NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Real-World PHEV Fuel Economy Prediction

DOE Annual Merit Review

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Organization: NREL

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Project ID: VSS047

This presentation does not contain any proprietary, confidential or otherwise restricted information

PHEV = plug-in hybrid electric vehicle

Up-Front Summary

- 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

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

Budget

Corresponding funding:

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

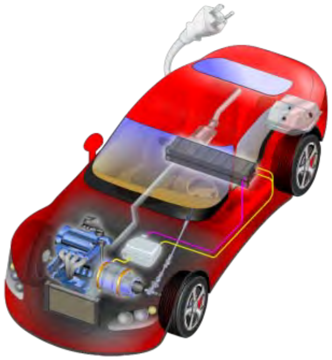
Project Partners

- 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



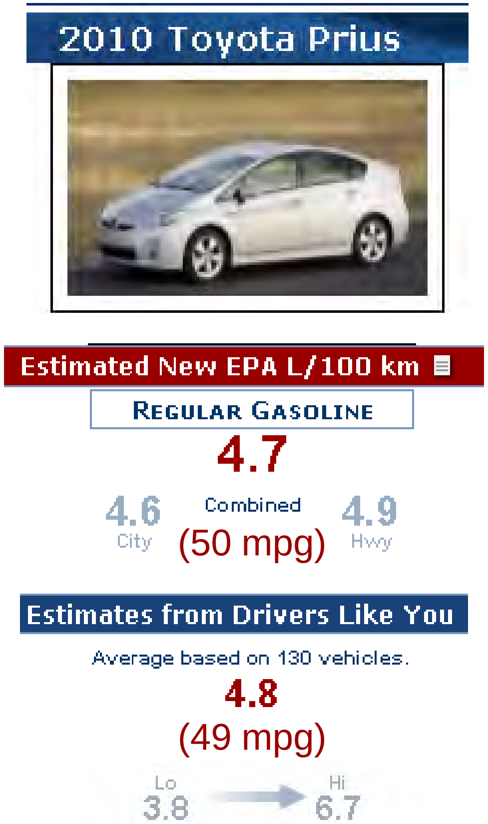
Elaborating on Project Relevance

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 ≈ 3.4 L/100 km (≈ 70 mpg)
- Official adjustments to raw results

  - EPA window sticker estimate
  - Provides reasonable real-world prediction



CV = conventional vehicle
HEV = hybrid electric vehicle

Picture and data accessed 3/3/2011 from www.fueleconomy.gov

PHEV Fuel Economy Milestones/Outputs

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

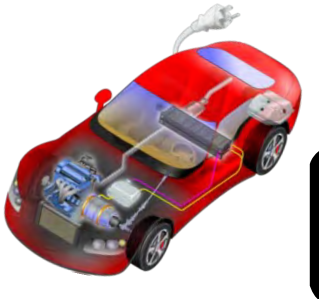
- 6/10 – SAE J1711: Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles
- 9/10 – SAE J2841: Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data

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

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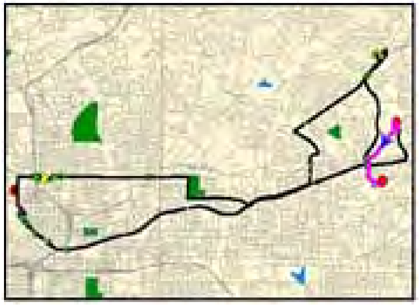
- Identify in-use fuel economy issues and basic prediction options
  - Evaluate against aftermarket conversion PHEV test data

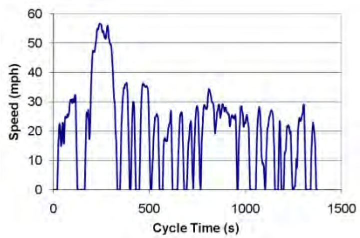


- Develop vehicle simulations over large real-world driving sample

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



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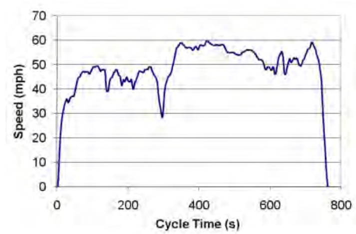

  - City/hwy plus US06 (adds aggressiveness component)

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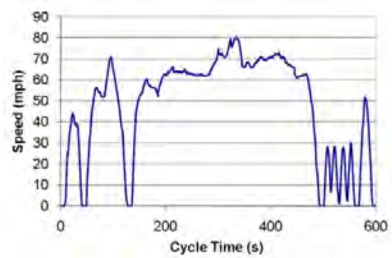

  - Full 5-cycle test (adds temperature/accessory load component)

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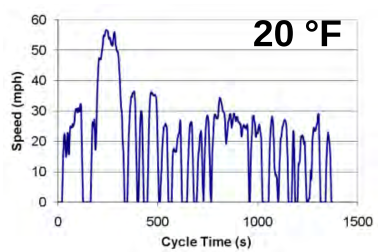

