Multicylinder Diesel Engine for LTC operation

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Diesel Engine Development

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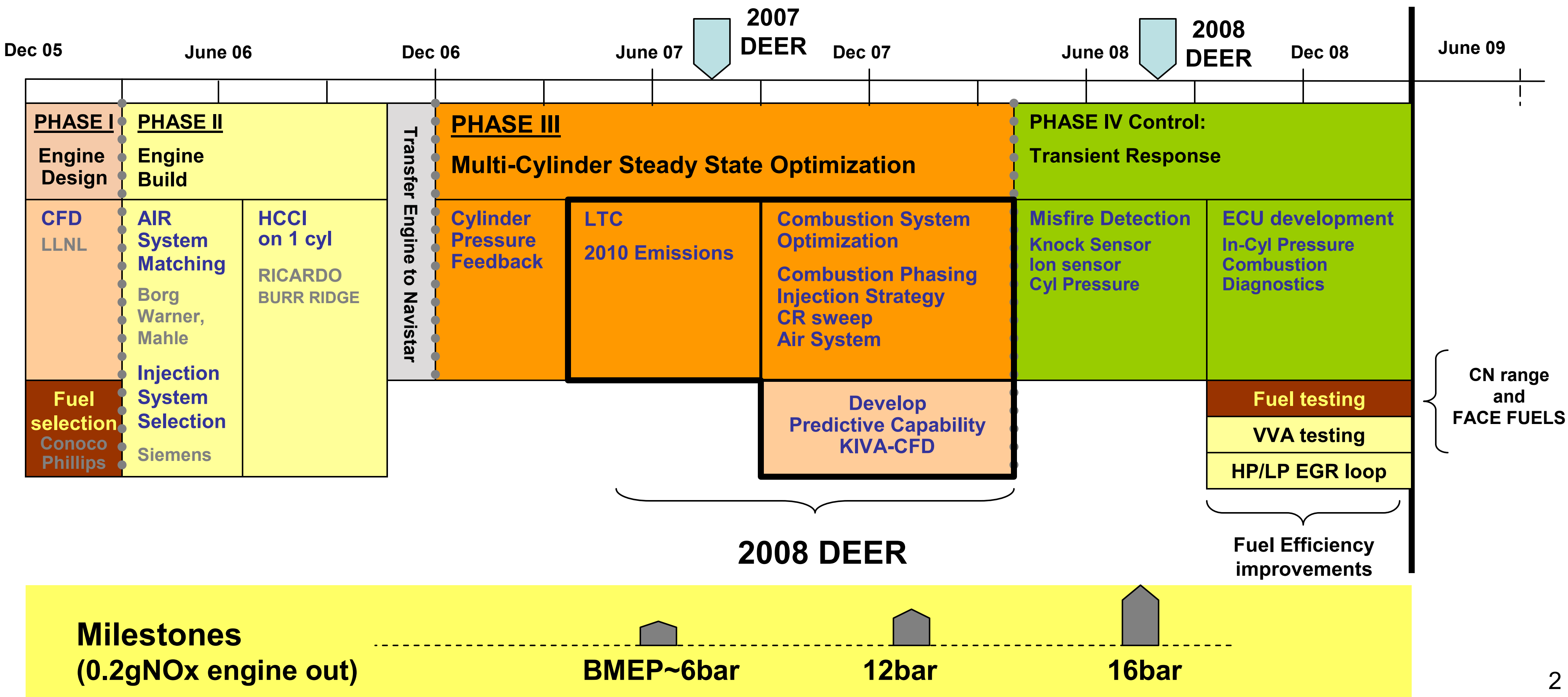
NAVISTAR ENGINE GROUP

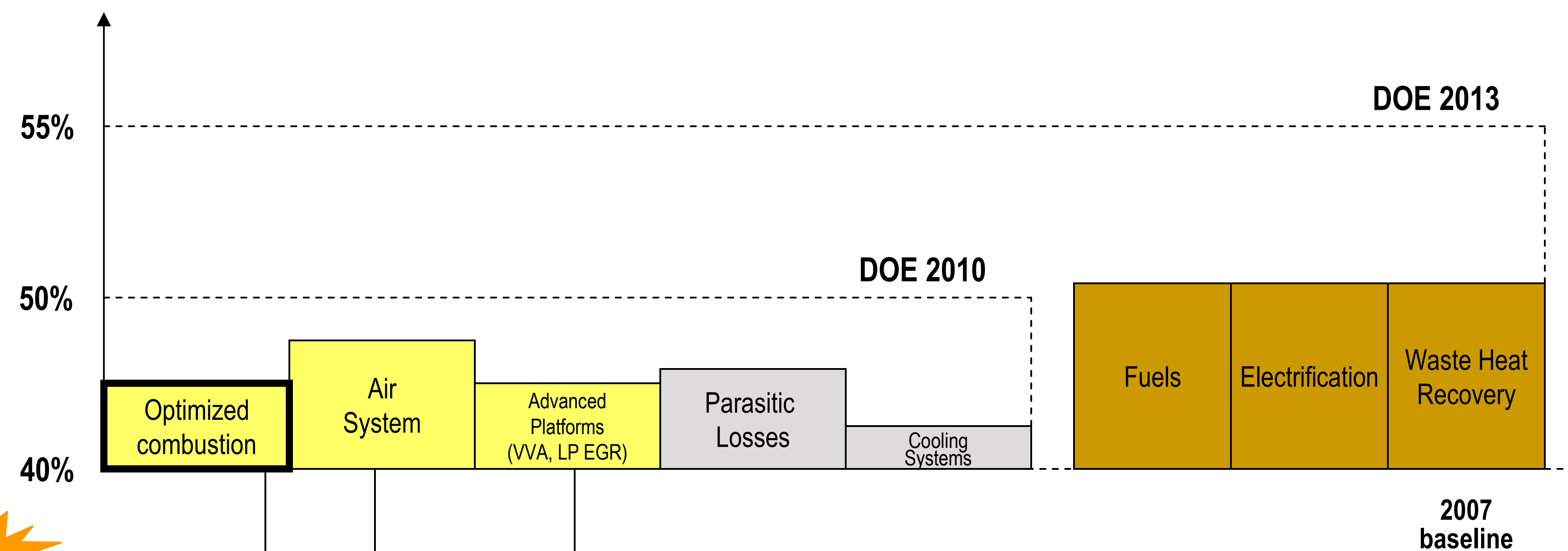
Goals and Objectives

- **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



Emission Driven

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

Optimize TC system / operation
Reduced back pressure

Optimize CR and ER
VVA

Discussed Here

Supporting work:

Engine Testing

1-D Cycle Simulation
KIVA-CFD Modeling

Detail Energy Balance

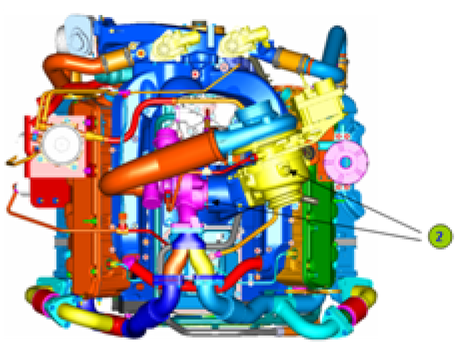
Engine Build

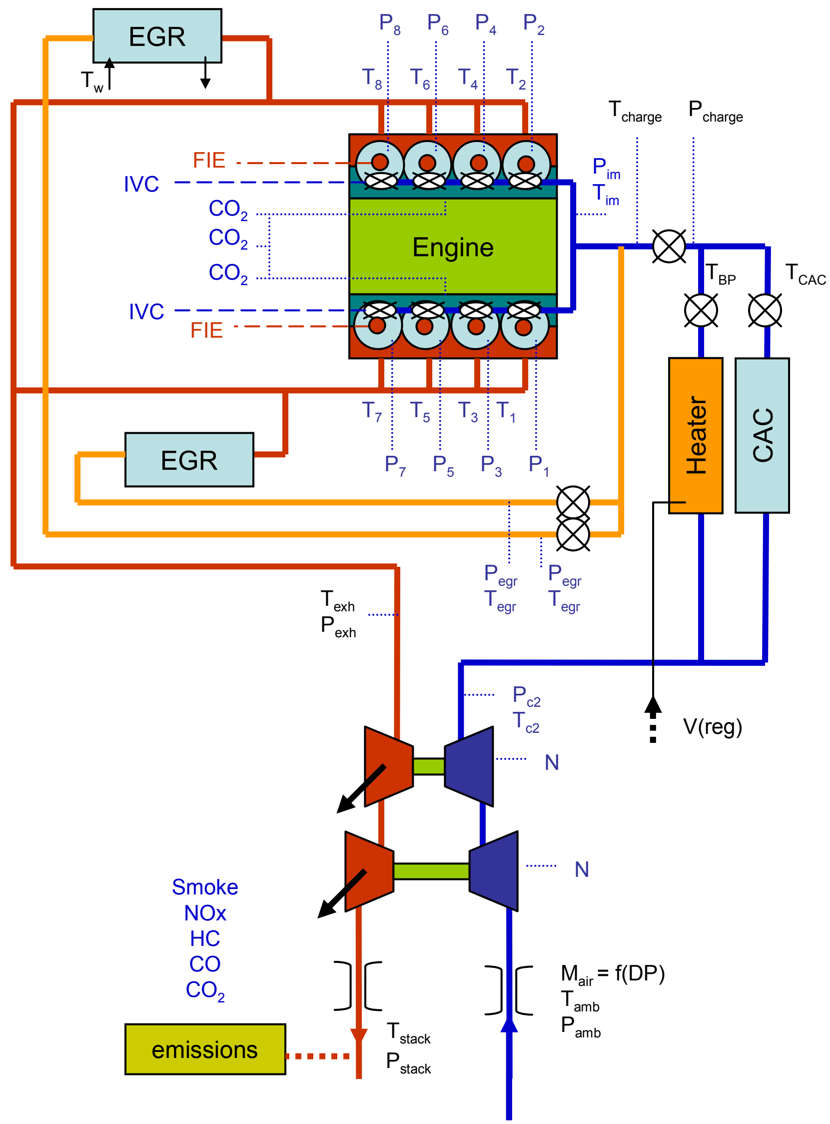
Base Engine:

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





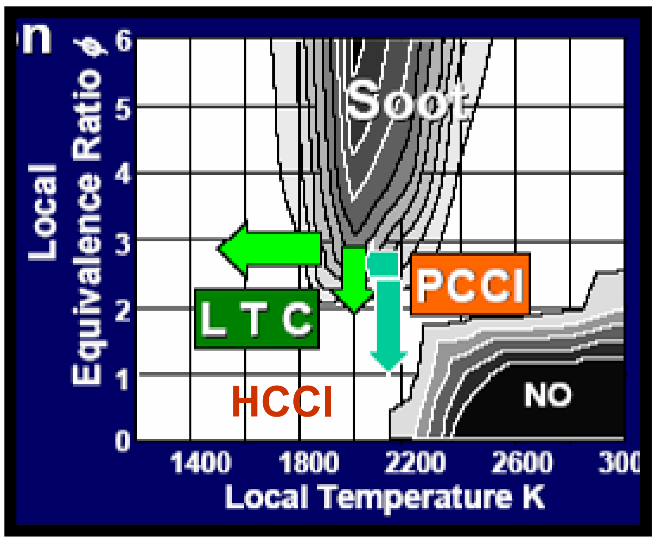
	Base engine	V8 Test Engine	SCTE
Displac. Bore Stroke	6.4L 98.5mm 105mm	6.4L 98.5mm 105mm	0.75L 95mm 105mm
FIE	DI Common Rail	DI Common Rail	DI Common Rail
CR	16	12-16.5	15-16.5
Turbo Charger	Single Stage VNT	Dual Stage VNT	Surge tank
EGR system	HP loop Single Cooler	HP loop Dual Cooler	cooled
IVC EVO	-133 BTDC 132 ATDC	-133 BTDC 132 ATDC	-133 BTDC 132 ATDC

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

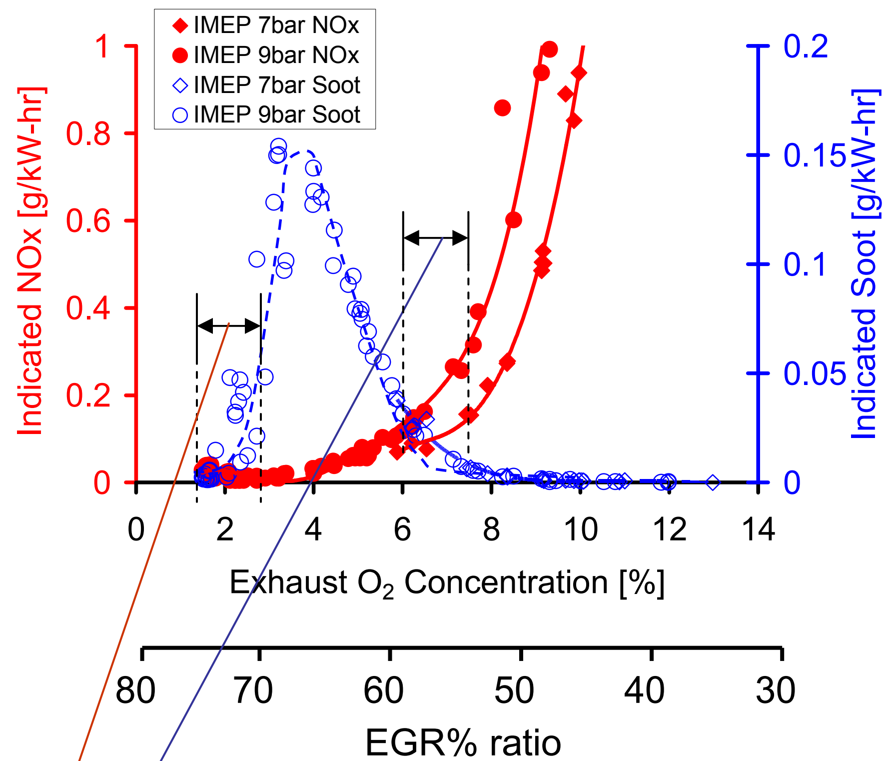


[Herzog et. al 1992]
[Akihama et. al 2001]

