PHEV Operation Experience and Expectations

by

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• There is a need to understand the interaction between PHEV vehicle attributes and the vehicle usage pattern
PHEV Benefits Tied to Usage Pattern

- **PHEV Benefits**
  - **Efficiency** in Charge-Sustaining Mode
  - **Petroleum Displacement** in Charge-Depleting Mode

<table>
<thead>
<tr>
<th>Mode</th>
<th>conventional (petroleum displacement)</th>
<th>Hybrid (petroleum displacement)</th>
<th>Plug-in Hybrid (petroleum displacement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge-Sustaining Mode</td>
<td>~10-35%</td>
<td>~35-70%</td>
<td></td>
</tr>
<tr>
<td>Charge-Depleting Mode</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Distance**
  - Charge-Depleting Mode
  - Charge-Sustaining Mode
• Travel Profile Database
• PHEV Impact on Components
  — Energy Storage
  — Power Electronics
  — Engine Emissions
• Integration of Vehicles and Renewables
Objective

Collect and use data from regional travel surveys with GPS components for simulation to better quantify real-world benefits of advanced vehicle technologies.
Summary of Available Data

  - 6 Counties near LA
  - 470 households
    » 631 vehicles
    » 1225 days of travel
  - 48% of vehicles include multiple days
    » 2% with more than 1 week
  - Primarily weekdays
    » 80 units collected
    weekend travel too

- St. Louis
  - 147 households
    » 227 vehicles

- Kansas City (2004)
  - 368 vehicles

- Laredo
  - 234 vehicles

- Tyler/Longview
  - 343 vehicles

- Rio Grande
  - 376 vehicles

Each data set stored in a different format
Automated processing more challenging than expected
St. Louis Travel Data Analysis
Daily Driving Distance Similar to 1995 NPTS Data

St. Louis HHTS Data

• St. Louis data set includes 227 vehicles from 147 households
• Complete second by second driving profile for one day for each traveler
• 8650 miles of travel
• St. Louis data is a small representative sample of real data
• NPTS data is generated from mileage estimates

** HHTS – Household Travel Survey
NPTS – National Personal Travel Survey
Sample Real World Duty Cycle
PHEVs Reduce Fuel Consumption By >50% On Real-World Driving Cycles

Vehicle in-use activity pattern and simulated fuel consumption
  - In-use bars show morning, midday and evening usage peaks; at most 12% of vehicles in use at once
  - Cumulative fuel consumption lines consider entire fleet using specified architecture

<table>
<thead>
<tr>
<th>Fleet Averages</th>
<th>MPG</th>
<th>L/100km</th>
<th>Wh/mile</th>
<th>$/mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>26</td>
<td>9.05</td>
<td>-</td>
<td>9.1</td>
</tr>
<tr>
<td>Hybrid</td>
<td>37</td>
<td>6.36</td>
<td>-</td>
<td>6.5</td>
</tr>
<tr>
<td>PHEV 20</td>
<td>58</td>
<td>4.06</td>
<td>140</td>
<td>5.4</td>
</tr>
<tr>
<td>PHEV 40</td>
<td>76</td>
<td>3.10</td>
<td>211</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Assumptions
- PHEVs begin fully charged and do not charge until they finish driving for the day
- Gasoline is $2.41/gallon and electricity is $0.09/kWh for energy cost comparison (purchase price differences not included)

Published at Transportation Research Board Annual Meeting, 2007.
Four Potential Daily Recharge Strategies

Immediate End of Travel Day

Delay to 10pm

3 ways to control a single daily charge

Optimized to Off-Peak

Multiple charging events per day

Opportunity Charging
Recharge Scenario Impacts on PHEV Petroleum Consumption Benefits

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

Base Case assumes one full charge per day.

PHEV20 with Opportunity Charge provides greater benefits than PHEV40 with a single daily recharge.
PHEV Component Impacts Summary

• Energy Storage (Dave Howell)
  — PHEV introduces more long duration power pulses
  — Time at SOC depends on recharge behavior

• Power Electronics (Susan Rogers)
  — PHEVs produce higher thermal loads on PEEMs and increase battery bus voltage fluctuation

• Engine/Emissions Control (Lee Slezak)
  — CDE PHEV simulations suggest potential reduction in emissions by reducing initial daily cold starts and total daily engine starts
Charge depleting electric (CDE) is likely to have short high power events and moderate long duration energy equiv. events.
Charge depleting hybrid (CDH) will have lower but longer peak pulse and slightly lower energy equiv. pulse power requirements.
In CDH lower power case, the Peak and Energy Equiv. Pulse Powers may have similar level and duration.
PHEV Time At SOC Impacted by Charging Scenario

Based on Simulation of 227 duty cycles from St. Louis

How will differences in time at SOC impact battery life?

% of Day at State of Charge

Fully Discharged

State of Charge Zone

Fully Charged
PHEV impacts on APEEM

• Objective:
  — How will PHEV operation impact the APEEM system requirements?
PHEV Motor Operation From Real-World Simulations

- PHEVs more closely match an EV as PHEV AER increases.

- 227 cycles.
- >900,000 data points.
- Limited to key “on” data.
Output Battery Voltage Fluctuation

%Δ Relative to Median
HEV: 3%
PHEV20: 22%
PHEV40: 24%

• Based on simulation results for CDE PHEV
• Today’s CDH PHEV maybe different
HEV

- HEV current and voltage fluctuations greater than PHEV
- Impacts usage and thermal trends of DC/DC converter
- Results are battery chemistry dependent
PHEV Impacts on Engine/Emissions Control

- **Objective:**
  - How is the engine used differently in a PHEV and how might this impact emissions?

