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Low Temperature Combustion Demonstrator for High Efficiency Clean Combustion

DOE Contract: DE-FC26-05NT42413

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DOE MERIT REVIEW
WASHINGTON, D.C.
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National Energy Technology Laboratory
Department of Energy

Project ID ace_37_deojeda

Program Overview

Goals and Objectives

Extend LTC load Range to 12bar BMEP and higher (16.5)
Improve BSFC by 5% over base engine

Barriers

Overcome high unburned HCs and poor fuel economy
Improve BSFC

Budget

Total Project Funding:	DOE	$3,006,716
	Contractor	$3,797,467
Funding Received in FY08:		$1,216,807
Funding for FY09:		$300,000

Partners

Navistar, Principal Investigator, 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
Ricardo, engine development support

Navistar 6.4L V8 Engine Demonstrator

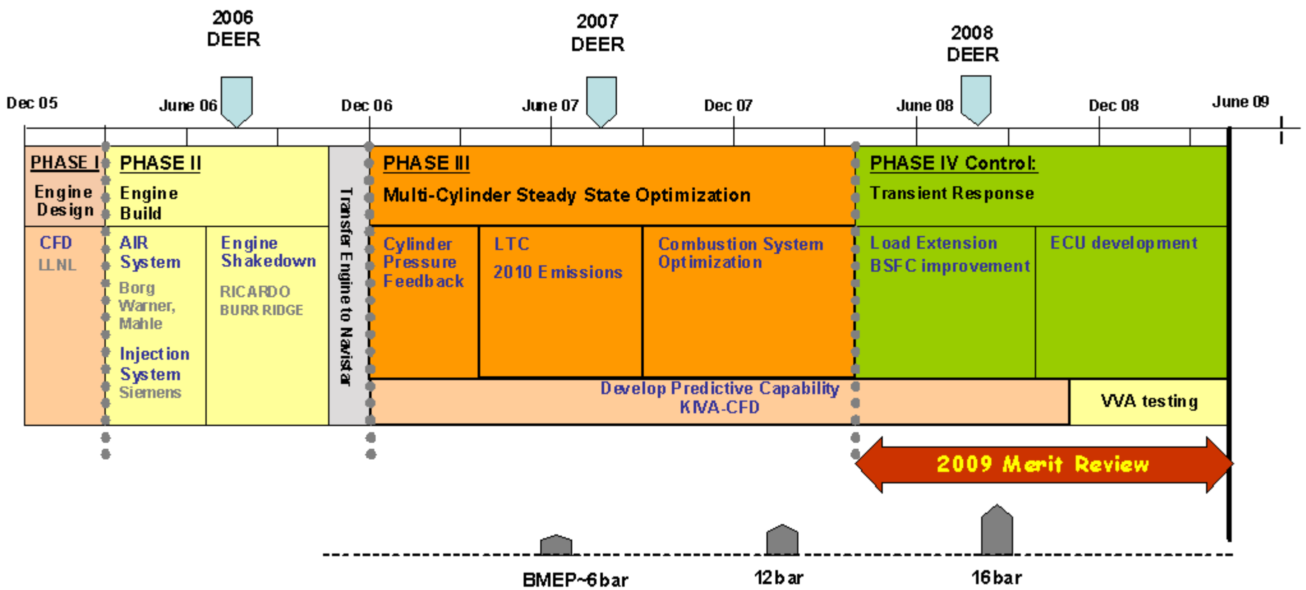
1.1 Goals and Objectives

- **Overall goal:**
  - Demonstrate application of Low Temp. Comb. to Navistar's 6.4L V8
    - Target 2010 emissions without NOx after-treatment and with minimized soot
    - Target today's Diesel fuel
  - Improve break thermal efficiency to 5% over current production
  - The technology generated in project to be capable for production

- **Phase III-IV objectives (2008-2009):**
  - Demonstrate steady-state mapping up to 12.6 bar BMEP
    - Establish injection strategy, boundary conditions (temp, AFR, EGR).
  - Demonstrate Transient Response
    - Develop control system for robust combustion process.
    - Optimize fuel / charge air mixtures in transient
    - Implement combustion feedback system
    - Limit fuel penalty and emissions between steady state and transient .

1.2 Goals and Objectives

Project Timeline and FY 2009 Milestones



Milestones

August 2008	Demonstrated 0.2 gNOx engine at above 16 bar bmep
October 2008	Demonstrate up to 5% bsfc fuel efficiency improvements
December 2008	Run Transient cycles with combustion feedback with HC mitigation
February 2009	Installed VVA engine in dynocell
March 2009	Demonstrated 90% soot reduction with VVA at part load

2. Barriers

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- **Low temperature combustion (LTC),** proven to limit NOx and Soot can lead to high hydrocarbon emissions and poor fuel economy:
  - Fuel injection, CA50 control, and charge air mixture preparation is used to limit HCs, soot, bsfc.
  - Combustion diagnostic tools are used to gain combustion stability and extend the working range.
- **LTC is characterized by ignition timing highly dependent on fuel-charge mixture homogeneity and mixture temperatures**; *variations in EGR, injector delivery, local cooling*, can lead to significant cylinder-to-cylinder ignition timing variation:
  - A control system based on combustion detection and coordinated fueling and air-system management minimizes the variation among cylinders allowing to reduce soot and HCs.
  - This work is complemented with an electro-hydraulic valve actuation. System capabilities are currently being mapped on the engine.
  - Combustion feedback is demonstrated on a production controller.
- **Engine must accommodate a range of fuel properties representative of US geography**
  - Engine testing accommodate batches of Diesel fuels ranging from of 42-58 CN as provided by ConnocoPhillips.

