Heavy Truck Engine Development & HECC

DE-FC05-00OR22805

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DOE Merit Review

February 26, 2008

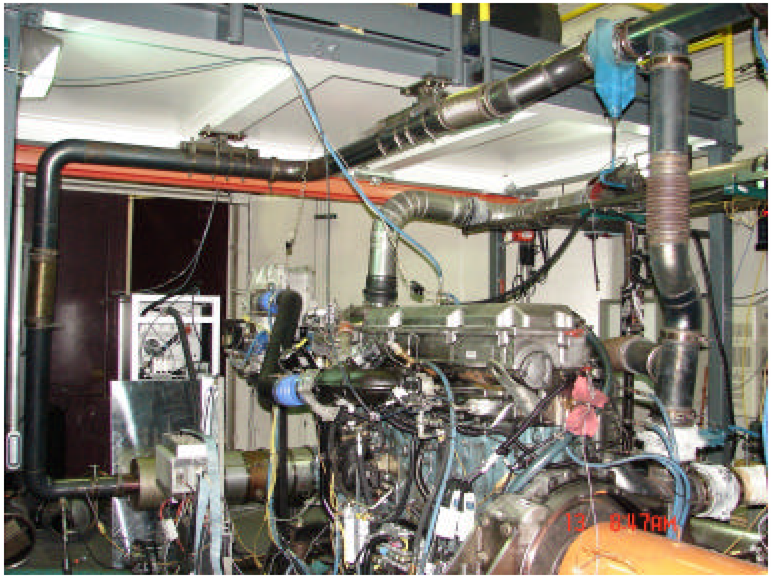
Outline

- Purpose of Work
- Responses to Previous Year Reviewers' Comments
- Approach
- Performance Measures and Accomplishments
- Barriers/Challenges
- Collaborations/Interactions
- Publications/Patents
- Future plan
- Summary

Purpose of Work

Explore advancements in engine combustion systems using high-efficiency clean combustion (HECC) techniques to minimize cylinder-out emissions while optimizing engine fuel economy

Multi-cylinder Test-bed



- Emphasis on Enabling Sub-system Technologies
  - Advanced combustion system technologies
  - Flexible, precise fuel injection
  - Air and EGR system technologies
  - Advanced multiple input multiple output control technologies

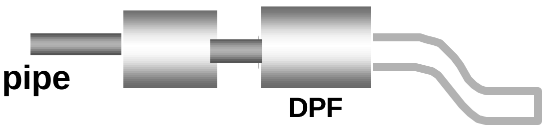
Response to Reviewer's Comments

- Technology transfer/collaborations with industry/universities/other labs.
  - Review comments:
    - *"Generally agreed that no major collaborations were mentioned. No collaborations were described in the presentation."*
  - Response
    - While the program had several collaborations, we did not include a specific slide at the last year review.
    - It will be fully addressed in this review

- Specific recommendations/additions to or deletions from the work scope
  - Review comments:
    - *"Please show more data to support your claims next year."*
  - Response:
    - Being a public forum, we are limited to the amount of details we can provide at this merit review meeting
    - All the data is always presented at our reviews with DOE Technical managers
    - Nevertheless, a large amount of data will be included in this presentation.

System Development Approach

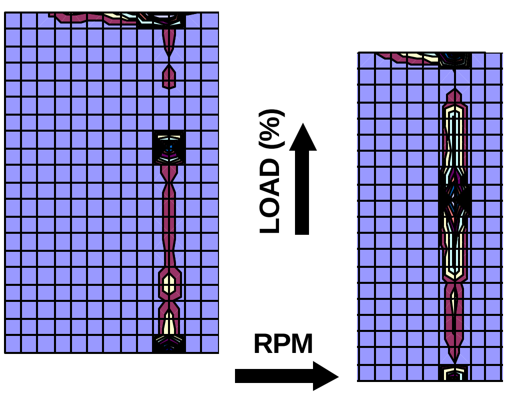
Integration of aftertreatment systems



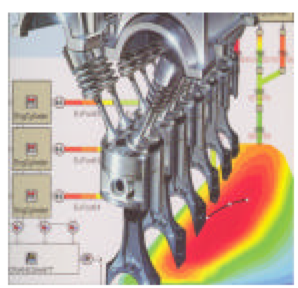
Evaluation on truck operation for overall technology assessment and refinement

Steady State and Transient Dynamometer Testing

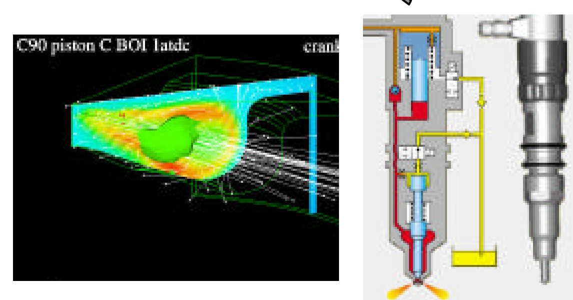
Selecting road-load operating conditions



