“A Systems Approach to Meet Tier 2 Bin 5”

ERC - 2005 Symposium
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Overview
1. Introduction
2. Current Market Situation
3. Emission Requirements
4. Potential Approaches and Technologies
5. Initial Demonstrator Results
6. Summary
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Evolution of Specific Power

![Graph showing the evolution of specific power over model years from 1930 to 2010.](image)

Published Values
Future HSDI Diesel Engines

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Gas Mileage vs. Vehicle Weight

![Graph showing gas mileage vs. vehicle weight.](image)

Gasoline Vehicles
DI Diesel Vehicles
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### Performance Comparison

<table>
<thead>
<tr>
<th></th>
<th>Diesel</th>
<th>Gasoline</th>
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</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>160 kW</td>
<td>170 kW</td>
</tr>
<tr>
<td>Max. Velocity</td>
<td>235 km/h</td>
<td>237 km/h</td>
</tr>
<tr>
<td>Acceleration (0-62 mph)</td>
<td>8.6 s</td>
<td>8.4 s</td>
</tr>
<tr>
<td>Fuel Consumption</td>
<td>9.8 L/100km</td>
<td>13.2 L/100km</td>
</tr>
<tr>
<td>Vehicle Sales Price</td>
<td>59.500 €</td>
<td>61.500 €</td>
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Source: „ADAC“ 2005

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Current Market Situation

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U.S. Federal Emissions Legislation (Tier 2)

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Combustion System Interdependencies

- Fuel Injection System
- Peak Pressures
- EGR System
- Compression Ratio
- Combustion System
- Turbocharging
- Nozzle/Bowl Design
- Charge Air Motion
- Intercooling

EGR-System Requirements

- Fast response of EGR-valve
- Repeatable and accurate positioning of EGR-valve
- Closed loop operation
- Low variability of re-circulation rate among individual cylinders (equal distribution)
- Efficient exhaust gas cooling (high heat flux)
- Low exhaust gas cooler performance deterioration due to deposits
- Compact, light-weight design
- Corrosion-free materials
- Low cost
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Turbocharging/Intake Air Management (BMW)

- Below 1800 rpm, only small turbo works (vehicle launch)
- Between 1800-3000 rpm both turbos work; open air and exhaust flap
- Beyond 3000 rpm, only the large turbo supplies fresh charge

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(Inter-) Cooling

- Audi 3.0L V6
- VW 1.9L TDI
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Charge Air Motion and Nozzle/Bowl Design

Basic Engine Data:
- General Engine Data (e.g. Stroke, Bore, CR, Bowl Geometry, Inj. Nozzle Layout, Valve Timing, Intake Swirl vs. Valve Lift etc.)
- Thermodynamic Measurement Data (e.g. Cyl. Press. vs. CA, Inj. Press. vs. CA, Air Flow, Fuel Flow, Torque, Speed, etc.)

EPOS
(1-Cylinder Process Simulation)

Output:
- Cyl. Pressure
- Cyl. Temperature

KOMA
(Combustion Bowl and Nozzle Layout)

Geometrical Injection Spray Distribution

Verification with New Engine Data (e.g. Torque, Power Output, Intake Swirl, CR, Inj. Timing, Inj. Pressure, Boost Pressure, etc.)

DESAS
(Diesel Injection Spray Deflection Simulation)

Modification of Bowl / Nozzle Layout if Necessary.

Engine Testing with New Combustion System Layout

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Performance Development History

- $P_{max} \leq 135$ bar
- $P_{max} \leq 150$ bar
- $P_{max} > 150$ bar

$P_{max} = 150...200$ bar
eventually up to 220 bar,
according to emission legislation

specific power [kW/l]

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<td>IDI Engines</td>
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Combustion System Approaches

- New Combustion System
  - Chamber Geometry
  - Charge Density + Motion
  - Advanced Control
  - Injection Strategy

Conventional Swirl-Assisted Combustion System

T I M E

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Tier 2 Bin 5 Combustion System Development

- Combustion System
- Controls & Strategies
- Tier 2 Bin 5 Vehicle
- Fuel Injection System
- EGR System
- Boost System
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Tier 2 Bin 5 Emissions Control System Development

- Rapid Warm-Up
- Controls & Strategies
- Tier 2 Bin 5 Vehicle
- Lean/Rich Modulation
- Filter Regeneration
- Sulfur Removal

**Rapid Warm-Up**

- Engine Speed [rpm]
  - 1000
  - 1500
  - 2000
  - 2500
  - 3000
- Temperatures [°C]
  - 0
  - 100
  - 200
  - 300
  - 400
  - 500
  - 600
  - 700
- Time [s]
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
  - 70
  - 80
  - 90
  - 100
  - 110
  - 120

**Vehicle Speed [mph]**
- 0
- 20
- 40
- 60

- Final Rapid Warm-Up Calibration
- No Intervention
- Retarded Begin of Injection
- Throttled Intake Manifold Pressure
- Upstream PreCatalyst
- Downstream PreCatalyst
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Lean/Rich Modulation

Engine Speed = 2261 rpm
Load = 8.04 bar BMEP
BOI Post Injection -45 °CA
Rail Pressure During Rich Phase = 1050 bar
Rail Pressure During Rich Phase = 1200 bar
Rail Pressure During Rich Phase = 1400 bar

Sulfur Removal (Desulfurization)

1st Stage:
- Throttle to Lambda 1.1

2nd Stage:
- Apply Post Injection
  Lambda control between 0.97 and 0.98

3rd Stage:
- Disable Post Injection

4th Stage:
- Dethrottle after 5-10 seconds waiting period
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Filter (DPF) Regeneration

- DPF Temperatures
- Differential Pressure across DPF
- Exhaust Flow and Oxygen Level

Start of DPF regeneration intervention

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**Engine Specification**
- **Arrangement:** In-Line 4-Cylinder
- **Displacement:** 1.9 L
- **Rated Power:** 100 kW @ 4000 rpm
- **Max. Torque:** 330 Nm @ 2000 rpm
- **Bore/Stroke:** 79.5/95.5 mm

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APBF-DEC Light-Duty Vehicle Demonstrator

**ECS-A:** DOC + NAC
- **Cell Density:** 400 cpsi
- **Volume:** 1.34 L
- **Diameter:** 4.16 inch
- **Length:** 6 inch
- **Wall thickness:** 4.5 mil

**ECS-B:** NAC
- **Cell Density:** 400 cpsi
- **Volume:** 1.34 L
- **Diameter:** 4.16 inch
- **Length:** 6 inch
- **Wall thickness:** 4.5 mil

**All ECS:** CDPF
- **Cell Density:** 200 cpsi
- **Substrate Material:** SiC
- **Volume:** 2.5 L
- **Diameter:** 5.66 inch
- **Length:** 6 inch
- **Cell Geometry:** Square

**State-of-the-art ECU**
ETAS ASCET-SD® ES1000
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Summary

- Current market situation and requirements make the diesel engine an attractive solution.
- Discussions about CO₂ limitations, CAFE, independence on foreign oil, and fossil fuel preservation strengthen the position of the diesel engine.
- Technologies developed show high potential to allow competitive reintroduction of diesel engines into U.S. market.

Meeting Tier 2 Bin 5 is a systems approach!