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

Advanced Electric Vehicle Testing and Evaluation Results

John Smart

AT&T Fleet Operations Alternative Fuel Vehicle Planning Session
St. Louis, MO – Nov 11, 2009

This presentation does not contain any proprietary or sensitive information
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
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 fleet managers and consumers in making informed vehicle purchase, usage, and operating decisions
AVTA Testing by Technology

- **Plug-in hybrid electric vehicles (PHEVs)**
  - 12 models, 216 vehicles, 1.1 million test miles
- **Hybrid electric vehicles (HEV)**
  - 18 models, 47 vehicles, 4.7 million test miles
- **Full-size battery electric vehicles (BEVs)**
  - 40 EV models, 5+ million test miles
- **Neighborhood electric vehicles**
  - 23 models, 200,000 test miles
- **Urban electric vehicles**
  - 3 models, 1 million test miles
- **Hydrogen internal combustion engine vehicles**
  - 7 models, 400,000 test miles
Focus on advanced electric vehicles

Outline

• Comparison of vehicle technology and operating characteristics
• Vehicles available today
• HEV and PHEV test results to date
• Big picture considerations for PHEVs
• Possible future vehicles
Comparison of Vehicle Technology

Conventional vehicle with internal combustion engine (ICE) only
Comparison of Vehicle Technology

- Hybrid Electric Vehicle (HEV) with ICE and electric drive
- Does not plug in to electric grid
Comparison of Vehicle Technology

- **Plug-in Hybrid Electric Vehicle (PHEV) with ICE and electric drive**
Comparison of Vehicle Technology

- Battery Electric Vehicle (BEV) with electric drive only
Conceptual Comparison of Vehicle Operation

Hypothetical 15 mile drive cycle
Conceptual Comparison of Vehicle Operation

Conventional vehicle

PHEV10 (all-electric capable)

HEV

BEV (100 mi range)

Charge Sustaining (CS)

Charge Depleting (CD)

MPH

0 20 40 60 80 100 120

0 20 40 60 80

time

% SOC

engine on

engine off
AVTA is collaborating with auto makers to begin testing OEM PHEVs and BEVs. HEV and conversion PHEV testing continues.

AVTA has done extensive testing of vehicles available to date.

* Refers to PHEVs and BEVs produced for the mass market. OEMs have produced PHEVs and BEVs in low volume intermittently since the 1990’s.
HEV TESTING
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HEV Fleet / Accelerated Reliability Testing MPG - By HEV Model

Miles per Gallon

- Gen I Civic: 37.6
- Insight: 45.2
- Gen I Prius: 41.0
- Silverado: 17.9
- Accords: 28.1
- Gen II Prius: 44.2
- Escapes: 26.7
- Lexus RX400h: 23.4
- Highlander: 24.4
- Camry: 33.6
- Gen II Civic: 39.1
- Saturn Vue: 26.6
- Altima: 30.2
- Tahoe: 21.8
AVTA HEV Fleet MPG and EPA MPG

Percent EPA MPG > or < AVTA Fleet MPG

-14%  -12%  -10%  -8%  -6%  -4%  -2%  0%  2%  4%  6%  8%  10%  12%  14%  16%  18%  20%  22%  24%  26%  28%  30%  32%  34%  36%

New EPA > AVTA  Old EPA > AVTA

- 2003 Civic
- 2001 Insights
- 2002 & 2003 Prius
- 2004 4WD Silverado
- 2004 2WD Silverado
- 2005 Accords
- 2004 Prius
- 2005 4WD Escape
- 2004 2WD Escape
- 2006 AWD Lexus RX400h
- 2006 2WD Lexus RX400h
- 2006 AWD Highlander
- 2007 Camry
- 2007 2WD Saturn Vue
- 2007 2WD Altima
- 2008 Tahoe 2WD

Average

'08 Tahoe - no old EPA Ratings
## HEV Maintenance and Repairs

### HEV Fleet Testing
Advanced Vehicle Testing Activities
Maintenance Sheet for 2006 – Highlander

VIN #: JTEDW21A160006395

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**U.S. Department of Energy**

**Energy Efficiency and Renewable Energy**

*Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable*
HEV Per Mile Costs and Per Month MPGs

HEV Fleet Testing
Advanced Vehicle Testing Activities

2005 Honda Accord
VIN #: JHDMC36495CB06017

Fleet Performance
Description:
This vehicle is operated throughout the valley of Phoenix, Arizona by JP Morgan Chase Bank of Arizona’s courier fleet.
It is operated six days a week, transferring documents between branches and a central processing center on city streets and urban highways as well as interstate courier routes.