3.1 Approach: Combustion Modeling

A comprehensive approach towards combustion modeling encompassed:

1. Spray Model

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

- **tetradecane**
- **KH-RT breakup**
- **Turbulent dispersion**

[1] Reitz and Diwakar, SAE 870598
[2] de Ojeda and Karkkainen, 2006 DEER

2. Fuel Oxidation Chemistry

- **n-heptane (C_7H_{16})**
- **Calibration of LTC Reactions**
  - $C_7H_{15}O_2 = C_7ket_{12} + OH$
  - $CO + OH = CO_2 + H$
  - $k(T) = AT^b \exp(-E_a / R_u T)$

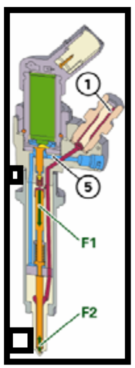
Patel et al, SAE 2004-01-0558

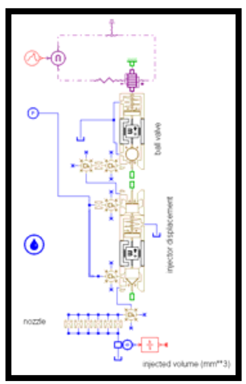
3. Emission Model

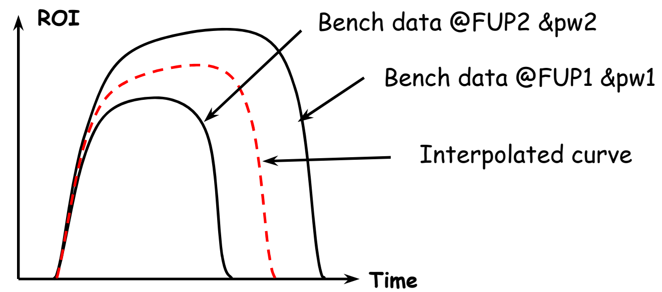
- NOX RSC ~ 1.4
- Soot asf ~ 200
- (Hiroyasu and NSC model, C2H2 as precursor)

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

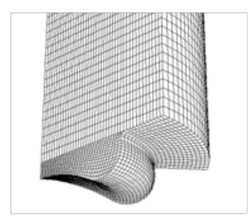
4. ROI Model

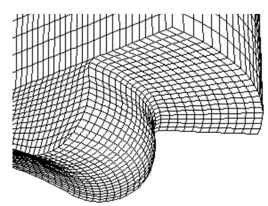






5. K3Prep used for grid generation





3.2 Approach:
Predictive tools with PCCI

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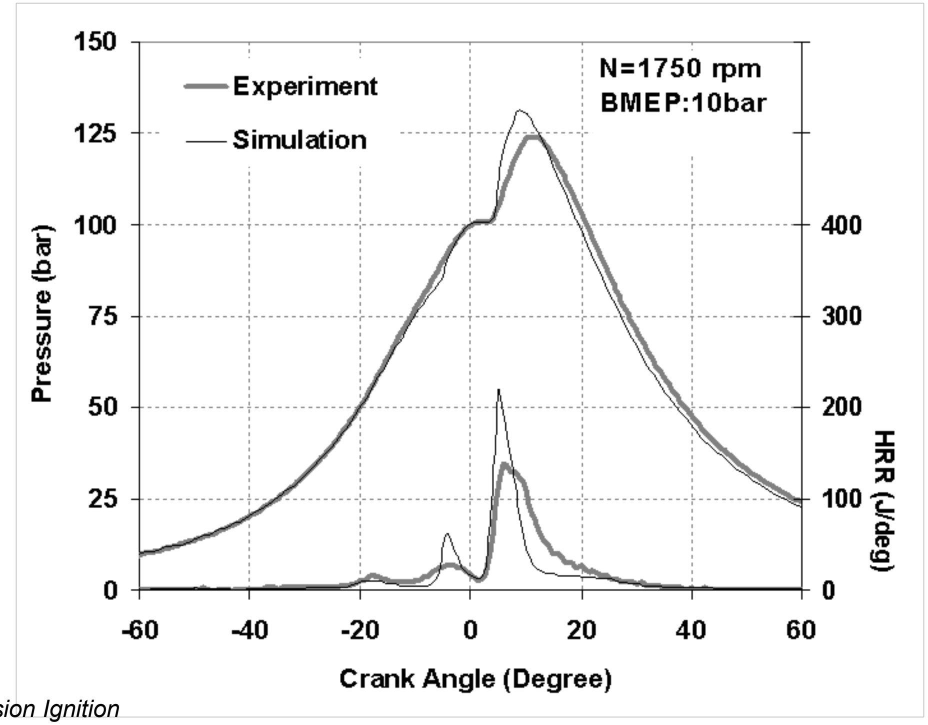
- Advantages of pilot injection consist in promoting cool flame chemistry and suppressing "early" ignition
- Simulations with pilot injection predicted lower NOx-soot emissions without bsfc penalty
- Simulations showed faster rates of combustion but captured well the start of combustion (as with the single shot injection cases)

Test-conditions

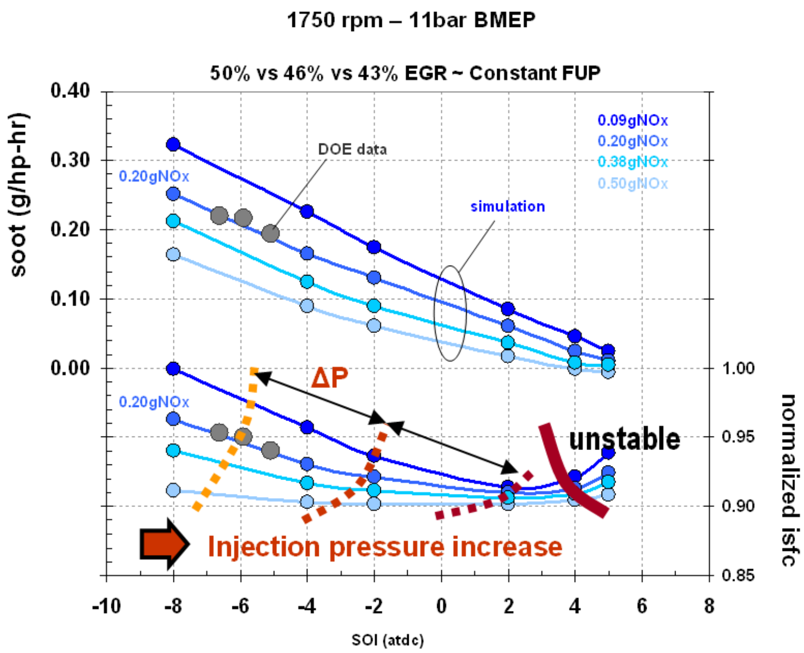
Engine Speed (RPM)	1750
BMEP (bar)	10.8
Equivalence Ratio	0.7
EGR Ratio	44.4%
Intake Temperature (°C)	43
Intake Pressure (kPa, abs)	230
Commanded Rail Pressure (MPa)	144
Pilot Injection Commanded Start of Main Injection	14mg/stk 50°BTDC
Main Injection fueling Commanded Start of Main Injection	35.7mg/stk 7.7°BTDC