Example Operating Conditions Over Truck Routes

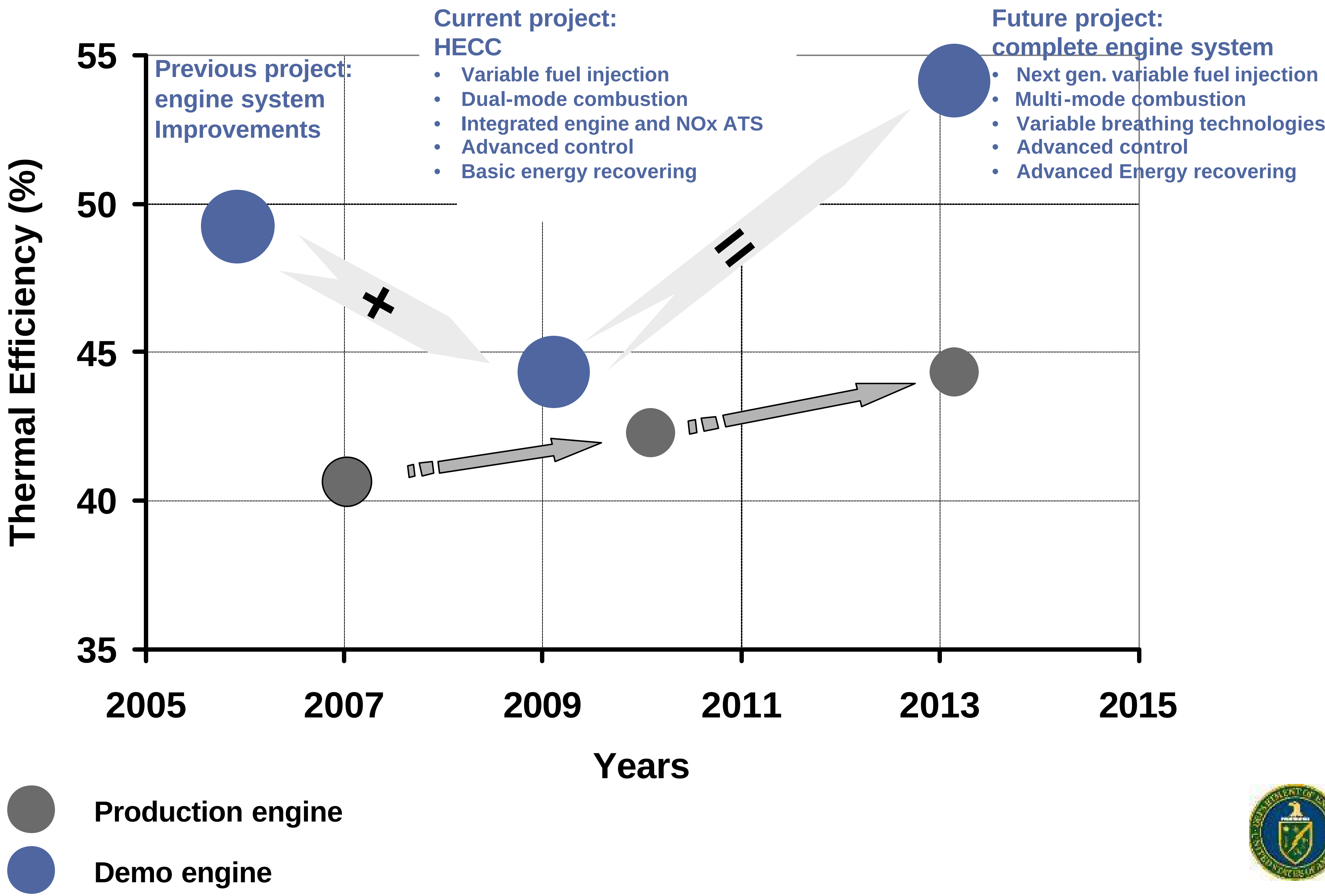


Integrated Analytical Simulation Tools



Component Optimization

Thermal Efficiency Roadmap

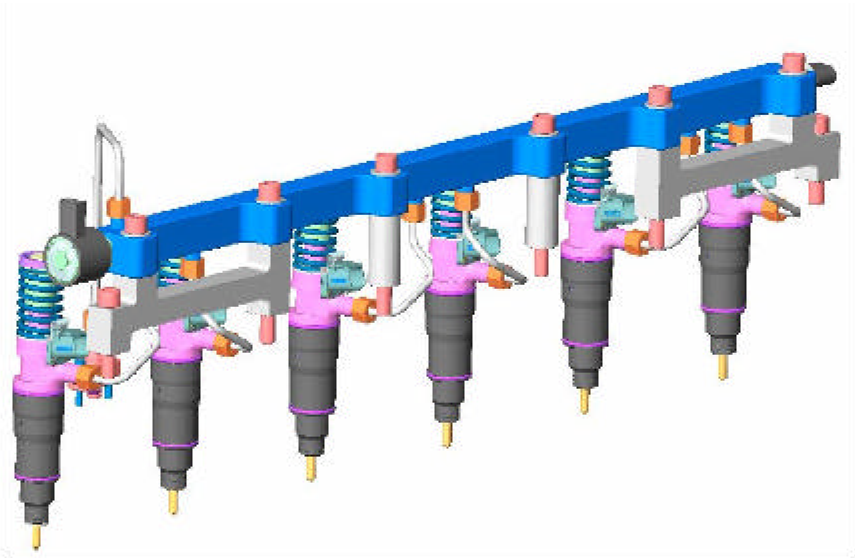


Performance Measures and Accomplishments

- Advanced fuel injection system
- Design optimizations with variable nozzle
- Innovative combustion system optimization
- Next generation control logic
- Real Time Combustion Control

Advanced Fuel Injection System

- Advanced fuel injection with full flexibility of injection events was procured and being evaluated.
- Beyond state-of-the-art variable nozzle technology is being evaluated
  - A new dual-mode combustion strategy is emerging, substantially reducing emissions, while significantly improving fuel economy



