.

To begin, we are conducting gear contact kinematic analyses for different levels of size reductions to establish material, surface, and lubricant requirements in terms of wear scuffing and contact fatigue lives. Performance evaluation/testing methodologies are being developed to determine wear, scuffing, and contact fatigue life. The test methodologies will be used to evaluate state-of-the-art and newly developed materials, surface finishes, and lubricants for the gearbox. If the project is successful, optimized technologies that can facilitate different levels of size reduction in drive systems will be available to OEMs and their suppliers for implementation and commercialization.

Results and Discussion

In FY 2011, we conducted contact kinematic analysis of meshing gear teeth to determine the impact of size reduction on wear, scuffing, and contact fatigue lives. The analysis showed that a 25% reduction in size will reduce the scuffing and wear life by one-third and the contact fatigue life as much as two-thirds. The challenge then is the development of materials, surface, and lubricant technologies to simultaneously increase wear, scuffing, and fatigue lives.

During FY 2012, we devoted our efforts to the development of a tribological performance test approach for meshing gear contact kinematics. In the test methodology, based on the WAM technology of Wedeven Associates Inc., the surface velocities of the two contact surfaces are independently controlled. This capability enables the determination of frictional behavior, as well as failure and damage mechanisms under various contact conditions prototypical of meshing gear teeth.

We also assessed the impacts of thin-film surface coatings in combination with lubricant technology on the friction and wear performance. The nine commercially available thin-film coatings shown in Table 2 were tested with the four lubricants listed in Table 3. The tribological performance of these coatings was compared with that of state-of-art case carburized 4118 steel gear material. Figure 3 shows the frictional behavior of different coatings when lubricated with a model lubricant containing anti-wear and anti-friction additives.

Table 2. Thin-film coatings evaluated and their properties

Coatings	Deposition method	Type	Thickness (μm)	Manufacture Hardness (Hv)	Nano Hardness (GPa)	Roughness (nm)
4118-Steel	none	No layer	0	850	7	19
DLC-1	PACVD	multilayer	1.9	1200-1500	12-15	172
DLC-2	PACVD	multilayer	2.6	1000-1500	10-15	133
DLC-3	PACVD	multilayer	3.5	1500-3000	16	56
CrN	PVD	monolayer	5.0	800-1100	10	16
CrSiCN	PVD	monolayer	3.4	2700-3000	29	6.6
AlTiN	PVD	bilayer	2.4	3500	34.5	91
TiB_2	PVD	monolayer	1.9	3650	34-37	30
TiCN	PVD	monolayer	0.9	4000	39	49
TiN	PVD	monolayer	3.7	3000	29-30	87

Table 3. Lubricants tested with the various coatings

LUBRICANT	PAO-10	PAO-4+ Additives	Synthetic A	Synthetic B
Viscosity 40°C (cSt)	71.1	15-20	233.5	132
Viscosity 100°C (cSt)	10.70	4.20	18.7	17.5
Viscosity Index	-	-	92	146
Flash point (°C)	272	204	235	221
Pour point (°C)	-51	-57	-15, 5	-45
Density (kg/m^3) at 15.6C	837	819	905	860

Although the steady-state friction for most coatings was higher than that for the uncoated steel surfaces, some coatings had comparable or even lower friction. Since the additives were designed to react with ferrous surfaces, the presence of a coating could certainly reduce the effectiveness of these additives, resulting in higher friction. It is nonetheless noteworthy and encouraging that some coatings exhibited lower friction than the bare steel surfaces. When tested with the state-of-art fully formulated lubricant, more coatings showed similar or better frictional performance compared to the uncoated materials (Figure 4).

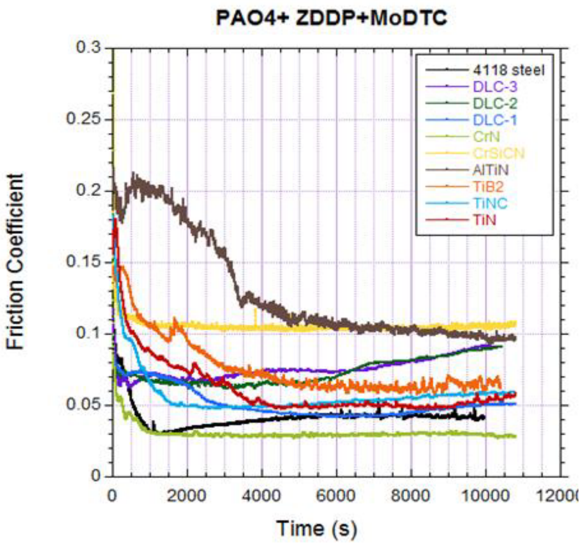


Figure 3. Variation of friction with time for coatings tested with model lubricant.

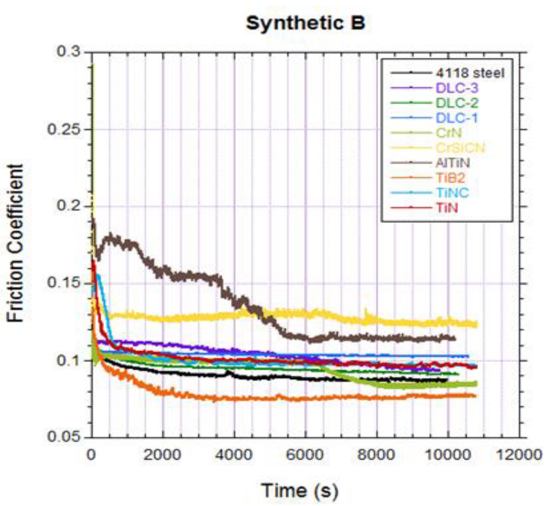


Figure 4. Variation of friction with time for coatings tested with state-of-art advanced lubricant.

Results for the wear performance of the coatings in Table 1 are shown in Figure 5. For unformulated 4118 steel, wear was substantial. With the lubricant formulations, significant reduction in wear was observed. With the various coatings, however, the effectiveness of the additives in reducing wear was significantly compromised. The amount of wear in many coatings and formulated lubricants was higher than the uncoated steel wear with the same lubricants. Nevertheless, some coatings and additives yielded substantial wear reduction. Wear reduction in these combinations is better than state-of-art lubricant and steel alone. Analysis conducted last year showed that reduction of gear size by 20% will require at least doubling the wear life. Results of our test showed that selection of an appropriate coating and lubricant combination can enable the achievement of this wear life goal.

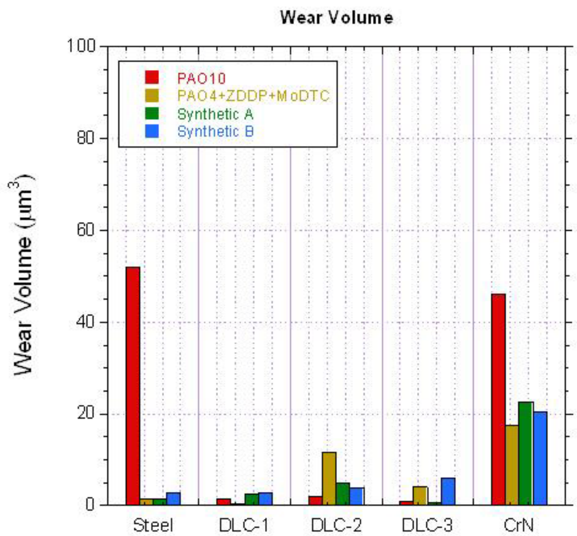


Figure 5. Wear of counter-face roller tested against various coatings in different lubricants.

Examination and analysis of different coatings tested with different lubricants showed that formation of tribochemical films occurred in some cases. The tribochemical film is the usual pathway to enhance friction and wear performance of ferrous surfaces. The observation of such films in coatings suggests the possibility of further enhancement of tribological performance through coating additives.

Conclusions

To reduce transportation vehicle driveline size and weight through high power density, and to realize the consequent fuel savings, we must substantially increase the wear, scuffing, and contact fatigue lives of driveline components. For 20% size reduction, doubling of the wear and scuffing life as well as tripling of the contact fatigue life is required. We identified combinations of coatings and lubricants with significant wear reduction compared to the current state-of-art steel and lubricant. Some other coatings were observed to result in higher friction and more wear by negating the beneficial effect of additives. The observation of tribochemical film formation in some coatings suggests opportunity and pathway for further improvement in tribological performance.

VII.F.3. Products

Publications

1. O. O. Ajayi, C. Lorenzo-Martin, D. Singh, and G. R. Fenske, "Performance Evaluation of Hard Ceramic Coatings for Tribological Applications" Presented at 36th International Conference and Exposition on Advanced Ceramics and Composites, January 22-27, 2012, Daytona Beach, FL (Invited Talk).
2. C. Lorenzo-Martin, O. O. Ajayi, S. Torrel, R. A. Erck, and G. R. Fenske, "Effect of Carbon-based Thin Film Coatings on Frictional Behavior under Boundary Lubrication Regime" Presented at 2012 STLE Annual Meeting, May 6-10, 2012, St. Louis, MO.
3. C. Lorenzo-Martin, O. O. Ajayi, S. Torrel, N. Demas, and G. R. Fenske, "Tribological Behavior of Ti-Based Thin Film Coatings under Boundary Lubrication Regime" Presented at 2012 STLE Annual Meeting, May 6-10, 2012, St. Louis, MO.
4. C. Lorenzo-Martin, O. O. Ajayi, S. Torrel, N. Demas and G. R. Fenske, "Effect of Hard Thin Film Coatings on Tribochemical Film Behavior under Lubricated Sliding Contact," Proceeding 36th International Conference on Advanced Ceramics and Composite, January 22-27, 2012**,** Daytona Beach, FL.

VII.G. DOE/DOD Parasitic Energy Loss Collaboration

Principal Investigator: George Fenske
Coworkers: Nicholaos Demas, Robert Erck
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL, 60439
Phone: (630) 252-5190; Email: gfenske@anl.gov

CRADA Contact: Ricardo, Inc.

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: lee.slezak@ee.doe.gov

VII.G.1. Abstract

Objective

- Develop a web-based toolkit based on FMEP (friction mean effective pressure) maps to predict the impact of key tribological engine parameters on vehicle fuel economy.
- Identify pathways to reduce parasitic friction losses in engines.
- Develop high-fidelity database on key tribological parameters (boundary friction) for use in a toolkit for identifying low-friction solutions.
- Validate mechanistic models by performing instrumented, fired-engine tests with single-cylinder engines to confirm system approaches to reduce friction and wear of key components.
- Identify common issues associated with commercial and military ground vehicles on the impact of low-friction lubricant technologies to reduce parasitic friction losses and vehicle efficiency.

Approach

- Integrate Ricardo's suite of engine dynamic simulation codes (PISDYN, RINGPAK, VALDYN, and ENGDYN) to develop FMEP maps as functions of engine speed and load for different tribological conditions (lubricant viscosity, asperity friction, surface finish, and lubricant chemistry) and for generic sizes of spark ignition (SI) and compression ignition (CI) engines (small, medium, and large).
- Model changes in contact severity loads on critical components that occur with low-viscosity lubricants.
- Evaluate the potential of advanced low-friction surface treatments (e.g., use of coatings, surface texturing, and additives) to reduce parasitic losses and predict potential fuel economy improvements.
- Measure friction and wear improvements on advanced laboratory rigs and fired engines to validate model calculations.
- Develop component maps of parasitic energy losses for typical civilian (e.g., small and medium SI engines) and military (e.g., medium and heavy CI engines) vehicles.

