U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Analysis

2018 Annual Progress Report

Vehicle Technologies Office

Disclaimer

Acknowledgements

Thank you to the principal investigators and their teams for contributing to this Annual Progress Report. Their hard work and ideas result in the success of the Vehicle Technologies Office Analysis Program and the office as a whole, and enable important improvements in fuel economy and the efficiency of the transportation system as a whole.

The Analysis Program would also like to acknowledge Energetics for its support in preparing, publishing, and managing the compilation of this report.

Acronyms

AEO	Annual Energy Outlook
AFV	alternative fuel vehicle
ANL	Argonne National Laboratory
ARB	California Air Resources Board
AVCEM	Advanced Vehicle Cost and Energy-use Model
AWARE	Available Water Remaining
BatPaC	Battery Performance and Cost Model
BEAM	Behavior, Energy, Autonomy, and Mobility model
BEV	battery electric vehicle
CAV	connected and automated vehicle
CCS	carbon capture and storage
CF	characterization factor
CHP	combined heat and power
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DCFC	direct current fast charge
DOE	U.S. Department of Energy
DR	demand response
EEMS	Energy Efficient Mobility Systems Program
EERE	Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EV	electric vehicle
EVI-Pro	Electric Vehicle Infrastructure Projection tool
eVMT	electric vehicle miles traveled
EVSE	electric vehicle supply equipment
FAF	Freight Analysis Framework
FCEV	fuel cell electric vehicle
FCTO	Fuel Cell Technologies Office
FOTW	Fact of the Week
FY	fiscal year
gCO_2e	grams CO_2 equivalent
GPRA	Government Performance and Results Act
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
GWh	gigawatt hour
HDV	heavy-duty vehicle
HEV	hybrid electric vehicle
HWC	human water consumption
ISG	integrated starter generator
kWh	kilowatt hour
LDV	light-duty vehicle
MA3T	Market Acceptance of Advanced Automotive Technologies Model
mpg	miles per gallon

mph	miles per hour
MS	Microsoft Corporation
MSRP	manufacturer’s suggested retail price
NEAT	Non-Light Duty Energy and GHG Emissions Accounting Tool
NG	natural gas
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PDF	Portable Document Format
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PV	solar photovoltaic
R&D	research and development
RE	renewable energy
SMART	Systems & Modeling for Accelerated Research in Transportation
SOC	State of Charge
TDP	Transportation Data Program
TOU	time-of-use
USDOT	United States Department of Transportation
EPA	U.S. Environmental Protection Agency
VMT	vehicle miles traveled
VTO	Vehicle Technologies Office

Executive Summary

During fiscal year 2018 (FY 2018), the U.S. Department of Energy Vehicle Technologies Office (VTO) funded analysis projects supportive of VTO's goals to pursue early stage research in vehicle and mobility system technologies to improve energy efficiency, increase energy reliability and security, improve transportation affordability, and promote economic growth. VTO analysis projects result in a foundation of data, analytical models, and applied analyses that provide insights into critical transportation energy problems and assist in research investment prioritization and portfolio planning.

This document presents a brief overview of VTO analysis efforts and progress for projects funded in FY 2018. Each of the progress reports includes project objectives, approach, and highlights of the technical results that were accomplished during the fiscal year.

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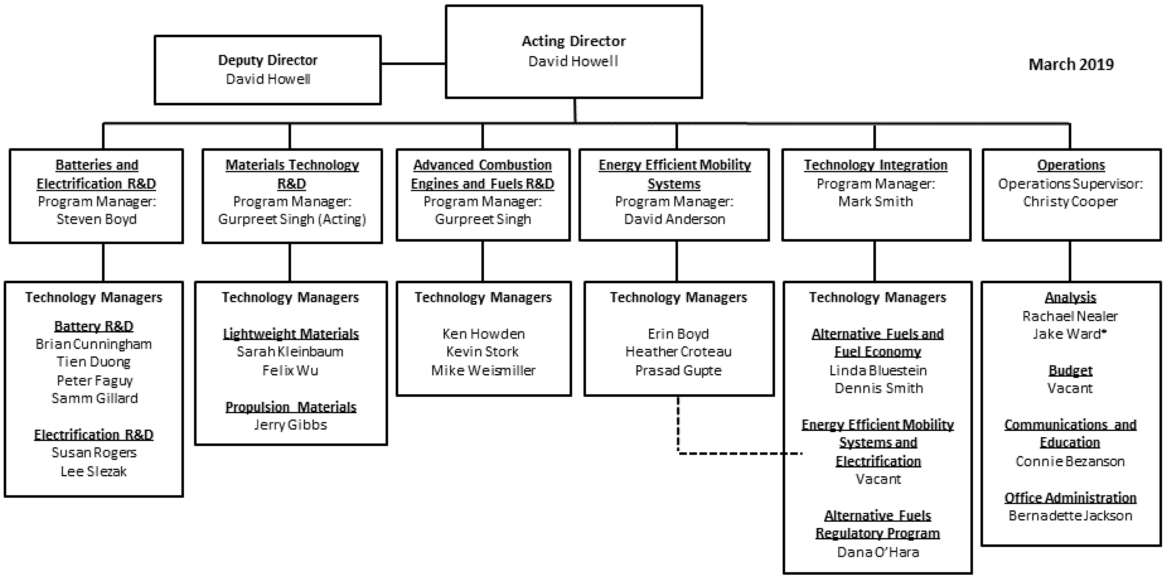
Vehicle Technologies Office Overview

Vehicles move our national economy. Annually, vehicles transport 11 billion tons of freight[1] – more than $32 billion worth of goods each day[2] – and move people more than 3 trillion vehicle-miles.[3] Growing our national economy requires transportation and transportation requires energy. The transportation sector accounts for 70% of U.S. petroleum use. The United States imports 20% of the petroleum consumed – sending more than $15 billon per month[4] overseas for crude oil. The average U.S. household spends nearly one-sixth of its total family expenditures on transportation[5], making transportation the most expensive spending category after housing.

To strengthen national security, enable future economic growth, improve energy efficiency, and increase transportation energy affordability for Americans, the Vehicle Technologies Office (VTO) funds early-stage, high-risk research on innovative vehicle and transportation technologies. VTO leverages the unique capabilities of the national laboratory system and engages private sector partners to develop innovations in electrification, including advanced battery technologies; advanced combustion engines and fuels, including co-optimized systems; advanced materials for lighter-weight vehicle structures; more efficient powertrains; and energy efficient mobility systems.

VTO is uniquely positioned to address early-stage challenges due to strategic public-private research partnerships with industry (e.g. U.S. DRIVE, 21st Century Truck Partnership) that leverage relevant expertise. These partnerships prevent duplication of effort, focus DOE research on critical R&D barriers, and accelerate progress. VTO focuses on research that industry does not have the technical capability to undertake on its own, usually due to a high degree of scientific or technical uncertainty or is too far from market realization to merit industry resources.

Organization Chart



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[1] Bureau of Transportation Statistics, DOT, 2016. Table 3-1 Weight and Value of Shipments by Transportation Mode https://www.bts.gov/archive/publications/transportation_statistics_annual_report/2016/tables/ch3/table3_1

[2] Ibid.

[3] Transportation Energy Data Book 37th Edition, ORNL, 2018. Table 3.8 Shares of Highway Vehicle-Miles Traveled by Vehicle Type, 1970-2016.

[4] EIA Monthly Energy Review https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf

[5] Bureau of Labor Statistics, Consumer Expenditure Survey, 2017. Average annual expenditures and characteristics of all consumer units, 2013-2017. https://www.bls.gov/cex/2017/standard/multiyr.pdf

Analysis Program Overview

Introduction

VTO invests in research and development of advanced vehicle technologies and energy-efficient mobility systems that will increase America's energy security, economic vitality, and quality of life. The impact of VTO's investments depends on the eventual commercialization of supported technologies. Therefore, maximizing the benefits achieved requires development of a portfolio based on a fundamental understanding of the complex system within which transportation technologies are manufactured, purchased, and used. This system is shaped by the actions and interactions of manufacturers, consumers, markets, infrastructure, and the built environment.

The VTO Analysis Program supports mission-critical technology, economic, and interdisciplinary analyses to assist in prioritizing VTO technology investments and to inform research portfolio planning. These efforts provide essential vehicle and transportation system data, modeling and simulation, and integrated and applied analyses, using the unique capabilities, analytical tools, and expertise resident in the national laboratory system.

Key questions addressed by these data, modeling, and analysis efforts include:

- What vehicle segments and use domains have the greatest potential for efficiency gains, fuel cost savings, economic growth, and protection of human health? In what applications can new technologies make the greatest impact?
- What trends in vehicle miles of travel (VMT), vehicle ownership, fuel and technology choice, infrastructure development, consumer behavior, and other factors are likely to impact the achievement of future benefits?
- As sales of electric vehicles (EVs) grow, what are the infrastructure needs? How will they impact the electricity grid? Will this trend save consumers money and improve human health?
- How is freight transportation changing? How can we improve the efficiency of moving the goods we buy?
- How will developments in vehicle connectivity, autonomy, and ridesharing impact energy demand? How do we ensure these developments lead to an efficient transportation system?
- What will the future look like if we meet all our subprogram targets? What if our subprograms fall short?

Goals

The goals of the VTO Analysis Program are to:

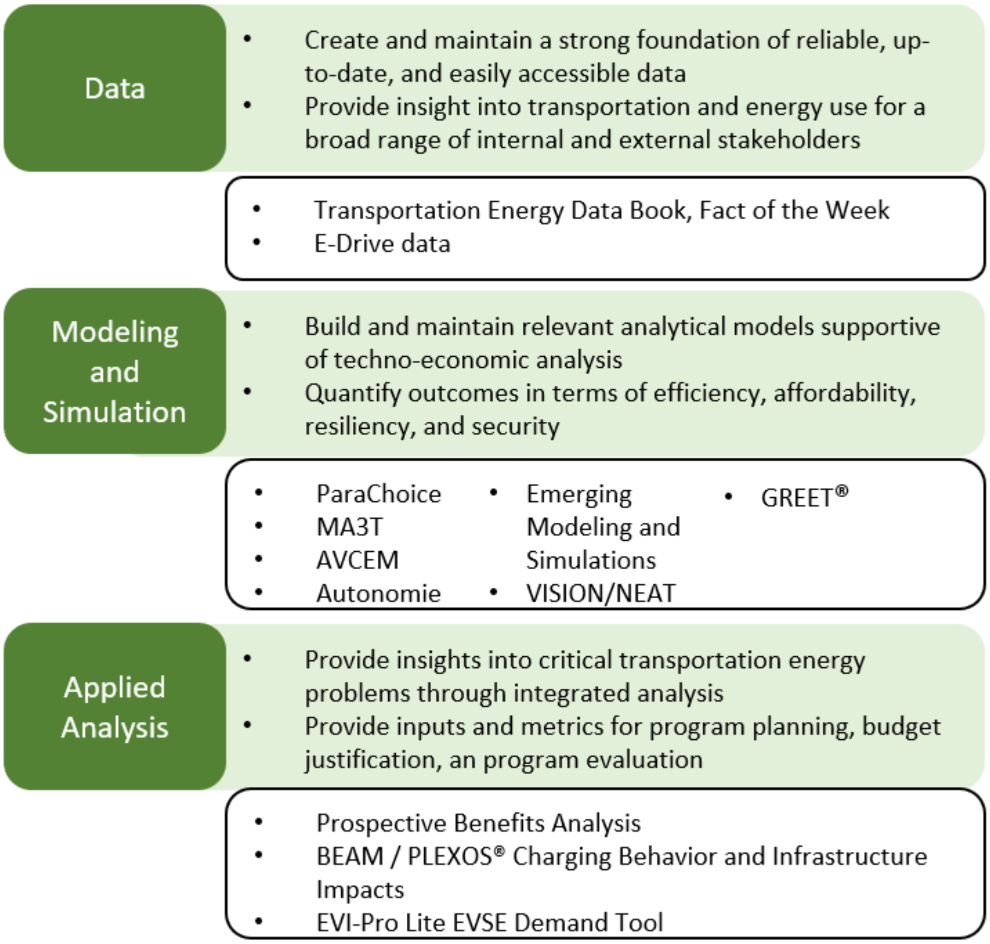
- Assist VTO in prioritizing technology investments and inform research portfolio planning
- Support quantitative assessment of vehicle and mobility technology impacts
- Provide insight into transportation and energy use problems for a broad range of internal and external stakeholders.

To achieve these goals, the Analysis Program supports activities with the following three broad objectives:

- Create and maintain a strong foundation of data
- Build, maintain, and exercise relevant analytical models
- Execute insightful integrated analyses that provide greater understanding of critical transportation energy problems.

Program Organization Matrix

The Analysis Program activities are organized within three areas as described above: (1) data, (2) modeling and simulation, and (3) applied analysis. The figure below illustrates the relationship between these three areas, the program goals, and the activities summarized in this report.



Data

- Create and maintain a strong foundation of reliable, up-to-date, and easily accessible data
- Provide insight into transportation and energy use for a broad range of internal and external stakeholders

- Transportation Energy Data Book, Fact of the Week
- E-Drive data

Modeling and Simulation

- Build and maintain relevant analytical models supportive of techno-economic analysis
- Quantify outcomes in terms of efficiency, affordability, resiliency, and security

- ParaChoice
- MA3T
- AVCEM
- Autonomie
- Emerging Modeling and Simulations
- VISION/NEAT
- GREET®

Applied Analysis

- Provide insights into critical transportation energy problems through integrated analysis
- Provide inputs and metrics for program planning, budget justification, an program evaluation

- Prospective Benefits Analysis
- BEAM / PLEXOS® Charging Behavior and Infrastructure Impacts
- EVI-Pro Lite EVSE Demand Tool

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I Transportation Data Program

I.1 Transportation Energy Data Book, Vehicle Technologies Market Report, Fact of the Week

Stacy C. Davis, Principal Investigator
Oak Ridge National Laboratory
2360 Cherahala Blvd.
Knoxville, TN 37932
E-mail: DavisSC@ornl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2017	End Date: September 30, 2018	
Project Funding (FY18): $400,000	DOE share: $400,000	Non-DOE share: $0

Project Introduction

Transportation analysts and VTO staff require quality current and historical data and information on the transportation sector to inform stakeholders. The Transportation Data Program (TDP) provides a wealth of information which is used as a DOE resource to improve analyses of the transportation sector, which contribute to program planning, evaluation, and technology research in the public and private sectors. Stakeholders use this data to help move the U.S. towards affordable transportation, reduce our petroleum dependence, and increase our national security.

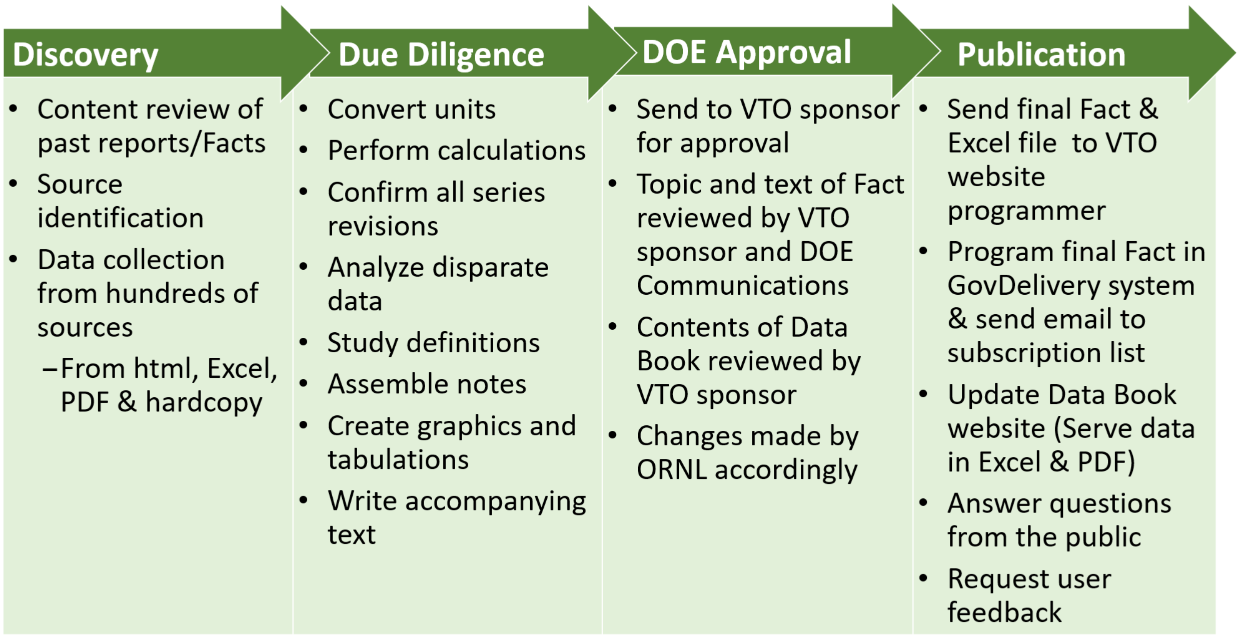
Objectives

The objective of the TDP is to provide quality data and information for the VTO Analysis Program and stakeholders. Specifically, the project: (1) produced the text, graphics, and data for a Fact of the Week (FOTW) that is posted on the VTO website each week and is sent to a subscription list via email, (2) produced updated tabular and graphical data on the transportation sector that were posted on the Transportation Energy Data Book website twice a year as Editions 36.1 and 36.2, and (3) produced a draft of Edition 37 of the Transportation Energy Data Book, including updated data and information.

Approach

Oak Ridge National Laboratory's (ORNL) approach for the TDP can be categorized into four stages: discovery, due diligence; approval; and publication (Figure I.1.I). Data are discovered from a myriad of public and private sources, and ORNL performs due diligence to ensure the data are defined and notated correctly. In this stage of the approach, ORNL works with other laboratories (e.g., Argonne National Laboratory [ANL] and the National Energy Renewable Laboratory [NREL]), government agencies (e.g., Federal Highway Administration), and private companies (e.g., Wards Automotive) to compile and understand the data that are collected, being careful to ensure data are comparable. Explanatory text is written, and tabulations/graphics are generated in Microsoft (MS) Word and/or MS Excel. Each FOTW and the tabulations/graphics in the Transportation Energy Data Book are reviewed and approved by the DOE before final publication. Publication of the FOTW is in a website posting on the VTO Transportation Fact of the Week (https://energy.gov/eere/vehicles/transportation-fact-week) web page and programming in the GovDelivery system sending an email to the subscription list every week, typically on Monday afternoons. The PDF and

MS Excel files for the Transportation Energy Data Book (https://cta.ornl.gov/data/index.shtml) are posted on the website hosted by ORNL. The major topics for the TDP publications are provided in Table I.1.1.



Discovery

- Content review of past reports/Facts
- Source identification
- Data collection from hundreds of sources
  - From html, Excel, PDF & hardcopy

Due Diligence

- Convert units
- Perform calculations
- Confirm all series revisions
- Analyze disparate data
- Study definitions
- Assemble notes
- Create graphics and tabulations
- Write accompanying text

DOE Approval

- Send to VTO sponsor for approval
- Topic and text of Fact reviewed by VTO sponsor and DOE Communications
- Contents of Data Book reviewed by VTO sponsor
- Changes made by ORNL accordingly

Publication

- Send final Fact & Excel file to VTO website programmer
- Program final Fact in GovDelivery system & send email to subscription list
- Update Data Book website (Serve data in Excel & PDF)
- Answer questions from the public
- Request user feedback

Figure I.1.I: Approach for the transportation data program at ORNL

Table I.1.1 Major Topics for the Transportation Data Program at Oak Ridge National Laboratory

Transportation Energy Data Book Topics	Fact of the Week Topics
Petroleum	Sales
Energy	Petroleum
Light Vehicles & Characteristics	Fuel Economy
Heavy Vehicles & Characteristics	Travel Behavior
Alternative Fuel & Advanced Technology Vehicles & Characteristics	Gasoline
Fleet Vehicles & Characteristics	Electric Vehicles
Household Vehicles & Characteristics	Cost to Consumer
Nonhighway Modes	Diesel
Transportation & the Economy	Import/Export
Emissions	Infrastructure
Energy Conversions	Heavy-duty Vehicles
	Behavior/Ownership, and More…

Results

FOTW 997 through 1048 were posted on the VTO website during FY 2018 (Table I.1.2). For FY 2018, FOTW content accounted for 180,887 pageviews, or 30% of all VTO website pageviews during the FY. Of those, 163,537 were unique visits, meaning that some visitors (17,350) to FOTW content were repeat visitors. Of all VTO website visits, 45% (155,995) entered the site through a FOTW landing page. Fact 915, *Average Historical Annual Gasoline Pump Price from 1929-2015*, had the highest number of pageviews of any VTO website page – 105,594 or 18% of all website pageviews during the FY.

The weekly email for the FOTW (referred to as a newsletter), began on July 27, 2015, with 50 email subscribers. All subscriptions are voluntary and an "unsubscribe link" is provided in every email. As of the end of FY 2018, there were 12,176 subscribers to the Transportation FOTW newsletter.

Table I.1.2 Facts of the Week which were Posted on the VTO website in FY 2018

Fact Number	Fact Title	Date Posted on Website
1048	The United States Supplies 16% of World Petroleum	September 24, 2018
1047	Daily Vehicle Miles Traveled Varies with the Number of Household Vehicles	September 17, 2018
1046	The Average Household Vehicle Was Driven 10,200 Miles in 2017	September 10, 2018
1045	77%-82% of Energy Put into an Electric Car is Used to Move the Car Down the Road	September 3, 2018
1044	12-30% of Energy Put into a Conventional Car is Used to Move the Car Down the Road	August 27, 2018
1043	Engine Compression Ratio and Gasoline Octane Rating Diverge Following Ban of Leaded Gasoline	August 20, 2018
1042	In 2017 Nearly 60% of All Vehicle Trips Were Less than Six Miles	August 13, 2018
1041	Households Take Fewer Vehicle Trips in 2017	August 6, 2018
1040	Average Vehicle Occupancy Remains Unchanged From 2009 to 2017	July 30, 2018
1039	Transportation Expenditure Types Vary by Income Category	July 23, 2018
1038	Companies Now Offer Vehicle Subscription Services	July 16, 2018
1037	Model Year 2017 Vehicles Were More Fuel Efficient with Improved Horsepower and Acceleration	July 9, 2018
1036	Transportation was Nearly 16% of Household Expenditures in 2016	July 2, 2018
1035	Pennsylvania Has the Highest State Gasoline Taxes	June 25, 2018
1034	Short-Haul Shipments of Gasoline Transported Primarily by Truck and Pipeline While Long-Haul Shipments Transported Primarily by Rail and Water	June 18, 2018
1033	Washington State Has the Greatest Fuel Cost Savings for an Electric Vehicle Versus a Gasoline Vehicle	June 11, 2018
1032	Workers in New York State Had the Longest Commute Times in 2016	June 4, 2018
1031	Three-fourths of All Workers Drove Alone to Work in 2016	May 28, 2018
1030	Plug-in Vehicles Consumed Nearly Two Terawatt-hours of Electricity in 2017	May 21, 2018
1029	Plug-In Vehicles Displaced 216 Million Gallons of Gasoline in 2017	May 14, 2018
1028	The Price of a Gallon of Premium Gasoline Averaged 50 Cents Higher than Regular Gasoline in 2017	May 7, 2018
1027	Manufacturers Recommend Premium Gasoline for 47% of New Vehicle Models in 2017	April 30, 2018
1026	Nearly Two-Thirds of U.S. Plug-In Vehicles Were Assembled in the United States	April 23, 2018
1025	China's Plug-in Vehicle Market Share was More Than Double That of the U.S. for 2017	April 16, 2018

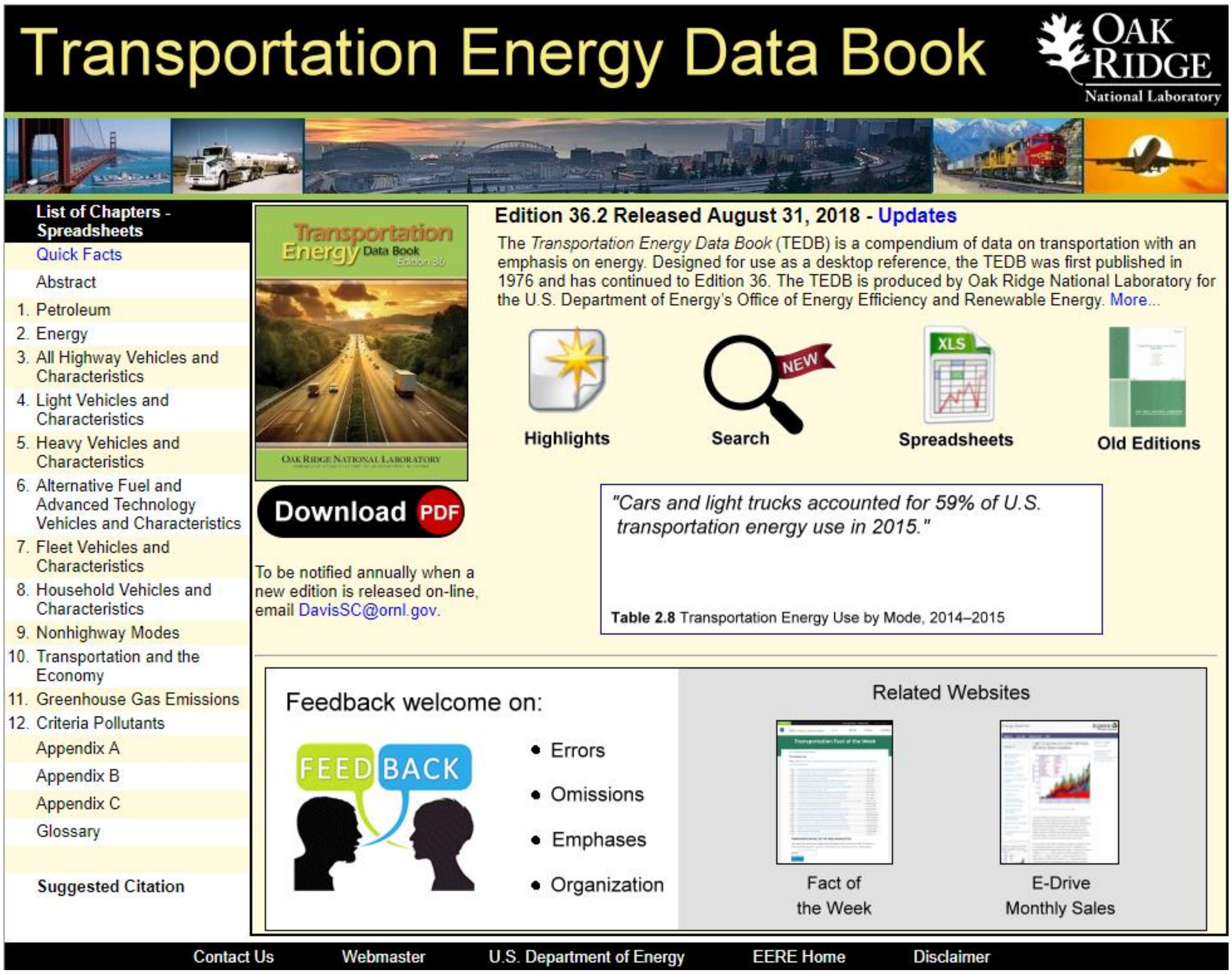
Fact Number	Fact Title	Date Posted on Website
1024	Changes in Vehicle Miles of Travel Often Mirror Gasoline Price Changes	April 9, 2018
1023	Gross Domestic Product Continues to Outpace Vehicle Miles Traveled	April 2, 2018
1022	U.S. Crude Oil Exports Skyrocketed in 2016 and 2017	March 26, 2018
1021	Texas, North Dakota, and the Gulf of Mexico Account for Two-Thirds of U.S. Crude Oil Production	March 19, 2018
1020	Transportation-related Employment was 16% Higher in 2017 Than in 1990	March 12, 2018
1019	About 11 Million Employees were in Transportation-related Jobs in 2017	March 5, 2018
1018	About Half of All New Cars and Light Trucks Have Gasoline Direct Injection	February 26, 2018
1017	Non-Hybrid Stop-Start Systems Doubled for Light Trucks from 2016 to 2017	February 19, 2018
1016	Thirty Percent of Model Year 2017 Cars Have Continuously Variable Transmissions	February 12, 2018
1015	Nearly Half of All New Cars Sold In 2017 Achieved Fuel Economy Above 30 Miles per Gallon	February 5, 2018
1014	Vehicle-Miles in 2016 were Seven Times More Than in 1950	January 29, 2018
1013	Highest Average Gas Prices are in the West	January 22, 2018
1012	On-Road Vehicles Are Responsible for Three-Fourths of Transportation Energy Use	January 15, 2018
1011	Light Vehicle Market in 2017 Shows High September Sales	January 8, 2018
1010	All-Electric Light Vehicle Ranges Can Exceed Those of Some Gasoline Light Vehicles	January 1, 2018
1009	Nearly Five Billion Trips Were Made Using Transit Rail in 2016	December 25, 2017
1008	Median All-Electric Vehicle Range Grew from 73 Miles in Model Year 2011 to 114 Miles in Model Year 2017	December 18, 2017
1007	California has over 15,000 Electric Vehicle Charging Units, Ten Percent of which are Fast Chargers	December 11, 2017
1006	Plug-in Electric Vehicle Charging Infrastructure Needs for Nationwide Coverage	December 4, 2017
1005	Eleven Diesel Models for Sale in the U.S. in Model Year 2017	November 27, 2017
1004	California Had the Highest Concentration of Plug-in Vehicles Relative to Population in 2016	November 20, 2017
1003	Cars Constituted a Larger Fraction of Light-Duty Vehicle Sales for Fleets than Retail Vehicle Sales in 2016	November 13, 2017
1002	The Trade Deficit of Petroleum in 2016 Was at its Lowest Since 1998	November 6, 2017
1001	One Thousand Transportation Analysis Facts of the Week have been Published Online	October 30, 2017
1000	U.S. Petroleum Production Met Demand from Transportation Petroleum Consumption in 2015	October 23, 2017
999	Despite Rise in Vehicle Miles of Travel, Highway Pollutants in 2016 Are Less Than Half as in 2002	October 16, 2017
998	Highway Vehicles Responsible for a Declining Share of Pollutants	October 9, 2017

Fact Number	Fact Title	Date Posted on Website
997	Average Age of Cars and Light Trucks Was Almost 12 Years in 2016	October 2, 2017

On October 23, 2017, the TDP celebrated the posting of the 1,000th FOTW. An ORNL report titled *Historical Review of the Transportation Analysis Fact of the Week, 1996–2017* was released that same month, which examined the themes of published facts and traced analytical trends of FOTW topics. The most popular themes addressed in the FOTW were vehicle fuel economy, petroleum use and production, vehicle sales, and traveler behavior. Facts on vehicle electrification and advanced combustion technologies were more popular in the last few years, showing their relevance to the DOE mission.