Major Operations & Maintenance Events:
Repaired electrical door lock @ 79,722
Cost: $321.17

Vehicle Specifications
Engine: 1VTEC-V6
Electric Motor: 11.9 kW
Battery: Nickel metal hydride
Seatbelt Positions: Five
Payload: 962 lbs
Features: Front wheel drive, regenerative braking

See HEVConnect Baseline Performance Fact Sheet for more information.

Ford Escapes - Monthly Fuel Economy

For more information contact:
EEER Information Center
1-877-EEER-INF (1-877-337-3463)
www.eere.energy.gov
PHEV TESTING
12 PHEVs Models in Testing/Demonstrations

Aftermarket PHEV conversions
- Hymotion Prius (A123Systems)
- Hymotion Escape (A123Systems)
- EnergyCS Prius, 2 models (Valence and Altairnano)
- 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)

OEM PHEVs
- Renault Kangoo (Saft NiCad)
- Ford E85 Escape prototype (Johnson Controls/Saft)

(All batteries are Li-Ion unless noted)
PHEV Testing Methods

Perform independent testing of PHEVs using:

• Baseline performance testing:
  – closed test tracks and dynamometers

• Accelerated testing:
  – dedicated drivers operating on defined on-road loops

• Fleet testing:
  – everyday non-directed fleet and public use, with onboard data loggers

• Laboratory testing of PHEV batteries
PHEV Testing Objectives

Quantify the following:

• Energy consumption (gasoline and electricity)
• Driving and charging patterns
• Effect of use on vehicle energy consumption, battery life, and the electrical grid
• Infrastructure requirements
PHEV Testing Objectives

... to answer the following:

• What are the potential petroleum savings and electricity demands?

• Will drivers adapt to plugging in (charging) PHEVs to maximize mpg?

• What are the charging infrastructure needs, including 110V versus 220V? Fast charging?

• Is vehicle-to-grid (V2G) charging a benefit or liability to the vehicle operator? To automakers and utilities?

• Are PHEVs technically and economically feasible as a transportation option?
Dynamometer Testing - City

- Hymotion Prius Gen I
- 5 kWh supplemental A123Systems (Li-ion) battery pack
- Urban Dynamometer Driving Schedule (UDDS)
Dynamometer Testing - Highway

- Hymotion Prius Gen I
- 5 kWh supplemental A123Systems (Li-ion) battery pack
- Highway Fuel Economy Driving Schedule (HWFEDS)
PHEV On-road Accelerated Testing

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

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<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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### Hymotion Prius Gen I – Accelerated Testing

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Each total distance slightly greater than 600 and 640 miles. HEV version = 44 mpg
## EnergyCS Prius (Valence) – Accelerated Testing

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Each total distance slightly greater than 600 miles. HEV version = 44 mpg
### Hymotion Escape – Accelerated Testing

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<td>15.69</td>
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<tr>
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<td>18</td>
<td>12</td>
<td>3</td>
<td>600</td>
<td>26.1</td>
<td>17.72</td>
<td>33.5</td>
</tr>
<tr>
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<td>3100</td>
<td>1344</td>
<td>162</td>
<td>5440</td>
<td></td>
<td></td>
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</table>

Weighted Average 42.5

Each total distance slightly greater than 600 miles. HEV version = 27 mpg
## Electrovaya Escape – 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 Gals</th>
<th>MPG</th>
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<td>10</td>
<td>1</td>
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<td>4</td>
<td>60</td>
<td>600</td>
<td>135.2</td>
<td>9.55</td>
<td>65.1</td>
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<tr>
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<td>600</td>
<td>55.8</td>
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<td>2</td>
<td>8</td>
<td>12</td>
<td>6</td>
<td>600</td>
<td>20.9</td>
<td>21.17</td>
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<tr>
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<td>18</td>
<td>12</td>
<td>3</td>
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<td>19.01</td>
<td>30.9</td>
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<tr>
<td>Total</td>
<td>2340</td>
<td>3100</td>
<td>1344</td>
<td>162</td>
<td>5440</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Weighted Average 36.7

Each total distance slightly greater than 600 miles. HEV version = 27 mpg
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

Most Vehicle Conversions
- Prius & Escapes
- Li-ion Batteries

Gov’t, Public + Private Partners

Data analysis & Reporting

INL

30+18=48

UV

Canada

59+37=96

34

1 in CT

1 in DC

1 in

ORNL

1

1

1

10+15=25

3

1

5

3

4

13

ANL

1

1

OSU

1

3

1

2

2

6

1

1

UV

Finland

287 Total PHEVs
204 Operating
71 Coming ‘09
12 Out of Service
Hymotion Prius PHEV Fleet Testing Reports

- Summary reports posted monthly on web
- Individual vehicle reports only go to the respective fleets each month
Hymotion Prius – 2008

