Low Temperature Combustion Demonstrator for High Efficiency Clean Combustion

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Advanced Combustion Technologies
DOE DEER CONFERENCE
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• Goals and Objectives
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• Technologies Leveraged
• Engine Setup
• Combustion Approach
  – Injection strategies
  – PCCI effects: tests and simulation
  – Variable Valve Actuation
• Emissions and Performance
  – LTC Thermal Efficiency
  – Variable Valve Actuation
  – Compression Ratio
• Fuel Properties
• Conclusions
Goals and Objectives

• **Demonstrate the application of low temperature combustion:**
  – Yield 2010 NOx and DPF tolerant soot in-cylinder emissions
  – Study is carried out on a production platform (Navistar 6.4L)
  – Use today’s Diesel fuel
  – Target min load 12.6bar, up to 16.5bar
  – Improve engine thermal efficiency

• **Develop technology capable for production implementation:**
  – Cylinder pressure diagnostics
  – ECU and sensing technologies
  – Fuel and air system
## Project Timeline

### 2005

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### 2006

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### 2007

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### 2009

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### Engine Design Phase
- Air System Matching
- Fuel Injection Optimization
- Control System Procurement
- SCTE benchmark

### Engine Build
- Cylinder Pressure Feedback
- Combustion System Optimization / KIVA
- Compression Ratio

### Multi-Cylinder Steady State
- 6 bar BMEP milestone
- 12 bar BMEP milestone
- 16.5 bar BMEP milestone

### Transient
- Control System
- FTP demonstration

### Brake Thermal Efficiency Targets
- Brake Thermal Efficiency milestone

### Variable Valve Actuation
- Combustion System Impacts

### Fuel Impacts
- Impacts of Fuel Properties

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2010 Emissions + BSFC gains

Last Phase Development
Technologies Leveraged

Combustion Efficiency
- Combustion Phasing
- Combustion Duration

Enablers
- Injection strategy (PCCI)
  - High Inj Pressure
  - Controls
- Cyanlde Heat Rejection
  - High Boost / Lean
- Efficient Turbocharging
  - CR and VVA

Parasitic Losses

Bottoming Cycles
- Rankine Cycle
- Turbo Compounding

Aftertreatment Management
## Engine Setup

### New Engine Configuration

<table>
<thead>
<tr>
<th>Base engine</th>
<th>V8 Test Engine</th>
<th>SCTE</th>
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<tr>
<td>Displac. Bore Stroke</td>
<td>6.4L 98.5mm 105mm</td>
<td>6.4L 98.5mm 105mm</td>
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<tr>
<td>FIE</td>
<td>DI Common Rail</td>
<td>DI Common Rail</td>
</tr>
<tr>
<td>CR</td>
<td>16</td>
<td>12-16.5</td>
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<tr>
<td>Turbo Charger</td>
<td>Single Stage VNT</td>
<td>Dual Stage VNT</td>
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<tr>
<td>EGR system</td>
<td>HP loop Single Cooler</td>
<td>HP loop Dual Cooler</td>
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<tr>
<td>IVC EVO</td>
<td>-133 BTDC 132 ATDC</td>
<td>variable 132 ATDC</td>
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</table>
Variable Valve Actuation

VVA system Assembly:

*Adjust intake valve closing on each cylinder.*
*Adjustments on each combustion cycle.*
Combustion Approach

HCCI: Lean, Homogenous (Φ ~ 0.2)
Temp controlled ignition

LTC: Similar to Conventional
Diesel Diffusion (Φ ~ 1 -1.2)
Very-high EGR (~60%)

PCCI: Improved mixture
Increased ignition delay
Higher injection pressures
Ignition timing closer to TDC
Less dependent on very-high EGR
Further bowl – injector matching

Examples of Early PCCI - SAE 2008-01-0057

[Herzog et. al 1992]
[Akihama et. al 2001]
Injection Strategies

**Injection Strategy: Pilot + Main + Post**
Load: > 12 bar BMEP

- Pilot for enhanced homogenity
- Post for soot-oxidation

**Injection Strategy: Pilot + Main**
Load: 10~12 bar BMEP

- Pilot for enhanced homogenity

**Injection Strategy: Pilot + Main**
Load: <10 bar BMEP

Crank Angle Degree (CAD)
PCCI Effects (test data)

BSFC improvement of 1-2% can be identified by PCCI or fuel pilot and harvested with accurate cylinder pressure control.

