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 ACE043

AGENDA

- 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

PROGRAM OVERVIEW

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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

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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

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Phase		Budget Period
I	**Applied Research and Exploratory Development** Engine Design Phase CFD parametric studies	October 2005 – May 2006
II	**Development of Technologies and Engine Build** Boost System Procurement EGR and Cooling System Procurement Fuel Injection System Optimization and Procurement Engine Shakedown	June 2006 – May 2007
III	**Multi-Cylinder Engine Steady State Testing** Combustion Feedback Development Low Temperature Combustion with 2010 EPA emissions Combustion System Optimization Design Variable Valve Actuation Technology	June 2007 – Jan 2009
IV	**Fuel Economy Optimization** Load Extension Milestone Steady State BSFC improvement Milestone Transient and Fuel Economy Demonstration Fuel Variability Demonstration System Integration (ECU, VVA)	Feb 2009 – May 2010

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Barriers	Technology Roadmap
High unburned hydrocarbons	- Higher fuel injection pressure, multiple injections - Charge temperature control - Improve fundamental understanding of the combustion process (improved chemical mechanisms)
Fuel economy	- Improved air system design - Minimize EGR driving pressure differential
Combustion stability *Cylinder-to-Cyl EGR and cooling variability*	- Fuel-Air modeling and control management - Implement combustion feedback - Variable Valve Actuation
Limited power density	- Improved vehicle cooling system (low temperature radiator) - Two stage turbo system - Increased cylinder pressure capability
Transient response	- Two stage turbo - CAC bypass
Accommodate fuel properties representative of US geography *Diesel fuels ranging from of 42-58 CN*	- Sensors - Combustion diagnostics

COLLABORATION S
AND PARTNERSHIPS

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Collaborations	Technologies
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

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]

- 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
  - $C_7H_{15}O_2=C_7ket_{12}+OH$
  - $CO+OH=CO_2+H$
  - $k(T)=AT^b\exp(-E_a/R_uT)$

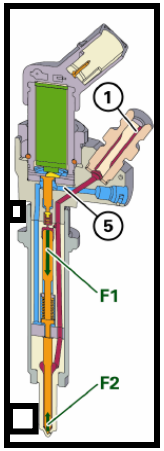
Patel et al, SAE 2004-01-0558

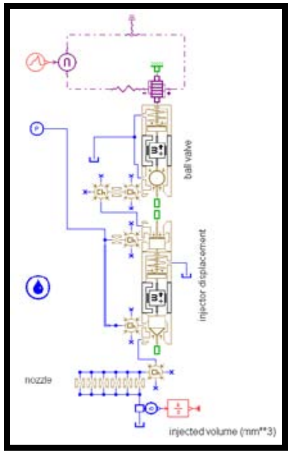
3. Emission Model

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

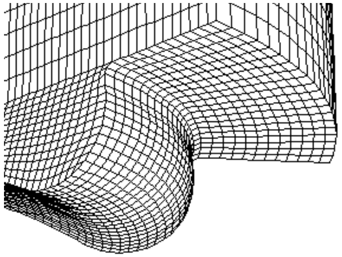
Smith et al, GRIv3 - Mech 3.0
Kong et al, IECS 2005-1009
Hiroyasu and d Kadota, SAE 760129

