Clean Diesel – Real Life Fuel Economy

Alexander Freitag - Robert Bosch LLC
CO2 Reduction and Energy Challenge

Agenda

1. The Challenge
2. Legislation
3. Current Status
4. The Diesel Advantage
5. Further CO₂ Reduction Potential
6. Summary
Global Warming & Lack of Resources

Global Warming increase

Oil production rising w/o new oil fields ⇒ lack of resources

Fuel Economy Improvement / CO₂-Emissions reduction
Offer technologies to support CO₂-reductive comportment
CO2 Reduction and Energy Challenge

U.S. Greenhouse Gas Emissions by Sector

- **Transportation:** 28%
- **Electricity:** 33%
- **Industry:** 19%
- **Agriculture, Commercial, and Residential:** 20%
- **Other:** 2%
- **Aircraft:** 10%
- **Buses:** 1%
- **Other Trucks:** 20%
- **Ships and Boats:** 3%
- **Locomotives:** 3%
- **Passenger Cars:** 33%
- **Light-Duty Trucks:** 29%

Source: AIAM 2005
CO2 Reduction and Energy Challenge

Fuel Economy / CO2 Challenge

- ACEA-Selbstverpflichtung 2008: 140g/km (-25%)

Renewable Fuels

Resources

CO2 / Fuel Economy

Pollution (HC, CO, NOx, Particulates)

Power / Comfort


BOSCH Innovations
NAFTA Fuel Price Trend

Fuel prices have Doubled in 4 years!

Diesel Systems

Source: EIA 04-09-07
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Legislation & Commitments

<table>
<thead>
<tr>
<th>EU</th>
<th>CAFE</th>
<th>CARB</th>
<th>CHINA</th>
<th>JAPAN</th>
</tr>
</thead>
</table>

**CAFE** = Corporate Average Fuel Economy  
**PC** = Passenger Cars, **LT** / **LDT** = Light Trucks (pick-ups, vans, SUVs), **MD(P)V** = Medium Duty (Passenger) Vehicles  
**GHG** = Greenhouse Gases  
**NHTSA** = National Highway Transportation and Safety Administration  
**CARB** = California Air Resources Board  
**mpg** = miles per gallon  
**China weight based limits (here for 1,09 tons curb weight)**  
**CAFE data NHTSA report October 2006**  
**EU data for ACEA (Association des Constructeurs Européens d'Automobiles) 6th EU Report 24.8.2006, for MY05 from T&E 2006**

**National Fuel Efficiency Policy**  
average CAFE 35.5 mpg PC & LT

**CARB GHG LDT2/MDPV**  
**CARB GHG PC/LDT1**  
**Japan fuel consumption PC average**  
**CARB/ZEV obligate large vol. OEM from 2012 E-Vehicles**

**Diesel Systems**
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Government Demand for Increased Fuel Economy

• National Fuel Efficiency Policy
  ➔ Released by President Obama on May 19, 2009
  ➔ Requires a national average fuel economy of 35.5 mpg (14.9 km/l) by 2016
  ➔ Regulation for MY2011 published
  ➔ California has agreed to defer to national standards beginning in 2012

![Graph showing GHG emissions for different years and types of vehicles, with bars for Car, Truck, and Average.](image)
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Emission and CO₂ Strategy

Development of CO₂ Emissions (New PCs, EU15)

- Gasoline Powertrain is catching up since 2004
- Sustainable effort required for further reduction of Diesel fleet CO₂

Data: 15 EU countries, Source: CR

PC = Passenger Car

Gasoline: 162.6 g/km
Diesel: 156.5 g/km
EU target: 120 g/km

SUV-impact to be carried by Diesel only

ACEA commitment 140 g/km

130 g/km complementary measures

-18.4%
Emission and CO₂ Strategy

EU15- Total Vehicle Registrations (PC)

SUV impact (increasing Gross Vehicle Weight 2004ff) hits mainly Diesel

⇒ Root cause for increase of Diesel CO₂ emissions 2004 ff.

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[Source: Polk Marketing Systems]
Emission and CO₂ Strategy

Development of CO₂ Emissions (New PCs, EU15)

Small
[1250-1470 kg]

Gasoline
Diesel

CO₂ [g/km]


Intro of DI-Diesel

appr. 30 g/km

Compact
[1470-1700 kg]

Golf V 1.6 FSI (75 kW)
Golf VI 1.4 TSI (77 kW)

SUV-impact

Upper Medium
[1810-1930 kg]

Golf VI 1.6 TDI Blue Motion (77 kW)

Also in future, Diesels will contribute to a significant CO₂ reduction in all classes!

Diesel Systems

Also in future, Diesels will contribute to a significant CO₂ reduction in all classes!