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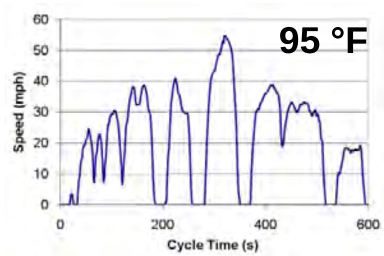

Project Approach

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)

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Technical Accomplishments

Progress made in a variety of areas

Detailed on following slides

- 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

$$\text{City MPG} = \frac{1}{\left(0.003259 + \frac{1.1805}{\text{FTP FE}}\right)} \qquad \text{Highway MPG} = \frac{1}{\left(0.001376 + \frac{1.3466}{\text{HFET FE}}\right)}$$

- 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

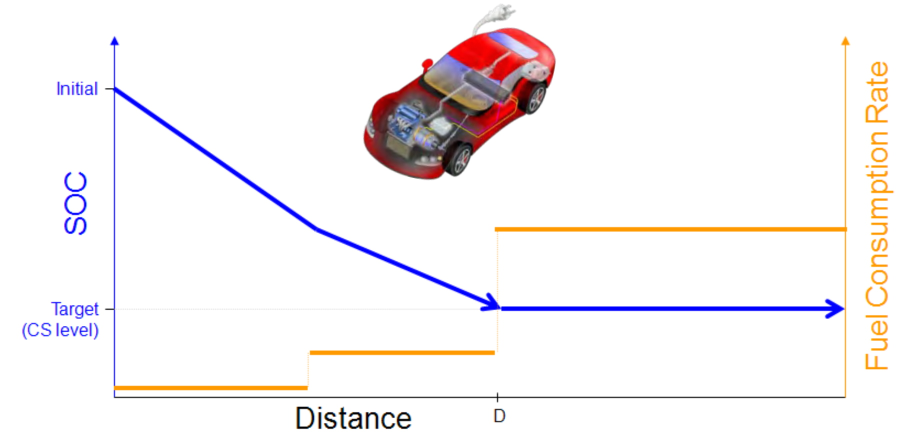
MPG = miles per gallon; FTP = Federal Test Procedure; HFET = Highway Fuel Economy Test; FE = fuel economy in mpg