Edition 36 of the Transportation Energy Data Book was the first online-only edition. This allowed for mid-year updates to the tables and graphics posted online. Previously, when a new year of data were available soon after the Transportation Energy Data Book was published, the user would wait for nearly a year for the next Transportation Energy Data Book to include the data. With the online-only version, updates can be made more often. In April 2018, Edition 36.1 debuted online with 53 tables and four figures updated to more recent data than was published in the original Edition 36. In August 2018, another 58 tables and 20 figures were updated for Edition 36.2. The draft of Edition 37 was completed and delivered on September 28, 2018, with a total of 216 tables and 60 figures of transportation data, many with historical series going back to 1970. The appendices contain an additional 38 tables. Edition 37 will be posted to the website once reviews and DOE approval are received.

The Transportation Energy Data Book website (Figure I.1.II) had 94,742 pageviews in fiscal year 2018, including 8,807 PDF file downloads and 12,495 MS Excel file downloads. Google Scholar reports 3,070 citations for the Transportation Energy Data Book. Website traffic logs show that 61.5% of the Transportation Energy Data Book website traffic is coming directly to the website and another 29.6% come from search engines, with the remainder from external referrers (8.5%) and social media (0.4%). One new feature of the website that debuted in September 2018 is a search page which allows the user to find data on their topic of choice quickly by typing a keyword. The search page links to both PDF and MS Excel versions of the tables and figures.


Transportation Energy Data Book

OAK RIDGE National Laboratory

List of Chapters - Spreadsheets
- Quick Facts
- Abstract
- 1. Petroleum
- 2. Energy
- 3. All Highway Vehicles and Characteristics
- 4. Light Vehicles and Characteristics
- 5. Heavy Vehicles and Characteristics
- 6. Alternative Fuel and Advanced Technology Vehicles and Characteristics
- 7. Fleet Vehicles and Characteristics
- 8. Household Vehicles and Characteristics
- 9. Nonhighway Modes
- 10. Transportation and the Economy
- 11. Greenhouse Gas Emissions
- 12. Criteria Pollutants
- Appendix A
- Appendix B
- Appendix C
- Glossary

Suggested Citation

Edition 36.2 Released August 31, 2018 - Updates

The *Transportation Energy Data Book* (TEDB) is a compendium of data on transportation with an emphasis on energy. Designed for use as a desktop reference, the TEDB was first published in 1976 and has continued to Edition 36. The TEDB is produced by Oak Ridge National Laboratory for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. More...

To be notified annually when a new edition is released on-line, email DavisSC@ornl.gov.

"Cars and light trucks accounted for 59% of U.S. transportation energy use in 2015."

Table 2.8 Transportation Energy Use by Mode, 2014–2015

Feedback welcome on:
- Errors
- Omissions
- Emphases
- Organization

Related Websites

Figure I.1.II Transportation Energy Data Book website home page

Data collected in the TDP also provided input data to other VTO programs and other Agency's models, such as: MA3T, GREET®, ADOPT, Parachoice, prospective program benefits analysis, the Energy Information Administration National Energy Modeling System, and the Environmental Protection Agency MOVES model.

Conclusions

Successful publication of the TDP in the form of weekly, monthly, and annual milestones delivered on-time and within budget with improvements over time, leads to analyses that support program planning and evaluation and technology research to address transportation efficiency and cost-effectiveness, which will help meet the research and development priorities of the DOE of energy dominance.

Key Publications

1. Gohlke, D. and Davis, S. 2017. "Historical Review of the Transportation Analysis Fact of the Week, 1996–2017." ORNL/TM-2017/695, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

2. Davis, S, Diegel, S., and Boundy, R. 2018. "Transportation Energy Data Book: Edition 37." ORNL/TM-2018/987, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [Draft completed in FY 2018. Published in final form in FY 2019.]

I.2 E-Drive Data

Yan Zhou, Principal Investigator
Argonne National Laboratory
9700 S Cass Ave
Lemont, IL
E-mail: yzhou@anl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2017 End Date: September 30, 2018
Project Funding (FY18): $50,000 DOE share: $50,000 Non-DOE share: $0

Project Introduction

Electric drive (E-drive) vehicle technologies include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). VTO supports analysis of light-duty (LD) market trends in order to assess potential benefits of VTO technologies and evaluate program activities. A major challenge is the lack of readily available historical sales in the U.S. and other markets to enable comparison. Such a comparison could help DOE to better understand the technology pathways in different regions. Vehicle original equipment manufacturers (OEMs) who are responsible for the vast majority of light-duty vehicle (LDV) sales in the U.S., as well as some automakers who have not previously sold vehicles in the U.S., have announced plans for vehicle electrification in the near future. Many research institutes and consulting companies are also projecting future E-drive vehicle sales and stock. VTO needs to be informed about OEMs' E-drive technology R&D plans as well as the difference and similarities of third-party projections.

Objectives

The objective is to collect and provide quality E-drive sales and incentive for the VTO Analysis Program.

Approach

Argonne National Laboratory (Argonne) collected monthly U.S. E-drive vehicle sales data by make/model and other related key data (e.g., gasoline price, Gross Domestic Product) and presented them in monthly summaries. Argonne distributed the monthly summaries to all subscribers and published selected information on Argonne's website (https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates). Argonne also collected and summarized the sales information for other regions (China, Europe, and Japan) through working with Tsinghua University, China, and provided comparison of different markets to VTO and other DOE offices through reports and presentations as needed.

Argonne also collected and summarized the OEMs' announcements of their future vehicle electrification plans through press releases, announcements at auto trade shows, and interviews. Argonne also summarized the projections of E-drive vehicle sales and stock developed by different studies through publications and press releases. Argonne published selected results on VTO's Transportation Fact of the Week website. Based on the cumulative sales data, Argonne estimated the energy consumption of the electrified LDV market and published an LDV electrification impact report.

Results

Plug-in Electric Vehicle Sales

Since the introduction of the Chevrolet Volt (PHEV) and Nissan LEAF (BEV) in the U.S. market in December 2010, an increasing number of PHEVs and BEVs have become available. Up to August 2018, 433,237 BEVs and 508,704 PHEVs were sold in the U.S. Plug-in electric vehicles (PEVs) (including BEVs and PHEVs) account for more than 2% of LDV sales in the U.S. Currently, PHEVs and BEVs are available in diverse vehicle size classes ranging from two-seaters to standard sport utility vehicles. However, until recently, most mass-market BEVs had an electric driving range of less than 100 miles. Figure I.2.I shows monthly sales by make and model in the U.S. Note that the Tesla Model 3 (the light blue color on the right side) was introduced in late 2017, and has been one of the bestselling PEV models in the U.S. The 10-top selling PEV models account for over 80% of the annual PEV sales.

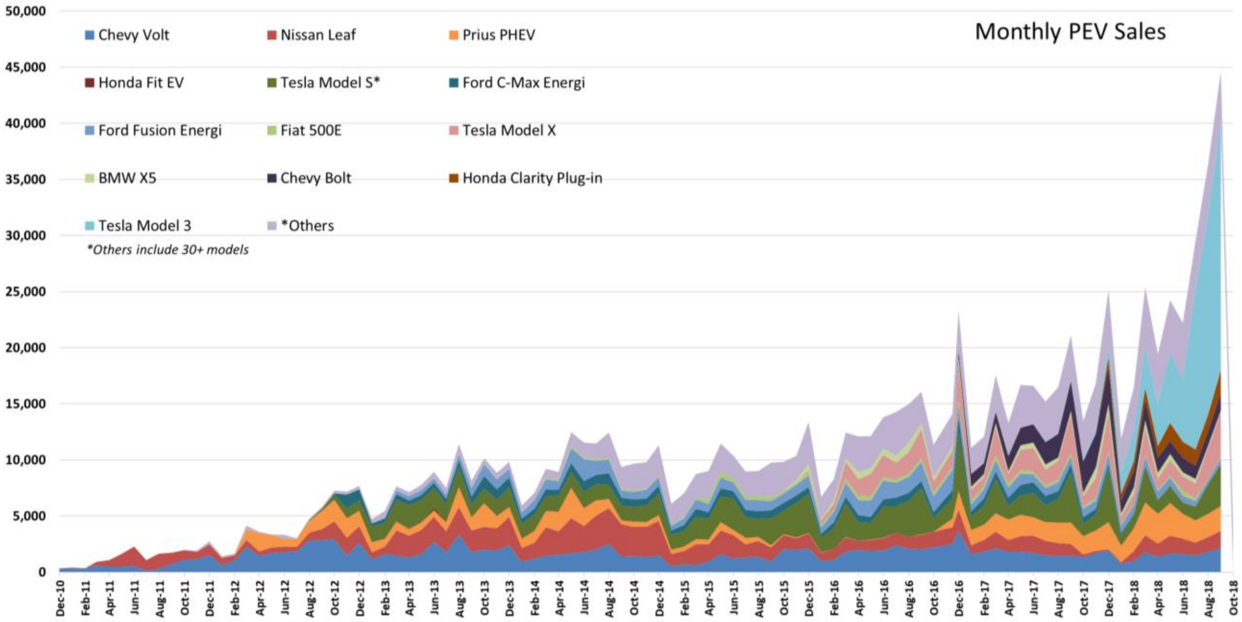


Figure I.2.I PEV monthly sales in the United States

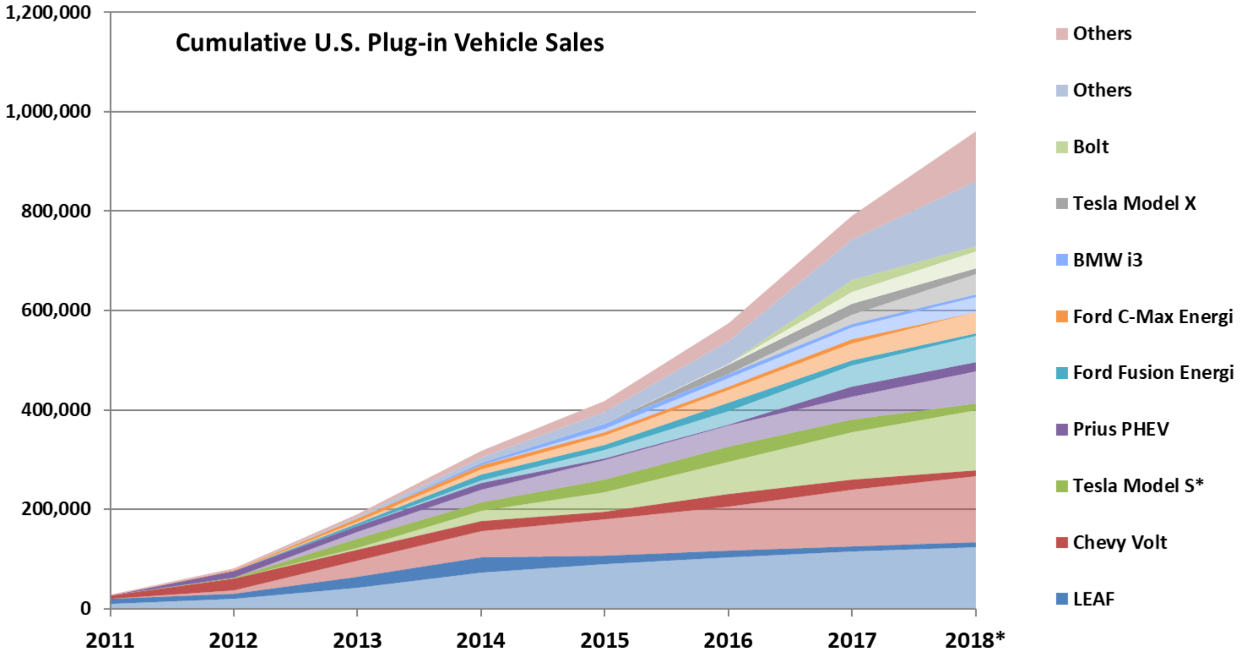


Figure I.2.II Cumulative United States plug-in vehicle sales

Figure I.2.III shows the annual PHEV and BEV sales comparison of China, Europe, and the U.S. China became the biggest PEV market in the world in 2015 and has maintained the lead position over the last two years. About 80% of PEVs sold in China are BEVs due to the largely BEV-focused policies.

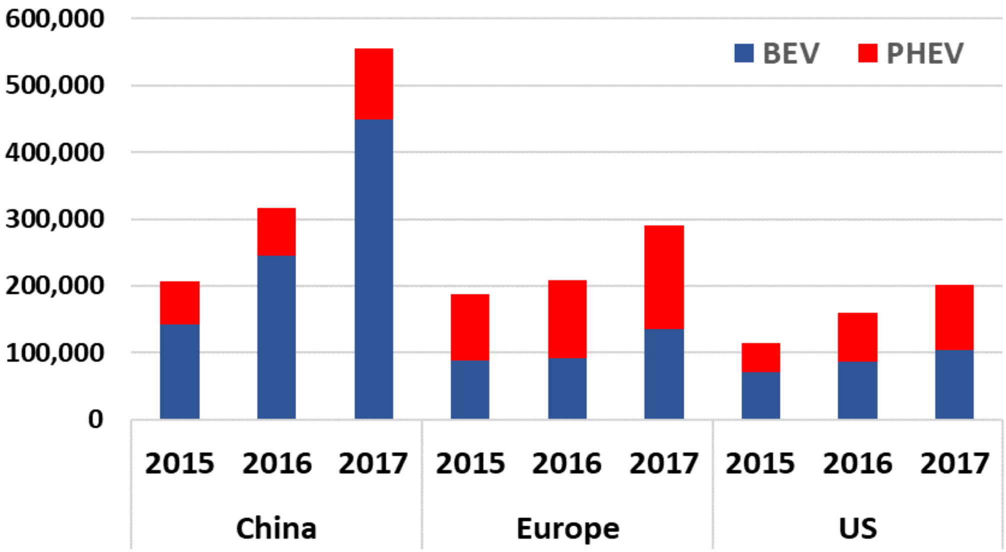


Figure I.2.III PEV sales by type and region, 2015, 2016, and 2017

Impact of LDV Electrification

Using the historic vehicle sales, the vehicle electric driving range, and the effective utility factor, the total electrically-driven vehicle miles travelled (eVMT) across the national LDV fleet can be estimated. Through 2017, nearly 16 billion miles were powered by electricity in the U.S. In 2017, 5.8 billion miles were driven by light-duty PEVs; approximately 58% was by BEVs. Combining eVMT with knowledge of vehicle electricity efficiency allows us to determine the total electricity consumption by PEVs in the U.S., shown in Figure I.2.IV. To find the total electricity consumption, the estimated eVMT in each month is multiplied by the electricity consumption per mile for each vehicle model. Through 2017, a total of 5.4 terawatt-hours of electricity have been consumed by PEVs. In 2017, the total electricity use for LDVs was 1.9 terawatt-hours. In 2017, the average PHEV consumed 2,500 kilowatt-hours (kWh) of electricity, and the average BEV consumed 3,500 kWh of electricity.

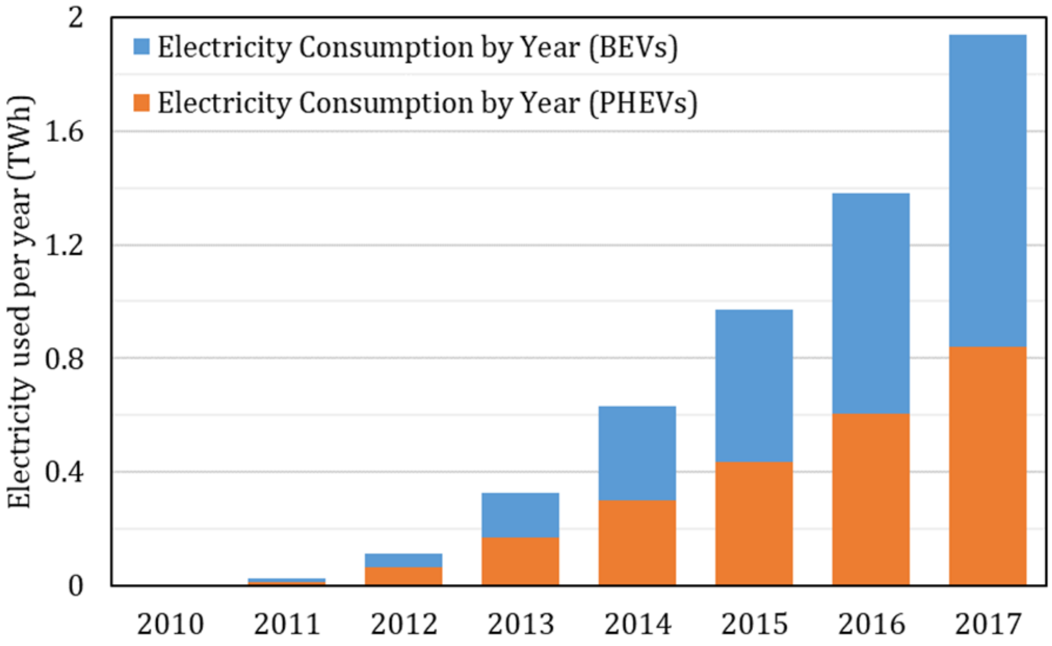


Figure I.2.IV Electricity consumption by PEVs by year

Original Equipment Manufacturer Plans for Electrified Vehicle Development
Since 2017, 30 vehicle OEMs from the U.S. market and others announced plans for vehicle electrification in the near future through press releases, announcements at auto trade shows, and interviews. As of September 2018, these 30 automakers have publicly announced plans to produce over 250 models of PEVs by 2025. Not all of these vehicles will be available in the United States. Daimler, Ford, Hyundai, and VW have all increased their focus on electrification, either by acceleration of deployment release of new models, underscores the accelerating trend towards electrification. Automakers have made increasing electric vehicle announcements in the last two years.

Summary of Plug-in Electric Vehicle Projections
Since October 2017, 14 studies projected electrified LDV sales, sales share, and/or vehicle stock. A few caveats exist when examining these projections. First, some studies project sales share and sales volumes, while others project stock share and stock. Second, not all studies separate PHEVs and BEVs. Third, only two studies, the U.S. Energy Information Administration's Annual Energy Outlook and Argonne's BaSce report provide separate projections for passenger cars and light trucks. Figure I.2.VFigure I.2.V summarizes the latest PEV projections made by different studies. BaSce results are from program success case. AEO low oil case is not included because in which the PEV market penetration is negligible. Projections of PEV sales varied from 20% to 90% by 2040.

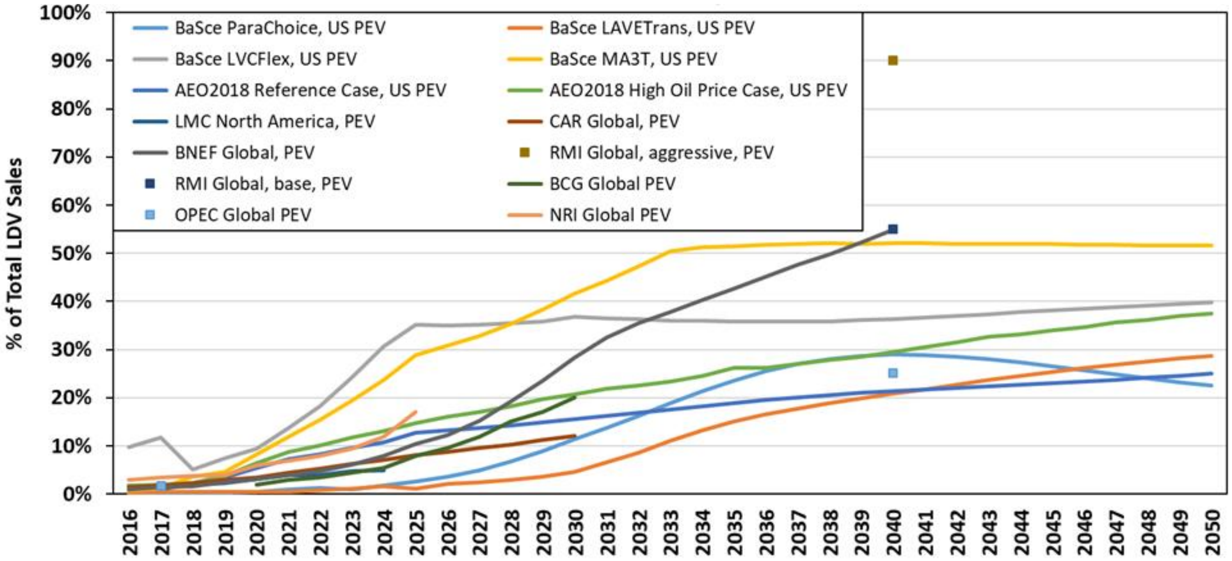


Figure I.2.V PEV sales share projections by 2050

Conclusions

As of August 2018, a total of 433,237 BEVs and 508,704 PHEVs have been sold in the U.S. PEVs (including BEVs and PHEVs) now accounts for more than 2% of monthly LDV sales in the U.S. started from July 2018. Compared to the PEV adoption rate in China, the growth of PEV sales in the U.S. has been more gradual. Total PEV sales in China were about 550,000 vehicles in 2017, while U.S. PEV sales were just under 200,000. The share of BEVs to PHEVs sold in China were much different than in the U.S. In China, 81% of PEV sales were BEV in 2017, while in the U.S., BEV accounted for just over half (53%).

In 2017, the total electricity used by PEV LDVs was 1.9 terawatt-hours. In 2017, the average PHEV consumed 2,500 kWh of electricity, and the average BEV consumed 3,500 kWh of electricity. In 2017, the average BEV avoided the use of nearly 410 gallons of gasoline, and the average PHEV avoided the use of 260 gallons. Cumulatively, through 2017, PEVs have avoided the use of over 600 million gallons of gasoline, 353 million gallons by BEVs and 248 million gallons by PHEVs.

As of September 2018, 30 automakers have publicly announced plans to produce over 250 models of PEVs by 2025. Not all of these vehicles will be available in the United States. Projections of annual PEV sales percentage made by different studies from October 2017 to September 2018 vary from 20% to 90% in the year 2040.

Key Publications

1. David, G., and Zhou, Y. 2018. "Impacts of Electrification of Light-Duty Vehicles in the United States, 2010 - 2017." ANL/ESD-18/1, 2018. Web. doi:10.2172/1418278.

2. Guo, Z., Zhou, Y., and Campbell, R. 2018. "Residual Value Analysis of Plug-in Vehicles in the U.S." Proceedings of 97th Transportation Research Board Annual Meeting, Washington, D.C., Jan. 2018.

3. Guo, Z., and Zhou, Y. 2019. "Residual Value Analysis of Plug-in Vehicles in the U.S." *Energy Policy*, Volume 125, February 2019, Pages 445-455.

II Modeling and Simulation

II.1 ParaChoice Model

Rebecca Levinson, Principal Investigator
Sandia National Laboratories
7011 East Avenue
Livermore, CA 94550
E-mail: rslevin@sandia.gov

Brandon Heimer, Principal Investigator
Sandia National Laboratories
7011 East Avenue
Livermore, CA 94550
E-mail: bwheime@sandia.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2013	End Date: Project continuation evaluated annually	Non-DOE share:
Project Funding (FY18): $200,000	DOE share: $200,000	$0

Project Introduction

Sandia National Laboratories' (SNL's) Parametric Choice Model (ParaChoice) supports the U.S. Department of Energy Vehicle Technologies Office (VTO) mission. Using early-stage research as input, ParaChoice supports the informed development of technology that will improve affordability of transportation, while encouraging innovation and reducing dependence on petroleum. Analysis with ParaChoice enables exploration of key factors that influence consumer choice, as well as projecting the effects of technology, fuel, and infrastructure development for the vehicle fleet mix. Because of the distinct differences between requirements, needs, and use patterns for light duty vehicles (LDVs) relative to heavy duty vehicles (HDVs), this project separately models the dynamics of each of these segments to accurately characterize the factors that influence technology adoption.

Objectives

The lifetime project objective is to provide system-level analysis of the dynamics among the LDV and HDV fleets, fuels, infrastructure mix, and emissions. These capabilities have been instantiated in the ParaChoice model, a parametric vehicle choice model that can be used to identify trade spaces, tipping points, and sensitivities. Furthermore, parametric analyses can help quantify the effects of uncertainty introduced by data sources and assumptions.

LDV analysis goal: Determine the potential for alternative fuel vehicles (AFVs) to penetrate the market, reduce LDV petroleum consumption and emissions, and impact energy use. Determine factors that influence alternative energy vehicle penetration and impact, the path to more efficient vehicles, tipping points for impactful market penetration, and system sensitivities. Present LDV analysis results uses the external ParaChoice results viewer.

HDV analysis goal: Evaluate the potential for AFVs to increase freight hauling efficiency, decrease fuel use and reduce exhaust emissions, similarly to LDV. The capability to handle vocational HDVs was added to ParaChoice to enable these analyses this year. A segmentation analysis is required to determine the classes and types of vehicles that should be added to the HDV portion of ParaChoice.

Approach

ParaChoice models the system of energy sources, fuels, and LDV or HDV vehicles (Figure II.1.I). Simulations begin with today's energy, fuel, and vehicle stock and projects out to 2050. At each time step, vehicles compete for share in the sales fleet based on value to consumers. The simulation assesses generalized vehicle cost for each vehicle at every time step. A nested multinomial logit choice function assigns sales fractions based on these costs and updates the vehicle stock accordingly.

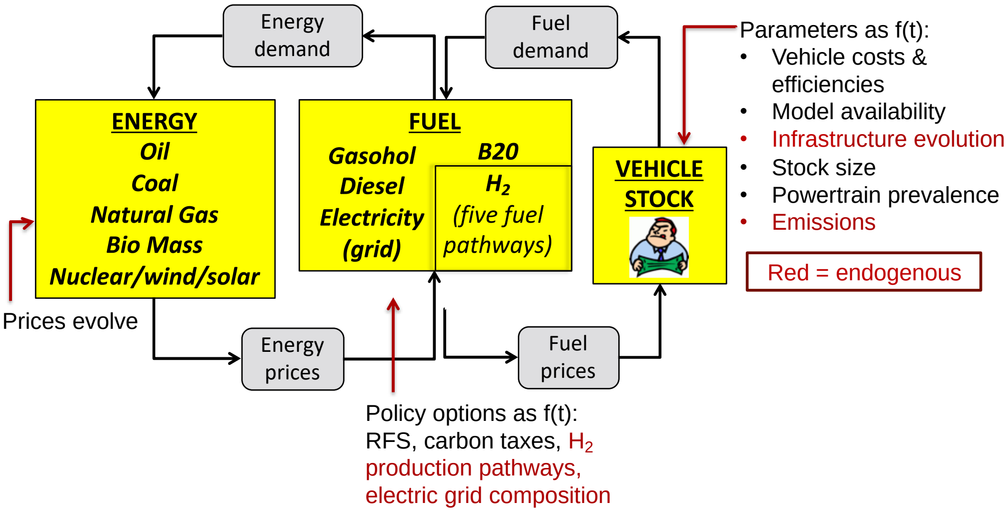


Figure II.1.I ParaChoice system dynamics model structure

ParaChoice is designed to enable parameterization that can be used to explore uncertainty and trade spaces, easily allowing identification of tipping points and system sensitivities. Uncertainty analyses possible using ParaChoice include trade space analyses where two parameters are varied, generating hundreds of scenarios; and sensitivity analyses where many parameters can be varied at once, generating thousands of scenarios. Parameter ranges are selected to explore plausible and "what if" regimes, and provide thorough coverage of possible future states. Analysis products using ParaChoice provide insights into: (1) perspectives in uncertain energy and technology futures; (2) sensitivities and tradeoffs between technology investments, market incentives, and modeling uncertainty; and (3) the set of conditions that must be true to reach performance goals.

Vehicles, fuels, and populations are segmented to study the competition between powertrains and market niches; see Figure II.1.II. Baseline inputs into the ParaChoice model include the following data and modeling outputs: the Energy Information Administration Annual Energy Outlook 2016 (energy prices); Argonne National Laboratory's (ANL) Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (emissions); the Oak Ridge National Laboratory (ORNL) housed National Household Travel Survey (NHTS) (LDV fleet segmentation); Polk (HDV fleet segmentation); ANL's Autonomie (LDV price projections); National Petroleum Council (HDV price projections); and the Alternative Fuel Data Center (2010-2017 fueling stations and policies by state).

Results

To visualize results from ParaChoice model runs and to help understand the impact of various parameters on modeling outputs, the results are made available through an interactive online Results Viewer (https://h2-msm-vm.sandia.gov/parachoice). The Results Viewer for the LDV analyses was updated this year based on feedback from the VTO program office.

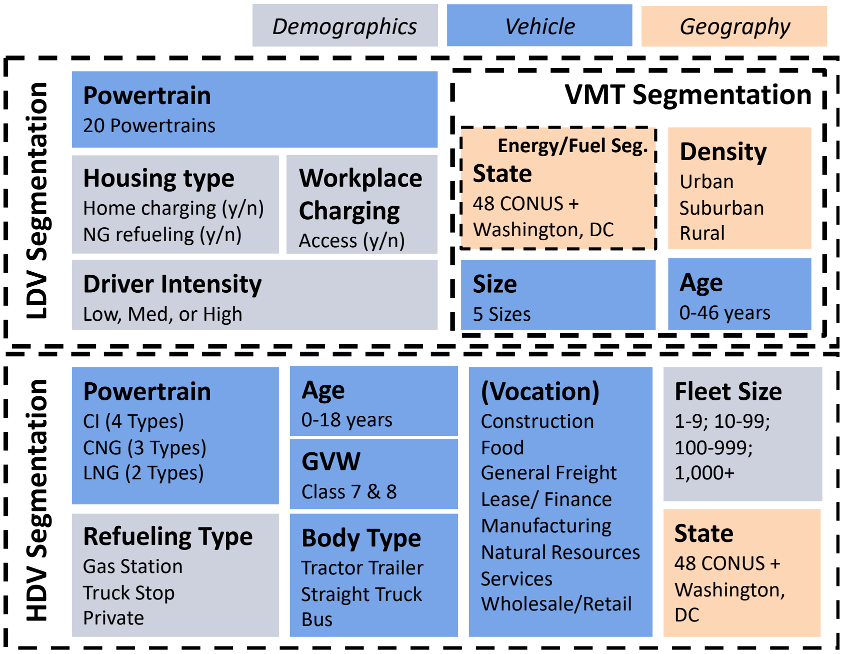


Figure II.1.II LDV and HDV segmentation options grouped into themes of buyer demographics (e.g., access to workplace charging or truck stop versus gas station refueling), vehicle options (e.g., powertrain or body type) and geography (e.g., State or population density)

To identify the combination(s) of HDV fleet segments and novel technologies that have the potential to significantly decrease petroleum use and/or criteria emissions, the team quantitatively characterized the fleet of HDVs by elucidating the taxonomy of the Class 7 & 8 HDVs according to vehicle stock (informing vehicle original equipment manufacturer (OEM) decisions), annual vehicle miles traveled (VMT) and annual fuel consumption. Fuel consumption was broken down further by truck (informs buyer purchase decision, and when compared to VMT, informs the potential for technology improvements that affect efficiency or accessories), by typical fleet size for segment (informs buyer purchase decision and risk tolerance of buyers) and for segment (informs OEM manufacture decision and potential petroleum and environmental impacts).

