Current Status and Outlook of Hybrid Vehicle Technologies

- Driving Forces for Alternative Powertrains
- Current Status
- Outlook

Huei Peng

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The University of Michigan
Driving Forces for Change

- High crude oil price
- Tightening fuel economy regulations
- Need for diverse transportation energy sources
- Investment to sustain (or to take) leadership in the automotive industry
Why Hybrids?

- Hybrid technologies are a key to meet these challenges.
On May 19, 2009, President Obama announced that EPA and NHTSA will work together to create one National Program specifying both greenhouse gas emissions and CAFÉ standards. The plan is to achieve CO2 emission of less than 250g/mi (156g/km) by 2016, which is estimated to be equivalent to 35.5mpg.
Short-Term Fuel Economy Target of US

The new rule is measured in CO₂ emission per mile, as part of the national greenhouse gas (GHG) emissions standards under the Clean Air Act

Phase-in period: 2012 to 2016, footprint dependent

Figure 1 – CO₂ (g/mi) Car Standard Curves

Figure 2 – CO₂ (g/mi) Truck Standard Curves

http://www.epa.gov/oms/climate/regulations/420f10014.htm
Short-Term EU CO2 Rule

- By 2012, 65% of new cars must achieve the target of 130g/km, and by 2015, 100% of cars must satisfy this target.
- By 2020, the carbon emission level is planned to be reduced to 95g/km (not final).
- A sliding scale penalty for higher emitting cars.

Compiled CO2 standards

<table>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>240</td>
<td>228</td>
<td>205</td>
<td>198</td>
<td>191</td>
<td>181</td>
<td>172</td>
<td>152</td>
<td></td>
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<tr>
<td>European Union</td>
<td></td>
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<tr>
<td>China</td>
<td>185</td>
<td>167</td>
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<tr>
<td>Japan</td>
<td>141</td>
<td>125</td>
<td></td>
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</tr>
</tbody>
</table>

- **United States**
  - 240 (26 mpg)
  - 228
  - 205
  - 198
  - 191
  - 181
  - 172 (34 mpg)
  - 152 (39 mpg)

- **European Union**
  - 154 (39 mpg)
  - 130 (45 mpg)
  - 95 (61 mpg)

- **China**
  - 185 (33 mpg)
  - 167 (36 mpg)
  - 145 (41 mpg)

- **Japan**
  - 141 (42 mpg)
  - 125 (47 mpg)
  - 109 (53 mpg)


*All targets are expected to be phased in. CO2 emissions targets are in grams per kilometer (g/km) and are based on the New European Driving Cycle (NEDC). Mileage targets are in miles per gallon (mpg) and are based on Corporate Average Fuel Economy (CAFE) standards.*

*California has agreed to conform to the U.S. government’s targets for 2012 through 2016. Previously, the state had enacted stricter legislation.*

*This is based on the government’s released scenarios of a 47- to 62-mpg target for 2025; 47 mpg is expected to be the most likely target.*

*From motor vehicle technology only. The European Union plans to call for a further 10 g/km reduction in CO2 emissions through other improvements (for example, to air-conditioning technology) and the use of biofuels.*
Outline

- Driving Forces for Alternative Powertrains
- Current Status
- Outlook
Hybrids Grew From 1.2% to 2.8% (2005-2009)

http://www.greencarcongress.com/sales/
## 2009 Hybrid Market

### 2009 global hybrid registrations

<table>
<thead>
<tr>
<th>Location</th>
<th>Registrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>265,501</td>
</tr>
<tr>
<td>Japan</td>
<td>249,619</td>
</tr>
<tr>
<td>Canada</td>
<td>16,167</td>
</tr>
<tr>
<td>Netherlands</td>
<td>13,686</td>
</tr>
<tr>
<td>UK</td>
<td>13,661</td>
</tr>
</tbody>
</table>

### Top 5 global hybrid markets

<table>
<thead>
<tr>
<th>Location</th>
<th>Registrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
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<td>13,686</td>
</tr>
<tr>
<td>UK</td>
<td>13,661</td>
</tr>
</tbody>
</table>