Excess pilot deteriorates performance due to premature combustion.
**PCCI Effects (simulation)**

1750 rpm – 10.7 bar BMEP

**2 mg pilot**

**Temperature**

- 316
- 356
- 362
- 368

**EQR**

- Pilot injection
- Main Injection
- Diffusive Combustion

**14 mg pilot**

**Temperature**

- Pilot injection
- Main injection

**EQR**

- Pilot “ignition source” contributes to
  - *faster burn of the main injection* 360º-365º
  - *reduces diffusion burn* 370º-390º
Higher injection pressure can yield better thermal efficiency (5-7%). Improvements are coupled with soot reduction.

1750 rpm – 10.7 bar BMEP
Efficiency path at 0.2gNOx emissions
Variable Valve Actuation

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NOx (ppm)  Smoke (FSN)  EGR%  BSFC (g/hp-hr)

2058 rpm / 219Nm

Baseline IVC
SOI and TQ FBK OFF
IVC FBK OFF

Baseline IVC
SOI and TQ FBK ON
IVC FBK OFF

155 deg IVC
SOI and TQ FBK ON
IVC FBK OFF

165 deg IVC
SOI and TQ FBK ON
IVC FBK ON

145 deg IVC
SOI and TQ FBK ON
IVC FBK ON

Cylinder-to-Cylinder Fuel “trim”

Cylinder-to-Cylinder IVC “trim”

IVC adjustment
Normalized 13 Mode Composites
Baseline Product Mix-Applications vs. LTC Option
LTC Thermal Efficiency

Conventional Diesel Approach
Multiple calibrations with NOx optimized to 0.5 – 1.2 gNOx engine out
Max – Average – Min shown

LTC
NOx optimized to below 0.2 gNOx engine out
BSFC gains can be 5-10% better

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1671 rpm and 4.2 bar BMEP

All data at NOx < 0.2g/bhp-hr

Early intake valve closing:

- Reduces ECR
- Enhancing LTC ~ longer $\tau_{id}$
- Better BSFC ~ lower EGR
- Soot reduction of over 90%
Compression Ratio may be optimized:

- Favor optimum combustion phasing
- Other issues will limit low compression ratios
Fuel Properties

- Fuel properties affect ignition delay
- Fuels for PCCI reduce
  - Reliance on post/pilot injection for soot reduction
  - Late CA50 for prolonging ignition delay

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<th>FACE 5</th>
<th>FACE 6</th>
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<tr>
<td>Cetane Number</td>
<td>Low</td>
<td>High</td>
<td>High</td>
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<tr>
<td>Aromatic Content (Vol%)</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>T90 (°F)</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
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1671RPM
IMEP=10.6bar
CA50=12deg ATDC

Improved BTE

Lower CN
Lower T90
**Summary**

Applied low temperature combustion to the Navistar 6.4L V8 engine:

**Operating range:**

LTC with 0.2g NOx/bhp-hr operation attained at the rated 16.5 BMEP. Soot contained to DPF capable regeneration (similar to base engine).

**Fuel Economy:**

LTC – CR showed improvements of up to 5%.
LTC – PCCI demonstrated 1-2% BSFC.

**VVA enhances the application of LTC like chemistry:**

- Longer ignition delays
- Excellent soot management
Acknowledgements

Project Partners

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Navistar
ENGINE GROUP

CFD

Lawrence Livermore National Laboratory

Ricardo

ConocoPhillips

BorgWarner Turbo & Emissions Systems

MAHLE

Jacobs Vehicle Systems

Continental

Combustion Diagnostics

Diagnostics