U.S. Department of Energy’s Vehicle Technologies Program

PHEV Operations, Performance and Charging Profiles

Jim Francfort
Hawaiian Electric Company
Webcast - October 2009

Idaho National Laboratory

- Eastern Idaho based U.S. Department of Energy (DOE) Federal laboratory
- 890 square mile site with 3,600 staff
- Support DOE’s strategic goal:
  - Increase U.S. energy security and reduce the nation’s dependence on foreign oil
- Multi-program DOE laboratory
  - Nuclear Energy
  - Fossil, Biomass, Wind, Geothermal and Hydropower Energy
  - Advanced Vehicles and Battery Development
  - Energy Critical Infrastructure Protection
AVTA Background and Goals

• The Advanced Vehicle Testing Activity (AVTA) is part of DOE’s Vehicle Technologies Program
• The Idaho National Laboratory (INL) and Electric Transportation Engineering Corporation (ETEC) conduct the AVTA. Argonne National Laboratory performs dynamometer testing

• The AVTA goals:
  – Provide benchmark data to technology modelers, research and development programs, vehicle manufacturers (via VSATT), and target and goal setters
  – Assist fleet managers in making informed early adaptor vehicle purchase, deployment and operating decisions

AVTA Testing by Technology

• Plug-in hybrid electric vehicles (PHEV)
  – 12 models, 187 vehicles, 850,000 fleet test miles
• Hybrid electric vehicles (HEV)
  – 17 models, 45 vehicles, 4.5 million test miles
• Neighborhood electric vehicles
  – 23 models, 200,000 test miles
• Hydrogen ICE (internal combustion engine) vehicles
  – 7 models, 500,000 test miles
• Full-size battery electric vehicles (BEVs)
  – 40 EV models, 5+ million test miles
• Urban electric vehicles
  – 3 models, 1 million test miles
12 PHEVs Models in Testing/Demonstrations

- Hymotion Prius (A123Systems)
- Hymotion Escape (A123Systems)
- Ford E85 Escape (Johnson Controls/Saft)
- EnergyCS Prius, 2 models (Valance and Altair Nano)
- Electrovaya Escape (Electrovaya)
- Hybrids Plus Escape, 2 models (Hybrids Plus and K2 Energy Solutions)
- Hybrids Plus Prius (Hybrids Plus)
- Manzanita Prius (lead acid)
- Manzanita Prius (Thunder Sky)
- Renault Kangoo (Saft NiCad)
- (All batteries are Lithium unless noted)

PHEV Testing Methods and Objectives

- Perform independent testing of PHEVs, using:
  - Baseline performance testing: closed test tracks and dynamometers
  - Accelerated testing: dedicated drivers operating on defined onroad loops
  - Fleet testing: everyday unstructured \ non-directed fleet and public use, with onboard data loggers
  - Laboratory testing of PHEV batteries
- Testing used to document:
  - Battery life, charging patterns and profiles
  - Vehicle operations, fuel use (electricity and gasoline) and infrastructure requirements
  - Driver influences on fuel use
  - Individual PHEV models and PHEV concepts
  - PHEV life-cycle costs
PHEV Operating Modes

- **Charge sustaining (CS) mode**: from start to finish of a single trip, there is no energy available for electric drive propulsion in the PHEV battery. Therefore, the battery state-of-charge (SOC) is sustained.

- **Charge depleting (CD) mode**: from start to finish of a single trip, there is energy available for partial or full electric drive propulsion in the PHEV battery. Therefore, the battery SOC is being depleted during the trip.

- **Mixed CD/CS mode**: there is energy in the battery pack at the start of a single trip, but the PHEV battery is fully depleted before the trip ends.