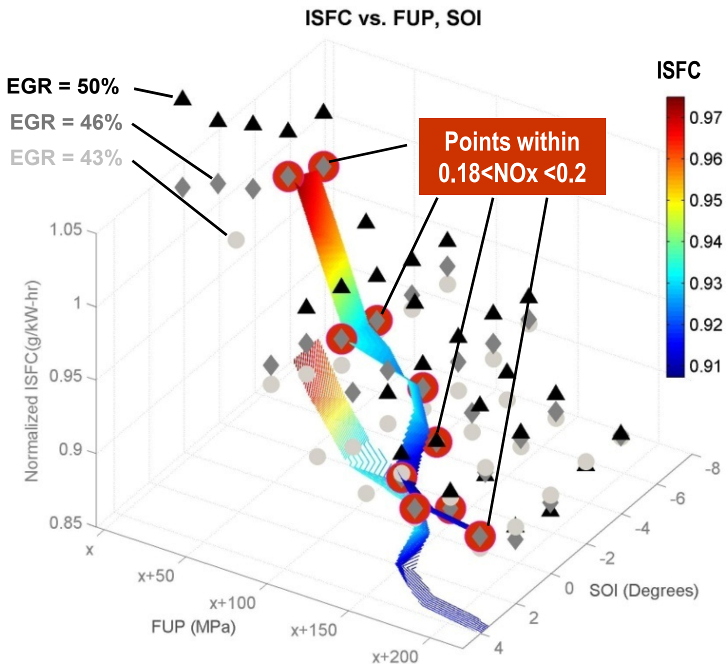


Development of a Fuel Injection Strategy for Partially Premixed Compression Ignition Combustion", William de Ojeda, Phil Zoldak, Raul Espinosa, Raj Kumar, 2009-01-1527

3.3 Approach:
Comprehensive Modeling of Injection Pressure Effect

- Injection strategies, combining injection timing with injection pressure and EGR can effectively yield improvements in thermal efficiency (in the range of 5-7%)
- BSFC improvements are coupled with soot reduction



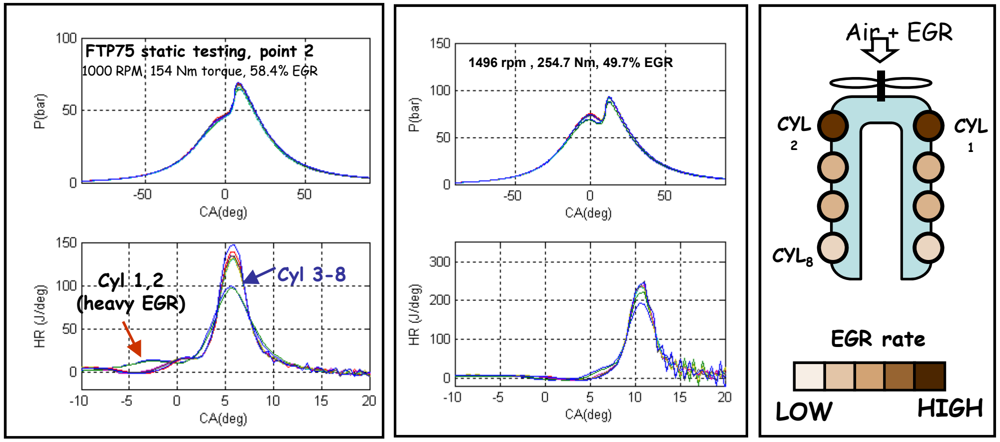


5% potential improvements are possible with injection pressure

3.4 Approach

Robust Combustion Control

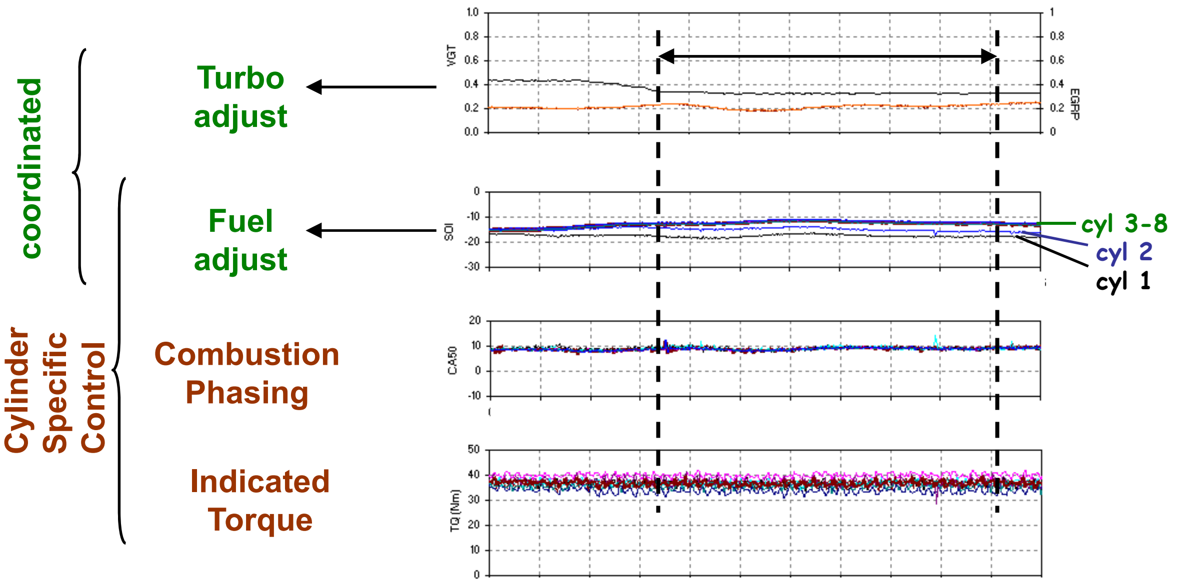
(1) The control system is key enabler to make up for the deficiency in symmetry of the engine, particularly pronounced under high EGR conditions.