Source: Polk Marketing Systems
CO2 status versus requirements

Classification by vehicle footprint – Industry

-29% -13%

-30% -12%

-26%

-31% -28%

CO2 targets calculated from latest Fuel Economy Policy May 2009

vehicle data: US market 2008
bubble size represents segment volume
number in bubbles indicate individual CO2 reduction target

Diesel Systems
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Clean Diesel – Fuel Economy and Real-world Performance

Clean Diesel – clean CO2 reduction potential for the U.S. available *today*

-33% fuel consumption,
-25% CO2

*PFI = port-fuel injection gasoline engine

Data Source: Kraftfahr-Bundesamt (KBA) 03.2007

NOx+HC

-90%*

PM

-98%*

* T2B5/LEVII compared to LEV0 in 1985

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EU5 / EU6 emission strategies and CO2 reduction potential

DI Diesel engine passenger cars certification

Data Source: Kraftfahrt-Bundesamt (KBA) 12/2005

**) Tier 2, Bin 5 (Half/Full: 5 years, 50,000mi / 10 years, 120,000mi)
Catalyst with Denoxtronic – for low NOx emissions

- SCR (Selective Catalytic Reduction) reduces NO\textsubscript{x} emissions w/o increasing fuel consumption.
- A reduction agent is sprayed into the exhaust gas stream.
- With Bosch Denoxtronic, NO\textsubscript{x} emissions are reduced by about 85%.

Reduction agent NH\textsubscript{3} and NO\textsubscript{x} are converted into water and nitrogen.
Clean Diesel – Fuel Economy and Real-world Performance

Optimizing the Diesel System

Combustion Process
- Reduction of compression ratio
- Partly homogenous combustion

Air Management
- Swirl-/Throttle Valve
- Turbo Charger/VTG
- EGR coolers
- Advanced Intercoolers

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

Tolerance Reduction
- Zero Fuel Calibration
- Fuel Balancing Control
- Individual Cylinder Control
- Model Based Functions

Exhaust gas management
- $\lambda$-Control
- Diesel Particulate Filter
- $\text{NO}_x$ Reduction

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Clean Diesel – Fuel Economy and Real-world Performance

Bosch Injection Systems – Evolution of Pressure

Nozzle pressure
bar
2500
2000
1500
1000
500
0

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Clean Diesel – Fuel Economy and Real-world Performance

Roadmap CRS for PC

Piezo-valve CR System

- CRS Premium line
  - CRS5.2 2400 bar
  - CRS5.1 2200 bar
- CRS Top line
  - CRS3.3 2000 bar
  - CRS3.2 1800 bar
  - CRS3.0 1600 bar

Solenoid-valve CR System

- CRS High line
  - CRS2.6 2000 bar
  - CRS2.5 1800 bar
- CRS Mid line
  - CRS2.2 1600, CRS2.0 1450 bar
  - CRS1.3 1400 bar
  - CRS1.2 1400 bar
  - CRS1.1 1450 bar
- CRS Base line

Clean Diesel – Fuel Economy and Real-world Performance

Efficient emission reduction is a combined effort

- **NO\textsubscript{X}** reduction
- Noise reduction

- **boost pressure**
- **p\textsubscript{rail}**

Enhanced boost pressure leverages higher rail pressures @ part load

*1590kg vehicle; FC=6l/100km*
Clean Diesel – Fuel Economy and Real-world Performance

Current US Diesel Vehicles meeting LEVII:

- Daimler M/R 0.03/0.03 (SCR)
- Daimler GL 0.04/0.04 (SCR)
- Audi Q7/Touareg 0.04/0.05 (SCR)
- BMW X5 0.03/0.03 (SCR)
- BMW 3series 0.04/0.04 (SCR)
- VW Jetta 0.04/0.05 (LNT)

Current US Diesel Vehicles meeting LEVII: Clean Diesel – Fuel Economy and Real-world Performance

Diesel Systems
Real American Driving Profile

New study based on GPS-monitored CA mid-size sedan owners:
- Median CA driving intensity is between highway and US06 cycles.
Emissions follow real-world driving, not test cycles

Clean Diesel – Fuel Economy and Real-world Performance

- CAFÉ is 55% city, 45% highway
- EPA five cycle is 43% city, 57% highway
- tax incentives are 100% city
- Energy intensity of real-world driving profile in average is comparable to highway cycle and beyond

Emissions follow real-world driving, not test cycles

Cycle based calculation vs. 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
Diesel-Hybrid: The Combination of Strength

- **European test cycle (NEDC)**
- **City part of test cycle (ECE)**
- **Out-of-city-part of test cycle (EUDC)**

**Fuel consumption [l/100km]**

- **Toyota Prius II**
  - Hybrid domain due to dynamic driving cycle
  - Diesel domain due to efficient combustion engine

- **Citroën C4 HDI**

**Inertia mass [kg]**

- **Diesel-Hybrid: The Combination of Strength**

Diesel-Hybrid: The Combination of Strength

Diesel hybrid domain due to dynamic driving cycle and efficient combustion engine.
Clean Diesel – The Diesel Advantage