Delphi

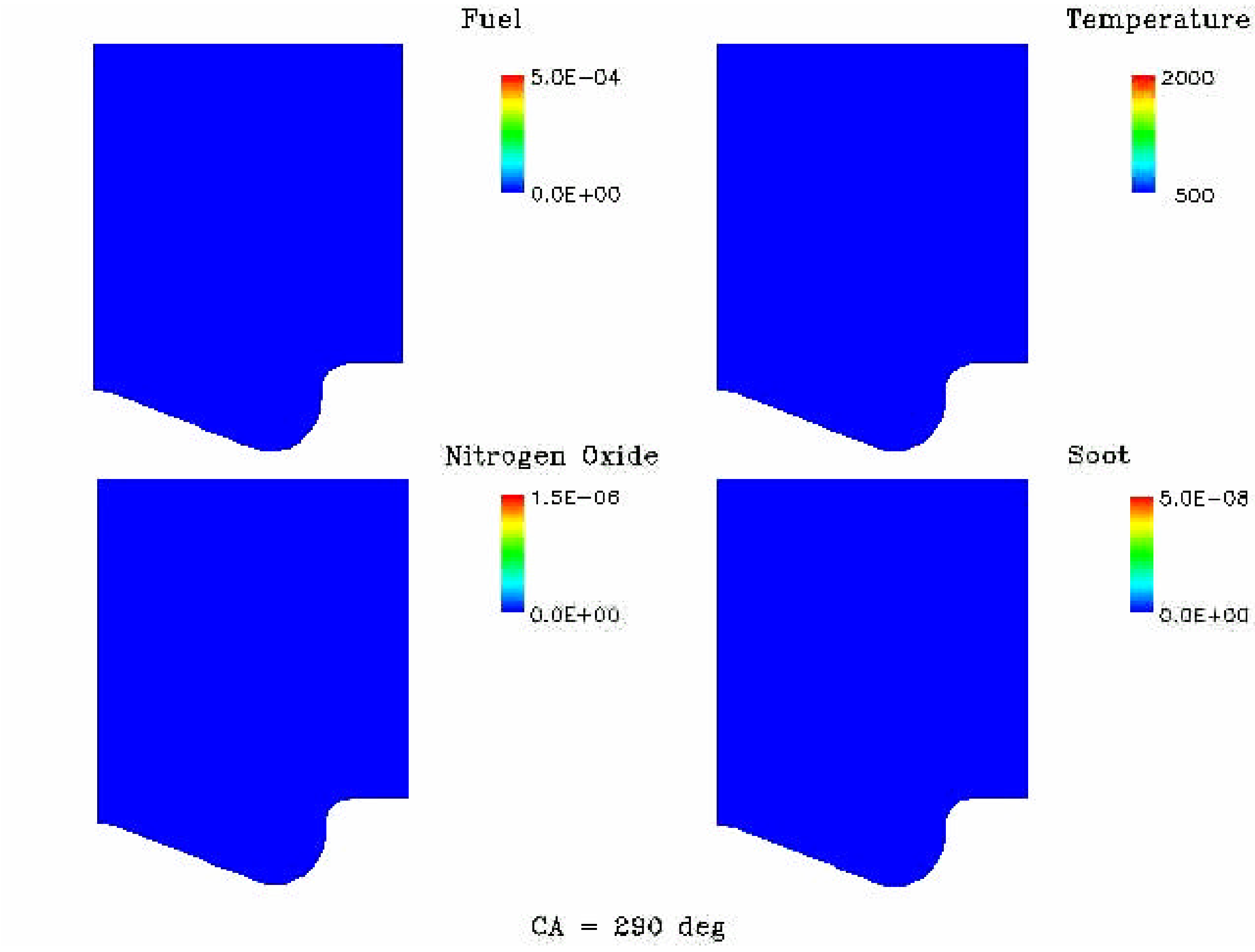
QLC QuantLogic Corp.

Design Optimization with Variable Nozzle (A25)

Case	BSFC [g/kW·hr]	NOx [g/hp·hr]	Soot [mg/m3]	CO [g/hp·hr]	HC [g/hp·hr]
Baseline	222	1.592	0.767	0.47	0.071
Dual Injection Mode	195.2	0.07	0.349	0.473	0.189
Improvement	12%	96%	54%	-1%	-166%

- 12% BSFC Improvement
- Significant reductions in both NOx (96%) and soot (54%)
- Only small increase in CO, and HC is not quite significant as opposed to other HCCI/LTC technologies

Innovative Dual Mode Combustion Strategy (A25)



Design Optimization with Variable Nozzle (A50)

Operating Conditions	BSFC [g/kW·hr]	NOx [g/hp·hr]	Soot [mg/m3]	CO [g/hp·hr]	HC [g/hp·hr]
Baseline	212.9	1.087	13.16	1.31	0.099
Dual Injection B	193.5	0.245	1.15	0.792	0.783

- 9.1% BSFC improvement
- 77% NOx reduction
- 91% soot reductions

Design Optimization with Variable Nozzle (B100)

- Significant BSFC benefits
  - 5.1% BSFC improvement
- Significant NOx and soot emissions reduction
  - 59% NOx reduction
  - 55% Soot reduction
  - Much lower CO and HC emissions than baseline

Operating Conditions	BSFC [g/kW·hr]	NOx [g/hp·hr]	Soot [mg/m3]	CO [g/hp·hr]	HC [g/hp·hr]
Baseline	190.3	1.087	0.064	0.239	0.036
Dual Injection F	**180.5**	**0.443**	**0.029**	**0.171**	**0.004**

