Powertrain Trends and Future Potential

Dr. Johannes-Joerg Rueger
Sr. Vice President, Robert Bosch

Panel “New Directions in Engine and Fuels”
DEER Conference,
Dearborn, August 4, 2009
Powertrain Trends and Future Potential

Agenda

• Global Trends – Fighting Global Warming

• Future of Powertrain Systems – Efficient CO2 reduction @ reasonable costs

• Clean Diesel – Neglected in the U.S. for Too Long
CO₂ emission reduction is a world-wide topic!
Worldwide Powertrain Trends

Production: Vehicles World by Region

Mio.

- Diesel
- DI-Gasoline
- PFI-Gasoline
- Flex-Fuel, CNG, LPG
- Hybrid, EV
- Estimation 10.2008

Source: DS/MKS 9840144

North & Latin America
Europe
Japan & Thailand
China
India
Other Regions

% Diesel Share

Source: C/AS LTFC Cycle I 2009 Group View

* Other Regions = Australia, Africa and Asia w/o Japan, Thailand and China

DI-Gasoline = Direct Injection Gasoline; EV = Electric Vehicle;
CNG = Compressed Natural Gas; LPG = Liquified Petroleum Gas

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Worldwide Powertrain Trends

Powertrains for Passenger Cars – Timeline

- Gasoline
- Diesel
- Alternative fuels
- Hybrid
- HCCI
- Electric/Battery
- Range extender
- Electric/Fuel cell
- Gasoline
- Diesel
- Alternative fuels
- Range extender
- Hybrid

1997 2015

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The Future – Not Just Electric Driving

CARB Scenario for the Introduction of Electric Cars

share of “conventional” technology

95% 80% 60%

Early Commercialization  Market Acceptance (Ramp Up of New Technology)  Fleet Turnover

2010 2020 2030 2040 2050

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from: Cackette, California Air Resources Board, January 2009

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Future of Powertrain Systems

Efficient Emission Reduction

Reduction of Vehicle CO₂-Emissions

Direct: oCCS¹)

Hydraulic Efficiency

Mechanic Efficiency

Thermodynamic Efficiency

Low NOₓ-Combustion as enabler

Indirect:

Conventional Powertrain

Electrified Powertrain

Downsizing

Downspeeding

Optimized DeNOx

¹) Optimized Conventional Combustion System
Future Potential of Conventional Combustion Engines

CO₂ Emissions (New PCs, EU15)

Small
[1250-1470 kg]

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂ [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>180</td>
</tr>
<tr>
<td>2000</td>
<td>160</td>
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<tr>
<td>2002</td>
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<td>2006</td>
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<tr>
<td>2008</td>
<td>80</td>
</tr>
<tr>
<td>2010</td>
<td>60</td>
</tr>
<tr>
<td>2012</td>
<td>40</td>
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</tbody>
</table>

Compact
[1470-1700 kg]

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂ [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>180</td>
</tr>
<tr>
<td>2000</td>
<td>160</td>
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<tr>
<td>2002</td>
<td>140</td>
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<td>2008</td>
<td>80</td>
</tr>
<tr>
<td>2010</td>
<td>60</td>
</tr>
<tr>
<td>2012</td>
<td>40</td>
</tr>
</tbody>
</table>

Medium
[1700-1810 kg]

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂ [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>220</td>
</tr>
<tr>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>2002</td>
<td>180</td>
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<tr>
<td>2004</td>
<td>160</td>
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<td>2006</td>
<td>140</td>
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<tr>
<td>2008</td>
<td>120</td>
</tr>
<tr>
<td>2010</td>
<td>100</td>
</tr>
<tr>
<td>2012</td>
<td>80</td>
</tr>
</tbody>
</table>

Upper Medium
[1810-1930 kg]

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂ [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>280</td>
</tr>
<tr>
<td>2000</td>
<td>260</td>
</tr>
<tr>
<td>2002</td>
<td>240</td>
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<td>2004</td>
<td>220</td>
</tr>
<tr>
<td>2006</td>
<td>200</td>
</tr>
<tr>
<td>2008</td>
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<td>160</td>
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<td>2012</td>
<td>140</td>
</tr>
</tbody>
</table>

Drastic gains achievable for both, Gasoline and Diesel technology

Source: Polk Marketing Systems

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Future Potential of Conventional Combustion Engines

CO₂ Emissions for Diesel & Gasoline Technologies

Compact Class, NEDC

Gasoline AND Clean Diesels provide potentials for further CO₂ reduction
## Evolution in Clean Diesel & Gasoline Technology