Ref. AVL

Representative data from SCTE

IMEP	7, 9 bar
N	1200 rpm
P_{intake}	2 bar
M_f	28, 33 mg/stke

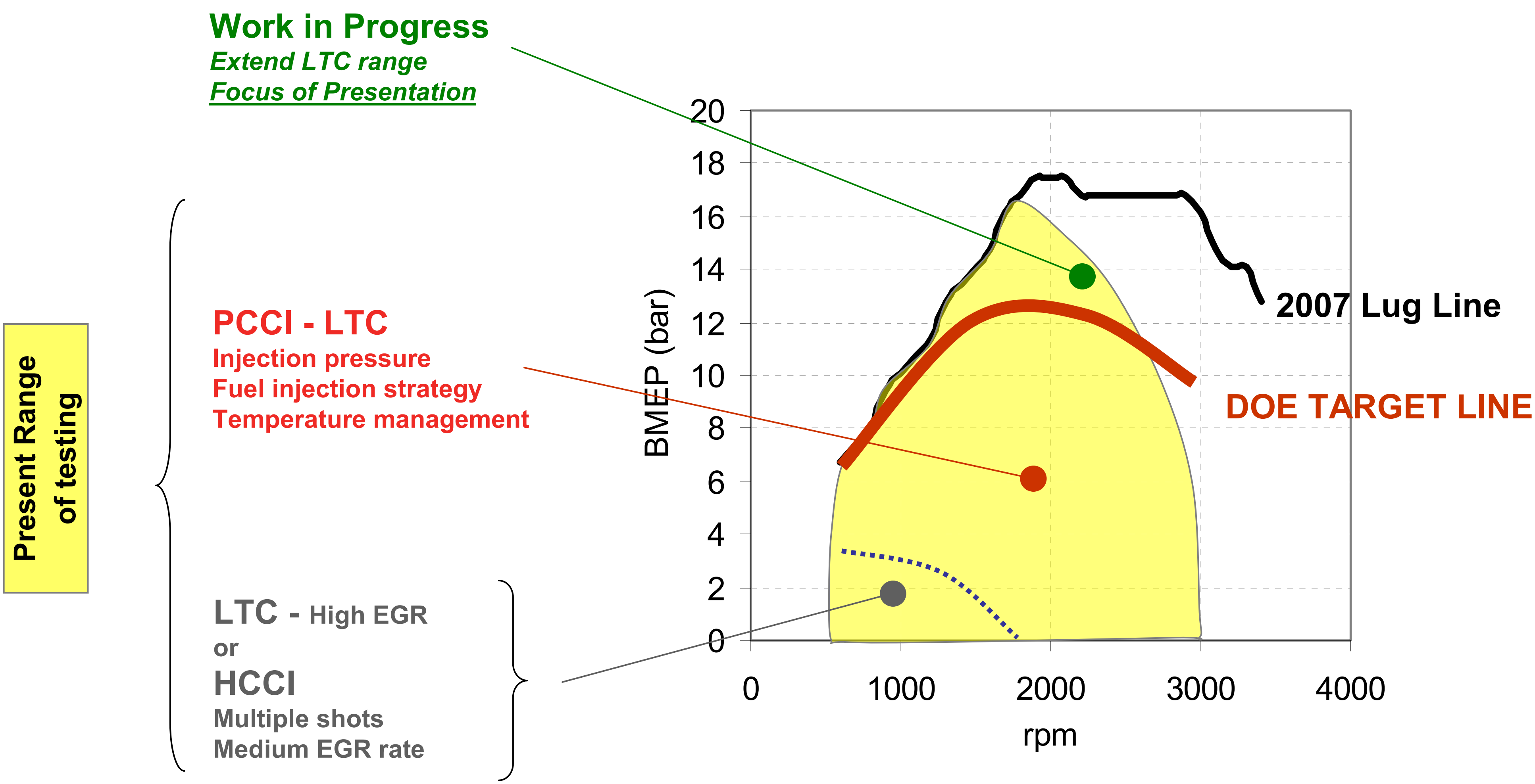


Low Temperature Combustion

PCI

Engine Mapping
Optimization

Target of Program:
Implement LTC trough 12.5 bar BMEP on a production platform
Meet NOx and SOOT 2010 targets without after-treatment
Promote BSFC to meet 2007 levels and wok towards DOE targets of 50 to 55% efficiency.

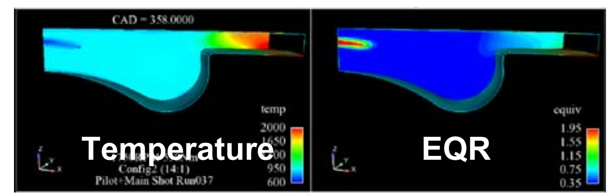


Combustion System Optimization
Approach

PCCI – LTC BMEP load gains:

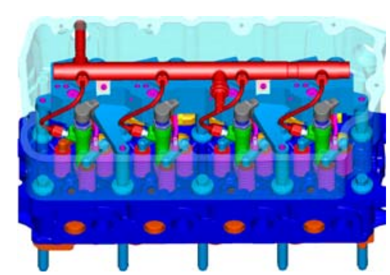
Fundamental understanding → **Engine Testing**

- **1-D Thermodynamic Models**
- **CFD**
  - **KIVA** → **LTC**
  - **ROI and Spray models** → **Multiple Shot**
- **Fuel Properties**
  - Diesel Surrogates
  - FACE Fuels



Emerging Technologies

- **Turbo Systems**
- **Cooling**
- **Fuel Injection Equipment**
- **VVA**



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

Summary

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)

Positive Impact of Early Injection (early PCCI)

Single Shot Injection

Multi-Cylinder Engine Testing

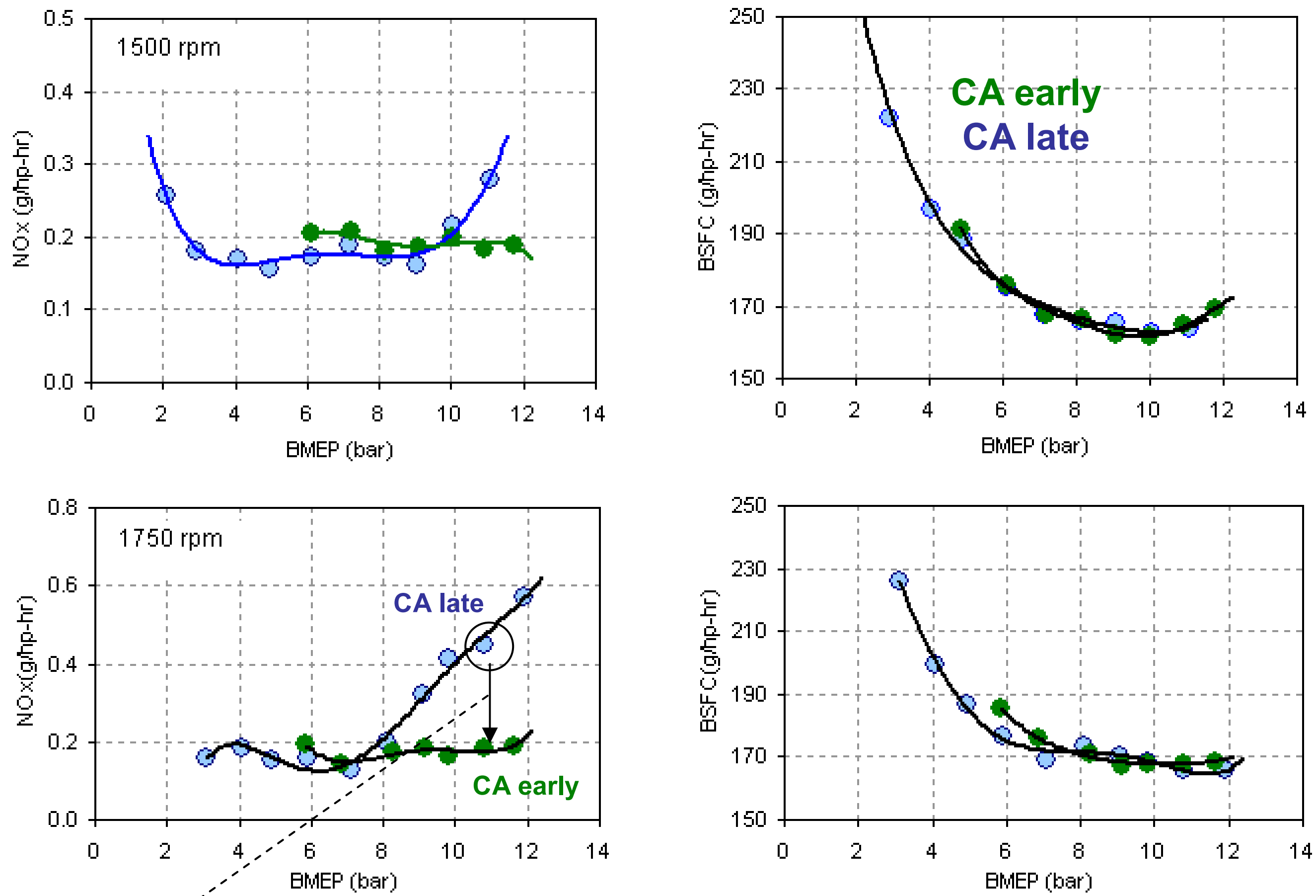
Path to reducing flame temps

- 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

Injection Strategy
Combustion Phasing Optimization

Positive Impact of Early Injection (early PCCI)

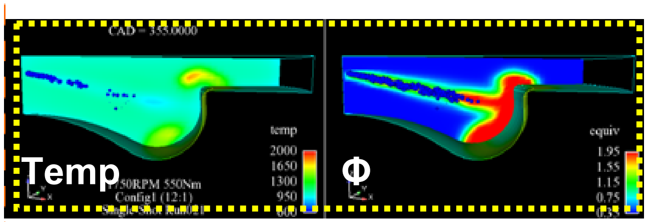
1. The local chemistry shows leaner and cooler combustion.
2. The early injection aids to better entrainment and vaporization of the fuel.
3. The rate of combustion is more rapid.