The number of registered Class 7 & 8 vehicles for each truck type was estimated using data from the Polk 2011 data [1], the U.S. Department of Transportation's Federal Transit Administration 2011 Annual Vehicle Inventory [2] and the Federal Highway Administration Highway Statistics Series for bus registrations [3]. The vehicle population numbers were compared across all sources, and the final values used in ParaChoice are presented in Figure II.1.III. The stock shares by vehicle type were estimated using the 2002 Vehicle Inventory and Use Survey (VIUS) [4]. The "Other" category includes all truck use types that accounted for ≤5% of the total for that market segment.

The average annual VMT by truck-tractors and single-unit trucks were estimated from VIUS 2002 [4]. The annual VMT for transit and school buses were estimated to be 34,053 miles/year and 12,000 miles/year, respectively, from the U.S. Department of Energy's Alternative Fuels Data Center [5]. Motor homes' annual VMT was estimated to be 2,546.71 miles/year from the 2009 NHTS [6].

The short- versus long-haul split fraction was determined for each body or trailer type by applying a mileage threshold (100,000) to the annual miles from VIUS 2002. For analysis purposes, long-haul vehicles travel approximately 110,000 miles annually, and short-haul trucks with "day cabs" travel approximately 80,000 miles annually [6]. Histograms of annual VMT for truck-tractors and single-unit trucks are shown in Figure II.1.IV and Figure II.1.V. The short- versus long-haul split fractions for the five truck-tractor segments are shown in Table II.1.1. Essentially all single-unit trucks travel less than 110,000 miles annually, and therefore, are short-haulers by definition.

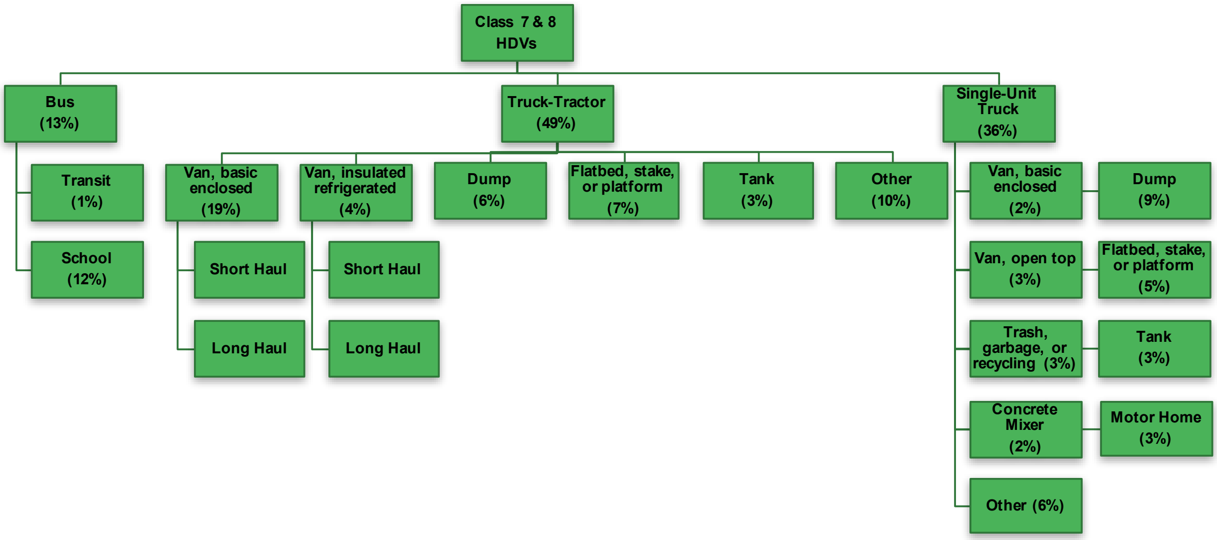


Figure II.1.III Segmentation of the HDV (Class 7 & 8) vehicles into subcategories using a tree structure that elucidates the percent vehicle fraction. The first segmentation is buses (13%), truck-tractor (49%) and single-unit trucks (36%).

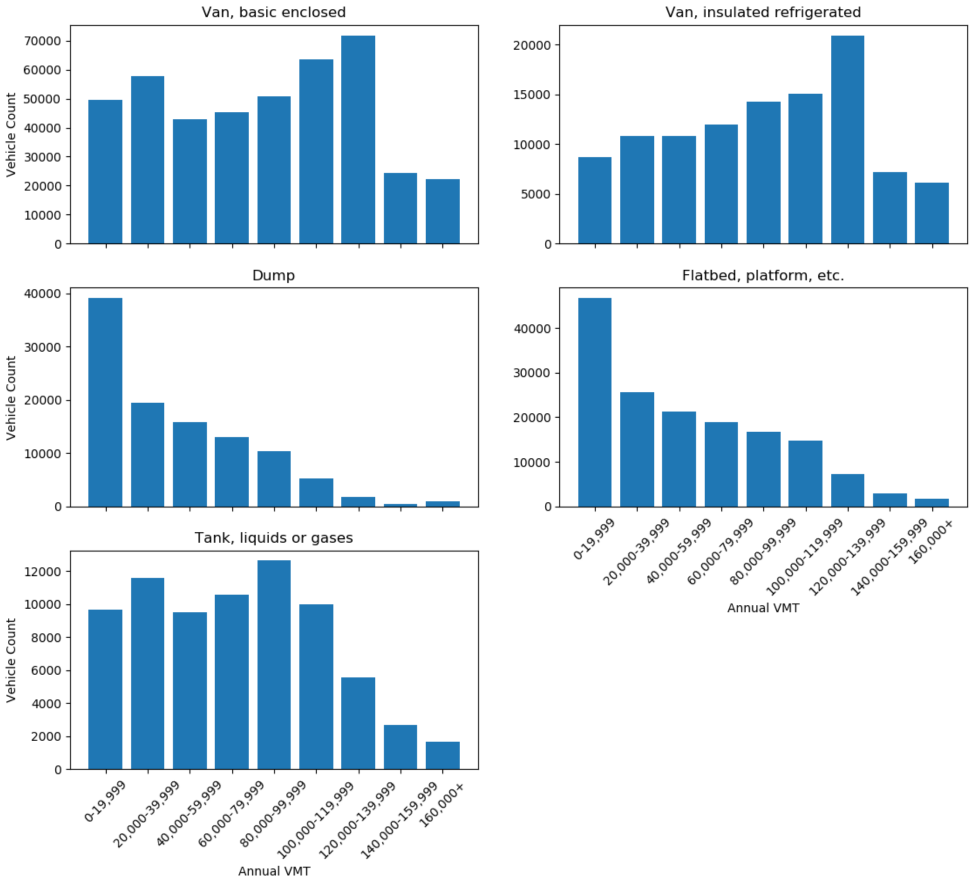


Figure II.1.IV Bar graphs showing the VMT for five subsections of truck tractors (van-basic, van-insulated, dump, flatbed, tank). VMT ranges are broken into nine bins distributed equally from 0-160k+ miles per year.

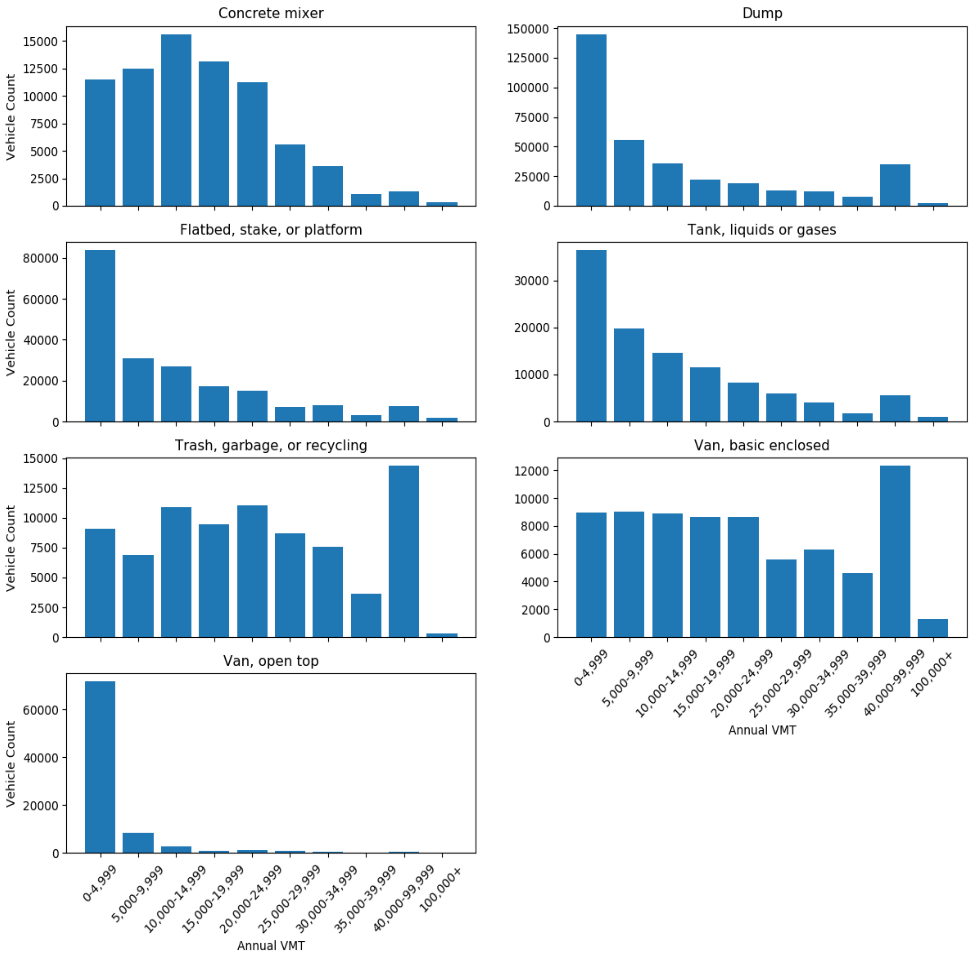


Figure II.1.V - Bar graphs showing the VMT for seven subsections of single-unit trucks (concrete mixer, dump, flatbed, tank, trash, van-basic, van-open). VMT ranges are broken into 10 bins distributed from 0-100k+ miles per year.

Table II.1.1 Truck-tractor short- vs. long-haul split fractions

	Van, Basic	Van, Refrigerated	Dump	Flatbed	Tank
Short-haul	0.58	0.53	0.92	0.83	0.73
Long-haul	0.42	0.47	0.08	0.17	0.27

Key findings from the HDV segmentation analysis are the following:

- HDV segmentation by vehicle stock looks quite different than by annual VMT or fuel use (see Figure II.1.VI). Truck-tractors account for only approximately half of Class 7 & 8 HDVs, but travel approximately three-quarters of the total annual miles and consume three-quarters of fuel. Of these, the long-haul trucks dominate.
- Sectors where alternative energy technologies have been successful are relatively small: refuse (e.g., compressed natural gas, CNG) is 2.2% by VMT, 2.8% by fuel use and 2.4% by vehicle stock; and transit buses (e.g., hybrid electric, CNG/ liquefied natural gas) is 1.2% by VMT, 2.1% by fuel use and 1.0% by vehicle stock.

- Nearly all single-unit trucks are short-haulers. There are approximately 1.7 million single-unit trucks in the fleet, and thus there may be a large enough market in a given body type of single-unit trucks for OEMs to be interested to make new, alternative powertrain versions. The short range of single-unit trucks may make them good candidates for electrification.

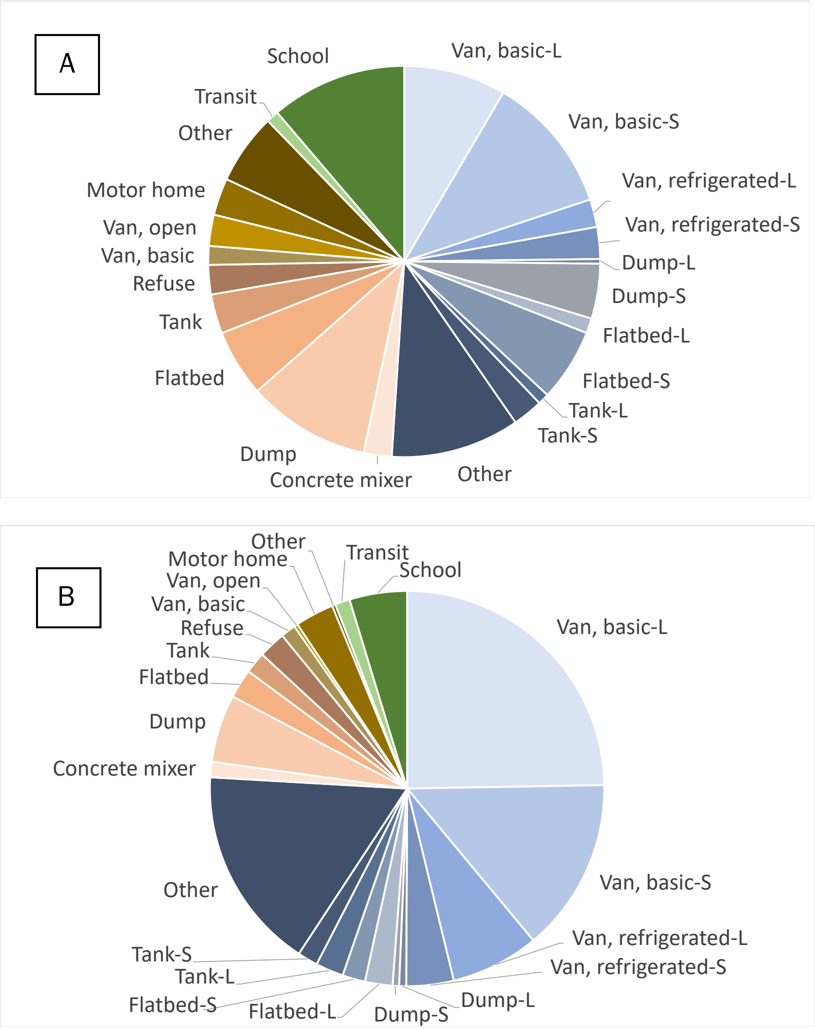


Figure II.1.VI Pie charts of HDV fleet by vehicle count represented as a percentage of total fleet (A) and by VMT as a percentage of total fleet miles (B). The "-L" and "-S" suffixes indicate long- or short-haulers, respectively. Truck-tractor segments are shown in blue-gray, single-unit trucks in orange, and buses in green. Segmentation of HDV fleet by total fuel consumption is similar to the VMT segmentation.

Conclusions

ParaChoice is a validated, system-level model of the dynamics existing among vehicles, fuels, and infrastructure. The model leverages other DOE models and inputs to simulate fuel production pathways that scale with demand from vehicles. It is designed for parametric analysis in order to understand and mitigate uncertainty introduced by data sources and assumptions. Native parametric capabilities are also useful for identifying trade spaces, tipping points and sensitivities. ParaChoice is not simply a tool for creating scenario sales projections; its results help analysts understand relationships among the LDV and HDV stocks, fuel use, and emissions. Findings from the segmentation analysis will be combined with the fuel and emissions analysis in FY 2019 to determine where alternative powertrains have the potential be the most efficacious.

Key Publications

1. Levinson, R. and West, T. 2018. "Impact of convenient away-from-home charging infrastructure," *Transportation Research Part D,* 65, 288-299.

References

1. R. Polk and Co., U.S. Vehicle Registration Data MY 2005-2016, Jan. 2015. Compiled by SRA International, Inc.

2. U.S. Department of Transportation Federal Transit Administration 2011 Annual Vehicle Inventory; https://www.transit.dot.gov/ntd/data-product/2011-annual-database-revenue-vehicle-inventory Federal Highway Administration Highway Statistics Series for bus registrations; https://www.fhwa.dot.gov/policyinformation/statistics/2011/mv10.cfm

3. U.S. Census Bureau Vehicle Inventory and Use Survey (VIUS), 2002; https://www.census.gov/library/publications/2002/econ/census/vehicle-inventory-and-use-survey.html

4. U.S. Department of Energy's Alternative Fuels Data Center; https://www.afdc.energy.gov/data/10309

5. 2009 National Household Travel Survey (NHTS); https://nhts.ornl.gov/tables09/fatcat/2009/avmtvs_VEHAGE_VEHTYPE.html

6. North American Council for Freight Efficiency 2016 Annual Fleet Fuel Study. https://nacfe.org/wp-content/uploads/2018/01/NACFE-2016-Annual-Fleet-Fuel-Study-FINAL-Report-082316_0.pdf

II.2 Market Acceptance of Advanced Automotive Technologies

Zhenhong Lin, Principal Investigator
Oak Ridge National Laboratory
2360 Cherahala Boulevard
Knoxville, TN 37932
E-mail: linz@ornl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2017 End Date: September 30, 2018
Project Funding (FY18): $620,000 DOE share: $620,000 Non-DOE share: $0

Project Introduction

Modeling acceptance of advanced energy efficient vehicle technology is important to the DOE mission and to its stakeholders to understand and quantify the future value of research and development (R&D). Technology impacts (e.g., energy consumption, consumer costs, energy security) are often used to justify and prioritize R&D investments in advanced vehicle technologies. However, consumers may view technologies differently than engineers, scientists, and economists. Meanwhile, suppliers seek less risk, more market certainty, and good public image, in addition to profits. This presents challenges in understanding and modeling supplier behavior (e.g., product provision and pricing decisions) and the resulting technology acceptance of advanced vehicle technologies.

To alleviate these challenges, the MA3T (Market Acceptance of Advanced Automotive Technologies) model was developed to simulate the market penetration and dynamics in transition scenarios toward energy efficient vehicle and mobility technologies in the highway sector. The key output of the model is annual sales share of a vehicle or mobility technology (e.g., 42-volt micro hybrid, 200-mile battery electric vehicle (BEV), or autonomous shared mobility). Model inputs include consumer segmentation and attributes, technology cost and performance, infrastructure availability and prices, and government incentives. All these inputs can be easily changed, and the operation of the model only requires installation of Microsoft Excel.

The MA3T model was originally developed to focus on fuel choices and was later adapted and upgraded to: (1) MA3T-CN that simulates plug-in electric vehicle (PEV) market penetrations in China, (2) MA3T-Global that estimates transportation energy transitions in different regions and countries around the world, and (3) MA3T-MobilityChoice that simulates market penetrations and synergies of electrification, automation, and shared mobility. Some of the work was funded by international organizations and the private sector. Currently, published applications of the model cover the topics of: (1) compliance analysis of the fuel economy standards, (2) program benefit estimates for multiple DOE program offices, (3) biogas electricity incentives for PEVs, (4) PEV market penetration sensitivity, (5) market effect of vehicle automation on electrification, and (6) impact of dynamic wireless charging on PEV sales.

Objectives

The objectives of the MA3T project are to: (1) develop a user-friendly, useful, and credible simulation tool in support of techno-economic analysis with respect to energy-relevant vehicle technologies; (2) close key knowledge gaps in fundamental issues for reaching Objective 1 above (e.g., how to quantify range anxiety cost), (3) advance discussions of vehicle technologies through publications, and (4) use the model as a coherent intellectual platform to collect industry feedback and conduct quick-turnaround scenario analysis of interest to stakeholders.

Approach

The core of the MA3T model is based on the nested multinomial logit theory, the immediate output from which is the purchase probability of each technology choice by each consumer segment. These probabilities are then translated into vehicle sales by technology, vehicle population, energy consumption, and emissions. These outputs are also used as feedbacks to dynamically affect the conditions and purchase probabilities of the next time step. For example, greater sales lead to more vehicle makes and models and further accelerate market penetration. Inputs of the model include consumer segmentation and attributes, technology cost and performance, infrastructure availability and prices, and government incentives.

The original MA3T model was focused on choice of fuel types (e.g., gasoline conventional vehicles versus hybrid electric vehicles (HEVs) versus PEVs). One major component of the project is to adopt existing or develop new methods for quantifying assumptions and show their impacts on market acceptance (sales and population), energy consumption, and the economy. Assumptions that can be quantified include but are not limited to: (1) Mobility – what if shared mobility eliminates first/last-mile inconvenience? (2) Consumer – what if consumers demand a three-year payback? (3) Technology – what if batteries cost $80/kilowatt-hour by 2030 and what if vehicle automation increases travel demand? and (4) Infrastructure – what if 100kW fast-charging is strategically offered? Investigating these assumptions and their impacts on technology acceptance of advanced vehicles is an important ongoing task for the team.

In particular, to improve the future MA3T modeling assumptions, in FY 2018, the primary effort of the team was to explore charging infrastructure requirements to meet the travel needs for both personal vehicles and commercial vehicle fleet (e.g., taxi). These analyses are important to understand the linkage of the charging infrastructure support and BEV technology acceptance that could be modeled by the MA3T model. As demonstrated in the results section later, the team highlights major findings of three studies conducted by the team in FY 2018.

Results

1. *Electric vehicle feasibility for taxi vehicles*

In a paper published in Transportation Research Part C [1], the research team analyzed the electric taxi feasibility based on the travel activities of current conventional gasoline vehicle taxis. The study extracts 10 variables from the trip data of the New York City yellow taxis to represent their spatial-temporal travel patterns in terms of driver-shift, travel demand and dwell, and examines the implications of these driving patterns on the BEV taxi feasibility. The BEV feasibility of a taxi is quantified as the percentage of occupied trips that can be completed by BEVs of a given driving range during a year.

As shown in Figure II.2.I, each yellow circle represents one current public charging station in New York City. There are 280 stations in total, among which 223 (80%) are located in Manhattan, two are at the John F. Kennedy International Airport and four are at the LaGuardia Airport. Most of these charging stations are installed with Level 2 chargers. The results in this study indicate that the existing public charging infrastructure is far from sufficient to support a large BEV taxi fleet. In 2016, there were 85,200 registered for-hire vehicles, which includes taxis, green cabs, black cars and private cabs. The simulation approach results in this study suggests that by adding merely 372 new charging stations, shown as green circles in Figure II.2.I, it could potentially make BEVs with 200- and 300-mile ranges feasible for more than half of the taxi fleet. These 372 simulated new charging stations are strategically located at various locations where taxies frequently dwell. The results also show that taxis with certain duty cycle characteristics are more suitable for switching to BEV-200 or BEV-300, such as fewer daily shifts, fewer drivers assigned to the taxi, shorter daily driving distance, fewer daily dwells, but longer per event dwelling time, and higher likelihood to dwell at the borough of Manhattan.

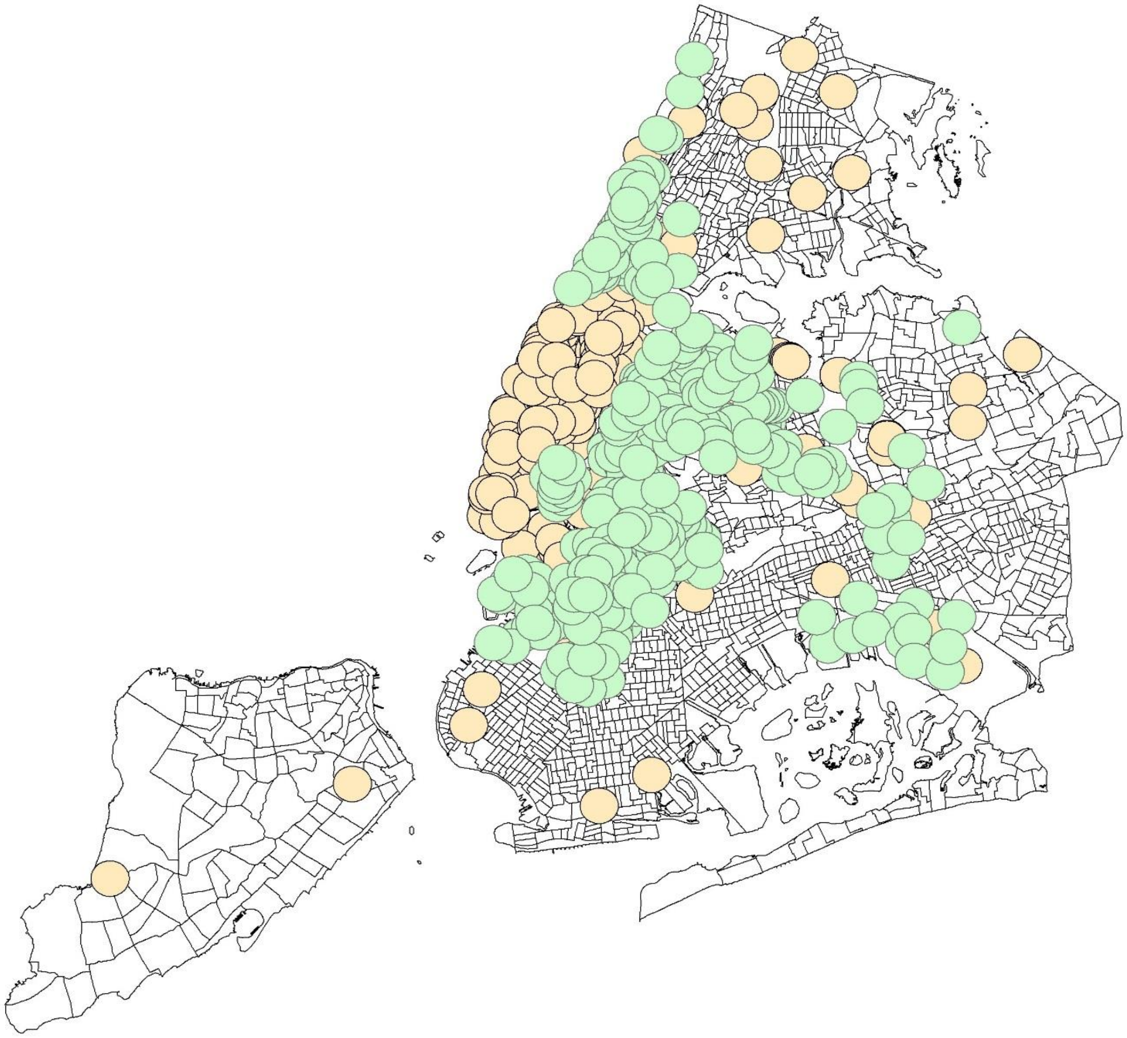


Figure II.2.I Expanded public charging network in New York City for the taxi fleet, with a buffer of 0.5-mile radius (Yellow circles represent current charging stations with a buffer, and green circles represent new charging stations with a buffer)

2. *Fast charging along major corridors*

Another study conducted by this project in FY 2018 focused on the charging infrastructure development to benefit BEV technology acceptance [2]. Compared to the first study, the second study was dedicated to investigating where and when new fast charging stations could be located along major corridors, and how many chargers are needed for each charging station to meet the growing inter-city travel demand of BEV travelers. Compared to prior research, one major contribution of this study was to model randomness in charging activities at charging stations, an important factor to model charging congestion and charging station utilization problems.

The research team introduced the level of service concept, formulated using stochastic chance constraints to determine the charging station capacity. In particular, the level of service is measured in terms of the design, or minimum, probability for a BEV user to find a vacant charger within a certain time limit. As shown in Figure II.2.II, the research team considered five sets of relationships based on different levels of service. For each scenario, the average charging time is assumed to be 0.5 hour. Among the five scenarios, the highest level of service is to guarantee 99% probability for BEV users to find to a vacant charger within 0 minutes (i.e., immediately after arriving at the station), labeled as “99%+0 minutes+0.5 hour”, and the lowest level of service, “90%+30 minutes+0.5 hour”, is to guarantee 90% probability for BEV users to find a vacant charger within 30 minutes. The step relationship in Figure II.2.II Charging station capacity with different levels of service (e.g., the “99%+0 minutes+0.5 hour” service level will guarantee 99% probability for BEV users to find to a vacant charger within 0 minutes when the average charging time is 0.5 hour). represents a gradual increase in the charging station capacity as the number of chargers is increasing for each station. It was found that, when the number of chargers is relatively small (e.g., one or two chargers), the total capacity is limited and adding additional chargers does not increase the capacity significantly. The reason is that the randomness in charging activities limits the utilization rate when the station size is small. However, when more chargers are installed, adding additional charger could realize the full or near-full capacity of each added charger.

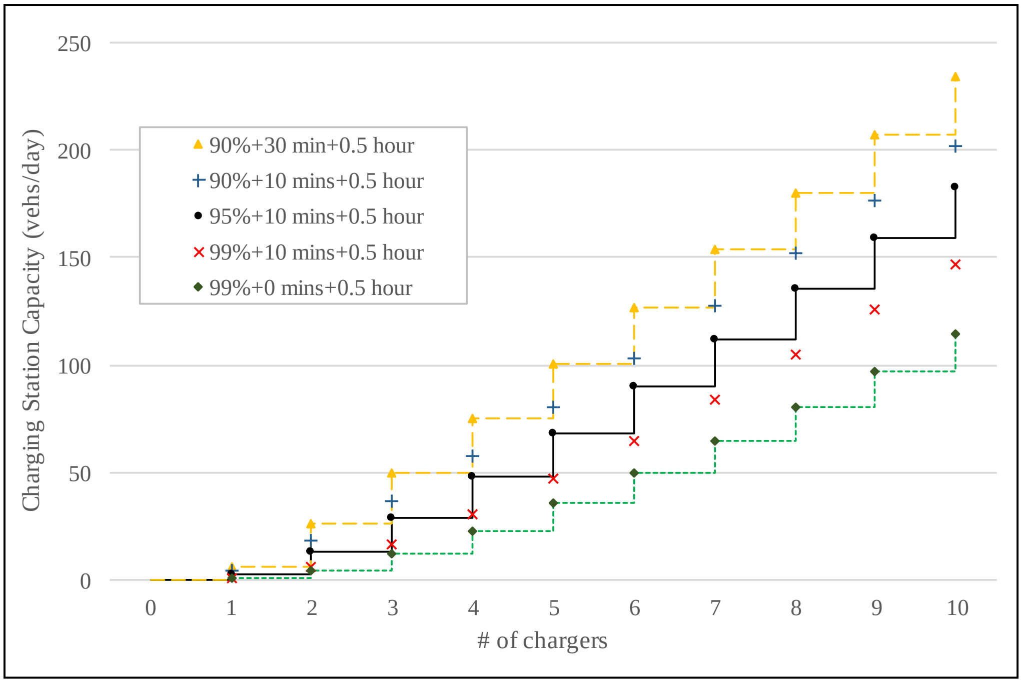


Figure II.2.II Charging station capacity with different levels of service (e.g., the “99%+0 minutes+0.5 hour” service level will guarantee 99% probability for BEV users to find to a vacant charger within 0 minutes when the average charging time is 0.5 hour).