Innovative Combustion System Optimization

DETROIT DIESEL

New Approach

Best Emissions and / or
Best Fuel Economy
Targets / Objectives

↓

Genetic Optimization Scheme

Hardware

Piston bowl,
compression ratio,
swirl ratio

Injection System

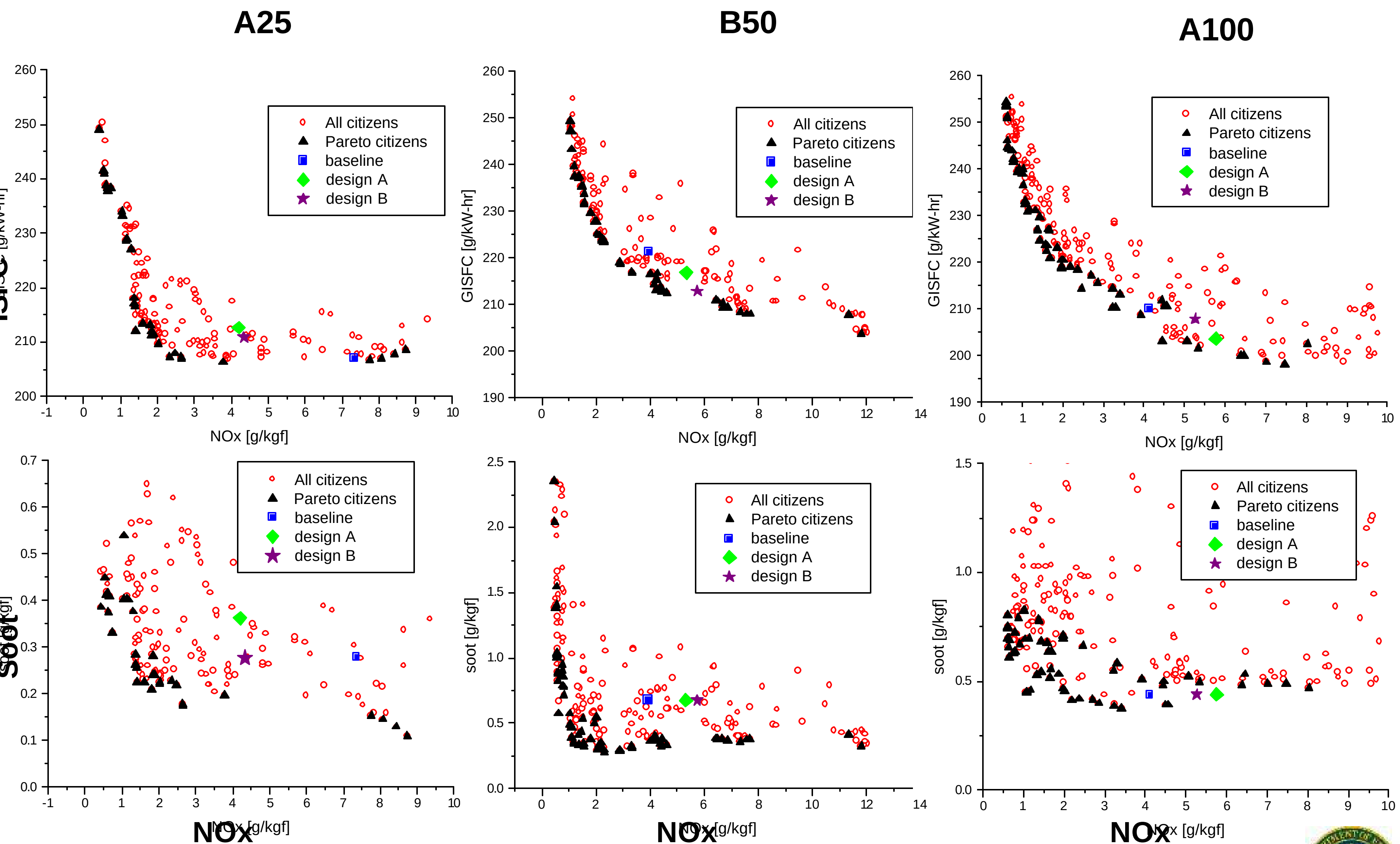
Number of holes,
spray angle,
hydraulic flow rate,
tip protrusion,
multiple injection

Calibration

Injection timing.
injection pressure,
EGR rate,
injection scheme

- New approach is able to significantly shorten development cycle in achieving program objectives

