Integrated Powertrain and Vehicle Technologies for Fuel Efficiency Improvement and CO₂ Reduction

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Outline

• Historical fuel efficiency trends
• Contribution of DOE projects
• Changing regulatory environment
• Engine and vehicle fuel efficiency technologies
  • In production
  • In development
  • In concept phase
• Summary
Engine Development Challenges

Regulations:
Emissions, Noise, Diagnostics

Technical constraints:
• Material limits
• Heat rejection
• Controller speed and bandwidth
• Weight

Economic constraints:
• Initial cost
• Cost of ownership
• Development costs

Customer requirements:
Fuel economy, Performance, Durability
On-Highway Emission Regulations

- **NOx**
  - 1994: 5.0 g/hp-hr
  - 1998: 4.0 g/hp-hr
  - 2002: 2.5 g/hp-hr
  - 2007: 1.2 g/hp-hr
  - 2010: <0.1 g/hp-hr

- **PM**
  - 1994: 500 PPM
  - 1998: 500 PPM
  - 2002: 200 PPM
  - 2007: 15 PPM
  - 2010: <0.015 PPM

- **Sulfur**
  - 1994: 20%
  - 1998: 38%
  - 2002: 52%
  - 2007: 83%
  - 2010: 90%
Thermal Efficiency Trends – Heavy-Duty Diesels

Based on Lysinger, DEER 2006; updated
## Contribution of DOE Projects

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Funding Sources</th>
<th>Engine</th>
<th>Start of production</th>
<th>BSFC improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VGT control</td>
<td>Increase EGR rate and controllability; transient improvement</td>
<td>NZ-50/DELTA</td>
<td>Series 60</td>
<td>2002</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>EGR cooler</td>
<td>Reduce pressure drop, increase heat transfer, reduce fouling</td>
<td>NZ-50</td>
<td>Series 60</td>
<td>2004</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>Virtual EGR Controller</td>
<td>Reduce hardware cost, improve control robustness</td>
<td>NZ-50/LEADER</td>
<td>Series 60</td>
<td>2007</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>DOC/DPF</td>
<td>Reduce regeneration frequency, pressure drop, and failure rate</td>
<td>LEADER/DELTA</td>
<td>Series 60, DD15</td>
<td>2007</td>
<td>2 - 2.5</td>
</tr>
<tr>
<td>Dual solenoid injectors/cam</td>
<td>Reduce parastic loss; higher injection pressure at lower speeds and loads</td>
<td>Smart Materials / NZ-50</td>
<td>Series 60</td>
<td>2007</td>
<td>1.5 - 2</td>
</tr>
<tr>
<td>Advanced combustion and piston design</td>
<td>Reduce emissions at low loads and improve BSFC</td>
<td>NZ-50</td>
<td>Series 60</td>
<td>2007</td>
<td>1 - 1.5</td>
</tr>
</tbody>
</table>

### Notes:
1. Commercial spin-off conducted as separate industry funded projects
2. BSFC improvements from individual technologies are not additive
Contribution of DOE Projects (Continued)
Changing Regulatory Environment

• NOx and PM are at near-zero levels
  • Government leadership on regulation
  • Engine manufacturers investment
  • End-user costs
• On-board diagnostics (OBD)
• Fuel efficiency and CO₂
  • Various agencies involved
  • Timing, content not yet clear
  • May potentially complicate DOE-Industry cooperation on technology development
• Increased importance of engine/powertrain/vehicle integration
Technologies for Heavy-Duty On-Highway Diesel Engines and Vehicles

- In production
  - Turbocompounding
  - Predictive cruise control
  - SCR (few months away)

- In development
  - Model based controls
  - Aerodynamic enhancements

- Concept phase
  - Waste heat recovery
  - Hybridization
Engine Turbocompound

**Measure**
Turbocompound

**Mode of operation**
All time

**Potential**
≈ 3 % Fuel

**Status**
In production

**Limitations**
Turbo compound achieves high efficiency primarily at high torque. Limited effectiveness at low torque.
Predictive Cruise Control

- Enables the truck to “see” the road that lies ahead
  - Uses on-board GPS and 3D digital maps
  - Contains high precision slope data for over 200,000 highway miles in 48 states
  - ‘Sees’ upcoming hills up to 2 kilometers ahead
- Enables vehicle systems to be optimized for fuel economy
Engine Calibration Management

Measure
Optimize combustion strategy off-board by leveraging fuel injection rate shape, multiple injection events, increased injection pressure, and corresponding adjustments in air/EGR management, within design and regulatory constraints.