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**Hymotion Prius Gen I – UDDS Fuel Use**

- 5 kWh A123Systems (Li) and Prius packs (AC kWh)

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**Hymotion PHEV Prius MPG & kWh - UDDS Testing**
Hymotion Prius Gen I – HWFEDS Fuel Use

- 5 kWh A123Systems (Li) and Prius packs (AC kWh)

![Graph showing Hymotion PHEV Prius MPG & kWh - HWFEDS Testing](image)

Each Bar - 1 HWFET Test Cycle, Labeled by Cumulative Miles

PHEV Accelerated Testing

- Accelerated testing in Phoenix over 5,440 onroad miles
- GPS units track distance, average and maximum speeds

<table>
<thead>
<tr>
<th>Cycle (mi)</th>
<th>Urban (10 mi)</th>
<th>Highway (10 mi)</th>
<th>Charge (hr)</th>
<th>Reps (N)</th>
<th>Total (mi)</th>
<th>Reps (%)</th>
<th>Miles (%)</th>
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<td>Total</td>
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<td>1,344</td>
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<td>Average</td>
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<td>57%</td>
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### Hymotion Prius Gen I – Accelerated Testing

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<th>Charge (hr)</th>
<th>Reps (N)</th>
<th>Total (mi)</th>
<th>Electricity AC kWh</th>
<th>Gasoline Gals</th>
<th>MPG</th>
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**Total** 2340 3100 1404 167 5,440 **Weighted Average** 79.5

Each total distance slightly greater than 600 and 640 miles. HEV version = 44 mpg

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### Hymotion Prius Gen II – Accelerated Testing

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</tbody>
</table>

**Total** 2340 3100 1404 167 7,840 **Weighted Average**

Each total distance slightly greater than 600 and 640 miles. HEV version = 44 mpg
Hymotion Prius Gen II – Accelerated Testing

- 40 mile city/highway loops – high ambient temperatures results in incomplete charging

![Graph showing temperature versus battery temperature for Hymotion Prius Gen II](image)

PHEV Fleet Testing Partners

- 75+ testing partners in the U.S. and Canada:
  - 36 Electric utilities and 2 clean-air agencies
  - 10 City, county and state governments
  - 7 Private companies and advocacy organizations
  - 8 Universities and colleges and 4 Canadian provinces
  - 2 PHEV companies 1 sea port and 1 DOD facility

- Testing partners include:
PHEVs and Demonstration Locations

227 Total
179 Operating
36 Coming '09
12 Out of Service

PHEV Fleet Testing Reports

- Summary reports posted monthly on web
- Individual vehicle reports only go to the respective fleets each month, 1,060+ reports to date (August 1, 2009)
- 153 Hymotion Prius PHEVs, 780,000 miles, 86,000 trips, 20,500 charging events, 47,000 kWh used. V2Green and Kvaser data logger reports
Hymotion Prius (V2Green Logger) Fleet Tests

- March 01/08 to July 01/09. 110 PHEVs, 498,000 miles, 54,000 trips, 12,400 charging events and 31,000 kWh used.

Hymotion Prius PHEVs – CS Trips

- MPG and aggressive driving impacts March ‘08 – May ‘09

Data from 150 Hymotion Prius with V2Green and Kvaser loggers.
Hymotion Prius PHEVs – CS/CD Mixed Trips

- MPG and aggressive driving impacts March ‘08 – May ‘09

Data from 150 Hymotion Prius with V2Green and Kvaser loggers

Hymotion Prius PHEVs – CD Trips

- MPG and aggressive driving impacts March ‘08 – May ‘09

Data from 150 Hymotion Prius with V2Green and Kvaser loggers
MPG Results - Charge Depleting (CD) Mode

Percent of 22,700 CD Trips and 151,000 CD Miles by MPG Grouping

Data from 150 Hymotion Prius with V2Green and Kvaser loggers

Ambient Temperature MPG Impacts

Hymotion Prius Fleet Fuel Economy

Average Ambient Temperature [C]

Average Fuel Economy [MPG]
Engine Operations by Ambient Temperatures

Hymotion Prius Fleet - Percentage of Miles with Engine On

<table>
<thead>
<tr>
<th>Average Ambient Temperature [°C]</th>
<th>Percent Miles Engine On [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -20C</td>
<td>100%</td>
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<tr>
<td>-20 to 0C</td>
<td>80%</td>
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<tr>
<td>-10 to 0C</td>
<td>60%</td>
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<tr>
<td>0 to 10C</td>
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<tr>
<td>10 to 20C</td>
<td>20%</td>
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<tr>
<td>20 to 30C</td>
<td>0%</td>
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<tr>
<td>&gt; 30C</td>
<td>0%</td>
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</table>