Cyl 1,2 have heavier EGR due to not-optimum mixing

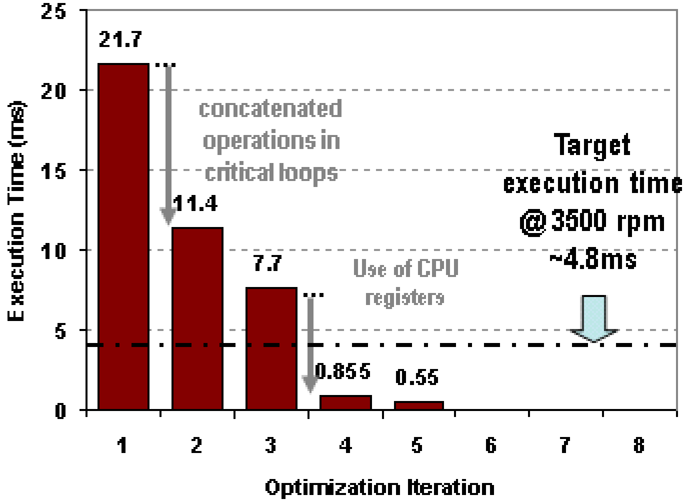
Similar trends at higher speeds and loads

(2) The misfire detection routines are effective in conjunction with the fuel and air-system controls to maintain combustion phasing and power output among all cylinders

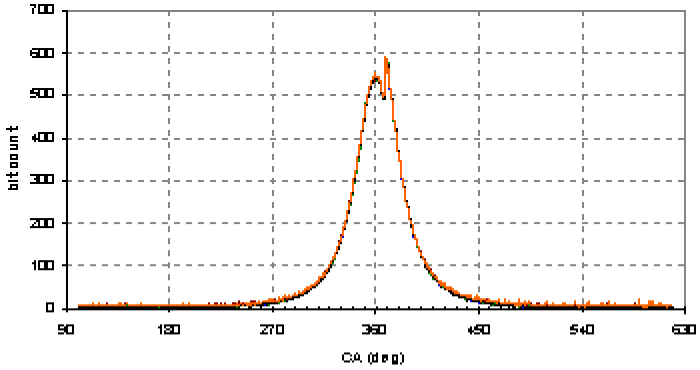


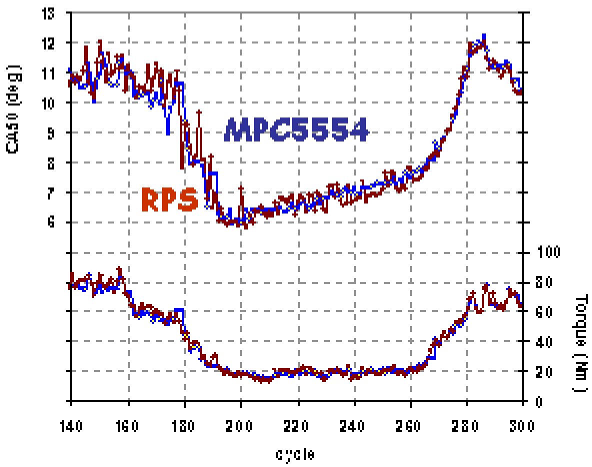
ECU capability

1. **Demonstrated successful steps to unload main processor on the production ECU**



2. **Demonstrated multi-cylinder pressure DAQ acquisition at speeds above 3500rpm**





3. **Demonstrated and benchmarked TQ and CA 50 estimates during FTP cycle**

- The MPC handles seamlessly the 50% mass burn fraction (CA50) and individual torque estimates on a cycle-to-cycle basis.
- The level of accuracy is comparable to that resolved by a lab-grade Rapid Prototype System (RPS) such as dSPACE.

Control Supervisor impact on LTC Soot

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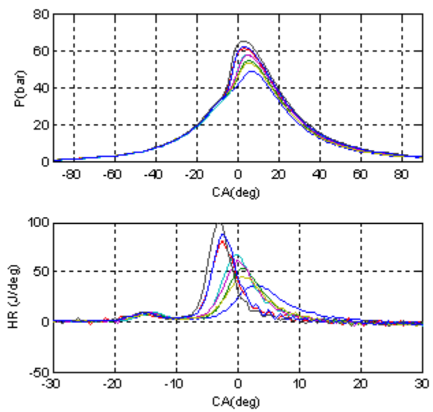
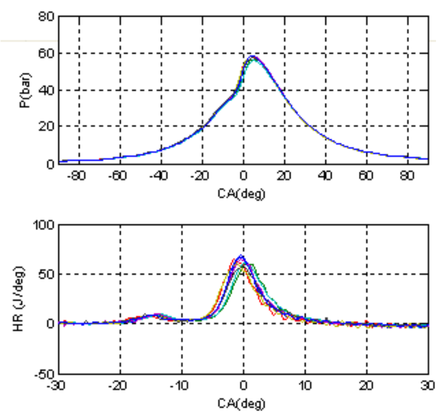
Example NOx reduction by application of LTC *adjusting injection timing alone to generates a semi-homogenous mixture*

&

reduction of soot by application of close loop control
better ignition control



Pressure and heat release traces
without close feedback



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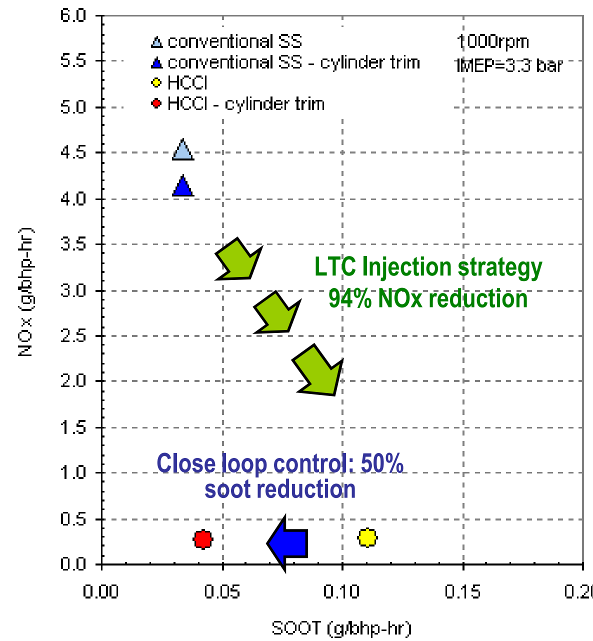