4. ROI Model





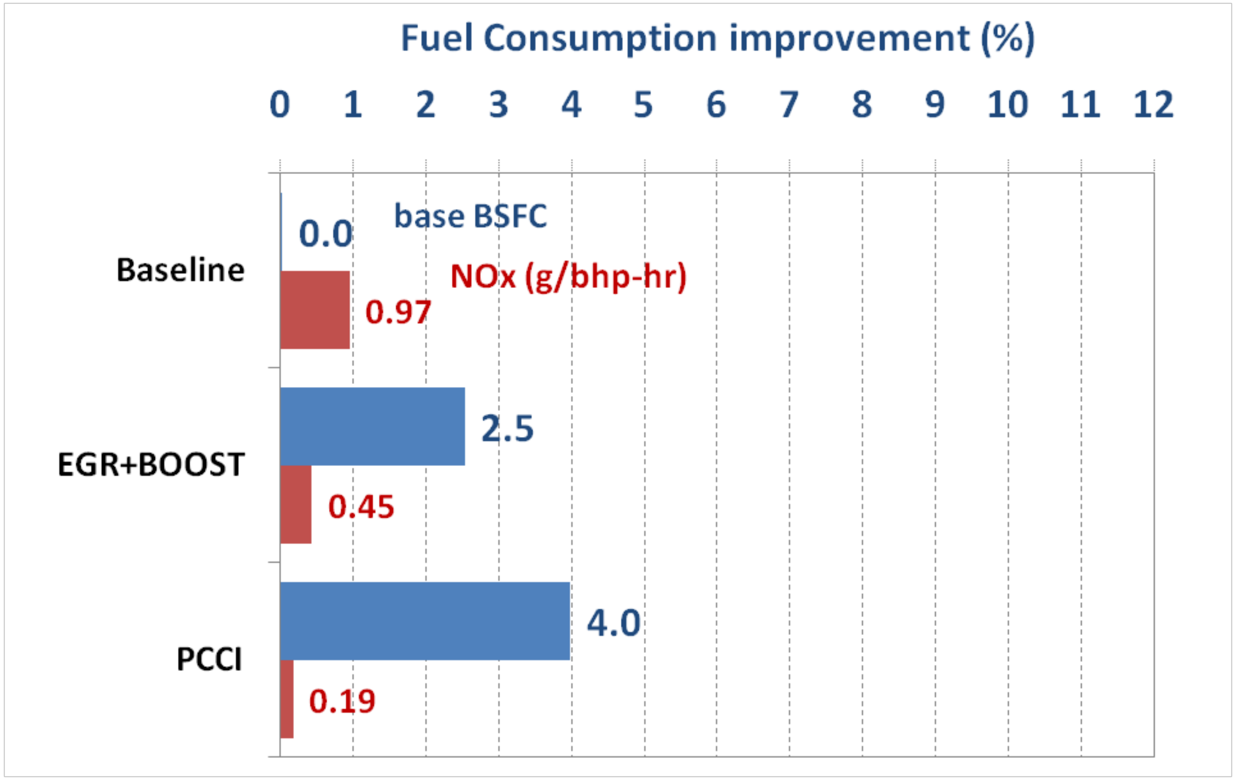
5. K3Prep used for grid generation



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

Key Deliverables for FY 2009-2010

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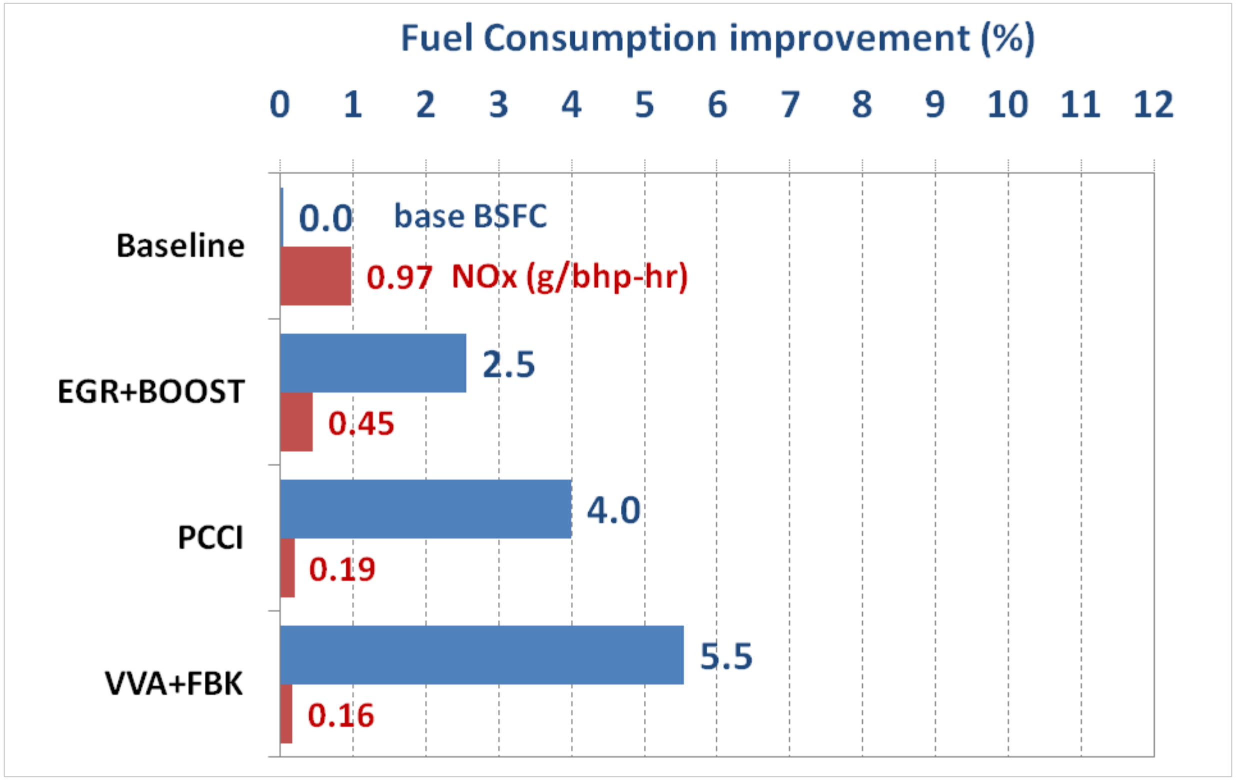
Extension of Efficient LTC operation:

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

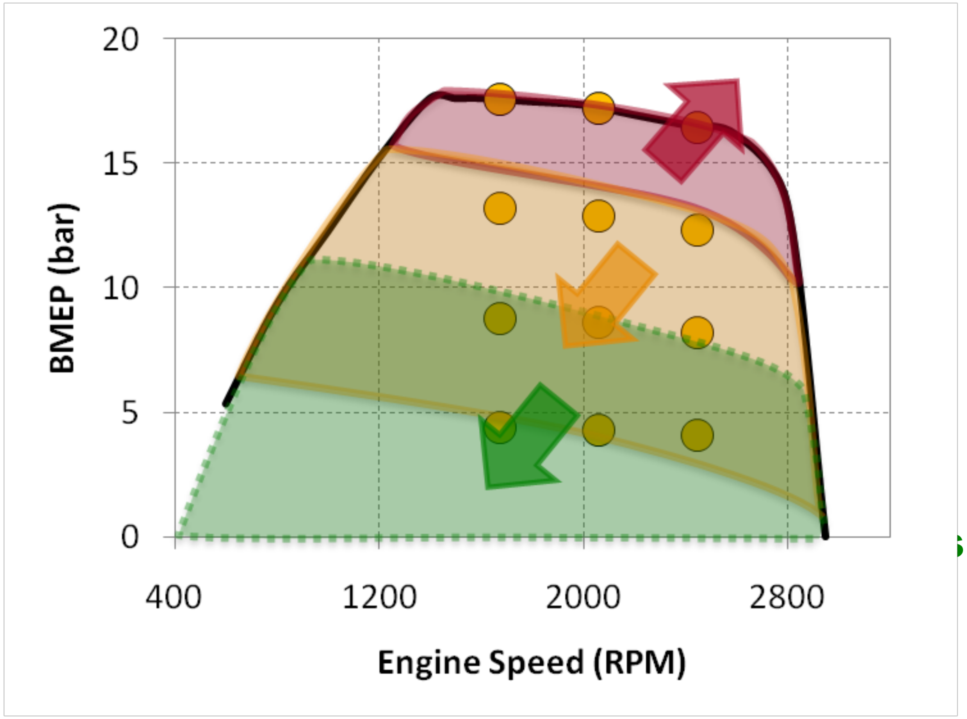
Introduced and engineering margin for 0.2g NOx target

Improved cycle average fuel consumption by 5.5%

Soot reduction was improved by 0.05g/bhp-hr

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

Advantages of VVA

Extension of Efficient LTC operation:

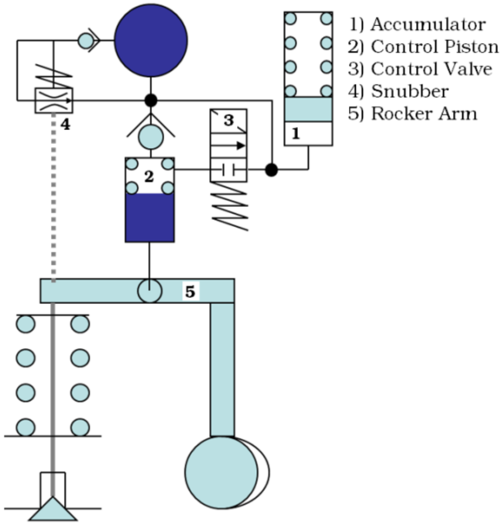
1. VVA provided greater control over the combustion process :
   - Reduced charge variability among cylinders
   - Allowed to extend the PCCI range (control over effective compression ratio)
2. Combustion diagnostics
   - Feedback was extended to VVA
   - Implementation did no tax the ECU performance.

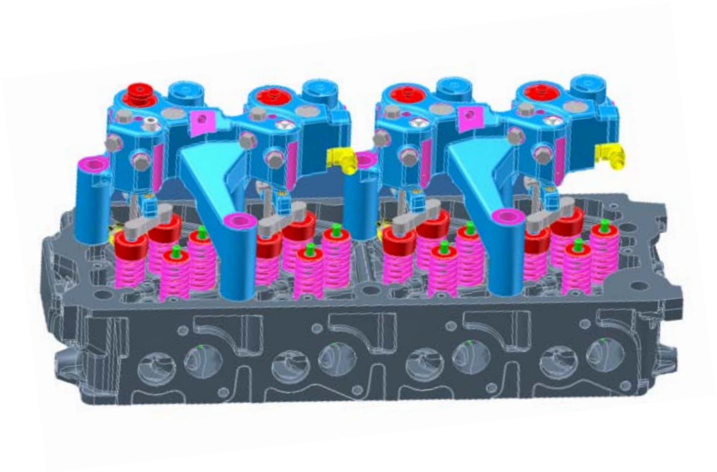
Full integration of VVA

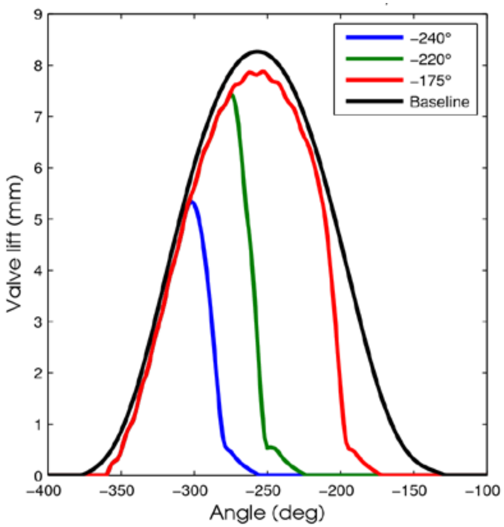
An Effective VVA Device

Advantages of Electro-Hydraulic System:

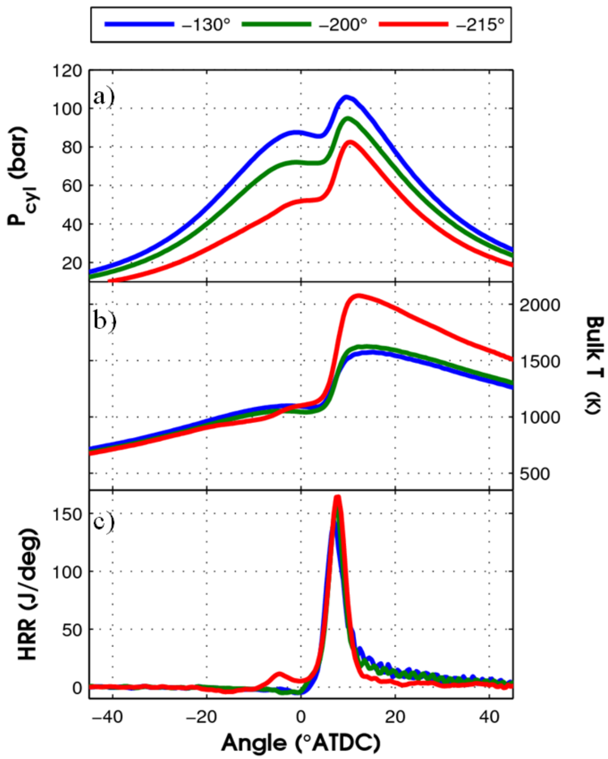
- Simple and Robust
- Fine resolution for IVC
- Cylinder to cylinder adjustment
- Cycle to cycle adjustments
- Simple package over baseline valve train



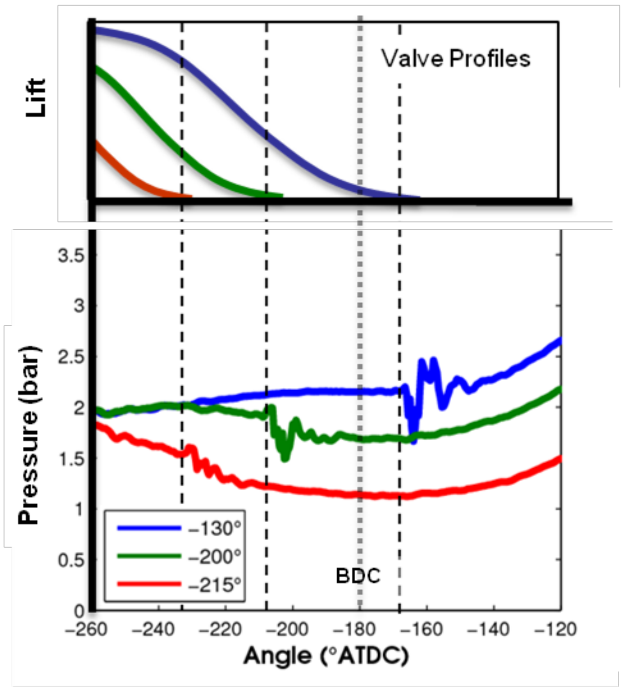




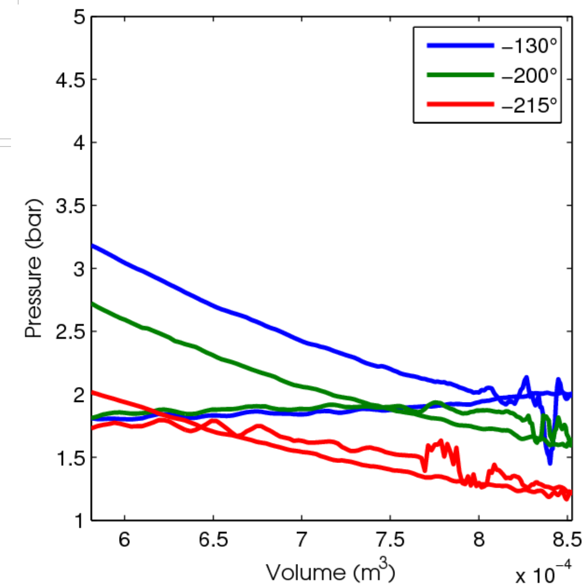
1
lowered effective CR



2
Early intake valve closing (EIVC)
lowered in-cylinder pressure



3
EIVC produces a nearly isentropic expansion (reduced losses)



4
increase ignition delay and promote cool flame chemistry

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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%