### Top 5 US hybrid markets

<table>
<thead>
<tr>
<th>Location</th>
<th>Registrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>26,677</td>
</tr>
<tr>
<td>New York</td>
<td>21,193</td>
</tr>
<tr>
<td>San Francisco</td>
<td>15,799</td>
</tr>
<tr>
<td>Washington, DC</td>
<td>11,595</td>
</tr>
<tr>
<td>Chicago</td>
<td>8,990</td>
</tr>
</tbody>
</table>

### Brand Share

- **Toyota**: 72%
- **Honda**: 11%
- **Ford**: 9%
- **GM**: 5%
- **Nissan**: 3%

### Hybrid Types

- **10% parallel hybrids**
- **90% power split hybrids**

### Models

- **Toyota Prius**: 46.8%
- **Lexus HS 250**: 7.9%
- **Lexus RX 400h**: 6.4%
- **Toyota Camry**: 6.0%
- **Toyota Highlander**: 4.1%
- **Lexus GS 450h**: 0.2%
- **Lexus LS 600hL**: 0.1%
- **Honda Insight**: 6.5%
- **Honda Civic**: 1.9%
- **Ford Fusion**: 6.2%
- **Ford Escape**: 4.1%
- **Mercury Milan**: 0.5%
- **Mercury Mariner**: 0.5%
- **Chevy Silverado**: 1.1%
- **Chevy Tahoe**: 0.9%
- **GMC Yukon**: 0.8%
- **Cadillac Escalade**: 0.8%
- **Saturn Vue**: 0.7%
- **Saturn Aura**: 0.6%
- **Chevy Malibu**: 0.5%
- **Nissan Altima**: 3.3%

## 2010 Hybrid Market

### Four observations:

- **Market share did not grow since 2009**
- **Out of 30 available models, only**
  - 3 sold more than 20,000 units/year
  - 7 sold more than 10,000 units/year
- **10% parallel hybrids**
  90% power split hybrids
- **Micro-hybrids (start/stop) did not do well**