Upgraded Engine Build with VVA

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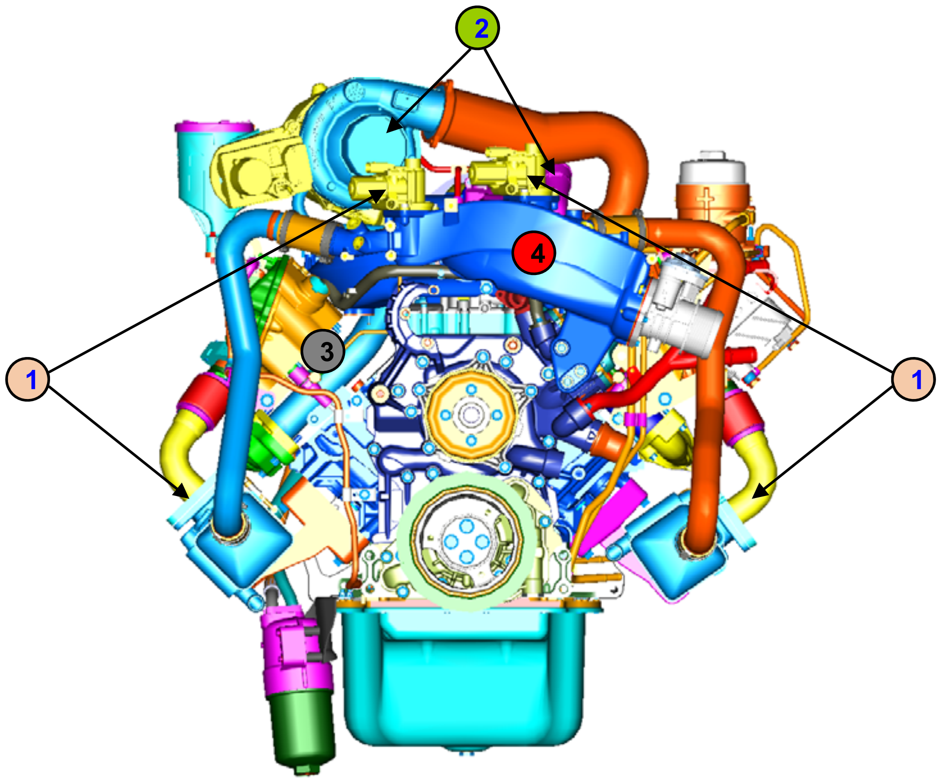
Engine build encompass:

(1) Dual-path EGR system

(2) Two-stage TC each with VNT stages

(3) High-flow cylinder head

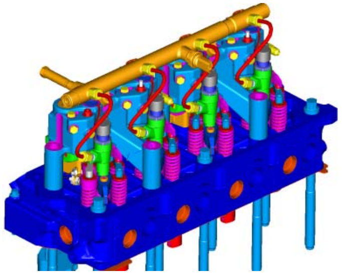
(4) EGR mixture



Upgraded Engine as of Feb 2009:

VVA system Assembly*: capable to adjust intake valve closing on each cylinder. Electro-hydraulic control allows cylinder-to-cylinder adjustment. The control can adjust commands each combustion cycle.*

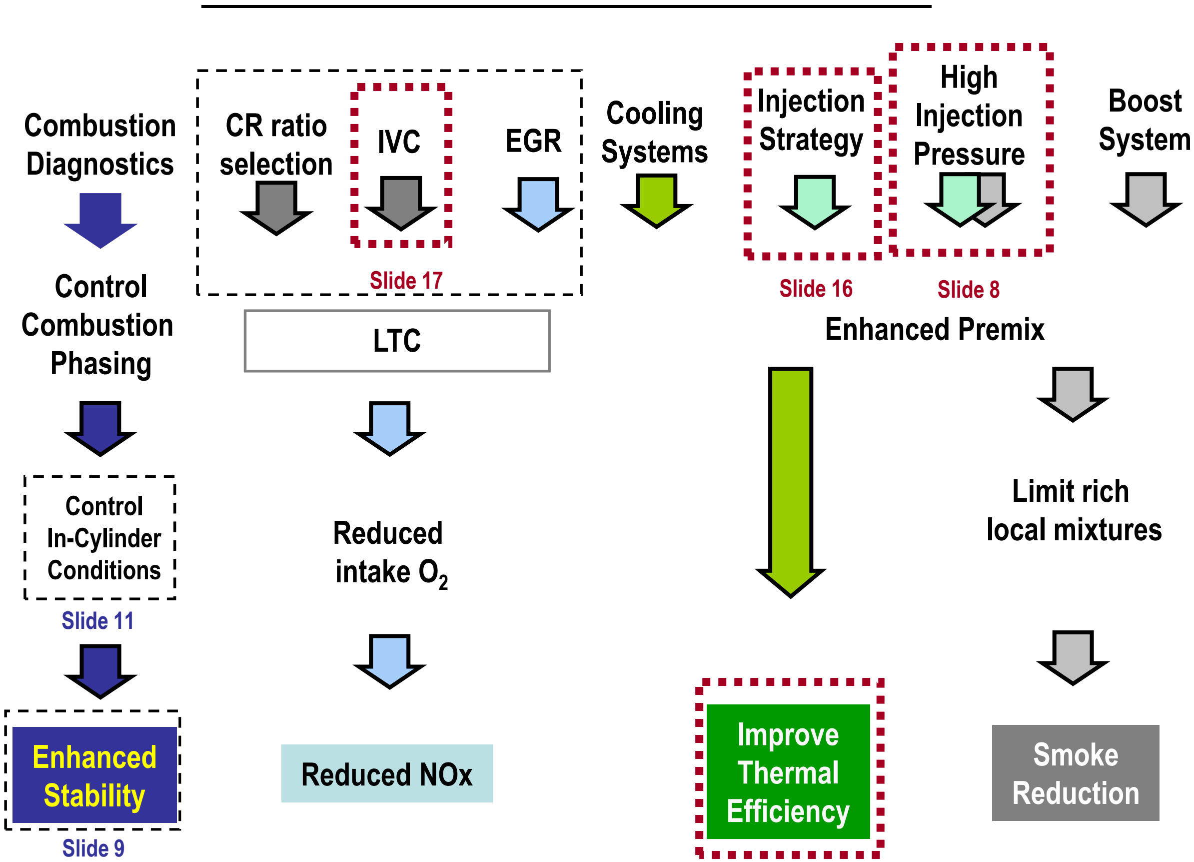
Tests are examining impact on thermal efficiency and emissions.



