Low Temperature Combustion Demonstrator for High Efficiency Clean Combustion

DE-FC26-05NT42413

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26 Feb 2008

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Outline

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1. Goals and Objectives

- **Overall goal:**
  - Demonstrate the application of low temperature combustion (LTC) to the ITEC 6.4L V8 production engine targeting 2010 emissions without after-treatment, using today's Diesel fuel.
  - The technology generated in project to be capable for production implementation.

- Phase I objectives (Nov 2005-March 2006): Engine hardware simulation and design
- Phase II objectives (April-Oct 2006):Procurement and prove-out of main components:

  Fuel injectors, charge air-EGR system, control system with cylinder pressure feedback

- **Phase III objectives:** (November 2006-July 2008): Steady-state mapping

  Establish injection strategy, boundary conditions (temp, AFR, EGR); include effects of VVA / VCR.
  Develop control system to control combustion process.
- **Phase IV objectives:** (August 2008-Dec 2009): Transient Response and Vehicle Installation

- **Key technical challenges addressed:**
  - Optimization of fuel and charge air mixture to sustain LTC conditions
  - Limit engine out emissions to 2010 levels (0.2 gNOx/bhp-hr, 0.01gPM/bhp-hr)
  - Improve stability of combustion with control system

    Using Cylinder Pressure Transducers and alternative sensors as a production feasible alternative
  - Minimize hydrocarbon emissions and maintain or improve bsfc

2. Barriers

- **Low temperature combustion (LTC),** proven to limit NOx and Soot can lead to high hydrocarbon emissions and poor fuel economy:
  - Fuel injection and charge air mixture preparation is used to limit HCs and bsfc.
  - Combustion diagnostic tools are used to gain combustion stability and extend the working range of the engine.

- **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 injector fueling and air-system management successfully minimizes the variation among cylinders.
  - This work will be complemented with and electro-hydraulic valve actuation system applied to each cylinder. System is currently being assembled.
  - Work is being carried out to show a path towards a production feasible control system (based on pressure and *alternative sensing* technology) and a dedicated high speed acquisition card on production micro-controller.

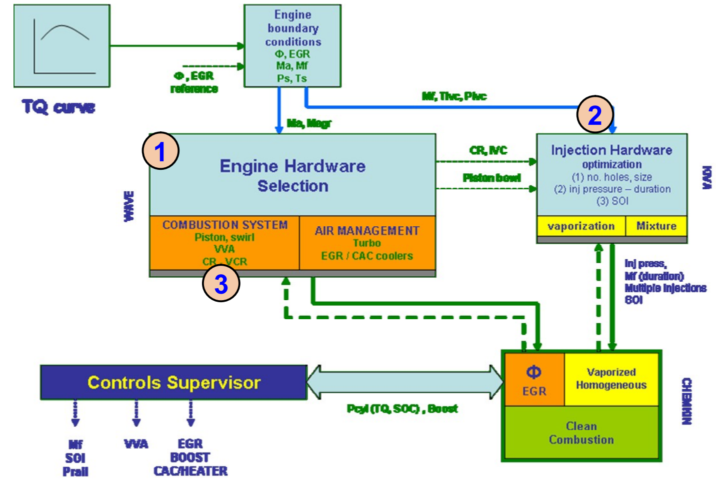
- Engine must accommodate a range of fuel properties representative of US geography
  - Engine testing will accommodate three batches of Diesel fuels ranging from of 42-58 CN as provided by ConnocoPhillips.

3. Approach

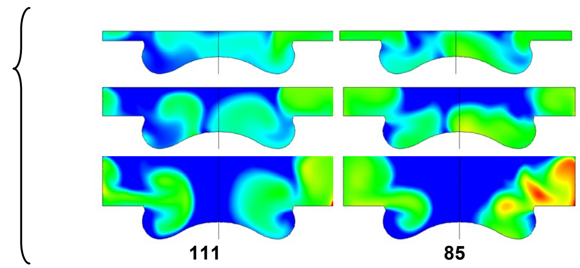
System Approach to enable LTC:

1. Modeling

- a. Thermodynamic Cycle Simulation
- b. Combustion Modeling

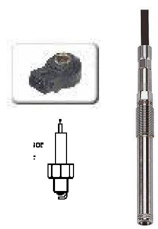


2. Injector Hardware Optimization



3. Control Supervisor

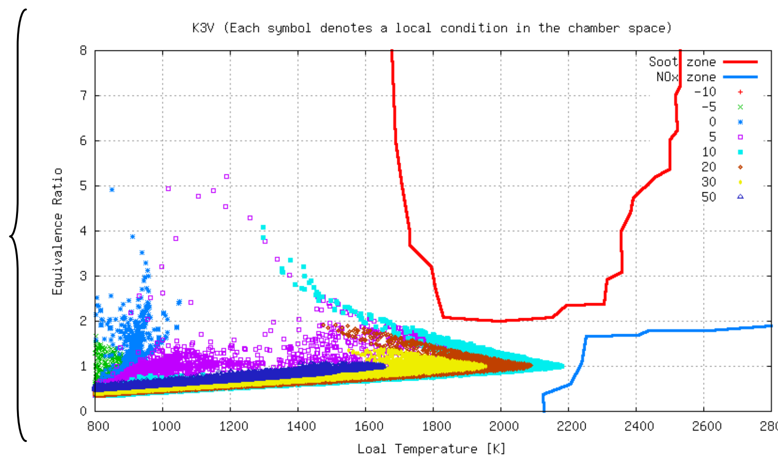
- a. coordinated boost/EGR
- b. close-loop control
- c. misfire detection



4. Engine testing

- a. Steady State Testing:
  - a. Multi-cylinder Engine
  - b. Single-cylinder Engine
- b. Transient Evaluation
- c. Combustion Modeling Evaluation

Suggested in '07 merit review



4. Performance Measures/Technical Accomplishments/ Progress/Results

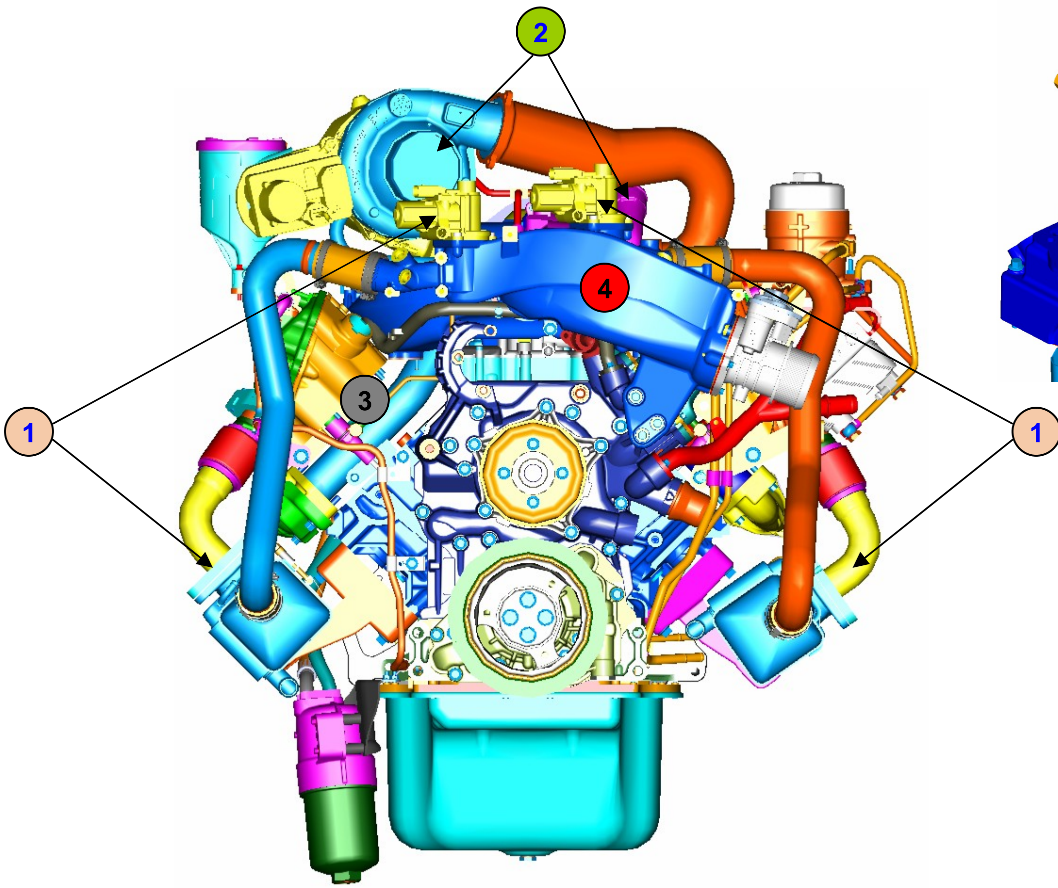
1. **Completed engine Build** (task 1 of Phase III)
   - Engine Build with EGR and Turbocharger completed and used for testing with a variety of compression ratios from 12-17.
   - Engine build with VVA currently being assembled.