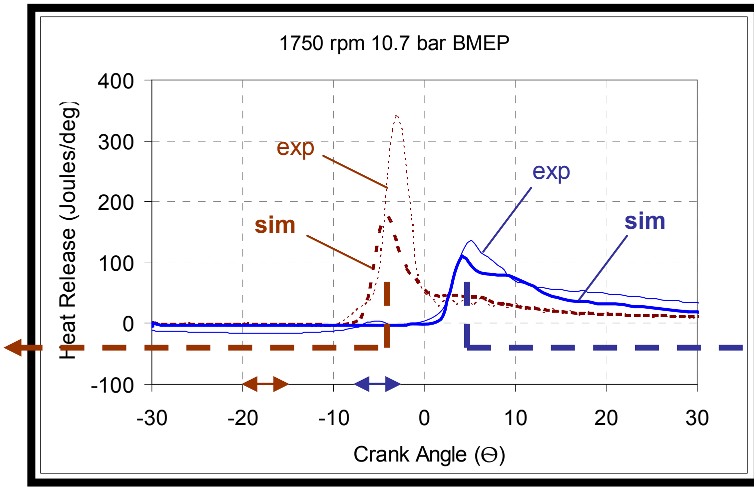
1750 rpm – 10.7 bar BMEP
KIVA vs. Engine Data