Energy Consumption and CD Range

<table>
<thead>
<tr>
<th></th>
<th>Gasoline Fuel Economy (mi/gal)</th>
<th>Electrical Energy Consumption (AC Wh/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>48</td>
<td>72</td>
</tr>
<tr>
<td>CD Trips</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Mixed Trips</td>
<td>52</td>
<td>183*</td>
</tr>
<tr>
<td>CS Trips</td>
<td>41</td>
<td>0</td>
</tr>
</tbody>
</table>

* Includes miles from CD trips and CD portion of mixed trips

Average Charge Depleting Range (mi) 31.6

Definition of Trip Types

- **CD Trip** = trip that begins and ends in charge depleting mode
- **Mixed Trip** = trip that begins in charge depleting mode and ends in charge sustaining mode
- **CD Trip** = trip that begins and ends in charge sustaining mode
Hymotion Prius – 2008

Monthly fuel economy shown for all vehicle months in 2008 when a vehicle drove > 300 mi
Hymotion Prius – 2008

Distance Driven Relative to Charging

<table>
<thead>
<tr>
<th>Trip Type</th>
<th>Trips</th>
<th>Distance (mi)</th>
<th>Percent of Total Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>17,913</td>
<td>85,225</td>
<td>29%</td>
</tr>
<tr>
<td>Mixed</td>
<td>2,894</td>
<td>72,737</td>
<td>24%</td>
</tr>
<tr>
<td>CS</td>
<td>12,007</td>
<td>138,642</td>
<td>47%</td>
</tr>
</tbody>
</table>

Average number of charging events per vehicle per month when driven: 17.8
Average number of charging events per vehicle per day when driven: 1.1
Average distance between charging events: 39.0
Average number of trips between charging events: 4.3
Hybrids Plus Escape – 2008

Energy Consumption and CD Range

<table>
<thead>
<tr>
<th></th>
<th>Gasoline Fuel Economy (mi/gal)</th>
<th>Electrical Energy Consumption (AC Wh/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>38</td>
<td>111</td>
</tr>
<tr>
<td>CD Trips</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Mixed Trips</td>
<td>43</td>
<td>162*</td>
</tr>
<tr>
<td>CS Trips</td>
<td>32</td>
<td>0</td>
</tr>
</tbody>
</table>

* Includes miles from CD trips and CD portion of mixed trips

Average Charge Depleting Range (mi) 63.8

![Fuel Economy by Trip Type](chart1)

![Grid Electricity Consumption by Operating Mode](chart2)
### Hybrids Plus Escape – 2008

#### Distance Driven Relative to Charging

<table>
<thead>
<tr>
<th>Trip Type</th>
<th>Trips</th>
<th>Distance (mi)</th>
<th>Percent of Total Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>2,104</td>
<td>12,130</td>
<td>59%</td>
</tr>
<tr>
<td>Mixed</td>
<td>57</td>
<td>3,164</td>
<td>15%</td>
</tr>
<tr>
<td>CS</td>
<td>576</td>
<td>5,180</td>
<td>25%</td>
</tr>
</tbody>
</table>

#### Average number of charging events per vehicle per month when driven
- **30.7**

#### Average number of charging events per vehicle per day when driven
- **2.0**

#### Average distance between charging events
- **29.3**

#### Average number of trips between charging events
- **3.9**
Effect of Aggressive Driving on MPG

MPG vs. Trip Aggressiveness (Percent of trip above the 40% accelerator pedal position)

From 13 Hymotion Priuses, 775 trips, 6,291 miles, May 2008
Effect of Ambient Temperature on MPG

Hymotion Prius Fleet Fuel Economy

Average Ambient Temperature [°C]

-20C to -10C
-10C to 0C
0C to 10C
10C to 20C
20C to 30C
30C to 40C
>40C

Average Fuel Economy [MPG]

All Trips
CD
CD/CS
CS
BIG PICTURE
CONSIDERATIONS FOR PHEVS
PHEV Advantages

• Reduced petroleum consumption and emissions
  – Displace combustible fuel with electricity
  – Recover energy during regenerative braking and other benefits of HEV technology

• Use existing gas station infrastructure

• Minimal electric grid changes needed - add connector and electric vehicle supply equipment (EVSE)

• At home battery charging, well below cost of gasoline

• Zero emission potential (all-electric capable vehicles in CD mode)

• Lower fuel costs compared to HEVs

• Potential for off-peak charging

• Potential for V2G charging (this is a BIG maybe)

Primary Source Electric Drive Transportation Association (EDTA)
http://www.electricdrive.org/index.php?ht=d/Articles/cat_id/5599/pid/9673
PHEV Challenges

- Cost and complexity of two powertrains
- Drivers adapting to dual-fuel scenario
- Component availability - batteries, powertrains, power electronics (early challenge)
- Higher initial capital cost
- Cost of batteries and potential battery replacements
- Added weight
- Probable need for public recharging infrastructure
- Challenge to move charging to off-peak times
- If large PHEV batteries are successful, will BEVs replace PHEVs?

