Multicylinder Diesel Engine for LTC operation

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Diesel Engine Development
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Goals and Objectives

- Demonstrate the **application of low temperature combustion to**:
  - Yield 2010 NOx and Soot in-cylinder emissions
  - Study is carried out on the Navistar 6.4L engine using today’s Diesel fuel
  - Target load 12.6 bar
  - Improve engine thermal efficiency

- Develop technology **capable for production implementation**.
Goals and Objectives

Improve Thermal Efficiency

- Optimize TC system / operation
- Reduced back pressure

- Optimize CR and ER
- VVA

Supporting work:

- Engine Testing
- 1-D Cycle Simulation
- KIVA-CFD Modeling
- Detail Energy Balance

2007 baseline

DOE 2010

DOE 2013

- Optimized combustion
- Air System
- Advanced Platforms (VVA, LP EGR)
- Parasitic Losses
- Cooling Systems

Emission Driven

- Short combustion duration
- Combustion Phasing
- Injection strategy (PPCI)
- VCR
- Injector Bowl Match
- Injection pressure

2008 DEER
Dearborn, MI August 4-7

Fuels
Electrification
Waste Heat Recovery
**Base Engine:**
Common rail
Single stage VNT turbocharger
Single EGR cooler.

**Present build encompass:**
1. Dual-path EGR system
2. Two-stage TC each with VNT stages
3. High-flow cylinder head
4. EGR mixture
5. Low CR pistons
6. Multi-hole injectors

### Parameters

<table>
<thead>
<tr>
<th>Base engine</th>
<th>V8 Test Engine</th>
<th>SCTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displac.</td>
<td>6.4L</td>
<td>0.75L</td>
</tr>
<tr>
<td>Bore</td>
<td>98.5mm</td>
<td>95mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>105mm</td>
<td>105mm</td>
</tr>
<tr>
<td>FIE</td>
<td>DI Common Rail</td>
<td>DI</td>
</tr>
<tr>
<td>CR</td>
<td>16</td>
<td>15-16.5</td>
</tr>
<tr>
<td>Turbo</td>
<td>Single Stage VNT</td>
<td>Dual Stage VNT</td>
</tr>
<tr>
<td>Charger</td>
<td></td>
<td>Surge tank</td>
</tr>
<tr>
<td>EGR system</td>
<td>HP loop Single Cooler</td>
<td>HP loop Dual Cooler</td>
</tr>
<tr>
<td>IVC</td>
<td>-133 BTDC</td>
<td>-133 BTDC</td>
</tr>
<tr>
<td>EVO</td>
<td>132 ATDC</td>
<td>132 ATDC</td>
</tr>
</tbody>
</table>

**Diagram:**
- EGR
- Engine
- Turbocharger
- EGR Cooler
- Heater
- CAC
- Emissions
- IVC
- CO2
- CO2
- CO2
- Smoke
- NOx
- HC
- CO
- CO2
- P1
- P2
- P3
- P4
- P5
- P6
- P7
- P8
- T1
- T2
- T3
- T4
- T5
- T6
- T7
- T8
- T charge
- T cool
- T stack
- T exhaust
- M air
- P air
- P stack
- P egr
- T egr

**Equations:**
- \( T_{charge} = P_{charge} \)
- \( P_{im} = T_{im} \)
- \( T_{SP} = T_{CAC} \)
- \( T_{charge} = P_{charge} \)
- \( V(reg) = M_{air} = f(DP) \)
- \( T_{stack} = P_{stack} \)
- \( T_{exh} = P_{exh} \)
Definition of LTC

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

**LTC:** Similar to Conven’l Diesel Diffusion (Φ ~ 1 -1.2)
Very-high EGR (~60%)

**PCCI:** Improved mixture, increased ignition delay
Higher injection pressures
Fuel injection timing (closer to TDC)
Less dependent on very-high EGR
Further bowl – injector matching