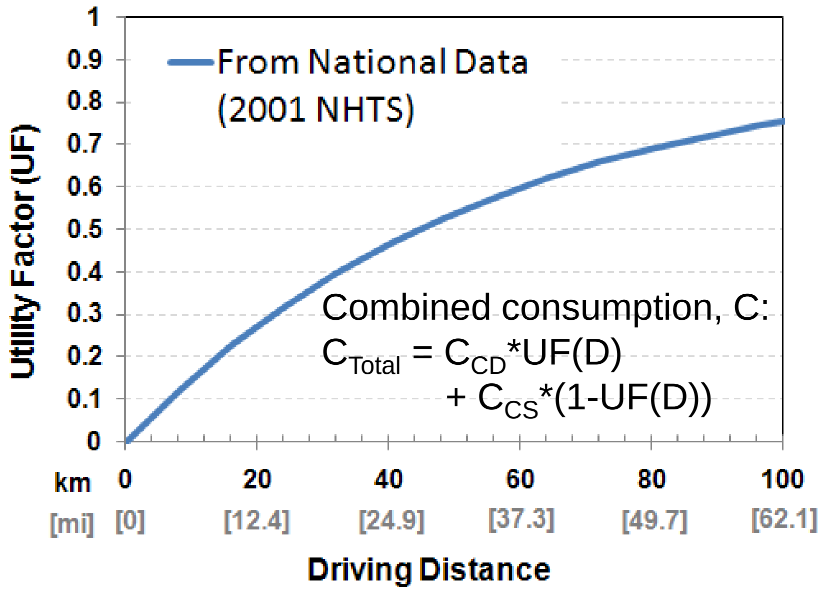
Technical Accomplishments

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





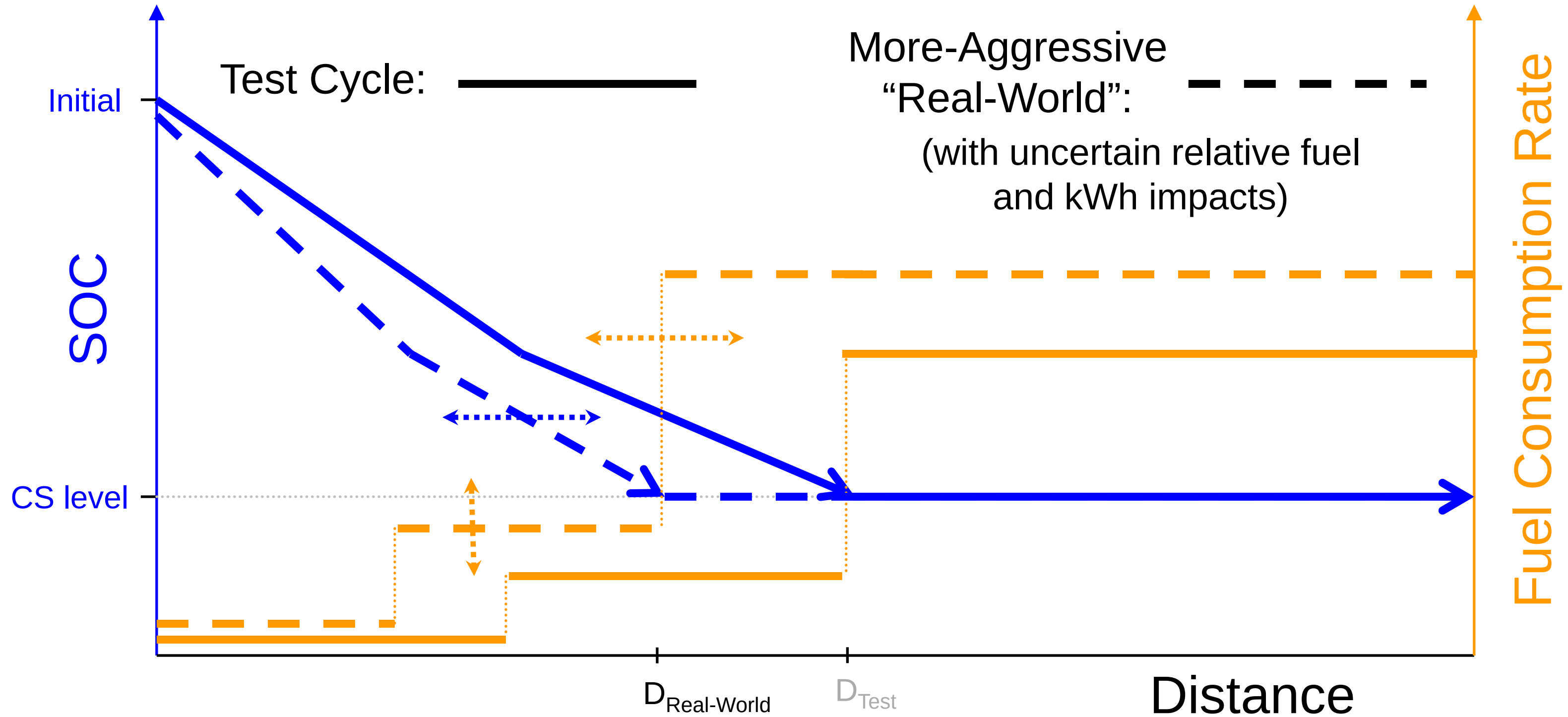
SOC: Vehicle battery’s state-of-charge
NHTS: National Household Travel Survey