3. *Global energy modeling with MA3T*

In FY 2018, the MA3T model also received more international attention. For example, the model was recently used by a paper published by *Nature Energy* (impact factor: 46.859) to investigate interaction of consumer preferences and the global transition to the mass adoption of AFVs (e.g., BEVs) [3]. In particular, the paper focuses on five non-financial vehicle purchase attributes that are modeled by the MA3T model. Since the paper focuses on the energy implications in the global context, the MA3T model originally developed specific to the U.S. light duty vehicle market, is extended in the paper to other counties and regions by considering regional multipliers.

4. *Market penetration of micro HEVs*

Oak Ridge National Laboratory (ORNL) and Argonne National Laboratory (Argonne) are jointly-conducting analysis of market penetrations of micro HEVs. Argonne is focusing on literature review of past market development, performance, incremental costs and third-party projections and ORNL is focusing on simulating market penetrations of micro HEVs using the MA3T model. The MA3T mode was modified to include 12V micro HEV (and will include 48V micro HEV in the next step). Preliminary results from MA3T were shown in

Figure II.2.III and Figure II.2.IV, which is for comparison, presents the market penetration without 12V micro HEV technology. The results suggest that micro HEVs can be market competitive, strengthening conventional ICE vehicles and suppressing (or delaying) sales growth of HEVs and PEVs.

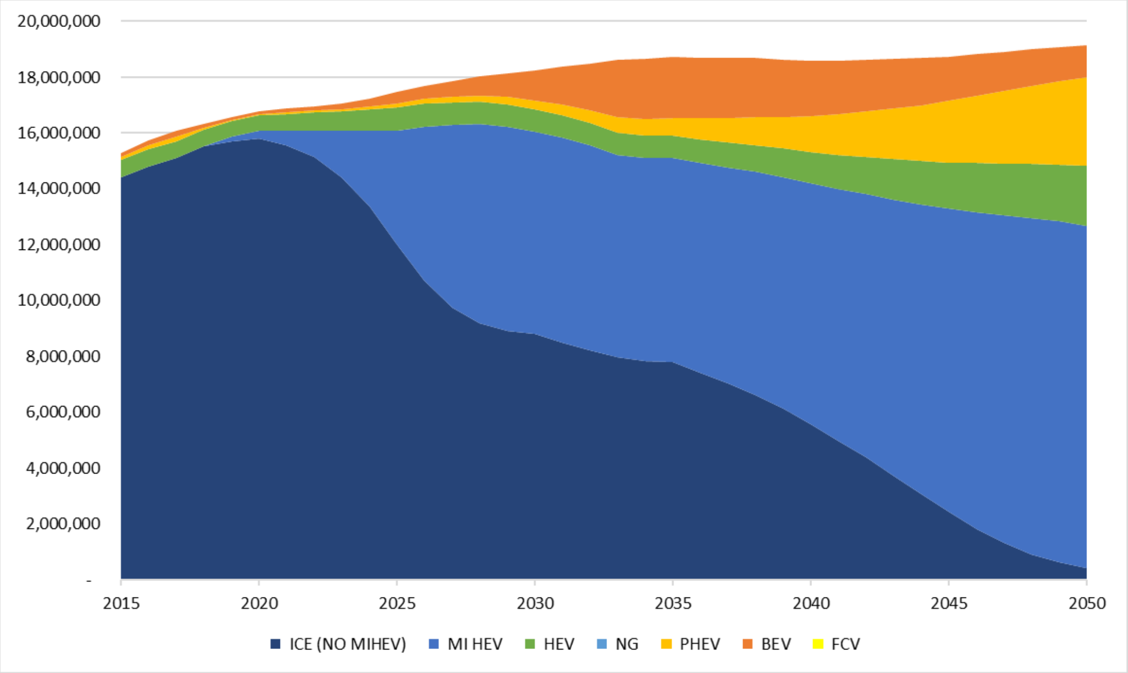


Figure II.2.III Market penetration analysis of scenarios with micro HEV technology (12V) using the MA3T model

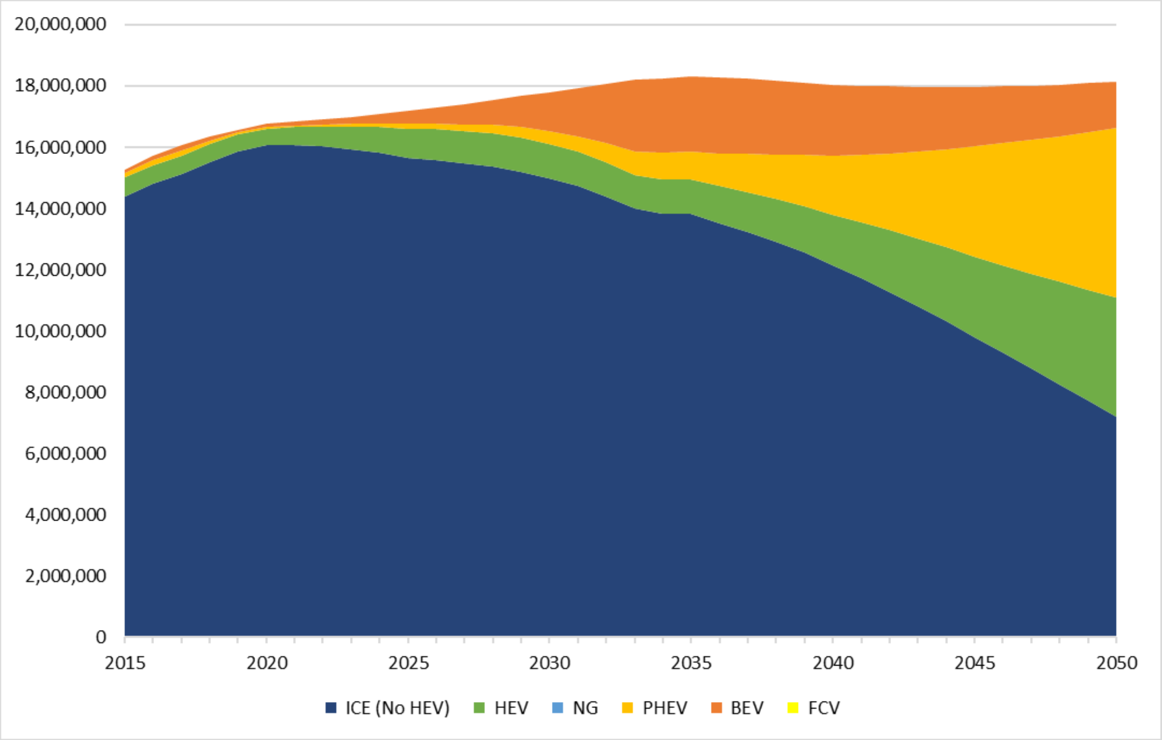


Figure II.2.IV Market penetration analysis of scenario without micro HEV technology (12V) using the MA3T model

Conclusions

In FY 2018, the research team conducted research on vehicle technology related topics to investigate potential extensions of the MA3T model and identify opportunities to improve the existing assumptions within the MA3T model. As demonstrated in the results section, two charging infrastructure related studies were highlighted. These two studies could enable the future MA3T model to model linkage of advanced public charging infrastructure support and the technology acceptance of BEVs. In addition, with the continuous improvement of the MA3T model, the model is getting more international attention and usage. The model is currently used to study market penetrations of micro HEV technologies.

During FY 2018, the project team published 12 peer-reviewed journal papers (one on high-impact journals), and four technical reports. Several manuscripts are currently under review for journal publication.

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II.3 Emerging Modeling and Simulations (Argonne National Laboratory)

David Gohlke, Principal Investigator
Argonne National Laboratory
9700 S. Cass Avenue
Lemont, IL 60439
E-mail: gohlke@anl.gov

Jarod Kelly Principal Investigator
Argonne National Laboratory
9700 S. Cass Avenue
Lemont, IL 60439
E-mail: jckelly@anl.gov

Michael Wang Principal Investigator
Argonne National Laboratory
9700 S. Cass Avenue
Lemont, IL 60439
E-mail: mqwang@anl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2017 End Date: September 30, 2019
Project Funding (FY18): $595,000 DOE share: $595,000 Non-DOE share: $0

Project Introduction

This project brings together several tasks at Argonne National Laboratory (Argonne) with the overarching purpose of improving DOE Vehicle Technologies Office (VTO) technology manager knowledge and awareness of advanced vehicle technologies. Project tasks include: (1) understanding the potential market penetration of hybridized internal combustion engine (ICE) vehicles, (2) understanding cost markups of vehicles relative to manufacturing costs, (3) assessing tipping points for cost parity for advanced vehicle and fuel technologies, (4) estimating potential impacts of using right-sized vehicles for commutes, (5) examining material flows, and (6) broadly evaluating VTO-funded models. Understanding the cost of different vehicles relative to each other is important for understanding the total magnitude of impact of advanced vehicle technologies on the vehicle market and fleet. Fuel-efficient vehicles that are prohibitively expensive will not have a major impact on energy use due to lack of consumer adoption.

Objectives

Analytical modeling of vehicle technologies informs DOE VTO program manager’s research and development (R&D) decisions. Each task will inform DOE VTO Technology Managers on topics related to the VTO research portfolio, including costs and environmental impacts of advanced vehicle technologies.

Approach

This project was composed of multiple tasks, each designed to supply necessary information to VTO program managers.

Task 1: Market penetration of micro/mild/full hybridization in ICE vehicles

As worldwide fuel economy standards become more stringent, automobile manufacturers are considering and implementing different degrees of vehicle hybridization and electrification to comply. There are different levels of vehicle electrification, ranging from vehicles with only a battery for engine starting to vehicles that only use electricity for propulsion. This task assessed the historical and projected forecasts and technology costs of micro-, mild-, and full-hybrid vehicles. Understanding the incremental costs of these technologies is necessary to understand their potential market uptake. Pulling data from multiple sources, including the U.S. Environmental Protection Agency (EPA), the International Council on Clean Transportation, and the European Automobile Manufacturers Association, the research team compared technology costs and worldwide trends in, and projections of, hybrid electric vehicles. The foreign market is import to this task because some hybrid electric technologies currently have a higher market penetration outside of the U.S. This serves as an example of a more mature hybrid vehicle market and lowers future technology costs in the U.S. market. Information about projected vehicle costs and fuel consumption for different levels of hybridization has been supplied to Oak Ridge National Laboratory (ORNL) for use in the Market Acceptance of Advanced Automotive Technologies (MA3T) vehicle choice model to quantify the potential impact of ICE hybridization on vehicle purchases and fleetwide fuel economy.

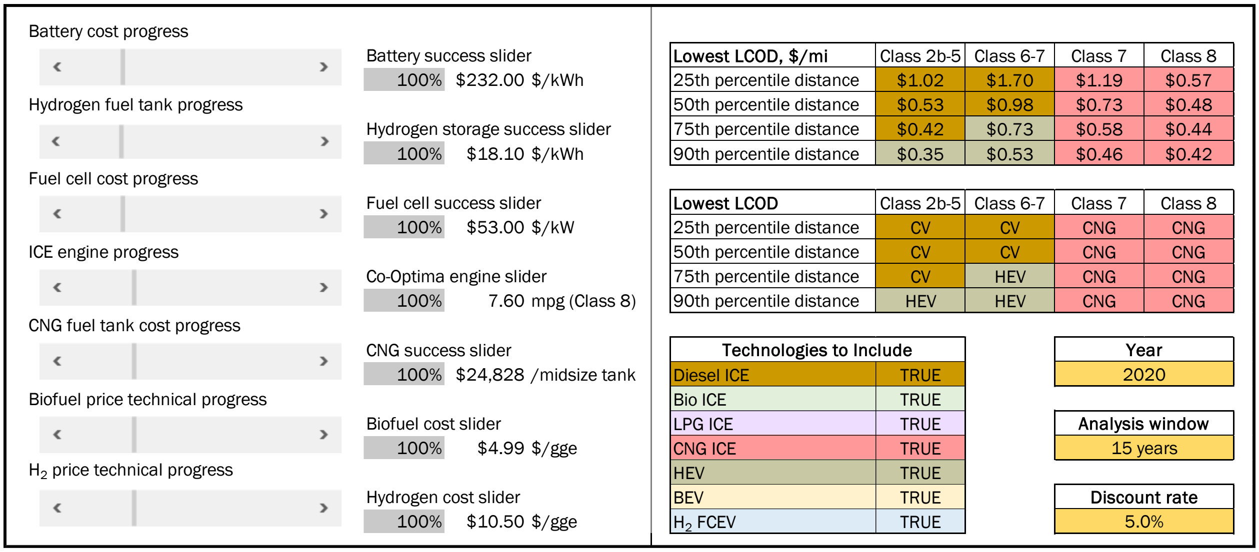
Task 2: Automotive cost markup
Historical original equipment manufacturer (OEM) vehicle manufacturing costs and sale prices are important for understanding current and emerging vehicle technologies and OEM technology decisions. This information aids early stage R&D for cost reductions and to provide U.S. consumers with affordable vehicle choices. The current practice is to translate available OEM manufacturing costs (or cost estimates) into sales prices via a markup factor. There is concern that a singular factor neither captures OEM mark ups nor provides proper estimates for emerging technologies. This project examined the cost versus price relationships of light-duty vehicles (LDVs), while considering powertrain variance.

The objective of this task was to examine the state of the LDV cost markup literature. The task examined publications, including DOE national laboratory reports, journal articles, regulatory documents, and associated public comments. Data from the literature was examined and evaluated for observed trends, such as the possibility of markup factor variance with vehicle size, class, vehicle components, features, etc. The research team examined available information to gain insight into markup factors. The research team also interviewed automotive experts to understand the OEMs' general approach to markup. Estimates of markup factors informed by this literature and analysis will be presented to DOE sponsors in a summary report. Gaps in the literature were identified along with a set of recommendations for filling them.

This study first conducted a literature review of the current and historical state of cost, retail price equivalent (RPE), and the manufacturer's suggested retail price (MSRP) research related to LDVs. Estimates of markup factors were made based upon the literature review and expert consultation. The literature review may or may not provide insights into how markup factors differ across vehicle segments. Collected data and estimates were partitioned and analyzed to provide markup factors based on parameters such as vehicle size, class, or features.

Task 3: Transportation energy market segmentation analysis
Transportation energy use is complex and varied, spanning such mobility modes as LDV passenger travel, heavy-duty and other modes of freight movement, and even the flow of some liquid commodities via pipeline. At the request of Office of Energy Efficiency and Renewable Energy (EERE) leadership, this project analyzed cost, energy use, and related metrics across the transportation sector and created a strategic understanding of cost and energy use by transportation market segment. This project took a comprehensive view of transportation, and scope included highway modes including LDV and heavy-duty vehicles (HDVs), aviation, marine, and rail, both today and estimated into the future. Analysis and energy accounting included considerations of transportation energy and vehicle stocks and flows over time. The resulting outputs depict transportation costs on a cost per mile basis and energy consumption by mode (and other appropriate disaggregations). These was compared with VTO investment in advanced technologies to examine the alignment with transportation energy benefits opportunities in terms of energy and petroleum consumption, emissions, and cost (and associated potential reductions of each).

A suite of transportation energy analytical and visualization tools was developed to be usable to DOE VTO Technology Managers. This project included iterative discussion with EERE leadership to ensure that the tools and visualizations were aligned with expectations by the time final deliverables were prepared. Some tools and visualizations that resulted from this effort include: 1) a transportation energy road atlas; 2) parametric heat maps of cost and energy use, organized by parameters of interest (e.g., levelized cost by vehicle type and payload); and 3) a spreadsheet tool that combines visualizations that are exportable to a presentation format with analytical tools that can continued to be refined to answer future transportation costs by segment and energy questions. Figure II.3.I shows a portion of the spreadsheet tool, highlighting visualization and sliders representing technological progress. This capability for dynamic calculations enables performing tipping point analyses, to find what technology advancement is necessary for new vehicle technologies to be cost competitive with incumbent technologies.



Battery cost progress

Battery success slider
100% $232.00 $/kWh

Hydrogen fuel tank progress

Hydrogen storage success slider
100% $18.10 $/kWh

Fuel cell cost progress

Fuel cell success slider
100% $53.00 $/kW

ICE engine progress

Co-Optima engine slider
100% 7.60 mpg (Class 8)

CNG fuel tank cost progress

CNG success slider
100% $24,828 /midsize tank

Biofuel price technical progress

Biofuel cost slider
100% $4.99 $/gge

H_2 price technical progress

Hydrogen cost slider
100% $10.50 $/gge

Lowest LCOD, $/mi	Class 2b-5	Class 6-7	Class 7	Class 8
25th percentile distance	$1.02	$1.70	$1.19	$0.57
50th percentile distance	$0.53	$0.98	$0.73	$0.48
75th percentile distance	$0.42	$0.73	$0.58	$0.44
90th percentile distance	$0.35	$0.53	$0.46	$0.42

Lowest LCOD	Class 2b-5	Class 6-7	Class 7	Class 8
25th percentile distance	CV	CV	CNG	CNG
50th percentile distance	CV	CV	CNG	CNG
75th percentile distance	CV	HEV	CNG	CNG
90th percentile distance	HEV	HEV	CNG	CNG

Technologies to Include	
Diesel ICE	TRUE
Bio ICE	TRUE
LPG ICE	TRUE
CNG ICE	TRUE
HEV	TRUE
BEV	TRUE
H_2 FCEV	TRUE

Year
2020

Analysis window
15 years

Discount rate
5.0%

Figure II.3.I Portion of the visualization dashboard for Task 3, showing levelized cost of driving (LCOD) for medium- and heavy-duty vehicles. Sliders on the left side are able to be changed, resulting in dynamic changes to LCOD calculations.

Task 4: Household vehicle rightsizing

A large fraction of driving in the U.S. is by single-occupancy personal vehicles. According to the latest data from the National Household Travel Survey (NHTS), the average mileage-weighted vehicle occupancy is 1.67 total passengers per vehicle. While SUVs are among the largest passenger vehicles with high passenger carrying capabilities on the roadways, they only have a slightly higher occupancy factor at 1.83 than the entire category. This shows that many passenger vehicles are not being utilized to their greatest capacity. In particular, commutes to and from work account for nearly 30% of household travel, according to the most recent NHTS [1]. From the most recent American Community Survey, 76.6% of commuters travel alone [2]. This survey revealed that the average vehicle occupancy for all travels is 1.7, but decreases to 1.2 when considering only commutes. Because commuters often travel alone, they would potentially be able to use smaller more efficient vehicles. This task’s analysis compared current real-world commuting patterns to those from hypothetical right-sized vehicles, specifically from vehicle subscription services that are currently available or expected to be announced. These services allow users to use smaller vehicles (e.g., for their daily commute) while having access to a larger vehicle as their needs arise (e.g., family travel, hauling/towing, recreational excursions).

Task 5: Automotive material flows

Life cycle inventory analysis allows researchers to evaluate the energetic and emissions consequences of industrial activities. The materials database within the Greenhouse Gases, Regulated Emissions, and Energy

Use in Transportation (GREET) model provides insight into the major automotive materials along with many secondary and tertiary materials. These aggregate insights are limited by the spatial and temporal fidelity of the data. Acknowledging the spatial heterogeneity of materials production, Argonne has previously conducted aluminum sector analyses that elucidated the spatial variance associated with aluminum in the U.S. largely because of electricity consumption. By examining the supply chain flows of major automotive materials, the research team can better understand automotive materials.

The objective of this task was to provide enhanced spatial resolution for several major automotive materials including steel, iron, and aluminum, which together comprise nearly 80% of LDV mass. While the research team has already probed the locationality of aluminum's electrolysis process, this task seeks to pursue not only these variations, but also to identify the sources of these major automotive materials in a supply chain sense. The outcomes of this work provided insights into where automotive materials are sourced within the U.S., and in so doing, allows a perspective of how much automotive production contributes to the energy demands within different regions and locales.

This task investigated material flow analysis and supply chain literature for iron, steel, and aluminum, and tied it to the life cycle inventory approach used within GREET. This task formalized a methodology for conducting this analysis and developed underlying data structures to facilitate the organization of such data. The major outcome of this analysis was insights into the spatial impacts of the three primary automotive materials, but it will also laid a foundation for analyses of other materials.

Task 6: Model deep dive

To help DOE find gaps in modeling capabilities, this analysis details the use and purpose of each VTO-funded model, the differences between them, and how the models interact to answer questions beyond the capability of any singular model. This task compared analytical modeling workflows used by VTO and the national labs to answer questions about energy, environmental, and economic impacts of advanced vehicle technologies. These different modeling flows include SMART Mobility, Government Performance and Results Act required VTO/Fuel Cell Technologies Office (FCTO) Benefits Analysis, and Analysis of Sustainability, Supply, Economics, Risk and Trade (ASSERT) within the Co-Optimization of Engines and Fuels initiative. Beyond the modeling described here, Argonne based an analyst, David Gohlke, on site in Washington D.C. at DOE headquarters to give technical support to VTO program managers.

Results

Task 1: Market penetration of micro/mild/full hybridization in ICE vehicles

Vehicle costs of hybridization were examined, looking at incremental costs of hybrid vehicles relative to conventional ICE vehicles. One way of discerning the cost of hybridization (from a consumer perspective) is to compare the MSRP of the hybrid vehicle and a comparable conventional ICE vehicle. Using a comparison tool on the FuelEconomy.gov website [3], and using the Internet Archive to locate data from 2013, the research team found that the average price premium for hybridization is dropping (Figure II.3.II). Fitting a linear trend to the data shows a decline of approximately $300/year. The average premium of hybridization for model year 2018 vehicles is $1,600 relative to a comparable conventional ICE vehicle. Figure II.3.II also shows that this price premium is relatively constant across all price points, though seemingly a little higher for more expensive/luxury vehicles.

This data on the costs of hybrid vehicles will be used to inform the MA3T model developed by ORNL. In addition to conventional ICE vehicles, 12-volt micro-hybrid vehicles with stop-start and regenerative braking were incorporated into the MA3T model using cost and fuel economy information from this project. Preliminary results show that micro-hybridization can strengthen the market share of ICE vehicles while suppressing sales of plug-in electric vehicles. Future work will incorporate 48 volt mild-hybrid ICE vehicles with stop-start, regenerative braking, and the capability to have the battery assist propulsion or to minimize accessory load.

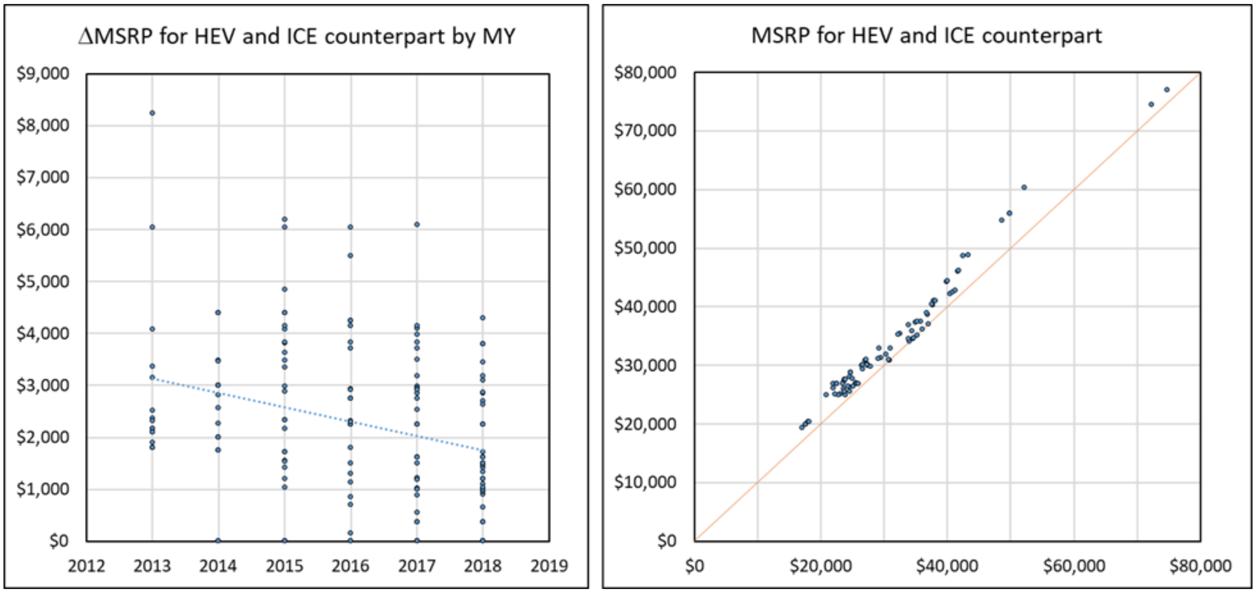


Figure II.3.II Comparison of MSRP for HEV and comparable ICE vehicles. Data source: FuelEconomy.gov, 2018.

Task 2: Automotive cost markup

This task is in the literature gathering stage. The research team has examined much of the available cost markup literature, and markup factors have been evaluated at the component level and the full vehicle level. Markup factors can be further partitioned for components that are made by the OEM and components made by suppliers. Those components made by the OEMs have higher markup factors than those produced by suppliers.

The collected literature focuses on the RPE, which is the vehicle or component sales price needed in order to earn a competitive rate of return on the production investment. There is a relative industry consensus that an average RPE markup factor of 1.5 is appropriate for a fully-manufactured component (i.e., from a supplier) and a factor of 2.0 for the markup over the variable cost (i.e., for OEM produced components) [4][5]. Indeed, this 1.5 markup factor has been used by the National Highway Traffic and Safety Administration (NHTSA) within a recent related rulemaking [6]. Rogozhin (2009) developed technology specific RPE values for the U.S. EPA that consider technology complexity and the technology's production time-frame (i.e., a short run or a long run) [7]. These multipliers range between 1.05 and 1.45 for short runs, and 1.02 and 1.26 for long runs. None of these values are higher than the industry consensus, and the National Research Council points out that this implies that increased regulation would be lower than the overall industry RPE, an unlikely outcome [4]. There have also been top down analyses using automotive firm financial documents to determine OEM RPE markup factors and these range from 1.42 to 2.08 [4][7]. This project consulted with other researchers to examine the cost and price of LDVs to verify these findings.

Preliminary literature study shows an industry agreement regarding RPE markups of 1.5 for supplier produced components and 2.0 for OEM produced components. However, these factors obscure the reality of the individual components, and a body of literature exists that attempts to determine these factors on a case-by-case basis accounting for technology advancement.

Task 3: Transportation energy market segmentation analysis

Efforts toward developing a graphical transportation energy atlas are summarized in Figure II.3.III, a transportation-specific Sankey diagram showing the energy sources on the far left, the intermediate energy carriers in the middle, and the end-use sectors on the right. Figure II.3.III shows all energy use in the U.S. The majority of transportation energy is used by LDVs and HDVs, fueled by petroleum energy (gray).

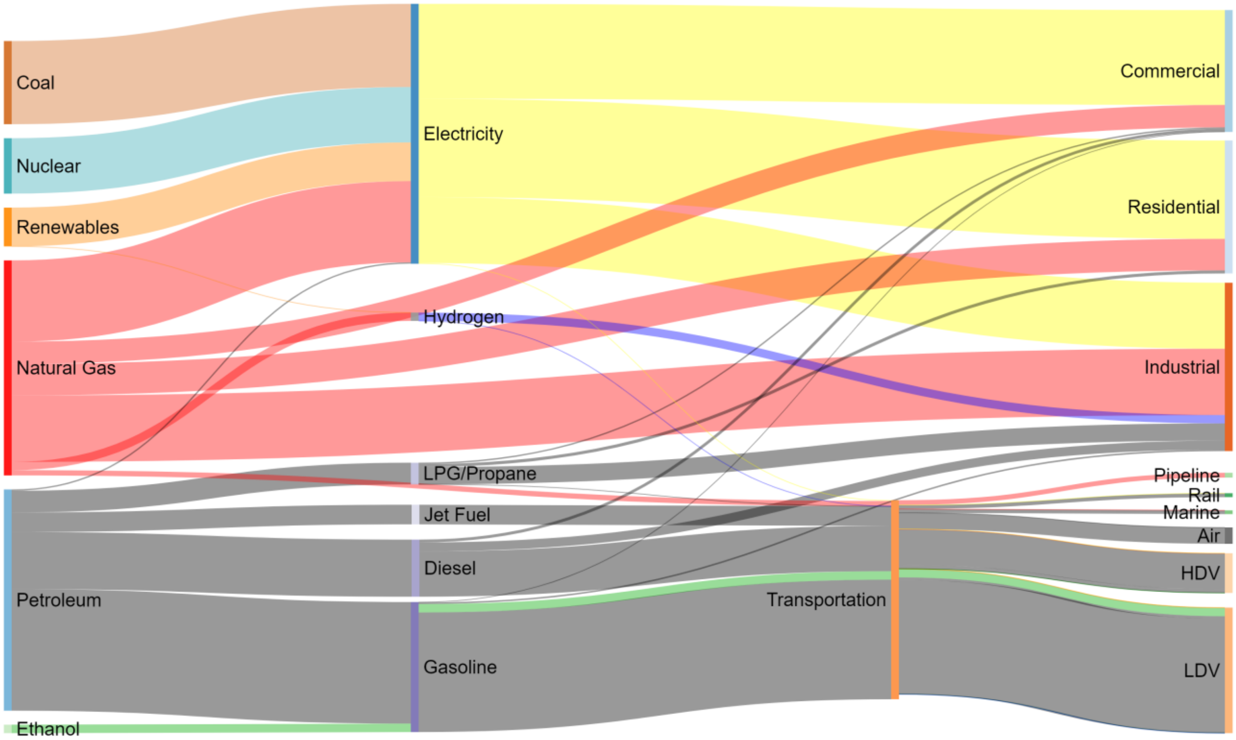


Figure II.3.III Sankey diagram of energy use in the United States in 2016.

For these on-road modes, a Microsoft Excel tool was developed to represent the cost per mile of different fuels and vehicle powertrains for varying assumptions. The modeling was done for different vehicle segments, exploring different use cases, represented by different vehicle sizes and travel behavior. Results from this analysis were presented internally to DOE technology managers to inform their decision-making.

