Reducing Vehicle Petroleum-based Fuel Consumption: What are our options?

Presentation to Small Cities Council Steering Committee

Rexburg, ID
Aug 1, 2008

John Smart

INL/MIS-08-14599
Idaho National Laboratory (INL)

• What is INL?
  – Laboratory owned by DOE and operated by Battelle Energy Alliance

• What Does INL Do?
  – Develop, demonstrate and promote technology solutions to our country’s, region’s and state’s most difficult challenges in:
    ✓ Nuclear Energy
    ✓ National and Homeland Security
    ✓ Energy, Environment, and Infrastructure
The Role of National Laboratories in Improving Our Energy Future

- The DOE systems of laboratories exists to do the work industry and universities will not, should not, or cannot do.

National Laboratories are the “crown jewels” of the nation for development of our nuclear science and technology capabilities; an American competitive advantage and an asset to their communities, states, and region.
Energy Research Areas

- Nuclear
- Biomass
- Wind
- Hydro
- Geothermal
- Fossil
- Batteries
- Alternative Energy Vehicles
- Electric Grid Stability/Security
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
Outline

• US energy big picture
• Survey of vehicle technology
• AVTA test activities and results
• Trade-offs
• Broader picture (beyond technology)
• Discussion
US Energy Big Picture

Areas of concern

• Energy security
  – Insufficient domestic supply forces us to import energy (oil)

• Global climate change
  – Tailpipe and smoke stack CO₂ emissions

• Economic stability
  – Your wallet (energy prices, food prices, other costs)
  – Your job security
  – Not just state of economy today, but worry about future
Sources and Uses of Energy in US

**US Petroleum Usage**
- Transportation: 70%
- Industrial: 23%
- Residential & Commercial: 5%
- Commercial: 2%

**US Transportation Sector Energy Sources**
- Petroleum: 96%
- Natural Gas: 2%
- Biofuel: 2%

**US Petroleum Usage Source:**
- Petroleum: 40%
- Natural Gas: 23%
- Biomass: 4%
- Coal: 22%
- Renewables: 8%

Source: Energy Information Administration
US Transportation Energy Usage

- Light Duty Vehicles: 62%
- Aircraft: 11%
- Freight/Other: 27%

Source: Energy Information Administration
Reducing Petroleum Consumption of Light Duty Passenger Vehicles

• Reduce number of vehicles
  – Find other ways to get around, or share

• Increase vehicle efficiency
  – use less to do the same amount of work… or more work!

• Increase energy diversity
  – use another fuel source
Survey of Major Vehicle Technologies

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

• Electric Drive
  – Small “neighborhood” battery electric vehicle (NEV)
  – Hybrid electric vehicle (HEV)
  – Plug-in hybrid electric vehicle (PHEV) or Extended range electric vehicle (EREV)
  – Full size battery electric vehicle (EV)
  – Fuel Cell Vehicle (FCV)

Black = currently on market
Blue = entering market as aftermarket conversions
Red = under development, limited number of vehicles in market
What is the direction for the future?

• Lots of possibilities, no “silver bullet”
• Complex technological and societal trade-offs with every path
• Consensus is that electrification will play key role in diversifying energy
AVTA Testing History

• Plug-in hybrid electric vehicles
  – 6 models, ~75 vehicles in fleets
• Hybrid electric vehicles
  – 14 models, 3.7 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
Hybrid Electric Vehicles (HEV)

- Uses electric motor(s) and battery pack to provide power source in addition to internal combustion engine
- Charges battery pack by capturing energy normally wasted during braking and coasting
- Uses that energy to drive motor(s) for power during acceleration
- Does not plug in to electrical grid for recharging
- Manufactures can tune to improve fuel efficiency or performance
### Hybrid Electric Vehicles (HEVs) in Testing

