National Renewable Energy Laboratory
Innovation for Our Energy Future

Light Duty Plug-in Hybrid Vehicle Systems Analysis

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National Renewable Energy Laboratory

2009 DOE Vehicle Technologies Annual Merit Review

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Project Overview
Light Duty PHEV Systems Analysis

Timeline

- NREL PHEV analysis initiated in FY05
- Providing Ongoing program support

Budget

- Prior (DOE) – $300K (FY05-FY07)
- FY08 (DOE) – $200K
- Future (DOE) ~$150K/yr for 3 years

Barriers

- High cost of PHEV technology needs alternative value streams
- Optimal implementation strategy is unclear and is highly dependent on consumer behavior
- Achieving battery life goals for PHEV application is challenging

Collaborations

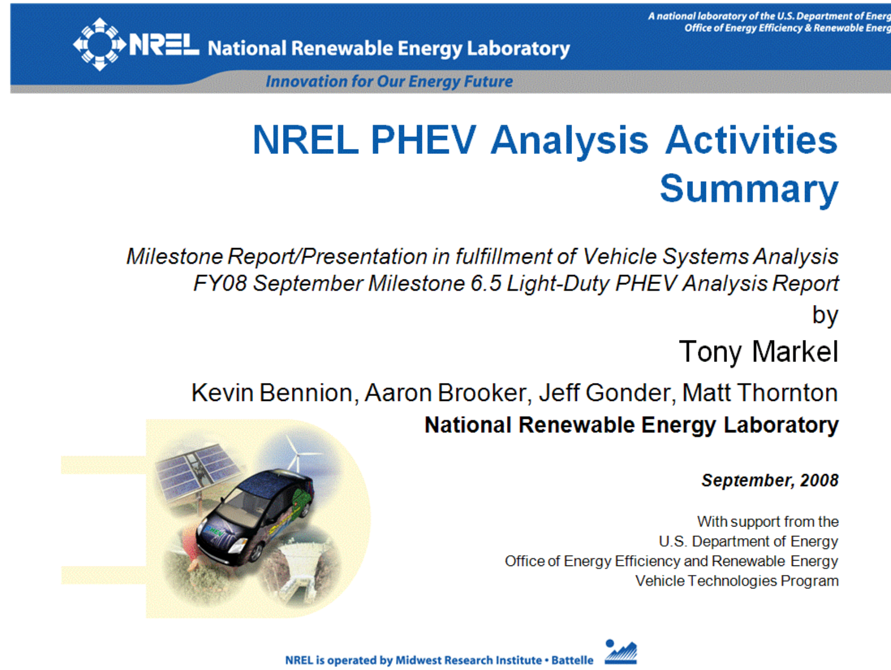
- SAE Standards Committee
- General Motors
- Value Proposition Team
- Vehicle Systems Technical Team
- Metro Planning Organizations
- Other Labs

Objective and Approach

- Objective
  - — NREL provides light duty PHEV systems analysis to support the development and introduction of PHEV technology to significantly reduce petroleum consumption.
- Approach
  - — Real-world travel pattern analysis and impacts
  - — PHEV and renewables interaction
  - — Economic analysis
  - — PHEV/Bio-fuel integration
  - — Test procedures for PHEVs
- Deliverables
  - — Year end report on LD PHEV analysis activities

Milestones

Light Duty PHEV Systems Analysis Report (Sept. 2008):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Office of Energy Efficiency & Renewable Energy

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NREL PHEV Analysis Activities Summary

Milestone Report/Presentation in fulfillment of Vehicle Systems Analysis FY08 September Milestone 6.5 Light-Duty PHEV Analysis Report

by

Tony Markel

Kevin Bennion, Aaron Brooker, Jeff Gonder, Matt Thornton

National Renewable Energy Laboratory

September, 2008

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Vehicle Technologies Program

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Compilation of analysis insights on PHEV technology

- PHEV technology leads to less engine starts than an HEV
- Opportunity charging can enhance the utility of a small battery pack
- Battery life modeling is critical for evaluation of operating scenarios
- Cost benefit scenario of PHEVs is highly dependent on fuel and component pricess

Accomplishments Summary

- Real-world travel pattern analysis and impacts
  - Processed and ran simulations using LA travel data
  - Presented at *EVS-23, CRC On-Road Emissions Workshop, Plug-in 2008,* and *Advanced Automotive Battery Conference*
  - Conducted simulations addressing life implications of energy storage usage profiles
  - Spectrum of duty cycles expanded with Austin and San Antonio
  - Highlight the fuel savings value of opportunity charging through simulations
- PHEV and renewables interaction
  - Completed simulations of PHEV charge/discharge synched with Wind
  - Collaborated with SEAC on value and emissions benefits to utilities
- Economic analysis
  - Developed an economic scenario analysis worksheet allowing comparison of powertrain options
- PHEV/Bio-fuel integration
  - Ethanol application analysis highlights the need to capture supply constraints
- Test procedures for PHEVs
  - Worked with SAE committee (Labs and Industry) to evolve the J1711 standard

Outline for Accomplishments Summary Slides

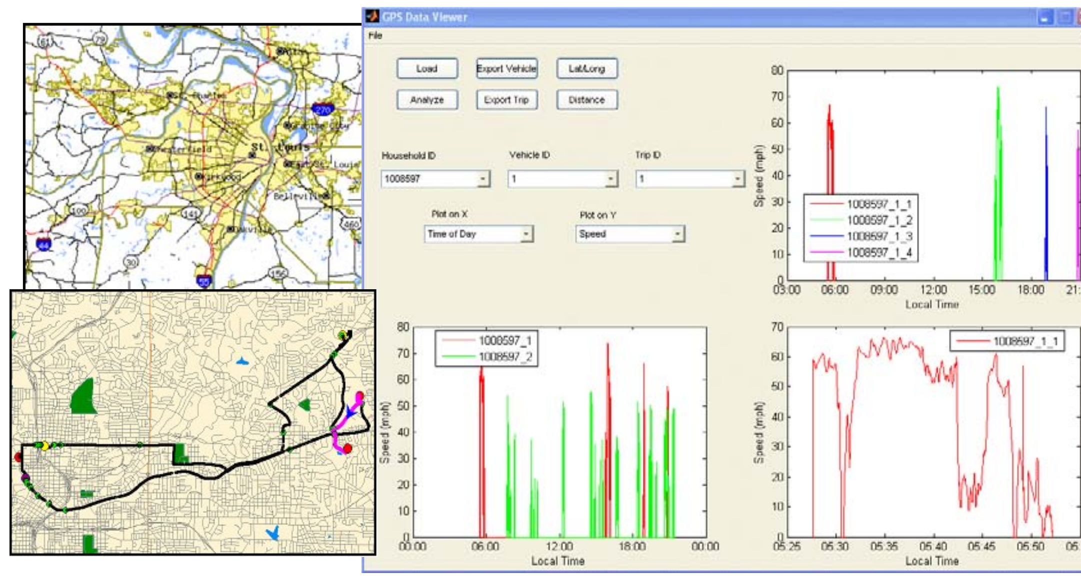
- Travel pattern data applications
- Battery cost/life modeling for PHEVs
- Integration with renewables
- PHEV economic assessment tool
- PHEV test procedure status

Technical Accomplishments
Travel Survey Data Applications

- Objective
  - Gain a better understanding of consumer travel behavior and its influence on the benefits of advanced vehicle technology under on-road (real-world) operating conditions
- Approach
  - Collect, process, and analyze existing travel survey data for use in vehicle systems simulations
  - Simulate vehicle operation under on-road usage patterns of several vehicle technology scenarios focusing on PHEV impacts
- Importance
  - Results will highlight potential real-world benefits and shortfalls in technology which can lead to a more robust vehicle design