The Microsoft Excel tool allows for assumptions to be changed dynamically. These assumptions include timeframe (2015 to 2050), technological progressions (e.g., reductions in cost of vehicle components), fuel prices (implicitly including fueling and plug-in electric vehicle charging infrastructure), economic factors (e.g., discount rate and payback period), and vehicle travel/usage patterns (e.g., fueling requirements and mileage driven). In this analysis, LDV modeling is derived from modeling from the Argonne-developed Autonomie (vehicle energy consumption and performance analysis system simulation tool), referencing vehicles simulated for the VTO/FCTO benefits analysis report [8]. This project is being performed in coordination with the National Renewable Energy Laboratory, which is modeling fuel efficiency and cost of medium- and heavy-duty vehicles using the Future Automotive Systems Technology Simulator (FASTSim) tool. Fuel prices largely come from the Energy Information Administration's Annual Energy Outlook [9].

Task 4: Household vehicle rightsizing and Task 5: Automotive material flows
These tasks began at the end of the fiscal year and have no technical results to report yet.

Task 6: Model deep dive
For DOE VTO Technology Managers, the research team generated a phase-space diagram of the analytical models supported by VTO's Analysis Program during Fiscal Year 2016. Plotting a graphical representation of these models helped DOE VTO Technology Managers identify potential overlap between modeling efforts and to address gaps in VTO modeling capabilities. One axis of interest in this representation is the physical scale which the models can explore (e.g., from component level to national-scale aggregation). The representation also shows if a model is more focused on environmental metrics (including fuel consumption) or economic metrics (such as vehicle costs).

Conclusions

The tasks described herein assist DOE VTO Technology Managers in making informed decisions for R&D investment.

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II.4 Advanced Vehicle Cost and Energy-use Model (AVCEM)

Mark A. Delucchi, Principal Investigator
Institute of Transportation Studies
University of California
Berkeley, CA 94720
E-mail: madelucchi@berkeley.edu

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2015 End Date: September 30, 2019
Project Funding (FY18): $70,000 DOE share: $70,000 Non-DOE share: $0

Project Introduction

VTO supports the development of alternative fuel and high-efficiency advanced vehicle technologies in the interest of reducing fuel consumption and fuel costs while increasing the nation's energy security. Advancing this mission requires an understanding of how DOE-supported technologies are (or will be) used once deployed in the marketplace, both as a prerequisite for the retrospective calculation of investment effectiveness and resulting program benefits and for prospective evaluation of future technologies. As such, interest in the Advanced Vehicle Cost and Energy-use Model (AVCEM) model is aligned with the program's need to understand the total costs and benefits associated with advanced vehicle technologies. This interest supports DOE goals of fuel consumption reduction, and energy security.

AVCEM is a multi-pathway model of energy use and lifetime cost for a wide range of advanced vehicle and fuel combinations. The model estimates manufacturing cost, associated retail cost, and total private and external lifetime cost of a vehicle designed to meet performance and range specifications (Figure II.4.I). It can be used to investigate the relationship between the lifetime cost(s)—the total cost of vehicle ownership and operation over the life of the vehicle, from both a private (consumer) and external costs (costs not borne by the vehicle owner) perspective—and important parameters in the design and use of the vehicle.

While AVCEM is a vehicle-design and vehicle lifetime-cost model, the model's cost capabilities in particular offer a unique opportunity to explore best practices in cost modelling as well as methods for internalizing unpriced, displaced, or geographically and temporally diffuse costs (externalities), along with the results of doing both in concert. More specifically, the methodologies for expanding and improving the model will intentionally leverage a modular approach such that step-wise task-based report-outs offer useful understanding of the analytical issues associated with the development of individual modules. Furthermore, this also contributes to the final task, which, as the sum of the various modular prerequisite pieces, comprises the running of a final model for a comprehensive analysis of advanced vehicle lifetime cost.

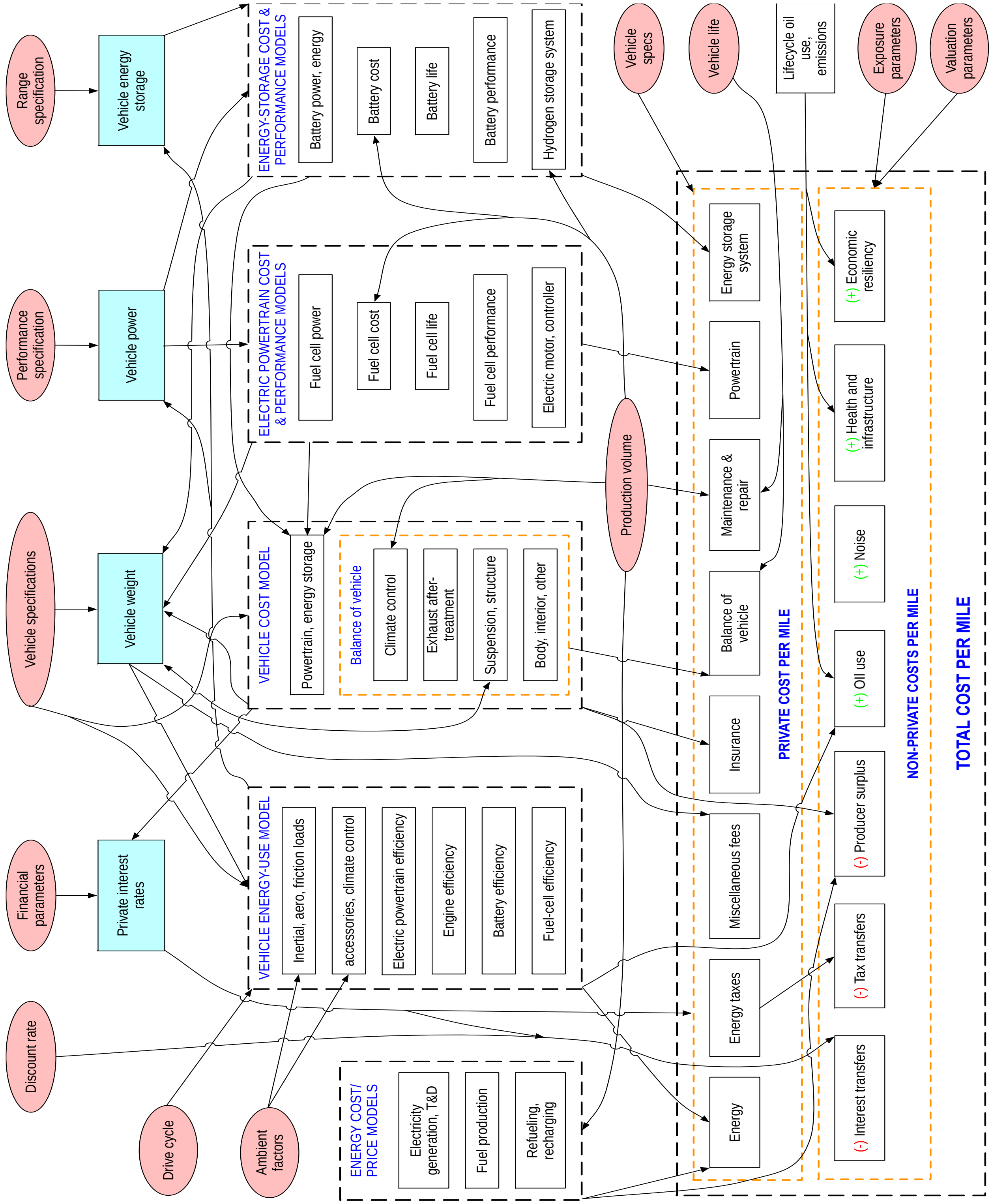


Figure II.4.I Structure of AVCEM

Objectives

As mentioned above, the development of AVCEM is intended to support a long-term effort to estimate advanced vehicle technology lifetime total costs to inform stakeholders and support DOE goals of emissions reduction and petroleum consumption reduction to improve affordability and national security.

Approach

Table II.4.1 shows the project tasks and expected products in FY 2018. Table II.4.2 focuses on the approaches used to analyze battery performance, cost, and lifetime, which are key parts of the project. Figure II.4.II shows the approach to estimating the consumer cost of vehicles.

Table II.4.1 Summary of tasks and progress in FY 2018

Task	Expected products	Highlights and status; next steps
1. Discounting analysis	• Paper & report recommending discount rate(s) as a function of perspective and time-horizon	Finalized the conceptual framework and formal analysis of the discount rate. Continued writing paper and AVCEM documentation report
2. Retail vs. Manufacturing Cost	• Paper & report recommending retail-price-equivalent multipliers for nascent and mature technologies, and details of underlying accounting	Organized materials for paper and AVCEM documentation report. Next steps are to continue documentation and collaborate with Argonne National Laboratory (ANL)
3. Battery Cost	• Demonstration of reduced-form version of ANL's BatPaC model • Model documentation	With colleagues at UC Davis, performed validation of the newly added hybrid-vehicle battery cost model. Collaborated with German colleagues who are developing a similar cost model. Continued writing paper and AVCEM documentation report
4. Battery Lifetime	• Demonstration of reduced-form version of NREL's battery lifetime model • Model documentation • Paper & report	Battery testing lab in Germany completed all of the battery aging tests and sent the data to UC Berkeley for analysis. In consultation with German colleagues, we began devising new functional forms to fit the new battery test data. Next steps are to continue to review and revise the battery lifetime model and paper and draft report
5. External-cost analysis	• Paper & report on external costs of advanced vehicles	Worked on models of external costs of oil use and producer-surplus component of oil prices. Updated analysis of air quality impacts and valuation functions. Finished organizing materials for AVCEM documentation report. Started to develop a comprehensive integrated-assessment framework for valuing all costs and benefits of energy systems, including but not limited to transportation energy. Next steps are continued work in all areas.
6. Integration of PEVI/PLEXOS and AVCEM	• Incorporation into completed and documented revision of AVCEM	Analysed costs of electricity generation, transmission, and distribution system for use in linking PEVI/PLEXOS with AVCEM. (This is necessary because neither PEVI, nor PLEXOS, include costs of the distribution system, and the cost estimates in PLEXOS are not necessarily consistent with those in AVCEM)

Table II.4.2 Focus on analysis of battery performance, cost, and lifetime

Li-ion chemistry anode/cathode	Performance	Manufacturing cost	Lifetime
graphite/nickel-cobalt-aluminum (NCA)	UCD-EVPSL (tests of Gaia cell) and other data	Reduced form version of ANL BatPaC model	Revision and expansion of NREL lifetime model w/TUM
graphite/iron-phosphate (FP)	UCD-EVPSL (tests of A123 cell) and other data	Reduced form version of ANL BatPaC model	Simple extension of revised NREL model w/TUM test results
titanate/ manganese-oxide (MO)	UCD-EVPSL (tests of Altairnano cell)* and other data	Reduced form version of ANL BatPaC model	
graphite/ MO	Based on NCA battery	Not included in present analysis (available in BatPaC however)	Simple extension of revised NREL model w/TUM test results
graphite/nickel-manganese-cobalt (NMC)	Based on NCA battery	Reduced form version of ANL BatPaC model	Simple extension of revised NREL model

UCD-EVPSL = UC, Davis, Electric Vehicle Propulsion Systems Laboratory; ANL = Argonne National Laboratory; NREL = National Renewable Energy Laboratory; TUM = Technical University of Munich.

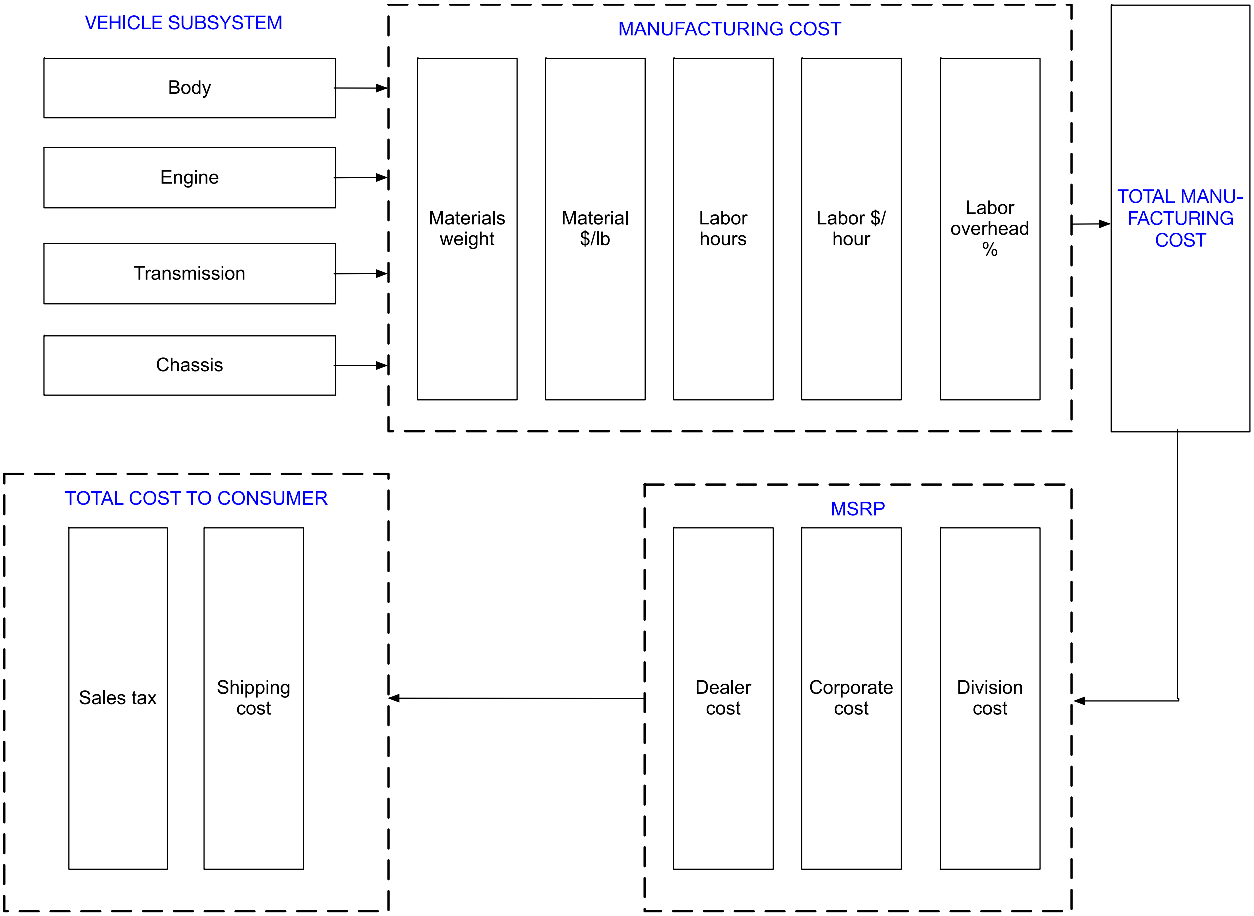
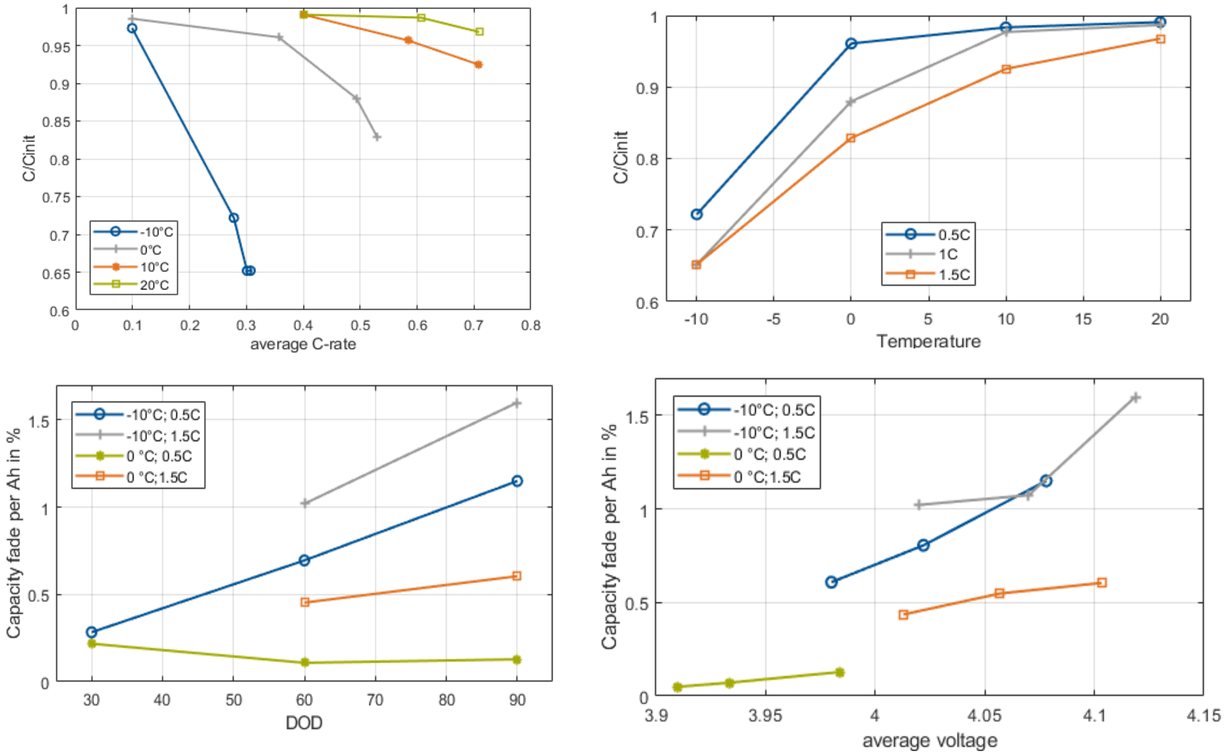


Figure II.4.II Estimating manufacturing cost, overhead, and retail cost in AVCEM

Results

Because the AVCEM project is not scheduled to be finished until the end of FY 2019, the full model and its sub-components have not yet been completed. Consequently, final quantitative technical results are not available. However, results from the battery lifetime testing are shown in Figure II.4.III.



Note: The top two graphs show capacity fade (ratio of final to initial capacity) as a function of average C-rate and temperature. The bottom two graphs show capacity fade (in percentage of battery capacity (in amp-hours [Ah] lost per Ah throughput) as a function of Depth of Discharge and the average voltage.

Figure II.4.III Battery lifetime testing experimental results from the Technical University of Munich

Conclusions

See summary of FY 2018 progress in Table II.4.1.

Key Publications and Presentations

1. Delucchi, M. 2018. “External Costs of Transportation Modes,” meeting with Federal Highway Administration Office of Transportation Policy Studies, Lawrence Berkeley National Laboratory, September 13 (2018).
2. Delucchi, M. “*AVCEM – The Advanced Vehicle Cost and Energy Use Model*,” meeting with US Department of Energy Vehicle Technologies Office, Lawrence Berkeley National Laboratory, July 13 (2018).
3. Delucchi, M. *AVCEM: Advanced-Vehicle Cost and Energy-use Model, AVCEM Documentation, Overview of AVCEM*, Institute of Transportation Studies, University of California, Berkeley, CA (2018).
4. Delucchi, M. AVCEM: Advanced-Vehicle Cost and Energy-use Model, AVCEM Documentation, External Costs and Other Adjustments to Social Cost, draft report for DOE, Institute of Transportation Studies, University of California, Berkeley, CA (2017).

5. Delucchi, M. *AVCEM: Advanced-Vehicle Cost and Energy-use Model, AVCEM Documentation, Model of Battery Performance, Cost, and Lifetime*, draft report for DOE, Institute of Transportation Studies, University of California, Berkeley, CA (2017).

Acknowledgements

The Principal Investigator acknowledges the contribution of Mike Mills as an investigator.

II.5 GREET®

Michael Wang, Principal Investigator
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
E-mail: mqwang@anl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2017 End Date: September 30, 2018
Project Funding (FY18): $350,000 DOE share: $350,000 Non-DOE share: $0

Project Introduction

The Greenhouse gas, Regulated Emissions, and Energy use in Transportation (GREET®) model conducts life cycle analysis of vehicle and fuel systems by modeling fuel cycles, vehicle manufacturing cycles, and vehicle operations. The model's outputs include energy use, emissions, and water consumption. By building on the existing GREET modeling platform, this project addressed new and emerging life cycle environmental issues to (1) quantify progress toward reducing transportation-sector petroleum use and air emissions via improved vehicle efficiency and fuel substitution (e.g., electric vehicles), (2) identify bottleneck energy- and emissions-intensive stages in fuel/vehicle pathways, and (3) enable the Vehicle Technologies Office and other stakeholders to guide research and development decisions to attain specific energy consumption reduction goals.

Objectives

The objectives of this project are described below for two different project tasks:

1. Address life cycle issues related to power generation from domestic energy sources such as coal and natural gas (NG). In particular, the goal of this task was to evaluate technology options that reduce emissions associated with the use of domestic fuel sources, such as coal and NG, for power generation. Combined heat and power (CHP) generation and post combustion carbon capture and storage (CCS) were evaluated for inclusion in GREET.
2. Develop a water scarcity index to quantify the impacts of regional water use associated with implementing new energy systems. In particular, the goal of this task was to develop a high-fidelity water stress index using high spatial resolution data to guide decision-making at the local level regarding energy system implementation within the United States.

Approach

For Task 1, the GREET model was expanded to conduct life cycle emissions analysis of new technology options (mainly CHP and CCS) associated with fossil energy-based power generation technologies. The evaluated power generation technologies for CHP and CCS were steam turbine, combined cycle, NG powered fuel cells, and coal powered steam turbines.[1][2] The life cycle analysis in GREET for these technology pathways includes energy use and emissions associated with coal and NG extraction, processing and transportation to power plants, conversion to electricity (and heat for CHP plants), heat and electricity needed for CCS, and transmission and distribution of the generated electricity.

For Task 2, researchers employed the Available WAater REmaining (AWARE) method and improved the AWARE-Global model by incorporating local measured data. In particular, high-resolution freshwater supply and demand data were acquired to develop the AWARE-US characterization factor (CF), a water scarcity index that indicates regional water scarcity by comparing available remaining water at the U.S. county level to the corresponding U.S. average value.

Results

Figure II.5.I shows the life cycle carbon dioxide (CO_2) equivalent emissions of the U.S. average electricity generation mix in 2016, and for individual coal and natural gas power generation technologies, including the CHP and CCS technology options. The U.S. average generation mix produced emissions of 540 gCO_2e/kWh, while coal, NG steam, NG fuel cell and NG combined cycle produced 1,080, 770, 570 and 470 gCO_2e/kWh, respectively. The CHP technology options reduce emissions by 250 and 270 gCO_2e/kWh for coal and NG steam turbine generation technologies respectively, and by 310 and 90 gCO_2e/kWh for the NG fuel cell and combined cycle technologies, respectively. Integrated CCS technology reduces emissions by 860 gCO_2e/kWh when applied to coal steam turbine technology, and by 340 gCO_2e/kWh when applied to the low emitting NG combined cycle technology. The results show that emissions associated with fossil-based power generation technologies can be significantly reduced by utilizing byproduct heat from thermal and fuel cell power cycles, and by employing CCS technologies with fossil power generation technologies.

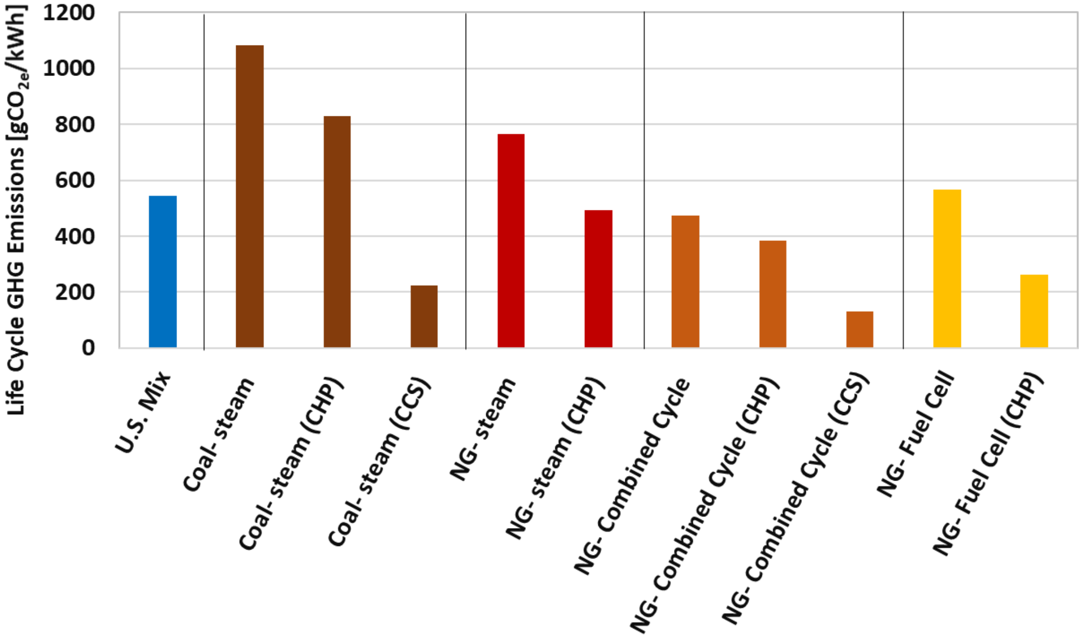


Figure II.5.I Life cycle CO_2 equivalent emissions of coal and NG power generation technologies.

On the basis of measured runoff and human water use data, this project estimated county-level natural runoff, human water consumption (HWC), and environmental water requirement (EWR), and calculated AWARE-US CFs for each county in the contiguous U.S.[3] Figure II.5.II shows the calculated AWARE-US CFs at the county level. Counties that appear white on the map are those where water stress is less than the U.S. average (CF <1), while counties displayed in red experience significant water scarcity. The map shows that the central and southwestern U.S. have higher CFs, while eastern regions have CFs that are generally lower than the U.S. average. Some counties surrounding the lower Mississippi River basin have higher CF values than neighboring counties because of water consumption for irrigation, even though their natural runoff is relatively high. Counties having a CF of 100 have very limited available freshwater resources, with high utilization of these resources to meet their HWC needs. In these counties, an increase in HWC may reduce water supply reserved for EWR, causing degradation of aquatic ecosystems.

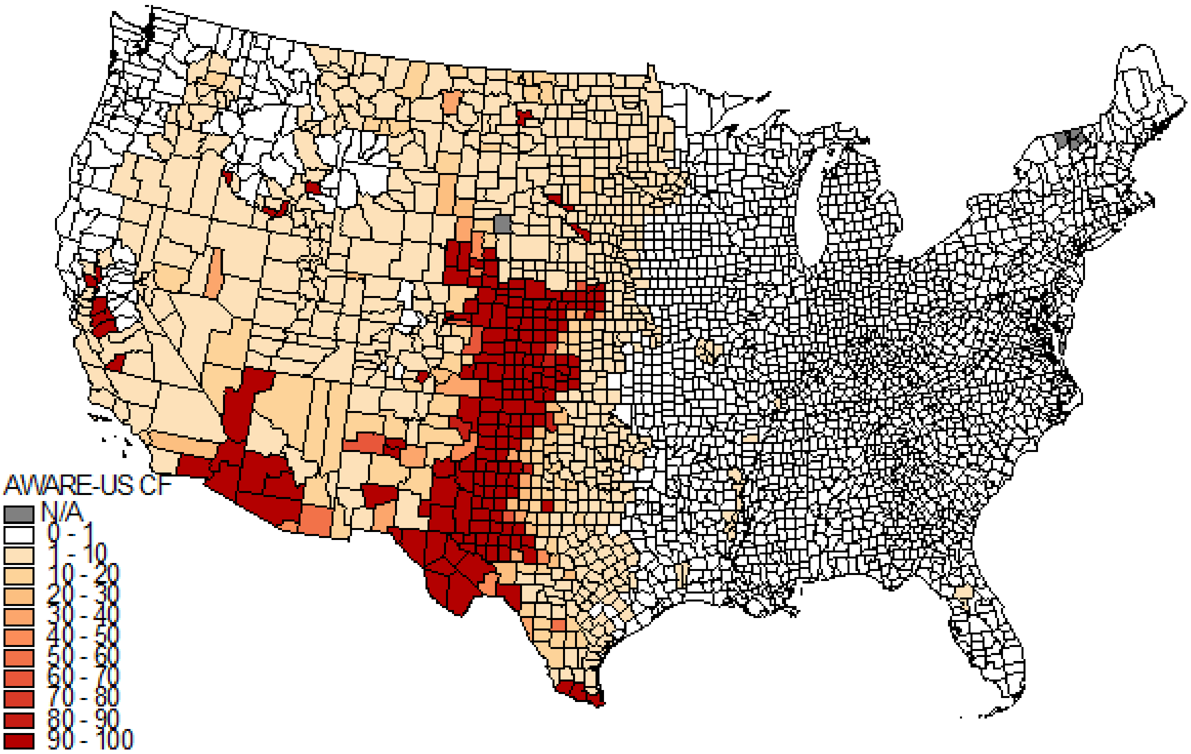


Figure II.5.II AWARE-US characterization factor at the county level

Conclusions

The results of this project show that CO_2 equivalent emissions associated with fossil-based power generation technologies can be significantly reduced by utilizing the byproduct heat from thermal and fuel cell power cycles in CHP configurations, and by employing CCS technologies in fossil power generation plants. The CHP technology reduce emissions by 250, 270, 310 and 90 gCO_2e/kWh for coal, NG steam turbine, NG fuel cell, and NG combined cycle generation technologies, respectively. Integrated CCS technology reduces emissions by 860 and 340 gCO_2e/kWh when applied to the coal and NG combined cycle generation technologies, respectively. This project also acquired and used measured freshwater supply and demand data to improve the AWARE-Global model concept and develop AWARE-US characterization factors at the county level. Incorporating high-resolution data improves the reliability of regional water impact analysis using the AWARE-US model.

References

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2. Kelly, J., and Elgowainy, A. 2017. “Addition of Combined Heat and Power Electricity Plants to the GREET® Model,” Argonne National Laboratory Technical Memorandum, available at: https://greet.es.anl.gov/publication-chp_add_2017

3. Lee, U., Xu, H., Daystar, J., Elgowainy, A., and Wang, M. 2018. “Evaluation of Water Supply and Demand for Regional Water Consumption Impact Analysis in the United States.” Science of the Total Environment, 648:1313-1322. DOI: 10.1016/j.scitotenv.2018.08.250.