The Multi-Objective Genetic Algorithm Optimization Methodology



Optimization did not target specific combustion concepts

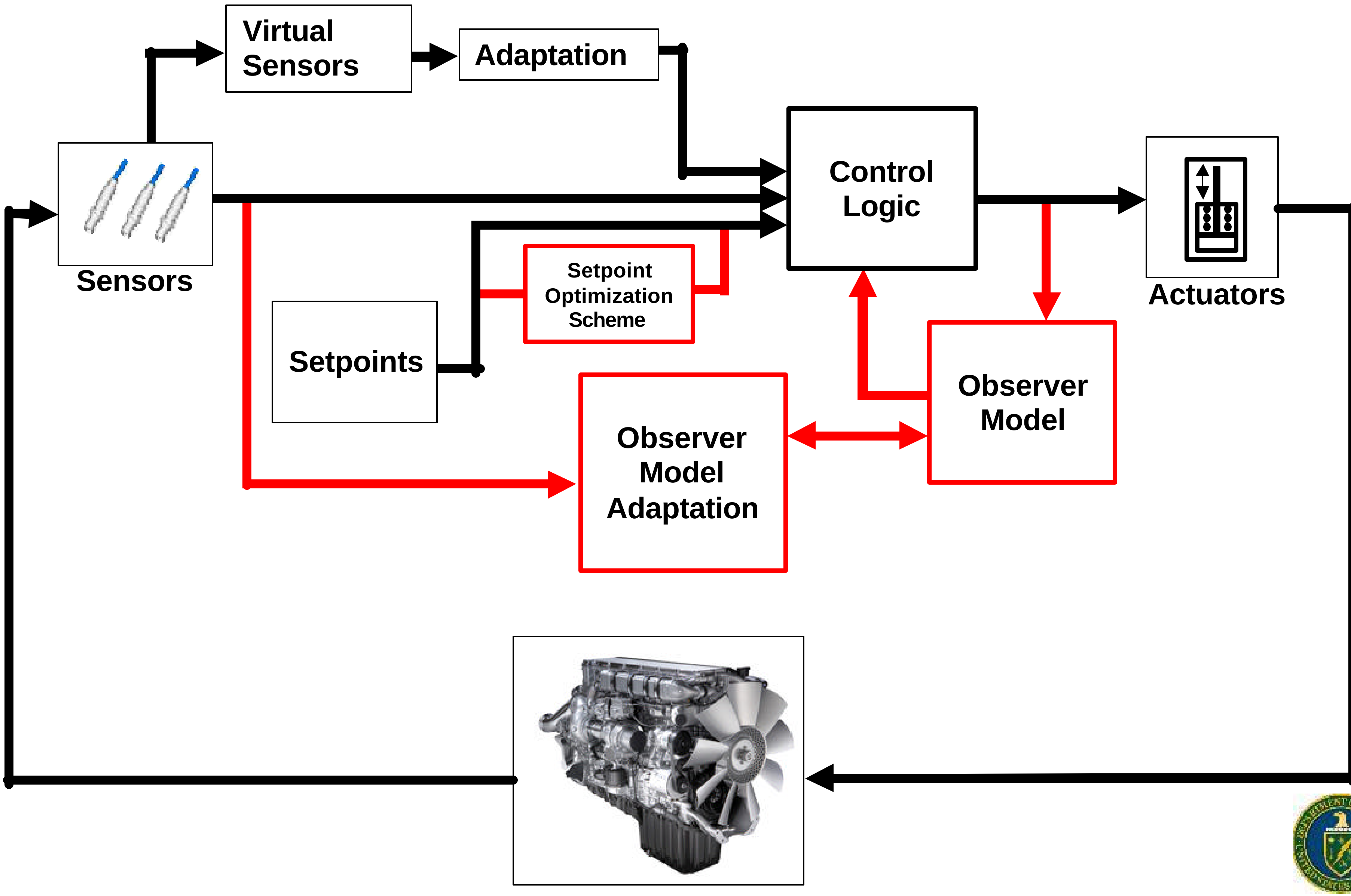
Specific Combustion Optimization on PCCI

The objective is to achieve similar soot and NOx emissions to that of the baseline case but with a ~10% fuel consumption improvement

run	Soot	NOx	gisfc	Fuel economy improvement
	g/kgf	g/kgf	g/kW-hr	%
base	0.23	3.24	233.3	-
1	0.12	5.27	201.1	13.8
2	0.41	7.76	223.0	4.4
-----	-----	-----	-----	-----
11	0.33	1.98	212.9	8.7
12	**0.19**	**3.72**	**208.1**	**10.8**

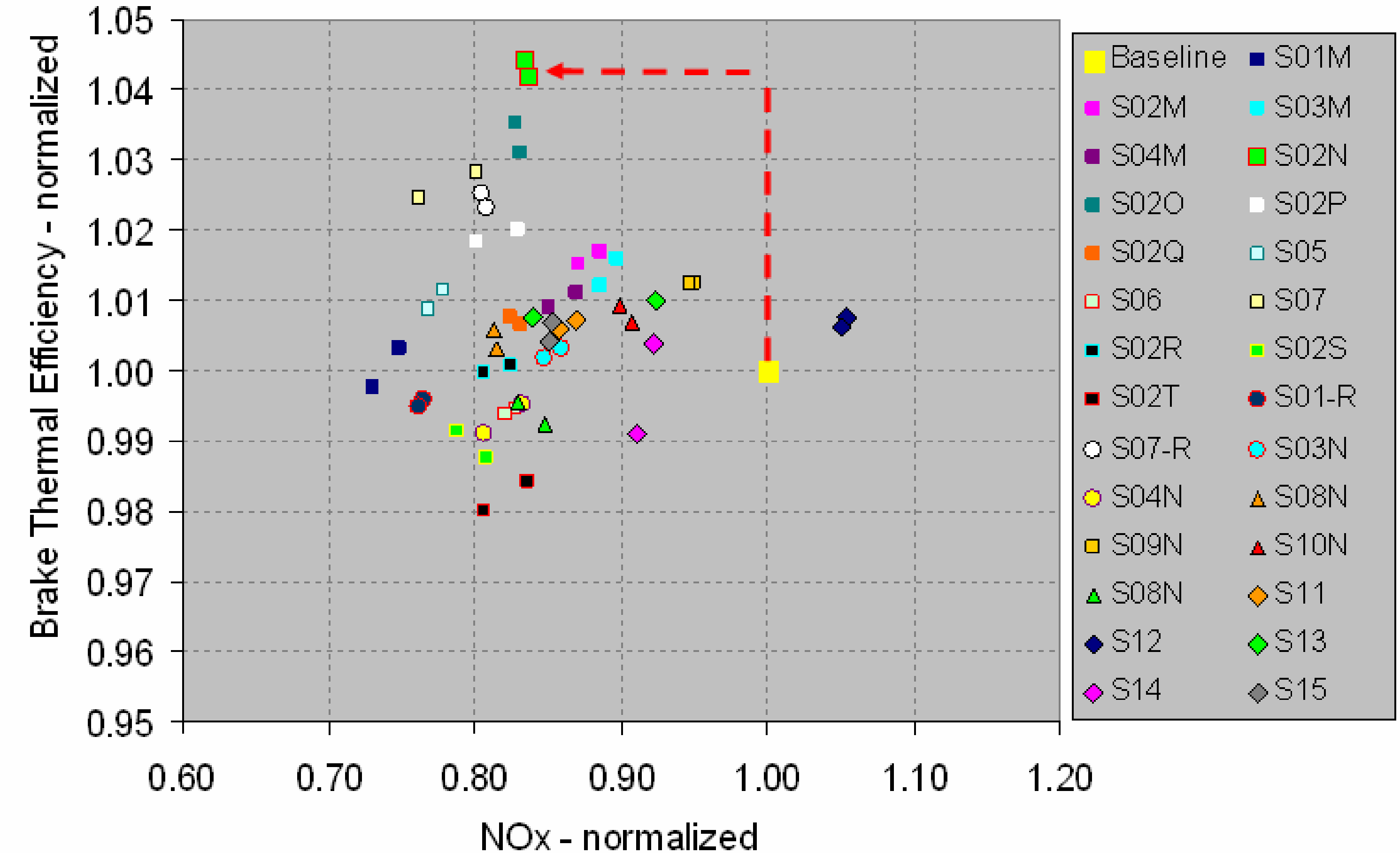
- 10.8% fuel economy improvement was obtained while maintaining the same emission level as baseline.
- Engine testing is under way and more results will be reported in the next review meeting

