US Department of Energy
Vehicle Technologies Program
PHEV Research and Development Areas

System / component level activities include:

- Energy storage
  - Advanced battery cells, packs and full systems
    - Cost, life, low temperature performance, tolerance abuse and safety
  - Monitoring of all technologies (capacitors, flywheels, etc)

- Power electronics and electric Motors
  - Cost, size, thermal control, integrated systems development

- Definition of PHEV component requirements
Vehicle Technology Analysis and Evaluation activities include:

- **Modeling and Simulation**
  - Reference Vehicle Definition
  - Analytical Tool Development
  - Technology Verification
- **Integration and Validation**
  - Hardware-in-the-Loop System Integration
  - Technology Validation
- **Laboratory and Field Evaluation**
  - Vehicle / Component Testing
  - Model Validation
Cooperative testing agreements provide access to non-DOE owned PHEVs operating in demonstration fleets. Partners include:

- New York State Energy Research Development Agency (NYSERDA)
- City of Seattle, King County, Port of Seattle, Puget Sound Clean Air Agency
- Tacoma Power
- State of Hawaii
- National Rural Electric Cooperative Association
- University of California-Davis
- PHEV conversion companies
  - Hymotion
  - EnergyCS
  - others
US Department of Energy PHEV Technology Acceleration and Deployment Activity (TADA)

- Funding opportunity for vehicle manufacturers to put prototype PHEVs in field over next three years
- Proposals selected for negotiation from:
  - General Motors
  - Ford Motor Co.
  - Chrysler / General Electric
Idaho National Laboratory

- Eastern Idaho based U.S. Department of Energy (DOE) multi-program 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
- The INL has managed DOE’s Advanced Vehicle Test Activity since the late 1980’s
Advanced Vehicle Testing Activity (AVTA)

• Part of the U.S. Department of Energy’s Vehicle Technologies Program

• INL and Electric Transportation Engineering Corporation (ETEC) conduct the AVTA’s light-duty vehicle testing, with Argonne National Laboratory performing dynamometer testing

AVTA Goals

• Determine actual petroleum displacement and overall operating cost of advanced technology vehicles

• Provide benchmark data to industry and government research and development programs

• Assist consumers in making informed vehicle purchase, usage, and operating decisions
AVTA Testing History

• Plug-in hybrid electric vehicles
  – 9 models, ~70 vehicles in fleets
• Hybrid electric vehicles
  – 14 models, 4+ million test miles
• Hydrogen ICE (internal combustion engine) vehicles
  – 6 models, 400,000 test miles
• Full-size electric vehicles
  – 40 EV models, 5+ million test miles
• Neighborhood electric vehicles
  – 16 models, 200,000 test miles
• Urban electric vehicles
  – 3 models, 1 million test miles
PHEV Models Tested by AVTA

Nine different PHEV models are in or have completed various testing / demonstration activities

- Hymotion Prius
- EnergyCS Prius
- Hymotion Escape
- HybridsPlus Escape
- HybridsPlus Prius
- Manzanita lead acid Prius
- Electrovaya Escape
- Ford E85 Escape
- Renault Kangoo

- Daimler Sprinter expected to start testing in Spring 2009
PHEV Testing Objectives

Perform independent testing of PHEVs using:

- **Baseline performance testing**
  - closed test tracks and dynamometers

- **Accelerated on-road testing**
  - dedicated drivers operating on defined routes

- **Fleet testing**
  - monitor everyday uncontrolled use with onboard data loggers

- **Lab and field off-board charging / grid interaction studies**
PHEV Testing Objectives
Study and document
• How the vehicles are driven
• How the vehicles are charged
• The effect on
  – Gasoline and electricity fuel use
  – Battery life
  – Facility / grid demand and energy profiles
• Charging infrastructure requirements
• Cost / benefit of fast charging, vehicle-to-grid charging
• Overall PHEV life-cycle costs
PHEV Baseline Performance Testing

- These and other test results at http://avt.inl.gov

### U.S. Department of Energy Advanced Vehicle Testing Activity

#### Base Vehicle Description
- Make: Toyota
- Model: Prius
- Year: 2006
- VIN: 3TFBU326767508841
- Number of Passengers: 5
- Hybrid Configuration: Series/Parallel