<table>
<thead>
<tr>
<th>Model</th>
<th>Count</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 Honda Insight</td>
<td>6</td>
<td>Completed</td>
</tr>
<tr>
<td>2002 Gen I Toyota Prius</td>
<td>6</td>
<td>Completed</td>
</tr>
<tr>
<td>2003 Gen I Honda Civic</td>
<td>4</td>
<td>Completed</td>
</tr>
<tr>
<td>2004 Chevrolet Silverado (2- &amp; 4-WD)</td>
<td>2</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2004 Gen II Toyota Prius</td>
<td>2</td>
<td>Completed</td>
</tr>
<tr>
<td>2005 Ford Escape (front &amp; 4-WD)</td>
<td>2</td>
<td>Completed</td>
</tr>
<tr>
<td>2005 Honda Accord</td>
<td>2</td>
<td>Completed</td>
</tr>
<tr>
<td>2006 Lexus RX 400h (front &amp; 2 AWD)</td>
<td>3</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2006 Toyota Highlander (AWD)</td>
<td>2</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2006 Gen II Honda Civic</td>
<td>2</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2007 Saturn Vue</td>
<td>2</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2007 Toyota Camry</td>
<td>2</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2008 Nissan Altima</td>
<td>2</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2008 GM 2-mode Tahoes</td>
<td>2</td>
<td>Ongoing</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>39</strong></td>
<td><strong>to date</strong></td>
</tr>
</tbody>
</table>
HEVs Baseline Performance Testing

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

- Insight
- Gen I Prius
- Gen I Civic
- Gen II Prius
- Silverado
- Accord
- Escape
- Highlander
- RX400h
- Gen II Civic
- Camry
- Vue
- Average

MPG SAE J1634 Air On
MPG SAE J1634 Air Off

Miles per Gallon

0 5 10 15 20 25 30 35 40 45 50 55 60

Idaho National Laboratory
Onroad Test miles per HEV model

- Minimum 320,000 test miles per HEV model in 36 months

Yellow bar = testing complete
Onroad Miles per gallon by HEV model
HEV Maintenance and Repairs

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

VIN # JTEDW21A160006395

<table>
<thead>
<tr>
<th>Date</th>
<th>Mileage</th>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/14/2005</td>
<td>4,855</td>
<td>Changed oil, rotated tires</td>
<td>$31.99</td>
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<tr>
<td>1/5/2006</td>
<td>9,952</td>
<td>Changed oil, rotated tires</td>
<td>$28.04</td>
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<tr>
<td>1/31/2006</td>
<td>15,749</td>
<td>15K service</td>
<td>$187.05</td>
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<tr>
<td>2/22/2006</td>
<td>20,783</td>
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<td>$28.07</td>
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<td>3/15/2006</td>
<td>26,197</td>
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<td>4/17/2006</td>
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<td>4/26/2006</td>
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<td>5/18/2006</td>
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<td>6/9/2006</td>
<td>47,475</td>
<td>15K interval service, 45K preventative maintenance</td>
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<tr>
<td>7/5/2006</td>
<td>53,711</td>
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<td>7/26/2006</td>
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<td>$346.86</td>
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<td>8/21/2006</td>
<td>65,947</td>
<td>Changed oil</td>
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<tr>
<td>9/12/2006</td>
<td>71,030</td>
<td>Changed oil, replaced wiper blades</td>
<td>$57.20</td>
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<tr>
<td>9/14/2006</td>
<td>71,053</td>
<td>Check engine light on - Code PA93 Inverter cooling system malfunction inverter coolant low warranty</td>
<td></td>
</tr>
<tr>
<td>9/24/2006</td>
<td>73,015</td>
<td>Replaced windshield</td>
<td>$272.87</td>
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<tr>
<td>10/6/2006</td>
<td>75,949</td>
<td>75K service</td>
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<tr>
<td>12/6/2006</td>
<td>90,270</td>
<td>Changed oil</td>
<td>$39.00</td>
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</table>
HEV Life-Cycle Costs per Mile

HEV Cost per Mile

- $0.00
- $0.10
- $0.20
- $0.30
- $0.40
- $0.50
- $0.60
- $0.70
- $0.80
- $0.90

04 Prius 159.9k
04 Silverado 88k
04 Silverado 85k
05 Accord 134k
05 Accord 138k
06 Highlander 124k
06 Highlander 52k
05 Escape 156k
05 Escape 148k
06 RX400h 118k
06 RX400h 82k
06 Civic 66k
06 Civic 81k
07 Camry 82k
07 Camry 50k
07 Vue 54k
07 Vue 12k

Wh Average

Operating costs = fuel, insurance & registration
HEV Accelerated Testing Results

AVTA accelerated testing and EPA miles per gallon

HEV Fleet Testing MPG

AVTA Fleet  EPA New Combined  EPA Old Combined

Miles per Gallon

Gen I Civic  Insight  Gen I Prius  4WD  2WD  Accords  Gen II Prius  4WD  2WD  AWD  2WD  AWD  Camry  Gen II Civic  Vue
Plug-in Hybrid Electric Vehicles (PHEV)

