High Efficiency Clean Combustion for Heavy-Duty Engine

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Outline

- Program Overview

- Technical Details
  - Advanced Fuel Injection System
  - Combustion Optimization
  - Advanced Next Generation Control

- Summary
Program Objectives

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

- Maximize thermal efficiency with integrated engine and DPF+SCR aftertreatment system while meeting 2010 emission regulations.

- 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
System Development Approach

Focus on integrated engine and DPF+SCR system, maximizing thermal efficiency while meeting 2010 emissions

Selecting road-load operating conditions

Example Operating Conditions Over Truck Routes

Integrated Analytical Simulation Tools

Component Optimization

Evaluation on truck operation for overall technology assessment and refinement

Integration of aftertreatment systems

Steady State and Transient Dynamometer Testing
Current project: 
Combustion focus
• High efficiency clean combustion
• Dual-mode combustion

• Variable fuel injection
• Basic energy recovery
• Advanced control

Future project: 
complete engine system
• Next gen. variable fuel injection
• Multi-mode combustion
• Variable breathing technologies
• Advanced control
• Advanced Energy recovery
• Engine + DPF+SCR integration
• Powertrain integration

Previous project: 
Total engine system improvements
• Variable fuel injection
• Basic energy recovery
• Advanced control

Thermal Efficiency Roadmap

<table>
<thead>
<tr>
<th>Years</th>
<th>2005</th>
<th>2007</th>
<th>2009</th>
<th>2011</th>
<th>2013</th>
<th>2015</th>
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<tbody>
<tr>
<td>Thermal Efficiency (%)</td>
<td>45</td>
<td>50</td>
<td>55</td>
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- Production engine
- Demo engine
Advanced Fuel Injection System

- Advanced fuel injection with full flexibility of injection events was procured and being evaluated.
  - System combines unit injectors and an accumulator rail
  - Medium pressure rail (up to 1000 bar) to provide early / late injection events
  - Unit injector to provide high pressure short duration main injection
  - Combined rail / unit injector operation for boot shape and close pilot / post injections
  - Unit injectors to act as rail pressure source (no rail pump required)
Variable Nozzle Technology

- Introduced variable fuel injection technology into the program with high potential to significantly enhance high efficiency clean combustion.
- Great potentials have been demonstrated analytically throughout different speeds and loads
  - Significant fuel economy improvement, ranging from 5% to 12%
  - Substantial NOx and soot emission reductions, ranging from 50% to 90%
- Variable nozzles have been procured, and assembled with advanced fuel injection system.
- Flow bench tests are underway, and the engine tests will follow soon.
Micro-Variable Circular Orifice (MVCO)

First phase injection with conical spray and narrow spray angle produced by MVCO Nozzle

Second phase injection with multi-jet spray and wide spray angle produced by MVCO Nozzle

QLC QuantLogic Corp.
Advanced Combustion Development

- Genetic combustion optimization
- Fuel injection and piston bowl optimization
- New combustion concept exploration
- Multi-mode combustion with advanced fuel injection system and variable nozzle technology
- Real time combustion control
- In-cylinder pressure sensor
- Ionization sensors

Automated selection of engine operating parameters for optimal emissions reduction

Example of Start of Combustion detection, 2003.04.25
Sample of less from Cy1. Yellow trace: Detected SOC for just this cyl
White trace: Detected SOC using all cyl.

![Graph showing NOx emissions versus soot production](image)

- Baseline
- Optimum
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>
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<tr>
<th>run</th>
<th>Soot</th>
<th>NOx</th>
<th>gisfc</th>
<th>Fuel economy improvement</th>
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<tr>
<td></td>
<td>g/kgf</td>
<td>g/kgf</td>
<td>g/kW-hr</td>
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<tr>
<td>base</td>
<td>0.23</td>
<td>3.24</td>
<td>233.3</td>
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<td>11</td>
<td>0.33</td>
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<td>12</td>
<td>0.19</td>
<td>3.72</td>
<td>208.1</td>
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10.8% fuel economy improvement was obtained while maintaining the same emission level as baseline.

Engine testing is just under way and preliminary results show 5.03% BSFC improvement. More tests will be reported soon.
Next Generation Model-Based Controller

Model Based Controller

CONTROLLER

Engine Sensors

Physical and Virtual

Setpoints

SPEED

FUEL

BSFC

NOx

PM

HC

CO

Torque

Engine Actuators

Position Feedback

Aftertreatment Model

Adaptation

Real-Time Optimizer

Emissions Model

Emissions Model

Engine Model

Model Based Controller

Controller

Engine Model

Engine Sensors

SPEED

FUEL

BSFC

NOx

PM

HC

CO

Torque

Adaptation

Hot

Cold

Transient

Altitude

Smoke control

Regeneration

Aging

Real-Time Optimizer
Application of Transient Calibration Optimization to FTP Cycle

4% Thermal Efficiency Improvement

With Next Generation Model Based Controller

And 15% NOx and 25% PM Reduction Simultaneously

Each point marker designates one calibration FTP set point
Transient Calibration Optimization (FTP Tests)

Next Generation Model Based Controller breaks traditional BSFC-NOx Trade-off Curve toward more Fuel Economy Improvement
Barriers/Challenges

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

- Combustion mode transition
  - Need robust controls methodologies

- Next generation model based control
  - Computational power and speed in engine control unit
  - Model integration complexity with real time engine, aftertreatment, and emission model that must be adaptive, robust, and precision
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 returns
  - Advanced fuel injection system coupled with variable fuel injection nozzle
  - Genetic combustion system optimization
  - Transient control optimization

- Significant benefits with advanced fuel injection system and variable nozzle technology have been demonstrated. A new combustion strategy covering the entire operating range is emerging.
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