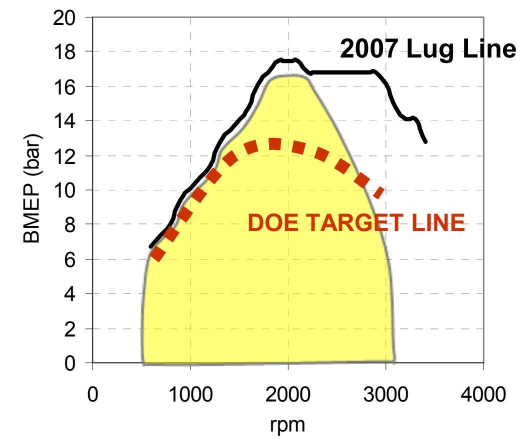
LTC Combustion Development to 16.5 bar

Combustion Strategy for LTC Performance Improvement

(NOx, soot, HC, BSFC reduction)



Present Range of testing



Impact of LTC over conventional technology

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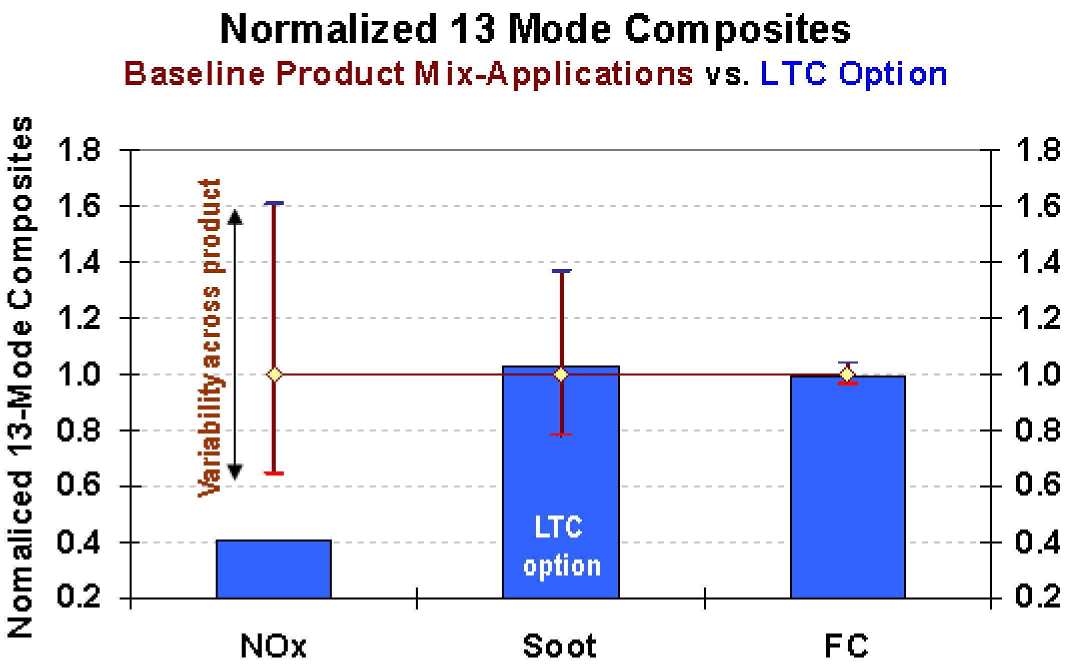
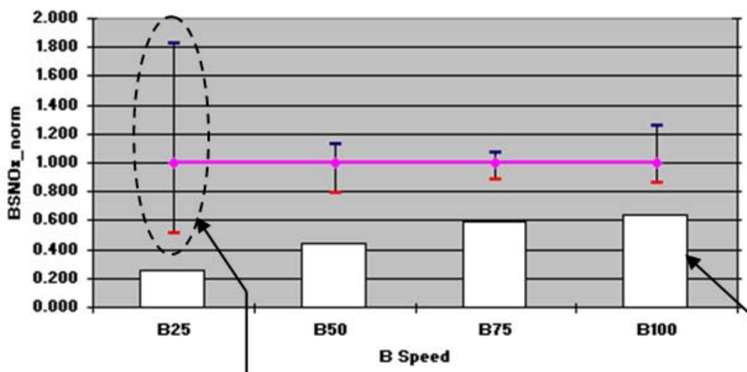
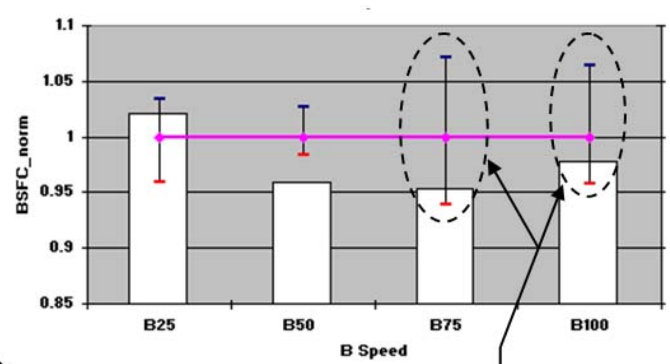
1. LTC can lower NOx from 0.5 – 1.2g levels to 0.2gNO/ghphr 2010 targets
2. Soot levels are maintained compatible to DPF regeneration requirements
3. LTC maintains or improves fuel consumption (FC) across the engine map



Statistical Analysis of multiple calibrations shows:
*** LTC can maintain favorable tradeoff between emissions and fuel economy**
*** Data is normalized around the average of baseline product**