Next Generation Control Logic



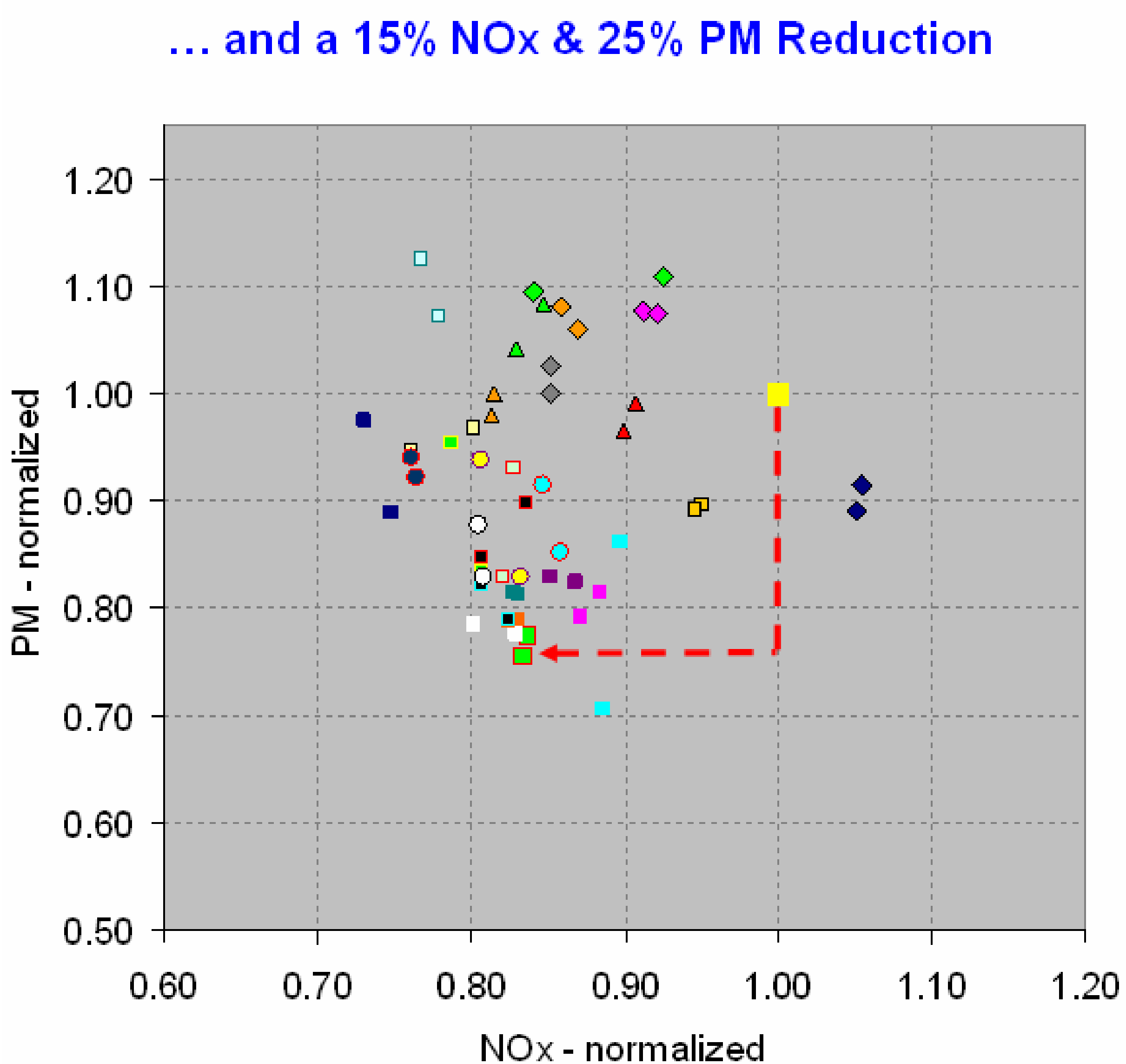
Transient Calibration Optimization (1)

