Low Temperature Combustion Demonstrator for High Efficiency Clean Combustion

DOE Contract: DE-FC26-05NT42413

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This presentation does not contain any proprietary or confidential information
• Project Overview
• Statement of Project Objectives
  – Project Timeline
• Barriers
• Collaborations and Partnerships
• Approach
• Accomplishments
  – Summary of Previous deliverables
  – Present deliverables:
    • Extension of Efficient LTC operation
    • Variable Valve Actuation
    • Fuel formulation impacts
• Future Work – Proposal
• Summary
Goals and Objectives
- Apply Low Temperature Combustion (LTC) to a production MD Diesel Engine
- Demonstrate EPA 2010 emissions without NOx after-treatment
- Improve BSFC by 5% over base engine

Barriers
- Overcome combustion stability of LTC due to high EGR use
- Lack of fundamental understanding of the LTC combustion process
- Insufficient combustion diagnostic technologies that can be integrated onto production ECU

Budget
- Total Project Funding: DOE: $4,021,234
  Contractor: $5,153,881
- DOE Funding Received in FY2009: $555,000
  Navistar Funding: $850,000
- DOE Funding Planned for FY2010: $460,000
  Navistar Funding: $567,000

Partners
- Navistar, controls system, engine testing
- UCB, combustion detection
- LLNL, CFD and chemical modeling of fuel spray and combustion
- Siemens, fuel Injector design and procurement
- ConocoPhillips, fuel formulation and supply
- BorgWarner, turbocharger system design and procurement
- Mahle, piston design and procurement
STATEMENT OF PROJECT OBJECTIVES

1. **Demonstrate the application of LTC on a MD Diesel Platform**
   - Target 2010 emissions without NOx after-treatment
   - Minimize soot (target 2007MY DPF loading requirements)
   - Improve brake thermal efficiency to 5% over MY2007 baseline
   - Generate technology in project to be capable for production
   - Baseline engine is the Navistar’s EPA compliance MY2007 6.4L V8 engine

2. **Develop enabling technologies**
   - Charge air and EGR system designs
   - Combustion feedback Control
   - Variable Valve Actuation System

3. **Technology integration roadmap on engine platform**

4. **Validate program under a present fuel variability**
## PROJECT TIMELINE

<table>
<thead>
<tr>
<th>Phase</th>
<th>Budget Period</th>
<th>Details</th>
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CFD parametric studies |
| II. Development of Technologies and Engine Build | June 2006 – May 2007 | Boost System Procurement  
EGR and Cooling System Procurement  
Fuel Injection System Optimization and Procurement  
Engine Shakedown |
Low Temperature Combustion with 2010 EPA emissions  
Combustion System Optimization  
Design Variable Valve Actuation Technology |
| IV. Fuel Economy Optimization | Feb 2009 – May 2010 | Load Extension Milestone  
Steady State BSFC improvement Milestone  
Transient and Fuel Economy Demonstration  
Fuel Variability Demonstration  
System Integration (ECU, VVA) |
<table>
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<tr>
<th>Barriers</th>
<th>Technology Roadmap</th>
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<tr>
<td>High unburned hydrocarbons</td>
<td>- Higher fuel injection pressure, multiple injections&lt;br&gt;- Charge temperature control&lt;br&gt;- Improve fundamental understanding of the combustion process (improved chemical mechanisms)</td>
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<tr>
<td>Fuel economy</td>
<td>- Improved air system design&lt;br&gt;- Minimize EGR driving pressure differential</td>
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<tr>
<td>Combustion stability <em>Cylinder-to-Cyl EGR and cooling variability</em></td>
<td>- Fuel-Air modeling and control management&lt;br&gt;- Implement combustion feedback&lt;br&gt;- Variable Valve Actuation</td>
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<tr>
<td>Limited power density</td>
<td>- Improved vehicle cooling system (low temperature radiator)&lt;br&gt;- Two stage turbo system&lt;br&gt;- Increased cylinder pressure capability</td>
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<tr>
<td>Transient response</td>
<td>- Two stage turbo&lt;br&gt;- CAC bypass</td>
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<tr>
<td>Accommodate fuel properties representative of US geography <em>Diesel fuels ranging from of 42-58 CN</em></td>
<td>- Sensors&lt;br&gt;- Combustion diagnostics</td>
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<tr>
<td>Collaborations</td>
<td>Technologies</td>
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</table>
| Navistar       | - Principal Investigator  
                  - Controls system development  
                  - Variable Valve Actuation design  
                  - Engine testing |
| UCB            | - Combustion detection |
| LLNL           | - CFD and chemical modeling of fuel spray and combustion |
| Siemens        | - Fuel injector design and procurement |
| ConocoPhillips | - Fuel supplier  
                  - Fuel formulation and kinetic modeling support |
| BorgWarner     | - Turbocharger system design and procurement |
| Mahle          | - Piston design and procurement |
Approach

Combustion Modeling

1. Spray Model
   Used models from the literature that capture the liquid spray break up [1] to optimize injector and bowl configurations [2]

   \{ tetradecontane \\
   KH-RT breakup \\
   Turbulent dispersion \}

   n-heptane (C7H16)

2. Fuel Oxidation Chemistry
   Calibration of LTC Reactions

   \[ C_{15}H_{15}O_2 = C_7 ket_{12} + OH \]
   \[ CO + OH = CO_2 + H \]

   \[ k(T) = A T^{\beta} \exp(-E_a / R_u T) \]

