Real-World PHEV Fuel Economy Prediction

DOE Annual Merit Review
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Organization: NREL

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PHEV = plug-in hybrid electric vehicle
• Estimating PHEV fuel economy on standard cycles is complicated
  – Issues: Fuel and electricity use; CD and CS operation
  – Extensive procedure development (ANL led, NREL et al. support)
• “Raw” standardized test results do not represent real-world
  – Objective in-use predictions critical for technology assessment
• Real-world fuel economy prediction is also complicated
  – Which drive cycles to use and how to combine the results
  – Changing rate of fuel and/or electricity use
  – Considerations for CD vs. CS mode
  – Potential variation in depletion distance
  – Appropriately weighting each operating mode
  – Impact from different powertrain topologies
• Project is developing various options, evaluating strengths/weaknesses and recommending preferred approach(es)

CD = charge depleting; CS = charge sustaining
Project Overview

Timeline
Activities specific to current effort:
- Started late 2009
- Ending late 2011
- Project is 60% complete

Budget
Corresponding funding:
- Total (all DOE): $250k
  - FY11: $100k
  - Prior: $150k

Barriers Addressed
- Lack of standardized test protocols
- Real-world performance prediction
  - Assess realistic fuel savings
  - Justify development costs
  - Set reasonable expectations
- Simulation and prediction methodologies

Project Partners
- ANL (procedures & dyno testing)
- SAE J1711 task force (procedures)
- INL (field evaluation results)
Project Relevance

Important to understand real-world energy use

• Address barriers from overview slide
  – Lack of standardized protocols
  – Simulation and prediction methodologies
  – Set expectations prior to developing/deploying each vehicle generation

• Objective technology evaluation

• PHEV fuel economy very sensitive to driver behavior
  – Driving aggressiveness and accessory loads
  – Distance driven between recharge opportunities
    • CD vs. CS proportioning
Elaborating on Project Relevance

Established real-world prediction for CVs/HEVs
(No consensus approach for PHEVs!)

- Existing standard vehicle test procedures
  - E.g., Federal Test Procedure (FTP or city test) and Highway Fuel Economy Test (HFET)
  - “Raw” result for Prius $\approx 3.4 \text{ L/100 km} \ (\approx 70 \text{ mpg})$

- Official adjustments to raw results
  - EPA window sticker estimate
  - Provides reasonable real-world prediction

CV = conventional vehicle
HEV = hybrid electric vehicle
PHEV Fuel Economy Milestones/Outputs

SAE standards (ANL led, NREL et al. supported)

- 9/10 – SAE J2841: Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data

NREL deliverables to DOE on real-world evaluation

- 6/10 – Multi-day GPS Travel Survey Data Report: Using GPS Profiles, Including Multi-day, to Assess PHEV Fuel Efficiency
- 9/11 – Report on Real-World PHEV Fuel Economy Prediction
Project Approach

Building Blocks

• Revise PHEV calculation procedures for standard test cycles

• Identify in-use fuel economy issues and basic prediction options
  – Evaluate against aftermarket conversion PHEV test data

• Develop vehicle simulations over large real-world driving sample
Project Approach

Develop details for variety of prediction approaches

- Based on different standard cycle options (CD & CS tests)
  - Just using historic city and highway cycles
  - City/hwy plus US06 (adds aggressiveness component)
  - Full 5-cycle test (adds temperature/accessory load component)
Evaluate the potential prediction approaches

- Confirm real-world simulations provide reasonable basis
  - Adjusted CV and HEV certification tests vs. real-world results
- Consider issues with different PHEV powertrain designs
- Summarize strengths and weaknesses of different approach options
- Also evaluate against automaker PHEV data
  - E.g., as results become available from DOE’s PHEV Technology Acceleration and Deployment Activity (TADA)
Progress made in a variety of areas