II.6 Autonomie - Model and Functionality Development to Support VTO Analysis

Ram Vijayagopal, Principal Investigator
Argonne National Laboratory
9700 S. Cass Ave
Lemont, IL, 60439
E-mail: rvijayagopal@anl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

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Project Introduction

Autonomie (www.autonomie.net) is the primary tool used by the Department of Energy (DOE) for analysis of vehicle energy consumption and performance. Developed in collaboration with the General Motors Company, Autonomie is a MATLAB©-based software environment and framework for automotive control system design, simulation, and analysis. To support studies funded by DOE, Autonomie is constantly updated with new vehicles, control logic, and test procedures.

Relevance to VTO Analysis Program: Availability of validated simulation tools is necessary to evaluate the impact of the DOE Vehicle Technologies Office (VTO) R&D portfolio on energy use at the national level. All of the models and controls that are developed for VTO Analysis Program work are incorporated into Autonomie and are freely-available to support any activity funded by the U.S. Government. In the past year alone, Autonomie was used to support several federal agencies such as the DOE Fuel Cell Technologies Office (FCTO), the Department of Transportation (USDOT) National Highway Traffic Safety Administration (NHTSA), and agencies under the Department of Defense.

Objectives

In FY 2018, Argonne National Laboratory was tasked with the following objectives:

1. Develop representative models for medium- and heavy-duty vehicles (M and HDVs).
2. Determine the appropriate powertrain component sizes for various electrified vehicles.
3. Quantify the fuel saving potential of electrified powertrains in M and HDVs.
4. Develop a methodology to estimate the impact of technology changes over the next few decades.
5. Develop a database of vehicles to serve as the source for assumptions and inputs to vehicle modeling.

Approach

M & HDVs account for over 26% of the petroleum consumption in the U.S.[1]. The benefits of electrified powertrains for light-duty vehicles have been widely studied [2], but the impact of M & HDVs is not well understood. A comprehensive simulation that includes several types of vehicles is necessary to understand how specific powertrain technologies affect different purposes and use cases. As a step in that direction, this work evaluates the impact of electric powertrains on performance and fuel savings on a transit bus. Default models available in Autonomie [3] are used as references for the modelling and simulation work mentioned in this paper. Truck models were defined to cover the class, vocation, and powertrain combinations shown in

Table II.6.1. The powertrains considered in this study are conventional (Conv), mild hybrid electrics with integrated starter generators (ISG), strong parallel hybrid electric vehicles (HEV), range-extended plug-in hybrid electric vehicles (PHEV), and battery-powered electric vehicles (BEV).

Table II.6.1 Truck Class, Purpose, and Powertrain Choices Considered in this Study

Purpose	USDOT Class	Powertrains
Delivery	3	Conv
Delivery	4, 6	Conv, ISG, HEV, PHEV, BEV
Day Cab	7,8	Conv
Sleeper Mid and Low Roof	8	Conv
Sleeper High Roof, Vocational	8	Conv, ISG, HEV, PHEV, BEV

Trucks are quite unique in their design and performance capabilities. It is difficult to specify a generic set of design parameters for the set of vehicles in Table II.6.1. The U.S. Environmental Protection Agency (EPA) and NHTSA have done extensive surveys as part of their rulemaking process for regulating M & HDVs. Their publication puts forward a reasonable set of assumptions for these vehicles. For present-day vehicles, Autonomie adopts the same assumptions used by EPA and NHTSA [4].

Component Assumptions

The advanced vehicles considered in this study were based on technology that is already available in the market. All files used in this study were from the library components available in Autonomie. The fuel map for the engines is from the EPA's regulatory tool, Greenhouse Gas Emissions Model [5]. The efficiency maps for the motors either correspond to maps of permanent magnet motors used in various light-duty vehicles (LDVs), or are based on data provided by motor manufacturers, or on test data from national laboratories. Mild and strong hybrid electric vehicles use battery packs with high power density (630 W/kg). PHEVs and BEVs use battery packs with high energy density (100 Wh/kg). Vehicles such as the Chevrolet Malibu Hybrid, Hyundai Sonata Hybrid, Nissan Leaf (BEV), and others have similar power and energy densities. Electric machines and power electronic components are assumed to have specific power rating of 1.9 kW/kg and 10.5 kW/kg, respectively [6]. Auxiliary electric loads are split between mechanical and electrical loads for the conventional and mild HEVs. All auxiliary loads are electrified for HEVs, PHEVs, and BEVs.

Sizing Logic

This study followed a performance-based approach for sizing the electrified powertrain components [7],[8]. This method was an extension of the approach followed for LDVs in earlier studies. The performance requirements of various vehicles are summarized in Table II.6.2. Cargo capacity and performance are important to carry out the daily operations of commercial vehicles. For this study, it was expected that any proposed design employing an advanced powertrain should achieve or exceed, the conventional vehicle's performance when tested with the same cargo mass. This requirement included a 2% tolerance to minimize the number of simulations that were needed to compute the component sizes.

The actual vehicle test weight might change based on the mass of the components used in the powertrain. During the sizing process, mass of the vehicle is recomputed along with updates to the component sizes to estimate the test weight of the vehicle.

Table II.6.2 Truck Class, Purpose, and Performance Requirements Considered in this Study

USDOT Class	Purpose	0–30 mph (s)	0–60 mph (s)	Grade Speed 6% (mph)	Max. Speed (mph)	Desired Daily Driving Range (miles)
8	Tractor	18	66	30	65	500
8	Vocational	18	66	30	60	200

7	Tractor	18	70	30	65	500
7	Vocational	18	70	25	60	200
6	Delivery	12.6	48	33	70	150
3	Delivery	6.4	28.5	50	70	150
4	Delivery	10	28.5	40	70	150

Sizing Electrified Powertrains

Sizing logic for every powertrain ensures that the model satisfies continuous load requirements (e.g., cruise and grade) and transient demand (acceleration tests). For hybrids, the internal combustion engine is expected to provide the continuous load. Both the combustion engine and the electric motor may be used to meet the acceleration demand. For BEVs, motor and battery will have to meet both continuous and transient loads. Although a steady 6% grade climb at high speeds may not be a critical requirement for some vocations, in the interest of using a uniform sizing approach, all vehicles will be evaluated for the same set of performance parameters. The performance values must be within the sizing tolerance of the values shown in Table II.6.2 for all truck powertrain variants.

Mild Hybrids with Integrated Starter Generator

In this study, we assumed that the primary function of the mild hybrid system is to enable start-stop functionalities and sustain the electrical loads when the engine is off. Although the electric motor can be used for regenerative braking and acceleration assist, those functionalities did not play a role in sizing components for the ISG. The overall architecture is shown in Figure II.6.I, the electrical system model consists of multiple batteries, power converter, and electric loads.

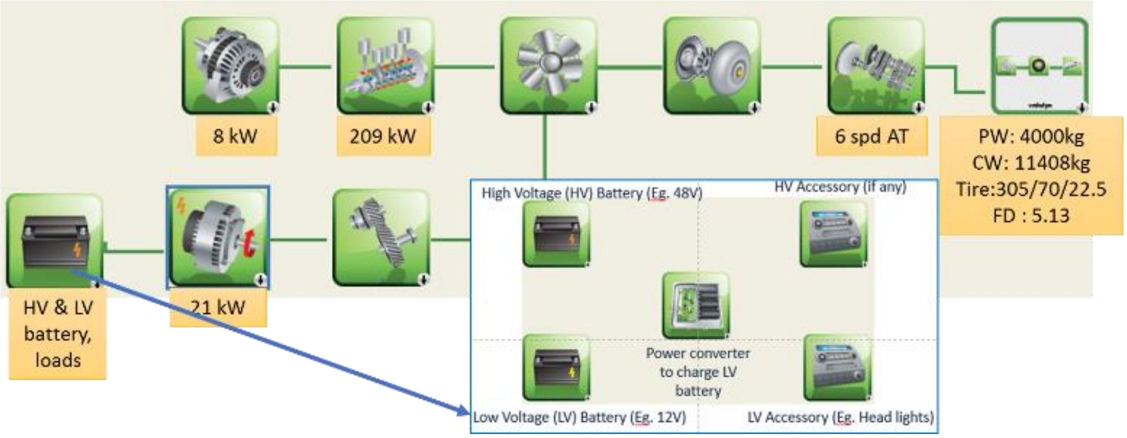

Figure II.6.I Sample micro hybrid architecture as modeled in Autonomie.

Data from alternator and starter motor suppliers show the capabilities of their electric machines and the vehicles and engines where their products are used [9]. This data helped to estimate the maximum motor and alternator power available in present-day vehicles. The new mild hybrid system should be capable of meeting the peak power of the starter motor, continuous load of the alternator, and of storing enough energy in the battery to substitute the maximum alternator load for at least one minute. The duration is assumed to be one minute, because EPA gives additional off-cycle credits for LDVs that can keep their engines off for a similar duration during urban driving conditions.

The vehicle retained the conventional starter and low voltage system. The battery should have usable energy equivalent to the desired electric load for at least one minute, while operating within the allowable State of Charge (SOC) window of 10%. The components can be further optimized for fuel economy, but in this study, the goals for the ISG system were to avoid idling, regenerate part of the power during braking, and maintain performance at minimum incremental cost. The additional weight of the 48 V Li-ion battery and ISG systems in a medium- or heavy-duty truck is small compared to the vehicle test weight and does not require resizing the engine.

Hybrid Electric Vehicles

Although multiple hybrid architectures are relevant to these applications, this study uses a pre-transmission hybrid architecture (shown in Figure II.6.II) for HEVs. All mechanical loads are electrified for this vehicle because the engine could be off during low speed operations and all auxiliary loads should be met by the battery during that period.

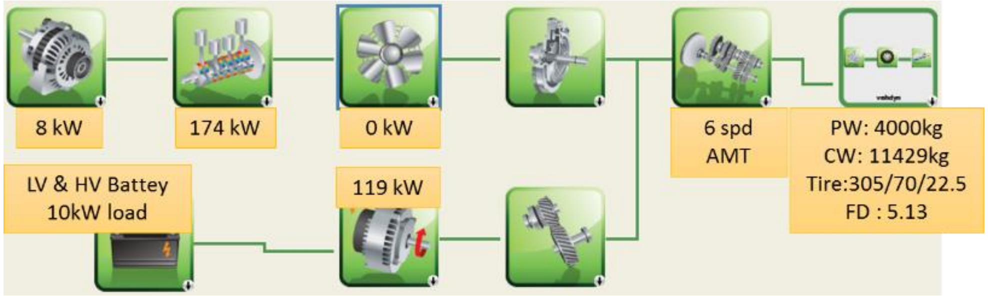

Figure II.6.II Sample pre-transmission hybrid architecture as modeled in Autonomie

The objective in the sizing logic is to provide sufficient motor power to maximize regenerative braking in the California Air Resources Board (CARB) transient drive cycle. The battery was sized to provide the peak motor power even at 40% SOC, the lower limit of the operational window assumed for a HEV application. The model does not achieve 100% recuperation of braking energy owing to the vehicle control logic design and efficiency losses. The control logic employs mechanical brakes below a speed threshold, and if the desired deceleration rate is set higher than 2.5 m/s^2. These control calibrations could be updated based on drivability requirements. It was recognized that the adopted sizing logic was not the optimum solution for maximizing fuel economy. However, comparisons of sizing results and prototype vehicle component sizes show that this approach was reasonable and yielded results close to those found in prototypes from truck manufacturers [10].

Plug-In Hybrid Electric Vehicles

PHEVs in this study have a series range extender architecture as shown in Figure II.6.III. Cruising at highway speeds is the only continuous power requirement activity considered for engine sizing in PHEV trucks.

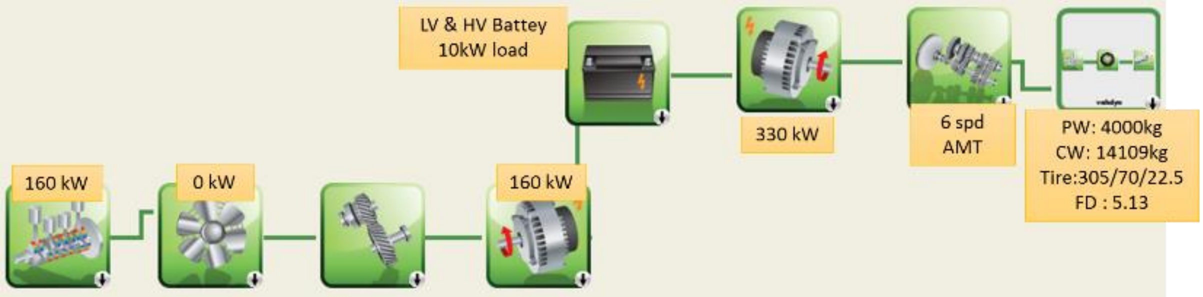

Figure II.6.III A sample series range extender architecture as modeled in Autonomie

While grade climbing is a prolonged event, its duration is limited, and its occurrence can be predicted and prepared for. Technology demonstrator trucks produced in the DOE SuperTruck Program have already demonstrated that vehicles can use route information to improve their control parameters [11]. It would be feasible to use the engine to partially charge the battery prior to encountering a prolonged hill climbing scenario. The grade test includes an 11-mile run at 6% grade, a proxy for the Davis Dam test. In this sizing procedure, the vehicle starts the grade test with a 50% battery SOC. The electric motor will get its energy primarily from the battery; the engine will assist as needed.

The motor is large enough to ensure that the vehicle met all performance requirements described earlier in this report. The simulation model considers thermal derating of the electric machine. The outcome means that toward the end of cruise and grade tests, the motor will be operating at or near its continuous rating. The model thus ensures the continuous operating power is high enough for the vehicle to meet the cruise and grade performance targets.

The driving range for PHEVs is arbitrarily fixed at half of the daily driving distance requirement. A mid-day charging, if possible, would lead to full daily operation with electric power alone. The electric driving range is established at highway cruising conditions because those conditions consume the most energy for electric operation, and thus determine the usable energy needed from the battery pack. The maximum possible depth of discharge is assumed to be 75% for this battery pack. The power available in such a pack is normally sufficient to power the motor, which was verified by the sizing logic.

Battery Electric Vehicles

The sizing logic for BEVs is a subset of the logic employed for PHEVs. The electric driving range was assumed to be the entire daily driving requirement. Depth of discharge was assumed to be 85% for BEV battery packs. The battery energy capacity and motor power are determined using the procedure explained in the Plug-In Hybrid Electric Vehicles section above. The battery pack has sufficient power to meet the motor demands.

Results

Models for M & HDVs have been added to Autonomie. Over 300 new vehicles were defined, sized, and evaluated for fuel consumption in this study. The generic versions of those vehicles are provided in Autonomie to support other DOE-funded activities. The process to evaluate the impact of technology progress on energy consumption was also developed. Over 80 parameters were identified that could change when new technologies are implemented. All these assumptions were translated to Autonomie variables and applied to vehicle models before they are simulated on regulatory drive cycles. The detailed results from this study will be published as a separate report. Here, we present a summary of the fuel savings potential of various powertrains on different drive cycles in Figure II.6.IV. The drive cycles considered in this study were the same as those used by EPA and NHTSA for their regulatory analyses.

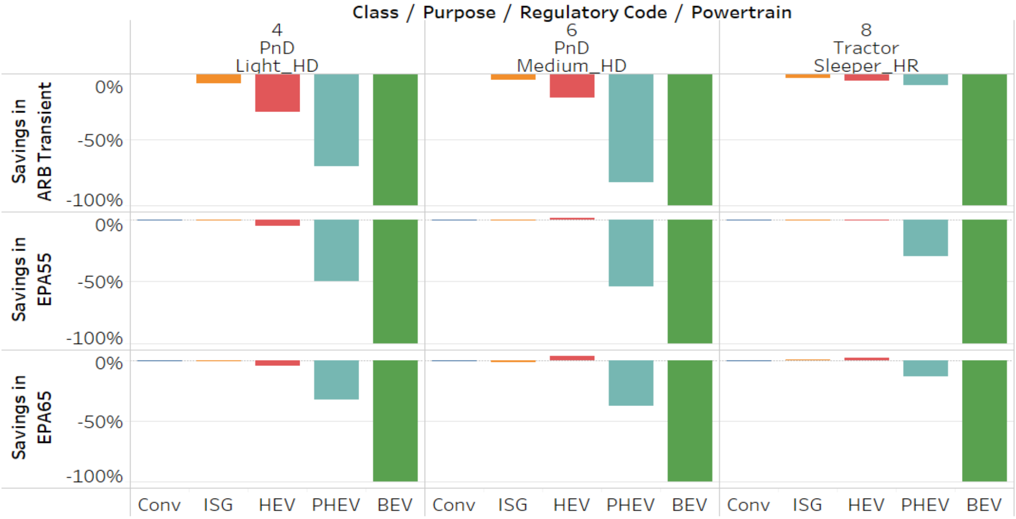

Figure II.6.IV Fuel saving potential of various powertrains on regulatory drive cycles

Note: Data assume full daily driving distance is driven.

Figure II.6.IV shows that for smaller M & HDVs (Classes 4 and 6), HEVs offer substantial fuel savings on the California Air Resources Board transient drive cycle. The other two drive cycles in this study have very little speed variation. PHEVs and BEVs are needed to achieve significant fuel displacement in the high-speed drive cycles (55 mph and 65 mph runs with varying grade).

The vehicles' control algorithms do play a critical part in these results, and the team is exploring ways to improve the controls to get the most benefit out of the electrified powertrains.

Vehicle Attribute Database

A database consisting of vehicle attributes and parameters of vehicles present in the United States market has been developed and validated. The database currently holds the following statistics:

- Vehicle model year spans: 2011 - 2019
- Total number of vehicles (accounting for redesigns): 1780
- Total number of vehicle powertrains: 15

Some of the primary data metrics in the database includes:

- Vehicle weight
- Fuel economy / electrical energy consumption
- Vehicle design specifications (frontal area, drag coefficient, etc.)
- Vehicle performance specifications
- Vehicle cost & sales

The database is used to derive different vehicle attributes such as frontal area and drag coefficient that would help in redesigning baseline vehicles for different vehicle classes and performance types.

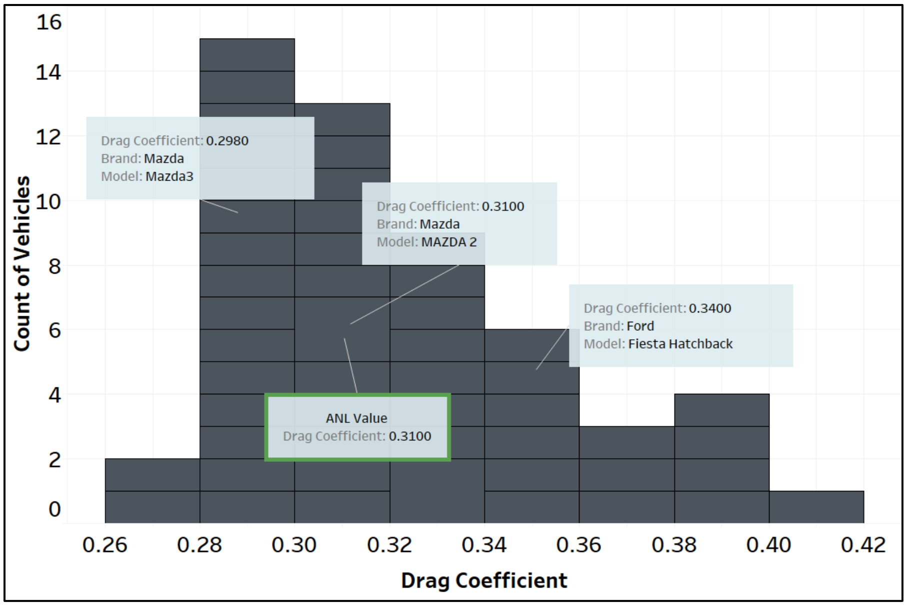

Figure II.6.V: Distribution of drag coefficient values of compact (base) vehicle class

The database is also used to validate Autonomie vehicle simulations in terms of different energy analyses as well as component performances. For example, Figure II.6.VI below shows the analysis of engine power versus vehicle acceleration time(s) between simulation results as well as the vehicles existing in the vehicle attribute database.

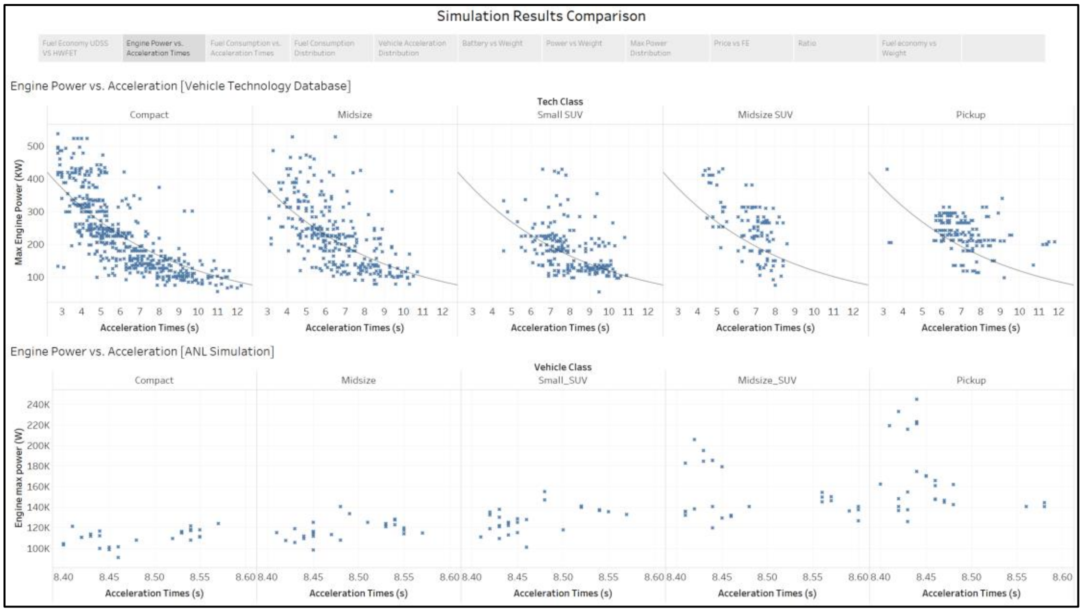

Figure II.6.VI: Engine power versus vehicle acceleration time(s)

The database provides an easy reference for several important vehicle attributes as well as fuel consumption results. It is an ongoing work to keep it updated with new vehicles, and to expand it beyond LDVs.

Conclusions

This study developed vehicle models to represent regulatory vehicles for medium- and heavy-duty trucks and integrated those models into Autonomie. These models are in addition to the existing 15 trucks from multiple classes, ranging from box trucks to construction vehicles. Performance requirements were defined for each vehicle type. A performance-based sizing process was applied to various powertrain architectures to determine appropriate component sizes for all powertrain variants of trucks. The fuel economy and manufacturing cost estimates for these trucks were provided to other teams to carry out market penetration analysis. The reference trucks added to Autonomie are already being used to support other DOE-funded activities. On LDV side, a database was developed to serve as a reference point for vehicle technology assumptions.

Key Publications

1. Vijayagopal, R., Rousseau, A., and Vallet, A. (2018) "Fuel Consumption and Performance Benefits of Electrified Powertrains for Transit Buses," SAE Technical Paper 2018-01-0321, 2018, https://doi.org/10.4271/2018-01-0321.

2. Vijayagopal, R., Rousseau, A., "Fuel Consumption and Performance Benefits of Electrified Powertrains for Trucks", submitted to the International Electric Vehicle Symposium and Exhibition 2019 (EVS32).

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II.7 VISION/NEAT Annual Update

Yan Zhou, Principal Investigator
Argonne National Laboratory
9700 S. Cass Ave
Lemont, IL 60439
E-mail: yzhou@anl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2017 End Date: September 30, 2018
Project Funding (FY18): $150,000 DOE share: $150,000 Non-DOE share: $0

Project Introduction

Developed with DOE Vehicle Technologies Office (VTO) support over the past 10+ years, the VISION model and Non-light duty energy and GHG Emissions Accounting Tool (NEAT) (https://www.anl.gov/es/vision-model, https://www.anl.gov/es/neat-nonlight-duty-energy-and-ghg-emissions-accounting-tool) address the need to assess fleetwide energy and emission effects from market adoption of vehicle/fuel technologies. They track historical patterns of vehicle travel, fuel use, and emissions by mode and vehicle size/type. The result is a profile of the U.S. vehicle fleet that is consistent with the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) Reference Case, the U.S. Department of Transportation's (DOT) Freight Analysis Framework (FAF), and a long-term forecast of advanced vehicle/fuel systems.

Relevance to the VTO Analysis Program: The VTO Analysis Program has a long history of developing, improving, and applying analytical models to support evaluations of VTO's research and development (R&D) portfolios, DOE-wide efforts like the Quadrennial Technology Review, multiagency activities and partnerships such as U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (DRIVE) and the SuperTruck Program, and broader efforts involving organizations like the National Research Council. It is critical to continue developing these tools since they permit benefit estimation for the program at the national level.

Objectives

In FY 2018 Argonne National Laboratory (Argonne) updated VISION/NEAT to align the base case with annual AEO and FAF projections. VISION/NEAT was also revised to reflect energy and emission coefficients from the latest GREET®, and Argonne began working on developing an on-line version of the VISON model.

Approach

Since vehicles, especially heavy-duty vehicles (HDV), are long-lived assets, the penetration of advanced vehicles/fuel systems into the total fleet can take decades. In addition, estimates of fleet-wide energy and emission effects must account for vehicle survival, technology trends, and macroeconomic factors such as gross domestic product and energy prices. VISION/NEAT was developed to serve this goal. In this task, Argonne updated the model with historical and projected data on trends related to market adoption, vehicle usage and efficiency, and mode shares by using EIA AEO and DOT FAF forecasts along with GREET emission estimates. The team also enhanced the model's user interface, flexibility, and coverage.

Task 1. Annual update and upgrade of VISION/NEAT. VISION/NEAT was updated to align the base case with AEO2017 Reference Case and FAF4.0 projections. It was also revised to reflect energy and emission coefficients from the latest GREET model release. VISION/NEAT structure was streamlined with an improved interface for presenting inputs and parameters relevant to user-defined scenarios and for providing graphics and drop-down functions for users. Major inputs that can be changed by users in VISION and NEAT to define their own scenarios include, but are not limited to the following:

VISION:

- Market penetration by technology
- Fuel economy by technology
- Vehicle survival rate
- Alternative fuel energy and emission rate (per mile)
- Light truck share of total light-duty vehicle (LDV) market
- Fischer-Tropsch diesel/biodiesel in diesel (by volume)
- Electric generation mix
- Flex-fuel vehicle, vehicle miles travelled (VMT) share
- Ethanol production share by feedstock
- Hydrogen production share by feedstock
- LDV VMT growth rate
- Diesel share in heavy-duty truck VMT
- Fuel price (in comparison to gasoline)
- Vehicle cost (in comparison to conventional midsize car or light truck)

NEAT:

- Ton-mile change factors over 2010 values by commodity
- Ton-mile shares by mode within commodity
- Modal energy intensity/efficiency (Btu/ton-mile) by commodity
- Fuel shares by mode (petroleum fuels, biofuels, electricity)
- Electricity generation primary fuel shares (% kWh/fuel)

Task 2. On-line version of VISION (started in late FY 2018). Argonne began to develop an on-line version of VISION to simplify the usage of the model compared to the Excel version. This task started in late FY 2018 and is expected to be finished and released in FY 2019. The first version only covers LDVs. The major user-defined inputs are market penetrations and fuel efficiency of car and light truck, electric generation mix, annual VMT growth rate, and electric range of plug-in hybrid electric vehicles. The on-line version also has a graphic function to compare scenario results with base case results.

Results

Tasks 1 and 2. Argonne updated and released VISION 2018 version to users in September 2018. The VISION model is updated annually. The Base Case in the most recent version of the model reflects projections of light and heavy vehicle in the EIA AEO 2018. The EIA AEO 2018 projections end in the year 2050. In the 2018 VISION model update, these projections were extended to the year 2100. For emissions calculation, the VISION model uses carbon coefficients derived from Argonne's GREET model. The emissions coefficients are for the full fuel cycle. This release includes the following expansions and updates:

- Added alternative powertrain technologies to LDVs including battery electric vehicles with 300 miles range (EV 300) for both passenger cars and light trucks.
- Updated with emissions and upstream energy rates from GREET 1_2017 are listed at http://greet.es.anl.gov/.
- Updated with EIA AEO 2018 Reference Case data.

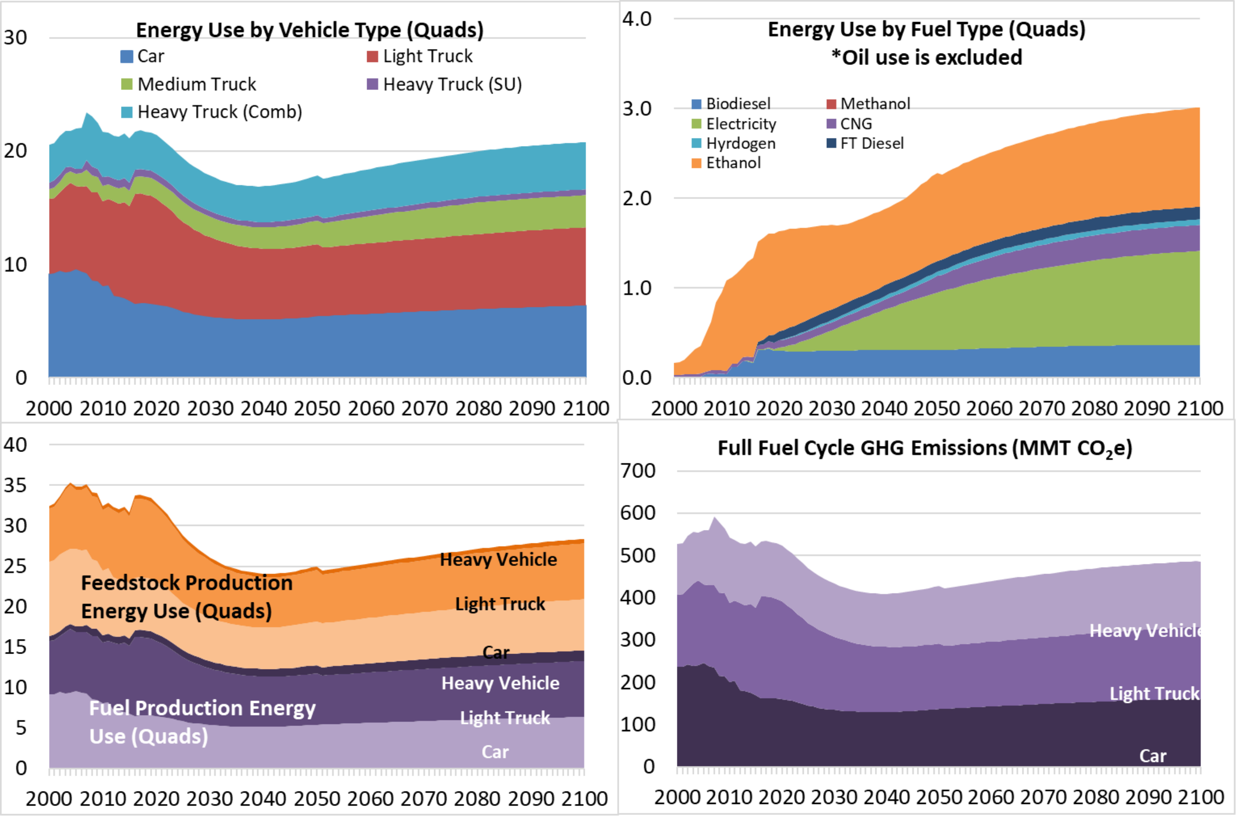

Figure II.7.I Long-term base case for LDVs and HDVs by fuel and vehicle type

Because NEAT model had a major update in FY 2017, Argonne also updated NEAT model user guide in FY 2018. The new user guide captures all new features and assumptions used in the updated version. The user guide was published in May 2018, and is available on-line for users to download.