Major Accomplishments

- Developed a Cooperative Research and Development Agreement (CRADA) between Argonne and Ricardo, Inc., to utilize Ricardo's engine simulation codes to predict parasitic energy losses.
- Developed test laboratory-scale technique and protocols to measure critical input parameter (asperity friction) for use in Ricardo codes. Developed Stribeck analytical technique to extract boundary friction data from experimental tests.
- Evaluated the impact of advanced friction modifiers to reduce asperity friction.
- Continued efforts with the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) to identify mutual areas of collaboration for lubricant development.

Future Activities

- Install Ricardo codes (PISDYN, RINGPAK, VALDYN, and ENGDYN) on Argonne computers and initiate execution of codes to develop a database for the web-based toolkit.
- Evaluate engine friction measurement techniques to validate predictive models and identify site for future engine validations.
- Develop database on critical boundary layer friction.

VII.G.2. Technical Discussion

Background

Multiple approaches are being pursued to improve the fuel economy of vehicles, including the development of advanced tribological systems involving advanced lubricants, materials, coatings, and engineered surfaces to reduce parasitic friction losses in engines (and drivelines). This project focuses on the development of a fast, web-based calculator to predict the impact of tribological parameters such as the boundary friction coefficient, lubricant viscosity, temperature, surface finish, speed, load, and visco-piezo properties on the fuel economy of engines typically used for ground transportation vehicles.

Introduction

Friction, wear, and lubrication affect energy efficiency, durability, and environmental performance of engines used in ground transportation vehicles. Total frictional losses in a typical engine may alone account for more than 10% of the total fuel energy (depending on the engine size, driving condition, etc.). The amount of emissions produced by these engines is related to the fuel economy of that engine. In general, the higher the fuel economy, the lower the emissions. Higher fuel economy and lower emissions in future diesel engines may be achieved by the development and widespread use of novel materials, lubricants, and coatings. For example, with increased use of lower viscosity oils (that also contain lower amounts of sulfur- and phosphorous-bearing additives), the fuel economy and environmental performance of future engine systems can be dramatically improved. Furthermore, with the development and increased use of smart surface engineering and coating technologies, even higher fuel economy and better environmental soundness are feasible.

Integration of advanced lubricant chemistries, textured/superfinished surfaces, and advanced component materials and coatings necessitates pursuing a systems approach. Changes in one system component can readily change the performance of other components. For example, application of a hard coating on a liner to improve its durability may decrease the durability of the mating rings. Also, lowering the viscous drag will cause certain components (e.g., bearings) to operate under boundary lubrication regimes not previously encountered, resulting in accelerated degradation. A systems approach is required to not only identify the critical components that need to be addressed in terms of energy savings, but also to identify potential pitfalls and find solutions.

The main goal of this project is to use advanced models of engine-component friction and contact loading to predict the impact of smart surface engineering technologies (e.g., laser dimpling, near frictionless carbon, and superhard coatings) and energy-conserving lubricant additives on parasitic energy losses from diesel engine components. The project also aims to develop more realistic databases on the boundary or asperity friction that are used in advanced codes to predict total (asperity and hydrodynamic) friction losses and, in the future, to validate the predictions using fired engines. Such information will help identify critical engine components that can benefit the most from the use of novel surface technologies, especially when low-viscosity engine oils are used to maximize the fuel economy of these engines by reducing churning and/or hydrodynamic losses. The long-term objective of the project is to develop a database that provides a “look-up” capability to predict the impact of lubricant viscosity, asperity friction, and surface finish on FMEP and contact severity at different engine operating modes.

Approach

Under the ANL/Ricardo CRADA, multiple codes (PISDYN, RINGPAK, VALVDYN, and ENGDYN) will be integrated to calculate from first principles the parasitic friction losses (FMEP) under prescribed engine conditions (load and speed) for a range of tribological parameters (asperity friction, lubricant viscosity, surface finish, and pressure-temperature-viscosity coefficients). The information will be provided in a series of spreadsheets that will enable users to calculate changes in FMEP and fuel consumption scaling factors (FCSFs) to predict changes in fuel consumption for different driving cycles.

For a given engine type (diesel or gas) and size (small, medium, or large), the database will consist of FMEP contributions from the ring pack, piston skirt, engine bearings, and valve train as a function engine mode (load and speed) for different lubricant viscosities, asperity friction, type (mineral or synthetic), and component surface finish. The database users will employ a recommended baseline configuration (viscosity, asperity friction, surface finish, and oil type), or users can specify their own baseline configuration and a new (variant) configuration. The users will also specify the engine modes (speed, load) and weighting factors. The web-based calculator will utilize the FMEP database to calculate differences in the FMEP (relative to the baseline), which will be used to scale the fuel consumption at each specified engine mode (speed, load) and thus predict the change in fuel consumption from the baseline.

The FMEP calculations will be performed for the following range of parameters:

1. Engine Type/Size – Diesel or spark-ignited, with sizes of small (1-2 L), medium (4-6 L), or large (9-12 L).
2. Engine Mode – A load vs. speed matrix that is either 4x4 or 5x5, with loads ranging from 0 break mean effective pressure (BMEP) to full (100%) design load and speed ranging from idle (circa 750 rpm) to full (100%) design speed.
3. Lubricant Viscosity – Six or seven viscosity grades, including 20W/50, 10W/40, 10W/30, 5W/30, 5W/20, 0W/20, and 0W/10.
4. Asperity Friction – Five model asperity frictions ranging from 25% to 125% nominal values. Asperity friction depends on the component (ring, skirt, valve train, or bearings). Friction coefficients are typically in the 0.10 to 0.15 range.
5. Surface Finish – Three or four surface finishes typical of state-of-art and advanced manufacturing processes. Surface finish depends on the component.
6. Oil Grade and Type of Basestock – Mineral and synthetic oils, which have different viscosity-pressure coefficients (Barus), as well as mineral-based and synthetic (PAO) basestocks.
7. Additive/Material – The impact of lubricant additives and advanced additives on FMEP and fuel consumption will be determined through the asperity friction parameter (item 4), i.e., changes in the asperity/boundary friction coefficient. The model user can use their own information on the impact of their technology on asperity friction, or information developed on a companion look-up table on experimental boundary friction values for typical additives.

The codes used to model the FMEP perform detailed calculations of the dynamic forces on the engine components and, in the process, provide information on the severity of the contact loading between moving components (e.g., between the rings and cylinder liner). Such information will also be tracked and used to predict changes in the contact severity for different tribological conditions as well as changes in the minimum oil film thickness. This information can, to a first approximation, be used to estimate the impact of the parameters on component durability (gradual wear) and reliability (sudden catastrophic failure, e.g., scuffing) and the need for improved wear resistance and/or surface finishes to accommodate a given low FMEP strategy.

A second task focuses on developing a high-fidelity database on asperity friction for use in the calculator. Our approach in this effort utilizes laboratory-scale tribometers to simulate engine conditions to measure asperity friction for a range of conventional and experimental material and lubricant combinations.

A third task, not discussed here, focuses on fired-engine validation studies to be performed in the second and third years of the CRADA.

Results

Our FMEP studies for a heavy-duty, large (9-12 L), diesel engine were reported previously [1-5]. Figure 1 shows an example of the FMEP map as a function of load and speed. This type of map will be used in the current Ricardo CRADA project.

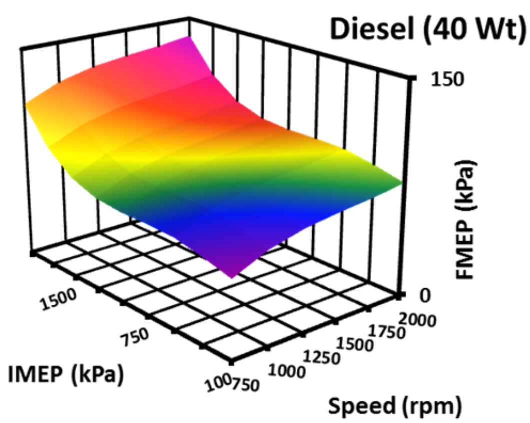


Figure 1. FMEP map for a large heavy-duty diesel engine for baseline asperity friction with 40 WT mineral oil.

The Ricardo CRADA will develop a series of maps for the range of conditions cited earlier. Such maps will then be used to generate fuel consumption scaling factors (FCSFs) defined as:

$$FCSF \equiv (IMEP + \Delta FMEP)/IMEP ,$$

where ΔFMEP is the change in the FMEP relative to the base case (40 WT oil with baseline asperity friction coefficients), and IMEP is the indicated mean effective pressure.

The experimental activities are aimed at identifying more realistic asperity friction coefficients. The current models assume the boundary friction coefficient is a fixed constant independent of temperature and interfacial composition/structure. The early models used in Refs. 1-4 assumed friction coefficients ranging from 0.005 to 0.12, depending on the component (0.005 for camshaft follower, 0.02 for cam bearing and rocker bushing, 0.05 for pushrod and rocker tip, 0.08 for piston skirt/liner, 0.12 for piston ring/liner, and 0.08 for the piston pin). In reality, the boundary friction is a function of temperature, additive package, and component material/coating. The laboratory-scale testing performed in this project utilizes bench-top rigs to simulate engine conditions and provide meaningful data on boundary friction coefficients that can be used in the models. In the meantime, the model predictions are performed by using a "what-if" or sensitivity basis, where the predictions are based on the assumption that the boundary friction is reduced by 25 to 90% to gauge the impact of asperity friction on fuel economy.

Figure 2. Pin-on-disc rig used to measure friction and wear under unidirectional sliding.

The codes used to model parasitic energy losses for different components separate losses into hydrodynamic and asperity contributions. Asperity friction is modeled as a fixed constant independent of temperature. The hydrodynamic friction is modeled using a mass-conserving solution to the Reynolds equations, where elasticity of the components is considered. The experimental portion of this project utilizes laboratory-scale rigs to quantify the friction (and wear) of lubricants at temperatures ranging from room temperature to 100°C. Photos of the laboratory-scale rigs are shown in Figures 2 and 3 for a pin-on-disc (POD) and high-frequency reciprocating rig (HFRR), respectively.

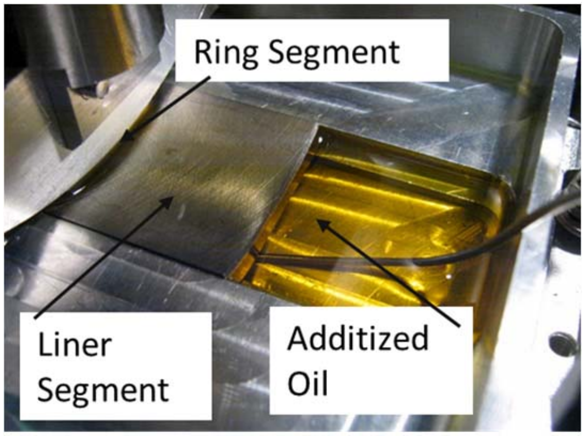


Figure 3. High-frequency reciprocating rig.

The reciprocating rig utilizes segments from a commercial piston/cylinder system, and it can be used to screen lubricants, materials, and surface finishes. The rings were made of hardened steel and had a CrN coating, and the liner segments were made of gray cast iron. The effect of liner finish was investigated. Two liner finishes, plateau honing and slide honing, were tested using PAO10 at a temperature of 23°C, a normal load of 50 N, and a reciprocating length of 20 mm. Three-hour tests were performed at 60 rpm (0.04 m/s) with ramps of speeds varying from 15 rpm (0.01 m/s) to 300 rpm (0.2 m/s) at the beginning and end of the test. Tests were repeated multiple times to ensure the data were reproducible. The plateau-honed liner exhibited a higher coefficient of friction than the slide-honed liner. Both finishes allow the contact to move from boundary into the mixed regime of the Stribeck curve. Each liner has a different boundary friction coefficient, with plateau honing at 0.11 and slide honing at 0.10. Each test has a positive and negative direction because of the reciprocating nature of the tests; however, the labels positive and negative are arbitrary. Figure 4 shows Stribeck-like curves. Figures 4(a) and 4(b) show the experimental data for the plateau-honed and slide-honed liner, respectively. Superimposed in these plots are simulated results using a Greenwood-Tripp asperity contact model to describe surface contact between the liner specimen and piston ring. It is obvious that the model over-estimates the experimental friction results. However, it is clear that the coefficient of friction for the slide-honed surfaces is lower than that of the plateau-honed surface.