   NOX RSC ~ 1.4
   Soot asf ~ 200
   (Hiroyasu and NSC model, C2H2 as precursor)

3. Emission Model

4. ROI Model

5. K3Prep used for grid generation

[1] Reitz and Diwakar, SAE 870598

Patel et al, SAE 2004-01-0558

Smith et al, GRIv3 - Mech 3.0
Kong et al, IECS 2005-1009
Hiroyasu and d Kadota, SAE 760129
Accomplishments

Previous History of Deliverables

Designed Efficient LTC operation:

1. Boost-EGR Control: optimized combustion phasing
2. PCCI – premixed fuel injection strategies

Achievement in Phase III of project:

0.2gNOx engine out
4% better cycle average fuel consumption

Next barrier:

Improve combustion stability and robustness
Accomplishments
Key Deliverables for FY 2009-2010

Extension of Efficient LTC operation:
1. Boost-EGR Control: optimized combustion phasing
2. PCCI – premixed fuel injection strategies
3. Application of Variable Valve Actuation and Combustion Feedback

Achievements in Phase IV of project:
More robust combustion system attained with VVA

- Introduced and engineering margin for 0.2g NOx target
- Improved cycle average fuel consumption by 5.5%
- Soot reduction was improved by 0.05g/bhp-hr
Accomplishments
Key Deliverables for FY 2009-2010

Enabling technologies for Efficient LTC operation

- Multi-Shot, EGR enabled PCCI
- Single-Shot, EGR enabled PCCI
- Enhanced PCCI single-shot, EGR with Variable Valve Actuation
Accomplishments

Advantages of VVA

Extension of Efficient LTC operation:

1. VVA provided **greater control** over the combustion process:
   - Reduced charge variability among cylinders
   - Allowed to extend the PCCI range (control over effective compression ratio)

2. **Combustion diagnostics**
   - Feedback was extended to VVA
   - Implementation did no tax the ECU performance.
Accomplishments

Full integration of VVA

An Effective VVA Device

Advantages of Electro-Hydraulic System:

- Simple and Robust
- Fine resolution for IVC
- Cylinder to cylinder adjustment
- Cycle to cycle adjustments
- Simple package over baseline valve train
Accomplishments
Thermodynamic effects VVA

1. Lowered effective CR

2. Early intake valve closing (EIVC)
   - Lowered in-cylinder pressure
   - EIVC produces a nearly isentropic expansion (reduced losses)

3. Increase ignition delay and promote cool flame chemistry
Accomplishments
Combustion effects VVA

Advancing Intake Valve Closing at 30% load

1. **NOx ~ 0.18g/bhp-hr held constant**
   - Combustion phasing ~ 7.5°
   - Accurate metering of EGR

2. **BSFC is reduced ~ 5%**
   - Reduced back-pressure
   - Offsets the increased CO and HC

3. **Soot is reduced ~95%**
   - Longer ignition delay
   - Lower temperatures at ignition

![Graph showing NOx and BSFC changes with advancing IVC timing]

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- Combustion Feedback (CBFK) was implement in Phase III to control combustion phasing.
- CBFK was extended in **Phase IV** to **control the charge** via individual cylinder-to-cylinder valve timing control: *effective system to further extend the engine PCCI operation*.

![Graphs showing combustion phasing and cylinder charge control](image-url)

- Cylinder charge is controlled with VVA – eliminates variability under LTC conditions.
- Combustion phasing is controlled with fuel timing.
VVA yielded simultaneous reduction of BSFC and PM
Comprehensive relationships in combustion parameters

All data at 0.2gNOx/bhp-hr

**Significant soot reduction (~95%)**

**Simultaneous with reduction in fuel consumption (~5%)**

Ref. SAE 2010-01-1124
The simulations helped diagnose the soot reduction mechanisms with advanced IVC:

- better mixture characteristics
- Dependency on local equivalent ratio
Accomplishments

Impact of Fuel Properties

The LTC process was validated across a range of fuel properties:

- Properties spanned CN, boiling point and aromatics*.
- The combustion was robust across the fuel ranges.
- Fuel reactivity has an impact over performance:
  - Efficiency improvements of 5% are possible.
  - Soot emissions can be greatly reduced.

The potential for improved performance was identified. This is a potential area for further development (see next slide).

* Ref. FACE Fuels Program
Extend the thermal efficiency via fuel reactivity

Fuel Consumption improvement (%)

Baseline
- Base BSFC: 0.0%
- NOx (g/bhp-hr): 0.97

EGR+BOOST
- 2.5%

PCCI
- 4.0%

VVA+FBK
- 5.5%

Fuel Reactivity
- 10.5%

Program target
Long term target
Summary

- **Applied low temperature combustion (LTC)** to the ITEC 6.4L V8 production engine:
  1. **Load:** Extended LTC operation to 16.5 BMEP.
  2. **Fuel Economy:** Improvements were increased from 4% to 5.5% by extending the application of PCCI by means of Variable Valve Actuation and combustion feedback.
  3. **NOx:** Engine out NOx was maintained below the 0.2g/bhp-hr target.
  4. **Soot:** 90% soot reduction was demonstrated at low to mid loads.

- **Engine testing was coupled to combustion fundamentals:**
  - Simulation was used to understand relation between LTC and the effective compression ratio.
  - Simulation was used optimize the implementation of VVA.

- **Capability for production implementation:**
  - A production ECU like module was developed to perform in-cylinder combustion control.
  - Controller performs cycle-to-cycle and cylinder-to-cylinder adjustments on the fuel and VVA systems.