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

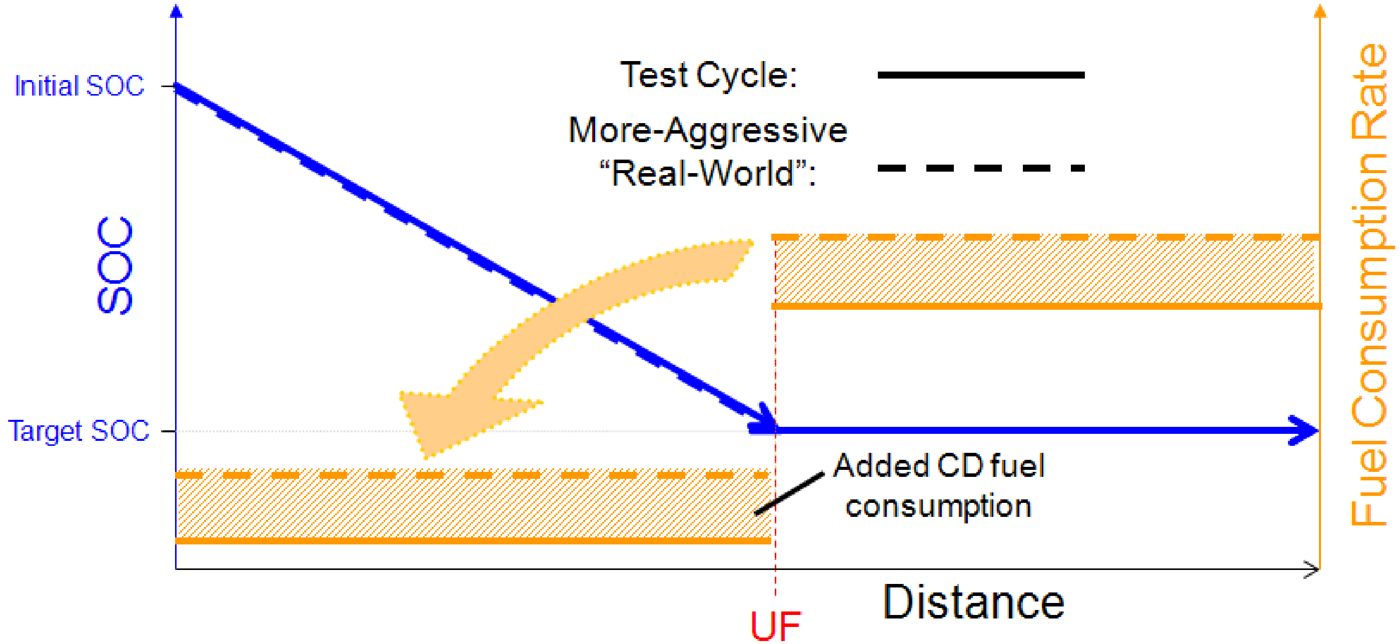


Technical Accomplishments

Develop potential methods via simplifying assumptions

E.g., “blended”/constant depletion rate method

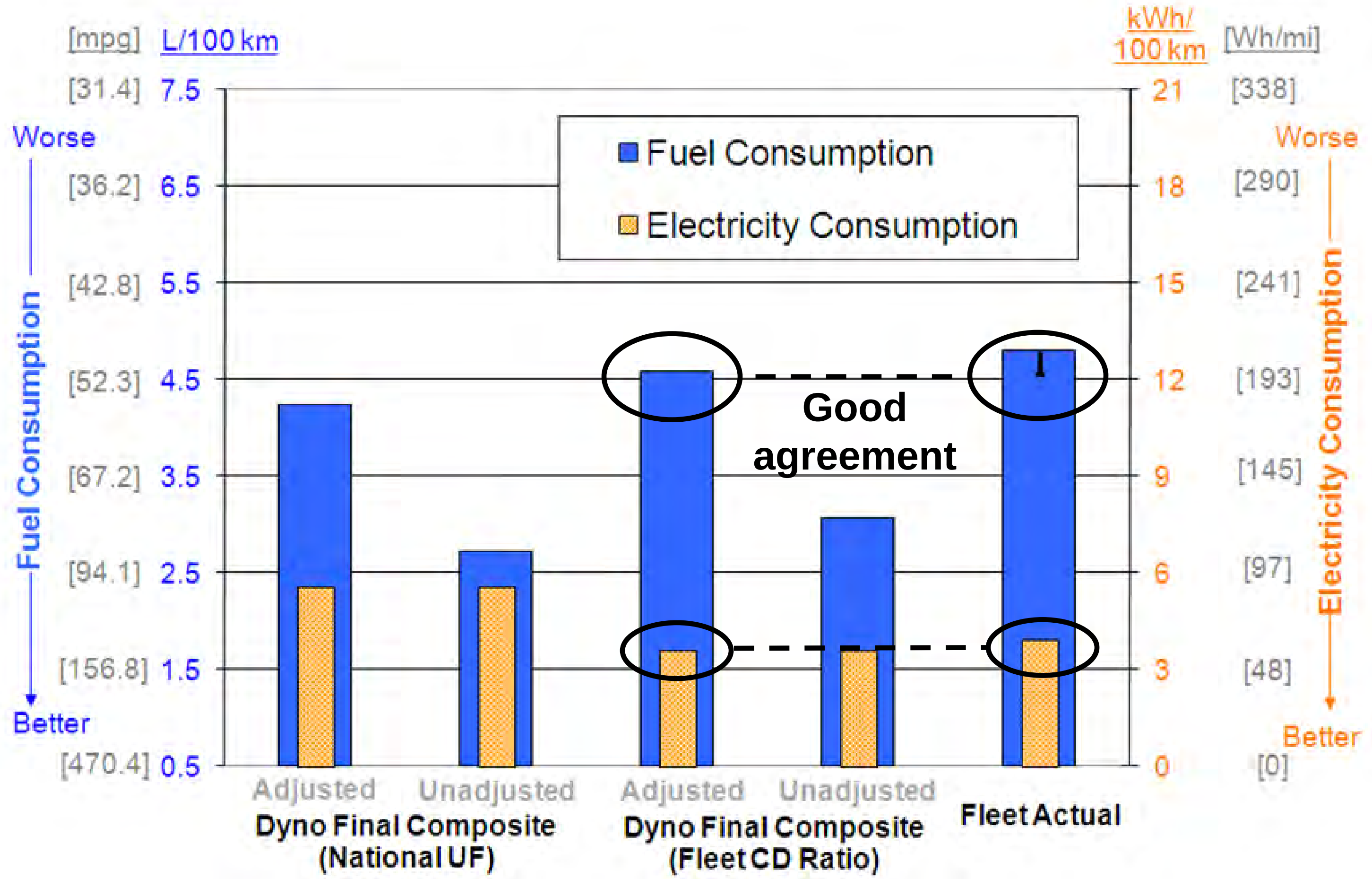
- Apply adjustment equation to CS result
- Retain the same UF-weighting distance from the actual test cycle results
- Assume “extra road loads” simply add CD fuel consumption at the same rate increment as for CS driving
- Actual PHEV may deplete slower or faster in the real-world