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

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Representative data from SCTE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>IMEP</td>
<td>7, 9 bar</td>
</tr>
<tr>
<td>N</td>
<td>1200 rpm</td>
</tr>
<tr>
<td>P_{intake}</td>
<td>2 bar</td>
</tr>
<tr>
<td>M_f</td>
<td>28, 33 mg/stke</td>
</tr>
</tbody>
</table>

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Graph showing Exhaust O₂ Concentration [%] vs. IMEP 7bar NOx and IMEP 9bar NOx, with indications of Indicated Soot [g/kW-hr] and EGR% ratio.
**Target of Program:**
Implement LTC through 12.5 bar BMEP on a production platform
Meet NOx and SOOT 2010 targets without after-treatment
Promote BSFC to meet 2007 levels and work towards DOE targets of 50 to 55% efficiency.

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**Work in Progress**
*Extend LTC range*
*Focus of Presentation*

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**Present Range of testing**

- **PCCI - LTC**
  - Injection pressure
  - Fuel injection strategy
  - Temperature management

- **LTC - High EGR**
  - or
  - **HCCI**
    - Multiple shots
    - Medium EGR rate

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**Graphical Representation**

- **2007 Lug Line**
- **DOE TARGET LINE**
Combustion System Optimization Approach

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PCCI – LTC BMEP load gains:

- Fundamental understanding
- Engine Testing
- 1-D Thermodynamic Models
  - KIVA
  - LTC
- CFD
  - ROI and Spray models
  - Multiple Shot
- Fuel Properties
  - Diesel Surrogates
  - FACE Fuels
- Emerging Technologies
  - Turbo Systems
  - Cooling
  - Fuel Injection Equipment
  - VVA
Combustion System Optimization
Highlights

Highlights

Injection strategy – Single Shot
- Effects of early timing vs. load increase
- Effective NOx control
- Modeling and experimental correlations

Transition to Multiple Shots
- Multiple Pilots
- Effective soot control (safeguard bsfc)
- Modeling and experimental correlations

Air System optimization
- Effects on Injection Strategy on BSFC
- Coordinate EGR / Turbo
- Advantages of VVA

Current Status
Operating at ~ 16 bar BMEP
- Can run with 40 - 50% EGR
- Yield 0.2gNOx/bhp-hr
- Reasonable soot (0.05-0.1g/bhp-hr)
- High combustion Efficiency

Next steps
Combustion optimization towards BSFC goals
- Take a piece-wise approach (vs one-step to 50%)
- FUP ~ comb duration
- Fuel specific formulations (e.g. non-sooting)

Summary
Positive Impact of **Early Injection** (early PCCI)

**Single Shot Injection**

**Path to reducing flame temps**
- Dilute charge $O_2$ concentration (AFR)
- Raise heat capacity of mixture (EGR)
- Reduce fuel rich zones (strength)

**Path to reduce in-cylinder PM**
- Optimize piston-injector match
- Increased boost
- Increase ignition delay (premixed burn)
  - Increased injection pressure
  - Early injection timings

**At higher loads:**
- Multiple injections
- Lower combustion temperatures

**Focus on Combustion mechanism** at 1750 10.7 bar reducing NOx and SOOT with injection timing
Positive Impact of **Early Injection** (early PCCI)

1. The local chemistry shows **leaner** and **cooler** combustion.
2. The early injection aids to better entrainment and vaporization of the fuel.
3. The rate of combustion is more rapid.

**Early Injection**

Image corresponds to Peak in HR trace

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**1750 rpm – 10.7 bar BMEP**

**KIVA vs. Engine Data**

**Late Injection**

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**Injection Strategy**

**Combustion Phasing Optimization**
Positive Impact of **Early Injection** (early PCCI)

Simulations highlight the impact of injection timing in the throughout the combustion process including, *ignition delay*, *premixed burn*, *mixing control burn*.

**1750 rpm – 10.7 bar BMEP**

Point of max hear release rate

Late injection timings show cells longer residence time within the NOx formation island.
Combustion optimization is driven by emission requirements.