- Revising standard cycle calculation procedures
- Understanding real-world prediction issues
- Developing basic adjustment options with simplifying assumptions
  - Using “MPG-based approach” with historic city and highway cycles
    \[
    \text{City MPG} = \frac{1}{0.003259 + \frac{1.1805}{\text{FTP FE}}} \quad \text{Highway MPG} = \frac{1}{0.001376 + \frac{1.3466}{\text{HFET FE}}}
    \]
- Applying one option to aftermarket conversion PHEV data
- Leveraging on-road GPS cycles to evaluate other powertrains
- Performing utility factor analysis with diverse multi-day data sets
- Further adjustment method development
- Confirming existing CV and HEV adjustment methods agree with corresponding distribution of real-world simulation results

MPG = miles per gallon; FTP = Federal Test Procedure; HFET = Highway Fuel Economy Test; FE = fuel economy in mpg
Technical Accomplishments

Supported J1711 revision to address PHEV testing issues

- Repeat cycles for full CD and CS testing
- Measure both fuel and electricity, and keep separated
- Combine modes using a utility factor (UF) and once daily charging assumption
- Obtain “raw” L/100 km (mpg) and kWh/100 km (Wh/mi) values for given test cycle

Combined consumption, C:
\[ C_{\text{Total}} = C_{\text{CD}} \times UF(D) + C_{\text{CS}} \times (1 - UF(D)) \]

SOC: Vehicle battery’s state-of-charge
NHTS: National Household Travel Survey
Technical Accomplishments

Understanding PHEV real-world adjustment issues
(Adjustments represent additional road loads vs. historic cycles)

- CS mode will use more fuel (straight forward)
- CD mode will use more fuel and/or change battery depletion rate
  - This impacts fuel, electricity and depletion distance for UF calculations

![Graph showing SOC and Fuel Consumption Rate]

Test Cycle: ___________________

More-Aggressive “Real-World”: ___________________
(with uncertain relative fuel and kWh impacts)
Technical Accomplishments

Develop potential methods via simplifying assumptions
E.g., “blended”/constant depletion rate method

- Apply adjustment equation to CS result
- Retain the same UF-weighting distance from the actual test cycle results
- Assume “extra road loads” simply add CD fuel consumption at the same rate increment as for CS driving
- Actual PHEV may deplete slower or faster in the real-world
Technical Accomplishments

Evaluate “blended method” against Hymotion Prius data

- In collaboration with ANL and INL
- Works well for blended PHEV; may not work as well for other designs
Technical Accomplishments

Leverage on-road drive cycles for PHEV evaluation

• Travel surveys increasingly use GPS (e.g., to aid regional transportation planning)
  – Improved technology and cost
  – Better accuracy and respondent burden

• Data sets from Texas DOT
  – 783 vehicles in San Antonio and Austin, TX
  – Collected in 2006
  – 24-hr, sec-by-sec drive profiles
  – Capture real-world aggressiveness and distances driven between stops
Technical Accomplishments

Assess different scenarios via simulation

**Mid-size car assumptions**

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<th>Units</th>
<th>CV</th>
<th>HEV</th>
<th>10</th>
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Average results (distance-weighted) from real-world simulations
Collaboration and Coordination

• ANL – procedure development and chassis dynamometer testing

• SAE J1711 – task force participation

• VSATT – present potential approaches

• EPA – share approach presentations; comment on proposed rulemaking

• INL – past and potential future fleet evaluation data sharing

USCAR = U.S. Council for Automotive Research LLC; VSATT = Vehicle Systems Analysis Technical Team
Future Work

FY11

• Complete remainder of project plan
• Deliver milestone to DOE
• Recommend preferred prediction approach(es)
  – Based on strengths and weaknesses of considered options

Options for Future

• Further evaluation against automaker PHEV fleet demonstration data
• Develop better test cycle(s) to represent real-world
  – Leverage NREL fleet duty cycle evaluation tool
Reiterating Project Plan