Mode of operation
All times.

Potential
~ 1%-4% fuel economy potential depending on range of engine/vehicle duty cycle.

Status
In use today for development and release of today’s product. More comprehensive tool suites and applications in future.
Engine Thermatic Oil Cooler

**Measure**
Thermatic control of oil temperature

**Mode of operation**
Active thermostat control to keep oil temperature at 110°C.

**Potential**
≈ 1.5 % average – more in cold weather.

**Status**
In production
Engine Aftertreatment

Measure
NOx aftertreatment enables combustion optimization to yield improved isfc
Substrates, canning designed for minimal back-pressure (reduced pumping work)
Optimized combustion to yield low engine-out PM and increased regeneration intervals

Mode of operation
All times

Potential
3-4% demonstrated in truck tests

Status
Product launch in January, 2010
Next Generation On-Board Controller

Measure
Next Generation Controller (NGC) consisting of Engine / ATS integrated forward and inverse controllers, including on-board real time optimizers and engine models, continuously operating within applicable design and regulatory constraints, and learned customer application patterns.

Mode of operation
All times.

Potential
~ 1% - 4% fuel economy potential.

Status
Development phase
Technologies In Development
Aerodynamic Enhancement Package

**Measure**
Developments are underway to improve tractor and trailer aerodynamics by reducing crosswind sensitivity, matching roof profiles commonly requested 5th wheel heights, and other minor enhancements.

**Mode of operation**
Effective during freeway operation, and in particular when crosswinds are present.

**Potential**
\[ \geq 2.5\% \], result is a function of vehicle specification and ambient conditions. Confirmed in fuel economy and wind tunnel tests.

**Status**
In development
Variable Fuel, Air, and EGR Management

**Measure**
Enhanced in-cylinder combustion efficiency /emission management via variable geometry fuel, air, and EGR hardware. Integrated and optimized to final ATS and vehicle configuration.

**Mode of operation**
All times.

**Potential**
~ 1%-4% fuel economy potential depending on range of operating application.

**Status**
Development phase
Real Time Combustion Control

**Measure**
Incorporate Start-Of-Combustion sensors in individual cylinders and use this signal for closed-loop combustion control

**Mode of operation**
All times.

**Potential**
~ 1% - 4% fuel economy potential.

**Status**
Concept phase

Courtesy: Woodward
Waste Heat Recovery

Measure
Energy recovery from various sources, i.e. engine exhaust, EGR, engine coolant.

Mode of operation
All times – with warmed up engine.

Potential
~ 2-8% fuel economy potential depending on system used and transfer of power. Most likely scenario is in combination with hybrid.

Status
Concept phase

Courtesy: Daimler Trucks
Innovation Truck

Aerodynamics
- Aero Roof Deflector
- Side View Camera
- Aero Side Extenders
- Rear Wheel Fairings
- Integrated Underbody Panel
- Aero Side Skirts
- Bumper Overlay

Mechantronics
- Hirschmann Antenna
- 7700 Integrated System
- Enhanced Stability Control
- Predictive Aux Load Mgmt

Chassis
- 6x2 Axle Configuration
- Freightliner Front Air Suspension
- Dual Ride Height
- SmartTire TPMS
- EPA10 Compliant

Power Systems
- SmarTire TPMS
- EPA10 Compliant
- SmarTire TPMS
- EPA10 Compliant
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Lessons of the Last Decade

• Meeting the most stringent emission standards in the world (EPA2002, EPA2007, EPA2010) required the strength of global organizations

• EPA2002 emission regulation was associated with a significant drop in engine thermal efficiency

• DOE support of R&D program helped avoid further efficiency drop in 2007

• EPA2010 will lead to simultaneous improvements in emissions and fuel efficiency for most manufacturers
Preparing for the Future

• Emphasis is shifting to fuel efficiency and CO₂
• Vehicle level regulatory targets are likely
  • Growing importance of engine/powertrain/vehicle integration
• Regulatory-driven and customer-driven technology development will now move in the same direction
• DOE support in evaluating high risk, high reward technologies is critical