Technical Accomplishments
Real-World Drive Cycle Resources

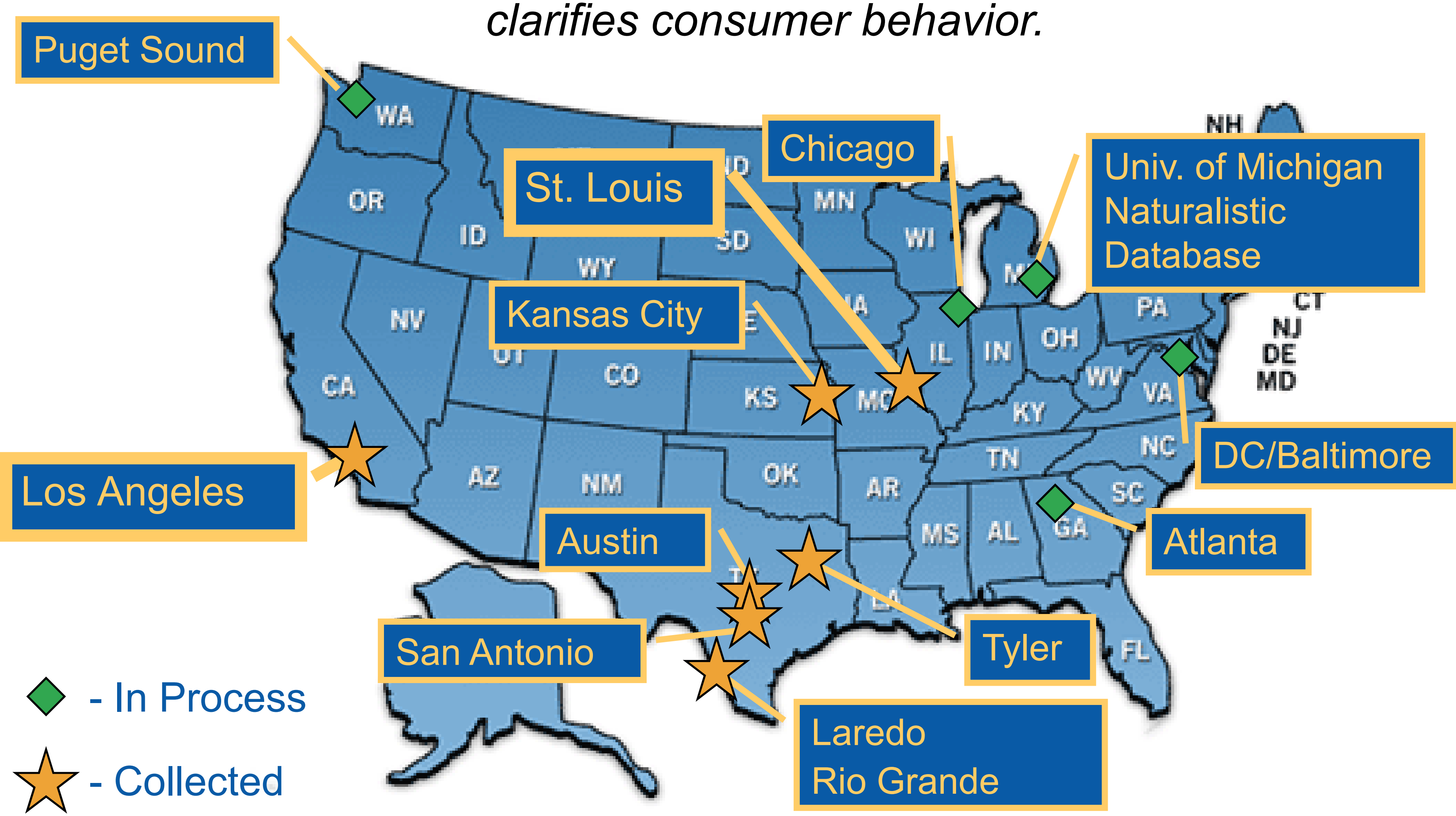
- Driving/travel survey is ongoing in many cities (e.g., St. Louis)
- Augmenting these surveys with GPS information from individual vehicles provide details needed for simulation



- 1Hz data collected
  - — Time of day
  - — Speed
  - — Altitude
  - — Latitude
  - — Longitude
- Key insights
  - — Speed and acceleration distributions
  - — Time of day usage for recharge analysis
  - — Combined impact of speed and grade
  - — Location and duration of stops for recharge opportunities

Technical Accomplishments
Available Travel Survey Data

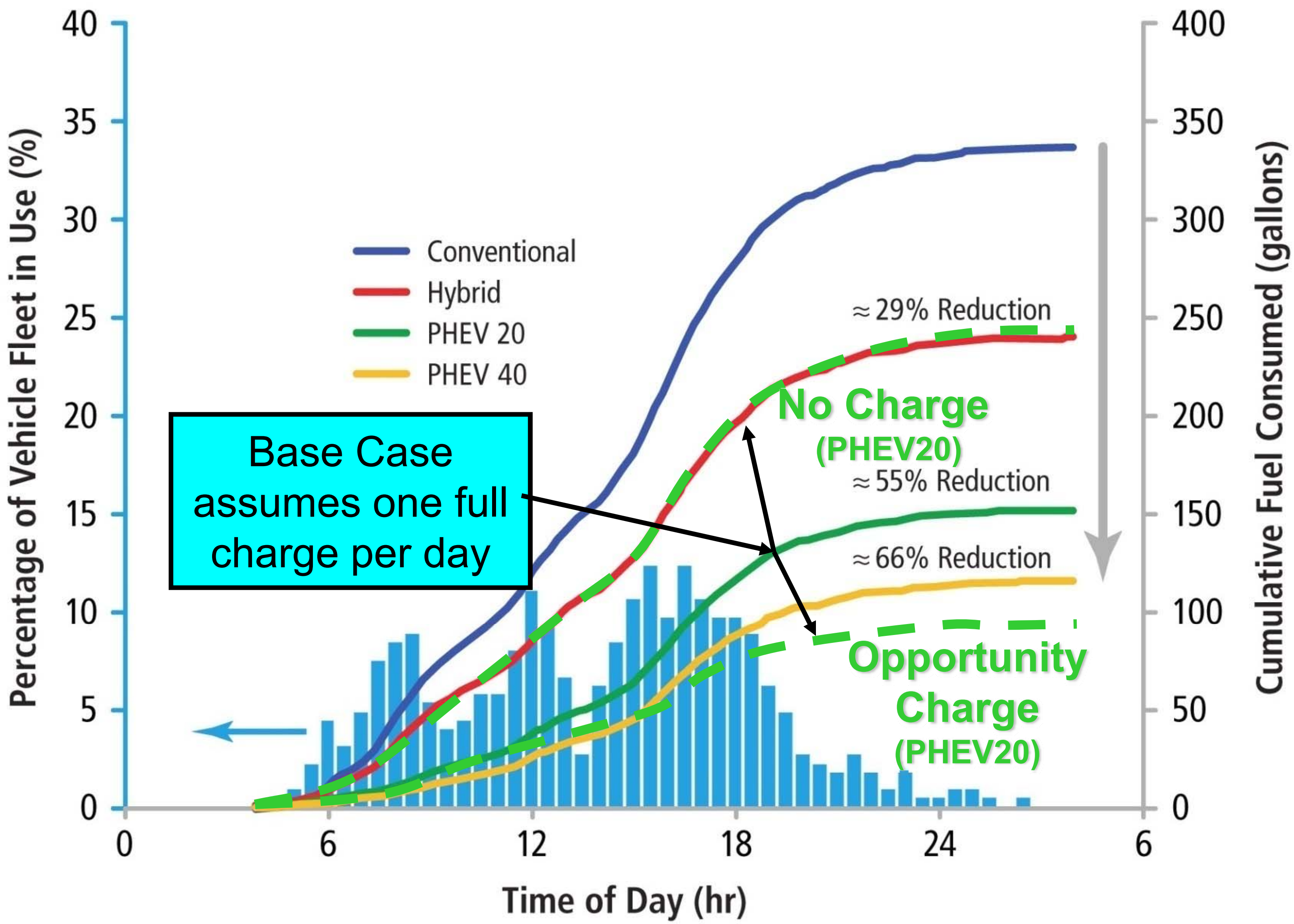
On-road data for vehicle simulation clarifies consumer behavior.



Technical Accomplishments

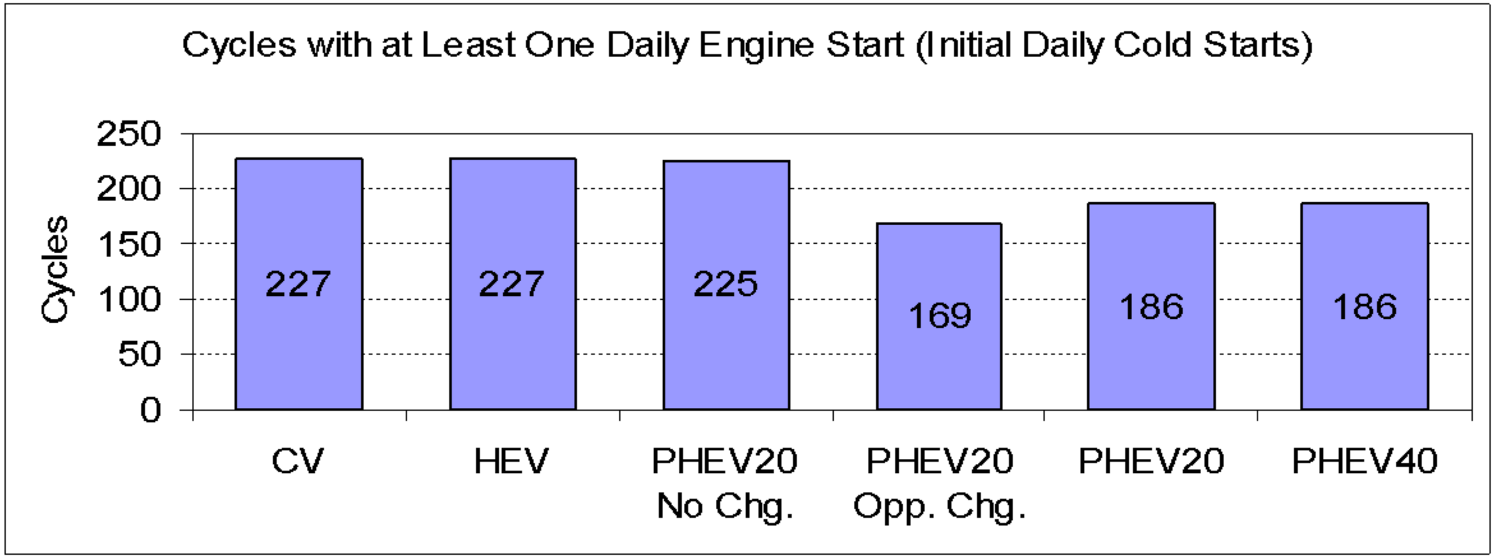
Recharge Scenario Impacts on PHEV Petroleum Consumption Benefits

