Hybrid Electric Vehicle Testing

Jim Francfort

Presentation Outline

• Background & goals
• Testing partners
• Hybrid electric vehicle testing
  – Baseline performance testing (new HEV models)
  – 1.5 million miles of HEV fleet testing (160k miles per vehicle in 36 months)
  – End-of-life HEV testing (rerun fuel economy & conduct battery testing @ 160k miles per vehicle)
  – Benchmark data: vehicle & battery performance, fuel economy, maintenance & repairs, & life-cycle costs
• WWW information location
Background

• Advanced Vehicle Testing Activity (AVTA) - part of the U.S. Department of Energy’s FreedomCAR and Vehicle Technologies Program

• AVTA Primary Goal - provide benchmark data for technology modeling, and research and development programs

• AVTA Secondary Goal - help fleet managers and other vehicle purchasers make informed purchase and operations decisions

• These activities are managed by the Idaho National Laboratory (INL also performs data analysis and reporting activities)
Testing Partners

• Qualified Vehicle Testers (50/50 cost share)
  – Electric Transportation Applications (lead)
  – Arizona Public Service
  – Bank One of Arizona
  – Red Cross
Testing Methods

• Baseline performance testing (dynamometer & closed track testing) – vehicle-to-vehicle comparisons
  – Acceleration, max speed, braking, handling, & two fuel economy tests - SAE J1634 drive cycle - air conditioning (AC) on & off

• Fleet (accelerated reliability) testing
  – Fuel use, miles, maintenance & repairs, & life-cycle costs in fleet operations
  – Two of each HEV model accumulate 160,000 miles

• End-of-life (at 160,000 miles) testing
  – Conduct battery capacity (Hybrid Pulse Power Characterization) & power testing (Static Capacity)
  – Rerun SAE J1634 tests (AC on & off)
Baseline Performance Testing

- 2002 test vehicles
  - Insight
  - Civic
  - Gen I Prius
- 2005 test vehicles
  - Accord
  - Gen II Prius
  - Silverado (2WD)
  - Escape (2WD)
  - Lexus RX400h (to be tested)
  - Toyota Highlander (to be tested)
Acceleration

HEV Acceleration

*0 to 50 mph for Insight, Civic and Gen I Prius. 0 to 60 mph for others
Maximum Speed in $\frac{1}{4}$ Mile

Max Speed in 1/4 mile

<table>
<thead>
<tr>
<th>Miles per Hour</th>
<th>Civic</th>
<th>Insight</th>
<th>Gen I Prius</th>
<th>Gen II Prius</th>
<th>Silverado</th>
<th>Escape</th>
<th>Accord</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>90</td>
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<td>100</td>
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</tbody>
</table>
Max Speed @ 6% Grade

Max Speed 1/4 mile (mph)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Miles per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civic</td>
<td>70</td>
</tr>
<tr>
<td>Insight</td>
<td>70</td>
</tr>
<tr>
<td>Gen I Prius</td>
<td>70</td>
</tr>
<tr>
<td>Gen II Prius</td>
<td>80</td>
</tr>
<tr>
<td>Silverado</td>
<td>90</td>
</tr>
<tr>
<td>Escape</td>
<td>80</td>
</tr>
<tr>
<td>Accord</td>
<td>100</td>
</tr>
</tbody>
</table>
Braking

Braking (Controlled Dry) from 60 mph

- Civic
- Insight
- Gen I Prius
- Gen II Prius
- Silverado
- Escape
- Accord

Feet
Baseline Performance MPG

Baseline Performance MPG (J1634 With & W/O Air)

Miles per Gallon

- Insight
- Gen I Prius
- Civic
- Gen II Prius
- Silverado
- Accord
- Escape
MPG (SAE J1634) - Air on/off Decrease

Percent MPG Difference (J1634 With & W/O Air)

-30%
-25%
-20%
-15%
-10%
-5%
0%

Insight  Gen I Prius  Civic  Gen II Prius  Silverado  Accord  Escape  Average
Normalized Discharge (SAE J1634)