Conclusions

Argonne's VISION/NEAT model was fully updated to match the projections in the EIA AEO 2018 Reference Case and FAF4.0. Alternative powertrain technologies were added to medium- and heavy-trucks in FY 2017. Historical vehicles sales, stock, fuel economy, and other information were collected and documented in the model. VISION/NEAT model has been used in several DOE/EERE programs and activities such as analysis program (AP), BaSce, SMART Mobility, and H2@Scale to evaluate the impacts of advanced vehicle technologies.

Key Publications

1. Y. Zhou. 2018. Non-Light-Duty Energy and Greenhouse Gas Emissions Accounting Tool (NEAT): Documentation and User Guide For Updated Domestic Freight Component, ANL/ESD-18/5, May 2018.

III Applied Analysis of Vehicle Technology Benefits

III.1 Applied Analysis of Vehicle Technologies Benefits

Thomas Stephens, Principal Investigator
Argonne National Laboratory
9700 South Cass Avenue
Lemont, IL 60439
E-mail: tstephens@anl.gov

Alicia Birky, Principal Investigator
Energetics
7075 Samuel Morse Drive
Columbia, MD 21046

Michael Dwyer, Principal Investigator
Energetics
7075 Samuel Morse Drive
Columbia, MD 21046
E-mail: mdwyer@energetics.com

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2015 End Date: September 30, 2019
Project Funding (FY18): $250,000 DOE share: $250,000 Non-DOE share: $0

Project Introduction

The Department of Energy's Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Office (VTO), in coordination with the Fuel Cell Technology Office (FCTO) and Bioenergy Technology Office, need to understand the potential energy, economic and environmental outcomes of successfully reaching goals of their research and development programs.

Objectives

The overall objective is to estimate the potential benefits attributable to successfully achieving VTO and FCTO program goals. The benefits to be estimated include petroleum savings, reductions in energy security costs, costs to consumers, and emissions out to the year 2050. An additional objective is to assess the sensitivity of these estimates to some of the input assumptions. The objectives for FY 2018 were to update the inputs and the analysis methodology to provide updated program benefits analysis of VTO and FCTO technologies in medium- and heavy-duty vehicles (M&HDVs) and to assess uncertainties in the earlier benefits analysis for light-duty vehicles (LDVs).

Approach

The approach requires development and analysis of scenarios comparing a scenario with completely successful development of VTO and FCTO technologies ("Program Success" case) to a future in which there is no contribution after FY 2020 by the VTO or FCTO to development of these technologies ("No Program" case). Inputs for the Program Success case, including vehicle attributes, vehicle use, and refueling were developed based on VTO and FCTO program goals a with additional details based on inputs from industry experts. The "No Program", or baseline, case was derived from the Energy Information Administration's Annual Energy

Outlook 2018 Reference case (AEO 2018 Ref case) [1], but with VTO and FCTO- technology research and development support removed.

Vehicles were simulated by Argonne National Laboratory (Argonne) using Argonne's Autonomie toolkit [2]. Inputs for diesel truck components were vetted with VTO Advanced Combustion Engine Technology Development Managers (TDMs), and Autonomie simulations were rerun using improved inputs for these vehicles. Preliminary inputs for other drivetrains were based on industry inputs and expert judgement, but will require additional review by VTO TDMs. Energetics enhanced and updated market penetration and stock evolution models for M&HDVs for several size classes to permit modeling of additional technologies in a wider range of size classes and applications than in previous benefits analyses. As the models were being upgraded and updated to the AEO 2018 Ref case, Energetics found errors in the stock tracking in the National Energy Modeling System used for the AEO 2018 Ref case. These errors resulted in erroneous size class allocations and fleet transfer (from fleets to non-fleets) of certain gasoline and diesel vehicles. In developing the baseline case, Energetics also identified a discrepancy between the miles-per gallon estimates in the AEO 2018 Ref case and the final Phase II fuel economy and emissions standards for vocational and Class 7/8 day cab vehicles. These were corrected in the base case of the ongoing benefits analysis.

The suite of models, from Autonomie to the market penetration model to the stock model, was exercised using available inputs and some placeholder values. Having these test run results provides confidence in the models performance and in the connections between models. Results of these test runs also provide some context for the parameters that still needing vetting by VTO and FCTO TDMs.

In addition to updating and enhancing M&DHV analysis, sensitivity of the VTO and FCTO program benefits in LDV benefits analysis results previously reported [2] was assessed by analyzing several side cases with varying input assumptions. The inputs varied in the side cases included:

- Petroleum fuel prices
- Battery and electric motor costs
- Glider (lightweight materials) cost
- Combustion engine costs

Assumptions about prices and costs are summarized in Table III.1.1. All other inputs such as costs of other vehicle components and all other vehicle characteristics including fuel economy were the same as in the MedH2Price_PS case, which is the same as the Program Success scenario in the prospective benefits analysis completed in 2017 [3], but with somewhat higher hydrogen prices.

Table III.1.1 Summary of LDV Side Case Assumptions

Case	Gasoline and diesel prices	Battery & elec motor costs	Engine cost	Glider cost
LowOil_PS	AEO2018 Low oil price	Program Success	Program Success	Program Success
HighOil_PS	AEO2018 High oil price	Program Success	Program Success	Program Success
HighCost_BEDT_PS	AEO2016 Ref	Motor: 1.5 x Progr Success, Batteries: 1.3 x Progr Success	Program Success	Program Success
HighCost_ACE_PS	AEO2016 Ref	Program Success	1.2 x Program Success	Program Success
HighCost_Matl_PS	AEO2016 Ref	Program Success	Program Success	1.2 x Program Success

Side cases were designed as variations on the MedH2Price_PS case, which is the same as the Program Success case in the prospective benefits analysis completed in 2017 [3], but with somewhat higher hydrogen prices.

The MedH2Price_PS case is an appropriate case to compare side cases with since it represents a possible future with successful implementation of VTO and FCTO technologies in LDVs. Petroleum consumption and consumer spending on fuels and vehicles were evaluated for the U.S. national level fleet of LDVs for each side case. The sensitivity of each was assessed by comparing outputs at two levels of a given input. Elasticities were calculated to quantify sensitivities by forming ratios of fractional changes of outputs to the fractional change in the corresponding inputs.

Results

In FY 2017, an analysis of VTO and FCTO program benefits was completed and documented in a report issued in November 2017 [3].

In FY 2018, analysis of VTO and FCTO benefits in M&HDVs was begun based on preliminary inputs, M&HDV model enhancements and updates were completed, and the models were run to demonstrate their upgraded functionality. The Energetics market penetration model was enhanced to represent two separate Class 7/8 combination tractor trailer markets in addition to the vocational market: sleeper cab and day cab, to model these two different market segments more realistically. The model was expanded to include two additional technology option slots, which enabled the inclusion of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs); neither of these powertrains have been included in the M&HDV benefits analysis previously. Hydrogen was added to the fuels list, and a framework was developed to account for fuel availability impacts. The model was also upgraded to handle separate fuel prices for centrally, versus non-centrally, fueled fleets. This will enable accounting for the anticipated difference in delivered costs of hydrogen (and perhaps electricity) for these two types of fleets. Energetics also upgraded and updated their stock model to track the stock by size class bins, truck configurations, and nine powertrain types. The stock model also tracks fuel demand and expenditures for centrally-fueled and non-centrally-fueled fleets, and reports energy use by fuel within the size class bins.

Energetics compared baseline results with the AEO 2018 Ref case, and the vehicle miles travelled (VMT) and energy distribution by size class, powertrain, and fuel were slightly different, as expected, due to errors in NEMS modeling for the AEO as described above. However, the discrepancies were small, and total energy consumption matched the AEO 2018 Ref case projections to within ±1.3%.

Energetics tested and ran the models with preliminary inputs and “placeholder” values for some inputs that have not been finalized. Additional vehicle simulations needed and inputs that require further vetting by VTO and FCTO were identified. Results from the analysis of side cases to the LDV benefits analysis showed that projections of petroleum use are sensitive to large changes in gasoline and diesel prices, but are fairly robust to changes in other inputs, as shown in Figure III.1.I.

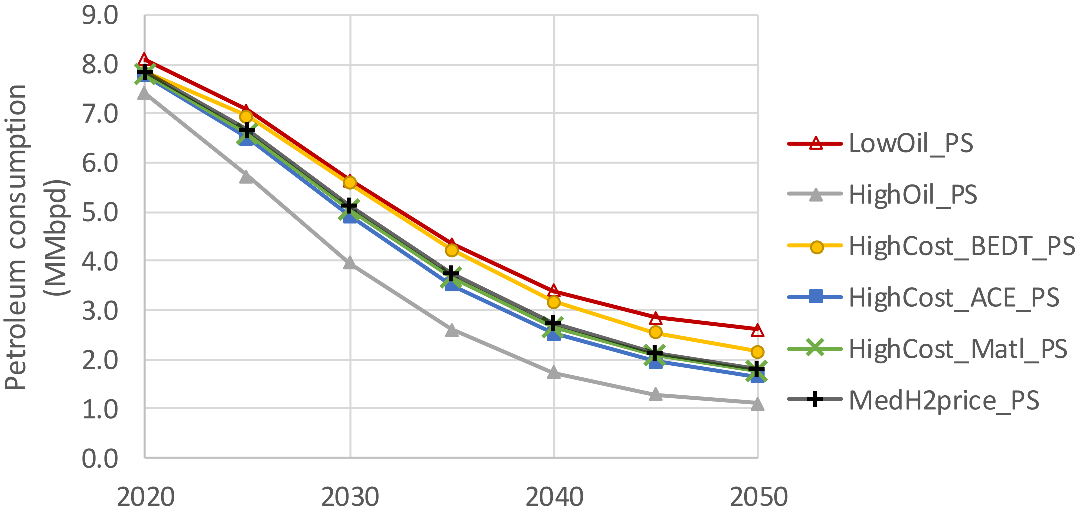

Figure III.1.I Projected petroleum consumption for the LDV side cases

However, to compare sensitivities to different inputs, it was necessary to normalize changes in outputs to the magnitudes of changes in inputs. The elasticities calculated as describe above give such normalized metrics of sensitivity. Elasticities of petroleum consumption, vehicle spending, and fuel spending with respect to the battery and electric drive system manufacturing cost are shown in Table III.1.2.

Table III.1.2 Elasticities of Petroleum Consumption, Consumer Vehicle Expenditures, and Consumer Fuel Expenditures with Respect to Different Inputs

	Input Variable			
	Gasoline and diesel prices	**Battery & elec motor costs**	**Engine cost**	**Glider cost**
Petroleum Consumption	−0.59	0.42	−0.33	−0.15
Consumer Vehicle Expenditures	0.03	0.07	0.05	0.71
Consumer Fuel Expenditures	0.46	0.22	−0.16	−0.13

The small value of elasticity of vehicle spending reflects a small increase in vehicle expenditures with a large increase in gasoline and diesel prices. The elasticity of fuel spending with respect to gasoline and diesel prices is larger, but less than 1.0, indicating that with much higher gasoline and diesel prices, consumers make fuel-saving adaptations, including adoption of more efficient powertrains and driving slightly less. The elasticity of petroleum consumption with respect to gasoline and diesel prices is consistent with long-term price elasticities of demand for gasoline.

Elasticities of petroleum consumption, vehicle spending, and fuel spending with respect to battery and electric drive system manufacturing cost indicate that higher-cost plug-in vehicles (PEVs) result in lower PEV adoption and significantly more petroleum consumption and increased spending on fuel. Higher-cost engines raise the purchase prices of conventional vehicles relative to prices of HEVs and PHEVs, and especially BEVs. These increases lead to higher PEV adoption and somewhat lower petroleum consumption and spending on fuel. Higher glider costs lead to slightly lower petroleum consumption, due to a slight reduction in VMT and to a very slight increase in adoption of more advanced powertrain vehicles. Higher glider costs lead to much higher spending on vehicles, which was expected since prices of all vehicles are increased by similar amounts, leaving consumers with no low-cost choice.

Conclusions

Analysis of VTO and FCTO benefits in M&HDVs was begun based on preliminary inputs, important M&HDV model enhancements and updates were completed, and models were run to demonstrate their upgraded functionality. The Energetics market penetration model was enhanced to represent Class 7/8 sleeper and day cab combination tractor trailer markets separately, and two additional technology options were added to enable inclusion of BEVs and FCEVs, which have not been included in the M&HDV benefits analysis previously. Hydrogen was added to the fuels list, and fuel availability was incorporated. The model was also upgraded to handle separate fuel prices for centrally versus non-centrally fueled fleets, which will enable accounting for the anticipated difference in delivered costs of hydrogen (and perhaps electricity) for these two types of fleets. Energetics also upgraded and updated their stock model to track the stock of size class bins/truck configurations and eight powertrain types. The stock model also tracks fuel demand and expenditures for centrally fueled and non-centrally fueled fleets, and reports energy use by fuel within size class bins

Energetics tested and ran the models with preliminary inputs and “placeholder” values for some inputs that have not been finalized. Having these test runs provides confidence in the models and in the connections between models. These test run results also provide some context for the parameters still needing vetting by VTO and FCTO TDMs. The team identified additional vehicle simulations needed and inputs that require further vetting by VTO and FCTO; these inputs will soon be established, and final modeling and analysis will be completed in FY 2019.

Generally, the changes seen in side cases with higher costs were as expected. When costs of certain vehicles or their fuels increase relative to other vehicle types, the market shares of those vehicles decreases. Increases in prices of gasoline and diesel lead to increased market shares of efficient conventional vehicles, PEV, and/or FCEV that use little or no petroleum, which decreases petroleum consumption. Increased glider costs, assumed here to be the same increase for all powertrain types, lead to very slight changes in market shares of different powertrain types and a very modest reduction in petroleum use, but a significant increase in expenditures on vehicles.

Comparing the magnitudes of the elasticities calculated, petroleum use and consumer spending are sensitive to, in order of highest to lowest sensitivity:

- Gasoline and diesel prices
- Battery and electric drive costs
- Combustion engine costs
- Glider costs

Elasticities were all significantly less than unity in magnitude, indicating that projections of petroleum use are fairly robust to uncertainties in these inputs. Results of this sensitivity analysis will be useful for developing improved scenarios and analyses for subsequent program benefits analysis.

Key Publications

1. Stephens, T., Birky, A., and Gohlke, D. 2018. “Vehicle Technologies and Fuel Cell Technologies Office Research and Development Programs: Prospective Benefits Assessment Report for Fiscal Year 2018.” Argonne National Laboratory, Argonne, IL, report ANL/ESD-17/22, November, https://www.osti.gov/scitech/biblio/1410412-vehicle-technologies-fuel-cell-technologies-office-research-development-programs-prospective-benefits-assessment-report-fiscal-year, accessed October 12, 2018.

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1. Energy Information Agency. Annual Energy Outlook 2018, with Projections to 2050, February 2018, www.eia.gov/aeo.

2. Argonne National Laboratory. Autonomie. https://www.autonomie.net/

3. Stephens, T.S., A. Birky, and D, Gohlke. Vehicle Technologies and Fuel Cell Technologies Office Research and Development Programs: Prospective Benefits Assessment Report for Fiscal Year 2018. Argonne National Laboratory, Argonne, IL, report ANL/ESD-17/22, November, https://www.osti.gov/scitech/biblio/1410412-vehicle-technologies-fuel-cell-technologies-office-research-development-programs-prospective-benefits-assessment-report-fiscal-year.

III.2 Plug-in Electric Vehicle Impacts

Colin Sheppard, Principal Investigator
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 95521
E-mail: colin.sheppard@lbl.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October, 2017 End Date: September, 2019
Project Funding (FY18): $250,000 DOE share: $250,000 Non-DOE share: $0

Project Introduction

As the power generation sector adds increasing levels of renewable energy (RE) generating capacity to the electric grid and the transportation sector experiences increasing vehicle electrification, the impacts of the integration between these technologies requires new analytical methodologies that couple capabilities across the transportation and power sectors. In this report, the research team analyzed a California case study because the state already has 370,000 plug-in electric vehicles (PEVs)—about half of the PEVs in the United States—and has a goal of reaching 1.5 million Zero Emission Vehicles, by 2025. In addition, California is pursuing a RE-dominant power generation portfolio with a mandate that 50% of the state's electricity consumption come from renewable sources by 2030.

Depending on whether PEV charging is unmanaged or managed in some way, this significant addition of PEVs to the California electric grid could either exacerbate, or help, with the integration of more RE. If PEVs are unmanaged, charging can coincide with the system's peak and increase ramping needs and costs through the use of inefficient and expensive "peaker" power plants. In addition to alleviating such peak loads and costs, by charging instead at times of low prices and high RE generation, managed PEVs could serve as a flexible load to help California's grid avoid RE curtailment and save money. In this analysis, the research team considered two forms of managed charging: (1) time-of-use (TOU) rates that incentivize drivers to charge during off-peak times overnight, and (2) smart charging demand response (DR) programs that allow an aggregator or other entity to directly control the charging power.

Numerous studies have investigated the impacts of such managed PEV charging on power systems with RE, but most existing literature either simplifies PEV charging behavior and charging infrastructure, or the dispatch of the power system. These simplifications could lead studies to overestimate the availability and willingness of PEVs to provide grid services as well as the value that PEV grid services can add to the grid. The travel demands of drivers, the location and availability of chargers, and the user acceptance of managed charging programs are important in modeling a realistic estimate of value of PEV grid services.

The analysis done in this project addressed these gaps by integrating a representation of smart and of unmanaged charging with a detailed power system model. The research team coupled the vehicle charging outputs of the agent-based BEAM (Behavior, Energy, Autonomy Mobility) simulation model to the Energy Exemplar developed PLEXOS® model (an industry standard tool for optimizing the economic dispatch of grid resources). The research team evaluated the system cost and RE curtailment impacts of the addition of 0.95 million PEVs (4% of California's current vehicle stock) to 5.0 million PEVs (20% of California's vehicle stock) PEVs under unmanaged, smart and TOU charging strategies on the California power system in 2025. It was assumed that the state would meet its Renewable Power Standard goal of RE penetration at 50% of annual electricity consumption.

In addition to the above work, the research team developed new capabilities to assess the demand for vehicles, charging infrastructure, and temporal electricity load if mobility were served by shared, automated, electric vehicle (SAEV) fleets rather than private vehicles.

Objectives

The project objective was to estimate the costs and benefits of integrating millions of plug-in electric vehicles into the California electric power system. The analysis had to quantify the impact on power system generators, including the curtailment of intermittent renewable energy, in addition to the impact on the cost of operating the grid.

The research sought to account for the charging behavior of PEV drivers and the consequences of constrained charging infrastructure using the BEAM model. Finally, the research sought to simulate the power sector as it is dispatched, using the PLEXOS® model, which minimizes cost in serving load reliably.

The objective also included an assessment of the nation-wide demand for charging and planning for vehicles and charging infrastructure if mobility were to be served by SAEV fleets.

Approach

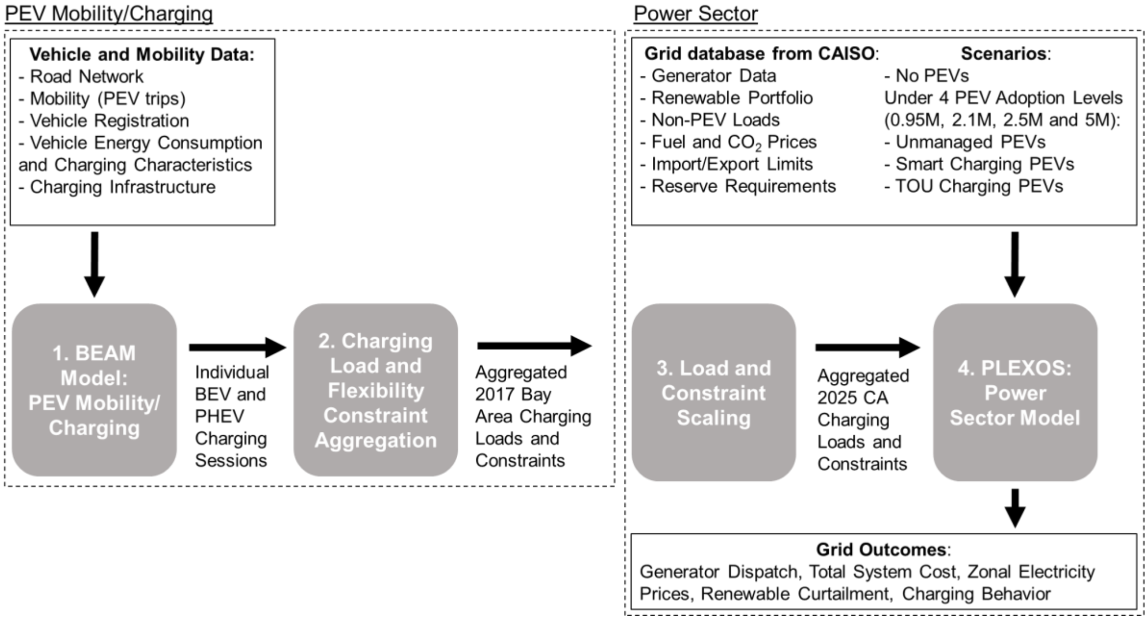

Figure III.2.I Vehicle-grid integration modeling framework with BEAM and PLEXOS® models

The modeling methodology is illustrated in Figure III.2.I and proceeds as follows:

1. *BEAM Model: PEV Mobility/Charging.* BEAM simulates PEV mobility and charging behavior for three representative weekdays for about 68,000 PEVs in the San Francisco Bay Area. Charging sessions (defined by the period of time the PEV is plugged in) are simulated as unmanaged, but the time between the end of active charging and the actual unplug event concluding the session is tracked for later use and exported as an input into the next step.
2. *Charging Load and Flexibility Constraint Aggregation.* The charging session data were analyzed and aggregated by vehicle type—battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV)—into both an unmanaged trajectory of delivered energy (when the vehicle charges immediately and at full power when it is plugged in), and an alternate trajectory that represents delaying charging to the maximum extent possible while still delivering the same amount of energy by the end of the charging session. These trajectories were treated as maximum and minimum constraints

that bounded the possible dispatch of smart charging loads and still ensured the same end battery state of charge (SOC) of the PEV as with unmanaged charging. Corresponding power constraints on smart charging were also produced based on the number of connected vehicles in each hour and were aggregated by vehicle type. For TOU charging, the researchers represented the response to off-peak TOU rates by forcing charging to begin at staggered times between 10 PM and 2 AM (to avoid inducing a sudden demand spike) for those PEVs that would already be plugged in overnight if unmanaged. The resulting TOU off-peak charging loads were aggregated by vehicle type. In order to capture the realistic behavior of an average day, for each of the charging strategies, the data from charging sessions from the second day of a three-day BEAM run of representative weekdays were used for the load and constraint aggregation. A full week of data, constructed by calibrating to observed charging data, were then repeated to create an annual data set for each charging strategy.

3. *Load and Constraint Scaling to California Vehicle Adoption Forecasts.* The aggregated unmanaged and TOU loads and smart charging constraints produced from BEAM in Step 2, based on approximately 68,000 PEVs in the San Francisco Bay Area, were scaled from magnitudes that represented the San Francisco Bay Area PEV stock in 2017 to that of the whole state of California in 2025. The scaling occurred in two parts, from the Bay Area to each utility zone in California based on respective BEV and PHEV vehicle stock as of 2016, and then from 2016 to California in 2025 based on CEC forecasted adoption levels. The CEC 2025 forecast included three scenarios: 0.95 million, 2.1 million, and 2.5 million PEVs. The research team used these three scenarios, and also added a “reach” scenario of 5.0 million PEVs in the state. It was assumed that current trends in PEV sales will continue, and that 60% of each 2025 adoption scenario will be met by BEVs and 40% by PHEVs.
4. *PLEXOS® Power Sector Model.* The scaled 2025 PEV loads and constraints were loaded into PLEXOS® along with power sector data from the database originally used by California Independent System Operator (CAISO) for the 2014 Long Term Procurement Planning process and updated by CAISO to reflect more recent changes on the electricity system. Each of the four PEV adoption levels (ranging from 0.95 million to 5.0 million PEVs), were run in PLEXOS® for the four scenarios described below (no PEVs, unmanaged PEVs, TOU charging PEVs, smart charging PEVs) and export as results the total system cost, electricity prices, renewable curtailment and generation, and charging behavior (charging behavior for smart charging is dispatched by PLEXOS® but unmanaged and TOU charging loads are the fixed loads from Step 3).
5. To assess the potential for SAEVs to serve mobility and their associated charging demand, the researchers developed a quadratically constrained quadratic programming problem with the following decision variables: (1) the size of the vehicle fleet disaggregated by vehicle range, (2) the number of charge points required to support the fleet disaggregated by power rating, (3) the dispatch of vehicles to serve customer demand, and (4) the dispatch of vehicles to charge given a time varying price of electricity.

Results

The research team found that integrating PEVs in an unmanaged charging scenario, compared to TOU and smart charging, has the following grid impacts for California in terms of total system cost and RE:

System Costs

- When PEVs are added to the grid, grid operating costs increase. The charging strategy strongly affects the degree to which costs increase (Figure III.2.II). Smart charging was projected to avoid 47% (with 0.95 million PEVs) to 51% (with 5.0 million PEVs) of the California system costs increases from unmanaged PEV charging. These costs reflect the wholesale operating costs to generate energy and do not include capital costs, transmission and distribution costs and any other adders that comprise the full cost of producing and delivering electricity, or of retail electricity rates for customers.
- About 80% of these benefits were projected to be gained through TOU charging without the implementation cost of smart charging controls and administration; 34% (with 0.95 million PEVs) to 42% (with 5.0 million PEVs) of system cost increases can be averted if PEVs already plugged in at home only charge overnight, based on current TOU off-peak rate schedules.

- Smart charging was projected to provide a value (by avoiding system operating costs) of about $90 to $140/PEV per year compared to unmanaged charging. TOU was projected to provide a value of about $60 to $120/PEV per year.
- The benefits of both managed charging strategies are non-linearly related to PEV adoption, and the benefits increase as the power system approaches its generation and transmission capacity limits. If 5.0 million PEVs participated in smart or overnight TOU charging, capital costs of new generators or transmission could be deferred without leaving load unserved during peak hours of the year.

RE Curtailment

- Among the PEV charging strategies considered, smart charging were projected to reduce California's RE curtailment the most—by an additional 12% (0.95 million PEVs) to 48% (5.0 million PEVs), relative to unmanaged charging.
- In contrast, nighttime TOU charging increases curtailment relative to unmanaged charging because of a load mismatch with times of high RE generation. With smart charging, the ability of PEVs to reduce RE curtailment is limited by the number of multi-hour, midday charging opportunities without queues at workplace or public chargers.

These grid impacts are specific to the California system, and will also ultimately depend on the evolution of the generation mix, curtailment-reduction policies (such as better coordination with neighboring balancing areas), distributed energy resources (such as other "smart" loads), and flexible supply-side resources (such as stationary battery storage). Nonetheless, most regions with aggressive PEV adoption can benefit from smart or TOU charging strategies to avoid operating and capital costs by reducing peak loads.

For SAEV fleets, the researchers found that all mobility in the United States currently served by 276 million personally owned vehicles could be served by 12.5 million SAEVs at a cost of $0.27/vehicle-mile or $0.18/passenger-mile. The energy requirements for this fleet would be 1142 GWh/day (8.5% of 2017 U.S. electricity demand) and the peak charging load 76.7 GW (11% of U.S. power peak).

Conclusions

This study unified (1) the BEAM model, which produces realistic PEV charging simulations incorporating driver behavior, mobility patterns, and detailed charging infrastructure constraints, with (2) PLEXOS®, which optimizes the power system dispatch with the addition of PEVs to estimate transmission-level impacts of unmanaged and managed PEVs. The research team evaluated the system cost and RE curtailment impacts of the addition of 0.95 million PEVs (4% of California's current vehicle stock) to 5.0 million PEVs (20% of California's vehicle stock) PEVs under unmanaged, smart and TOU charging strategies on the California power system, with the assumption that the state would meet its 50% Renewable Power Standard mandate.