Technical Accomplishments

Evaluate "blended method" against Hymotion Prius data

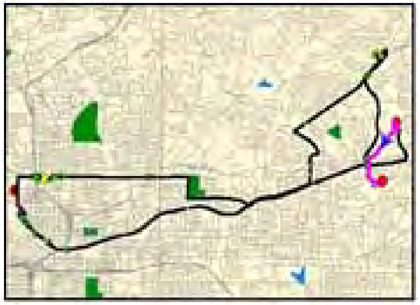
- In collaboration with ANL and INL
- Works well for blended PHEV; may not work as well for other designs



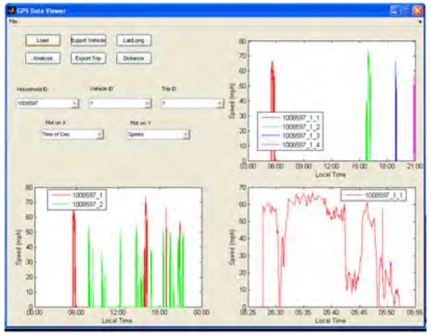
Technical Accomplishments

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



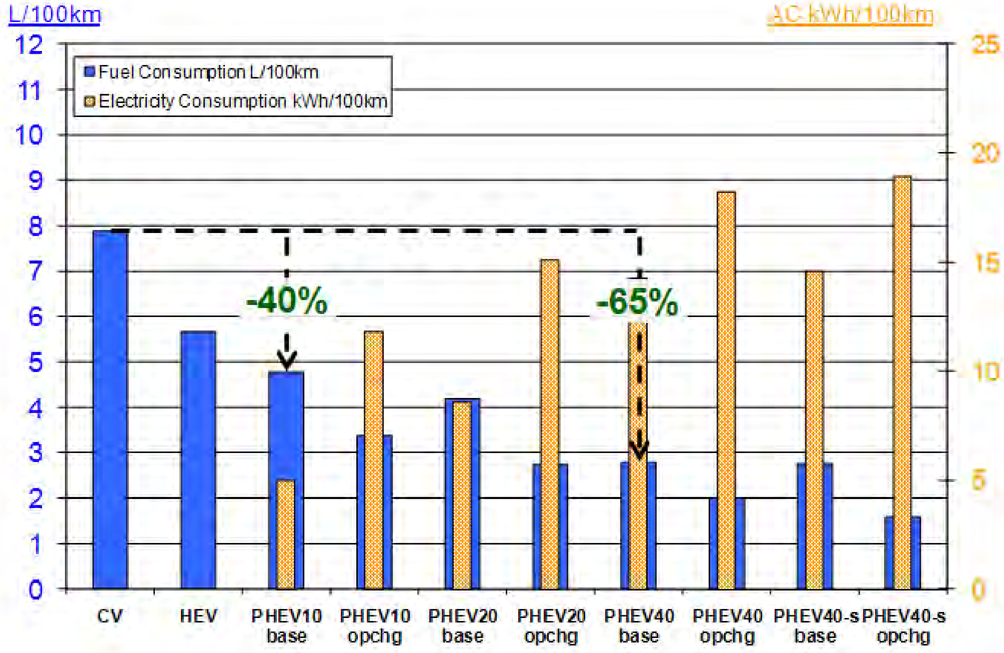
Technical Accomplishments

Assess different scenarios via simulation

Mid-size car assumptions

				PHEV			
	Units	*CV*	*HEV*	*10*	*20*	*40*	*40s*
Engine Power	kW	123	77	77	78	80	85
Motor Power	kW	n/a	36	40	41	43	130
ESS Energy (total, DC)	kWh	n/a	1.7	4.5	8.2	16.4	16.4
Curb Mass	kg	1473	1552	1578	1614	1694	1789

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

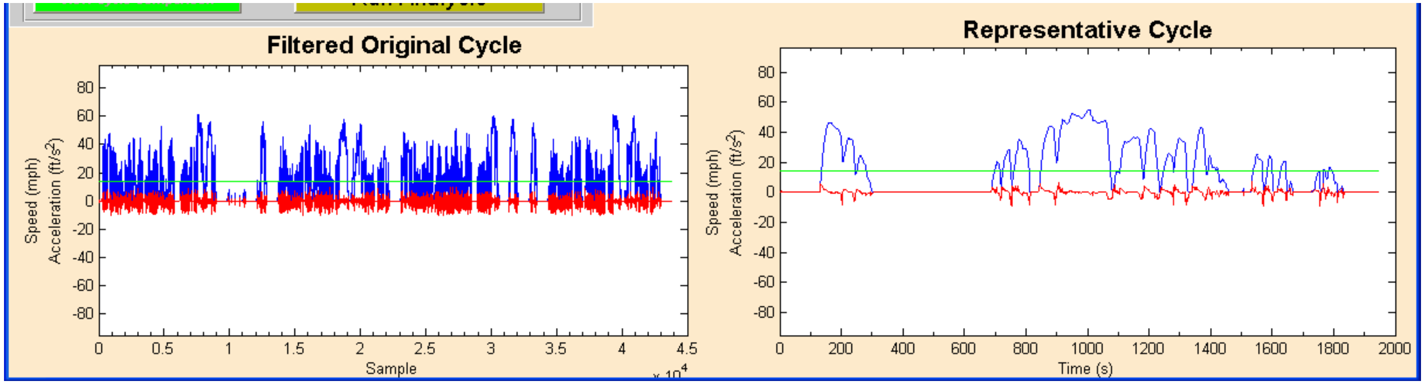
Future Work

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

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Summary

- 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

NREL contacts:

- Jeff Gonder – jeff.gonder@nrel.gov
- Robb Barnitt – robb.barnitt@nrel.gov

Questions?