- Like HEVs, PHEVs use motor(s) and battery pack in addition to IC engine
- Battery pack has much higher energy capacity for greater proportion of electric propulsion
- Vehicle must be plugged in to recharge battery pack; also captures braking energy
- Can plug into standard 110/120 VAC outlet
Plug-in Hybrid Electric Vehicles (PHEV)

- Aftermarket conversion companies installing battery packs in HEVs to convert to PHEVs
- Several auto makers have announced plans to produce PHEVs, including GM, Ford, Chrysler, and Toyota
- Many are promoting PHEVs as “100+ mpg” cars
PHEV Baseline Performance Testing

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

- MPG per FWHT Test
- Cumulative MPG
- Cumulative AC kWh
Hymotion Prius – Fuel Costs

Hymotion PHEV Prius UDDS & HWFEDS Fuel Cost per Mile

<table>
<thead>
<tr>
<th>Fuel Cost per Mile</th>
<th>HWFEDS</th>
<th>UDDS</th>
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<tbody>
<tr>
<td>$0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.005</td>
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<tr>
<td>$0.010</td>
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<td>$0.055</td>
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<tr>
<td>$0.065</td>
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<tr>
<td>$0.070</td>
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</table>

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

INL Idaho National Laboratory

Elec electric transportation engineering corporation
Hymotion Prius –
On-road Accelerated Testing

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Urban</th>
<th>Highway</th>
<th>Charge</th>
<th>Reps</th>
<th>Total</th>
<th>Electricity</th>
<th>Gasoline</th>
<th>MPG</th>
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<tbody>
<tr>
<td>(mi)</td>
<td>(10 mi)</td>
<td>(10 mi)</td>
<td>(hr)</td>
<td>(N)</td>
<td>(mi)</td>
<td>kWh</td>
<td>Gals</td>
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<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>
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<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>
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<tr>
<td>40</td>
<td>4</td>
<td>0</td>
<td>12</td>
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<td>600</td>
<td>84.10</td>
<td>6.05</td>
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<tr>
<td>40</td>
<td>2</td>
<td>2</td>
<td>12</td>
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<td>80</td>
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<td>8</td>
<td>640</td>
<td>43.99</td>
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<td>100</td>
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<td>12</td>
<td>6</td>
<td>600</td>
<td>35.98</td>
<td>8.43</td>
<td>73.2</td>
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<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>
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<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>
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</table>

Each total distance slightly greater than 600 and 640 miles. HEV version = 44 mpg
Ford Hybrid Escape with Hymotion PHEV conversion – EPA City Test

Hymotion PHEV Escape MPG & kWh - UDDS Testing

Each Bar = 1 UDDS Test Cycle. Labeled by Cumulative Miles.

Drive Cycle Fuel Economy
Cumulative AC kWhrs
Cumulative Fuel Economy

Ford Hybrid Escape with Hymotion PHEV conversion – EPA City Test
Ford Hybrid Escape with Hymotion PHEV conversion – EPA Hwy Test

Hymotion PHEV Escape MPG & kWh - HWFET Testing

Each Bar = 1 HWFET Test Cycle. Labeled by Cumulative Miles

[Graph showing mileage and energy consumption]
<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 kWh</th>
<th>Gasoline Gals</th>
<th>MPG</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>60</td>
<td>600</td>
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<tr>
<td>40</td>
<td>2</td>
<td>2</td>
<td>12</td>
<td>15</td>
<td>600</td>
<td>Ongoing</td>
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<td>4</td>
<td>12</td>
<td>15</td>
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<td>80</td>
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<td>12</td>
<td>8</td>
<td>640</td>
<td>77.69</td>
<td>16.05</td>
<td>41.3</td>
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<td>100</td>
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<td>8</td>
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<td>6</td>
<td>600</td>
<td>58.64</td>
<td>15.69</td>
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<td>3</td>
<td>600</td>
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<td></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>Weighted Average</td>
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<td></td>
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</tbody>
</table>

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

PHEVs, HEV & ICEs - Fuel Costs per Mile

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

Conventional gasoline
ICE, 20 MPG

Conventional gasoline
ICE, 30 MPG

PHEV conversion
Escapes from two different conversion companies in varying usage

Stock Toyota Prius HEV

PHEV conversion Priuses from two different conversion companies in varying usage
14 - Canada

PHEV Demonstration Fleet
Current and Future Vehicle Locations

67 with data loggers
68 adding CY08
? Probable add CY08
135+ Total end of CY08
26 Hymotion Prius - January thru May 2008