Primary source EDTA
http://www.electricdrive.org/index.php?ht=d/Articles/cat_id/5599/pid/9673
PHEV Purchase Considerations

• Has the vehicle emissions been certified by CARB, the EPA, or received an exemption?

• Has the vehicle been crashed tested and FMVSS certified per NHTSA requirements?
  – Conversions need crash testing – Don’t believe “its just another piece of luggage in the trunk”

• Has the manufacturer or vehicle converter made the vehicle available to DOE’s AVTA or other third party evaluator for testing?

• Current PHEVs have the potential to provide greater than 100 mpg – but may need “better” PHEV drivers

• Future PHEVs may be more robust to driving style and environment, but will always need to be charged

• Match mission to PHEV capabilities. Consider:
  – distance between charging opportunities
  – vehicle’s ambient operating temperature
  – trip distance (avoid very short trips in blended PHEVs)
POSSIBLE FUTURE VEHICLES
Announced PHEV Introductions*

- Chevrolet Volt Extended Range Electric Vehicle (EREV)
- Ford Escape PHEV
- Chrysler Town & Country PHEV/EREV
- Buick (formerly Saturn Vue) PHEV
- Toyota Prius PHEV
- Fisker Karma S PHEV/EREV
- Kia Forte LPG PHEV
- Hyundai PHEV
- BYD F3DM PHEV
- AFS Trinity SUV PHEV
- Raser/FEV SUV PHEV/EREV

* It’s not in production until it’s in production! Presenter makes no accuracy claim for the above information. Some info based on media reports.

Announced BEV Introductions*

- BMW Mini E BEV
- Nissan Leaf BEV
- Mitsubishi / Peugeot iMiEV BEV
- Subaru Stella and R1e BEVs
- ZENN city BEV
- Tesla / Daimler Smart Fortwo BEV
- Renault Kangoo BEV and others
- Ford Transit Connect and Focus BEVs
- Tesla Model S BEV
- BYD e6 BEV
- Toyota sedan BEV
- Volkswagen and Toshiba BEV
- ...

* Presenter makes no accuracy claim for the above information. Some info based on media reports

Acknowledgement

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

Additional Information

http://avt.inl.gov
or
http://www1.eere.energy.gov/vehiclesandfuels/avta/
Survey of Major Vehicle Technologies

- **Internal Combustion**
  - Gasoline
  - Diesel
  - Biodiesel
  - “Flex Fuel” gas + ethanol or methanol
  - Natural Gas
  - Hydrogen

- **Electric Drive**
  - Small “neighborhood” or “urban” battery electric vehicles (NEV or UEV)
  - Hybrid electric vehicle (HEV)
  - Plug-in hybrid electric vehicle (PHEV) or Extended range electric vehicle (EREV)
  - Full size battery electric vehicle (BEV)
  - Fuel Cell Vehicle (FCV)

Black = currently on market
Blue = entering market as aftermarket conversions
Red = under development, limited number of vehicles in market
HEV Dynamometer A/C MPG % Decrease

<table>
<thead>
<tr>
<th>Insight</th>
<th>Gen I Prius</th>
<th>Gen I Civic</th>
<th>Gen II Prius</th>
<th>Silverado</th>
<th>Accord</th>
<th>Escape</th>
<th>Highlander</th>
<th>RX400h</th>
<th>Gen II Civic</th>
<th>Camry</th>
<th>Vue</th>
<th>Altima</th>
<th>Tahoe</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>Percent MPG Decrease</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>-5%</td>
<td>-10%</td>
<td>-15%</td>
<td>-20%</td>
<td>-25%</td>
<td>-30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparing Fuel Cost

PHEVs, HEV & ICEs - Fuel Costs per Mile

- Conventional gasoline ICE, 20 MPG
- Conventional gasoline ICE, 30 MPG
- PHEV conversion Escapes
- Stock Toyota Prius HEV
- PHEV conversion Priuses

Each data point labeled by HWFEDS and UDDS Tests, Uneven Miles. Gas $4.00 gallon & kWh $0.10

[$0.03, $0.04, $0.05, $0.06, $0.07, $0.08, $0.09, $0.10, $0.11, $0.12, $0.13, $0.14, $0.15, $0.16, $0.17, $0.18, $0.19, $0.20, $0.21]
Hymotion Prius – Fuel Costs

Hymotion PHEV Prius UDDS & HWFEDS Fuel Cost per Mile

Each data point labeled by HWFEDS and UDDS tests, uneven miles. Gas $4.00 gallon & kWh $0.10