Technical Back-Up Slides

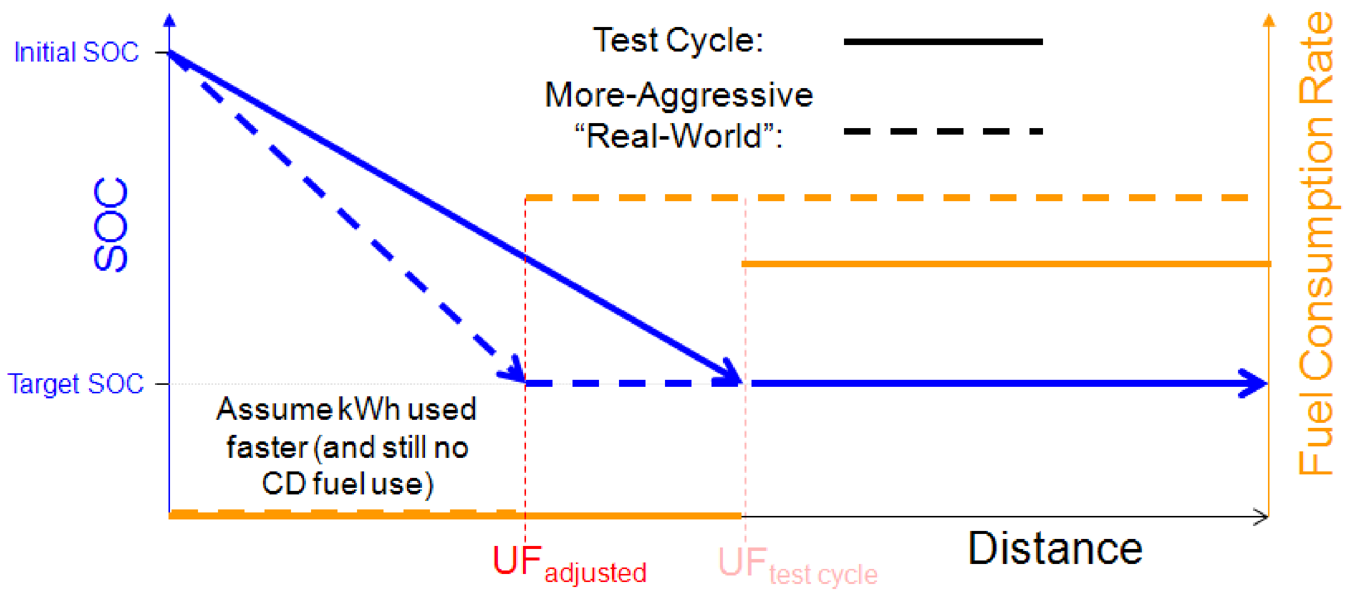
Description of Additional Accomplishments and Related/Synergistic Activities