#### Energy GS Plug-In Hybrid

<table>
<thead>
<tr>
<th>Vehicle Specifications</th>
<th>Vehicle Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weights</strong></td>
<td></td>
</tr>
<tr>
<td>Design Curv. Weight: 3100 lb</td>
<td></td>
</tr>
<tr>
<td>GVWR: 3700 lbs</td>
<td></td>
</tr>
<tr>
<td>Curb Weight: 2400 lbs</td>
<td></td>
</tr>
<tr>
<td>Curb Mass: 2400 lbs</td>
<td></td>
</tr>
<tr>
<td>Payload: 1600 lbs</td>
<td></td>
</tr>
<tr>
<td>Rollout: 1400 lbs</td>
<td></td>
</tr>
<tr>
<td><strong>Charge Depletion</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration: 60-MPH</td>
<td></td>
</tr>
<tr>
<td>Time: 11.54 seconds</td>
<td></td>
</tr>
<tr>
<td>Acceleration: 1/4-Mile</td>
<td></td>
</tr>
<tr>
<td>Time: 20.95 seconds</td>
<td></td>
</tr>
<tr>
<td>Maximum Speed: 75.7 MPH</td>
<td></td>
</tr>
<tr>
<td>Maximum Speed: 119 MPH</td>
<td></td>
</tr>
<tr>
<td><strong>Charge Sustaining</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration: 60-MPH</td>
<td></td>
</tr>
<tr>
<td>Time: 10.32 seconds</td>
<td></td>
</tr>
<tr>
<td>Acceleration: 1/4-Mile</td>
<td></td>
</tr>
<tr>
<td>Time: 15.08 seconds</td>
<td></td>
</tr>
<tr>
<td>Maximum Speed: 75.7 MPH</td>
<td></td>
</tr>
<tr>
<td>Maximum Speed: 119 MPH</td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Economy</strong></td>
<td></td>
</tr>
<tr>
<td>UDDS: 11.8 mpg</td>
<td></td>
</tr>
<tr>
<td>HWFET: 14.9 mpg</td>
<td></td>
</tr>
</tbody>
</table>

#### UDDS Fuel Economy

<table>
<thead>
<tr>
<th>Distance (miles)</th>
<th>Fuel Economy (mpg)</th>
<th>A/C Energy Consumed (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>118.0</td>
<td>0.83</td>
</tr>
<tr>
<td>20</td>
<td>137.6</td>
<td>0.64</td>
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<tr>
<td>40</td>
<td>124.7</td>
<td>0.52</td>
</tr>
<tr>
<td>60</td>
<td>104.8</td>
<td>0.38</td>
</tr>
<tr>
<td>80</td>
<td>94.7</td>
<td>0.56</td>
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<tr>
<td>100</td>
<td>89.1</td>
<td>0.65</td>
</tr>
<tr>
<td>200</td>
<td>77.9</td>
<td>0.63</td>
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</tbody>
</table>

#### HWFET Fuel Economy

<table>
<thead>
<tr>
<th>Distance (miles)</th>
<th>Fuel Economy (mpg)</th>
<th>A/C Energy Consumed (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>129.5</td>
<td>0.65</td>
</tr>
<tr>
<td>20</td>
<td>160.3</td>
<td>0.31</td>
</tr>
<tr>
<td>40</td>
<td>117.4</td>
<td>0.58</td>
</tr>
<tr>
<td>60</td>
<td>90.4</td>
<td>0.58</td>
</tr>
<tr>
<td>80</td>
<td>80.8</td>
<td>0.58</td>
</tr>
<tr>
<td>100</td>
<td>83.7</td>
<td>0.58</td>
</tr>
<tr>
<td>200</td>
<td>72.3</td>
<td>0.58</td>
</tr>
</tbody>
</table>

**Test Notes:**
1. Vehicle fuel economy is shown in miles per gallon (mpg).
2. Vehicle efficiency is shown in energy consumed per mile.
3. Vehicle performance is shown in acceleration time.
4. A/C energy is shown in kilowatt-hours (kWh).

****

Elec
electric transportation engineering corporation

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Idaho National Laboratory

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Toyota Prius with Hymotion PHEV conversion – EPA City Test

Hymotion PHEV Prius MPG & kWh - UDDS Testing

Each Bar - 1 UDDS Test Cycle, Labeled by Cumulative Miles
Toyota Prius with Hymotion PHEV conversion – EPA Highway Test

Hymotion PHEV Prius MPG & kWh - HWFET Testing

Each Bar - 1 HWFET Test Cycle, Labeled by Cumulative Miles
Hymotion Prius – On-road Accelerated Testing

<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>Electricity AC kWh</th>
<th>Gasoline Gal</th>
<th>MPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>60</td>
<td>600</td>
<td>136.33</td>
<td>4.81</td>
<td>127.2</td>
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<tr>
<td>20</td>
<td>1</td>
<td>1</td>
<td>8</td>
<td>30</td>
<td>600</td>
<td>122.02</td>
<td>5.37</td>
<td>115.9</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>0</td>
<td>12</td>
<td>15</td>
<td>600</td>
<td>84.10</td>
<td>6.05</td>
<td>101.1</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>2</td>
<td>12</td>
<td>15</td>
<td>600</td>
<td>87.22</td>
<td>5.78</td>
<td>106.9</td>
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<tr>
<td>40</td>
<td>0</td>
<td>4</td>
<td>12</td>
<td>15</td>
<td>600</td>
<td>79.82</td>
<td>8.54</td>
<td>73.1</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>4</td>
<td>12</td>
<td>10</td>
<td>600</td>
<td>55.33</td>
<td>8.98</td>
<td>68.9</td>
</tr>
<tr>
<td>80</td>
<td>2</td>
<td>6</td>
<td>12</td>
<td>8</td>
<td>640</td>
<td>43.99</td>
<td>11.36</td>
<td>58.3</td>
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<tr>
<td>100</td>
<td>2</td>
<td>8</td>
<td>12</td>
<td>6</td>
<td>600</td>
<td>35.98</td>
<td>8.43</td>
<td>73.2</td>
</tr>
<tr>
<td>200</td>
<td>2</td>
<td>18</td>
<td>12</td>
<td>3</td>
<td>600</td>
<td>15.0</td>
<td>11.02</td>
<td>54.8</td>
</tr>
<tr>
<td>Total</td>
<td>2540</td>
<td>3100</td>
<td>1404</td>
<td>167</td>
<td>5,440</td>
<td>Weighted Average</td>
<td>79.5</td>
<td></td>
</tr>
</tbody>
</table>