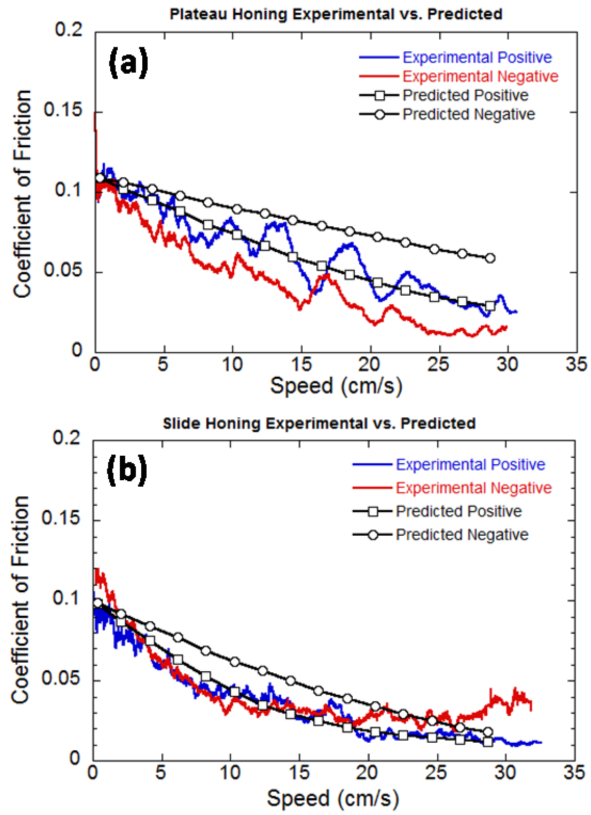


Figure 4. Stribeck-like curves for two liner surface finishes: (a) plateau-honed and (b) slide-honed.

Tests were also conducted to evaluate the performance of several lubricants. Figure 5 shows the results of tests performed using PAO10 basestock lubricant (three tests were conducted for repeatability) and PAO10 with different additives: Oxide 1, Oxide 2, MoS_2, molybdate ester, and molybdate ester with zinc dithiophosphate (ZDDP). PAO10 was used as a baseline and resulted in a coefficient of friction of around 0.13. The addition of either one of the oxide additives showed no difference in the coefficient of friction. The MoS_2 yielded a coefficient of friction of 0.05-0.07 with an initial decrease in the first few minutes of the test. Molybdate ester alone reduced the coefficient of friction to approximately 0.11, and when used along with ZDDP it reduced the coefficient of

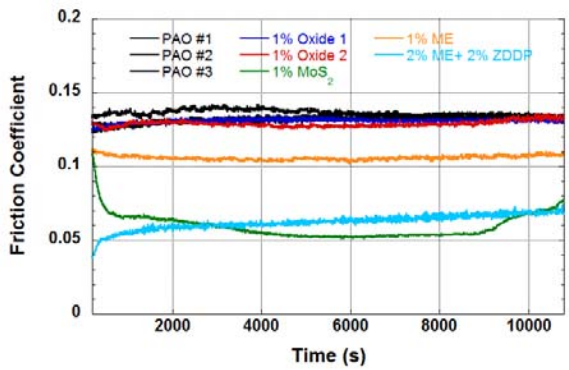


Figure 5. Coefficient of friction as a function of time for PAO10 and various additives.

friction significantly, to 0.05-0.07. From these results we concluded that the reciprocating rig is a good tool for screening of various additives within a lubricant.

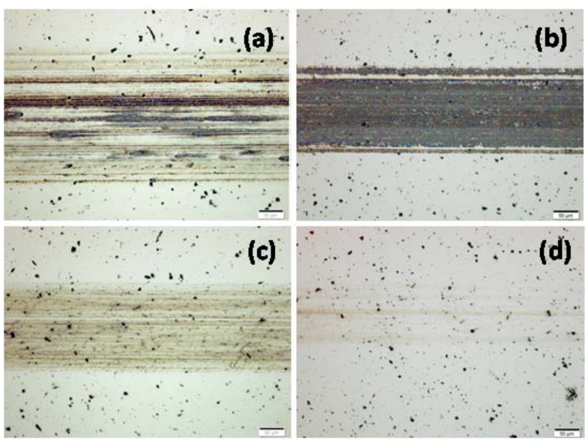


Figure 6. Wear tracks of flats for (a): PAO4, (b) PAO4 with oxide, (c) formulated oil, and (d) formulated oil with oxide.

The reciprocating rig was also used for ball-on-flat tests. These types of tests are simpler than the previous tests that used prototypical samples, and can be used to quantify wear while also measuring the coefficient of friction under high contact pressures (1 GPa). A 52100 steel ball was used against a mirror-finish 52100 steel flat. After these tests the wear tracks were examined for wear and the formation of tribofilms.

Figure 6 shows the wear tracks produced after testing using (a) PAO4, (b) PAO4 with an oxide additive, (c) a formulated oil without friction modifiers, and (d) formulated oil without friction modifiers with the same oxide additive. Clear differences can be seen between wear tracks. For example, localized abrasion is evident in Figure 6(a) with the partial formation of a tribofilm that looks inhomogeneous. Figure 6(b) shows the formation of a continuous tribofilm. Figure 6(c) shows some mild burnishing, while Figure 6(d) shows almost no wear track.

Examination of the balls showed that the addition of the oxide additive provided wear protection when added to the basestock oil. The results can be seen in Figure 7.

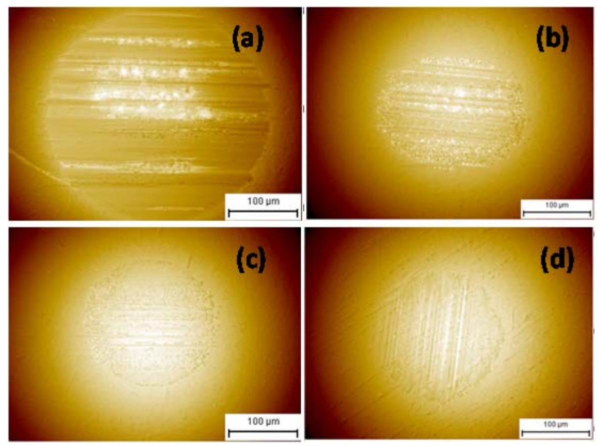


Figure 7. Wear scars on balls for: (a): PAO4, (b) PAO4 with oxide, (c) formulated oil, and (d) formulated oil with oxide.

Figure 7(a) shows a large contact patch due to the high wear, indicating that PAO4 offers little protection. Figure 7(b) shows that the addition of the oxide reduced wear significantly. There is little difference between Figures. 7(c) and 7(d).

Conclusions

The Parasitic Energy Loss Reduction project is examining the effects that tribological variables such as viscosity, boundary friction, and surface finish have on the friction losses in an engine and the overall vehicle fuel economy. Negotiations to establish a CRADA with Ricardo, Inc., have been completed to extend the heavy-duty diesel modeling to small- and medium-size engines and to include surface finish effects. Studies based on prior heavy-duty diesel engine models suggest that fuel economy of military ground vehicles can be significantly improved. Furthermore, due to military policies to perform periodic “resets” of vehicles, it may be feasible to retrofit military vehicles with improved materials and coatings on critical components and thus achieve even greater fuel economy improvements than achievable with advanced lubricants/additives alone.

Studies on HFRR and POD rigs indicate that more realistic information on boundary friction coefficients can be achieved as functions of temperature and composition. Several candidate additive approaches have been identified that show significant improvements in friction.

Future activities will focus on CRADA activities to develop realistic boundary friction databases for non-ferrous friction couples (materials, coatings, and additives) at temperatures prototypic of internal combustion engines. Also, code predictions will be validated using fired engines. Efforts to further define a cohesive collaboration with TARDEC are in progress under a formal memorandum of understanding developed between DOE and DOD to pursue advanced vehicle power technologies.

References

1. I. Fox, "Numerical Evaluation of the Potential for Fuel Economy Improvement due to Boundary Friction Reduction within Heavy-Duty Diesel Engines," ECI International Conf. on Boundary Layer Lubrication, Copper Mountain, CO, Aug. 2003.
2. George Fenske, "Parasitic Energy Loss Mechanisms," *FY 2006 Progress Report for Heavy Vehicle Systems Optimization* (2006).
3. George Fenske, "Parasitic Energy Loss Mechanisms: Impact on Vehicle System Efficiency," U.S. Department of Energy Heavy Vehicle Systems Review, Argonne National Laboratory, Argonne, IL, April 18-20, 2006.
4. G. Fenske, O. Ajayi, R Erck, C. Lorenzo-Martin, A Masoner, and A. Comfort, "Reliability of Powertrain Components Exposed to Extreme Tribological Environments," Proceedings of the 2010 Ground Vehicle Systems Engineering and Technology Symposium, Dearborn, MI, 2010.
5. George Fenske, Nicholaos Demas, and Robert Erck, "Agreement #19226/VSS Task # 111 – Efficiency Improvements through Parasitic Loss Reduction," *FY2011 Annual Progress Report for Vehicle Systems Optimization* (2011).

VII.G.3. Products

Publications

1. Tribological evaluation of piston skirt/cylinder liner contact interfaces under boundary lubrication conditions, N. G. Demas, R. A. Erck, and G. R. Fenske, Lubrication Science, 22: 3, 73–87, 2010.
2. Tribological studies of coated pistons against cylinder liners in laboratory test conditions, N. G. Demas, O. O. Ajayi, R. A. Erck, and G. R. Fenske, Lubrication Science, DOI: 10.1002/ls.1175, 2012.
3. Tribological effects of BN and MoS_2 nanoparticles added to polyalphaolefin oil in piston skirt/cylinder liner tests, N. G. Demas, E. Timofeeva, J. L. Routbort, G. R. Fenske, Tribology Letters, 47:1, 91-102, 2012.
4. Influence of surface texture on micro EHL in boundary regime sliding, R. A. Erck, O. O. Ajayi, C. Lorenzo-Martin, and G. R. Fenske, Extended Abstract, ASME/STLE 2012 International Joint Tribology Conference, October 8-10, 2012.

Tools & Data

Software tools that are provided for use in this project as part of the CRADA with Ricardo, Inc., include:

1. PISDYN
2. RINGPAK
3. VALDYN
4. ENGDYN

FAST AND WIRELESS CHARGING

VII.H. AVTA – Wireless Charging and Other EVSE Data Collection Activities

Principal Investigator: James Francfort
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2209
Phone: (208) 526-6787; Email: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VII.H.1. Abstract

Objective

- Benchmark wireless charging systems developed with DOE technology funding.
- Benchmark the cyber security of both wireless and conductive charging systems.
- Benchmark several wireless charging systems being developed independent of DOE funding.
- Benchmark the efficiencies of conductive electric vehicle supply equipment (EVSE) that the wireless charging systems are intended to replace and document the efficiency of existing EVSE systems for comparative purposes.
- Benchmark DC Fast Charging (DCFC) and Level 2 compatibility with new generations of plug-in electric vehicles (PEVs).
- Support the deployment of smart EVSE by testing the EVSE developed by the DOE Office of Electricity Delivery and Energy.