• Below averages do NOT tell the whole PHEV energy-use potential – see following May-only slides

<table>
<thead>
<tr>
<th>Charge / Operating Mode</th>
<th>Number of Trips</th>
<th>Distance Traveled (Miles)</th>
<th>Miles per Gallon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Depleting (CD)</td>
<td>3,073</td>
<td>14,820</td>
<td>59</td>
</tr>
<tr>
<td>Mixed CD / CS</td>
<td>404</td>
<td>11,121</td>
<td>49</td>
</tr>
<tr>
<td>Charge Sustaining (CS)</td>
<td>1,358</td>
<td>16,059</td>
<td>40</td>
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<tr>
<td>All trips combined</td>
<td>4,835</td>
<td>42,000</td>
<td>48</td>
</tr>
</tbody>
</table>
13 Hymotion Prius in May 2008 - MPG

- Below averages do NOT tell the whole PHEV energy use potential – see next 3 slides

<table>
<thead>
<tr>
<th>Charge / Operating Mode</th>
<th>Number of Trips</th>
<th>Total Distance (Miles)</th>
<th>Average Trip Distance (miles)</th>
<th>MPG</th>
<th>DC kWh per Mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Depleting (CD)</td>
<td>575</td>
<td>3,040</td>
<td>5.3</td>
<td>72.0</td>
<td>0.138</td>
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<tr>
<td>Mixed CD / CS</td>
<td>67</td>
<td>1,840</td>
<td>27.5</td>
<td>52.1</td>
<td>0.050</td>
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<tr>
<td>Charge Sustaining (CS)</td>
<td>133</td>
<td>1,411</td>
<td>10.6</td>
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<tr>
<td>Electric vehicle only (EV)</td>
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<td>127</td>
<td>0.9</td>
<td></td>
<td>0.236</td>
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<tr>
<td>Total</td>
<td>912</td>
<td>6,417</td>
<td>7.0</td>
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<tr>
<td>CD, CS, CD/CS results (excludes EV results)</td>
<td>775</td>
<td>6,291</td>
<td>8.1</td>
<td>55.9</td>
<td></td>
</tr>
</tbody>
</table>
13 Hymotion Prius MPG Vs. Speed

Trip Fuel Economy vs. Trip Average Speed - May 2008

Trip Fuel Economy (mpg) vs. Trip Average Speed (mph)

- CD trips
- CD/CS trips
- CS trips
13 Hymotion Prius MPG Vs. Distance

Trip Fuel Economy vs. Trip Distance

- CD trips
- CD/CS trips
- CS trips

Trip Distance (mi)

Trip Fuel Economy (mpg)
13 Hymotion Prius and Aggressive Driving

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

- CD trips
- CD/CS trips
- CS trips
- Log. (CD trips)
- Log. (CD/CS trips)

Trip Fuel Economy (mpg) vs. Aggressiveness Factor
PHEV Charging Infrastructure

- National Electric Code requires
  - Dedicated branch circuit
  - GFCI (ground fault circuit interrupt)
  - “EV” extension cord
  - Unique connector “plug”
Neighborhood Electric Vehicles (NEV)

• A NEV is technically defined as a “Low Speed Vehicle” (LSV) by the National Highway Traffic Safety Administration’s Federal Motor Vehicle Safety Standard No. 500.

• Per FMVSS No. 500, a LSV means a vehicle:
  – that is 4-wheeled
  – with a top attainable speed in 1 mile of more than 20 mph and not more than 25 mph on a paved level surface
  – with a Gross Vehicle Weight Rating of less than 2,500 pounds.
NEVAmerica Testing

- CARB requires all Neighborhood Electric Vehicles (NEVs) be tested by the AVTA
- 5 NEVs completing testing in 2008:
  - 2 Miles Automotive: sedan & pickup
  - 1 Zen sedan
  - 2 GEMs: 6 passenger sedan & extended range pickup
- 14 NEVs previously tested:
  - 8 Gems (Global Electric Motors)
  - 2 Th!nk Neighbors
  - 2 Frazier Nashes
  - 2 ParCars
Neighborhood Electric Vehicles (NEV)

- These and other test results at http://avt.inl.gov
## Neighborhood Electric Vehicles (NEV)
### Basic results for some vehicles tested