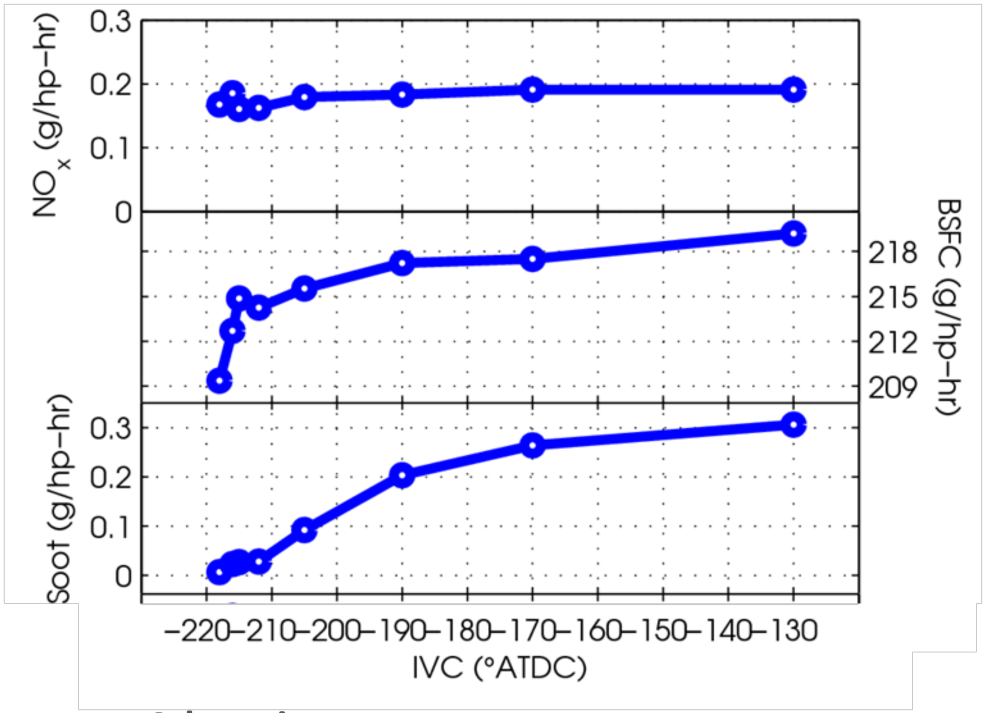
Reduced back-pressure

Offsets the increased CO and HC

3 Soot is reduced ~95%

Longer ignition delay

Lower temperatures at ignition



Advancing IVC timing ← **baseline**

Extension of LTC with Combustion Feedback

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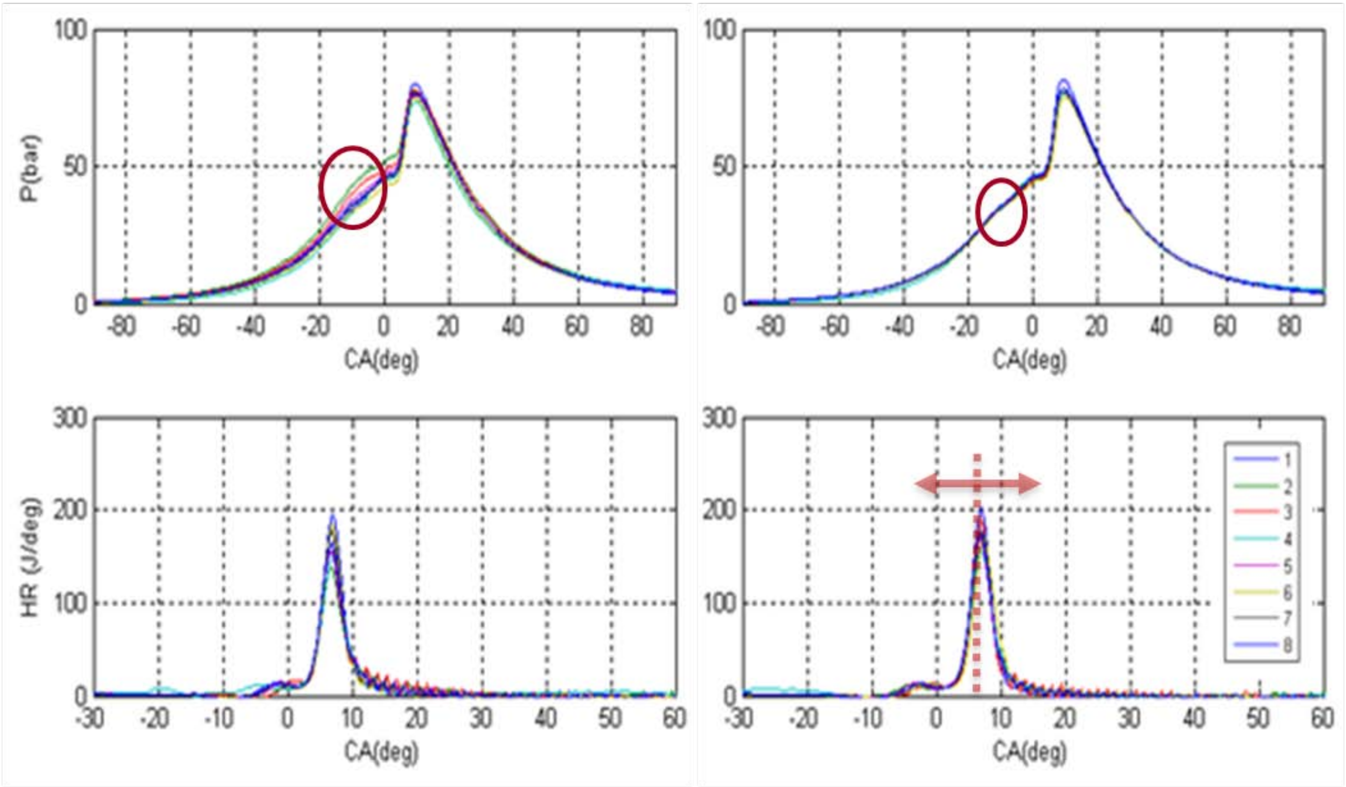
- Combustion Feedback (CBFK) was implement in Phase III to control combustion phasing.
- CBFK was extended in **Phase IV** to **control the charge** via individual cylinder-to-cylinder valve timing control: *effective system to further extend the engine PCCI operation*.