Details for developing and evaluating potential real-world prediction approaches

- Based on different standard cycle options (CD & CS tests)
  - Just using historic city and highway cycles
  - City/hwy plus US06 (adds aggressiveness component)
  - Full 5-cycle test (adds temperature/accessory load component)
- Confirm real-world simulations provide reasonable basis
  - Adjusted CV and HEV certification tests vs. real-world results
- Consider issues with different PHEV powertrain designs
- Analyze/examine results to identify strengths and weaknesses
• Estimating PHEV fuel economy on standard cycles is complicated
  – Issues: Fuel and electricity use; CD and CS operation
  – Extensive procedure development (ANL led, NREL et al. support)
• “Raw” standardized test results do not represent real-world
  – Objective in-use predictions critical for technology assessment
• Real-world fuel economy prediction is also complicated, e.g.:
  – Adjust rate of fuel and/or electricity use in each operating mode, as well as depletion distance for CD vs. CS weighting
  – Different impacts for different powertrain topologies (blended vs. “EREV”/high electric power PHEV)
• Project is developing various options, evaluating strengths/weaknesses and recommending preferred approach(es)

EREV = extended range electric vehicle
Special thanks to:
• Lee Slezak and David Anderson, DOE Vehicle Technologies Program

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Questions?
Technical Back-Up Slides
Description of Additional Accomplishments and Related/Synergistic Activities
Technical Accomplishments

Develop potential methods via simplifying assumptions
E.g., “All-electric”/CD distance reduction method

- CS fuel use can be adjusted as normal
- Only adjust electricity in CD mode (problematic to calculate)
- If made, adjustment yields new UF distance (usable energy depleted faster)
- But, result could be unachievable if motor/battery power insufficient to deplete energy over shorter distance
Technical Accomplishments

Examine UF options with multi-day data

• Fleet (distance-weighted) vs. individual (vehicle-weighted) predictions
  – Individual expected value should use multi-day data

SD/MDIUF = single-day/multi-day individual utility factor

FUF = fleet utility factor
Technical Accomplishments

Examine UF options with multi-day data

- Similar trends from additional regional data set, but offset
  - Other data/statistical expansion required

PSRC = Puget Sound Regional Council, data from 18 mo. Seattle area Traffic Choices Study
NREL Fleet Duty Cycle Tool Capabilities

Analyze and Characterize
- Calculates over 150 unique driving statistics
  - Stats for both raw data and generated test cycle
  - Max Speed, Average Speed, Stops per Mile, etc.
  - Filters and corrects for data errors
- Finds closest existing cycle.
  - Matched based on user selected driving statistics

Visualize
- Displays graphs, tables, and histograms of drive data
  - Graphs speed vs. time
  - Tabulates driving statistics
  - Acceleration histograms
- Creates Latitude and Longitude files for route visualization
  - Use Latitude and Longitude output to create route maps with Google Earth or other mapping software

Test Cycle Generation
- Generates custom duration test cycles for simulation and modeling
  - Cleans raw source data prior to custom test cycle creation
  - Outputs custom cycle speed vs. time points for dynamometer testing
Transportation Secure Data Center (TSDC)
www.nrel.gov/vehiclesandfuels/secure_transportation_data.html

Secure archival of and access to detailed transportation data
  – Travel studies increasingly use GPS → valuable data
  – TSDC safeguards anonymity while increasing research returns

Various TSDC functions
  – Advisory group supports procedure development and oversight
  – Original data securely stored and backed up
  – Processing to assure quality and create downloadable data
  – Cleansed data freely available for download
  – Controlled access to detailed spatial data
    • User application process
    • Software tools available through secure web portal
    • Aggregated results audited before release

Sponsored by the U.S. Department of Transportation (DOT)
Operated by the NREL Center for Transportation Technologies and Systems (CTTS); Contact: Jeff.Gonder@nrel.gov

GPS = global positioning system
* See recommendations from this 2007 National Research Council report: books.nap.edu/openbook.php?record_id=11865