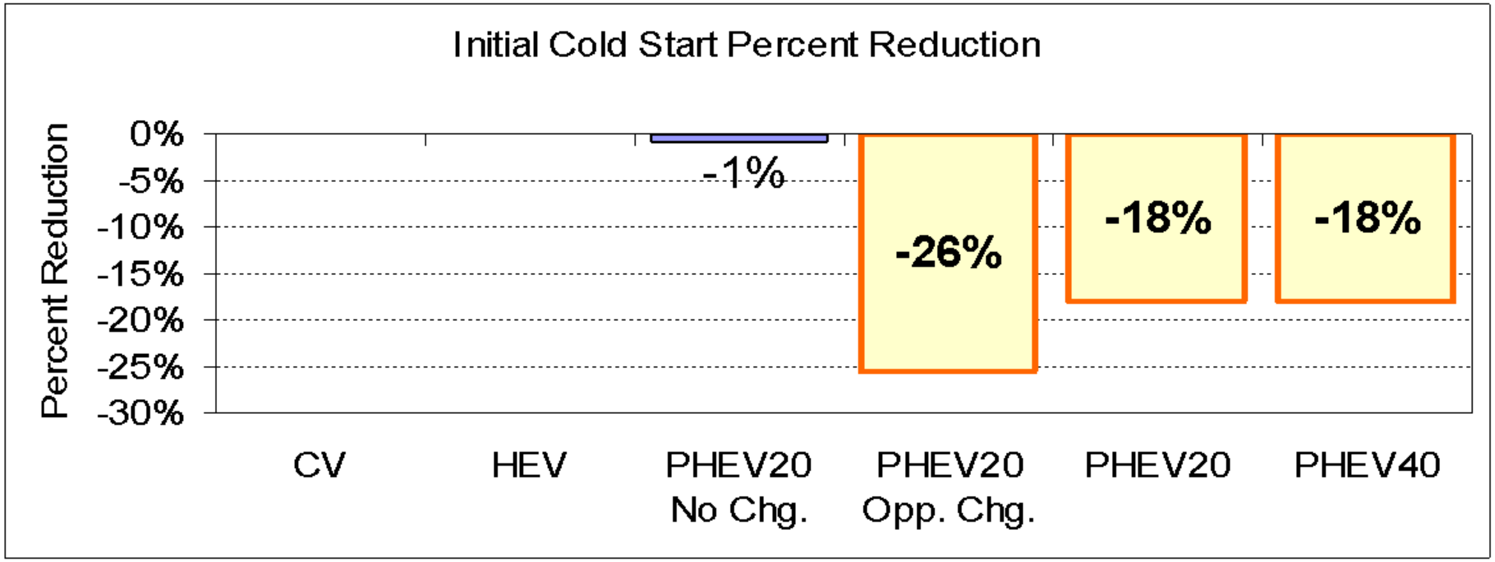
Opportunity charge: connect PHEV charger to grid any time that the vehicle is parked.



Technical Accomplishments

PHEVs Reduce Initial Cold Starts

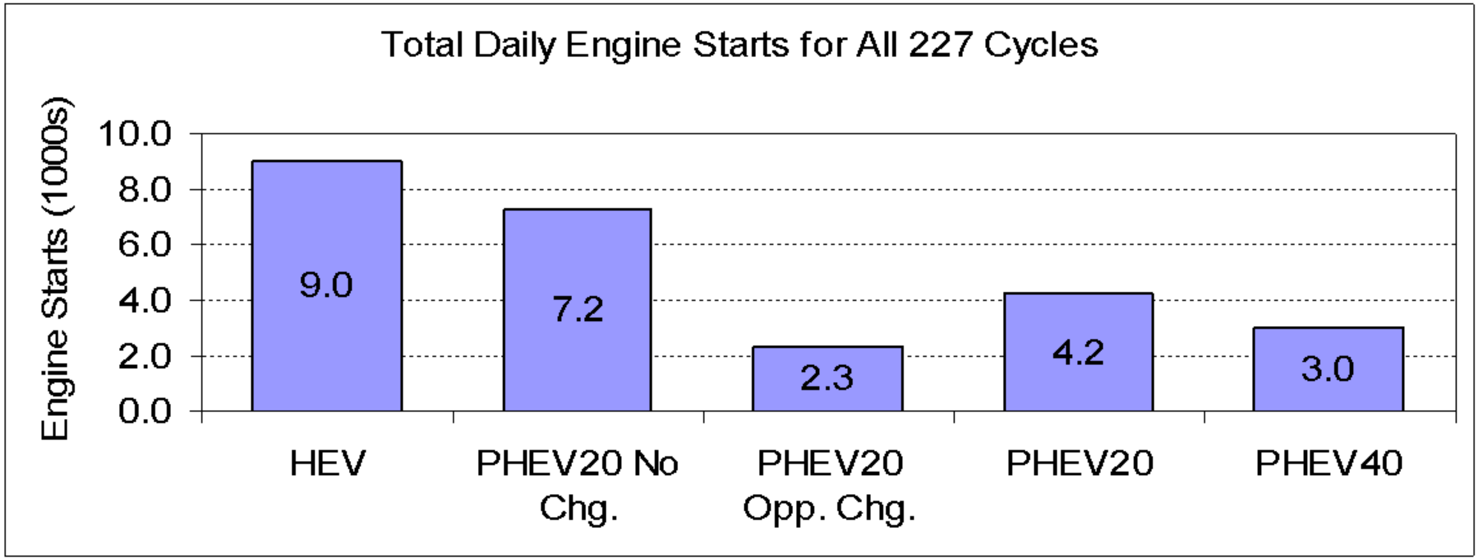


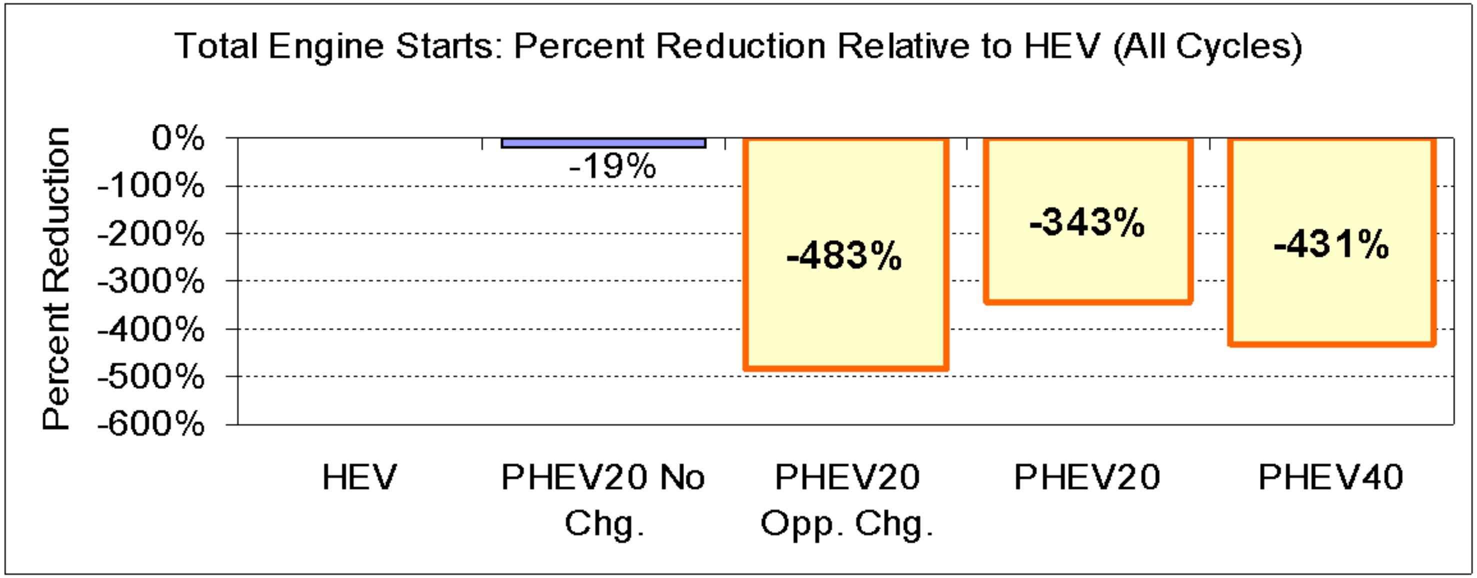


Bennion, K. 18th CRC On-Road Vehicle Emissions Workshop. 2008.

