Heavy Truck Engine Development & HECC
DE-FC05-00OR22805

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DOE Merit Review

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This presentation does not contain any proprietary or confidential information
Outline

- Purpose of Work
- Responses to Previous Year Reviewers’ Comments
- Approach
- Performance Measures and Accomplishments
- Barriers/Challenges
- Collaborations/Interactions
- Publications/Patents
- Future plan
- Summary
Purpose of Work

Explore advancements in engine combustion systems using high-efficiency clean combustion (HECC) techniques to minimize cylinder-out emissions while optimizing engine fuel economy.

- Emphasis on Enabling Sub-system Technologies
  - Advanced combustion system technologies
  - Flexible, precise fuel injection
  - Air and EGR system technologies
  - Advanced multiple input multiple output control technologies
Response to Reviewer’s Comments

- Technology transfer/collaborations with industry/universities/other labs.
  - Review comments:
    - “Generally agreed that no major collaborations were mentioned. No collaborations were described in the presentation.”
  - Response
    - While the program had several collaborations, we did not include a specific slide at the last year review.
    - It will be fully addressed in this review

- Specific recommendations/additions to or deletions from the work scope
  - Review comments:
    - “Please show more data to support your claims next year.”
  - Response:
    - Being a public forum, we are limited to the amount of details we can provide at this merit review meeting
    - All the data is always presented at our reviews with DOE Technical managers
    - Nevertheless, a large amount of data will be included in this presentation.
System Development Approach

Integration of aftertreatment systems

Evaluation on truck operation for overall technology assessment and refinement

Steady State and Transient Dynamometer Testing

Example Operating Conditions Over Truck Routes

Integrated Analytical Simulation Tools

Component Optimization

Selecting road-load operating conditions
Thermal Efficiency Roadmap

Thermal Efficiency (%)

Previous project: engine system improvements
- Variable fuel injection
- Dual-mode combustion
- Integrated engine and NOx ATS
- Advanced control
- Basic energy recovering

Current project: HECC
- Next gen. variable fuel injection
- Multi-mode combustion
- Variable breathing technologies
- Advanced control
- Advanced Energy recovering

Future project: complete engine system
- Next gen. variable fuel injection
- Multi-mode combustion
- Variable breathing technologies
- Advanced control
- Advanced Energy recovering

Years


Production engine
Demo engine
Performance Measures and Accomplishments

- Advanced fuel injection system
- Design optimizations with variable nozzle
- Innovative combustion system optimization
- Next generation control logic
- Real Time Combustion Control
Advanced Fuel Injection System

• Advanced fuel injection with full flexibility of injection events was procured and being evaluated.

• Beyond state-of-the-art variable nozzle technology is being evaluated
  - A new dual-mode combustion strategy is emerging, substantially reducing emissions, while significantly improving fuel economy
### Design Optimization with Variable Nozzle (A25)

<table>
<thead>
<tr>
<th>Case</th>
<th>BSFC [g/kW·hr]</th>
<th>NOx [g/hp·hr]</th>
<th>Soot [mg/m³]</th>
<th>CO [g/hp·hr]</th>
<th>HC [g/hp·hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>222</td>
<td>1.592</td>
<td>0.767</td>
<td>0.47</td>
<td>0.071</td>
</tr>
<tr>
<td>Dual Injection Mode</td>
<td>195.2</td>
<td>0.07</td>
<td>0.349</td>
<td>0.473</td>
<td>0.189</td>
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<tr>
<td>Improvement</td>
<td><strong>12%</strong></td>
<td><strong>96%</strong></td>
<td><strong>54%</strong></td>
<td><strong>-1%</strong></td>
<td><strong>-166%</strong></td>
</tr>
</tbody>
</table>

- 12% BSFC Improvement
- Significant reductions in both NOx (96%) and soot (54%)
- Only small increase in CO, and HC is not quite significant as opposed to other HCCI/LTC technologies
### Design Optimization with Variable Nozzle (A50)

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>BSFC [g/kW·hr]</th>
<th>NOx [g/hp·hr]</th>
<th>Soot [mg/m³]</th>
<th>CO [g/hp·hr]</th>
<th>HC [g/hp·hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>212.9</td>
<td>1.087</td>
<td>13.16</td>
<td>1.31</td>
<td>0.099</td>
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<tr>
<td>Dual Injection B</td>
<td>193.5</td>
<td>0.245</td>
<td>1.15</td>
<td>0.792</td>
<td>0.783</td>
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</tbody>
</table>

- 9.1% BSFC improvement
- 77% NOx reduction
- 91% soot reductions
Design Optimization with Variable Nozzle (B100)

- Significant BSFC benefits
  - 5.1% BSFC improvement
- Significant NOx and soot emissions reduction
  - 59% NOx reduction
  - 55% Soot reduction
- Much lower CO and HC emissions than baseline

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>BSFC [g/kW·hr]</th>
<th>NOx [g/hp·hr]</th>
<th>Soot [mg/m³]</th>
<th>CO [g/hp·hr]</th>
<th>HC [g/hp·hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>190.3</td>
<td>1.087</td>
<td>0.064</td>
<td>0.239</td>
<td>0.036</td>
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<tr>
<td>Dual Injection F</td>
<td>180.5</td>
<td>0.443</td>
<td>0.029</td>
<td>0.171</td>
<td>0.004</td>
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</tbody>
</table>
New Approach