Residual Value Comparison

Summary

1. Diesel achieving a 20% higher residual value than hybrid
2. Residual value is the most influencing factor in TCO
3. Jetta TDI already at 7500 miles/year an attractive solution

Factors for Total Cost of Ownership

Model
Sale Price Assumed
Depreciation
Taxes/Fees
Maintenence
Repairs
Insurance
Financing
Fixed Cost

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

Driving Distance [miles]
Fuel Price [USD]

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**CO2 Reduction and Energy Challenge**

**Energy Consumption in the Vehicle**

1. **Combustion Engine Optimization**
2. **Demand-Responsive Energy Mgmt.**
3. **Start/Stop, Hybrid, Electric Traction**
4. **Components Optimization**

**Losses of Drive**
- Idling losses 10%
- Mechanical work 15% - 20%

**Losses of Drivetrain**
- Thermal losses 70% - 75%
- Exhaust gas losses
- Idling losses

**Braking**
- Cooling system, Radiation
- Aerodynamic resistance
- Rolling resistance

**Waste Heat Recovery**
**Reduction of Resistances**
**Alternative Fuels**
**Influencing Driving Behaviour**
Survey of Measures (1/3)

1. Combustion engine optimization / Powertrain Optimization

- Gasoline direct injection
- Charging + downsizing
- Cylinder deactivation
- Variable valve actuation
- Mixture formation
- Variable compression ratio
- Controlled auto ignition (HCCI)

- Improved injection system
- Charge air optimization
- Downsizing
- Exhaust gas treatment to improve trade-off between consumption and pollutant emissions

- EGR w/ port deactivation
- Favorable operating points of combustion engine by additional gears or continuously variable transmission
- Optimized shift points (i.e. gear ratios, “down-speeding”) based on engine optimization
- Automatic transmission controls

Specific: gasoline / diesel

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## CO2 Reduction and Energy Challenge

### Survey of Measures (2/3)

<table>
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<tr>
<th>Measure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2</strong> demand-responsive energy management</td>
<td></td>
</tr>
<tr>
<td>➔ demand controlled electric cooling fan</td>
<td>➔ demand-responsive air conditioning</td>
</tr>
<tr>
<td>➔ thermal management coolant control valve</td>
<td>➔ demand-controlled fuel pump</td>
</tr>
<tr>
<td>➔ electric water pump</td>
<td>➔ climate control sensor</td>
</tr>
<tr>
<td>➔ electric oil pump</td>
<td></td>
</tr>
<tr>
<td>➔ electric power steering</td>
<td></td>
</tr>
<tr>
<td>➔ electronic battery sensing</td>
<td></td>
</tr>
<tr>
<td><strong>3</strong> start/stop, hybrid, electric vehicles</td>
<td></td>
</tr>
<tr>
<td>➔ start/stop</td>
<td>➔ regenerative braking</td>
</tr>
<tr>
<td>➔ hybrid drive</td>
<td>➔ electric vehicle / battery</td>
</tr>
<tr>
<td>➔ fuel cell</td>
<td></td>
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</tbody>
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### Survey of Measures (3/3)

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<th>Components Optimization</th>
<th>Reduction of Resistances</th>
<th>Alternative Fuels</th>
<th>Influencing Driving Behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>- high efficient generator</td>
<td>- weight reduction</td>
<td>- hydrogen</td>
<td>- gear shift indication</td>
</tr>
<tr>
<td>- efficient air conditioning</td>
<td>- low aerodynamic drag coefficient/reduced frontal area</td>
<td>- biofuels</td>
<td>- dynamic navigation system</td>
</tr>
<tr>
<td>- reduction of gearbox losses</td>
<td>- tires with low rolling resistance</td>
<td>- compressed natural gas</td>
<td>- car to X communication</td>
</tr>
<tr>
<td><strong>Waste Heat Recovery</strong></td>
<td>- reduced residual brake torque</td>
<td>- adaptive cruise control</td>
<td>- tire pressure monitoring</td>
</tr>
<tr>
<td>- heat exchanger</td>
<td>- friction reduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- thermoelectric generator</td>
<td>- radiator shutters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- latent heat storage</td>
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</tbody>
</table>
Advanced Clean Diesel

- Downsizing (2.2l to 1.6l)
- Turbo Charger Optimization: 1%
- Start/Stop w/ energy mgmt: 5%
- Thermo-Management: 1%
- Friction Reduction: 1%
- Combined w/ Downsampling: 2%

Overall further potential of up to 20% fuel consumption reduction
Fuel economy / technology costs: today’s landscape
CO2 Reduction and Energy Challenge

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Clean Diesel – Fuel Economy and Real-world Performance

• Diesel is **good**: less consumption, less CO2, less fuel costs, best adapted to real-world driving conditions, higher resale value

• Diesel is **clean**: meeting the tightest emission rules

• Diesel is **fun**: 50% higher torque

• For most consumers, Diesel is **most economical** and available **today**
Thank You

Alexander Freitag - Robert Bosch LLC