Approach

- Continue developing additional Non-Disclosure Agreements (NDAs) with wireless charging companies to initiate testing plans and actual testing.
- Refine cyber security test procedures and efficiency testing procedures.
- Refine offset and EMF testing procedures for wireless charging systems.
- Continue conducting EVSE Level 2 efficiency testing and document the results.
- Benchmark the smart EVSE developed from DOE Office of Electricity Delivery and Energy Reliability Financial Opportunity Assistance grants.
- Conduct DCFC manufactures and vehicle original equipment manufacturers (OEMs) joint research compatibility benchmarking.

Major Accomplishments

- Completed and published benchmarking results for eight Level 2 EVSE and benchmarked one Level 2 EVSE.
- Completed NDAs with several smart EVSE and wireless charging manufacturers.
- Initiated efficiency and cyber security testing of smart EVSE and wireless chargers with development of testing procedures and equipment.
- Completing NDAs with seven other manufacturers of smart EVSE and wireless charging systems.

- Use of anechoic testing facilities and EMF-complete free 150-mile roadway system for testing.
- Initiated DCFC and EVSE Level 2 compatibility project by developing funding and initial project plans as well as procuring OEM willingness to support project.
- Conduct benchmarking of incompatible EVSE Level 2 system and OEM vehicle.

Future Activities

- Continue benchmarking and publishing EVSE benchmarking results.
- Continue development of NDAs.
- Continue cyber security testing activities.
- Continue development of testing procedures as wireless testing continues.
- Continue EMF testing.
- Procure DCFCs and OEM prototype vehicles for compatibility demonstrations.

VII.H.2. PEVs Technical Discussion

Background

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing (AVTA) is part of DOE's Vehicle Technologies Program (VTP), which is within DOE's Office of Energy Efficiency and Renewable Energy (EERE). The AVTA is the only DOE activity tasked by DOE to conduct field evaluations of vehicle technologies that use advanced technology systems and subsystems in light-duty vehicles to reduce petroleum consumption. A secondary benefit is the reduction in exhaust emissions.

Most of these advanced technologies include the use of electric drive propulsion systems and advanced energy storage systems. However, other vehicle technologies that employ advanced designs, control systems, or other technologies with production potential and significant petroleum reduction potential, are also considered viable candidates for testing by the ATVA.

The AVTA light-duty activities are conducted by the Idaho National Laboratory (INL) for DOE. INL has responsibility for the AVTA's execution, direction, management, and reporting; as well as data collection, analysis and test reporting.

The current AVTA staff has 20+ years of experience testing grid connected, plug-in electric vehicles (PEVs) as well as PEV charging infrastructure. This experience includes significant use of direct current fast chargers (DCFCs) with lead acid and other battery chemistries in the middle 1990s and that important legacy of experience is still available today. In addition, the Idaho National Laboratory has significant experience performing cyber security testing for various Federal agencies that are also being used for this project. The AVTA is currently collecting performance and use data from more than 10,000 Level 2 EVSE from the two largest providers of EVSE as well as several additional EVSE manufacturers.

Introduction

With the expanding introduction and use of grid connected plug-in electric vehicles (PEVs) by fleets and individual taxpayers, there is in parallel continuing development of both private and public PEV charging infrastructure, collectively known as electric vehicle supply equipment (EVSE). This EVSE currently takes the form of Level 1 (110 Volt) and Level 2 (240 Volt) levels that safely supply AC electricity to the vehicle and the charger that resides on the vehicle. The third type of EVSE is the DCFC, which provides DC electricity to the vehicle and the power electronics equipment onboard the vehicle. For DCFC, the charger is actually located offboard the vehicle. Level 1 and 2 EVSE may either be in the form of "smart" EVSE, with functionalities such as revenue grade electricity meters, bidirectional communication capabilities and other "smart" features. The opposite of this are "dump" EVSE, which only provides electricity with minimal capabilities. By nature of its design, DCFC are also at least somewhat smart units. Normally, the term "EVSE" will refer to Levels 1 or 2, and DCFC will be referred to by its acronym. It should be noted that most installed EVSE are Level 2 units, which provide significantly shorter charge times than Level 1.

Adding to the complexity is the introduction of wireless charging systems which transfer energy without having the conductive connector of today's EVSE and DCFCs. To support the introduction of safe and efficient wireless charging systems, DOE and the AVTA are conducting a series of activities to test and benchmark. These activities include grants to support the development of smart EVSE and wireless charging, as well as benchmarking the efficiencies of the different charging options and testing for the vehicle-to-charging infrastructure compatibility. The activities discussed here detail the support activities being conducted by the AVTA and some of the benchmarked results.

Approach

The AVTA has developed a process to benchmark wireless charging systems developed with DOE technology funding as well as with other wireless providers. Initial testing has been conducted and all existing INL facilities and test equipment and locations are in place. Of significant importance is the development of NDAs in order to develop test procedures and share proprietary information. This is currently ongoing with several NDAs signed to date.

The INL will be benchmarking the cyber security of both wireless and conductive charging systems in partnerships with manufacturers of both. This is not an area that will receive significant disclosure.

Much discussion has occurred regarding efficiency of emerging wireless systems. For this reason, the AVTA is testing the current group of conductive EVSE that the wireless systems will be compared to.

Of concern to industry and DOE is the compatibility of both DCFC and EVSE Level 2 equipment with OEM vehicles. The AVTA has already benchmarked some problems with compatibility with the new generations of PEVs and this task has been expanded.

Working with SAE and several wireless charging providers, the AVTA has developed various testing regimes for offset and efficiency testing of wireless systems. This will be used to conduct several additional tests and the procedures will be refined.

INL has developed testing of conductive EVSE Level 2 efficiency procedures and this is being used to document grid to vehicle energy transfer efficiencies. This early work is being leveraged to support the benchmarking of the DOE Office of Electricity Delivery and Energy Reliability (OE) developed smart grid EVSE.

As is the AVTA's normal process, fact sheets and reports will be used to document benchmarking procedures and results, and the quantitative results will be published, with the exception of cyber security findings.

Results

There are eight Level 2 EVSE (Figures 1 to 8) that have completed initial benchmarking and the results are available at: avt.inel.gov/ evse.shtml. The fact sheet results document:

- Features
- Specifications
- Model tested
- Test conditions
- Test vehicle used
- Test Results, including, AC Watt energy consumption prior to, during steady-state, and at post charge, as well as steady-state charge efficiency
- Charge start and end profiles.

Figure 1. Aerovironment EVSE Level 2.

Figure 2. Blink EVSE Level 2.

Figure 3. Chargepoint EVSE Level 2.

Figure 4. Clipper Creek EVSE Level 2.

Figure 5. Eaton EVSE Level 2.

Figure 6. Leviton EVSE Level 2.

Figure 7. SPX EVSE Level 2.

Figure 8. Voltec EVSE Level 2.

The amount of EVSE standby energy consumption is directly tied to the “smartness” or features offered by each of the Level 2 EVSE. The more features the units offer, the more energy each EVSE will consume internally. Note that the energy transfer efficiencies range from a low of 97.91% to a high of 99.68% (Table 1).

Table 1. Level 2 EVSE testing results.

Manufacturer	Efficiency	Per Charge EVSE AC Watts Consumption
AeroVironment	99.30%	5.11
Blink	99.19%	13.4
ChargePoint	99.26%	6.9
Clipper Creek	99.24%	3.12
Eaton	99.48%	3.2
Leviton	99.24%	8.18
SPX	99.68%	1.8
Voltec	97.91%	2.2

Note – see avt.inel.gov/evse.shtml for specifications on models tested.

Most wireless charging companies are working towards a level of 90% or greater efficiency. This efficiency is often compared to Level 2 EVSE efficiency, but an apple-to-apple comparison of EVSE Level 2 and wireless charger efficiencies is not realistic due to the contrast in the power electronics of the competing technologies. Therefore, the AVTA is working with various manufacturers to develop equitable methods and onboard vehicle locations to benchmark energy efficiencies of different charging technologies.

The development of NDAs in preparation of performing charging performance testing and cyber security testing is a significant accomplishment and as FY 2012 ended, INL has completed several of these legal processes with respective manufacturers.

Testing has occurred and will continue to occur in both test laboratories and field locations. These include both manufacturer and AVTA owned facilities. By the luck of INL's location, an existing roadway system of nearly 900 square miles exists with no measureable EMF existing. In addition, existing test equipment includes:

- Chroma C8000
  - Programmable AC and DC loads
  - J1772 communication for functionality
  - Data collection with GPIB and Serial input
- Hioki 3390
  - 4 channel AC or DC current, voltage, power, integrated energy, power factor, efficiency, etc.
  - Serial and USB (to program) output
- Narda EHP200a
  - H-field (magnetic field strength) Amps/meter
  - E-field (electric field strength) Volts/meter
  - Fiber optical cable to USB (to program) only
- Coil Positioning System (+/- 15")
  - Require X, Y, Z, rotate, and tilt
  - Require feedback of position into data acquisition
- Anechoic chamber

The AVTA has also initiated the DCFC and EVSE Level 2 compatibility to new prototype OEM PEVs benchmarking by developing initial project plans and securing OEM and SAE participation commitments to support the project.

Conclusions

The benchmarking of the conductive, Level 2 EVSE is a very low cost way to demonstrate the efficiency and standby energy use of conductive chargers as a baseline to the future testing of both Smart EVSE and wireless charging systems.

Smart EVSE providers and the AVTA are developing the cyber security and efficiency test plans that will be used when the OE funded Smart EVSE are delivered during late FY 2012.

The NDAs necessary for testing implementation and test plan discussion continue to be put in place. The INL will also initiate the testing of full wireless systems in the first quarter of FY 2013.

The AVTA will also procure DCFCs and OEM prototype vehicles for compatibility demonstrations with the results presented to the OEMs and DCFC manufacturers.

VII.H.3. PRODUCTS

Publication

1. The test procedures for both the OE Smart EVSE and wireless testing are being developed, so they are not yet published. However, the eight Level 2 EVSE test results fact sheets, can be found at: avt.inel.gov/evse.shtml. In addition, the same website hosts six additional reports on Bi-Directional energy transfer technologies and other charging infrastructure reports.

VII.I. Mitigation of Vehicle Fast Charge Grid Impacts with Renewables and Energy Storage

Principal Investigator: Tony Markel
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
Phone: (303) 275-4478; Email: tony.markel@nrel.gov

DOE Program Manager: David Anderson
Phone: (202) 287-5688; Email: david.anderson@ee.doe.gov

VII.I.1. Abstract

Objective

- Quantify future potential power and energy demands of fast charging
- Assess potential for renewables to buffer fast charging grid impacts

Approach

- Simulate plug-in electric vehicles (PEVs) in real world driving patterns with broad variability
- Model state-of-charge for each vehicle in large fleets central to a single fast charging station
- Assess vehicle wait times while other's charge to appropriately aggregate electricity demand
- Model solar photovoltaic (PV) array output parametrically varying with array size and real-world irradiation data
- Quantify total demand, times of peak demand

Major Accomplishments

- Development and validation of a fast charger utilization simulation
- Analysis of photovoltaic and station energy storage sizing
- Publication and presentation of the analysis at the 26th International Electric Vehicle Symposium

Future Activities

- Detailed economic analysis
- Improved sizing routine
- Optimize system sizing and configuration

VII.I.2. Technical Discussion

The Electric Vehicle Grid Integration activity performs research supporting the introduction of plug in hybrid electric and electric vehicles (inclusively PEVs) and their interface with the utility grid. Addressing interface challenges and impacts to the utility grid is critical to market expansion and influence the role of renewables when charging PEVs. Analysis and collaboration with industry are required to quantify the potential and identify the research to support systems integration.