### 2010 Hybrid Market

<table>
<thead>
<tr>
<th>Model</th>
<th>CY2010</th>
<th>% of hybrid</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Prius</td>
<td>140,928</td>
<td>51.4%</td>
<td>22,120</td>
</tr>
<tr>
<td>Honda Insight</td>
<td>20,962</td>
<td>7.6%</td>
<td>18,200</td>
</tr>
<tr>
<td>Lexus RX450h</td>
<td>15,113</td>
<td>5.5%</td>
<td>44,735</td>
</tr>
<tr>
<td>Ford Fusion</td>
<td>20,816</td>
<td>7.6%</td>
<td>28,600</td>
</tr>
<tr>
<td>Toyota Camry</td>
<td>14,587</td>
<td>5.3%</td>
<td>27,050</td>
</tr>
<tr>
<td>Lexus HS 250h</td>
<td>10,663</td>
<td>3.9%</td>
<td>36,330</td>
</tr>
<tr>
<td>Toyota Highlander</td>
<td>7,456</td>
<td>2.7%</td>
<td>38,140</td>
</tr>
<tr>
<td>Honda Insight</td>
<td>7,336</td>
<td>2.7%</td>
<td>24,050</td>
</tr>
<tr>
<td>Ford Fusion</td>
<td>11,182</td>
<td>4.1%</td>
<td>30,570</td>
</tr>
<tr>
<td>Honda CR-Z</td>
<td>5,249</td>
<td>1.9%</td>
<td>19,345</td>
</tr>
<tr>
<td>Altima</td>
<td>6,710</td>
<td>2.4%</td>
<td>26,800</td>
</tr>
<tr>
<td>Linc. MKZ Hybrid</td>
<td>1,192</td>
<td>0.4%</td>
<td>34,645</td>
</tr>
<tr>
<td>Mercury Milan</td>
<td>1,416</td>
<td>0.5%</td>
<td>28,345</td>
</tr>
<tr>
<td>Porsche Cayenne</td>
<td>344</td>
<td>0.1%</td>
<td>67,700</td>
</tr>
<tr>
<td>Cad. Escalade</td>
<td>1,210</td>
<td>0.4%</td>
<td>74,135</td>
</tr>
<tr>
<td>Chevy Tahoe</td>
<td>1,426</td>
<td>0.5%</td>
<td>51,145</td>
</tr>
<tr>
<td>GMC Yukon</td>
<td>1,221</td>
<td>0.4%</td>
<td>51,610</td>
</tr>
<tr>
<td>Chevy Silverado</td>
<td>1,871</td>
<td>0.7%</td>
<td>38,725</td>
</tr>
<tr>
<td>Mercury Mariner</td>
<td>890</td>
<td>0.3%</td>
<td>30,115</td>
</tr>
<tr>
<td>Mazda Tribute</td>
<td>655</td>
<td>0.2%</td>
<td>20,555</td>
</tr>
<tr>
<td>GMC Sierra</td>
<td>522</td>
<td>0.2%</td>
<td>39,095</td>
</tr>
<tr>
<td>Mercedes S400</td>
<td>955</td>
<td>0.3%</td>
<td>91,000</td>
</tr>
<tr>
<td>Lexus GS450h</td>
<td>305</td>
<td>0.1%</td>
<td>58,950</td>
</tr>
<tr>
<td>BMW Hybrid 7</td>
<td>101</td>
<td>0.0%</td>
<td>102,300</td>
</tr>
<tr>
<td>Lexus LS600hL</td>
<td>129</td>
<td>0.0%</td>
<td>112,250</td>
</tr>
<tr>
<td>BMW X6</td>
<td>248</td>
<td>0.1%</td>
<td>88,900</td>
</tr>
<tr>
<td>Chevy Malibu</td>
<td>405</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>Saturn Aura</td>
<td>55</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>Mercedes ML450</td>
<td>766</td>
<td>0.3%</td>
<td>55,790</td>
</tr>
<tr>
<td>Saturn Vue</td>
<td>50</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td><strong>All hybrids</strong></td>
<td>274,763</td>
<td>2.4%</td>
<td></td>
</tr>
<tr>
<td><strong>All vehicles</strong></td>
<td>11,588,783</td>
<td>2.4%</td>
<td></td>
</tr>
</tbody>
</table>

US plug-in electric sales for May 2011

<table>
<thead>
<tr>
<th>Model</th>
<th>Units</th>
<th>vs. last month</th>
<th>CYTD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nissan LEAF</td>
<td>1,142</td>
<td>99.30%</td>
<td>2,167</td>
</tr>
<tr>
<td>Chevrolet Volt</td>
<td>481</td>
<td>-2.40%</td>
<td>2,184</td>
</tr>
<tr>
<td>Smart ED</td>
<td>8</td>
<td>-70.40%</td>
<td>87</td>
</tr>
<tr>
<td>All plug-in cars</td>
<td>1,631</td>
<td>344.40%</td>
<td>4,438</td>
</tr>
<tr>
<td>All vehicles</td>
<td>1,057,826</td>
<td>-8.40%</td>
<td>5,260,000</td>
</tr>
</tbody>
</table>

Sale volume significantly affected by the earthquake and tsunami of Japan

Both Leaf and Volt are likely to sell 5k-10k units each in 2011

Observations

- Power split hybrids dominate the hybrids market now, and the situation is likely to continue into the near future.

- Toyota Prius is more than half of the hybrid market—and they are expanding the name into a line of vehicles (Prius V, Prius C)

- Several companies offer multiple low-volume models that self-compete.

- Most hybrid models are not competitive (judging from their sales volume). They are mostly
  - Early (1st) iteration, and
  - Models with non-hybrid versions (Price premium is obvious, and identity is not obvious)
Internal Combustion Engines

- Wide adoption of Atkinson cycle engines
- Engine size (and weight) of hybrid vehicles continues to creep up slowly without impacting fuel economy
Batteries

- Hybrids: mostly use Ni-MH batteries for now. Li-polymer to be used in 2012 Hyundai/Kia (a few kW-Hr)

- Plug-in hybrids and pure electric vehicles: Li-Ion batteries (16-24 kW-Hr)

- Their energy density is 2 orders of magnitude lower than gasoline. No major breakthrough in sight
Electric Motors

- Significant improvement in efficiency/size/weight over the last few iterations. Further improvement is still needed.

