Comparison of energy consumption and costs of different hybrid and plug-in hybrid vehicle concepts in European and American context

IEA Implementing Agreement, Hybrid and Electric Vehicles Task 15: Plug-In Hybrid Electric Vehicles

11. April 2013
Hannover Messe

Dipl.-Wirt.-Ing. Martin Redelbach
Institut für Fahrzeugkonzepte
References
The presentation is based on the international cooperation between ANL, IFP and DLR in context of the IEA Implementing Agreement HEV

Joint Publications

B. Propfe, M. Redelbach, D. Santini, H. Friedrich:

A. Rousseau, F. Badin, M. Redelbach, N. Kim, A. Da Costa, D. Santini, F. Le Berr, H. Friedrich:
Comparison of Energy consumption and costs of different HEVs and PHEVs in European and American context, European Electric Vehicle Conference (EEVC), 19.-22. November 2012, Brussels, Belgium.
Agenda
The presentation analysis the competitiveness of different hybrid electric vehicle concepts

- Objective and approach
- Vehicle architecture
- Energy consumption (certification vs. real world)
- Maintenance and repair cost
- Total cost of ownership analysis
- International comparison of cost efficiency
Objective and approach
The presentation analysis the competitiveness of different hybrid electric vehicle concepts

- **Current challenges:**
  - Ambitious CO₂ reduction targets,
  - rising energy prices
  - growing awareness of fuel economy

- **Electrification of drivetrains** as main levers to improve energy efficiency

- **Cost competitiveness of electric vehicles:**
  - Production costs are higher conventional
  - Operating costs are lower due to low energy consumption

→ Fair comparison of cost efficiency across different powertrain alternatives from customer perspective
Vehicle architecture and setup
3 different hybrid electric powertrain concepts have been analyzed and compared to a conventional vehicle in midsize car segment.

**Component sizing**

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Parallel Hybrid</th>
<th>Input split Hybrid</th>
<th>Series Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Automatic</td>
<td>HEV</td>
<td>PHEV 30</td>
<td>PHEV 70</td>
</tr>
<tr>
<td>Vehicle Mass</td>
<td>kg</td>
<td>1220</td>
<td>1271</td>
<td>1340</td>
</tr>
<tr>
<td>ICE power</td>
<td>kW</td>
<td>105.9</td>
<td>80.2</td>
<td>50.7</td>
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<tr>
<td>El. machine 1 power</td>
<td>kW</td>
<td>25</td>
<td>70.3</td>
<td>103</td>
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<tr>
<td>El. machine 2 power</td>
<td>kW</td>
<td>34.9</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Battery power</td>
<td>kW</td>
<td>30</td>
<td>60.5</td>
<td>135</td>
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<tr>
<td>Battery energy</td>
<td>kWh</td>
<td>0.97</td>
<td>5.44</td>
<td>13.56</td>
</tr>
<tr>
<td>Battery P/E ratio</td>
<td>h⁻¹</td>
<td>31</td>
<td>11</td>
<td>10</td>
</tr>
</tbody>
</table>
Energy consumption

Different standardized driving cycles have been simulated:

- Certification test cycle
  - NEDC
  - UDDS

- Real-world test cycle
  - Artemis Urban
  - Artemis Motorway

Time (in s) vs. Speed (in km/h) graphs for each cycle.
Energy consumption
European certification procedure for plug-in hybrid electric vehicles

A  Battery fully charged (CD-Mode)

\[ M_1 = \frac{m_1}{D_{test1}} \]
\[ E_1 = \frac{e_1}{D_{test1}} \]

B  Battery fully discharged (CS-Mode)

\[ M_2 = \frac{m_2}{D_{test2}} \]
\[ E_4 = \frac{e_4}{D_{test2}} \]

CO₂ emission (in g/km)
\[ M = \frac{AER \cdot M_1 + 25 \cdot M_2}{AER + 25} \]

Electric energy consumption (in Wh/km)
\[ E = \frac{AER \cdot E_1 + 25 \cdot E_4}{AER + 25} \]