Monthly Fleet Testing MPG Results

Monthly MPG by Operating Mode

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<th>Month</th>
<th>MPG - All</th>
<th>MPG CD</th>
<th>MPG CD/CS</th>
<th>MPG CS</th>
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<td>80</td>
<td>75</td>
<td>70</td>
<td>65</td>
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<tr>
<td>May 2009</td>
<td>75</td>
<td>70</td>
<td>65</td>
<td>60</td>
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<tr>
<td>June 2009</td>
<td>70</td>
<td>65</td>
<td>60</td>
<td>55</td>
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<tr>
<td>July 2009</td>
<td>65</td>
<td>60</td>
<td>55</td>
<td>50</td>
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</table>
Testing Results by Fleet

Percent Miles Driven by Fleet and Operating Mode

Testing Results by Fleet – cont’d

Percent Trips Taken by Fleet and Operating Mode
Testing Results by Fleet – cont’d

Charging Statistics

- WA State 31
- California 18
- All V2Green 112
- Hawaii 6
- Canada 14

Testing Results by Fleet – cont’d

MPG by Fleet and Operating Mode

- WA State 31
- California 18
- All V2Green 112
- Hawaii 6
- Canada 14
Puget Sound PHEV Smart Charging Trials

- 13 Seattle PHEV’s participated in trials conducted by Seattle City Light using GridPoint’s Electric Vehicle Management Solution

- Types of Trials:
  - Time of Day Charging – Vehicles charging allowed only during certain hours of the day.
  - Goal Based Charging – Normalize power demand for vehicle charging around a goal load.
  - Economic Charging – Allow vehicle charging only when the price of electricity is below a threshold

Trial Analysis

- INL analyzed data collected from the participating vehicles during four trials:

<table>
<thead>
<tr>
<th>Trial and Description</th>
<th>Date Range Analyzed</th>
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</thead>
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<tr>
<td>Pre-Trials – No Charging Control</td>
<td>1/9/09-1/23/09</td>
</tr>
<tr>
<td>Trial 1 – Time of Day Charging</td>
<td>4/3/09-4/16/09</td>
</tr>
<tr>
<td>Trial 2 – Goal Based Charging – 7kW*</td>
<td>4/17/09-4/30/09</td>
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<td>Trial not included, 7kW load not reached</td>
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<tr>
<td>Trial 3 – Economic Charging</td>
<td>5/1/09-5/14/09</td>
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<tr>
<td>Trial 4 – Goal Based Charging – 3kW</td>
<td>5/15/09-5/28/09</td>
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</tbody>
</table>
Equivalent Battery Cycles

- The charging data can be used to estimate the equivalent battery cycles (e.g., a simple battery “odometer”)
- Equivalent cycles are based on a nominal capacity of 25.4 Ah (4700 Wh / 184.8 V)
- SCL1 appears to have experienced the most aging so far

<table>
<thead>
<tr>
<th></th>
<th>Pre-Trial</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Total</th>
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<td>2</td>
<td>3</td>
<td>9</td>
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<td>Port of Seattle 2</td>
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Estimated Equivalent Cycles

Gridpoint VCM with Hymotion L5 Plug-In Conversion Modules in Prius

- GridPoint Vehicle Connectivity Module (VCM):
  - Controlled charging, as directed by GridPoint’s server
  - Logged vehicle charging and driving data
- VCM controls charging by requesting the Hymotion pack wait to charge or charge at a specified power level (% of full) - no physical interruption of the circuit
- Uncontrolled Hymotion pack will begin to charge immediately when plugged in (as temperature, state-of-charge, etc allow)
Charging – No Control

Typical Charge, Single Vehicle - No External Control

0 5000 10000 15000 20000 25000 30000 35000
0 200 400 600 800 1000 1200 1400
AC Power [Watts]
Time [seconds]

Charging
$P_{avg} = 1100$ W

Post Charge
$P_{avg} = 6$ W

End-of-Charge

Results of Charging Trials – Trial #1

- When a vehicle is plugged in, the VCM establishes communication with control server, requests Hymotion pack charge only between 10pm-4am

Typical Charge, Single Vehicle - 10am to 4pm Charging

0 10000 20000 30000 40000 50000 60000
0 200 400 600 800 1000 1200 1400 1600
AC Power [Watts]
Time [seconds]

Charging
$P_{avg} = 897$ W

Post Charge
$P_{avg} = 5$ W

Standby
$P_{avg} = 40$ W

Vehicle Plugged In
Charging Begins
~10 PM
Charging Ends
Results of Charging Trials – Trial #1 (cont.)