![Simulations](image1)

![Test Bed](image2)
Simulations Suggest PHEVs Will Reduce Initial Cold Starts

Cycles with at Least One Daily Engine Start

<table>
<thead>
<tr>
<th></th>
<th>CV</th>
<th>HEV</th>
<th>PHEV20 No Chg.</th>
<th>PHEV20 Opp. Chg.</th>
<th>PHEV20</th>
<th>PHEV40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles</td>
<td>227</td>
<td>227</td>
<td>225</td>
<td>169</td>
<td>186</td>
<td>186</td>
</tr>
</tbody>
</table>

Initial Cold Start Percent Reduction

<table>
<thead>
<tr>
<th></th>
<th>CV</th>
<th>HEV</th>
<th>PHEV20 No Chg.</th>
<th>PHEV20 Opp. Chg.</th>
<th>PHEV20</th>
<th>PHEV40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td>0%</td>
<td>0%</td>
<td>15%</td>
<td>26%</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td>Percent</td>
<td>5%</td>
<td>5%</td>
<td>21%</td>
<td>25%</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td>Percent</td>
<td>10%</td>
<td>10%</td>
<td>26%</td>
<td>29%</td>
<td>18%</td>
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<tr>
<td>Percent</td>
<td>15%</td>
<td>15%</td>
<td>31%</td>
<td>32%</td>
<td>18%</td>
<td>18%</td>
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<tr>
<td>Percent</td>
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<td>36%</td>
<td>37%</td>
<td>18%</td>
<td>18%</td>
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<td>41%</td>
<td>42%</td>
<td>18%</td>
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<tr>
<td>Percent</td>
<td>30%</td>
<td>30%</td>
<td>46%</td>
<td>47%</td>
<td>18%</td>
<td>18%</td>
</tr>
</tbody>
</table>

PHEV simulations assume CDE scenario – electric operation on UDDS

8% more
Simulation Results Show PHEVs Reduce Total Daily Engine Starts

Total Daily Engine Starts for All Cycles

<table>
<thead>
<tr>
<th>Engine Starts (1000s)</th>
</tr>
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<tbody>
<tr>
<td>HEV</td>
</tr>
<tr>
<td>PHEV20 No Chg.</td>
</tr>
<tr>
<td>PHEV20 Opp. Chg.</td>
</tr>
<tr>
<td>PHEV20</td>
</tr>
<tr>
<td>PHEV40</td>
</tr>
</tbody>
</table>

- HEV: 9.0
- PHEV20 No Chg.: 7.2
- PHEV20 Opp. Chg.: 2.3
- PHEV20: 4.2
- PHEV40: 3.0

Total Engine Starts Percent Reduction Relative to HEV (All Cycles)

<table>
<thead>
<tr>
<th>Percent Reduction</th>
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<tbody>
<tr>
<td>600%</td>
</tr>
<tr>
<td>500%</td>
</tr>
<tr>
<td>400%</td>
</tr>
<tr>
<td>300%</td>
</tr>
<tr>
<td>200%</td>
</tr>
<tr>
<td>100%</td>
</tr>
<tr>
<td>0%</td>
</tr>
</tbody>
</table>

How many of these starts are:
- Cold
- Warm
- Hot

- HEV: 19%
- PHEV20 No Chg.: 483%
- PHEV20 Opp. Chg.: 343%
- PHEV20: 431%
- PHEV40: 431%
Sample Urban Driving Data from PHEV Test Bed

Much of drive below speed threshold

~90s  ~200s  ~20s

Engine on Due to Cat Temp?

Gasoline Consumption (gal)

SOC (%*10); Speed (kmph); Altitude (ft/10); Cat
Temp (C)
PHEV Economic Analysis

• Objective:
  — Evaluate alternative economic factors that could influence PHEV marketability
    » Ancillary services
    » Incentives and battery replacement
Ancillary Services

• Services that make the electric power system stable and reliable

• Examples:
  — **Regulation Reserve:** the instantaneous response to demand variation
  — **Spinning Reserve:** the instantaneous response to generator failure
  — Both require units operating but not producing energy
Ancillary Services: Frequency Response

Reg Up = Discharge Vehicle
Reg Down = Charge Vehicle

At saturation the charge/discharge rates are ~ ½ C rate (moderate)

ERCOT Regulation: Requirement vs. Deployed

1,000MW ~ 500,000 vehicles @ 2kW (120V 20A)
Closer to a million vehicles to account for availability.
Potential V2G Values

Assume *Regulation* =$30$/MW-h; *Spin* = $10$/MW-h

PHEVs Marketable with V2G?

Years after Purchase

Cumulative Cost (k$)

0 2 4 6 8 10 12

- PHEV 20 Single Charge
- PHEV 20 Mid-day Charge
- PHEV 20 V2G low
- HEV
- IC
- PHEV 20 V2G High

Gasoline $3/gal
Electricity $0.06/kWh off peak, $0.12/kWh on peak
Ancillary Services: $150/year low, $1500/year high
Conclusions

• Remember the purpose:
  — Reduce dependence and demand for petroleum for transportation  
    » National impacts maybe more important than personal economics

• PHEVs offer potential to impact dependence
  — Understanding usage pattern and component impacts is key to well designed and effective PHEV