<table>
<thead>
<tr>
<th>Make/Model</th>
<th>Max Range (mi)</th>
<th>Max Speed (mph)</th>
<th>Recharge time (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 Zenn 2 passenger</td>
<td>65</td>
<td>25</td>
<td>9 - 14</td>
</tr>
<tr>
<td>2007 GEM 6 passenger</td>
<td>40</td>
<td>25</td>
<td>9 - 14</td>
</tr>
<tr>
<td>2007 GEM Long bed</td>
<td>50</td>
<td>25</td>
<td>10 - 14</td>
</tr>
<tr>
<td>2005 GEM 4 passenger</td>
<td>41</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>2005 GEM 2 passenger</td>
<td>44</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>2005 GEM Long bed</td>
<td>41</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>2005 GEM Short bed</td>
<td>37</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>2002 Th!nk Neighbor 2 Passenger</td>
<td>39</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>2002 Th!nk Neighbor 4 Passenger</td>
<td>33</td>
<td>23</td>
<td>8</td>
</tr>
<tr>
<td>2001 Frazer-Nash Car</td>
<td>31</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>2001 Frazer-Nash Truck</td>
<td>33</td>
<td>25</td>
<td>1</td>
</tr>
</tbody>
</table>
Hydrogen and Compressed Natural Gas (CNG) Internal Combustion Engine Vehicle Testing
15% HCNG Dodge Van Emissions Testing

- 5.2 L CNG V8 (no modifications) with 71,000 HCNG test miles - no problems - 15.5 miles/GGE

<table>
<thead>
<tr>
<th>Percentage change in 15% HCNG emissions compared to 100% CNG emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total hydrocarbons</td>
</tr>
<tr>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>Oxides of nitrogen</td>
</tr>
<tr>
<td>Carbon dioxide</td>
</tr>
</tbody>
</table>
30% HCNG F150 Testing

- 5.4 L V8 CNG base engine – added supercharger, ignition modifications & exhaust gas recirculator
- Fleet testing HCNG miles: 17.3 miles/GGE

<table>
<thead>
<tr>
<th>Fuel Blend</th>
<th>0 to 60 mph (secs.)</th>
<th>Miles/GGE</th>
<th>Range (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNG</td>
<td>10.10</td>
<td>23.3</td>
<td>122</td>
</tr>
<tr>
<td>15% HCNG</td>
<td>10.97</td>
<td>22.6</td>
<td>110</td>
</tr>
<tr>
<td>30% HCNG</td>
<td>12.68</td>
<td>23.5</td>
<td>102</td>
</tr>
</tbody>
</table>
# 30% HCNG F150 Emissions Testing

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Percentage Change in Emissions Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NMHC</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Base</td>
</tr>
<tr>
<td>CNG</td>
<td>-80</td>
</tr>
<tr>
<td>15% HCNG</td>
<td>-78</td>
</tr>
<tr>
<td>30% HCNG</td>
<td>-89</td>
</tr>
</tbody>
</table>

NMHC=Non-Methane Hydrocarbons  
HC=Total Hydrocarbons  
CH\textsubscript{4}=Methane  
CO=Carbon Monoxide  
NO\textsubscript{x}=Oxides of Nitrogen  
CO\textsubscript{2}=Carbon Dioxide
50% HCNG F150 Emissions Testing

- Modifications
  - SVO heads, exhaust intercooler & supercharger
  - Exhaust gas recirculator & ignition modification
  - Equipped with 3 Quantum hydrogen 3,600 psi tanks with 9 kg total storage

Percent reduction in emissions (HCNG versus gasoline-fueled F-150)

<table>
<thead>
<tr>
<th></th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.5%</td>
<td>-43.3%</td>
<td>-97.0%</td>
<td>-16.7%</td>
<td></td>
</tr>
</tbody>
</table>

HC = total hydrocarbons
CO = carbon monoxide
CO2 = carbon dioxide
NOx = oxides of nitrogen
5.4L 16-valve 100% Hydrogen ICE Vehicle
- 5.4L V-8, 100% hydrogen 16-valve Ford/ETEC pickup
- 5 speed transmission, supercharged (3 psi), lean-burn
- Onboard hydrogen storage 3 Dynetek tanks @ 3,000 psi, 6.5 kg, aluminum vessel & fiberglass wrap
- SAE J1634 fuel economy (AC on): 14.5 miles/GGE
- SAE J1634 fuel economy (AC off): 18.0 miles/GGE
- Fleet testing – 18.5 miles per GGE (120 miles range)
5.4L 32-valve 100% Hydrogen ICE Vehicle