Early Injection

Image corresponds to Peak in HR trace

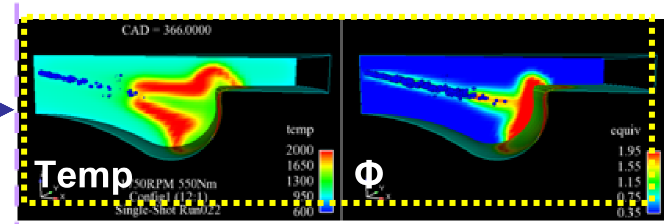
-5 atdc

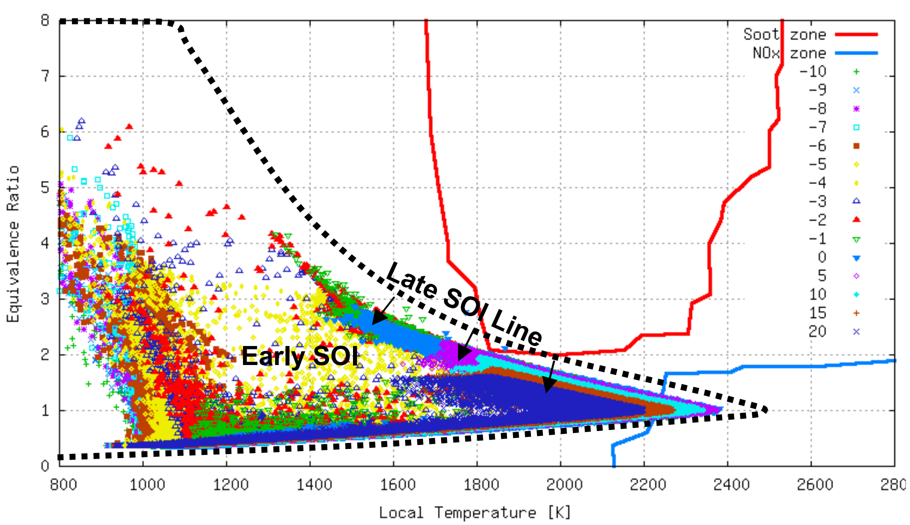


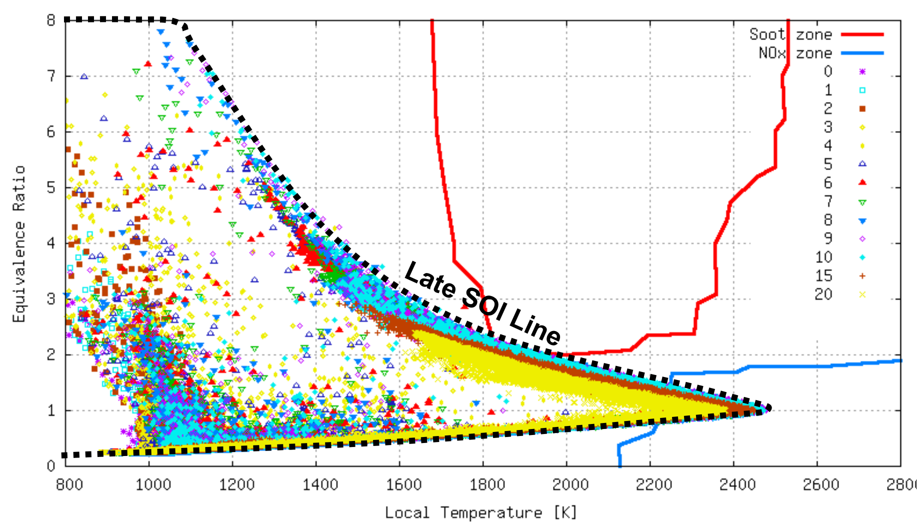


Late Injection

6 atdc

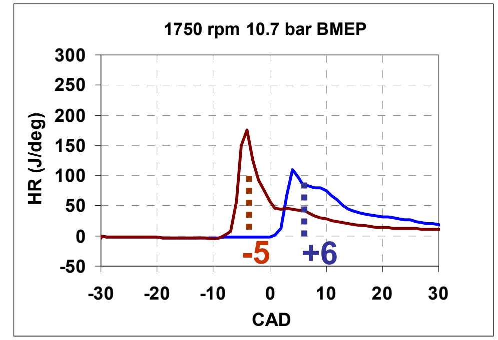






Injection Strategy

Combustion Phasing Optimization

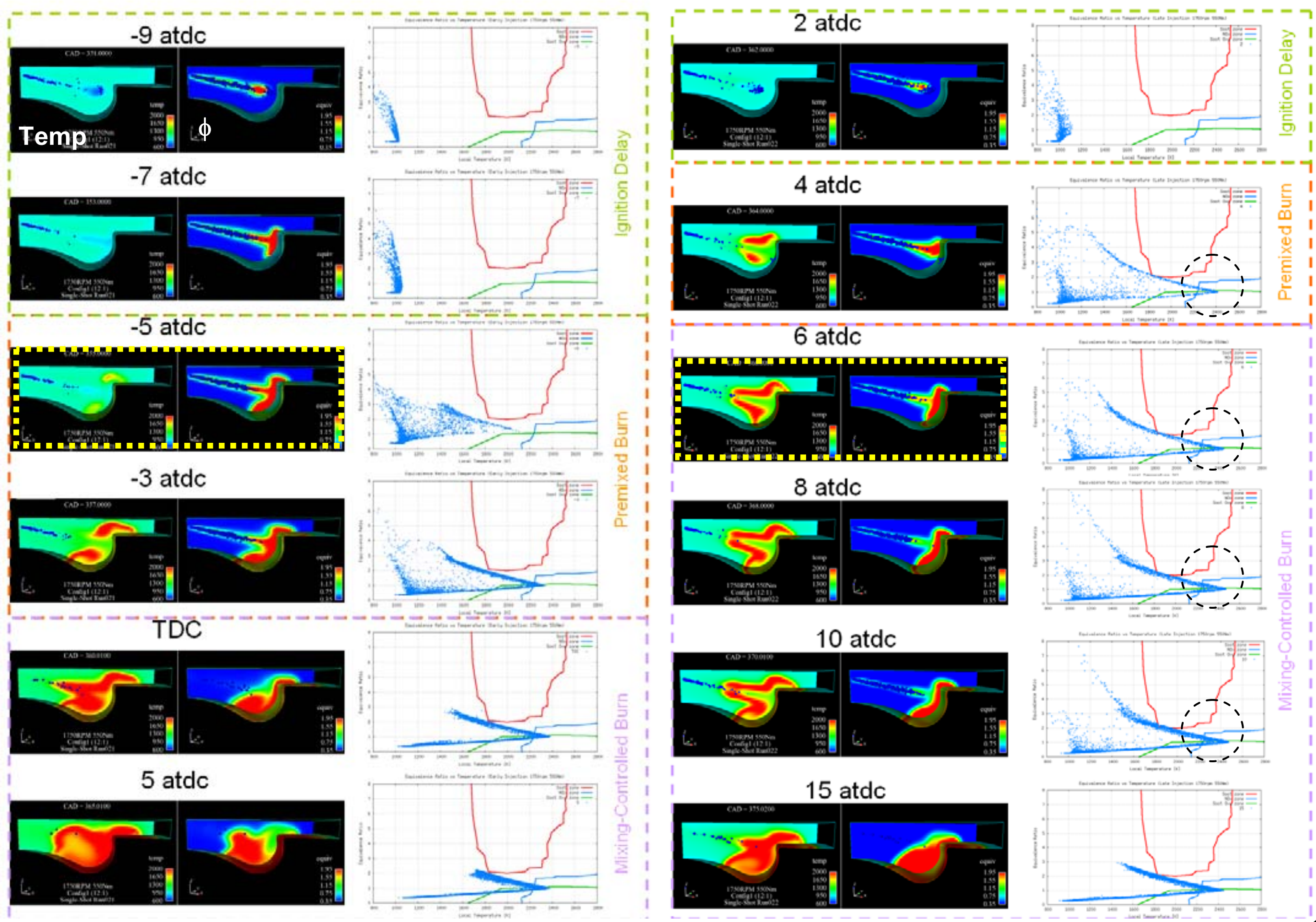


Positive Impact of Early Injection (early PCCI)

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



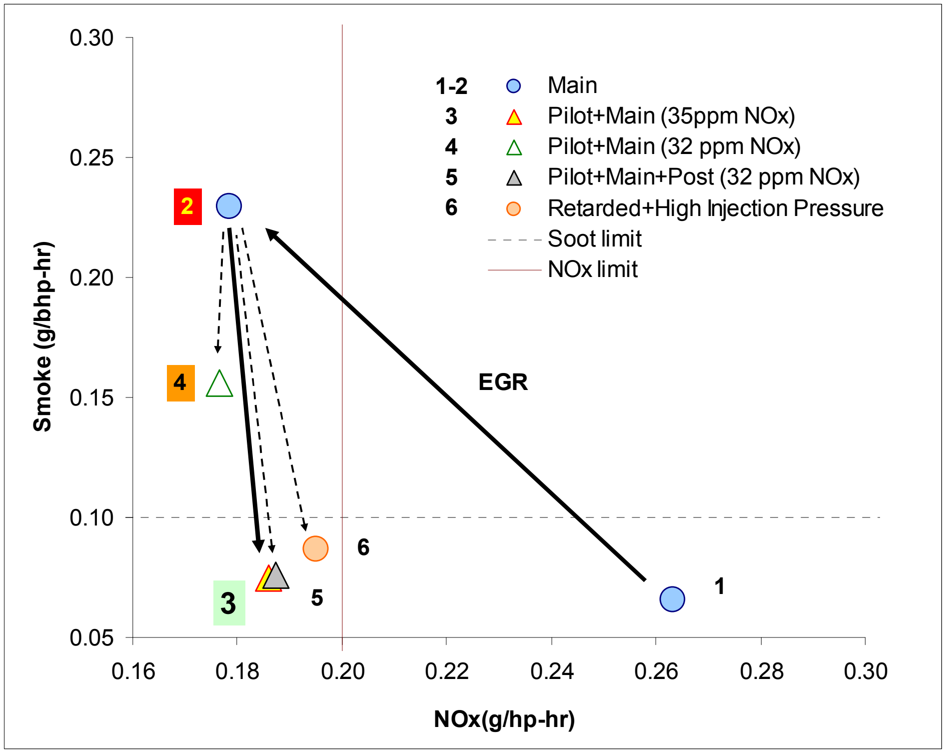
Late injection timings show cells longer residence time within the NOx formation island.

Injection Strategy
Transition to multiple-shot

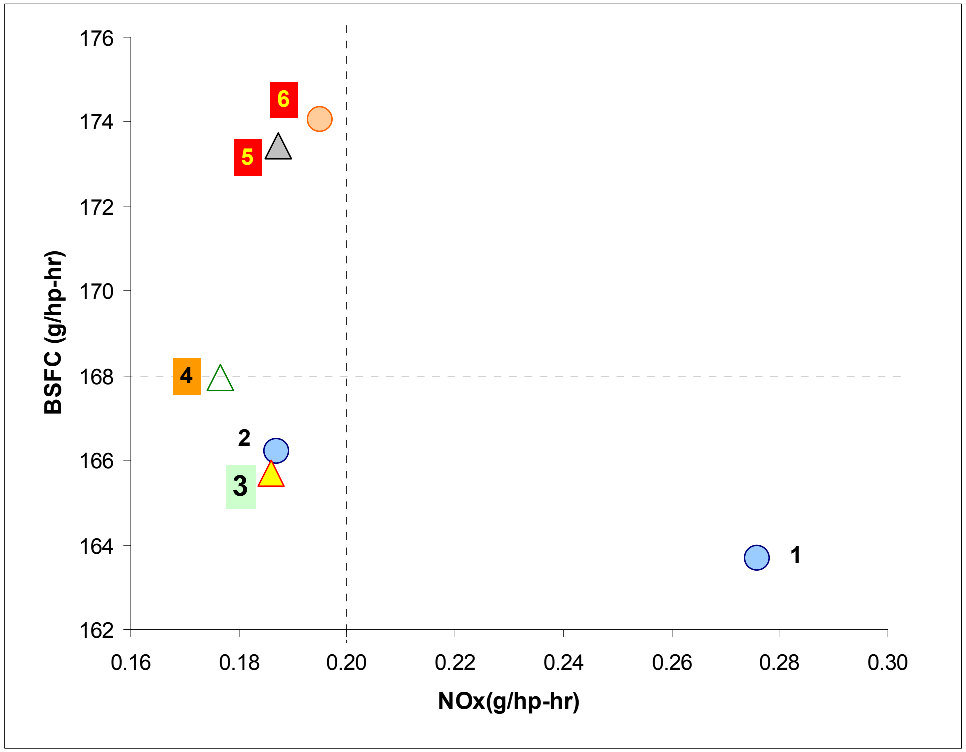
Combustion optimization is driven by emission requirements.

**Engine Data at
1750 rpm – 10.7 bar BMEP**

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

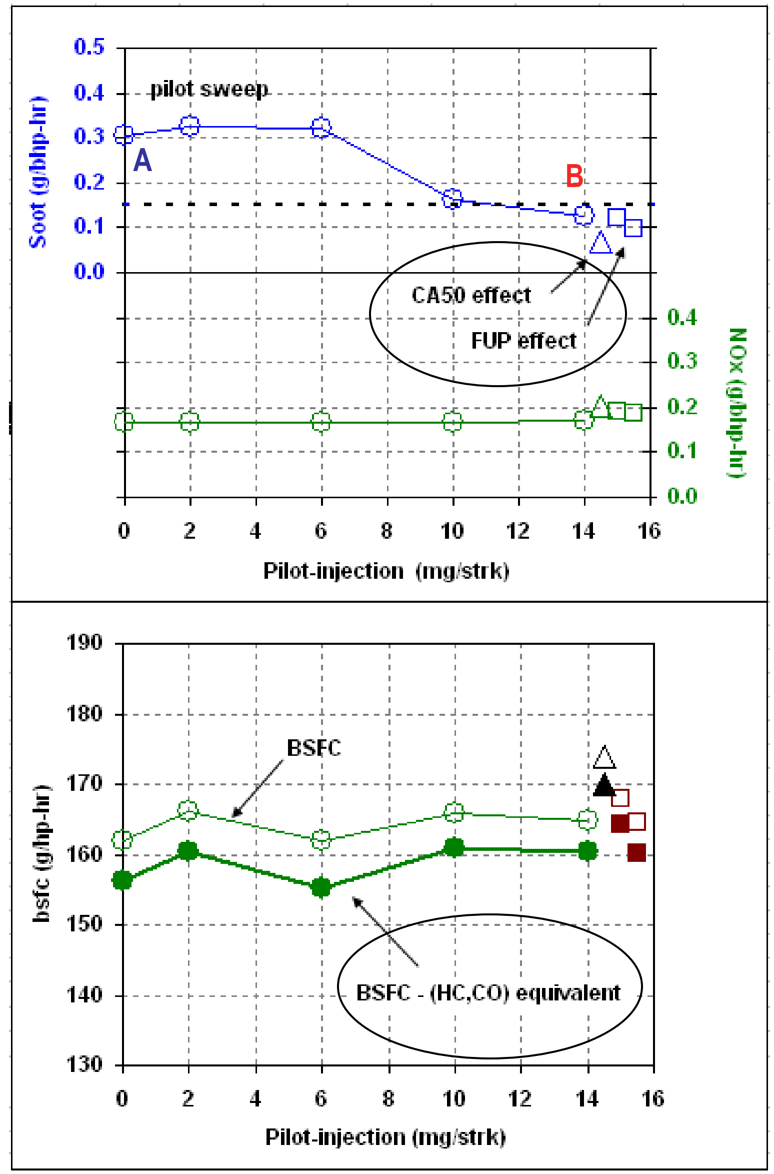
Pilot quantity is evaluated via soot and NOx tradeoff with respect to BSFC:

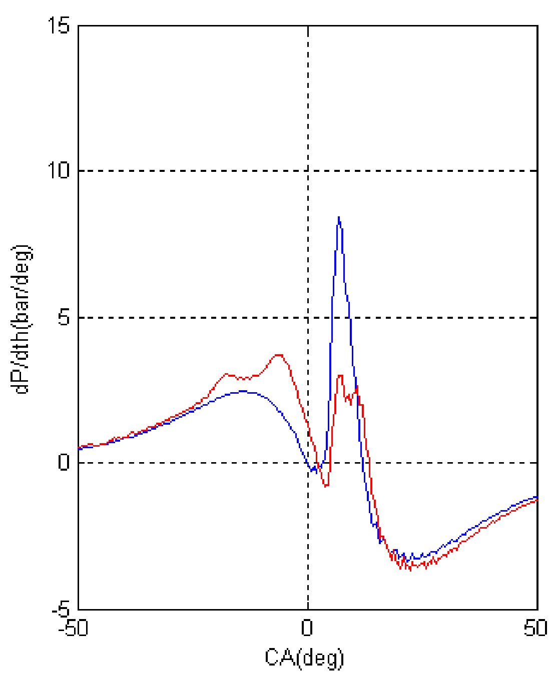
- Pilot quantity can reduce SOOT at constant fueling and NOx.
- The effect of pilot is sensitive to a minimum quantity
- Injection pressure and combustion phasing may weigh in to further optimize the present tradeoff without excess penalty to fueling
- It is effective to reduce the max rate of pressure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

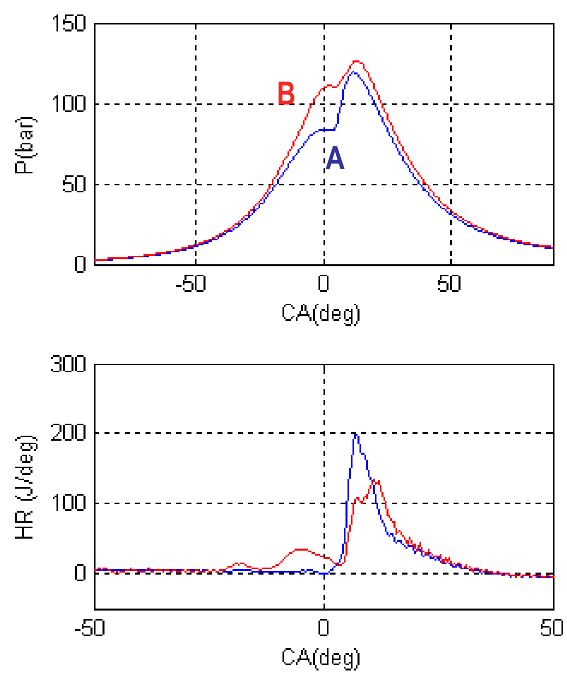
HC and CO with respect to BSFC

- Combined contribution appears to be minimum vs. BSFC

Engine Data at 1750 rpm – 10.7 bar BMEP







Injection Strategy

Pilot-shot optimization

Optimization of pilot quantity

Simulations captured the ignition characteristics of the pilot events.