The growing, though still nascent, plug-in electric vehicle (PEV) market currently operates primarily via level 1 and level 2 charging in the United States. Fast chargers are still a rarity, but offer a confidence boost to oppose "range anxiety" in consumers making the transition from conventional vehicles to PEVs. Because relatively no real-world usage of fast chargers at scale existed at the time of this study, NREL developed a simulation to help assess fast charging needs based on real-world travel data. Simulations were run for multiple scenarios, varying fleet sizes and station configuration. The grid impact of this usage is further quantified to assess opportunities for renewables integration; specifically, a high frequency of fast charging is found to be in demand during the late afternoons and evenings coinciding with grid peak periods. Proper integration of a solar array and stationary battery pack thus helps ease the load.

Background

Plug-in electric vehicles (PEVs) present a viable alternative to petroleum-fueled automobiles fulfilling a variety of common transportation needs. However, many conventional vehicle owners and operators are accustomed to refueling their vehicles in less than 5 minutes once or twice each week, and enjoy the ability to take occasional long-distance trips. The commonly available infrastructure that supplies power to PEV batteries is far from being able to practically "refuel" vehicles as quickly as conventional refueling.

The National Renewable Energy Laboratory (NREL) is studying the impact of fast charging to the local, regional, and nationwide grid infrastructure from PEV fast charging. This paper documents an initial phase of this research, characterizing potential usage patterns of a single fast-charge station with multiple charge ports by a local fleet. In addition, the study includes a look at sizing solar arrays and stationary batteries to accompany a fast charger, providing renewable fuel to PEVs and reducing electricity bills to the station.

Approach

To simulate fast charge usage based on real-world needs, NREL collected real-world driving times, speeds, and distances from the Puget Sound Regional Council's (PSRC) 2008 Traffic Choices Study. These data formed the basis for vehicle utilization in this study (psrc.org/transportation/traffic/)

The Traffic Choices Study was an investigation of the response of travel behavior to variable toll charges in the Seattle metropolitan area. The study placed global positioning systems in 445 vehicles from 275 volunteer households that recorded driving patterns over an 18-month average per household period. The experiment started with a 3-month control period in which no behavior was influenced by the tolls. This study uses data only from the control period.

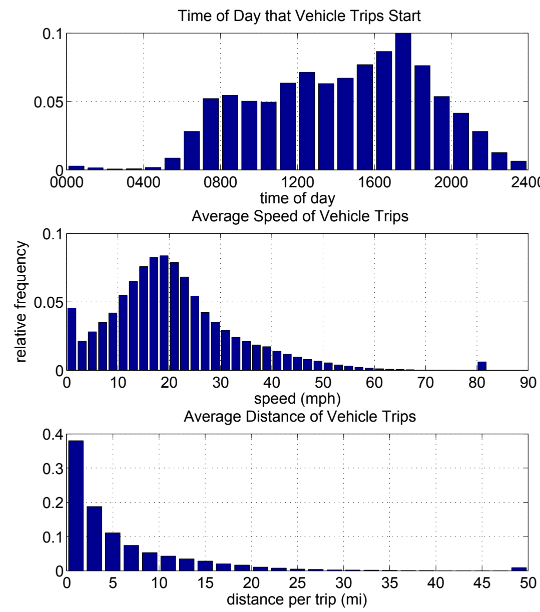


Figure 1. PSRC Vehicle Trips Summary

Vehicle usage profiles are selected from the Traffic Choices Study dataset randomly and modeled as all-electric vehicles with lithium-ion batteries of consistent size (varied as an input parameter). The vehicles are assumed to utilize a state-of-charge window of 80% (between 10% and 90%).

All PEVs are assumed to consume energy at an average rate of 300 Wh/mi, approximating an electric compact or midsize commuter vehicle. The parametric simulation is designed to evaluate scenarios of varying fleet size and vehicle battery size, as well as station design parameters.

For this study a "forgetfulness factor" of 10% is applied, indicating how frequently drivers forget to plug in their PEVs at home. Also, if a PEV owner is driving at midnight, it is assumed that they will not be charging overnight. The station operates on a "first come, first served" basis; wait times are applied to vehicles arriving after all ports are in use.

Results

NREL found that if fast charge stations were utilized as needed in scenarios where motorists drive electric vehicles as they drive conventional vehicles today, demand would likely be highest in the afternoon and evening hours.

The integrated simulation models the power exchange between the fleet, solar array, stationary battery, and utility. Power demand from fast charging the PEVs is supplied by the solar array, stationary battery, or grid depending on the availability of solar (time-of-day) and the stationary battery's state-of-charge. A sample day is shown in Figure 2. In this example, the sizing of the solar array and battery are inadequate to avoid peak demand charges and serve to mitigate grid impacts from only a small fraction of the fast charge events.

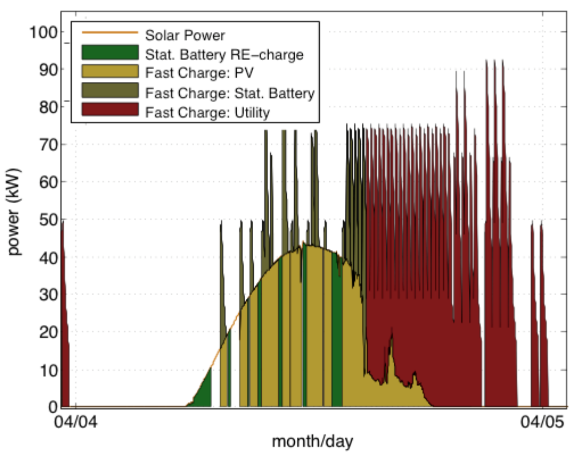


Figure 2. Sample Day – PV Required to Renewably Fast Charge.

Initially a sweep of the five parameters was conducted at three levels each (minus a few incompatible cases), yielding a result set for 168 different scenarios. Although a more in-depth analysis is anticipated during the following phases of this research, early results point to a strong correlation of fast charger utilization with both the size of the fleet it serves and the battery capacity of the PEVs. The results, shown in Figure 3, indicate that wait times are minimal for 200 car fleets supported by a single 4-port fast charger.

.

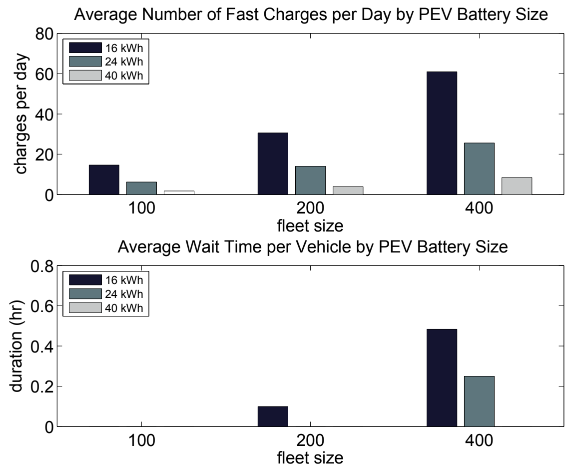


Figure 3. Average Station Utilization with Four Ports.

Conclusions

Depending upon the size and concentration of a local fleet of vehicles, fast charging stations may be in high demand. This study detailed a method of simulating potential use of fast chargers as well as the key data sets and assumptions.

Several trends appeared in the data, including a strong demand for fast charges in the afternoon and early evening hours. This may guide a renewable station designer to orient solar panels towards the west to shift the peak output later in the day, coinciding with the charging load.

In addition, a large PV array and stationary battery are necessary to confidently offset grid load. However, with upwards of 40 charges per day at a multi-port fast charge station serving 200-400 vehicles in a local area, the investment may pay for itself in charging fees and electric bill management. NREL plans to complete a more exhaustive design study of these trade-offs and their financial implications in FY 2013.

VII.I.3. Products

Publications

1. Simpson, M.; Markel, T.; *Plug-in Electric Vehicle Fast Charge Station Operational Analysis with Integrated Renewables*; presented at the 26th International Electric Vehicle Symposium, May 6-9, 2012.
2. DOE VT Annual Merit Review presentation eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/veh_sys_sim/vss076_markel_2012_o.pdf

VII.J. Wireless Charging Development/Demonstration

Principal Investigator: John M. Miller
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1469; Email: millerjm@ornl.gov

DOE Program Manager: Lee Slezak
Phone: (202) 586-2335; Email: Lee.Slezak@ee.doe.gov

VII.J.1. Abstract

Objective

- Extend prior ORNL open core, copper tube, high current Wireless Power Transfer (WPT) laboratory development to SAE level 2 stationary charging at 6.6 kW and >90% overall efficiency in a test and demonstration vehicle.
  - Air core designs cannot meet health and safety targets, therefore, novel soft ferrite cores are employed for field focusing and shielding.
  - Target for Vehicle application: Level 2 charging, 6.6 kW, $150 < z < 200$mm in an Equinox PHEV demonstration mule vehicle

Approach

- Insert Bullets on high level methodology here
- Development activities focused on highest efficiency, most compact, and lightest on vehicle WPT system for future commercialization efforts.
  - Power inverter based on best available silicon IGBT technology, that includes assessment of next generation devices having 5 times the switching capability
  - Coupling coil design supported with detailed EM FEA to guide material and structural design to be mechanically robust, magnetically shielded and electrically lowest loss
  - Comparison of magnetic resonance tuning that includes series-parallel, series-series, and parallel-series and how architecture influences real and reactive power flows
  - Control strategy is primary side regulation of power flow based on vehicle BMS messages and algorithm tailored to primary coil excitation voltage (duty cycle) and frequency inner loops
- Laboratory validation of power transfer to mule vehicle with 288V nickel metal hydride battery pack, including control authority over power flow.

Major Accomplishments

- Demonstrated 8.5 kW stationary wireless power charging of Equinox mule vehicle in the laboratory on 3 July 2012. NiMH pack voltage was 312V at 7 kW charging with indicated SOC of 57%. WPT coupling coil gap, z=150mm and dc input to battery efficiency was 88%.
- Team drafted proposal to DOE solicitation #DE-FOA-000667 Wireless Charging for Electric Vehicles that resulted in program award for three year contract.

Future Activities

- Program completed in July 2012. Future development will focus on meeting deliverables stated in FOA#667.

VII.J.2. Technical Discussion

Wireless Power Transfer (WPT) is emerging as a safe, convenient, flexible and autonomous charging method for plug-in and battery electric vehicles (PEV's). It is safe because the vehicle is inherently isolated from the grid connection via the large gap between WPT transmit pad and vehicle mounted receiver coil. This means that wireless charging can be done during inclement weather without need of bulky cable and heavy duty plugs. WPT charging is convenient and flexible not only because no cables and connectors are necessary but charging becomes fully autonomous. As the technology evolves it is not difficult to imagine a vehicle with magnetic field sensing or assisted by a parking aide being capable of positioning itself over a primary pad for optimum alignment and autonomous charging. Vehicle to infrastructure (V2I) communications adds to the autonomy benefit by handling all the bidirectional communications needed for charging transactions as well as providing the feedback channel for power flow regulation. The system level diagram of ORNL's primary side regulation is shown as Figure 1.

- Partity with conductive charging implies 85% to 90% overall efficiency between the grid connection and the vehicle battery pack.
- The primary contributor to this goal is coil to coil efficiency on the order of 96%-97% and the high frequency (HF) power inverter in the same range.
- Add to this the need for an active front end power factor correction, harmonic filtering and noise suppression in this same range (i.e., ~97%).
- Fully integrated WPT in a vehicle must be 96% to 97% efficient on average (i.e., a 4-block cascade yields 0.96^4=0.849 to 0.97^4=0.885), which is what ORNL has demonstrated.