• Rogue AC kWh – Energy drawn outside of allowable charging window:
  – Communication not established or lost - charging occurs
  – Cumulative standby energy draw when not charging

![Diagram of Energy Consumption by Type and Time]

![Diagram of Energy Drawn Outside of Commanded Window]

Results of Charging Trials – Trial #3

• Artificial price signal supplied, vehicles are to charge when energy price < $.08/kWh

![Diagram of Typical Charge, Single Vehicle - Economic Control]
Results of Charging Trials – Trial #4

- Vehicles’ charging controlled to normalize the resource load around 3 kW (Typical 7 Vehicle Max, 13 Possible)

![Graph showing typical charge, single vehicle - 3kW normalized load.

- Standby: $P_{avg}=37W$ (7 Segments)
- Charge: $P_{avg}=702W$ (8 Segments)
- Post Charge: $P_{avg}=6W$

Commercial Fleet, Uncontrolled Charging May 2009

- 66 vehicles, 1218 charging events
- Average Hourly Vehicle Charging Demand
- Average Hourly Vehicle Charging Demand (kW)
- Day of month
- Time of day (hrs)
- Time of day (hrs)
Commercial Fleet, Uncontrolled Charging May 2009
66 vehicles, 1218 charging events

Day of the Month - by Hour
Gray lines are average hourly demand for individual hours on that day
Red line is average hourly demand of all hours that day

Day of the Month - by Day
Gray lines are average daily demand for individual days in month
Red line is average hourly demand of all days

Private Fleet, Uncontrolled Charging May 2009
7 vehicles, 98 charging events

Day of the Week
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday

Average Hourly Vehicle Charging Demand

Day of month
Average Hourly Vehicle Charging Demand (kW)

Time of day (hrs)

Day of month
Time of day (hrs)

Average Hourly Vehicle Charging Demand (kW)

Time of day (hrs)
PHEV Charging Infrastructure Cost Report

- Analyzes PHEV infrastructure requirements in single and multi-family residential, and commercial facilities as well as driving trends. No site specific costs
- Charging infrastructure equipment/administrative costs:
  - Levels 1 (120V, 15 or 20 amp) and 2 residential
  - Levels 1 and 2 (208/240V ~40 amp) apartment complex
  - Level 2 commercial facility
- Battery sizes & charge times for various PHEV platforms
- Power electronics & battery costs for PHEV platforms

<table>
<thead>
<tr>
<th>Level 1 Residential</th>
<th>Labor</th>
<th>Material</th>
<th>Permits</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVSE (charge cord)</td>
<td>- -</td>
<td>$350</td>
<td>- -</td>
<td>$350</td>
</tr>
<tr>
<td>Residential circuit installation (20A branch circuit, 120 VAC/1-Phase)</td>
<td>$300</td>
<td>$131</td>
<td>$85</td>
<td>$516</td>
</tr>
<tr>
<td>Administration costs</td>
<td>$60</td>
<td>$43</td>
<td>$9</td>
<td>$112</td>
</tr>
<tr>
<td>Total Level 1 Cost</td>
<td>$360</td>
<td>$424</td>
<td>$94</td>
<td>$878</td>
</tr>
</tbody>
</table>

Report @ http://avt.inl.gov/pdf/phev/phevInfrastructureReport08.pdf
AVTA Webpage Use and Gasoline Costs

INL WWW Visitors & Gasoline Costs (all formulations, areas, and grades)

Number of Monthly Visitors

Visitors (left axis)

Gasoline Cost (right axis)

Linear (Visitors (left axis))

Linear (Gasoline Cost (right axis))

All Grades Gasoline Costs - End of Month

$1.25

$1.50

$1.75

$2.00

$2.25

$2.50

$2.75

$3.00

$3.25

$3.50

$3.75

$4.00

$4.25

Acknowledgement

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Additional Information

http://avt.inl.gov
or
http://www1.eere.energy.gov/vehiclesandfuels/avta/

INL/CON-09-17005