Best Emissions and/or Best Fuel Economy Targets/Objectives

Genetic Optimization Scheme

- Hardware
  - Piston bowl, compression ratio, swirl ratio
- Injection System
  - Number of holes, spray angle, hydraulic flow rate, tip protrusion, multiple injection
- Calibration
  - Injection timing, injection pressure, EGR rate, injection scheme

- New approach is able to significantly shorten development cycle in achieving program objectives
The Multi-Objective Genetic Algorithm Optimization Methodology

Optimization did not target specific combustion concepts
Specific Combustion Optimization on PCCI

The objective is to achieve similar soot and NOx emissions to that of the baseline case but with a ~10% fuel consumption improvement.

<table>
<thead>
<tr>
<th>run</th>
<th>Soot</th>
<th>NOx</th>
<th>gisfc</th>
<th>Fuel economy improvement</th>
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<tbody>
<tr>
<td></td>
<td>g/kgf</td>
<td>g/kgf</td>
<td>g/kW-hr</td>
<td>%</td>
</tr>
<tr>
<td>base</td>
<td>0.23</td>
<td>3.24</td>
<td>233.3</td>
<td>-</td>
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<tr>
<td>1</td>
<td>0.12</td>
<td>5.27</td>
<td>201.1</td>
<td>13.8</td>
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<td>2</td>
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<td>7.76</td>
<td>223.0</td>
<td>4.4</td>
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<td></td>
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<td>-----</td>
</tr>
<tr>
<td>11</td>
<td>0.33</td>
<td>1.98</td>
<td>212.9</td>
<td>8.7</td>
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<tr>
<td>12</td>
<td>0.19</td>
<td>3.72</td>
<td>208.1</td>
<td>10.8</td>
</tr>
</tbody>
</table>

- 10.8% fuel economy improvement was obtained while maintaining the same emission level as baseline.

- Engine testing is under way and more results will be reported in the next review meeting.
Next Generation Control Logic

- Virtual Sensors
- Adaptation
- Control Logic
- Observer Model
- Observer Model Adaptation
- Sensors
- Setpoints
- Setpoint Optimization Scheme
- Actuators
Best Optimized Calibration Provided a 4% Thermal Efficiency Improvement ...
Transient Calibration Optimization (2)

... and a 15% NOx & 25% PM Reduction

Optimization Project Was Geared Towards Fuel Economy Improvements

- **Baseline trade-off**
- **Optimizations**
Real Time Combustion Control

- Start of combustion detection (SOC) for LTC control
- Sensors are being installed in the engine
- Evaluation for SOC detection will begin in Q2-2008

Example of Start of Combustion detection, 2003.04.25
Sunplot of Ion from Cyl1. Yellow trace: Detected SOC for just this cyl
White trace: Detected SOC using all clys
Barriers/Challenges

- Technical challenges with variable nozzle technology are enormous
  - Needle lift control hardware availability
  - High sensitivity to needle position – design may not be robust to tolerances
  - Very high precision required in manufacture

- Genetic combustion optimization implementations
  - Engineering experience needs to be applied to create practical designs out of optimization results/recommendations

- Combustion mode transition
  - Need robust controls methodologies

- Cylinder pressure sensors for real time combustion control
  - Reliability and cost of sensors
  - High speed signal processing requirements
Collaborations/Interactions

- Oak Ridge National Lab
  - Engine testing with advanced fuel injection system and control
  - Emission analysis

- Supplier partners
  - Delphi Fuel Injection System
  - Quantlogic Inc.
  - Exergy Engineering LLC
  - Continental (previously Siemens)
  - Woodward

- Engine consulting company and universities
  - Atkinson LLC
  - FEV
  - University of Wisconsin
  - University of Illinois


Special Recognitions & Awards/Patents Issued


• Guangsheng Zhu and Houshun Zhang, “Invention of Squish-Induced Mixing-Intensified Low Emission Combustion (SIMILECOM).” Record of invention was submitted on August 16, 2007.

Future Work

• Variable injection nozzle technology
  - Hardware procurement is underway
  - Engine tests are expected in Q4-2008

• Advanced next generation fuel injection system
  - HECC evaluations with a new advanced fuel injection system in Q2-2008

• Transient combustion and control development
  - Real time combustion control using cylinder pressure sensors in Q2-2008

• Integrated system controls development
  - On-going, and more results will be available in the next review meeting
Summary

• Program is progressing well and aggressively. It is toward meeting the program objective with 10% thermal efficiency improvement by 2009.

• Identified key enabling technologies with high potential of leading to 55% thermal efficiency beyond 2013
  - Variable Fuel Injection Nozzle Coupled with Advanced Fuel Injection System
  - Genetic Combustion System Optimization
  - Transient Control Optimization

• Significant benefits with variable nozzle technology have been demonstrated analytically. A new dual mode combustion strategy covering the entire operating range is emerging.
Acknowledgements

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  - Gurpreet Singh
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• National Energy Technology Laboratory
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