Conventional Diesel Approach

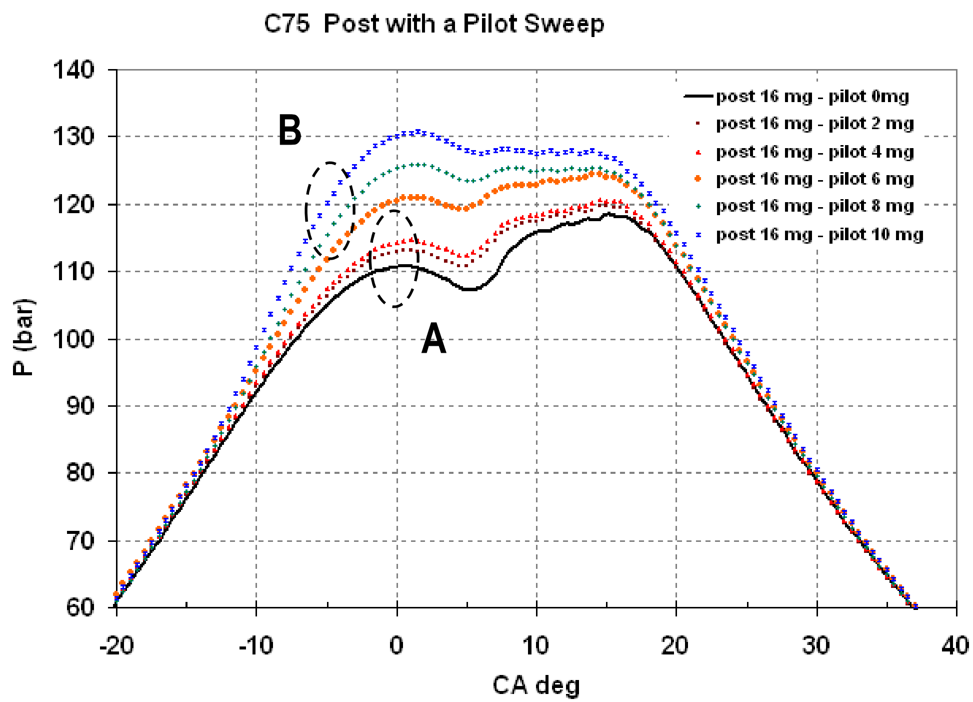
Multiple calibrations with NOx optimized to
0.5 – 1.2 gNOx engine out
Max – Average – Min shown

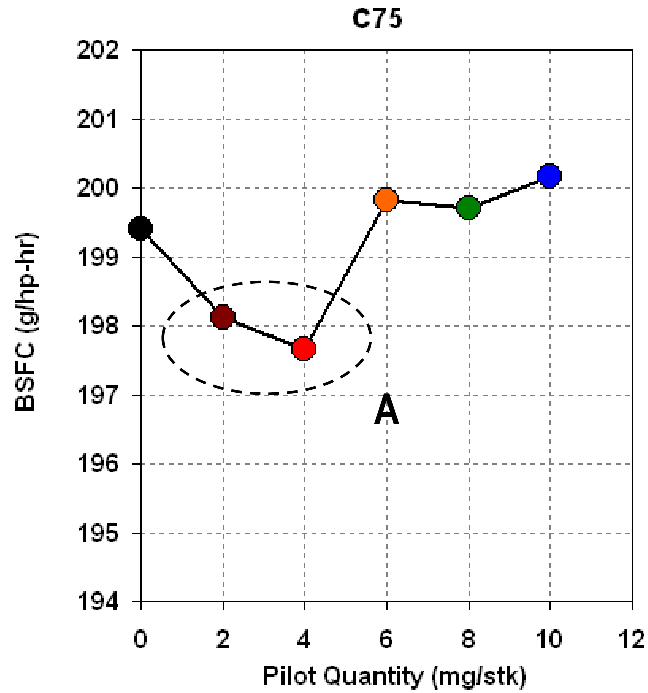
LTC

NOx optimized to
below 0.2 gNOx
engine out

BSFC
gains can be
5-10% better

Injection Strategy Optimization





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

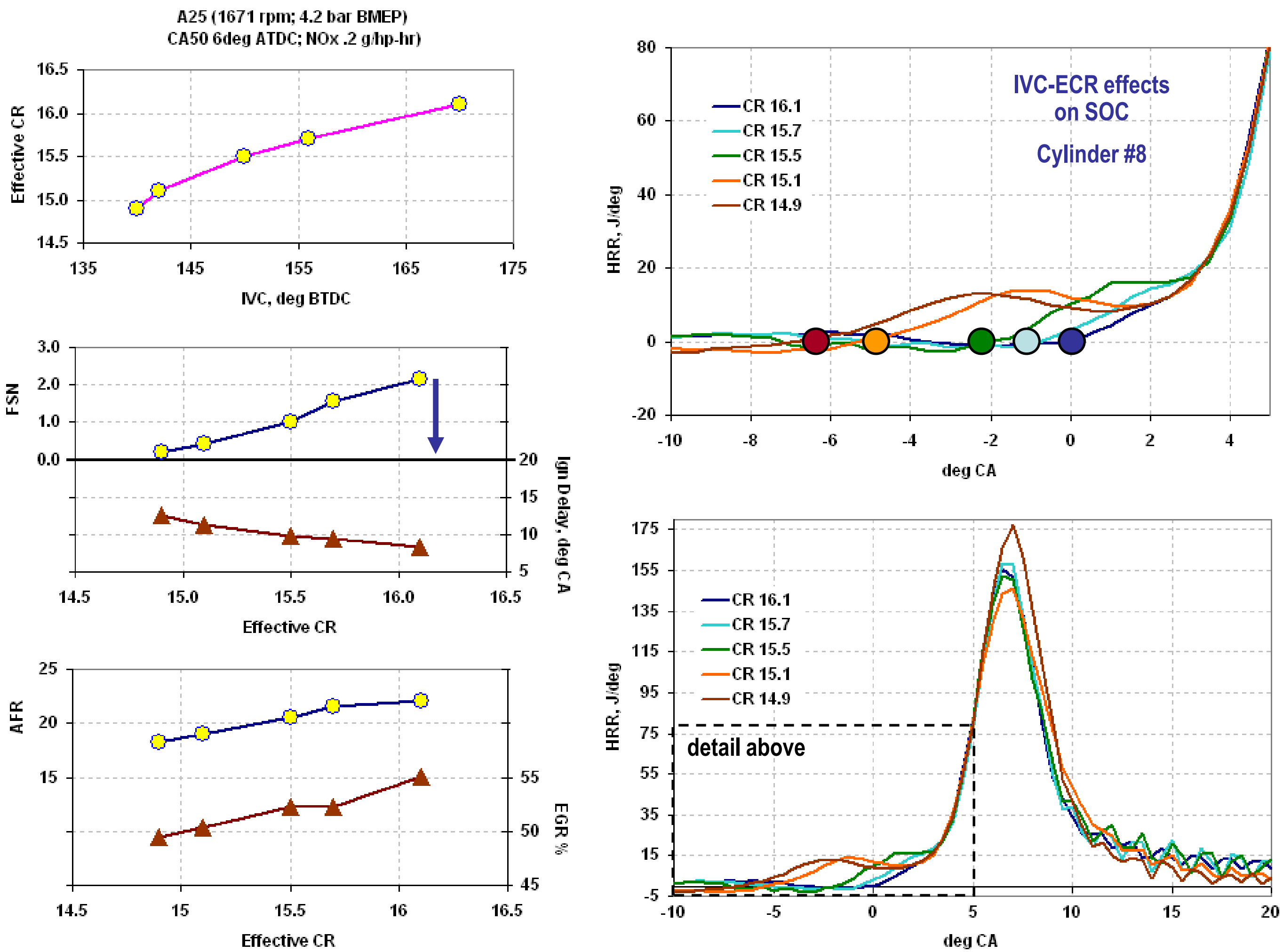
B Excess pilot deteriorates performance due to premature combustion.