Technical Accomplishments

PHEVs Reduce Total Daily Engine Starts

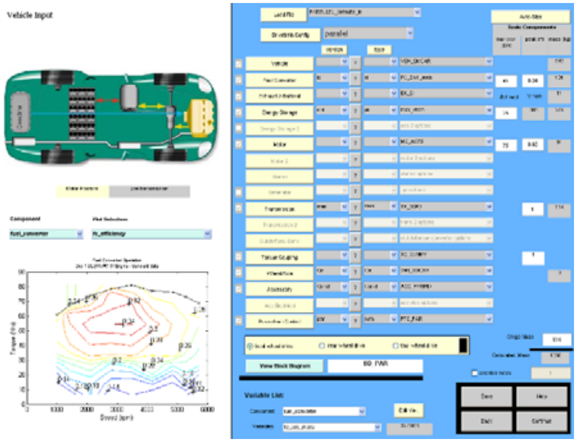




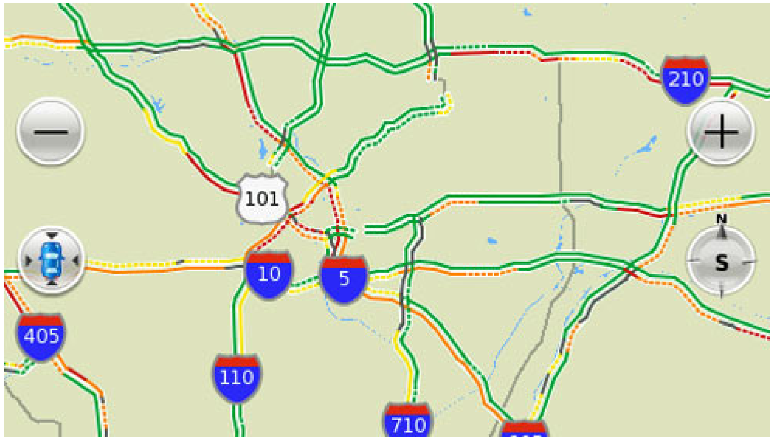
Bennion, K. 18th CRC On-Road Vehicle Emissions Workshop. 2008.

Technical Accomplishments

Preliminary Simulations Using LA Dataset



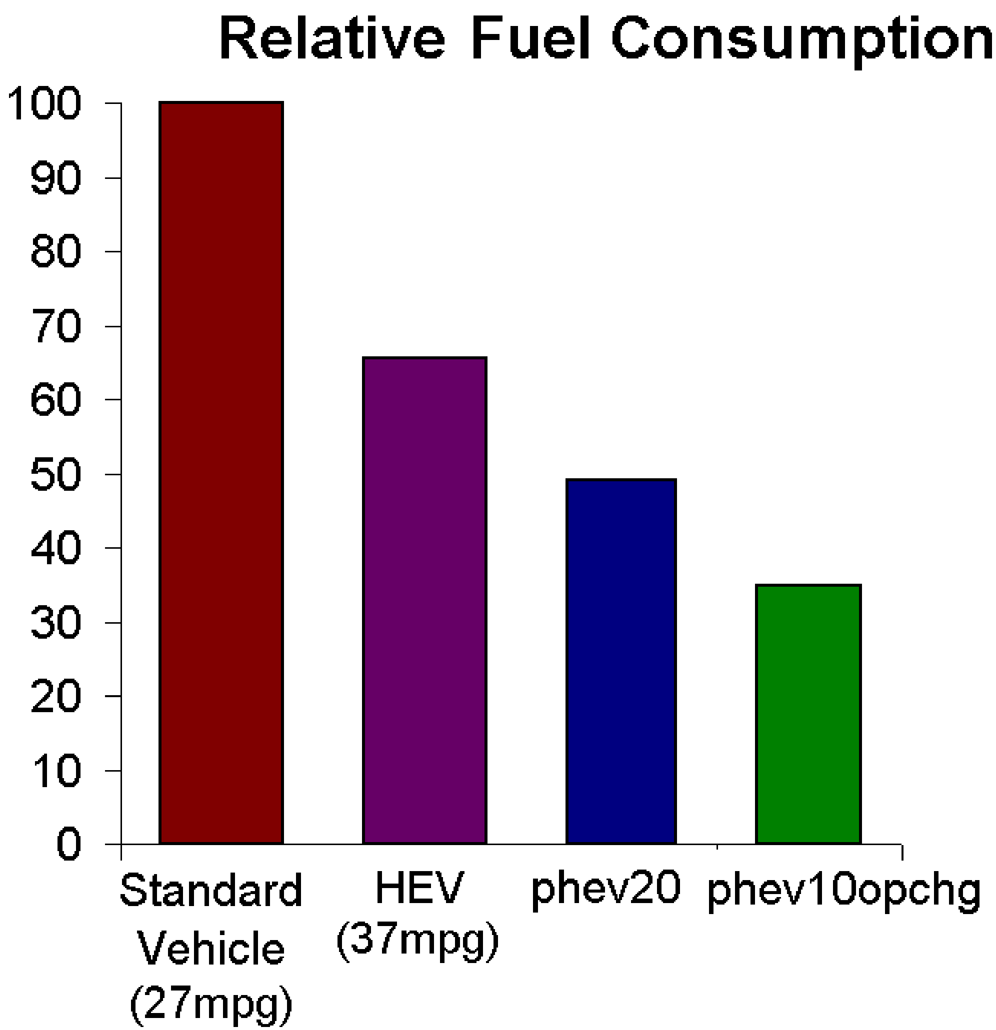
- Simulated 2 Vehicle scenarios:
  - — 4kWh battery, 10-mile range → PHEV10
    - » Opportunity Charged
  - — 9kWh battery, 20-mile range → PHEV20
    - » Evening Charge Only
- Theory:
  - — With opportunity charging, a smaller battery can be used and provide equal or greater fuel savings



Technical Accomplishments

Preliminary Simulations with LA Travel Data

- Opportunity charging with PHEV10 used 65% less fuel than standard vehicle fleet
- PHEV20, charging only overnight, used 49% less fuel
- Opportunity charging a PHEV10 increased fuel savings by 10% compared to a PHEV20 with overnight charging alone over 1100 unique driving profiles



Technical Accomplishments

Recent Simulation Conclusions

- PHEV10 with opportunity charging and PHEV20 vehicles have the capability to displace 51-61% of fuel use

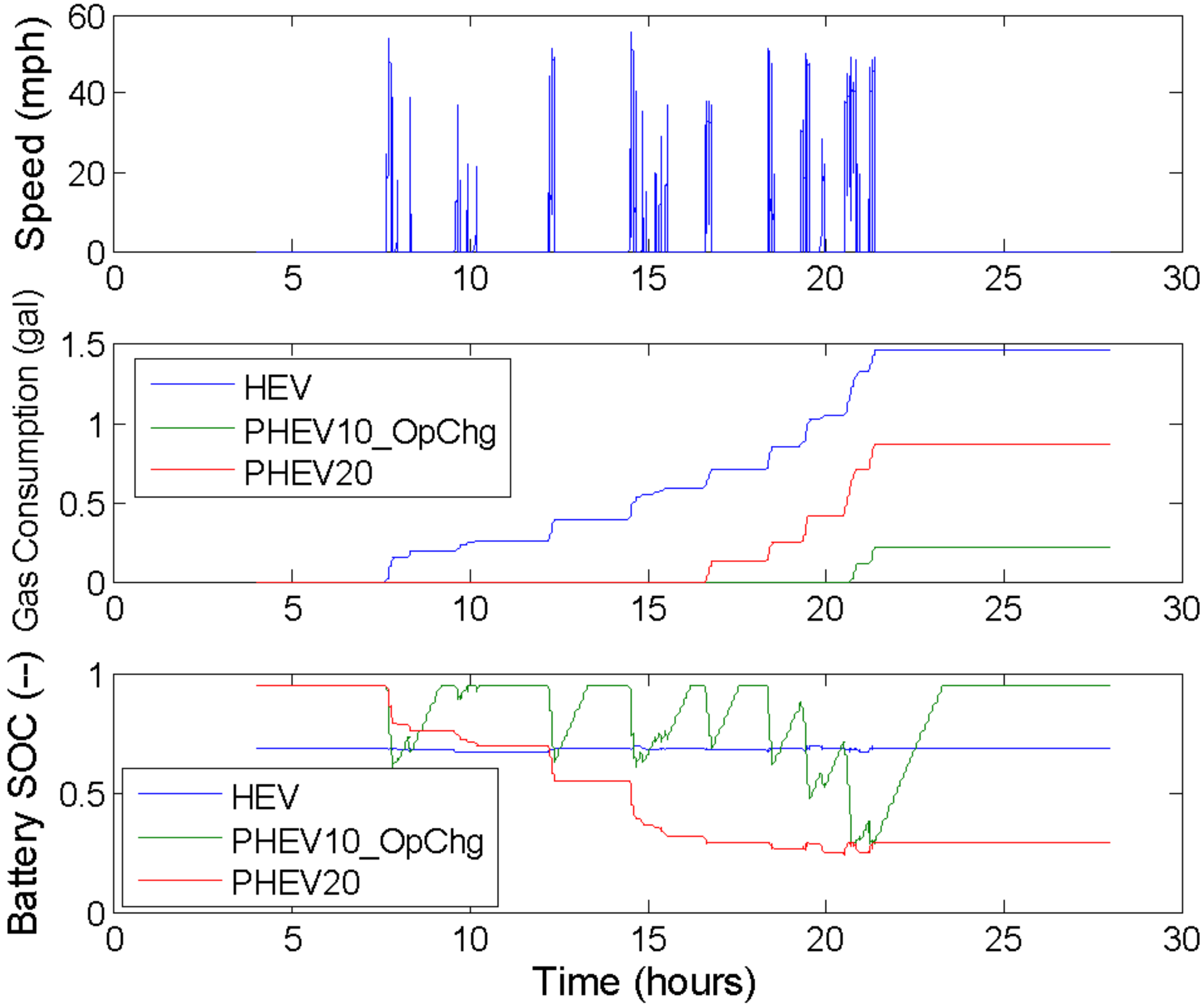
- Battery downsizing possible through opportunity charging