1) According to regulation 101; AER = all electric range
Energy consumption

US certification procedure for plug-in hybrid electric vehicles

\[ FC_{\text{glob}} = FC_{\text{dep}} \cdot UF + (1-UF) \cdot FC_{\text{sus}} \text{ (gpm)} \]

1) According SAE J1711 procedure
Energy consumption
Real world energy consumption depends on individual driver behavior

- Electric driving share
- Weighting of CD/CS-energy consumption

- Average driving seed
- Weighting of urban/motorway cycles

Source: DLR analysis of MiD 2008 data
Energy consumption
Comparison of gasoline and electricity consumption for standard EU test procedures and real world driving

Energy consumption is significantly higher in simulated real-world driving conditions than in EU test cycle (15-60% for fuel consumption)

1) Real world consumption calculated as weighted average of Artemis Urban and Motorway Source: Based on ANL and IFP simulation results
Energy consumption
Comparison of gasoline and electricity consumption for standard EU and US test procedures

Fuel consumption of PHEVs is 30-40% higher in US test procedure compared to EU; electric energy consumption 20-50% lower

Source: Based on ANL and IFP simulation results
Maintanence and repair cost
Bottom-up estimation of maintenance and repair costs of electric powertrains

Powertrain components

- Miscellaneous
- Coolant
- Cabin air filter
- Electrified Components
  - PE: DC/DC
  - PE: DC/AC
  - PE: AC/DC
- Charging system
- Traction e-motor
- Fuel cell
- Transmission
- Clutch
- Braking System
- Brake disk
- IC Engine
- Automotive battery (Pb)
- Generator
- Spark plug
- Rocker cover gasket
- Vee belt/Multi-groove belt
- Timing belt
- Fuel filter
- Muffler
- Engine oil

M&R costs for hybrids are lower than for conventional vehicle (up to -30% for PHEV70)
Hybrids can compensate higher initial purchase price by lower operating cost

**Year 2015 (in 1000 EUR)**

<table>
<thead>
<tr>
<th></th>
<th>Conventional ICE</th>
<th>PHEV70</th>
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</thead>
<tbody>
<tr>
<td>Purchase cost</td>
<td>28.3</td>
<td>37.4</td>
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<tr>
<td>Expected resale value</td>
<td>9.1</td>
<td>12.0</td>
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<tr>
<td>Fuel cost</td>
<td>7.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>0</td>
<td>1.7</td>
</tr>
<tr>
<td>Maintenance &amp; repair</td>
<td>3.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Other costs</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total Cost of Ownership</strong></td>
<td><strong>31.1</strong></td>
<td><strong>31.3</strong></td>
</tr>
</tbody>
</table>

Assumption: 14,000 km/year, 4 year holding period, country Germany
TCO analysis
Plug-in electric vehicles only payoff for frequent drivers

7000 km/year
- Conv. ICE: 18.3
- HEV 30: 20.0
- PHEV 70: 21.9
- Cumulated cost: 24.1

14000 km/year
- Conv. ICE: 19.3
- HEV 30: 21.1
- PHEV 70: 23.1
- Cumulated cost: 25.4

20000 km/year
- Conv. ICE: 20.1
- HEV 30: 22.0
- PHEV 70: 24.1
- Cumulated cost: 26.6

Cumulated cost for car owner over 4 years including resale in 1000 EUR (year 2015)

Source: ...
International comparison

PHEV are more attractive for EU than US customer mainly due to higher fuel prices in Europe

US calculation assumes 10 year holding period without resale value, US: short distance = 6600, typical distance = 18000, long distance = 32000 km
Conclusions

US and EU established comparable test procedures for electric vehicles → EU norm favors HEV/PHEV in terms of fuel consumption; real world consumption is significantly higher

Operating cost (energy and maintenance) for hybrids decrease with higher degree of electrification (party compensating the higher purchase price)

The cost efficiency of HEV and PHEV highly depend on driver behavior and energy prices → Break even is reached at lower mileages in EU case (due to higher fuel prices)
Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Institut für Fahrzeugkonzepte (FK), Stuttgart

Martin.Redelbach@DLR.de
+49 711 6862 8051