- 5.4L V-8, 100% hydrogen 32-valve Ford/ETEC pickup
- 12 pounds supercharger boost, with hardened valves & seats, and forged pistons with 11.5:1 compression
- 13.0 miles per GGE in fleet testing
- Onboard hydrogen storage 3 Dynetek tanks @ 5,000 psi, 15.3 kg (200-mile range)
6L V-8 100% Hydrogen ICE Vehicle

- Base vehicle: Chevrolet 1500HD crew cab (4 door) with 6L V8 CNG engine, converted by ETEC/Roush to 100% hydrogen
- 10.5 kg 100% hydrogen storage onboard @ 5,000 psi
- 200 Horsepower & 260 lb-ft torque
- 14 city & 20 highway miles per GGE - range of 140 to 200 miles
- Eight vehicles in fleet testing in Vancouver B.C.
Hydrogen and CNG Infrastructure
APS Alternative Fuel (Hydrogen) Pilot Plant

- Partners - Arizona Public Service (APS), Electric Transportation Applications (ETA), INL, & DOE
- First & longest operating hydrogen station in the U.S. – since June 2002
- Hydrogen produced onsite by electrolysis
- Hydrogen & CNG fueling
Pilot Plant - Layout

- Hydrogen Fuel Cell
- 2 H2 High psi tanks
- H2 Low psi tank
- H2 Compressor
- 2 CNG Compressors
- 6 CNG Tanks @ 3 psi levels)
Pilot Plant - Hydrogen Subsystems

- **H₂ Generator**
- **Dryer**
- **Low Pressure Storage**
- **Compressor**
- **Filter**
- **High Pressure Storage**
- **H₂ Out**

Flows:
- Water
- Electricity
- Oxygen
- H₂
Pilot Plant – Hydrogen Subsystems cont’d

- Proton Energy Systems’ HOGEN PEM stationary fuel cell operating in reverse
- Hydrogen Lectrodryer
- Hydrogen compressor
- Norman hydrogen filters
- Hydrogen - 99.9997% purity
Pilot Plant - Hydrogen Subsystems cont’d

- Low pressure hydrogen storage (lower tank)
  - 8,955 SCF @ 150 psi

- High pressure hydrogen storage (upper 2 tanks)
  - 17,386 SCF @ 6,000 psi (total both tanks)
Pilot Plant - CNG Subsystems

Street Service Low Pressure Natural Gas

Boost Compressor

Main Compressor

High Pressure Storage (3 levels)

CNG Output
Pilot Plant - CNG Subsystems cont’d

- **CNG Boost Compressor**
  - 300 scfm @ 60 psi

- **CNG Main Compressor**
  - 350 scfm @ 5,000 psi

- **CNG Storage/Pressure – 6 tanks**
  - 3 Low: 11,079 scf @ 3,600 psi
  - 2 Medium: 5,711 scf @ 4,500 psi
  - 1 High: 5,711 scf @ 5,000 psi
Pilot Plant - Fueling Dispensers
• 100% H₂, 100% CNG, blends of HCNG
• Includes metering & electronic billing interface
• Fully permitted for motor fuel dispensing
• Public access
Trade-offs

• Vehicle
  – Cost
  – Performance (acceleration, range, fuel efficiency, etc)
  – Robustness (performance and reliability under all conditions
    • cold and hot temps is big challenge!
  – Safety
• Refueling / recharging Infrastructure
  – Cost
  – Availability
• Unintended consequences -- “Robbing Peter to pay Paul”
  – Overall economic impact
  – Trading one dependence for another
Broader picture

- Efficiency improvements possible without new technology!
- Market trend shifting
  - Smaller vehicles
  - Right size vehicle for purpose (we still need trucks)
- Automakers will improve conventional vehicles
  - Reduce weight
  - Improve engine, driveline efficiency
  - Improve aerodynamics (function over form?)
Broader picture

- Best MPG is “n/a”
  - Public transit, bicycle, ride sharing
Acknowledgement

This work is supported by the U.S. Department of Energy’s Vehicle Technologies Program
Tien Duong, Lee Slezak and Ro Sullivan

Additional Information
http://avt.inl.gov
or
http://www1.eere.energy.gov/vehiclesandfuels/avta/
Discussion points

• What can small cities do?
  – Incentive ideas
    • Preferential parking
  – Example cities
  – Encourage market / public
  – Prepare for infrastructure
  – Encourage green buildings
  – Encourage green business

• Do you know where your power comes from?
• Do you know what you pay in gas? Electricity?
• Where can you plug in?