### Gasoline

<table>
<thead>
<tr>
<th>Pkg</th>
<th>Description</th>
<th>Displ. &amp; Torq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>G0</td>
<td>Port fuel injection (PFI)</td>
<td>2.0 l 200 Nm</td>
</tr>
<tr>
<td>G1</td>
<td>Direct injection (DI)&lt;sup&gt;1&lt;/sup&gt;, turbo, downsizing, start/stop&lt;sup&gt;3&lt;/sup&gt;, thermal management</td>
<td>1.4 l 210 Nm</td>
</tr>
<tr>
<td>G2</td>
<td>+ downsizing</td>
<td>1.1 l 200 Nm</td>
</tr>
<tr>
<td>G2H</td>
<td>+ hybrid&lt;sup&gt;2,5&lt;/sup&gt;</td>
<td>1.1 l 200+140 Nm</td>
</tr>
</tbody>
</table>

### Clean Diesel

<table>
<thead>
<tr>
<th>Pkg</th>
<th>Description</th>
<th>Displ. &amp; Torq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>Common rail system, turbo</td>
<td>2.0 l 340 Nm</td>
</tr>
<tr>
<td>D1</td>
<td>+ oCCS (opt. Combustion) + start/stop&lt;sup&gt;4&lt;/sup&gt; + thermal management&lt;sup&gt;7&lt;/sup&gt; + downsizing, + close PI</td>
<td>1.6 l 340 Nm</td>
</tr>
<tr>
<td>D2</td>
<td>+ NO&lt;sub&gt;x&lt;/sub&gt;-EGT</td>
<td>1.6 l 340 Nm</td>
</tr>
<tr>
<td>D3</td>
<td>+ downsizing</td>
<td>1.2 l 300 Nm</td>
</tr>
<tr>
<td>D3H</td>
<td>+ hybrid&lt;sup&gt;2,5&lt;/sup&gt;</td>
<td>1.2 l 300 + 140 Nm</td>
</tr>
</tbody>
</table>

**Medium class car (1 400 kg), 100 kW, MT5 (manual transmission), MVEG-cycle, EU6**

1) turbo-charged with downsizing and var. valve timing (VVT); 2) max. potential w/ downsizing, transmission optimization; 3) Start/Stop w/ recup., thermo management (ThM), Decos; 4) Start/Stop w/ recup., combustion optimization; 5) Battery 1.0 kWh; 6) ThM, down speeding, downsizing, T/C optimization; 7) CO<sub>2</sub> optimization; 8) VVL in 2-step, down speeding, downsizing; / costs 2014 / * Further Clean Diesel evolution steps D1 & D3 are not shown

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**Future Potential of Conventional Combustion Engines**

Medium class car (1 400 kg), 100 kW, MT5 (manual transmission), MVEG-cycle, EU6
Fuel Savings vs. Additional Component Costs

Premise: costs over 3 years at 15,000 km p.a., average fuel prices in Germany of 2006-2008: Diesel 1.20 €/l, Gasoline 1.33€/l

FE enhancement for Clean Diesels & Gasolines follows similar gradient
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Real American Driving Profile

Study based on GPS-monitored Californian mid-size sedan owners:

- Median Californian driving intensity is between highway and US06 cycles
Clean Diesel – Fuel Economy and Real-world Performance

Emissions follow real-world driving, not test cycles

cycle based calculation

real-world driving

Further potential of Clean Diesel with e.g. Start-Stop not even considered

Source: simulation based on Mercedes E-class, 1700kg, combustion 110kW, electrical 31kW, Li-Ion battery, 6-speed AT
Fuel Prices – Parallel Upwards Trend

EIA Diesel/Gasoline Price History and Forecast

Current (06/08/09) national average D/G = - 0.18 USD

Source: EIA

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Clean Diesel – Prevailing in Total Cost of Ownership (TCO)

Auction Results (Example Jetta TDI / Prius)

- **VW Jetta TDI**
- **Toyota Prius**

*Residual value [%]*

* Mileage [miles]*

- 5 year / 68k miles

* auction data from 2006 to Mid 2008

Source: Martec / Mannheim Auto Auction

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Clean Diesel – Prevailing in Total Cost of Ownership (TCO)

TCO example VW Jetta TDI

Fuel Price [USD] vs. Mileage [miles]

- Diesel = Gasoline - 25 ct
- Diesel = Gasoline
- Diesel = Gasoline + 25 ct

Current Price: 2.49 USD
Price delta: 0.18 USD

Break Even at 6500 miles/year

Source: Martec / Edmunds
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