The injection strategy can be tailored to reduce soot and NOx.

Options become reduced when fuel efficiency is to be preserved or improved.

Next focus on pilot strategy.
Injection Strategy
Pilot-shot optimization

Optimization of pilot quantity

Pilot quantity is evaluated via soot and NOx tradeoff with respect to BSFC:

- Pilot quantity can reduce SOOT at constant fueling and NOx.
- The effect of pilot is sensitive to a minimum quantity
- Injection pressure and combustion phasing may weigh in to further optimize the present tradeoff without excess penalty to fueling
- It is effective to reduce the max rate of pressure rise (A vs. B)

HC and CO with respect to BSFC

- Combined contribution appears to be minimum vs. BSFC

![Engine Data at 1750 rpm – 10.7 bar BMEP](image)
Optimization of pilot quantity

Simulations captured the ignition characteristics of the pilot events. Pilot liquid phase (A) vaporizes prior to main injection event. Results corroborate the BSFC – (HC, CO) balance from previous slide.

1750 rpm – 10.7 bar BMEP
SIMULATION vs. Experiments

Next Slide
Injection Strategy
Pilot-shot optimization

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1750 rpm – 10.7 bar BMEP
14 mg pilot
SIMULATION

Pilot mixture preparation

Pilot injection vaporizes

Low temperature combustion
Based on temperature distribution and heat release curve shows initial combustion at 340°

High temperature Pilot Combustion begins at 355°

Start of main injection

Suppression of the heat release from the main injection fuel occurs for approximately 4°

Main reaction take place
Pilot appears to ignite the main spray

HRR (J/deg) vs Crank Angle Degree
Injection Strategy
high load testing

1670 rpm – 16 bar BMEP

Baseline Engine

LTC @ <0.2gNOx

BSNOx (g/bhp-hr)

BSFC (g/bhp-hr)

BSOOT (g/bhp-hr)

0.1 1 10

0 0.1 0.2 0.3

3% 5% 10-15%

0.111 0.14 0.145 0.15 0.155 0.16 0.165 0.17 0.175 0.18 0.185 0.19
### Systems Approach

- Air system management
  - *coordinated EGR, ITH, VVA, VNT*
- Fuel Injection management
- In cylinder diagnostics
- Modeling and simulation
- Controls *Rapid Prototype Systems*

#### Multiple shot Strategies

- BSFC to DP: 1% ~ 10kPa

#### Single shot

- [Graph showing data points and lines]
VVA advantages:

- Improve volumetric efficiency at low speeds and loads
- Improve emissions by increasing ignition delay and reducing in-cylinder temperatures
- Maximize efficiencies and PCCI regions by using Miller-type cycles at part loads

Electro-hydraulic Intake Valve System control installed on the Navistar 6.4 L V8 engine.

FSN improvement islands ~ 2 FSN

BSFC improvements ~ 4%

Volumetric efficiency gains
Summary

• **Applied low temperature combustion**
  To target 2010 NOx engine out emissions using today’s Diesel fuel without active aftertreatment.

• **Approach focused on the combustion system** primarily looking to optimize
  a. The fuel injection strategy to favor premixing fuel into the charge cylinder mass.
  b. Optimize the operating boundary conditions, such as in-cylinder temperatures, EGR / in-cylinder O_2 content.
  c. Improve brake thermal efficiency.
  d. Rely on CFD to understand behavior of with pilot injection (prediction of ignition delay, heat release)

• **LTC was achieved**
  a. With EGR, temperature management for BMEP load levels of 6 bar.
  b. With EGR, high injection pressure and early injection timing for loads from 6-12 bar.
  c. Transitioning ot a multi-shot strategy at 12-16 bar load levels.

• **The technology gathered is capable for production implementation**

• **Future work will examine**
  a. The impact of VVA in the engine emissions and BSFC.
  b. The effects of a variety of fuel formulations will be tested in this platform.