- PMSM dominate. However the recent price increase/concerns of stable supplies might change the situation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2010 Prius (60 kW)</th>
<th>Lexus (110 kW)</th>
<th>Camry (70 kW)</th>
<th>2004 Prius (50 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak power density, kW/L</td>
<td>4.8</td>
<td>6.6</td>
<td>5.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Peak specific power, kW/kg</td>
<td>1.6</td>
<td>2.5</td>
<td>1.7</td>
<td>1.11</td>
</tr>
<tr>
<td>Inverter (including converter and excluding generator inverter)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak power density, kW/L</td>
<td>5.9</td>
<td>10.6</td>
<td>7.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Peak specific power, kW/kg</td>
<td>6.9</td>
<td>7.7</td>
<td>5</td>
<td>3.7</td>
</tr>
</tbody>
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DOE 2020 target

- 5.7
- 1.6
Rare Earth Metal Price

http://www.metal-pages.com/
Outline

- Driving Forces for Alternative Powertrains
- Current Status
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Fuel Economy Requirement

📍 For 2017-2025, the standard is still under discussion.

📍 The Obama administration has announced that it is targeting a range between 47 mpg and 62 mpg.

📍 Rumor is that the number for 2025 maybe 56.2 mi/gal.

📍 Is this target achievable?

✦ Volt: 95/90 mpg, Leaf: 106/92 mpg.

Electrified Vehicles 2011 and Beyond

- Lithium batteries begin to be adopted (Volt, Leaf, Hyundai Sonata)

- Plug-in vehicles with much bigger batteries become commercially available (Volt, Leaf, Smart ED, plug-in Prius?)

- Supply disruption due to the earthquake in Japan causes the sales to drop significantly starting March 2011.

- Market share of hybrids has not grown since 2009 (2.8%) but the situation is likely to change in 2012 with the dozens of new models to be launched
Power Split Hybrids

- Power split hybrids using a single planetary gear are likely to continue dominating the market (midsize and below).

- Vehicles using 2 or more planetary gears had not done well. For heavier vehicles (especially SUV/LT) however single planetary gear designs may not be enough.
Parallel Hybrids

✧ Up to 2011, Honda + Micro hybrids (start/stop)

✧ New models:
  ★ Hyundai/Kia MY2012, Porsche Cayenne, Infinity M35h
  ★ Nissan Altima will switch from power split to parallel configuration starting MY 2012

✧ Ideally use only one electric motor (cheaper) but also need a traditional transmission

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Engine</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonata</td>
<td>3,483</td>
<td>2.4L</td>
<td>35/40</td>
</tr>
<tr>
<td>Fusion</td>
<td>3,720</td>
<td>2.5L</td>
<td>41/36</td>
</tr>
<tr>
<td>Camry</td>
<td>3,680</td>
<td>2.4L</td>
<td>31/35</td>
</tr>
<tr>
<td>Prius</td>
<td>3,042</td>
<td>1.8L</td>
<td>51/48</td>
</tr>
</tbody>
</table>
Nissan P2 Design

http://bioage.typepad.com/.a/6a00d8341c4fbe53ef01310f5bdda9970c-popup
http://www.greencarcongress.com/2010/03/m35-20100304.html
Series Hybrids

✧ Not popular because of their lower efficiency

✧ Has unique potential for heavy vehicles or light weight EREV.
Ford Auto Start-Stop

Coming to North American cars, crossovers and utilities starting in 2012, the Auto Start-Stop system has been designed to work with conventional gasoline-powered vehicles with automatic and manual transmissions. It saves fuel and reduces emissions.