- Opportunity-charging means more cycling, and thus more battery wear, i.e. shorter lifetime

Technical Accomplishments

Sample of Charge Scenario Impacts

- 56 miles of driving over course of one day

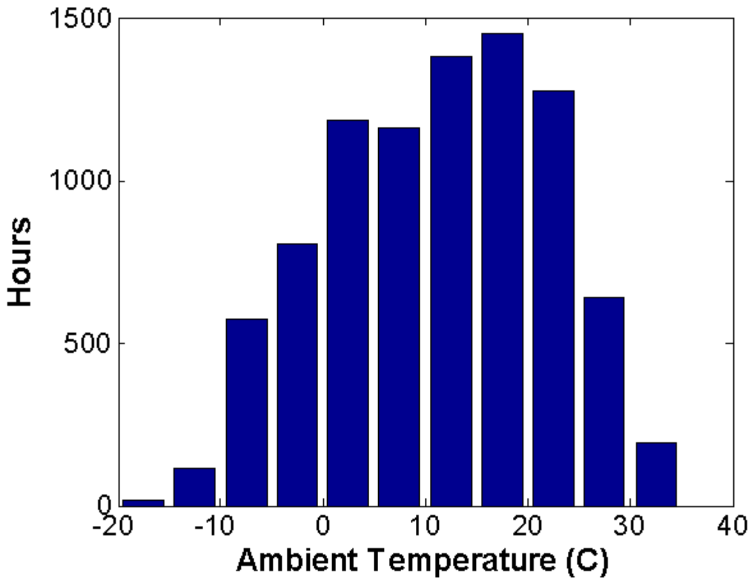


Need to understand how variation in cycling behavior impacts the battery performance over life of vehicle

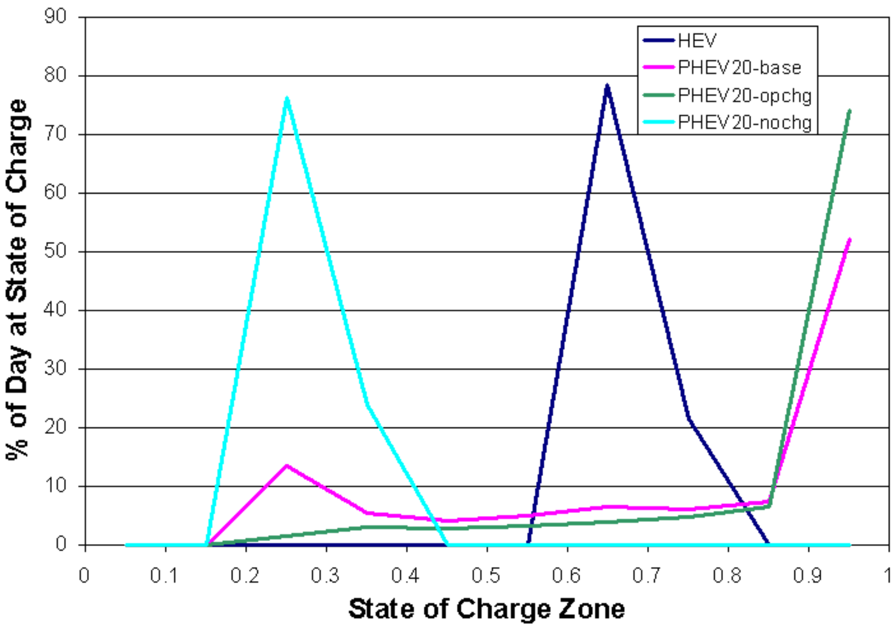
Technical Accomplishments

Factors Causing Battery Degradation

- Time at SOC
- Time at Temperature
- Operating Conditions



Ambient Temps in Golden
(March ‘07- March ’08)



Recharge Scenario and Travel Behavior impact time at SOC (AABC-07)

Technical Accomplishments
Collaboration with Energy Storage Task on Battery Attributes

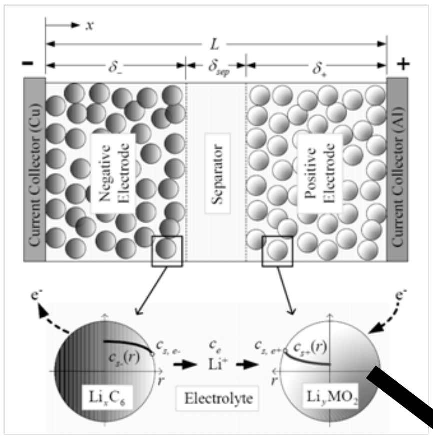
Goal: Develop linked parametric modeling tools to mathematically evaluate battery designs to satisfy challenging operational requirements for a PHEV.

- Reduce risk of
  - Premature battery failure
  - Falling short of consumer expectations
- Reduce incremental cost
  - Use data to minimize necessary energy/power margin
- Accelerate market penetration to achieve significant fuel savings

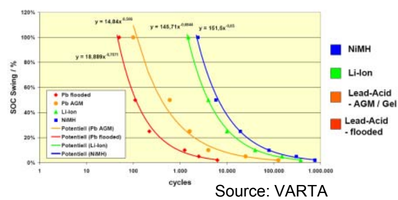
Technical Accomplishments
PHEV Battery Design Optimization by ES Team

Designing PHEV batteries to meet requirements, such as DOE/USABC, at minimum cost.