Technical Accomplishments

Develop potential methods via simplifying assumptions

E.g., “All-electric”/CD distance reduction method

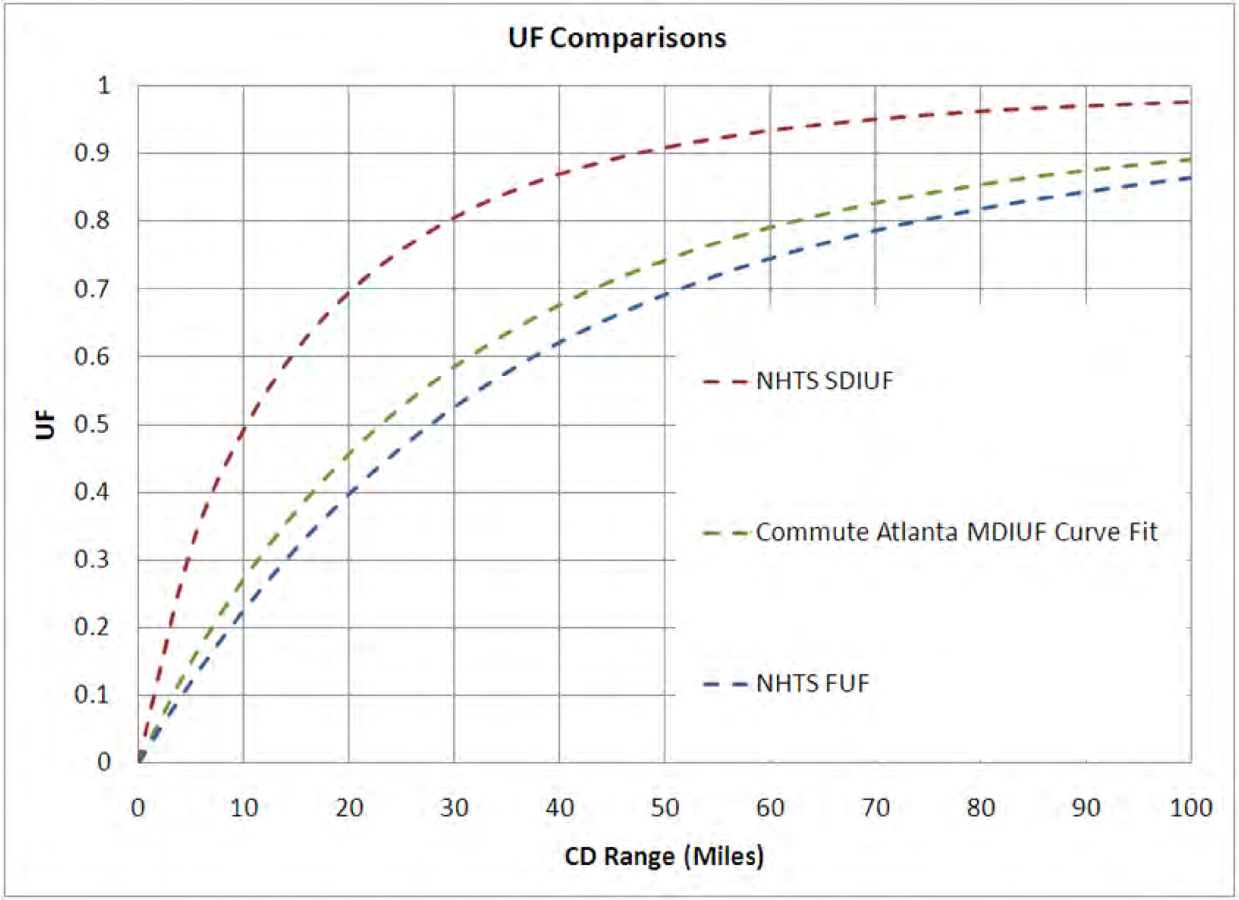
- CS fuel use can be adjusted as normal
- Only adjust electricity in CD mode (problematic to calculate)
- If made, adjustment yields new UF distance (usable energy depleted faster)
- But, result could be unachievable if motor/battery power insufficient to deplete energy over shorter distance



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



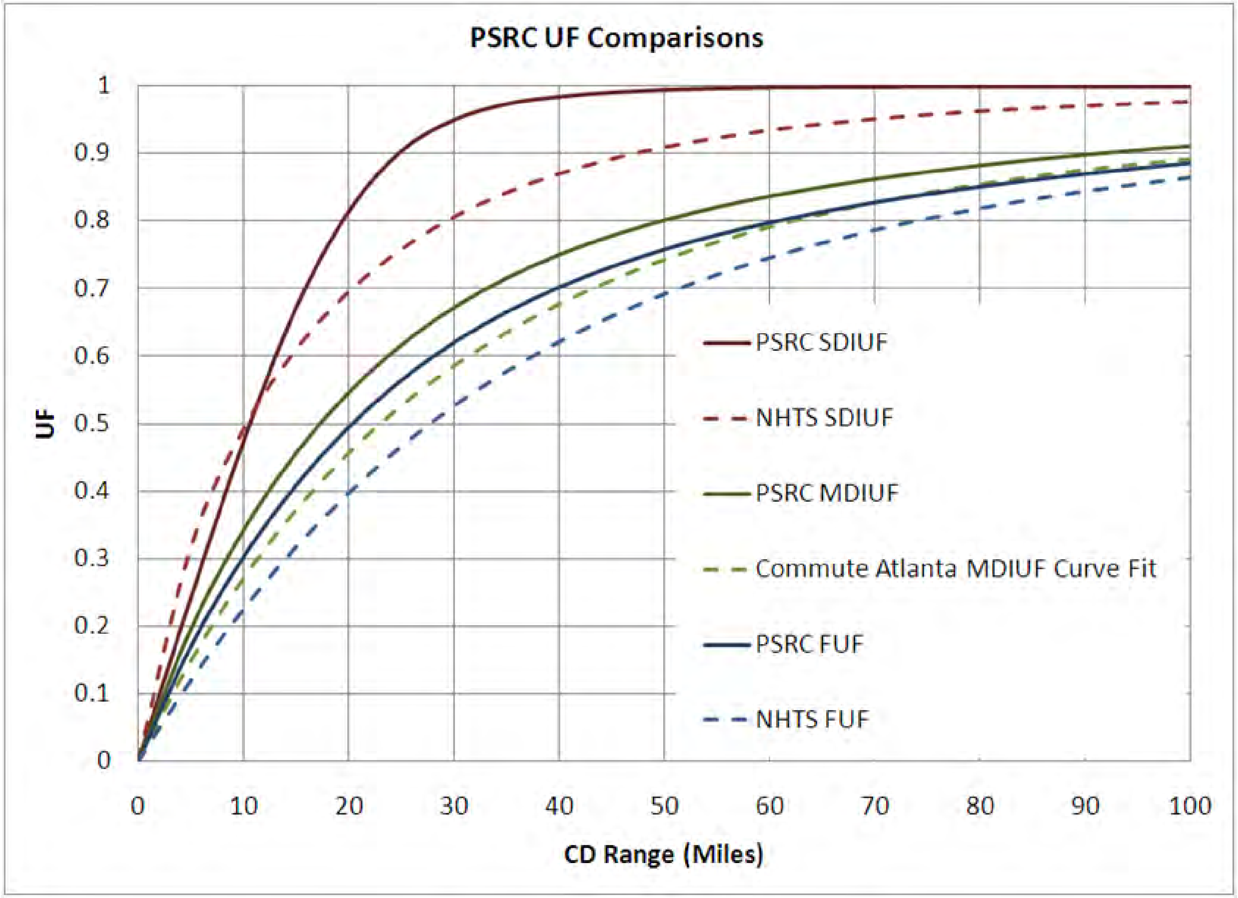
SD/MDIUF = single-day/ multi-day individual utility factor