Pilot liquid phase (A) vaporizes prior to main injection event

Results corraborate the BSFC – (HC,CO) balance from previous slide

1750 rpm – 10.7 bar BMEP
SIMULATION vs. Experiments

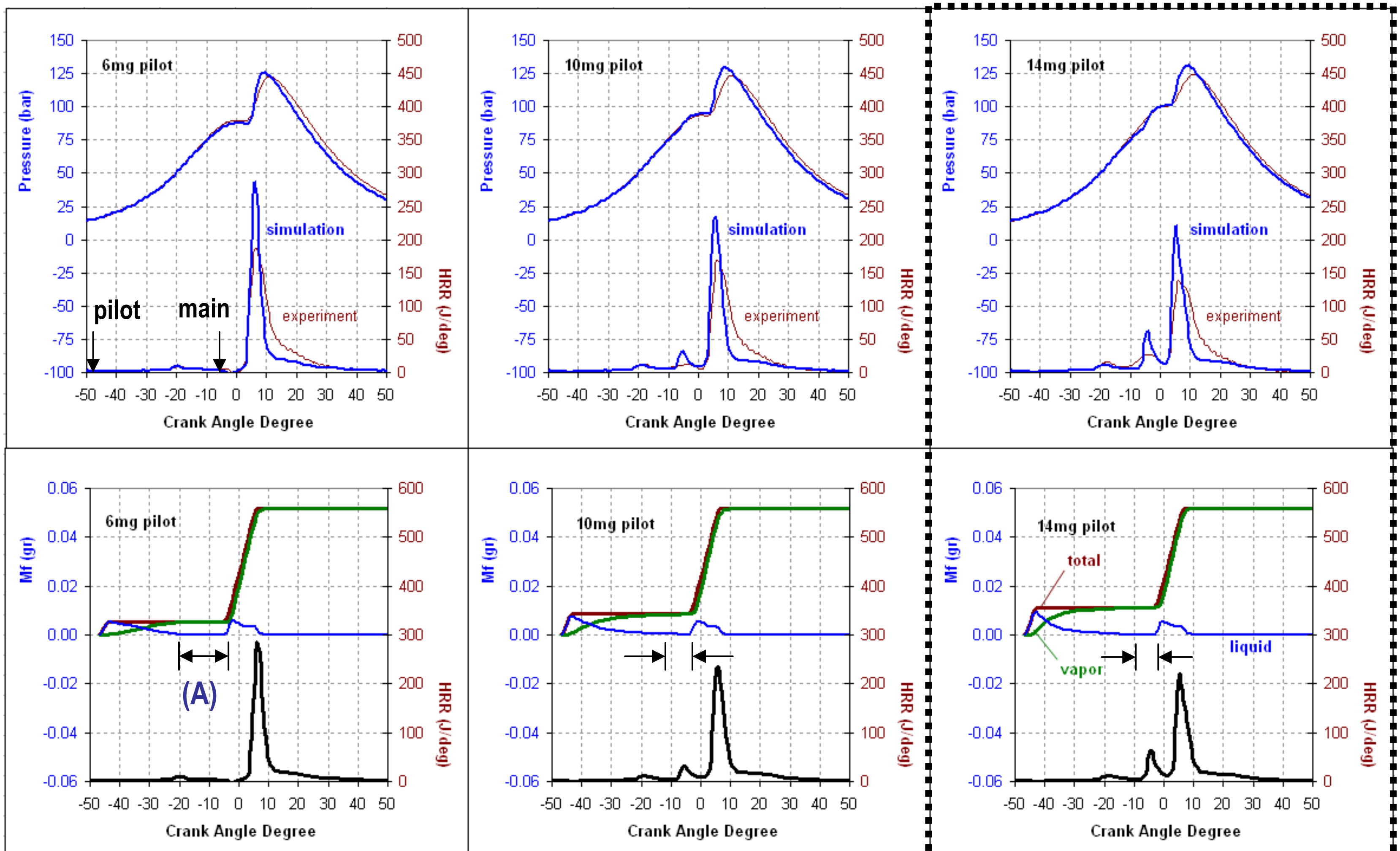
Next Slide

Cylinder Pressure

Heat release trace

Detail of Injection trace and fuel phase composition

Heat release trace

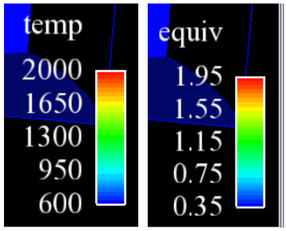


Injection Strategy
Pilot-shot optimization

2008 DEER
Dearborn, MI August 4-7

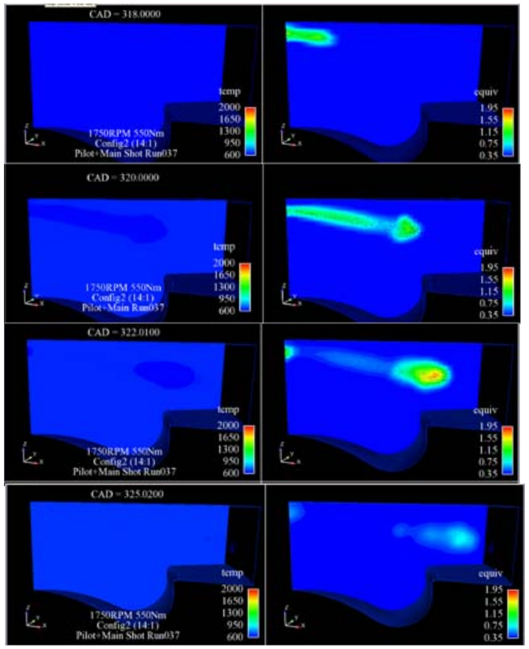
1750 rpm – 10.7 bar BMEP
14 mg pilot
SIMULATION

Pilot mixture preparation



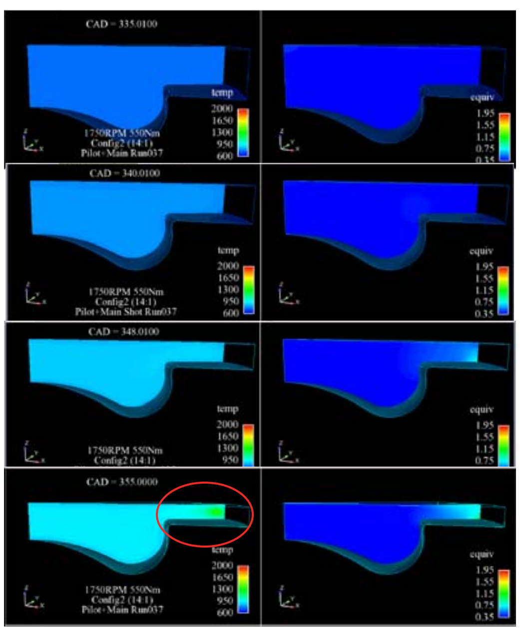
Temperature | EQR

318
320
322
325



Pilot injection
vaporizes

335
340
348
355

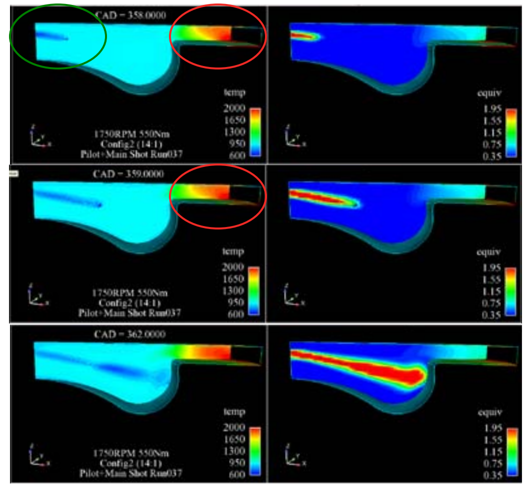


Low temperature combustion
Based on temperature distribution and heat release curve shows initial combustion at 340º