Normalized Discharge During SAE J1634

- Insight
- Gen I Prius
- Civic
- Gen II Prius
- Silverado
- Accord
- Escape

Air Off
Air On
28 HEVs - Fleet Testing Status

- 6 - 2001 Honda Insights: Aug/01 - March/05
- 6 - 2002 Gen I Toyota Prius: Nov/01 - April/05
- 4 - 2003 Honda Civics: May/02 - April/05
- 2 - 2004 Gen II Toyota Prius: Nov/03 - ongoing
- 2 - 2004 Chevrolet Silverado: Sept/04 - ongoing
- 2 - 2005 Honda Accord: Jan/05 - ongoing
- 2 - 2005 Ford Escape: April/05 - ongoing
- 2 - 2005 Lexus RX400h SUVs: May/05 - ongoing
- 2 - 2006 Toyota Highlander SUVs: Oct/05 - ongoing
1.5 Million HEV Fleet Testing Miles
Fleet Testing Fact Sheets

- Summarize real-world use:
  - Vehicle use
  - Major maintenance & repair events
  - Mileage profile
  - Cumulative fuel economy
  - Life cycle operating costs
Fleet Testing Average MPG

Cumulative MPG

- Civic
- Insight
- Gen I Prius
- Silverado
- Accords
- Gen II Prius
- Escapes
- Lexus
- Highlander
Fleet Testing Monthly MPG
Fleet Testing MPG Hot & Cool Months

HEV MPG - Hot Vs. Cool 3 Months
(Cool - Dec, Jan, Feb & Hot - June, July, Aug)

- Insight: 10.5% & 4.9 mpg
- Civic: 11.5% & 4.6 mpg
- Gen I Prius: 10.6% & 4.6 mpg
- Gen II Prius: 0.4% & 0.2 mpg
- Average: 8.16% & 3.6 mpg
MPG – Fleet, SAE J1634 & EPA

Drive Cycle, Feet/AR & EPA Miles Per Gallon

- Fleet/AR Testing
- J1634 - Air On
- J1634 - Air Off
- EPA City
- EPA Highway

Miles per Gallon

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Civic</th>
<th>Insight</th>
<th>Gen I Prius</th>
<th>Gen II Prius</th>
<th>Accord</th>
<th>Silverado</th>
<th>Escape</th>
<th>Lexus</th>
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<tbody>
<tr>
<td>Fleet/AR Testing</td>
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<tr>
<td>J1634 - Air On</td>
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<td></td>
</tr>
<tr>
<td>J1634 - Air Off</td>
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<td></td>
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<tr>
<td>EPA City</td>
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<td>EPA Highway</td>
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</table>
Maintenance & Repairs