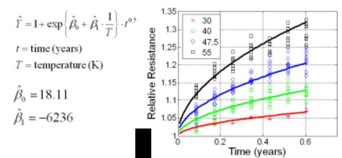
Performance Model



Life Model

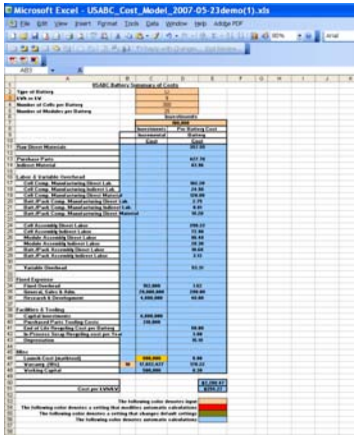


Source: VARTA

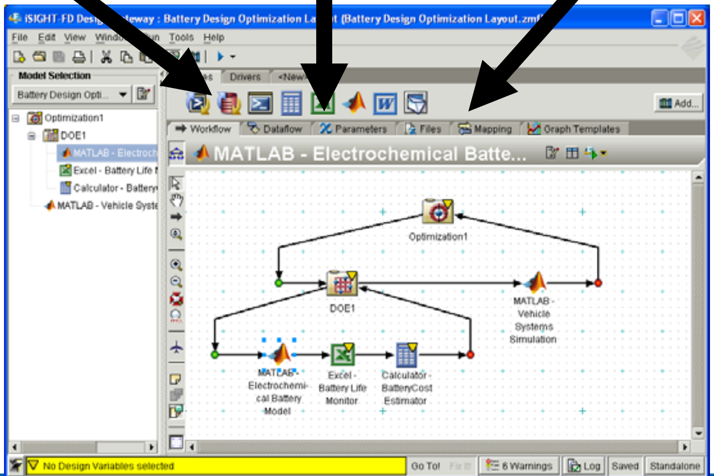


Source: INL, LBNL

Cost Model



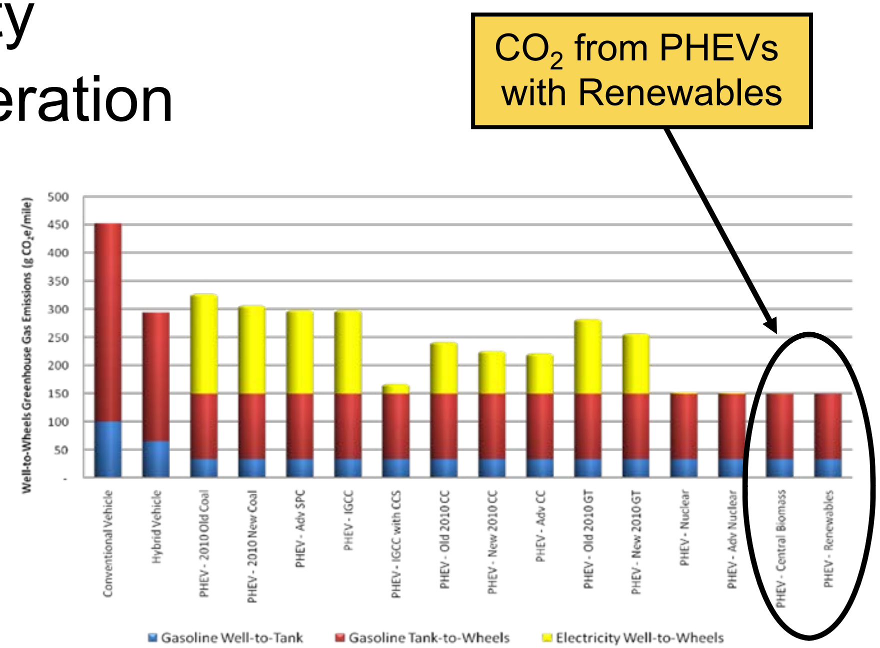
Optimization



Technical Accomplishments

Importance of V2G

- Offset the high cost of energy storage systems for PHEVs
- Ability to access a stranded resource and use it to,
  - Reduce cost of electricity
  - Expand renewable generation
  - Increase grid flexibility and reliability
  - Achieve CO_2 benefits of renewables fuels in transportation



EPRI/NRDC PHEV Impacts Study

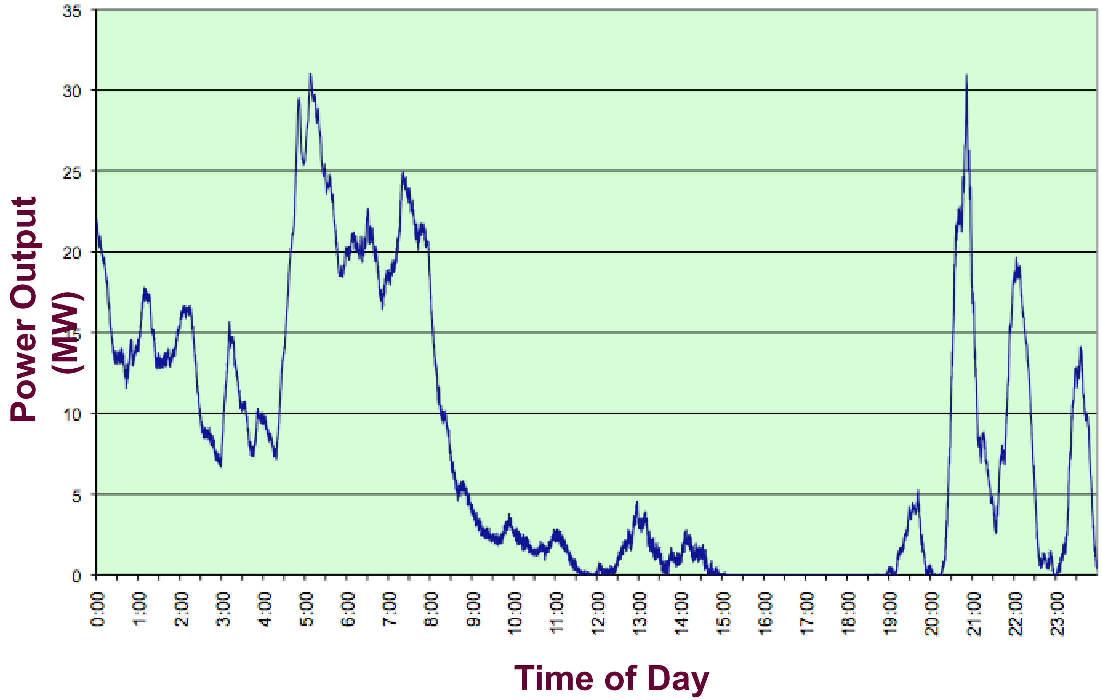
Technical Accomplishments
Wind power: a challenge for utilities

