The Past – Present – Future of Clean Diesel

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Powertrain Strategies for the 21st Century:
Facing the Challenge of Dramatic Fuel Economy Demands

reduced by Bosch

Diesel Systems
Conventional powertrains – Game over?

The Oil Party is nearly over

Crude Oil Extraction

Exa Joule/a

Year

0 500 1000 1500 2000 2500

0 50 100 150 200 250 300

Peak Oil
Beyond Oil

Odell
Medium Scenario
Campbell

Diesel Systems
Conventional powertrains – Game over ?

New powertrains: Estimated world market volumes

Internal Combustion Engines will remain the predominant power train for the near future

Diesel Systems
The Past – Present – Future of Clean Diesel

Agenda

The PAST of Clean Diesel

The PRESENT of Clean Diesel

The FUTURE of Clean Diesel
The Past – Present – Future of Clean Diesel

The PAST-PRESENT-FUTURE of Clean Diesel

- The first Diesel Engine, Paris World Exhibit
- Rudolf Diesel: “The use of vegetable oils for engine fuels might seem insignificant today, but such oils may become as important as the petroleum and coal tar products of the present.”
- First Trip in the US by a diesel-powered car (Packard Sedan with Cummins Engine) Indianapolis to New York, 800 miles for total cost of $1.38
- Oil Crisis 1970’s
- GM introduces as first North American OEM Diesel to the market accounting in 1981 for 10% of GM’s overall vehicle sales
- By mid-1980’s over 100 different diesel models to choose from: For OEM’s like Mercedes and Peugeot the sales of diesels accounted for up to 85% and Bosch introduced electronics to the fuel system
- Bosch revolutionizes the diesel Industry by introducing a Common Rail System. The market share in EUR for diesels accelerated from 1997 to 2007 from 20% to more than 50%, resulting in more than 50 million Systems sold by January 2009
- Mandated Ultra Low Sulfur Diesel in CA
- The New CLEAN Diesel get introduced - DIESEL no longer a dirty Word.
- Green Car of the Year 2 years in a row


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Consumer Consideration Index

Would you purchase a clean diesel?

- 2006: 13%
- 2007: 14%
- 2008: 17%
- 2009: 20%
- 2010: 23%
- Jan-11: 24%
- Feb-11: 25%
- Mar-11: 25%
- Apr-11: 28%
- May-11: 29%

Steady Increase in Consumer Consideration of Clean Diesel Technology

Source: CNW Research
Clean Diesel Technology achieved Take-Rate of > 30% in less than 2 years

Source: POLK Registration Data

Source: Polk

Bosch Diesel Systems
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Clean Diesel Launch Calendar

Clean Diesel Models will more than double within less than 3 years

Source: Bosch
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Alternative Powertrain Comparison


Diesel: 2,700 USD
Hybrid: 6,300 USD

12 PC/LD Models Average Take Rate: 30%

26 Models Average Take Rate: 5%*

*Not incl. hybrid/electric only vehicles e.g. Toyota Prius, Chevy Volt, etc.

Source: Polk / Edmunds

Clean Diesel Technology on par with other alternative Powertrains
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Total Cost of Ownership [TCO]

Clean Diesel offers TCO benefits (payback) in less than 18 months

Source: Carnegie Mellon University
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Powertrain diversification for Today and the Future

Variety of Technical solution needed to address energy reduction
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Strategies for T2B2/SULEV: Enhanced EGT

Available vehicles already signific. below T2B5, measures for achieving T2B2 defined

Tier2Bin5
Full useful life

Current Tier2Bin5 applications w/ Bosch Common Rail

Tier2Bin5 Base:
EU5/6 Low NOx-Combustion+ Efficient DeNOx

Full System Approach Required

Diesel Systems

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Optimizing the Diesel System

**Combustion Process**
- Reduction of compression ratio
- Partly homogenous combustion

**Fuel Injection System**
- New Generations
- Multiple Injections
- Reduced Tolerance
- Optimized Nozzle

**Tolerance Reduction**
- Zero Fuel Calibration
- Fuel Balancing Control
- Individual Cylinder Control

**Air Management**
- Swirl-/Throttle Valve
- Turbo Charger/VTG

**Exhaust gas management**
- Fast Catalyst Light-Off (reduce thermal losses)
- Diesel Particulate Filter
- NOx storage catalyst
- Catalyst temp control
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System Approaches for FTP SULEV compliance

1. **AdBlue Dosing**
   - Improved series technology
   - Needs enhanced heat up, FE ↓, GHG ↑

2. **AdBlue Dosing**
   - Add HC and NO\textsubscript{x} buffer for low temperature
   - Complex control strategy required

3. **HC Dosing**
   - Promises good low temperature efficiency
   - Performance depends only on thermal critical NSC (LNT)

4. **AdBlue Dosing**
   - Promises robustness and high efficiency
   - Complex and expensive

Different approaches are investigated to identify the best solution
Close-coupled SCR yields to a significant improvement in NOx conversion due to higher SCR temperatures.
Strategies for T2B2/SULEV: Current Status