Best Optimized Calibration Provided a 4% Thermal Efficiency Improvement …



SAE Paper, 2008-01-1365, 2008

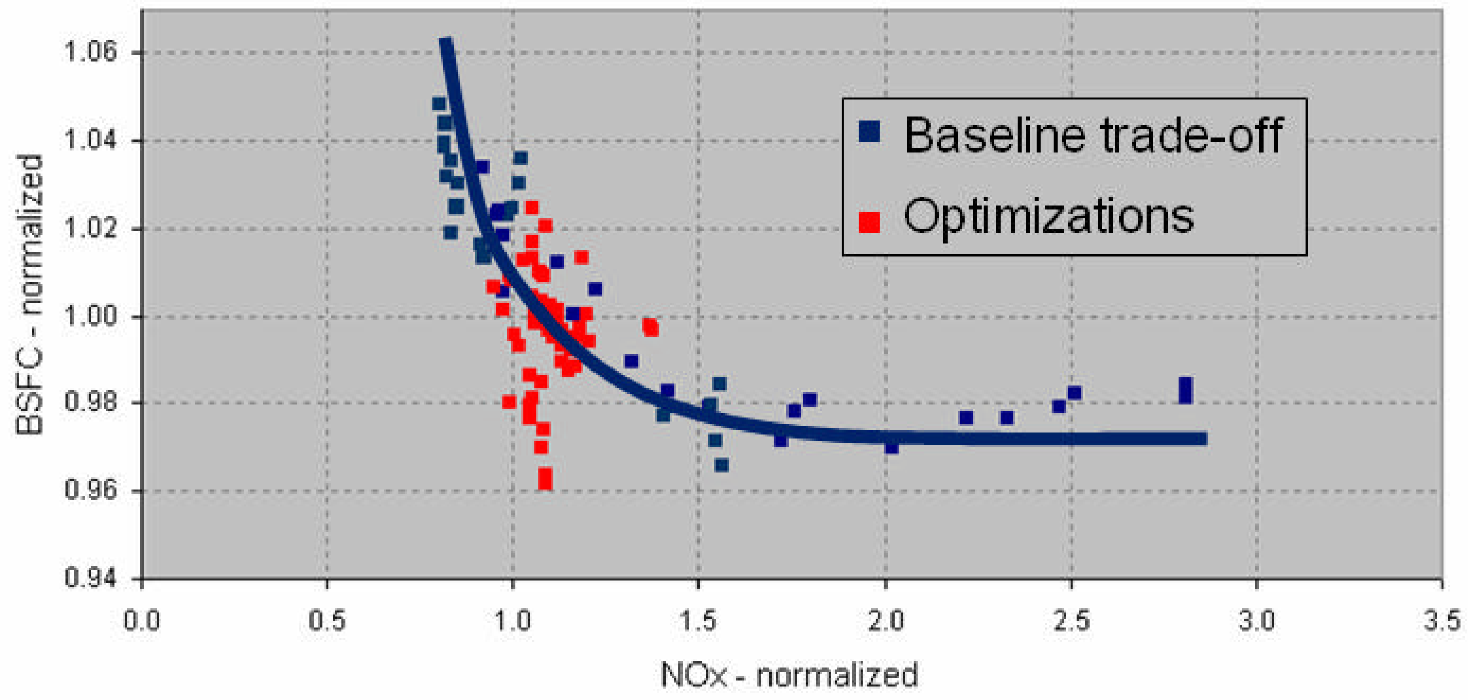
Transient Calibration Optimization (2)



SAE Paper, 2008-01-1365, 2008

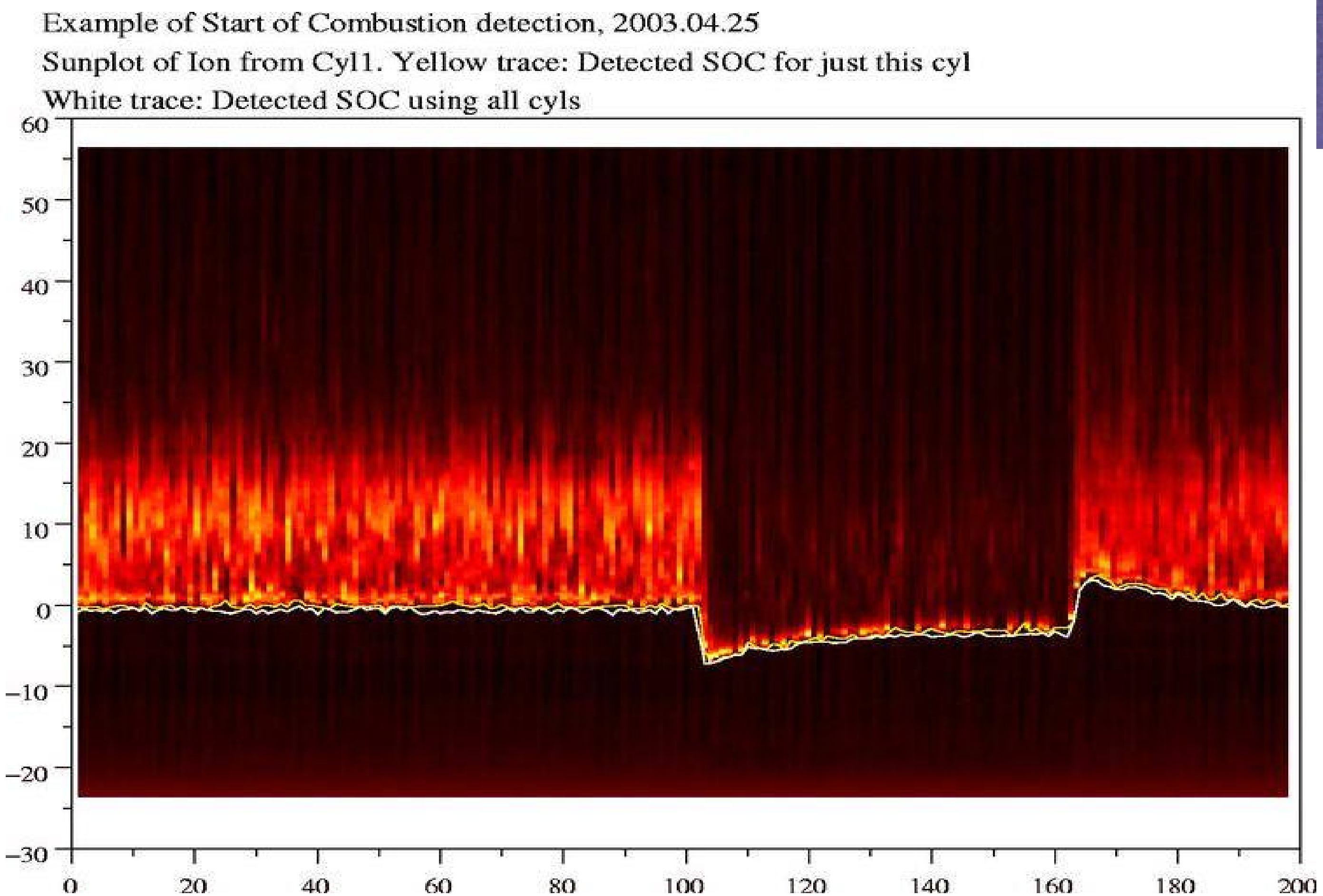
Transient Calibration Optimization (3)