cylinder charge is controlled with VVA – eliminates variability under LTC conditions

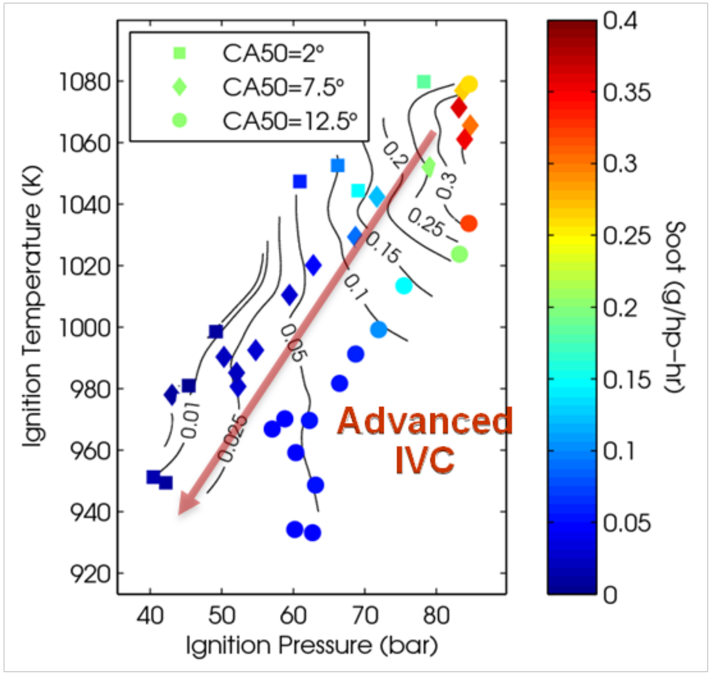
combustion phasing is controlled with fuel timing

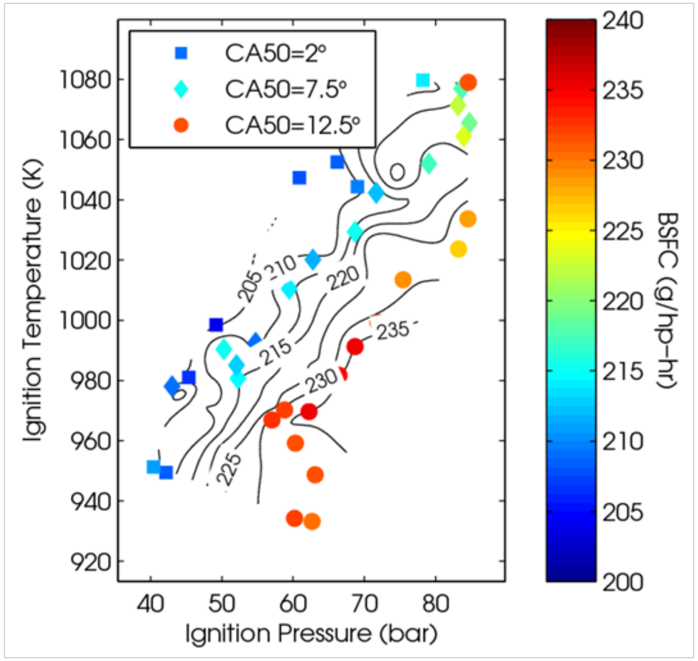
Extension of Efficient LTC with VVA strategy

