Cost-Benefit Analysis of Plug-In Hybrid-Electric Vehicle Technology

22nd International Electric Vehicle Symposium
Yokohama, Japan
October 25-28, 2006

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With support from the
Lee Slezak
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
FreedomCAR and Vehicle Technologies Program
Presentation Outline

• Plug-in hybrid-electric vehicle (PHEV) as a solution
• Potential petroleum reduction from PHEVs
• Simulation of PHEV efficiency and cost
  — Baseline vehicle assumptions
  — Powertrain technology scenarios
  — Components models (cost, mass, efficiency)
• Results
  — Component sizing
  — Fuel Economy
  — Incremental cost
  — Payback scenarios
• Conclusions & Next Steps
A Plug-In Hybrid-Electric Vehicle (PHEV)

An HEV with wall recharge capability and fuel flexibility

Fuel Flexibility

PETROLEUM

AND/OR

ELECTRICITY

BATTERY RECHARGE

ADVANCED ENGINE

ENGINE IDLE-OFF

ENGINE DOWNSIZING

REGENERATIVE BRAKING

ELECTRIC ACCESSORIES
Vision of Future Transportation

High Power ➤

Battery Advancement

Affordable High Power, Acceptable High Energy ➤

Affordable High Energy ➤

Electric Vehicles

Consumers Asking for Plug-In Capabilities

Plug-In HEVs: Early Adopters

PHEVs: Major Consumer Adoption (low-range)

Battery Electric Vehicles

Plug-In Hybrid Vehicles

HEVs: Major Consumer Adoption

HEVs: Early Adopters

Battery Electric Vehicles

PHEVs: Major Consumer Adoption (high-range)

Neighborhood Electric Vehicles

Fuel Cell Vehicles

Internal Combustion (ICE) Vehicles

Fuels

Gasoline, Ethanol Blends ➤

Diesel, Biodiesel Blends ➤

B20, Biodiesel ➤

E85, Cellulosic Ethanol ➤

Electricity ➤

Hydrogen ➤
PHEV Key Benefits and Challenges

**KEY BENEFITS**

- **Consumer:**
  - Lower “fuel” costs
  - Fewer fill-ups
  - Home recharging convenience
  - Fuel flexibility

- **Nation:**
  - Less petroleum use
  - Less greenhouse and regulated emissions
  - Energy diversity/security

**KEY CHALLENGES**

- Recharging locations
- Battery life
- Component packaging
- Vehicle cost

*Cost-Benefit Analysis*
Potential Petroleum Reduction from PHEVs

What are the relative costs?

Reduction in Charge-Sustaining Mode Petroleum Consumption (%)

Total Reduction in Petroleum Consumption (%)

Challenging for HEV technology

WHAT ARE THE RELATIVE COSTS?

Battery energy

Battery power

PHEV60

PHEV40

PHEV20

Prius (Corolla)

Escape

Civic

Accord

Highlander

Vue

HEV
Vehicle Configurations

- conventional automatic
- pre-transmission parallel hybrid: HEV or PHEV
- 2 technology scenarios
  – near term and long term

Approach

- Dynamic, power-flow simulation
- Calculates component sizes and costs
- Iterative mass-compounding
- Measures fuel/electricity consumption using NREL-proposed revisions to SAE J1711

Battery definition is key input to the simulation
Key Study Assumptions

• Usable State of Charge window varies from 40% for HEV0 to 70% for PHEV60
  — Based on battery life of 15 years and daily travel distance probability
• Mid-size car platform (Malibu/Camry)
  — High volume vehicle
  — Performance equivalent to existing vehicles
  — No platform engineering and no engine technology improvements
    » Isolate the PHEV technology impacts
• Battery attributes scale with Power/Energy ratio
Battery Definition as Key Input to Simulation

Input parameters that define the battery in BLUE

**Mass compounding**

- **PHEV range**
- **kWh/mi (from simulation)**
- **SOC window**
- **P/E ratio**
- **Performance constraints**

**DOH** = degree of hybridization

**Benefit of plugging-in**

- **Total MPG Benefit**

**Benefit of hybridization**

- **kWh usable**
- **kWh total**
- **kW_{motor}**
- **kW_{engine}**

**DOH** = degree of hybridization
Battery Models (Scaleable)

Battery Design Functions

Battery Cost Functions

Specific Power (W/kg) vs. Specific Energy (Wh/kg)

- NiMH (near-term scenario)
- Li-ION (long-term scenario)

Module Specific Cost ($/kWh) vs. Power-to-Energy Ratio (1/h)

- NiMH (near-term)
- Li-Ion (long-term)
Results: Battery Specifications

Battery Power vs Energy for PHEVs
Midsize Sedans

P/E = Energy/Total Energy

Long-term scenario
LI-ION BATTERIES

US06 all-electric

P/E = 20

P/E = 10

P/E = 6

P/E = 4

UDDS all-electric

UDDS blended

0 5 10 15 20 25 30
Total Battery Energy (kWh)

0 20 40 60 80 100 120
Battery Power (kW)

PHEV2
PHEV5
PHEV10
PHEV20
PHEV30
PHEV40
PHEV50
PHEV60
Results: Incremental Cost of Reduced Consumption

Reduction in Fuel Consumption vs Powertrain Cost Increment - Midsize Sedans

- HEV0
- PHEV2
- PHEV5
- PHEV10
- PHEV20
- PHEV30
- PHEV40
- PHEV50
- PHEV60

Long-term scenario

LI-ION BATTERIES

Higher battery power
Varying DOH
Lower battery power

~$8K

~50% reduction

Retail Cost Increment

Reduction in Annual Petroleum Consumption (gals.)