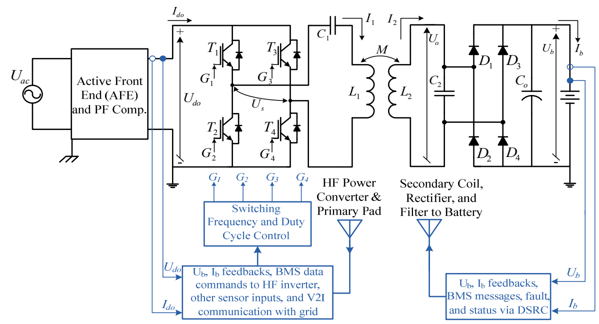


Figure 1. Architecture of ORNL Wireless Charging System.

The following sections summarize the development activities in WPT for coupling coil design and electromagnetics modeling, high frequency power inverter regulation, vehicle integration actions and lessons learned.

Coupling Coil Design

In WPT systems the coil design is the most important element in the overall system because it determines the power transfer level, and to a large extent the overall performance and efficiency, plus the shielding and magnetic emissions levels to be expected. The ORNL coil design has Litz cable coils laid over a soft ferrite structure all overlaid on a non-magnetic case having very low profile. Figure 2 illustrates an adjustable fixture fabricated for a primary and secondary coil pair wound with 7 turns of 5x1250x38AWG (i.e., 5 in hand) jacketed Litz cable.

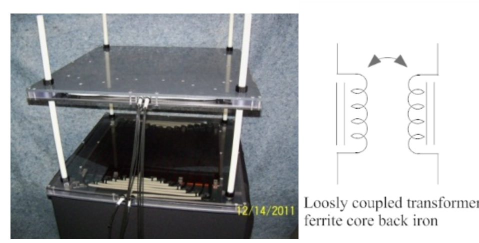


Figure 2. Coupling Coil and standard symbol.

Test data for the coupling coils shown in Figure1 are summarized in Table 1.

Table 1. Distributed winding coupling coil data

Parameter	R_{dc} (mΩ)	R_{ac} (mΩ) @ f=25 kHz	L_{11} (μH)
Primary/bottom	18.7	34.6	36.6
Secondary/top	18.7	34.6	36.2

Electromagnetics Modeling

Electromagnetic design of WPT coupling coils provides the most fundamental investigation into their performance. One approach develops the magnetic vector potential analytically as due to an ideal primary coil at a field point that lies at the location of the secondary coil. For a coil pair having a radius **a**, assuming infinitesimal conductor radius, and a coil to coil spacing, z. Then the radius from the primary coil origin to the field point is $r=\sqrt{(a^2+z^2)}$ and vector potential, $\mathbf{A}_\phi$, for a case of N_1 primary turns and I_1 Amps yield a primary excitation of N_1I_1 amp-turns. This primary excitation is depicted as **Idl** in Figure3 where $a_1=a_2=a$.

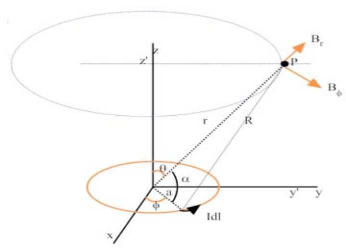


Figure 3. Graphic showing vector field analysis construct

In addition to analytical design of coupling coils solid models of the coils were ported to an electromagnetic finite element field solver. An illustration of B-field vector plot and CAD drawing are shown in Figure 4.

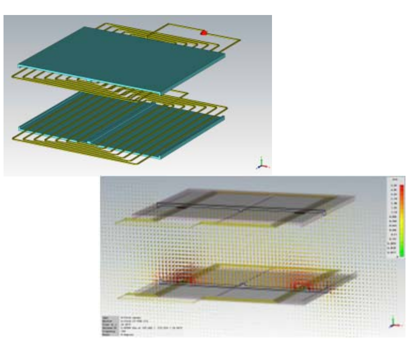


Figure 4. CAD .stp model and FEA results for distributed winding coupling coil. Analytical result for coupling coefficient: k=0.201, FEA result: k=0.199.

Coupling Coil Characterization

The variation of coupling coefficient with coil spacing, k(z), is one of the most important variables in WPT charging besides misalignment tolerance. In laboratory tests performed at ORNL an Industrial Electronics model 1500A Powertron amplifier and signal generator are used to apply high current to the primary coil of the coupling coil pair shown in Figure 2. The equations for coupling coefficient calculation for open circuit characterization (left) and inductance aiding measurements (right) are given by (1).

$$k_{oc}(z) = \frac{U_2}{U_1}\bigg|_{\substack{U_2=U_{oc}\\ I_1=10A_{rms}\\ gap=z}} \qquad k_{aid}(z) = \frac{L_{aid}-(L_1+L_2)}{2\sqrt{L_1L_2}}\bigg|_z \quad (1)$$

Open circuit testing makes use of a signal generator and high current amplifier to excite the primary coil at specified sinusoidal current, I_1 = 10A_{rms} and corresponding potential U_1 (V_{rms}). Measurement of secondary coil potential yields the open circuit voltage sought (1-left). The ratio is a direct measure of the coupling coefficient, $k_{oc}(z)$, at the specified coil spacing. Inductance aiding assessment of coupling coefficient is even more direct, it requires only a single piece of laboratory test equipment such as the Aglient model 34420 LCR meter. The respective coils, primary L_1 and secondary L_2 inductances are measured, then series connected for inductance aiding, L_{aid}, at specified gap z. Coupling coefficient $k_{aid}(z)$ is then found using (1-right).

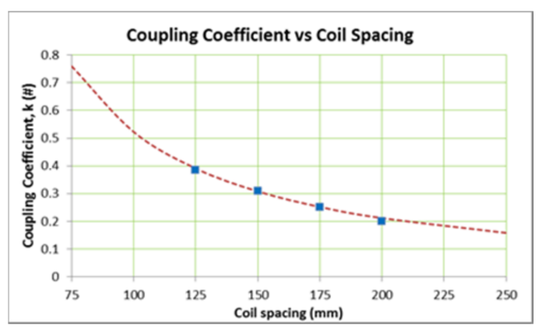


Figure 5. Measured Coupling Coil Coefficient of Coupling, k(z), of coupling coil set shown in Figure 2 (~0.3m radius).

Background

Useful WPT background concerns the relative size of coupling coils (D) versus spacing (d) and the controllable parameters for regulation of power flow. One result of the analytical work performed, shown graphically as Figure 3 is an assessment of D/d based on the flux produced by the primary coil of diameter D and summarized as (2) for flux density at the field point on the secondary coil perimeter.

$$B(r,\theta) = \hat{r}\frac{\mu_0 N_1 I_1 a_1^2}{2r^3}\cos\theta + \hat{\theta}\frac{\mu_0 N_1 I_1 a_1^2}{4r^3}\sin\theta \quad (2)$$

Under the constraint that radial and elevation components of the field vector (2) are identical leads to the minimum ratio of diameter to spacing.

$$\frac{\mu_0 N_1 I_1 a_1^2}{2r^3}\cos\theta = \frac{\mu_0 N_1 I_1 a_1^2}{4r^3}\sin\theta \overset{sub}{\Longrightarrow} 2\frac{d}{r} = \frac{a_1}{r}; \quad \therefore d \le \frac{a_1}{2} \quad (3)$$

Where, a_1=a=D/2 with the result that D/d>4.

The amount of power transferred to the secondary coil is governed by the switching frequency, duty cycle, and the input voltage of the inverter. For instance, the primary coil voltage can be expressed as (4) where the HF power inverter rail voltage is U_{d0}, pulse duty ratio, d, and angular frequency ω.

$$U_1(t) = \frac{4U_{d0}}{\pi}\sin\left(d\frac{\pi}{2}\right)\cos(\omega t) \qquad (4)$$

Frequency response of the ORNL WPT system depends on the load conditions (i.e., state-of-charge of the battery) and the coupling coefficient k(z) (i.e., vehicle coil to primary pad gap and any misalignment between primary and secondary coils).

Grid Side Power Regulation

Although the primary coil voltage can be controlled by the active front end converter to vary the dc rail voltage U_{d0}, the team first set out to study the effect of duty cycle control (parameter “d” in (4)) for best operating conditions in terms of efficiency and power transfer. In the ORNL laboratory setting the HF power inverter voltage was adjusted using a power supply. Also, in a commercialized version of this WPT technology a dedicated short range communication (DSRC) link as shown in Figure1 would be needed. The transmitter side of the DSRC collects the vehicle measurement data such as battery voltage, battery current, and battery management system (BMS) messages needed for regulation. The grid-side receiver side of the DSRC channel receives this information for control purposes along with supporting primary side measurements. Then, a DSP based embedded control system determines the switching frequency and the appropriate duty cycle according to the control law being used. The switching signals for the inverter IGBTs are generated by the DSP control algorithm and applied to the HF power inverter gate drives. The control system can also regulate the inverter power based on the reference power commands that can be received through the V2I communications from a smart grid compliant utility.

Power Inverter Development

The ORNL experimental inverter shown in Figure 5 employs dual Powerex Intellimod IGBTs in an H-bridge arrangement with each phase leg connected to one terminal of the primary coil and tuning capacitor network. The control system of the inverter is implemented within a TMS320F28335PGFA DSP module from Texas Instruments. While generating the switching signals, dead band control, shoot-through prevention, and condition monitoring based protection and termination systems have also been taken into account. For demonstration purposes, the inverter can also be controlled and monitored via RS232 by a host computer. The control system involves instantaneously varying the switching frequency and the duty ratio to adapt to the changing conditions such as battery SOC and the coupling coefficient while taking the efficiency and power transfer level into account.

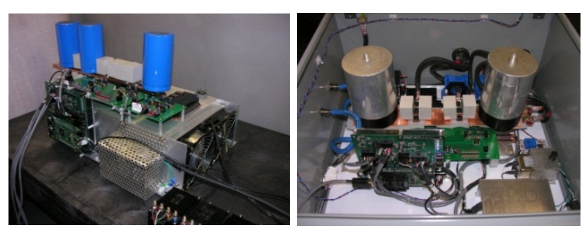


Figure 6. Experimental high frequency power inverter. Left: open chassis design, Right: boxed inverter.

Control of Power Flow

Of particular interest for WPT is the HF power inverter reactive burden due to voltage control of the primary coil in the process of power flow regulation. Experiments were undertaken at ORNL’s WPT laboratory to assess inverter reactive power (Q) during variation of duty ratio control when the coils are in full alignment, the gap is fixed and output power (P_o) is held constant. In these tests a Chroma model 63210 battery eliminator rated 15/150A, 125/500V, 14 kVA is operated in constant voltage (CV) mode at the desired vehicle battery potential. For these tests a different set of coupling coils were used that had been designed for an in-motion WPT charging application of a small battery electric vehicle (a GEM 4 wheeler with 72V PbAcid battery). Figure 7 shows the ORNL "pizza" coils, or 330 coil designs having 7 turns of 6 AWG Litz cable in the primary and 5 turns in the secondary coil. The coils are tuned to f_{01}=23 kHz with L_1=24 μH, C_1=2.0 μF and f_{02}=21.8 kHz L_2=18.4 μH, C_2=2.9 μF with turns ratio, n=0.876, R_{1dc}=9.08 and R_{2dc}=11.5mΩ.

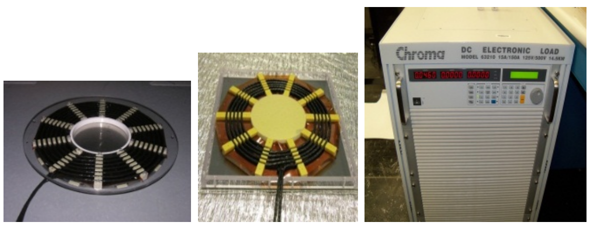


Figure 7. ORNL coil sets and battery eliminator used to assess real and reactive power variations due to duty ratio control of power.