Variability

…Hard to predict

…Intermittent power supply

Variable Daily Wind Power Output



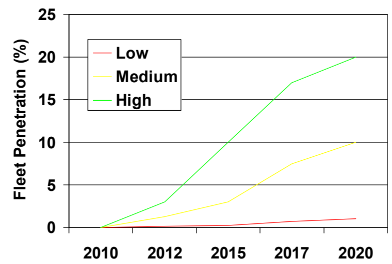
Lew & Milligan, 2008

Technical Accomplishments

Vehicle Operational Scenarios

A. PHEV penetration

1. < 1%
2. 10%
3. 20%

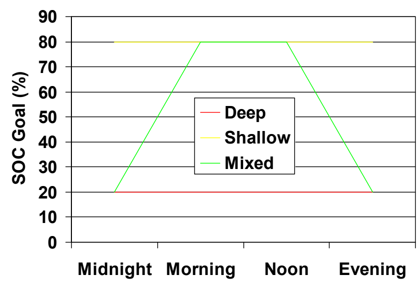


B. Battery Capacity

1. PHEV 10
2. PHEV 20
3. PHEV 40

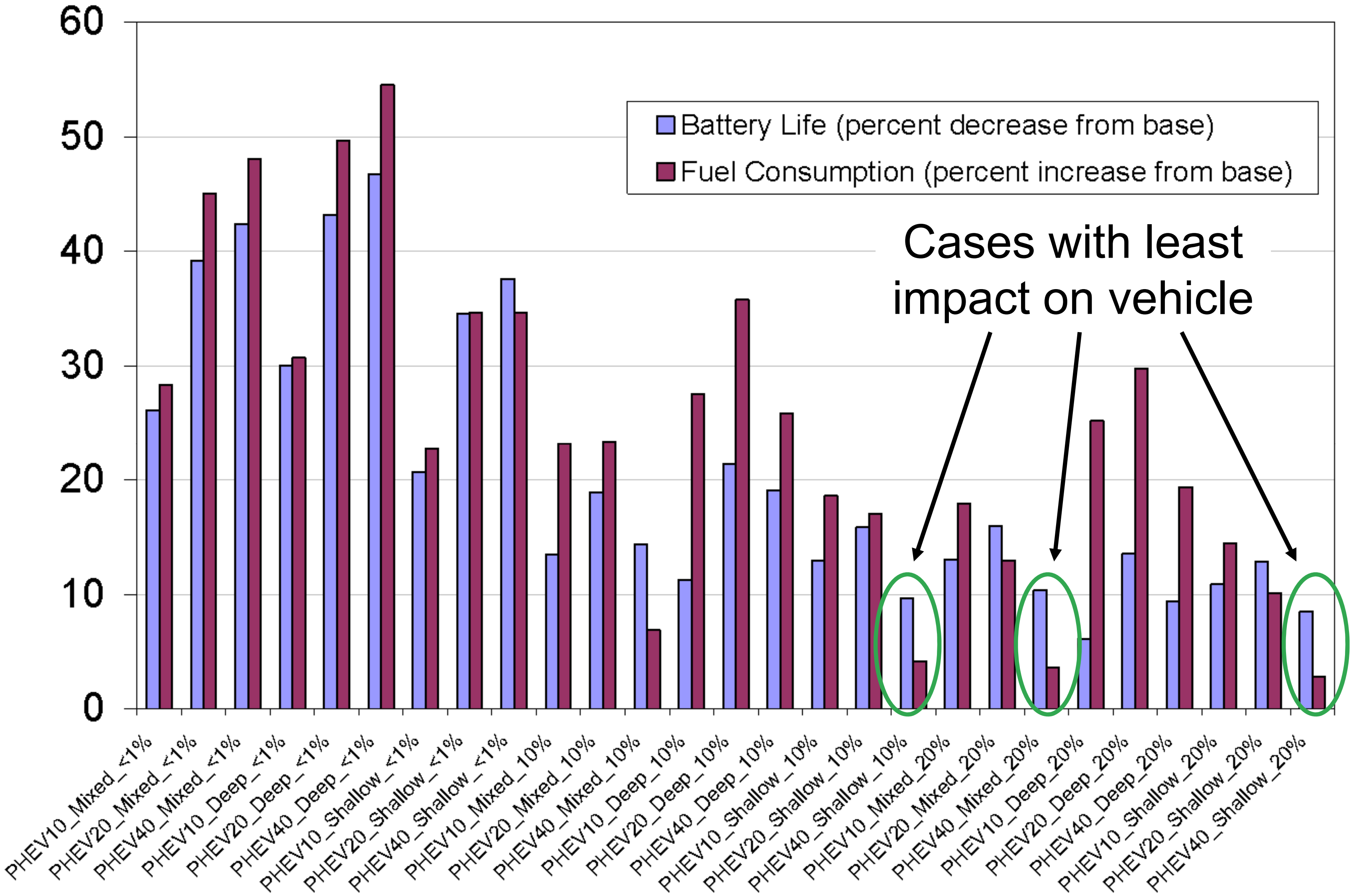
C. Charging strategy

1. Mixed
2. Deep
3. Shallow



Technical Accomplishments

Impacts on PHEVs Serving Wind Forecast Error



Technical Accomplishments

PHEV with Wind Analysis Conclusions

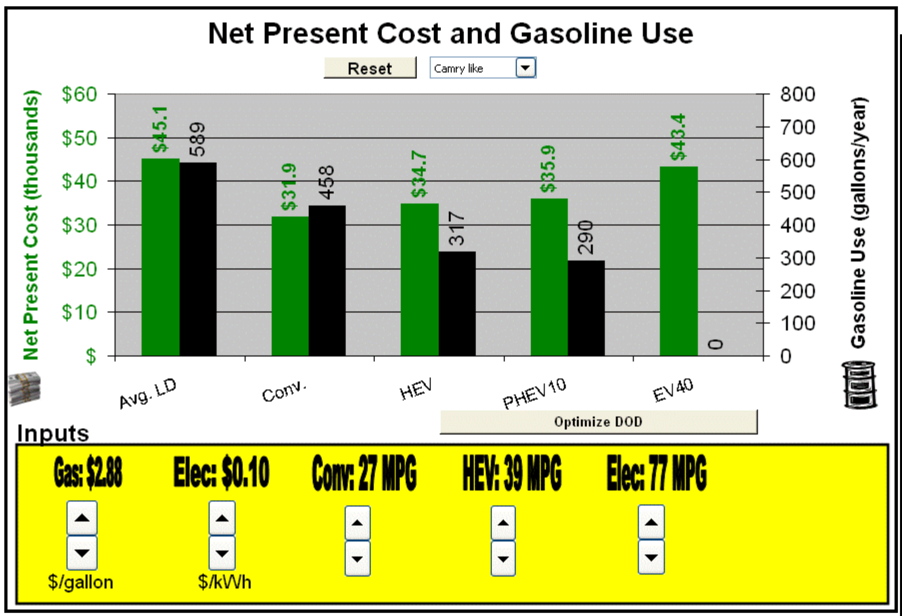
- To adequately compensate for forecast error with 20% wind:
  - — PHEV penetration needs to be significant (10-20%)
  - — PHEV 40s better at serving need with minimal impact on life and consumption however come with higher initial battery costs
  - — A mixed charging strategy is optimal for covering forecast error while minimizing battery impact and fuel consumption

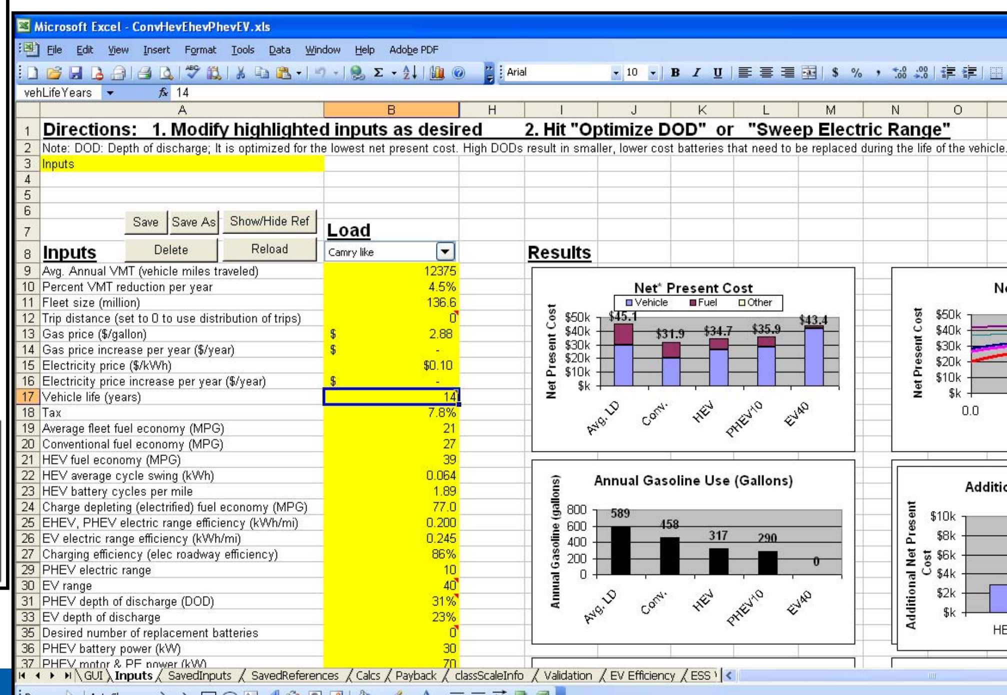
Many other renewable synergy scenarios yet to be explored!

Technical Accomplishments

PHEV Economic Analysis

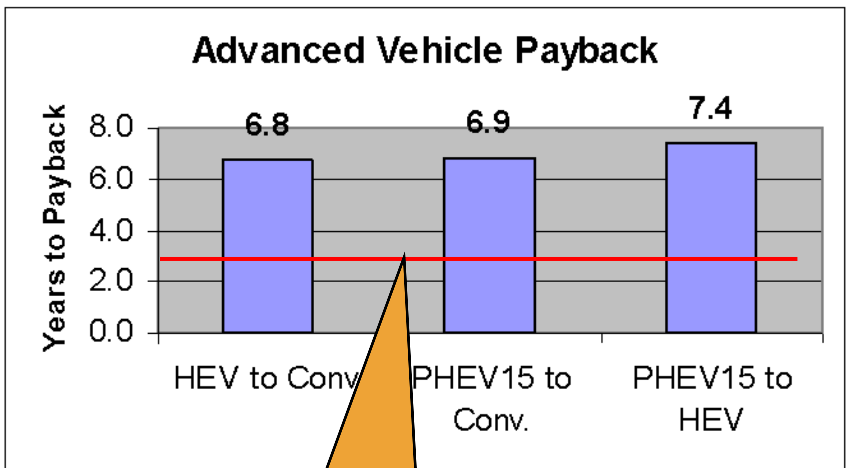
- Interactive spreadsheet to guide PHEV research
- Features include,
  - — Travel distance distribution options
  - — Impacts of design and usage on battery life
  - — Component and fuel costs varying with time



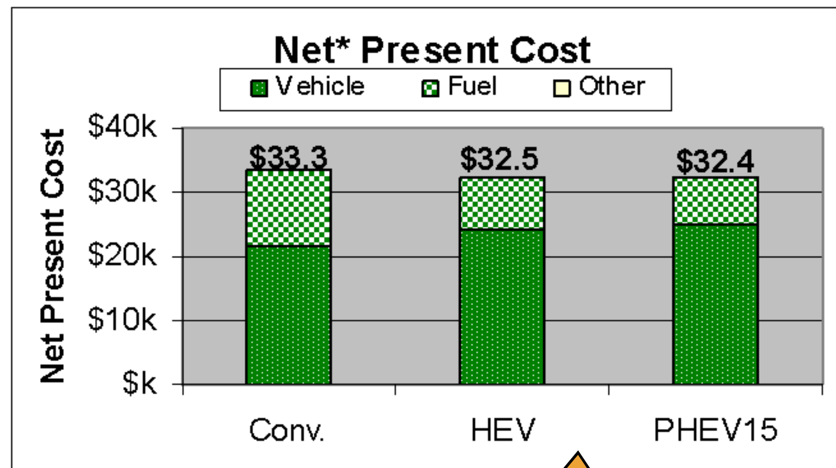


Technical Accomplishments
Net Present Cost Vs. Payback Results

- The net present cost (NPC) may prove that a scenario is a good monetary investment while payback criteria falsely suggests it is poor



3 year payback requirement isn't met

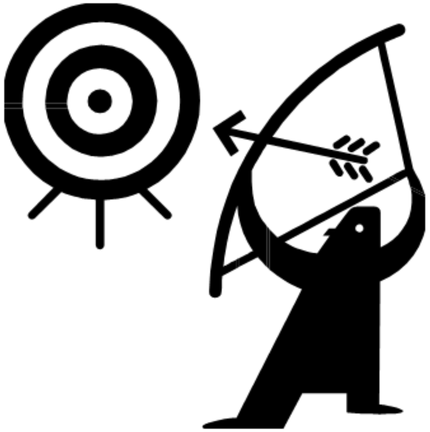


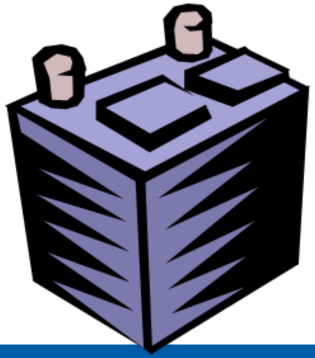
HEVs and PHEVs are a good investment

Scenario: PHEV15 using DOE battery, motor, and power electronic cost targets and A123 battery life
*Net present cost includes vehicle cost, taxes, fuel cost, battery replacement cost, and battery salvage payout