Conventional~660 gals
PHEV Energy Use

PHEV Onboard Energy Use: Long-Term Scenario

- Conventional HEV
- PHEV0
- PHEV10
- PHEV20
- PHEV40

Annual Petroleum Consumption (gals):
- Conventional: 600 gals
- PHEV0: 400 gals
- PHEV10: 300 gals
- PHEV20: 200 gals
- PHEV40: 100 gals

Annual Electricity Consumption (kWh):
- Conventional: 0 kWh
- PHEV0: 200 kWh
- PHEV10: 300 kWh
- PHEV20: 400 kWh
- PHEV40: 500 kWh

Long-term scenario: 23 mpg
LI-ION BATTERIES
Powertrain Costs Comparison – Long Term

Powertrain Costs (incl. retail markups)

<table>
<thead>
<tr>
<th>Component</th>
<th>Conventional</th>
<th>HEV0</th>
<th>PHEV10</th>
<th>PHEV20</th>
<th>PHEV40</th>
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</thead>
<tbody>
<tr>
<td>Engine</td>
<td>$6,002</td>
<td>$9,073</td>
<td>$12,307</td>
<td>$14,438</td>
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<td>Transmission</td>
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<td>$4,864</td>
<td>$6,915</td>
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<tr>
<td>Motor/Inverter</td>
<td>$1,680</td>
<td>$1,845</td>
<td>$1,877</td>
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<td>$2,024</td>
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<tr>
<td>Battery</td>
<td>$4,004</td>
<td>$1,994</td>
<td>$2,006</td>
<td>$2,970</td>
<td>$3,023</td>
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<tr>
<td>Charging Plug</td>
<td>$2,876</td>
<td>$2,930</td>
<td>$2,970</td>
<td>$2,970</td>
<td>$2,970</td>
</tr>
</tbody>
</table>

UDDS AER PHEVs

NREL National Renewable Energy Laboratory
Near-term HEV Fuel Savings Offset Incremental Cost

Cumulative Vehicle plus Energy (Fuel/Elec.) Costs

Years after purchase

Cumulative Cost

- $-
- $10,000
- $20,000
- $30,000
- $40,000
- $50,000
- $60,000

Near-term scenario
NIMH BATTERIES

- $3.00/gal.
- $0.09¢/kWh (2005 average, not off-peak)

Maintenance costs not included, no discount rate applied

PHEV40
PHEV20
PHEV10
HEV0
CV

$3.00/gal.
$0.09¢/kWh (2005 average, not off-peak)
Long-term Battery Cost Reductions Alone Insufficient For PHEV to Payback Relative to HEV

Cumulative Vehicle plus Energy (Fuel/Elec.) Costs

- $3.00/gal.
- $0.09¢/kWh (2005 average, not off-peak)

Maintenance costs not included, no discount rate applied.
Both Higher Gas Prices and Lower Battery Costs Required for PHEV to Payback Relative to HEV

Cumulative Vehicle plus Energy (Fuel/Elec.) Costs

- Long-term scenario
- LI-ION BATTERIES

- $5.00/gal. (future?)
- $0.09¢/kWh (2005 average, not off-peak)

Maintenance costs not included, no discount rate applied
Why Consumers Might Pay More for PHEVs?

1. Green image, “feel-good factor”
2. Of-peak charging
3. Tax incentives
4. Reduced petroleum use, air pollution and CO₂
5. National energy security
6. Less maintenance
7. Reduced fill-ups
8. Convenience of home recharging (off-peak)
9. Improved acceleration (high torque of electric motors)
10. Alternative business models
Conclusions

1. Systems simulation extremely important and valuable for quickly exploring the broad HEV/PHEV design spectrum.

2. Key factors in the HEV/PHEV cost-benefit equation include:
   - Battery costs
   - Fuel costs
   - Control strategy (particularly battery SOC window)
   - Driving habits (annual VMT and trip-length distribution)

3. Based on the assumptions of this study:
   - HEVs can reduce per-vehicle petroleum use by approximately 30%.
   - Per-vehicle petroleum use reduced by up to 50% for PHEV20s and 65% for PHEV40s.
   - Long-term powertrain cost increments are predicted to be $2k-$6k for HEVs, $7K-$11k for PHEV20s and $11K-$15k for PHEV40s.

4. Based on overall costs (powertrain plus energy):
   - HEVs become the most cost-competitive EITHER if gasoline prices increase OR projected battery costs are achieved.
   - PHEVs become cost-competitive ONLY if projected battery costs are achieved AND fuel prices increase.
   - Tax incentives and/or alternative business models (e.g. battery lease) may be required for successful marketing of PHEVs.