Effect of IVC

Early intake valve closing reduces effective compression ratio (ECR) enhancing LTC with soot reduction of over 90%

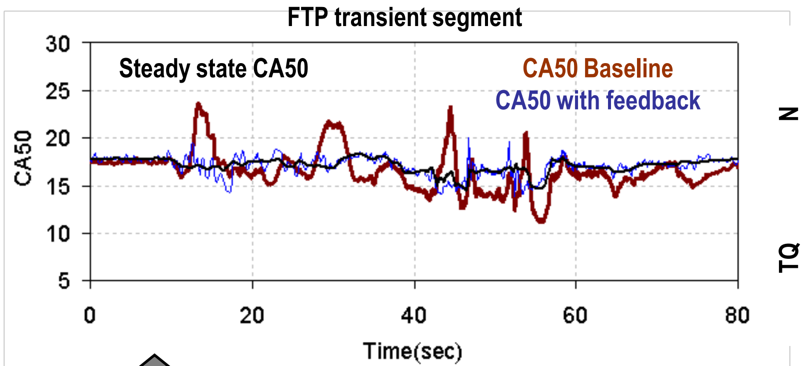
FSN decreases despite the decrease in AFR

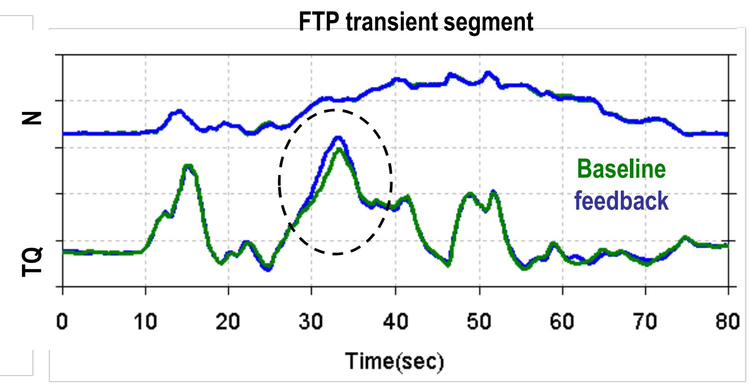
Over 90% soot reduction recorded at same BSFC

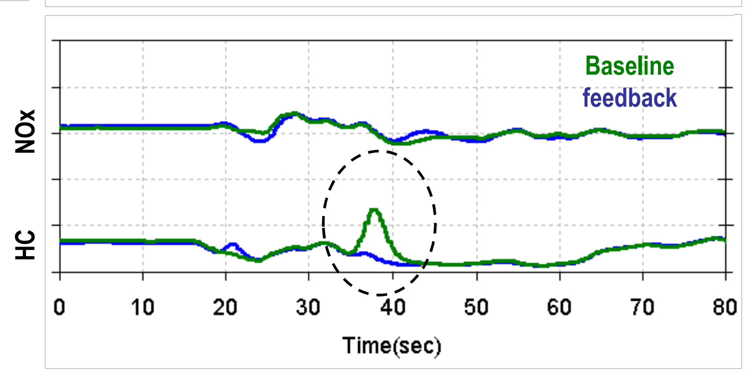


4.9 Performance Measures
Transient Results

1. Combustion feedback demonstrated enhanced capability towards better combustion control: tighter combustion phasing over baseline response.
2. HC is minimized over transient thus improving efficiency
3. Better combustion control results in improved drivability as noted in torque response.
4. Combustion feedback contributed to increased insight to modeling and predictability models.







(1) Improved combustion phasing

(2) Improved combustion efficiency

(3) Improved torque response

5. Continued Activities

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Accomplished Tasks to Date	Milestone	Comments
• Steady state mapping to 12.6 bar BMEP	✓	Present Report: extended to 16.5 bar
• NOx and Soot targets	✓	Present Report: 0.2 gNOx target met
• Demonstrate bsfc improvements	✓	Present Report: 0-5%
• ECU Development: capable of in-cylinder pressure feedback	✓	Present Report: Fully operational
• VVA Bench tests and Preliminary Mapping	✓	Present Report: 25% load
• Impact of Hardware: piston/ CR / bowl / injector	✓	Ref. Deer 2006-2008
• Combustion Sensing Technology (non-pressure sensors)	✓	Ref. Deer 2008

Next Activities

• Transient Testing		
– Model and controls to reduce HC, PM excursions	✓	Will continue development
– FTP runs	June 2009	
• VVA Testing: Extend IVC map	June 2009	
– Document emissions and performance		

6. Summary

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- Applied low temperature combustion (LTC) to the ITEC 6.4L V8 production engine:

  1. **Load:** Significant progress was made to extend LTC operation from 6 to 16.5 BMEP.
  2. **Fuel Economy:** LTC fuel economy potential was demonstrated with respect to current product over the 13 Mode cycle with 0.2gNOx/bhp-hr. Improvements of 5% were obtained at some of the 13 Modes (see slide 15).
  3. **Fuel Economy:** PCCI like injection strategies demonstrated 1-2% BSFC improvements with low emissions.
  4. **Soot:** Impact of VVA is currently being investigated. Initial results report 90% soot reduction at A25.

- Engine testing was coupled to combustion fundamentals:

  ✓ Simulation was used to predict 3-5% in combustion efficiency through increased injection pressure.

- Capability for production implementation:

  ✓ A production ECU like module was developed to perform in-cylinder combustion control.

  ✓ ECU with combustion feedback was used in transient tests with improved fuel efficiency (mitigating UHC).