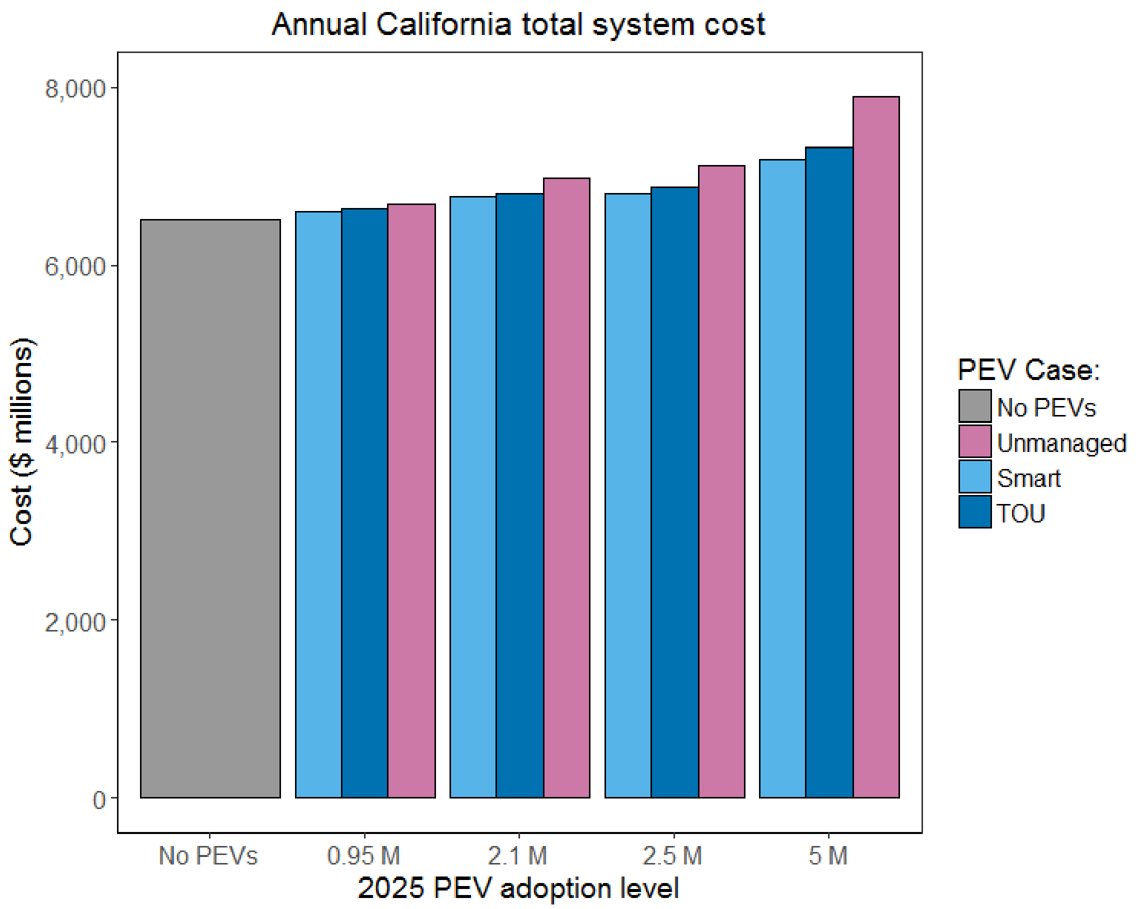

Figure III.2.II California 2025 annual total system costs

Remaining Research Gaps:

There are many areas remaining for further research on the impacts of managed charging on the grid, including:

- Testing different PEV adoption forecasts and different PEV fleet composition (e.g., vehicles with longer range).
- Testing different charging infrastructure scenarios, including the emphasis on fast versus slow charging, and added workplace charging infrastructure.
- Simulating the participation of aggregated PEV fleets in other grid services such as regulation and load-following through vehicle-to-grid.
- Testing different renewable generation mixes.
- Testing the impact of competing sources of grid flexibility including increased storage and DR, varied curtailment assumptions, and higher net export limits.

Finally, there are also many policy changes happening concurrently in California and the Western Electricity Coordinating Council, which could impact the conclusions of this study. For example, California is already coordinating with neighboring balancing areas through the Energy Imbalance Market, which could alleviate some of the curtailment problems highlighted here [1]. CAISO may also expand to other parts of the Western Electricity Coordinating Council, and there may be an increase in DR and load management from other end-uses besides PEVs to cope with curtailment. Lastly, there is a push to move residential electric customers in California to opt-out TOU rates in the next few years [2], which may incentivize load shifting during these curtailment periods, without the use of actively managed PEVs.

Key Publications

1. Sheppard, C., Szinai, J., Abhyankar, N., and Gopal, A. "Grid Impacts of Electric Vehicles and Managed Charging in California: Linking Agent-Based Electric Vehicle Charging with Power System Dispatch Models." Lawrence Berkeley National Laboratory, Report Forthcoming Fall 2018.
2. Szinai, J, Sheppard, C., Abhyankar, N., and Gopal, A. "Managing electric vehicle charging can reduce renewable energy curtailment and the cost of grid operations." Journal article, expected submission November, 2018.

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1. Golden, R., and Paulos, B. 2015. "Curtailment of Renewable Energy in California and Beyond," *Electr. J.*, vol. 28, no. 6, pp. 36–50, Jul. 2015.
2. John, J. 2017. "California's Flood of Green Energy Could Drive a Record 8GW of Curtailment This Spring," 21-Mar-2017. [Online]. Available: https://www.greentechmedia.com/articles/read/californias-flood-of-green-energy-could-drive-a-record-6-to-8-gigawatts-of. [Accessed: 06-Apr-2017].

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III.3 Modeling Framework and Results to Inform Charging Infrastructure Investments

Eric Wood, Principal Investigator
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
E-mail: Eric.Wood@nrel.gov

Matteo Muratori, Principal Investigator
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
E-mail: Matteo.Muratori@nrel.gov

Rachael Nealer, DOE Technology Manager
U.S. Department of Energy
E-mail: Rachael.Nealer@ee.doe.gov

Start Date: October 1, 2015 End Date: September 30, 2019
Project Funding (FY18): $625,000 DOE share: $625,000 Non-DOE share: $0

Project Introduction

The electrification of the transportation sector is poised to provide several benefits, including reducing the local and global environmental impact of the sector, currently the largest single carbon dioxide emitter in the United States, and significantly improving U.S. energy security, offering greater fuel diversity in a market currently dominated by a single energy source. Widespread market adoption of passenger plug-in electric vehicles (PEVs), however, requires major technology, market, consumer-attitude, and infrastructure advancements. This project focuses on barriers associated with charging infrastructure that, if overcome, could enable increased PEV sales.

Objectives

This project has multiple objectives revolving around PEV charging infrastructure:

- **EVI-Pro Lite:** Develop a public-facing web-based tool, Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite (https://www.afdc.energy.gov/evi-pro-lite), for projecting consumer demand for electric vehicle (EV) non-residential charging infrastructure.
- **PEV Charging Cost:** Develop tools and methodologies to assess the overall life-cycle levelized cost of PEV charging, including residential, workplace, public L2, and direct current fast charging (DCFC) cost options. Evaluate alternative design options to mitigate electricity costs for public DCFC stations, including on-site solar generation and electrical energy storage.
- **VTO Benefits Timing Analysis:** Assess how the timing of individual VTO technology advancements impact national-level PEV sales, energy, and emission benefits using the Automotive Deployment Option Projection Tool (ADOPT).
- **Future of Charging Infrastructure Benefits Analysis:** Estimate the electric vehicle adoption, cost, energy, and emission benefits from dynamic power transfer (e.g., using catenary, capacitive or inductive technology) with sensitivity to VTO technology targets and stationary electric vehicle supply equipment (EVSE) rollout.
- **Residential Charging Accessibility:** Estimate national accessibility to residential charging using publicly available data from the U.S. Census on residence types, tenure, household income, and vehicle ownership.

EVI-Pro Lite

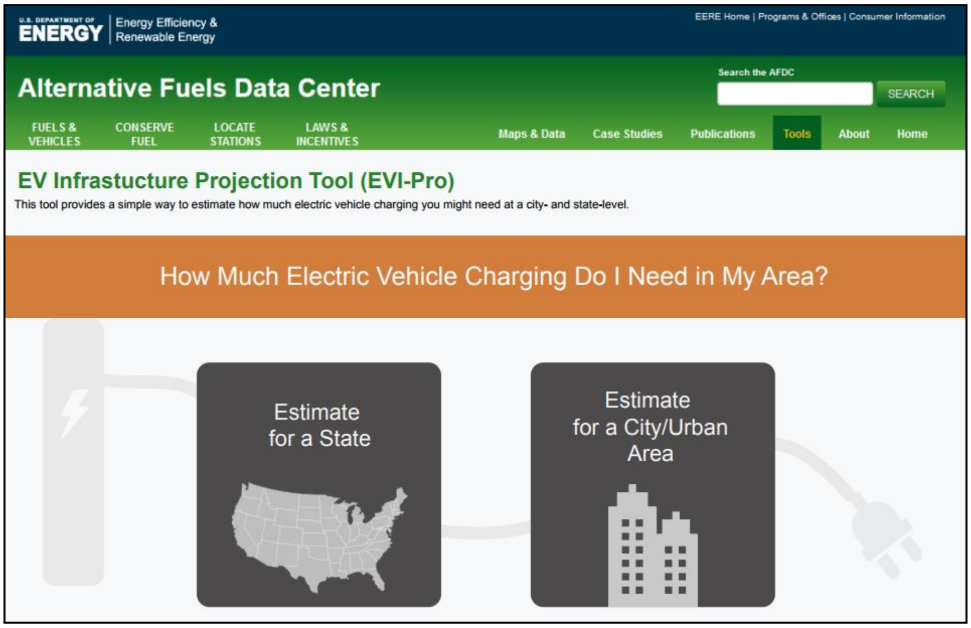
Estimating non-residential electric vehicle supply equipment (EVSE) requirements in rapidly evolving PEV markets is a technical challenge that state and city planners currently struggle with, particularly in light of the significant opportunities being made available through investments by Electrify America and others.

PEV charging infrastructure requirements—the number of charging stations and plugs required to provide a convenient and ubiquitous network of PEV charging opportunities—will evolve as PEV adoption increases. In particular, two driving forces characterize the charging infrastructure required to support a growing fleet of PEVs:

1. A basic level of geographic coverage is required to guarantee nationwide charging opportunities and enable long-distance travel for battery electric vehicles (BEVs).
2. Over time, a larger network of charging stations will be required to satisfy growing charging demand, increasing non-linearly with PEV market share.

EVI-Pro Lite is a simplified version of the EVI-Pro model. EVI-Pro was developed through a collaboration between the National Renewable Energy Laboratory (NREL) and the California Energy Commission, with additional support from the DOE's VTO. EVI-Pro uses detailed data on personal vehicle travel patterns, EV attributes, and charging station characteristics in bottom-up simulations to estimate the quantity and type of charging infrastructure necessary to support regional adoption of EVs.

EVI-Pro Lite is organized around the non-residential EVSE network required to satisfy consumer demand in low PEV share adoption scenarios (less than 10% of light-duty stock as PEVs). Charging demand estimates needed to serve growing PEV markets are made at either the state- or city-level based on user inputs for the number and type of PEVs anticipated in the region. The tool relies on the results of advanced PEV simulations using EVI-Pro run over millions of miles of real-world daily driving schedules. Technical considerations were made for the spatial density of PEVs, ambient temperature effects on electric driving range, and frequency of long-distance driving days requiring non-residential EVSE. Charging at non-residential stations is simulated on an as-necessary basis, such that consumers are able to maximize EV miles traveled. A screenshot of the EVI-Pro Lite splash page is shown in Figure III.3.I.



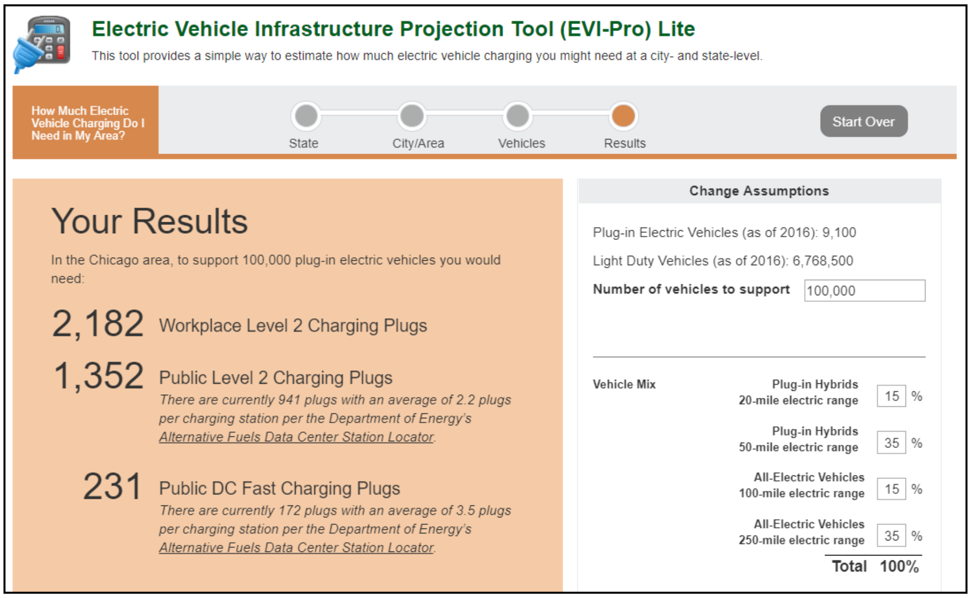
EV Infrastucture Projection Tool (EVI-Pro)

This tool provides a simple way to estimate how much electric vehicle charging you might need at a city- and state-level.

How Much Electric Vehicle Charging Do I Need in My Area?

Figure III.3.I Screenshot of the EVI-Pro Lite splash page.

EVI-Pro Lite went live as an application on the DOE Alternative Fuels Data Center in May 2018. Shortly thereafter, NREL led a public webinar to release/demonstrate the tool and address users' questions. The webinar was attended by approximately 150 individuals representing various state and local planning agencies. During the first five months online, EVI-Pro Lite received more than 3,900 pageviews with users spending on average over four minutes on the page (approximately four times longer than the average AFDC page visit). Anecdotally, NREL has received positive feedback from users representing state and local planning agencies, electric utilities, and automotive manufacturers. A screenshot of the results page for EVI-Pro Lite is shown in Figure III.3.II for a scenario with 100,000 PEVs in Chicago.



Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite

This tool provides a simple way to estimate how much electric vehicle charging you might need at a city- and state-level.

Your Results

In the Chicago area, to support 100,000 plug-in electric vehicles you would need:

2,182 Workplace Level 2 Charging Plugs

1,352 Public Level 2 Charging Plugs

There are currently 941 plugs with an average of 2.2 plugs per charging station per the Department of Energy's Alternative Fuels Data Center Station Locator.

231 Public DC Fast Charging Plugs

There are currently 172 plugs with an average of 3.5 plugs per charging station per the Department of Energy's Alternative Fuels Data Center Station Locator.

Plug-in Electric Vehicles (as of 2016): 9,100

Light Duty Vehicles (as of 2016): 6,768,500

Number of vehicles to support: 100,000

Vehicle Mix		
	Plug-in Hybrids 20-mile electric range	15 %
	Plug-in Hybrids 50-mile electric range	35 %
	All-Electric Vehicles 100-mile electric range	15 %
	All-Electric Vehicles 250-mile electric range	35 %
	Total	100%

Figure III.3.II Screenshot of the results page for EVI-Pro Lite for a scenario with 100,000 PEVs in Chicago.

Regardless of geographic scope, the EVI-Pro Lite tool results suggest that organizations planning for charging infrastructure to support consumer adoption of PEVs need to be aware of the importance of consumer preferences with respect to electric range and charging behavior. Furthermore, planners should focus on providing consumers with adequate charging coverage (particularly DCFC supporting adoption of BEVs) while monitoring station utilization over time and increasing charging capacity (both in terms of the rated charging station output power and number of plugs) as the PEV market continues to grow.

PEV Charging Cost

Previous studies and empirical evidence also show that the cost of electricity for DCFC stations can vary widely depending on the station characteristics, location, and utilization level [1]. Fixed and demand charges can lead to very high electricity costs under low DCFC utilization levels, potentially in excess of $2 per kilowatt-hours, that could undermine the DCFC business case [2].

Using NREL's Utility Rate Database and REopt model, the NREL research team evaluated the economic opportunities associated with on-site solar generation and energy storage, under thousands of electricity rates available in the U.S. and several PEV charging load scenarios. REopt is a techno-economic time series model that provides concurrent, multiple technology integration and optimization capabilities. Formulated as a mixed integer linear program, the REopt model identifies the optimal mix of candidate technologies, their respective technical specifications, and provides the dispatch strategy for operating these technologies at maximum economic efficiency. Most studies assume that average residential electricity pricing applies to driving a PEV. However, PEVs can be charged at different locations (home, workplace, public stations), using different power levels, and at different times of the day, which would allow leveraging cheaper time-of-use electricity prices. These dimensions lead to a wide range of costs for PEV charging. NREL researchers are building out capabilities to more accurately evaluate the cost of electricity to power PEVs across a range of locations, power levels, and times of day. This information is key to providing a holistic view of the tradeoffs in costs, energy, and time associated with VTO charging targets. The results of this work are relevant to the Beyond Batteries effort and the Mobility Energy Productivity work at NREL.

The cost of electricity for PEV fast charging varies greatly for different locations and station designs/usage. Low load factors (driven by low utilization with a low number of vehicles charging per day and/or low energy charged per charging event), results in very high electricity costs, particularly for rates with demand charges. However, the monthly and per vehicle cost of electricity decreases rapidly as charging station use increases. Optimal site design, including the use of DCFC in conjunction with other technologies such as energy storage and solar photovoltaic (PV), also offers additional opportunities to mitigate electricity cost. Significant cost savings can be achieved depending on the charging station location (including variations in electricity rates available and solar resource) as well as use and size of DCFC stations. Energy storage alone can help to mitigate demand charges and is more effective at reducing costs for "peaky" or low-utilization loads. PV systems primarily help to mitigate electricity energy charges and are more effective for loads that are more correlated with solar production. Still, high energy charges are the main driver of PV investment, even in areas with lower solar resource. Energy storage and PV can deploy synergistically to provide cost reductions for DCFC leveraging their ability to mitigate both demand and energy charges.

Figure III.3.III shows the median fixed, demand, and energy charges at sites where PV and/or energy storage could reduce electricity cost before (left-most bar) and after (right-most bar) technology implementation for four load scenarios (station size and electricity demand increases from Load A to Load D scenarios, as described in [1]), along with cost reductions in energy and demand charges in a waterfall format. DCFC electricity cost analysis in this project reviewed the current cost of electricity for PEV\ fast charging in the United States and assessed opportunities to use energy storage and PV systems to reduce the total system operating cost. Based on over 7,000 commercial electricity rates currently available, electricity cost was shown to vary greatly. In particular, at low electricity use, rates with demand charges show high average cost of electricity that decrease rapidly as utilization increases because fixed and demand charges are spread among a higher number of kilowatt-hours.

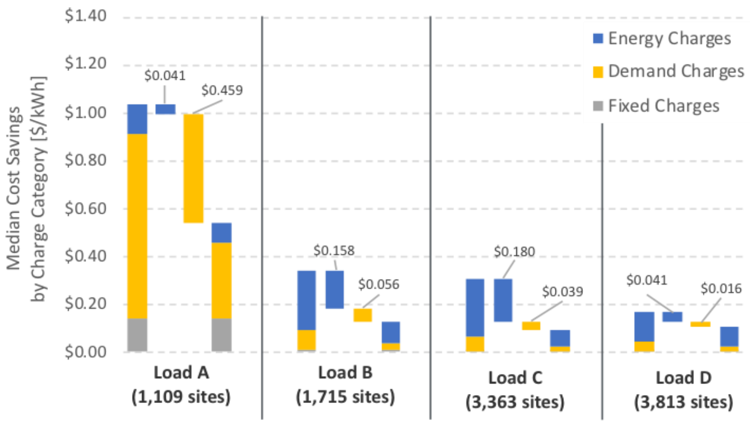


Figure III.3.III Median cost savings by category and load scenario for all sites where PV and/or energy storage were implemented. For each load scenario, the left bar shows median electricity cost when all electricity is purchased from the grid, the right bar shows the median cost achieved with technology implementation, and the waterfall bars highlight savings by charge category.

For some locations, these high costs can be mitigated by using technology solutions. This is particularly important in the near-term as the PEV customer base and charging station business cases evolve. The technology focus is on installing DCFC stations in conjunction with PV systems and/or energy storage (electrochemical battery). Significant cost savings can be achieved depending on location (including variations in electricity rates available and solar resource) as well as the use and power capacity of DCFC stations. Energy storage alone can help to mitigate demand charges and is more effective at reducing costs for “peaky” or low-utilization loads. However, the project’s results show that the decision to use energy storage alone is fairly insensitive to DCFC load, even though cost savings decrease for larger, higher utilization charging loads. On the other hand, PV systems primarily help to mitigate energy charges, and are more effective for loads that are more correlated with solar production in areas with lower solar resource. Energy storage and PV systems can be used synergistically to provide cost reductions for DCFC leveraging their ability to mitigate demand and energy charges.

Figure III.3.IV maps the variation of energy and demand charges as well as the technology recommendation for Load B. Results show that high energy charges are the main driver of PV investment, even in areas with lower solar resource (e.g., Vermont), though high solar resource (in combination with moderate energy charges) are driving some investment in the southwest. High demand charges are the primary drivers of energy storage investment. While intuitive, these maps illustrate the variability of energy and demand charges for scenario Load B and the geographic distribution of technology implementation to mitigate DCFC electricity cost. Similar results were seen for other load scenarios considered.

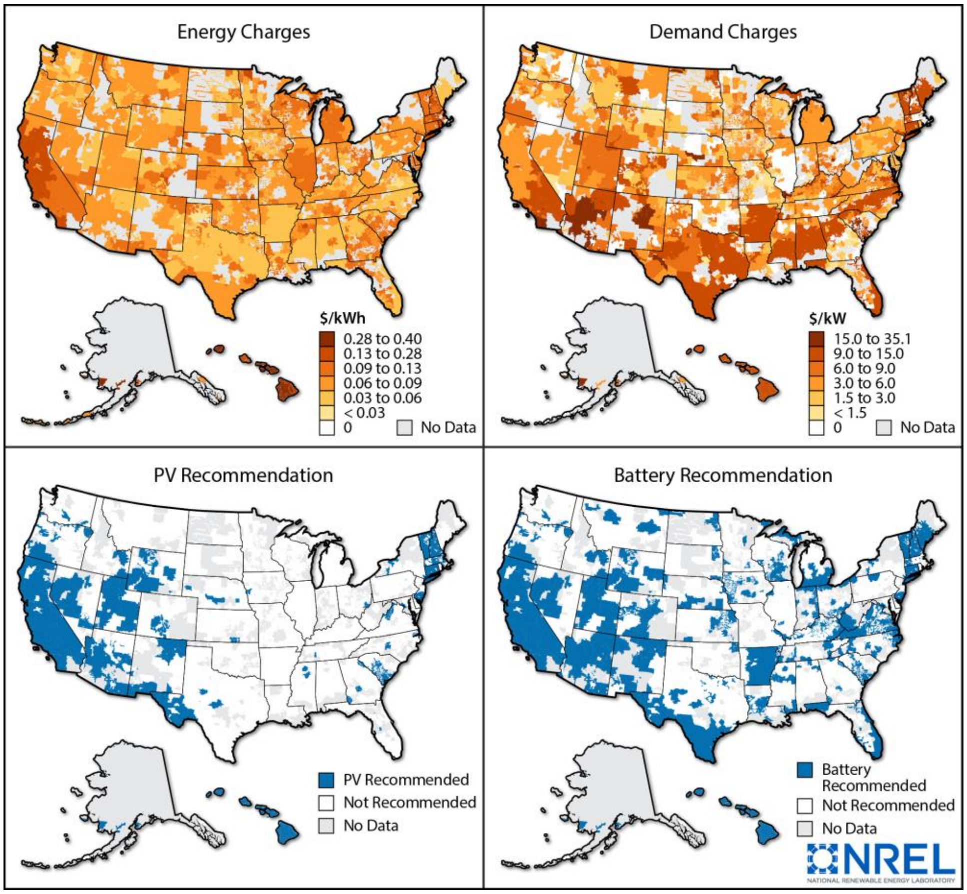


Figure III.3.IV Geographic distribution of energy and demand charges as well as the technology recommendation.

In general, technology solutions are effective at reducing electricity cost for DCFC at locations with high energy and/or demand charges, to reduce the overall average cost of electricity for fast PEV recharging. This study considered existing electricity rates and did not speculate on possible future electricity rates targeting DCFC that could provide lower electricity cost. Moreover, DCFC stations can pursue additional revenue streams that are not considered in this study including provision of grid services with the PV or energy storage and credits for producing a renewable fuel or exporting renewable electricity with the PV systems.

VTO Benefit Timing Analysis

The VTO Benefits Timing Analysis estimates the national-level sales, energy, and emission benefits of VTO technology advancements, how quickly they are achieved, and specific technology areas. The estimates are being made using the Automotive Deployment Option Projection Tool (ADOPT). ADOPT is VTO's highest scoring consumer choice model because it starts with all the existing vehicle options for a realistic representation of the market, validates extensively with past sales, evolves future vehicle options based on market conditions, captures the influence of policy such as incentives and regulations, and provides comprehensive transparency of inputs and results.

Preliminary results (based on vehicle component technology progress, but not substantial changes in electric vehicle range anxiety or recharging inconvenience that may result from expanded fast-charging infrastructure) show that achieving VTO's vehicle component technology goals has significant benefits, as shown in Figure III.3.V. Similar benefits were seen when achieving just the PEV-related technology targets, including those related to the battery and electric motor.

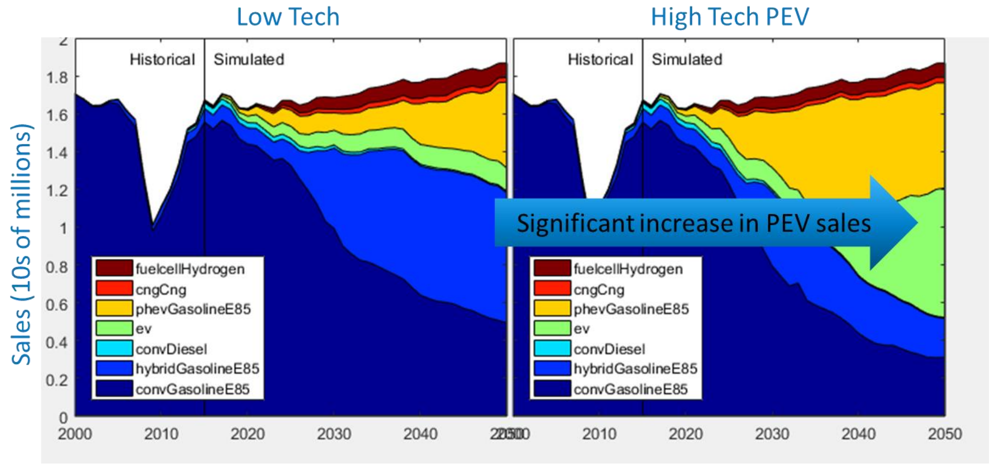


Figure III.3.V: Baseline VTO PEV sales benefits (preliminary results)

Achieving the technical targets at a slower rate significantly reduces the PEV sales, as shown in Figure III.3.VI.

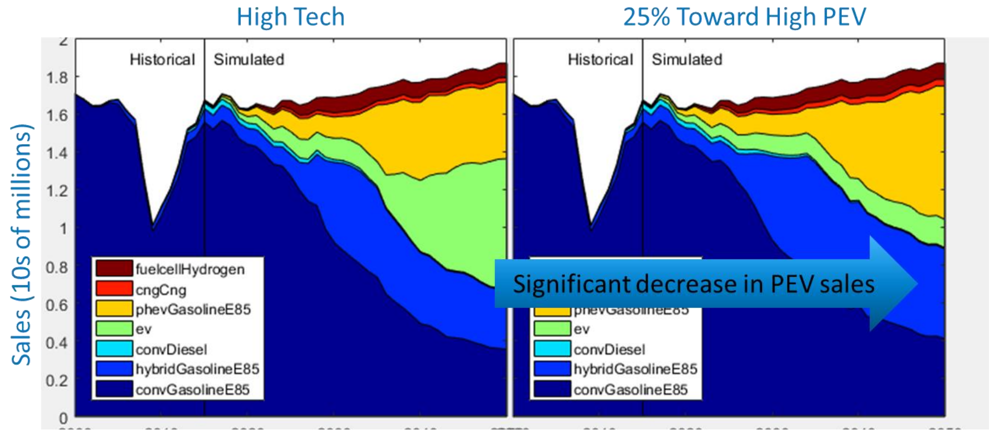


Figure III.3.VI: Baseline VTO benefit compared to achieving the technical targets over a longer timeframe (preliminary results)

Future of Charging Infrastructure Benefits Analysis

The NREL research team is also using ADOPT to estimate the impact of dynamic power transfer (DPT) (e.g., using catenary, capacitive or inductive technology) on cost to the consumer, PEV sales, energy, and emissions. The team is considering:

- Dynamic power transfer (DPT: catenary/capacitive/inductive) (previous analysis has shown that deployment on interstates/highways would cover 1% of roadways but 22% of travel)
- Sensitivity of VTO component technology goals on DPT
- Impact comparison of DPT with additional stationary level 2 charging (L2) and/or DC fast charging (DCFC)

The objective of this work is to assess different PEV charging infrastructure rollout strategies, especially related to DPT. Estimates of market share, cost, energy, and emission benefits from different types and amounts of charging infrastructure are being developed.

The value and cost of DPT is being added to ADOPT. The cost to the consumer is based on the level of power transfer to the vehicle, and the benefit varies by powertrain. For PHEVs, the benefit is reduced fuel cost for scenarios where DPT electricity use costs less than charge sustaining gasoline use. For BEVs, the benefit is an increase in effective range, or conversely a reduction in the range/recharge time penalty. This enables ADOPT to optimize future BEV batteries to a smaller and less expensive size without incurring consumer preference penalties with respect to range and recharge time.

Preliminarily ADOPT results show DPT significantly increasing BEV sales, and corresponding energy and emission benefits.

Residential Charging Accessibility

Finally, NREL is taking a critical look at U.S. residential charging availability. The promise of PEVs – zero tailpipe emissions, low operating cost, quiet operation, instant torque – remain elusive for consumers with inconsistent access to home charging. Lack of EVSE at multi-unit dwellings (MUDs), combined with sparse networks of DCFC, leave large segments of potential PEV consumers islanded without the charging infrastructure necessary to consider buying a PEV. Despite comprising a substantial percentage of U.S. population in areas with generally PEV-favorable demographics, analysis studies often treat MUDs in an ad-hoc manner given the unique ownership challenges they present. NREL's analysis is focused on highlighting challenges associated with PEV ownership in MUDs with an emphasis on solutions that could unlock large markets of potential PEV customers.

Key Publications

1. Wood, E., Raghavan, S., Rames, C., Eichman, J., and Melaina, M. 2017. "Regional Charging Infrastructure for Plug-in Electric Vehicles: A Case Study of Massachusetts." NREL Technical Report NREL/TP-5400-67436, Available at: http://www.nrel.gov/docs/fy17osti/67436.pdf

2. Wood, E., Rames, C., Muratori, M., Raghavan, S., Melaina, M. 2017. "National Plug-In Electric Vehicle Infrastructure Analysis" Report from the US DOE Office of Energy Efficiency and Renewable Energy, September 2017, https://www.nrel.gov/docs/fy17osti/69031.pdf

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4. Muratori, M., Kontou, E., Eichman, J. "Understanding Electricity Rates for Electric Vehicle Direct Current Fast Charging." Under review by Renewable and Sustainable Energy Review.

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