High temperature Pilot Combustion
begins at 355º

Temperature | EQR

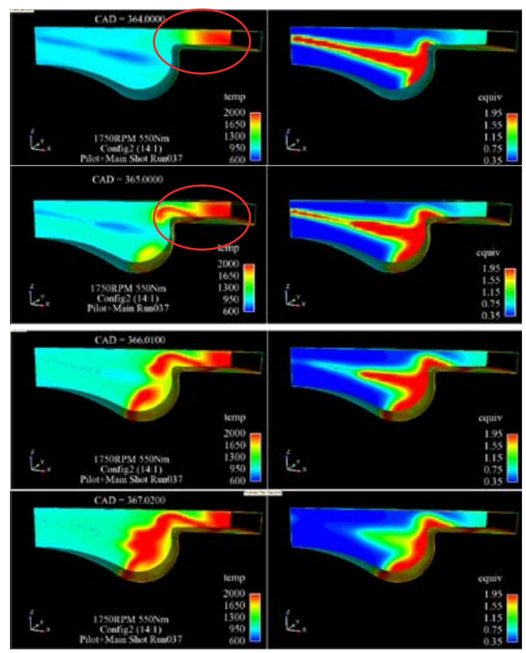
358
359
362



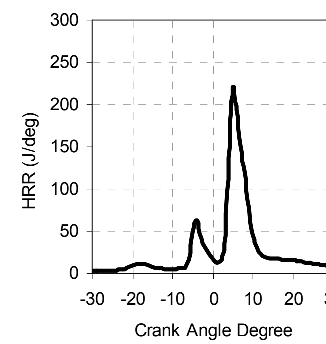
Start of main injection

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

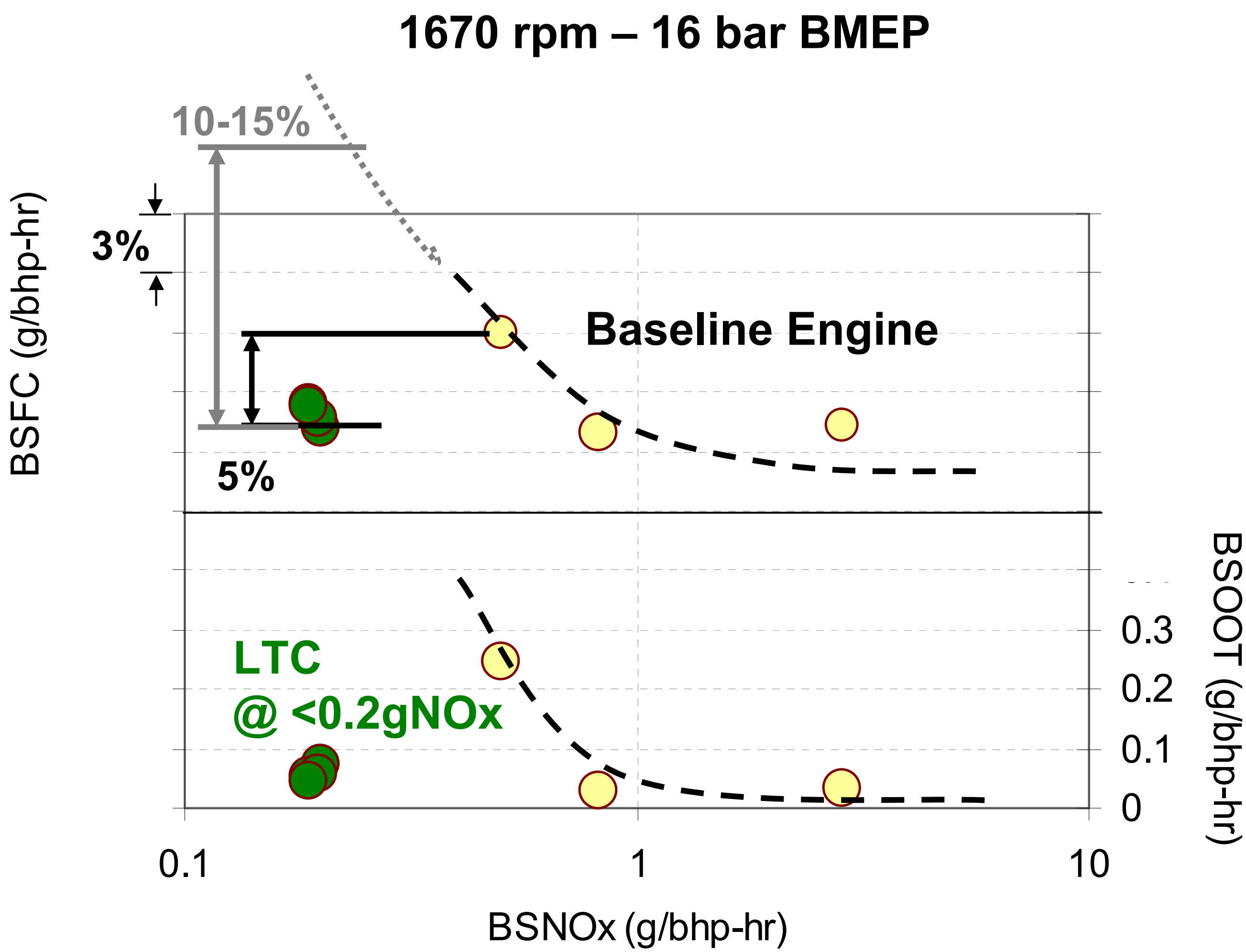
364
365
366
367



Main reaction take place
Pilot appears to ignite the main spray



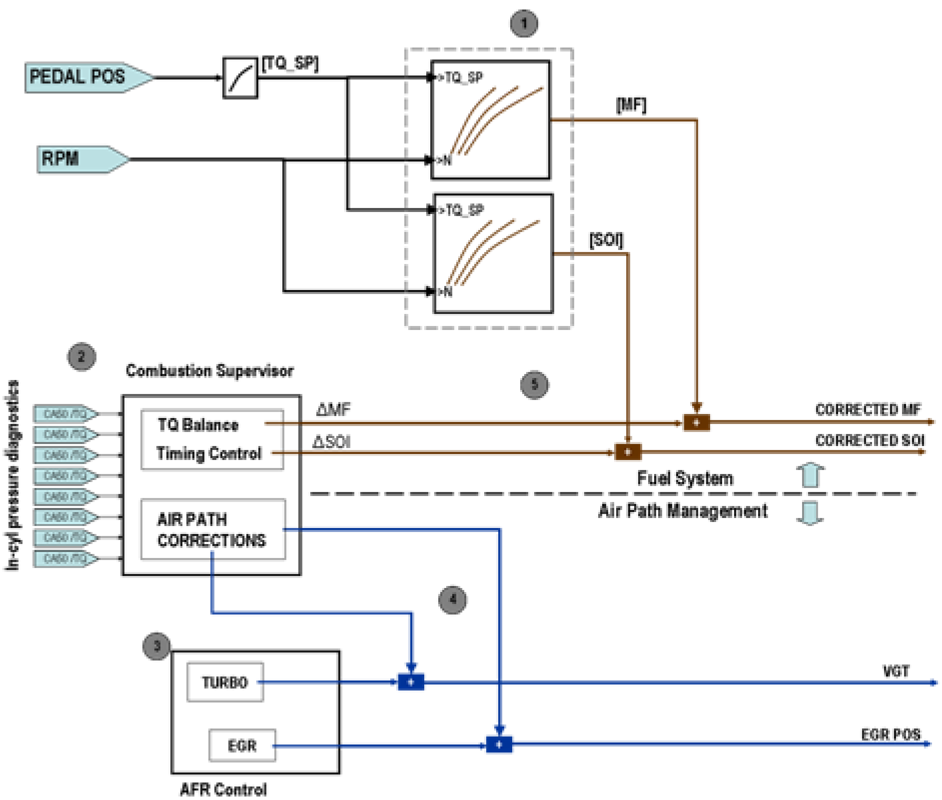
Injection Strategy
high load testing

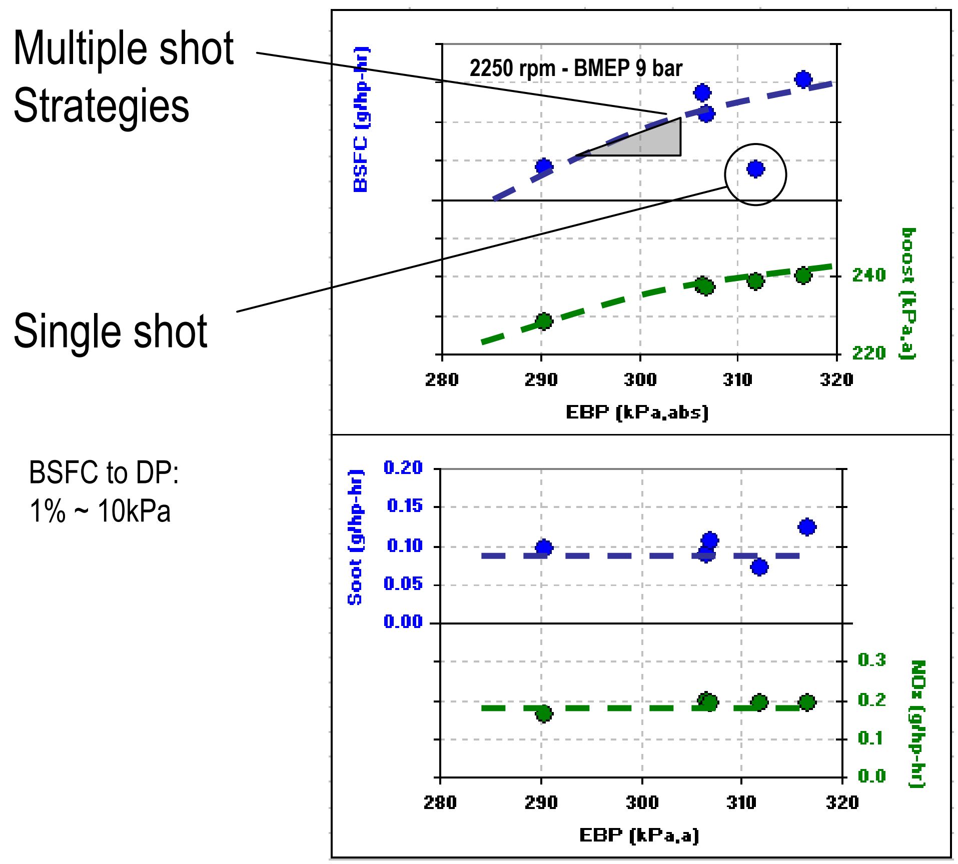


Air System Optimization
Model Based Control

Systems Approach

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

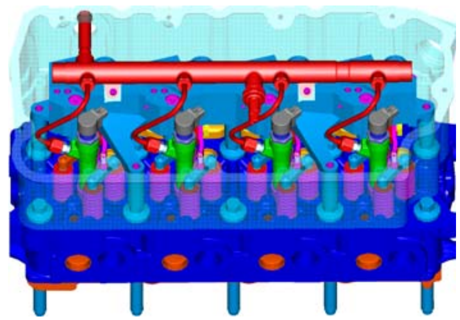




Air System Optimization
VVA design and Impact on Engine Performance

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.

Acknowledgements

Project Partners

NAVISTAR ENGINE GROUP — INTERNATIONAL

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- **CFD**
  - Lawrence Livermore National Laboratory
  - Ricardo
- **Fuels**
  - ConocoPhillips
- **Enabling Technologies**
  - BorgWarner Turbo & Emissions Systems
  - MAHLE
  - Jacobs Vehicle Systems™
  - SIEMENS
- **Combustion Diagnostics**
  - Berkeley, University of California

2008 Diesel Engine-Efficiency & Emissions Research Conference