- All events - date, mileage, description & cost/warranty

<table>
<thead>
<tr>
<th>Date</th>
<th>Mileage</th>
<th>Description</th>
<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>7/15/2002</td>
<td>5,081</td>
<td>Change oils and replace tires</td>
<td>$27.00</td>
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<tr>
<td>8/4/2002</td>
<td>9,879</td>
<td>Change oils and replace tires</td>
<td>$20.62</td>
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<tr>
<td>9/7/2002</td>
<td>15,022</td>
<td>15,000 mile service</td>
<td>$231.30</td>
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<tr>
<td>9/28/2002</td>
<td>16,708</td>
<td>Repair accident damage to left front (not included in maintenance costs)</td>
<td>$1,222.84</td>
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<tr>
<td>10/6/2002</td>
<td>20,142</td>
<td>Change oils and replace tires</td>
<td>$20.62</td>
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<tr>
<td>10/26/2002</td>
<td>26,147</td>
<td>Change oils and replace tires</td>
<td>$20.67</td>
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<tr>
<td>12/26/2002</td>
<td>33,220</td>
<td>Change oils and replace tires</td>
<td>$31.07</td>
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<td>2/13/2003</td>
<td>49,218</td>
<td>49,000 mile service</td>
<td>$341.30</td>
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<tr>
<td>2/13/2003</td>
<td>49,630</td>
<td>Repair accident damage to rear bumper (not included in maintenance costs)</td>
<td>$834.41</td>
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<tr>
<td>3/16/2003</td>
<td>53,301</td>
<td>Change oils and replace tires</td>
<td>$20.67</td>
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<tr>
<td>5/19/2003</td>
<td>69,205</td>
<td>Change oils and replace tires</td>
<td>$20.67</td>
</tr>
<tr>
<td>6/26/2003</td>
<td>74,285</td>
<td>20,000 mile service</td>
<td>$241.13</td>
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<tr>
<td>6/26/2003</td>
<td>77,828</td>
<td>Replace four tires and align front wheels</td>
<td>$166.33</td>
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<tr>
<td>7/15/2003</td>
<td>77,828</td>
<td>Check Engine Light Illuminated; dealer heard, no problem found warranty</td>
<td>$21.00</td>
</tr>
<tr>
<td>7/15/2003</td>
<td>80,425</td>
<td>Change oils and replace tires</td>
<td>$21.00</td>
</tr>
<tr>
<td>7/25/2003</td>
<td>90,036</td>
<td>Check Engine Light Illuminated. Dealer repaired an intermittent problem with a valve sticking warranty</td>
<td>$21.00</td>
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<tr>
<td>8/27/2003</td>
<td>90,704</td>
<td>90,000 mile service</td>
<td>$241.13</td>
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<tr>
<td>9/4/2003</td>
<td>96,353</td>
<td>Change oils and replace tires</td>
<td>$21.00</td>
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<tr>
<td>9/12/2003</td>
<td>96,353</td>
<td>Check Engine Light Illuminated. Updated PCM software installed by dealer.</td>
<td>$50.00</td>
</tr>
<tr>
<td>10/14/2003</td>
<td>99,616</td>
<td>Ignition switch replaced</td>
<td>$60.00</td>
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<tr>
<td>10/24/2003</td>
<td>99,912</td>
<td>Change oils and replace intake parts</td>
<td>$146.22</td>
</tr>
<tr>
<td>11/12/2003</td>
<td>115,656</td>
<td>Check Engine Light Illuminated. Dealer replaced the cruise control pressure sensor</td>
<td>$60.00</td>
</tr>
<tr>
<td>12/15/2004</td>
<td>156,894</td>
<td>Transmission shifting smoothly; transaxle replaced</td>
<td>$3,093.82</td>
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<tr>
<td>1/26/2004</td>
<td>157,759</td>
<td>Check Engine Light Illuminated. Catalytic converters replaced</td>
<td>$1,124.30</td>
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<tr>
<td>2/23/2004</td>
<td>163,201</td>
<td>15,000 mile service</td>
<td>$269.83</td>
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<tr>
<td>4/20/2004</td>
<td>113,055</td>
<td>10,000 miles service and accessory 12 volt battery replacement</td>
<td>$464.05</td>
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<tr>
<td>4/21/2004</td>
<td>113,055</td>
<td>Replace front brake</td>
<td>$132.30</td>
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<tr>
<td>5/22/2004</td>
<td>115,670</td>
<td>Change oils and replace tires</td>
<td>$21.00</td>
</tr>
</tbody>
</table>
Maintenance & Repairs Summary

• Civic & Insight - 6 continuously variable transmission (CVT) failures in 4 vehicles @ 97k, 99k, 89k & 77k miles. Again @ 157k & 146k miles

• Insight battery control module & traction battery replaced @ 72k miles

• Insight & Civic - 7 software upgrades & 3 catalytic converters replaced

• Gen I Prius - rack & pinion replacements 1st Prius @ 106k, & 2nd Prius @ 25k & 32k miles

• Other HEVs – normal maintenance @ lower mileages
Life-Cycle Costs (high mileage HEVs)