When the small 330mm diameter coils are operating at d=z=75mm (D/d=4.4) and inverter duty d=0.8 with battery potential, U_b=80V_{dc}, the power transfer peaks at 23 kHz with a load power, P_o=2 kW. The test vehicle is a GEM EV with 72V lead-acid battery. The real and reactive power levels are shown in Figure 8 top and primary and secondary coil voltage and currents in Figure 8 bottom taken at peak power and f=23.5 kHz.

When the inverter duty ratio is varied the fundamental component of the voltage applied to the primary coil varies according to (4) but the presence of reactive power leads to freewheeling diode conduction in the H-bridge that tends to "fill-in" the inter-pulse dead times shown in the bottom of Figure 8. It was found that keeping the load power (i.e., power to battery eliminator) constant as duty ratio "d" decreased required a complimentary increase in HF inverter rail voltage U_{d0}. The results are tabulated in Table 2. In Table 2 the heading VSI is the volt-sec-integral applied to the primary coil by the HF power inverter when the respective active switches are ON.

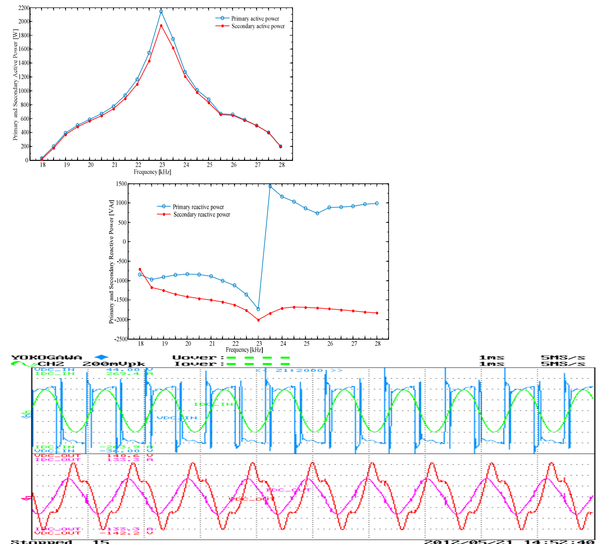


Figure 8. Top: measured inverter output and secondary P and Q, Bottom: the associated voltage and current waveforms.

Table 2. Inverter voltage vs duty effects on power

f	***Udo***	***d***	***VSI***	***Po***	***Q_1***
(kHz)	(Vdc)	(#)	(mWb)	(W)	(VA)
22.5	41.87	0.8	0.743	2055	-2249
22.5	55.26	0.6	0.736	2017	-3112
22.5	117.66	0.4	1.18	2011	-7005

Note that in Table 2 the measured input reactive power, Q_1, increases in proportion to the amount that duty ratio, d, is decreased while holding output power P_0 constant.

The implication of data in Table 2 is that WPT power inverters must therefore have a much higher reactive power rating than real power rating. Similar behavior was shown to be the case by other authors in the open literature. ORNL recommends that follow-on work then addresses the requirement for WPT systems to implement grid side power factor (PF) correction.

Introduction

The previous background section described power flow control in a WPT system via variation of HF inverter rail voltage, U_{d0}, and duty ratio modulation, d, of the quasi-square wave primary coil voltage excitation. In this section important fundamentals of WPT are presented that span some of the lessons learned at ORNL during the course of stationary charging research work performed.

- WPT, also referred to as inductive power transfer IPT, relies on the magnetic performance of a loosely coupled transformer (primary and secondary coil set).
- Loose coupling means very high leakage flux.
- High leakage flux results in poor regulation capability of a transformer and places a high reactive power burden on the drive inverter.
- Compensating capacitors on primary and secondary act to "tune out" the high leakage inductance. The most common compensating technique is primary series, S, and secondary parallel, P, or S-P tuning.
- Operating at, or close to, resonance leads to excessive primary current when the secondary coil is not present or not aligned to the primary.

Discussion of the last two points is essential to understanding the basics of WPT and expanding on this work. Experimental work done at ORNL's WPT laboratory show that S-P tuning results in a single peak power transfer above resonance, a sharp input PF transition from inductive to capacitive, relatively smooth secondary PF and a very broad coil-coil and input dc to output dc efficiency. In contrast, S-S tuning also exhibits a step edged but shallower power transfer peak across the resonant frequency, but a more dramatic PF swing with nearly double the reactive power at the input and modest coil-coil and dc input to dc output efficiency. For secondary only S-tuning the power transfer is lower, there are multiple input PF transistions below and above resonance and low efficiency. For these reasons the ORNL system relies on S-P tuning of the coupling coils.

The last bullet point is most significant to WPT control, especially as it applies to HF inverter rail voltage settings. ORNL developed coupling coils for a low voltage AEV (GEM vehicle with 72V lead-acid battery pack) that have non-unity turns ratio. Figure 9 is a modified version of Figure 1 showing the 1:n turns ratio primary to secondary defined with subscripts 1-primary and 2-secondary. The secondary side vehicle regenerative energy storage system (RESS) pack load reflected from dc to ac variables is shown as R_{ac} for convenience. Given a primary fundamental sinusoidal voltage (4) the input current, I_1, can reach excessive levels when the secondary is absent or when k(z) is very low, such as k(z)<0.15 or zero. Solving for input current I_1 when reflected load I_2' =0 yields (5).

$$I_1 = \frac{\omega C_1 U_1}{\omega C_1 R_1 + j\left(\left[\frac{\omega}{\omega_0}\right]^2 - 1\right)} \to \frac{U_1}{R_1}\bigg|_{\omega\to\omega_0} \quad (5)$$

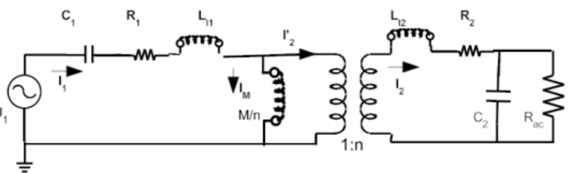


Figure 9. Coupling coil equivalent circuit with S-P tuning and equivalent load showing primary and secondary leakage inductance and magnetizing branch.

It is evident by inspection of (5) that the transitions in input PF when excitation frequency is crossing resonance are due to the sign change in the denominator's imaginary part ($\left[\frac{\omega}{\omega_0}\right]^2 - 1$). Input apparent power, $S=U_1xI_1$ or in phasor notation, $S=U_1/\underline{0}^o*I_1/\underline{\theta}$, where $\theta>0^o$ for $\omega<\omega_0$ and lagging PF.

WPT Lessons Learned

Advancing WPT technology requires learning from past experience what the essentials of wireless power coupling are and how to deal with practical, non ideal circumstances such as energizing the primary when no secondary is present and how the system behaves going from no-load (vehicle parked and initiating charging) to loaded (vehicle parked, aligned and battery under charge). The following subsections deal with these particular cases and some nuances found in testing at the ORNL WPT laboratory. Each of the three cases to follow will reference Figure 9 above.

A. Lessons Learned: Secondary Absent

This case is a direct result of (5) when k(z) is very low or zero and leads to a condition of excessive HF power converter current. Essentially, the primary tuning capacitor completely cancels the primary inductance resulting in extreme magnetizing current. Refer to Figure 9 for the case of non-unity turns ratio leading to the following definitions of primary, L_{l1}, and secondary, L_{l2}, leakage inductance and mutual inductance, M, noting that k(z)<1. Using (7) the input current I_1 for the non-unity turns case in Figure 9 results again in (5).

$$L_{l1} = L_1 - \frac{M}{n} \quad L_{l2} = L_2 - nM \tag{6}$$

$$M = k(z)\sqrt{L_1 L_2} \quad n = \sqrt{\frac{L_2}{L_1}} \tag{7}$$

$$\omega_{2L} = \frac{(1-k(z))}{L_2 C_2} \quad Q_2 = \omega R_{ac} C_2 \tag{8}$$

To compensate the WPT HF inverter rail voltage, U_{do}, must be adjusted to low values so that excessive magnetizing currents do not result.

B. Lessons Learned: Aligned, no Load

When the secondary is present and aligned but no load (R_{ac}=∞) the tuning capacitor, C_2, acts to short circuit the secondary leading to current I_2=I_{2sc}. In this case the input current I_1 becomes excessive as in (5) due to the secondary leakage and tuning capacitor impedance, Z_2', being reflected to the primary and in parallel with the magnetizing branch.

$$Z_2' = \frac{R_2}{n^2} + j\frac{1}{n^2}\left[\frac{\left(\frac{\omega}{\omega_{2L}}\right)^2 - 1}{\omega C_2}\right] \tag{9}$$

This case again shows that in the vicinity of the system resonance, the coupling coefficient dependent lower resonance point ω_{2L}, that input current I_1 is at least $U_1/(R_1+R_2/n^2)$. The only difference now is that two resonance conditions interact, primary (ω/ω_0) from (5) and (ω/ω_{2L}) from (9).

C. Lessons Learned: Aligned and Loaded

For the loaded case in Figure 9 and the conditions given in lessons learned subsection B are now revised to include a battery load dependent resistance reflected from dc to single phase ac coordinates as (10) where battery voltage is U_b and power P_o flows into the pack. Using this definition the derivation (9) is modified to replace element C_2 with C_2 in parallel with R_{ac} shown as Z_L' (11).

$$R_{ac} = \frac{\pi^2}{8}\frac{U_b^2}{P_o} \tag{10}$$

$$Z_L' = \frac{1}{n^2}\left[\frac{R_{ac}}{1+Q_2^2} - j\frac{R_{ac}Q_2}{1+Q_2^2}\right] \tag{11}$$

Input current I_1 then splits between the magnetizing branch and the secondary branch reflected to the primary such that output power is due to current flowing in the reflected load branch. Additional input current flows to satisfy the magnetizing branch current I_M.

Approach

As experience with WPT has been accumulated the designs have been refined to obtain higher plug to battery efficiency. However, other requirements are presenting themselves that ORNL must address in the quest for industry standardization of wireless charging. These include safety, a topic high on ORNL's list, and compliance with existing standards for high frequency magnetic field emissions.

ORNL is investigating and prototyping WPT with a high frequency isolation transformer between the power electronic converter and the tuned primary coil as shown in Figure 10. This architecture also comes very close to an LCL input configuration that is used in grid connected converters.

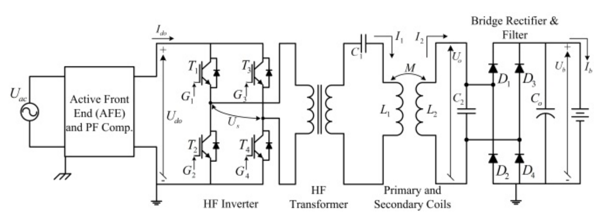


Figure 10. WPT architecture with isolation transformer.

Laboratory measured parameters for the HF Transformer are listed in Table 3 as derived from laboratory tests. Transformer shown in Figure 11 provides a safety benefit in that shock hazard of cut primary cable leads have no conductive path back to the utility connection even if the WPT charger is off. Secondary benefits include operation of the HF power inverter at higher rail voltages and thereby higher efficiency. For example, if $U_1(t)$ has peak value $100V_{ac}$ then $300V_{ac}$ would be delivered by the HF power inverter stage at 1/3rd the current.

Table 3. High Frequency Transformer Parameters

Parameter	Primary	Secondary
Turns (#)	12	4
Turns ration (#)	n=1/3	
Wire gauge (AWG)	5x#14 Litz	1x#6 Litz
Resistance (mΩ)	5.5	2.0
Self-inductance (µH)	1,000	113
Coupling coefficient	k=0.975	
Leakage inductance (µH)	25	4.67
Mutual inductance (µH)	M=975	

Figure 11. High frequency isolation transformer

A full inverter build was in progress at the completion of FY 2012 that includes the isolation transformer. This design, on a metal shelf that fits into a standard environmental NEMA enclosure, is shown in Figure 12.