Results of Bosch SULEV Study (9.2010)

- SULEV target met w/ degreened (low mileage) components
- After (thermal) life time aging: failed
  - Thermal stress (high temperature due to DPF regeneration & desulphurization) causes aging of catalysts

Improvements required:
More thermally stable catalyst and more precise temperature control
Strategies for “EU7” & T2B2: “Anti-Aging Package”

Target
Prevention of Thermal Degradation during Heating & De-Sulphurization

ENABLER

BOSCH "Anti-Aging Function Package"

1. **Predictive Temp. Control**
   - model based temp. calculation inside NSC during rich mode
   - Triggers & interrupts rich mode during de-sulphurization

2. **Adaptive Heating Control**
   - model based temp. calculation inside NSC during lean mode
   - Limits temperature inside NSC during heating mode (e.g. DPF heating)
   - Compensates tolerances & drifts
Dynamic SCR Catalyst Performance

**Vehicle:**
- 3.750 lbs

**Engine:**
- EURO5-compliant base engine
- “optimized conventional combustion system”
- 2.2 l 4-cylinder
- 110 kW @ 4.000rpm

**Exhaust System:**
- close-coupled DOC + cDPF
- SCR catalyst under floor
- Exhaust gas treatment de-greened, not aged

Average NOx Conversion over US06: 85%

Future improvements may limit but will not completely avoid drop downs

⇒ Steady state conversion will not be achieved over the entire cycle!
The Hybrid: Not only a Gasoline Alternative

**Fuel Consumption in g/kWh**

- **BMEP [bar]**
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12
  - 14
  - 16
  - 18
  - 20
  - 22

- **Engine Speed [rpm]**
  - 1000
  - 2000
  - 3000
  - 4000

**eHybrid Drive Advantage**

- **NOx**
  - High
  - Low

- **CO**
  - Low

- **HC**
  - Low

- **Soot**
  - High

**The Hybrid: Not only a Gasoline Alternative**

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The Hybrid: Not only a Gasoline Alternative

Split Test:
Battery balance is also forced at the end of UDC

Vehicle Speed

CO₂ emission reduction by combining urban with extra urban driving

* Basis: CO₂ Emission in g of Conventional Vehicle in NEDC
The Hybrid: Not only a Gasoline Alternative

Basis: CO₂ Emission in g/km of Conventional Vehicle* in NEDC

<table>
<thead>
<tr>
<th></th>
<th>CO₂ Emission (per cent of conventional*)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional Vehicle</strong></td>
<td>120%</td>
</tr>
<tr>
<td><strong>NEDC</strong></td>
<td>100%</td>
</tr>
<tr>
<td><strong>UDC</strong></td>
<td>90%</td>
</tr>
<tr>
<td><strong>EUDC</strong></td>
<td>80%</td>
</tr>
<tr>
<td><strong>HEV – Full Test</strong></td>
<td>75%</td>
</tr>
<tr>
<td><strong>NEDC</strong></td>
<td>60%</td>
</tr>
<tr>
<td><strong>UDC</strong></td>
<td>50%</td>
</tr>
<tr>
<td><strong>EUDC</strong></td>
<td>40%</td>
</tr>
<tr>
<td><strong>HEV – Split Test</strong></td>
<td>35%</td>
</tr>
</tbody>
</table>

*Conventional Vehicle: 1470 kg IW, 1.6 l Diesel Engine, Euro 5; HEV: 1590 kg IW, 1.6 l Diesel Engine + 25 kW E-Motor

Reduced CO₂ emission difference between urban and extra urban driving with hybrid

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Clean Diesel Greenhouse Gas Reduction Potential

- **Downsizing and -speeding** - enabled by optimized CCS *
- DeNOx
- Extreme downsizing

**CO₂ reduction**

- 2-3%
- 4-5%
- 1-2%
- 1%
- 2-4%
- 9-11%
- 22%
- 24%
- 29%

- **oCCS** – Package
- **DeNOx**
- **Extreme Downsizing to 4-cyl.**

**COMMENTS**

- %-value is reduction potential for stand-alone measures.
- “optimized CCS” - Package: engine (+ mgmt.) meas. for low NOₓ combustion
- DeNOx–Package: Active DeNOX-system (NSC NOx-trap or Sel. Catalytic Reduction).

Significant Potential in Greenhouse Gas reduction expected from Clean Diesel

- 22%
- 24%
- 5%
- 29%

SUV w/ 4605 lbs, Basis: 200 kW DI-Diesel, 700 Nm

* CCS= Conventional Combustion System | ** ThM= Thermal management | *** St/St= Start/Stop System
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Clean Diesel Greenhouse Gas Reduction Potential

Significant Potential in Greenhouse Gas reduction expected from Clean Diesel

Source: EIA report based on GREET model

*estimated based on Bosch internal simulations
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Summary

- Clean Diesel well accepted by Consumers due to clear benefits
- Clean Diesel shows potential to meet future emission regulation
- Clean Diesel offers additional potential for GHG reduction
- Clean Diesel an Economical solution for Today and Tomorrow