12V battery designed for long lasting service with no additional maintenance

Voltage quality module assures vehicle accessories function normally when engine is off

12V enhanced starter motor provides quick, quiet and seamless engine starts once driver removes foot from brake pedal

Top five benefits of Auto Start-Stop:
- Fuel economy gains of as much as 10 percent in city driving
- Vehicle emits zero emissions when stopped
- Vehicle remains warm or cool even when engine is off
- System is smooth, quiet and seamless
- No additional maintenance is required
GM eAssist:
Start/stop, regen, torque assist, torque smoothing

BMW EfficientDynamics
I do not agree with these numbers

Thoughts on Start/Stop(+) 

- Start/Stop(+) hybrids did not do well in the past. Will they sell in the future?
- In the past, some of the Start/Stop hybrids were designed (and/or perceived) as an inferior version of the traditional vehicles (e.g., 3.5L vs. 2.4L green-line hybrid)
- In the future, start/stop should be designed and promoted as
  - A plus (not a sacrifice)
  - A technology to achieve better fuel economy, and not a money-making option
Competition From Small Gasoline Cars

At $15,500

Squeezing room for compact and mild hybrids
- Fuel economy of city cycles much worse
Pursuit for Lower-Cost Motors

- Non (low) Rare-Earth magnets

- Switch Reluctance Motors that have
  - Lower torque ripple
  - Higher efficiency
  - Lower acoustic noise

T. Burress, ORNL, “A New Class of Switched Reluctance Motors Without Permanent Magnets”, 2011 DOE Merit Review
DOE Electric Drive Targets

APEEM Research Targets, Challenges, and Research Areas

Reduce Dependence on Oil
Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life

Technical Targets

<table>
<thead>
<tr>
<th>Year</th>
<th>Traction Drive System</th>
<th>Power Electronics</th>
<th>Motors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($/kW)</td>
<td>(kW/kg)</td>
<td>(kW/l)</td>
</tr>
<tr>
<td>2010</td>
<td>19</td>
<td>1.06</td>
<td>2.6</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>1.2</td>
<td>3.5</td>
</tr>
<tr>
<td>2020</td>
<td>8</td>
<td>1.4</td>
<td>4</td>
</tr>
</tbody>
</table>

Challenges

Research Areas

- Traction Drive System
  - Benchmarking technologies
  - Innovative system designs
- Power Electronics
  - Innovative topologies
  - Temperature-tolerant devices
  - Packaging
  - Capacitors
  - Vehicle charging
- Electric Motors
  - Permanent magnet (PM) motors
  - Magnetic materials
  - High-performance non-PM motors
  - New materials
- PEEM Thermal Management
  - Thermal system integration
  - Heat transfer technologies
  - Thermal stress and reliability

S. Rogers, OOV, DOE, “Advanced Power Electronics and Electric Motors (APEEM) R&D Program Overview”, 2011 DOE Merit Review
DOE Battery Cost Target

Outlook for Battery Cost and EV Production Capacity

On Track to Meet Administration’s Goal of 1 Million EVs by 2015

<table>
<thead>
<tr>
<th>Year</th>
<th>Battery Cost ($ per kWh)</th>
<th>Battery Production Capacity (10 kWh packs)</th>
<th>Vehicle Production (announced, cumulative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$1,000-$1,200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2009</td>
<td>$700-$950</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>$700-$950</td>
<td>50,000</td>
<td>45,600</td>
</tr>
<tr>
<td>2011</td>
<td>Goal = $500</td>
<td>150,000</td>
<td>223,200</td>
</tr>
<tr>
<td>2012</td>
<td>Goal = $500</td>
<td>144,000</td>
<td>486,200</td>
</tr>
<tr>
<td>2013</td>
<td>Goal = $300</td>
<td>500,000</td>
<td>854,200</td>
</tr>
<tr>
<td>2014</td>
<td>Goal = $300</td>
<td>488,000</td>
<td>1,222,200</td>
</tr>
<tr>
<td>2015</td>
<td>~10M kWh per year production capacity in 2015</td>
<td>&gt;8M kWh per year demand in 2015</td>
<td></td>
</tr>
</tbody>
</table>

David Howell, Energy Storage R&D, DOE2011 Merit Review
Outlook for Hybrids

✧ Key technology for fuel economy improvement

✧ Need to drive down cost—judicial use of technologies that are ready or soon to be ready to create competitive products.

✧ Only balanced designs win (but not all balanced designs will win)