VVA yielded simultaneous reduction of BSFC and PM

Comprehensive relationships in combustion parameters

All data at 0.2gNOx/bhp-hr





Ref. SAE 2010-01-1124

Significant soot reduction (~95%)

Simultaneous with reduction in fuel consumption (~5%)

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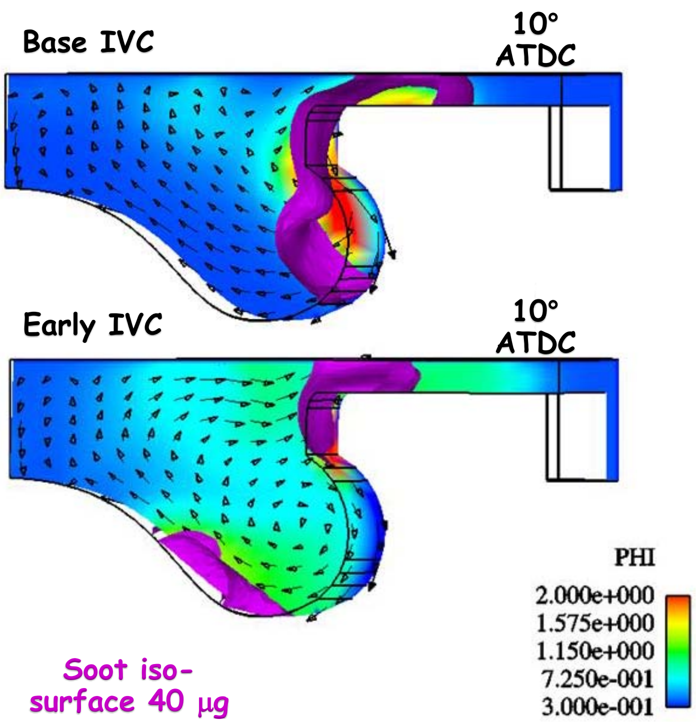
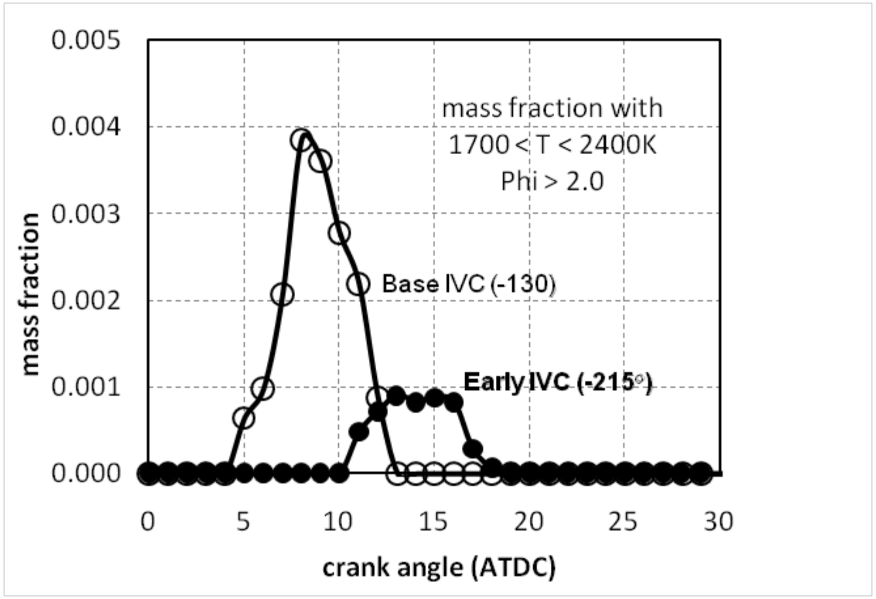
The simulations helped diagnose the soot reduction mechanisms with advanced IVC:

* better mixture characteristics
* Dependency on local equivalent ratio





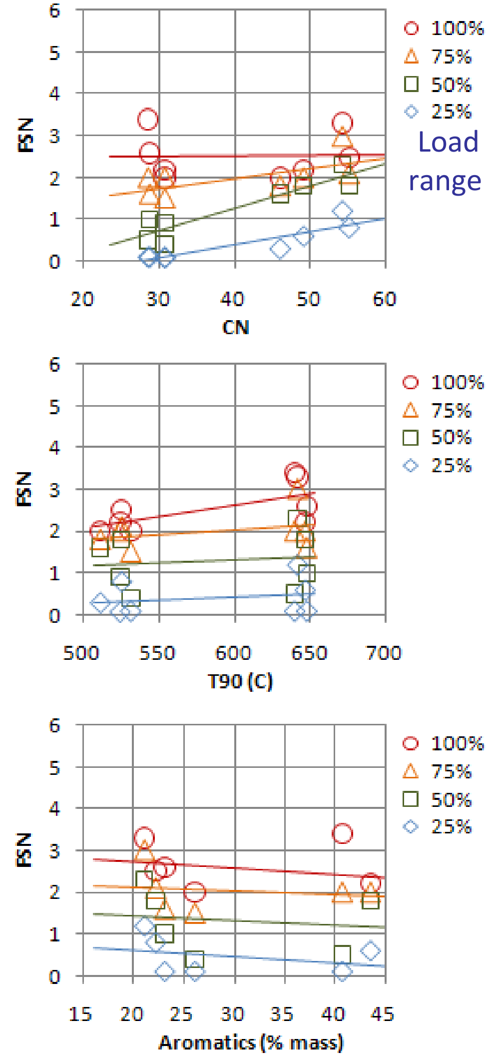
Accomplishments
Impact of Fuel Properties