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

14 - Canada

69 w/data loggers
64 adding CY08
? In discussion
133 Total end of CY08
PHEV Fleet Performance

- Data sampled from 28 Hymotion Prius vehicles
- Jan – Jun 2008
- 58,005 miles

Combined Fleet Cumulative Gasoline Fuel Economy by Trip Type

Distance Traveled by Trip Type

CD = Charge depleting
CS = Charge sustaining
PHEV Fleet Performance

- Same 28 Hymotion Priuses, Jan – Jun 2008
- Range of monthly vehicle fuel economy results:

Some cars are achieving potential!
PHEV Fleet Performance

- Same 28 Hymotion Priuses, Jan – Jun 2008
- Charging energy:

\[
\frac{3073 \text{ kWh}}{28185 \text{ mi}} = 108 \text{ Wh/mi}
\]

\[
58005 \text{ mi} \times 108 \text{ Wh/mi} = 6265 \text{ kWh}
\]

Need > twice the electricity for 100% charge depleting miles (all other things equal)
PHEV Fleet Performance

- For better gasoline fuel efficiency, use more electricity!
- Battery capacity limited, so plug in more often

- Or put another way:

  For charge depleting operation, distance driven between charging events must be less than charge depleting range
Fleet Distance vs. Range

Hymotion Prius
23 cars
Jan – Jul 2008

Same cars, date range
Includes all segments that started with SOC > 95%, ended in CS mode.
CD range is CD distance for each segment.
Fleet Fuel and Electricity vs. Segment Distance

MPG vs. Distance Driven Between Charging Events

DC kWh vs. Distance Driven Between Charging Events

(42 EV-only segments not included)
“Actual Mileage May Vary”

- Even when in charge depleting mode, gasoline fuel efficiency, electrical energy efficiency, and charge depleting range vary widely depending on usage.

- Causes of variation
  - Driver aggressiveness
  - Location (city, rural, highway)
  - Temperature
  - Payload
  - Etc.
Driver Aggressiveness

Aggressiveness measured by time at accelerator pedal position
- The deeper the pedal, the higher the aggressiveness

Effect of Aggressiveness on Trip Fuel Economy

28 Hymotion Priuses
Jan – Jun 2008
All trips with distance > 1 mi
Fuel Economy Seasonal Variation

Overall Gasoline Fuel Economy
Fleet Distribution by Month

Range of monthly vehicle fuel economy (mpg)

Month

Jan
Feb
Mar
Apr
May
Jun

0
20
40
60
80
100
120
140

max
med
min

28 Hymotion Priuses
Jan – Jun 2008
## Plug-in Charging Patterns

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average number of charging events per vehicle per month</td>
<td>20</td>
</tr>
<tr>
<td>Average number of charging events per vehicle per day when vehicle driven</td>
<td>0.7</td>
</tr>
<tr>
<td>Average number of trips between charging events</td>
<td>3.9</td>
</tr>
<tr>
<td>Average distance driven between charging events (mi)</td>
<td>34.0</td>
</tr>
<tr>
<td>Average duration of charging event (hr)</td>
<td>2.4</td>
</tr>
<tr>
<td>Average energy per charging event (DC kWh)</td>
<td>1.8</td>
</tr>
<tr>
<td>Average charging energy per vehicle per month (DC kWh)</td>
<td>35.3</td>
</tr>
</tbody>
</table>
Plug-in Charging Patterns

Time of Day When Driving

Time at the Start of Charging Events
Plug-in Charging Patterns

Energy Consumed vs. Time of Day When Charging
PHEV – Grid Interaction Testing

- **Time-of-day charging study** (Fall 2008)
  - Conducting charging demonstration with City of Seattle using 13 Seattle area PHEVs
  - Includes INL battery impact analysis
  - Uses V2Green wireless charging control

- **Charging infrastructure and facility demand study** (started May 2008)
  - Conducting charging demonstration with Tacoma Power to:
    - document charging infrastructure needs
    - determine demand and energy profiles of PHEV charging as portion of facility profiles
  - Using WiFi local energy meter (LEM) data collection system

- **Bidirectional vehicle-to-grid (V2G) charging study** with electric utilities participating (Fall 2008)
  - 6 kW and 20 kW levels, using two lithium battery PHEVs, V2Green cellular charging control, documenting infrastructure requirements and costs
Acknowledgement

INL/AVTA work is supported by the U.S. Department of Energy’s Vehicle Technologies Program

Pat Davis, Tien Duong, Lee Slezak and Ro Sullivan

Additional Information

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