Technical Accomplishments
Evaluation Scenarios

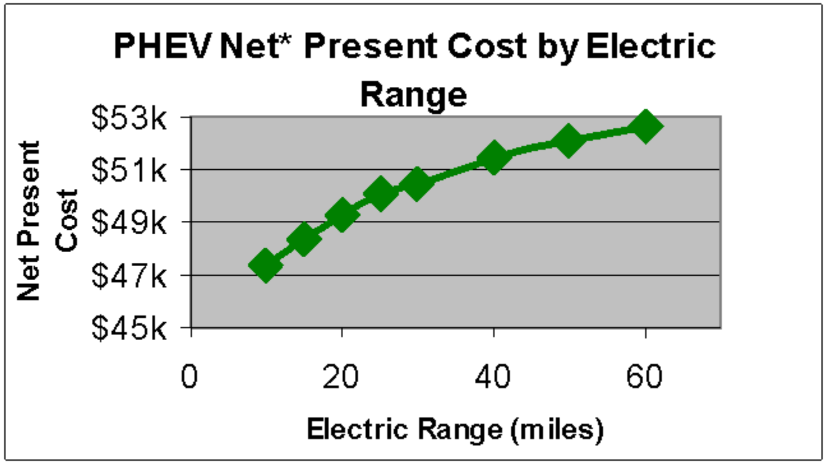
- PHEV10/30 (lowest NPC)
  - Today's values
    - » Battery cost
    - » Battery life
    - » Power electronics and motor cost
  - Projected values
    - » DOE's battery cost targets
    - » DOE's power electronics and motor cost targets
    - » A123's battery life



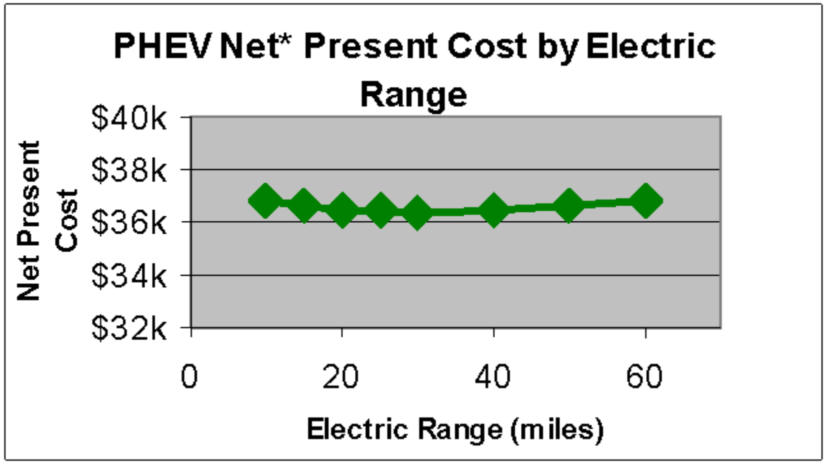


The Lowest NPC PHEV Electric Range Is 10/30 Miles

Today's Values



Projected Values



***Net present cost includes vehicle cost, taxes, fuel cost, battery replacement cost, and battery salvage payout**

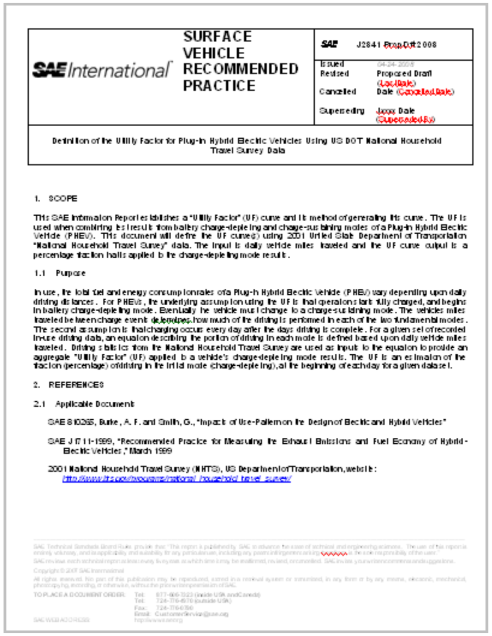
Technical Accomplishments

Questions PHEV Economics Can Help Answer

- Comparison of PHEV incentive scenarios.
- Replace batteries or size for vehicle life?
- Are PHEVs attractive to short distance drivers?
  - PHEV 20 for a 20 mile a day commute?
- What should the electric range be?
- What if the cost of electricity rises?
- What if gas price continues to climb?
- Future: Does V2G make economic sense?
- Others?

Technical Accomplishments
PHEV Test Procedures Development

- NREL active on SAE J1711 government-industry subcommittee
- Feedback to CARB, EPA
- Committee still working through difficult details (retaining consistency with past procedures, etc.)
  - — Document writing to begin soon
- J2841 "Information Report" on Utility Factor (UF) curve development will go to ballot soon
  - — Impending CARB procedures will reference
  - — Updateable independent of J1711 when new survey data available



SAE International SURFACE VEHICLE RECOMMENDED PRACTICE

SAE	J2841 Prop Dft 2008
Issued	04-24-2008
Revised	Proposed Draft (Last Date)
Cancelled	Date (Cancelled Date)
Superseding	Jxxxx Date (Superseded By)

Definition of the Utility Factor for Plug-In Hybrid Electric Vehicles Using US DOT National Household Travel Survey Data

1. SCOPE

This SAE Information Report establishes a "Utility Factor" (UF) curve and its method of generating this curve. The UF is used when combining test results from battery charge-depleting and charge-sustaining modes of a Plug-In Hybrid Electric Vehicle (PHEV). This document will define the UF curve(s) using 2001 United State Department of Transportation "National Household Travel Survey" data. The input is daily vehicle miles traveled and the UF curve output is a percentage fraction that is applied to the charge-depleting mode results.

1.1 Purpose

In use, the total fuel and energy consumption rates of a Plug-In Hybrid Electric Vehicle (PHEV) vary depending upon daily driving distances. For PHEVs, the underlying assumption using the UF is that operation starts fully charged, and begins in battery charge-depleting mode. Eventually the vehicle must change to a charge-sustaining mode. The vehicles miles traveled between charge events determines how much of the driving is performed in each of the two fundamental modes. The second assumption is that charging occurs every day after the days driving is complete. For a given set of recorded in-use driving data, an equation describing the portion of driving in each mode is defined based upon daily vehicle miles traveled. Driving statistics from the National Household Travel Survey are used as inputs to the equation to provide an aggregate "Utility Factor" (UF) applied to a vehicle's charge-depleting mode results. The UF is an estimation of the fraction (percentage) of driving in the initial mode (charge-depleting), at the beginning of each day for a given dataset.

2. REFERENCES

2.1 Applicable Documents

SAE 810265, Burke, A. F. and Smith, G., "Impact of Use-Pattern on the Design of Electric and Hybrid Vehicles"

SAE J1711-1999, "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles," March 1999

2001 National Household Travel Survey (NHTS), US Department of Transportation, website: http://www.bts.gov/programs/national_household_travel_survey/

Collaboration with Stakeholders

- Congressional Visitors
  - PHEVs and interconnection with renewables has highlighted visits of over 25 congressional member visits to NREL
- General Motors
  - Consulted on travel survey analysis and using results to support development of Volt
- Xcel Energy and V2Green
  - Collaboration on first in-use evaluation of Smart Charging and V2G algorithms
- Hymotion, EnergyCS, and Hybrids-Plus
  - Have experience with hardware from all three conversion vendors
- Tesla Motors and AC Propulsion
  - Interest and support in testing next generation EVs for battery life assessment and grid services
- Southern California Edison
  - Smart Garage demonstration provides good example of Home, Vehicle, Renewable interaction for future grid
- Google
  - Valuable discussions on technologies for future grid and vehicles

Future Work

- Light Duty Travel Behavior Repository and Impacts Analysis
  - Publish methods and provide data access
  - Vehicle analysis applications with multi-day datasets
- PHEV Emissions Reductions Strategies
  - Use analysis and thermal test stand to explore improvements
- Economic Scenario Analysis of PHEVs
  - End of life scenarios and V2G values to be considered
  - Collaboration with Value Proposition and Energy Storage efforts
- Low CO2 PHEV Pathway Analysis
  - Explore smart charging options leading to CO_2 reduction
- PHEV Test Procedures and Reporting
  - Continue support of SAE, EPA, and CARB efforts
- PHEV Ancillary Loads Analysis
  - Test method definition and impacts assessment

PHEV Analysis Project Summary

- Travel survey data and associated PHEV simulations are providing value in many areas
  - Linking usage profiles and energy storage life
  - Potential utility economic and emissions values
  - Availability and scale for synergy with renewables

- The work presented is addressing the real-world complexities and potential for expansion of the PHEV market