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

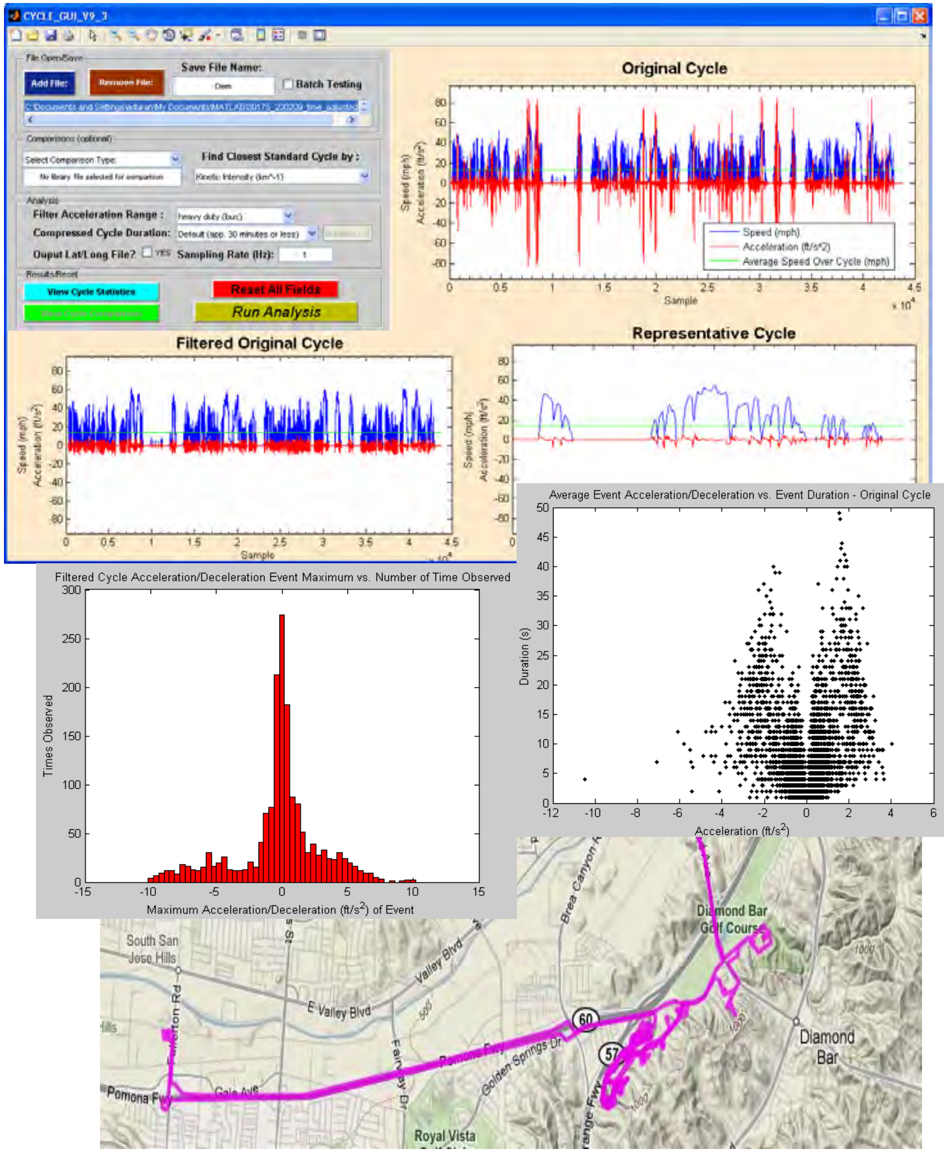


PSRC = Puget Sound Regional Council, data from 18 mo. Seattle area Traffic Choices Study

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

NRC report*

- 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