High Mileage HEV Life Cycle Costs

<table>
<thead>
<tr>
<th>Model</th>
<th>Cents per Mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civic 161.5k miles</td>
<td>22.0 cents/mi</td>
</tr>
<tr>
<td>Civic 161k miles</td>
<td>23.9 cents/mi</td>
</tr>
<tr>
<td>Insight 160k miles</td>
<td>19.4 cents/mi</td>
</tr>
<tr>
<td>Insight 146k miles</td>
<td>26.9 cents/mi</td>
</tr>
<tr>
<td>Gen I Prius 165k miles</td>
<td>17.7 cents/mi</td>
</tr>
<tr>
<td>Gen I Prius 160k miles</td>
<td>18.7 cents/mi</td>
</tr>
<tr>
<td>Average</td>
<td>21.5 cents/mi</td>
</tr>
</tbody>
</table>

(All 36 months of testing except 146k miles Insight - 41 months)
Life-Cycle Costs (low mileage HEVs)

Low Mileage HEV Life Cycle Costs

Cents per Mile

Ownership
Main/Repair
Registration
Gas ($2.50/gal)
Insurance

Average 58.9 cents/mi
Cost Components – High & Low mileage

Life Cycle HEV Operations Costs

- High Mileage HEVs
- Lower Mileage HEVs

Cost per Mile

- Insurance
- Gas ($2.50/gal)
- Registration
- Main/Repair
- Ownership
HEV Life-Cycle Costs (Weighted by Miles)

Costs include: Insurance, maintenance & repairs (excludes any collision costs), fuel @ $2.50 gallon, registration, & purchase – sales cost (or lease cost for Silverado)
End of Life (160k miles) Battery Capacity

**End of Life Battery Capacity Test Findings**

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>C1 Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civic 1</td>
<td>6.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Civic 2</td>
<td>6.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Insight 1</td>
<td>6.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Insight 2</td>
<td>6.5</td>
<td>5.4</td>
</tr>
<tr>
<td>Prius 1</td>
<td>6.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Prius 2</td>
<td>6.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

*Gen I Prius*
End-of-Life (160k miles) MPG - AC Off

New vs. End of Life J1634 Fuel Economy - Air Conditioning Off

*Gen I Prius
End-of-Life (160k miles) MPG - AC On

New vs. End of Life J1634 Fuel Economy - Air Conditioning On

*Gen I Prius
Percent Battery Capacity Used per Mile

*Gen I Prius*
End-of-Life Phase II (SAE J1634) Vs. Onboard-Vehicle-Computer MPG

<table>
<thead>
<tr>
<th>End-of-life Phase II HEV MPG Testing</th>
<th>Onboard computer fuel economy percentage above Phase II SAE J1634 fuel economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civic 1 AC off</td>
<td>+21.7%</td>
</tr>
<tr>
<td>Civic 1 AC on</td>
<td>+21.0%</td>
</tr>
<tr>
<td>Insight 1 AC off</td>
<td>+11.0%</td>
</tr>
<tr>
<td>Insight 1 AC on</td>
<td>+11.7%</td>
</tr>
<tr>
<td>Gen I Prius AC off</td>
<td>+15.7%</td>
</tr>
<tr>
<td>Gen I Prius AC on</td>
<td>+14.7%</td>
</tr>
</tbody>
</table>
Additional Near-term HEV Testing

- Hydrogen ICE HEV (HICEHEV) Hydrogen Prius from SCAQMD/Quantum
- Plug-in Diesel or Gas HEV (PIDHEV or PIGHEV) Dodge Sprinter (lithium) from Dodge
- PIGHEV Escape (lithium or lead) from vehicle converter Energy CS
- PIGHEV Gen II Prius conversion (Valence Li-Ion) from vehicle converter Energy CS
- Azure HEVs used by Purolator?
- Other OEM HEVs and/or Plug-ins?
http://avt.inl.gov