Optimization Project Was Geared Towards
Fuel Economy Improvements



Real Time Combustion Control

- Start of combustion detection (SOC) for LTC control
- Sensors are being installed in the engine
- Evaluation for SOC detection will begin in Q2-2008



WOODWARD Industrial Controls

Barriers/Challenges

- Technical challenges with variable nozzle technology are enormous
  - Needle lift control hardware availability
  - High sensitivity to needle position – design may not be robust to tolerances
  - Very high precision required in manufacture
- Genetic combustion optimization implementations
  - Engineering experience needs to be applied to create practical designs out of optimization results/recommendations
- Combustion mode transition
  - Need robust controls methodologies
- Cylinder pressure sensors for real time combustion control
  - Reliability and cost of sensors
  - High speed signal processing requirements

Collaborations/Interactions

- Oak Ridge National Lab
  - Engine testing with advanced fuel injection system and control
  - Emission analysis

- Supplier partners
  - Delphi Fuel Injection System
  - Quantlogic Inc.
  - Exergy Engineering LLC
  - Continental (previously Siemens)
  - Woodward

- Engine consulting company and universities
  - Atkinson LLC
  - FEV
  - University of Wisconsin
  - University of Illinois

Publications/Patents

1. Guangsheng Zhu, Houshun Zhang, Yury Kalish, Rakesh Aneja, "Heavy-duty Engine Combustion Optimization for High Thermal Efficiency Targeting EPA 2010 Emissions," 13th Annual Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, MI (Aug 13-16, 2007).

2. Marc Allain, Craig Savonen, Yury Kalish, and Houshun Zhang, "Next Generation Diesel Engine Control," 13th Annual Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, MI (Aug 13-16, 2007).

3. Rakesh Aneja, Sathish Sankara Chinthamony, Min Sun, and Guanggsheng Zhu "Integrated Vehicle and Powertrain Technology for EPA 2010 and Beyond," 13th Annual Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, MI (Aug 13-16, 2007).

4. Chris Atkinson, Marc Allain, Houshun Zhang, Yury Kalish, and Craig Savonen "Fuel Efficiency and Emissions Optimization of Heavy-Duty Diesel Engines using Model-Based Transient Calibration," 13th Annual Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, MI (Aug 13-16, 2007).

5. Chris Atkinson, Marc Allain and Houshun Zhang, "Using Model-Based Rapid Transient Calibration to Reduce Fuel Consumption and Emissions in Diesel Engines," SAE Paper, 2008-01-1365, 2008.

Special Recognitions & Awards/Patents Issued

- Marc Allain and Min Sun, "Method and System of Diesel Engine Setpoint Compensation for Transient Operation of a Heavy-Duty Diesel Engine", U.S. Patent No. 7,281,518, October 16, 2007.
- Guangsheng Zhu and Houshun Zhang, “Invention of Squish-Induced Mixing-Intensified Low Emission Combustion (SIMILECOM).” Record of invention was submitted on August 16, 2007.
- Jack Peckham, ”Next-Generation’ Computer Controls Can Boost Diesel Fuel Efficiency without Compromising Emissions, Performance, “ Diesel Fuel News, Volume 11, issues 20, September, 2007

Future Work

- Variable injection nozzle technology
  - Hardware procurement is underway
  - Engine tests are expected in Q4-2008
- Advanced next generation fuel injection system
  - HECC evaluations with a new advanced fuel injection system in Q2-2008
- Transient combustion and control development
  - Real time combustion control using cylinder pressure sensors in Q2-2008
- Integrated system controls development
  - On-going, and more results will be available in the next review meeting

Summary

- Program is progressing well and aggressively. It is toward meeting the program objective with 10% thermal efficiency improvement by 2009.

- Identified key enabling technologies with high potential of leading to 55% thermal efficiency beyond 2013
  - Variable Fuel Injection Nozzle Coupled with Advanced Fuel Injection System
  - Genetic Combustion System Optimization
  - Transient Control Optimization

- Significant benefits with variable nozzle technology have been demonstrated analytically. A new dual mode combustion strategy covering the entire operating range is emerging.

Acknowledgements

- Department of Energy Headquarters
    - Gurpreet Singh
    - Roland Gravel

- National Energy Technology Laboratory
    - Carl Maronde
    - Jeffrey Kooser