Figure 12. WPT system with AFE and isolation transformer. Copper foil wrapped inductor is part of the AFE and transformer in foreground with Litz windings.

End of program test results and field measurements are summarized in the Results section. Field measurements were made for the coupling coils placed beneath the test vehicle so position and height were adjustable as shown in Figure 13.

Figure 13. Equinox test vehicle with WPT coil pair.

Vehicle side integration is shown schematically in Figure 14 where the secondary coil is parallel tuned and full wave rectified to dc voltage. The dc is filtered and made available to the battery through a contactor that is needed to provide isolation and mutually exclusive operation with existing conductive charging (SAE J1772).

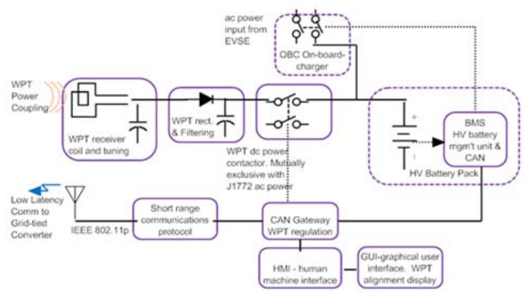


Figure 14. WPT vehicle side integration content.

Vehicle side content is the minimum possible with only secondary, tuning, rectification, filtering and protection functions included. Power flow regulation is via the communications interface to the grid side converter. With this approach the WPT systems under development and to be developed are future compatible with dc fast charge equivalent and with in-motion charging.

Results

With magnetic resonance coupling the power flow peaks in the neighborhood of the tuned frequency as shown in the power transfer plot of Figure 15.

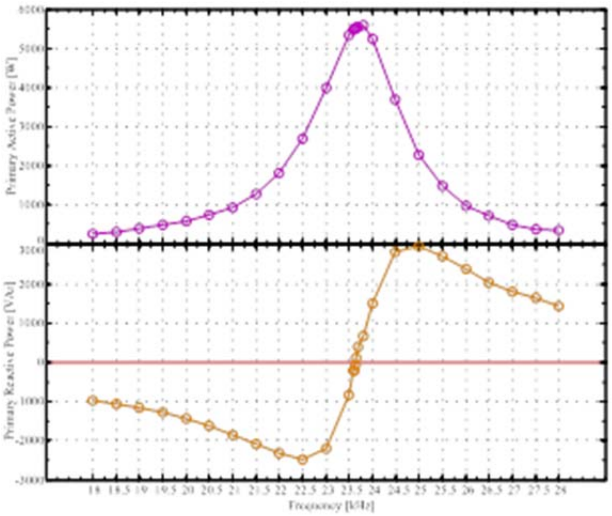


Figure 15. WPT real (P) and reactive (Q) power showing peak of 5.8kW at f=23.5 kHz and reactive power peaks of +/- 3 kVA on both sides of resonance.

Magnetic field measurements were performed consistent with international standards and using the same field measurement equipment that UL will use. Figure16 defines the three zones in WPT charging and the standardized field level maximums over the frequency range of WPT.

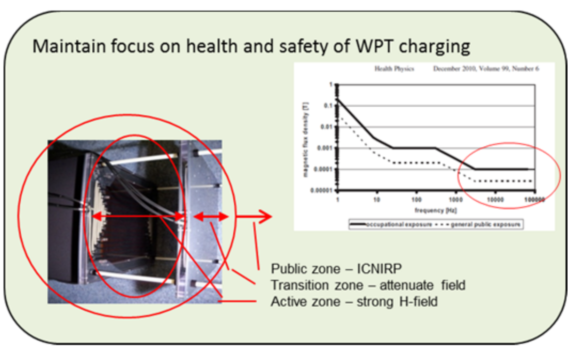


Figure 16. WPT zones and maximum magnetic field level of public zone: 27.3 µT peak and 6.25 µT body average

For the vehicle installation shown in Figure 13 the magnetic field measurement areas of interest are at the driver and passenger door at ankle level and in the passenger compartment at foot level. Table 4 summarizes the field measurements at 0.8m from primary coil center on the floor beneath the vehicle to ankle height at the rocker panel. Maximum field at the driver door must be less than 27.3 µT.

Table 4. Magnetic field at driver door at ankle height

Power [kW]	Electromagnetic Field [µT]
2	6.8402
4	8.7018
6	10.768
7	11.941

Field measurements in the passenger cabin versus power level are summarized in Table 5 at one position, the driver foot level. At the seat and headrest level the field will be much lower. This is consistent with (2) that states the magnetic induction at a field point reduces inversely as the cube of the distance from the source point.

Table 5. Magnetic field in passenger cabin at foot level

Power [kW]	Electromagnetic Field [µT]
2	0.0591
4	0.0884
6	0.0829

Over the course of this program coil-to-coil efficiency has been emphasized. For WPT the ac resistance of the windings are crucial because such high magnetizing current flows that generates the bulk of losses. For this reason Litz cable has been used and will continue being used. Figure17 shows the broad, nearly flat, efficiency characteristic of WPT across the resonance point. Future work requires at least 97% efficiency at maximum power.

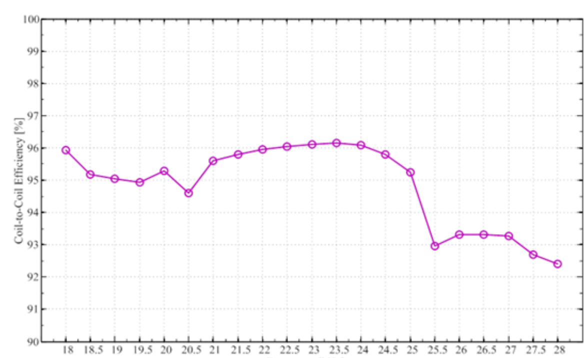


Figure 17. Distributed coil (Figure2) efficiency vs frequency.

Litz cable exhibits the slowest resistance rise with frequency of any wire, tube or ribbon conductor examined at ORNL. The modeled characteristic of Litz cable Rac(f) is given as (12) for reference.

$$R_1(f) = R_{1dc}\left\{1 + \frac{1}{12}\left(\frac{f}{f_0}\right)^2\right\} \quad (12)$$

Conclusions

Wireless power charging of EV's is an emerging technology that is finding widespread and rapid appeal as a safe, convenient and flexible means of charging. Simulation and experimental results on coupling coil performance and efficiency have been presented that show the close association of coil diameter to separation and the shielding benefits of ferrite backed coils. Lessons learned on WPT by the ORNL team are highlighted showing the strong influence the secondary, especially its absence, has on HF power inverter output current and PF. Future development activity will include effects of metal foils, foil backed paper and other objects in the active zone. ORNL also has laboratory funded research into dynamic WPT charging that is being designed around 48 kHz center frequency using high speed silicon IGBT's. Future power electronics may also transition to wide bandgap devices if improved efficiency can be shown to result. Finally, all of ORNL's activities in WPT are aimed to foster industry standardization through close collaboration with SAE and its wireless charging task force, J2954.

VII.J.3. Products

The direct outgrowth of this project has been several publications in highly respected international conferences and multiple invention disclosures.

Publications

ORNL experience on WPT has been published in internal reports and conference proceedings.

1. Heri Rakouth, John Absmeier, Andrew Brown Jr., John M. Miller, In-Soo Suh, Randy Summer, Richard Henderson, *EV Charging Through Wireless Power Transfer: Analysis of Efficiency Optimization and Technology Trends*, 34th FISITA 2012 World Automotive Congress, paper F2012-B06-001, Beijing, China, 27-30 November 2012 (*pending*)
2. John M. Miller, Cliff P. White, Omer C. Onar, and Phil M. Ryan, *Grid Side Regulation of Wireless Power Charging of Plug-in Electric Vehicles*, IEEE 4th Energy Conversion Congress & Exposition ECCE2012, Raleigh, NC, 15-20 September 2012
3. John M. Miller, Curtis W. Ayers, Larry E. Seiber, D. Barton Smith, *Calorimeter Evaluation of Inverter Grade Metalized Film Capacitor ESR*, IEEE 4th Energy Conversion Congress & Exposition ECCE2012, Raleigh, NC, 15-20 September 2012
4. John M. Miller, Omer Onar, *ORNL's In-motion WPT System*, Conference on Electric Roads and Vehicles, CERV2012, Newpark Resort and Hotel, Park City, UT, 16-17 February 2012
5. Michael Pickelsimer, Leon Tolbert, Burak Ozpineci, John M. Miller, *Simulation of an Electric Vehicle Class Wireless Power Transfer System as Viewed from the Power Grid*, IEEE International Electric Vehicle Conference, IEVC2012, CU-ICAR, Greenville, SC, 4-8 March 2012

Patents

Several invention disclosures covering various aspects of WPT have been submitted and out of these four have been submitted as patent applications.

Disclosures:

1. John M. Miller, Chester Coomer, Philip M. Ryan, *High Coupling Coefficient Wireless Power Transfer Coil*, Ref #827, submitted 10 Feb 2012
2. Steven Campbell, Paul Chambon, John M. Miller, Omer Onar, Phillip M. Ryan, Larry E. Seiber, Cliff White, *Stationary and Dynamic Wireless Power Charging using Point of Load Controlled High Frequency Power Converters*, DOE S-124,329, disclosure number 201102768, Dec. 2011

Applications Filed:

1. J. M. Miller, "Graphene-Coated Coupling Coil for AC Resistance Reduction" Disclosure Docket 2637.1, Filed September 2012.
2. J. M. Miller, "Regulation Control and Energy Management Scheme for Wireless

Power Transfer" Disclosure Docket 2638.1, Filed September 2012.

3. J. M. Miller, P.T. Jones, "Wireless Power Transfer Electric Vehicle Supply Equipment Installation and Validation Tool" Disclosure Docket 2639.1, Filed September 2012.
4. J. M. Miller, C. White, P.T. Jones, P. Chambon, "Vehicle to Wireless Power Transfer Coupling Coil Alignment Sensor" Disclosure Docket 2667.1, Filed September 2012.

Tools & Data

WPT development work is supported by specialized laboratory equipment:

1. Chroma model 63210 Battery Eliminator 15/150A, 125/500V, 14 kVA
2. Chroma model 61512 Programmable AC Source, 18 kVA
3. Narda EHP-50D, E&H Field Analyzer, 5Hz-100kHz, 0.3nT-10mT
4. FW Bell model 7010 Gauss Meter
5. Laboratory load bank, 1.5kW lamps x10, with DSP voltage regulator
6. Robicon regulated power supply, 600V, 600A, 200kVA available
7. Magna Power model MTDIII-1600-62, 1.6kV, 62A, 90kVA power supply
8. Electronic Measurements Inc EMHP 300V, 200A power supply
9. Yokogawa DL7480 20GS/s digital oscilloscope
10. Yokogawa DL7100 1 GS/s digital oscilloscope
11. Yokogawa PZ4000 power meter
12. Aglient model 34420 LCR meter
13. HP model 4274 multi-frequency LCR meter
14. Laboratory PC's, DMM's, fully isolated current and voltage sensors, ragowski current sensors
15. MagnaPower 100A, 1000V, 100kVA adjustable supply

Final Page of

FY 2012 Annual Progress Report

Vehicle and Systems Simulation and Testing

DOE/EE-0834 March 2013
Printed with a renewable-source ink on paper containing
at least 50% wastepaper, including 10% post consumer waste.

EPARTMENT OF ENERGY | Energy Ef iency & Renewable Energy

For more information
eere.energy.gov