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

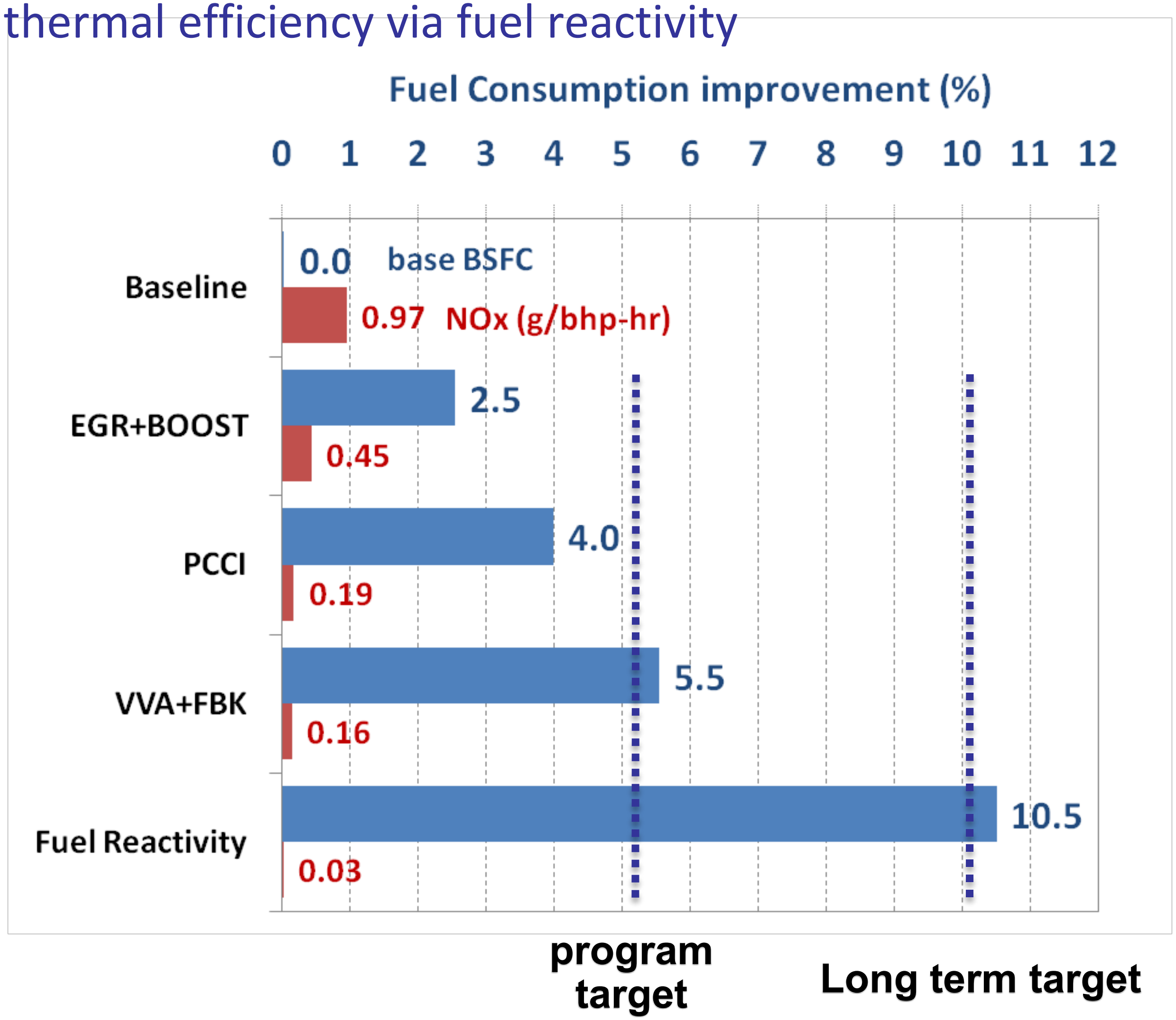
- Properties spanned CN, boiling point and aromatics*.
- The combustion was <u>robust across the fuel ranges</u>.
- Fuel reactivity has an impact over performance:
  - Efficiency improvements of 5% are possible.
  - Soot emissions can be greatly reduced.

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



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.