2. **Implementation of Close-Loop-Control** based on cylinder pressure (task 2 of Phase III)
   - Applied to LTC to equalize cylinder torque, start of combustion.
   - Successfully applied to attain stability of combustion in a multi-cylinder application.
   - Cylinder trimming significantly reduces emissions
   - Work is being extended to:
     - Non-pressure based sensors, initial results show good correlation with pressure data.
     - Misfire routines key to extend the operating regime (high EGR levels, higher loads)

3. **Steady state engine mapping** (task III to continue through end of Phase III – Nov 2008).
   - Tested to peak torque (11 bar bMEP) while achieving control over the combustion system to yield competitive fuel economy and 2010 level emissions.
   - Engine testing is being coordinated with simulations by LLNL/ITEC.
   - Steady State Mapping is being corroborated against the FTP cycle

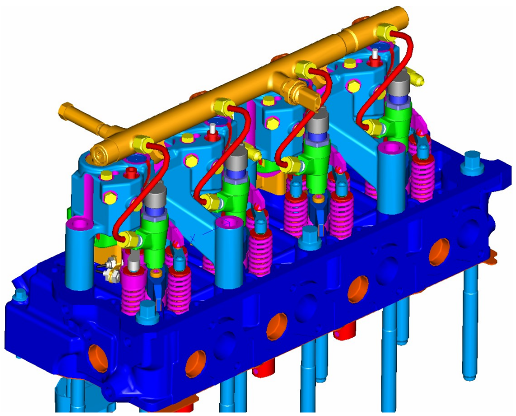
4.1 Completed Engine Build

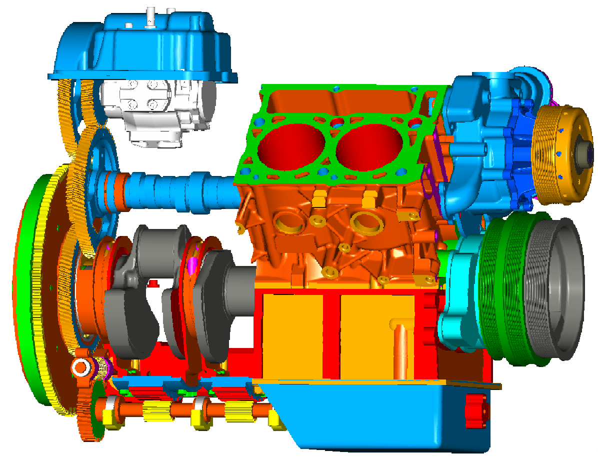
Present build encompass:
(1) Dual-path EGR system
(2) Two-stage TC each with VNT stages
(3) High-flow cylinder head
(4) EGR mixture



Next build underway targeted for Feb 2008:

1. VVA system Assembly on Feb 2008
   Bench testing March 2008
   Engine tests April-Nov 2008
2. VCR (design underway)

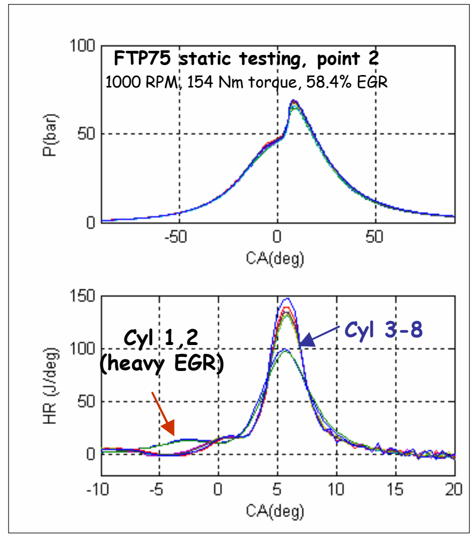


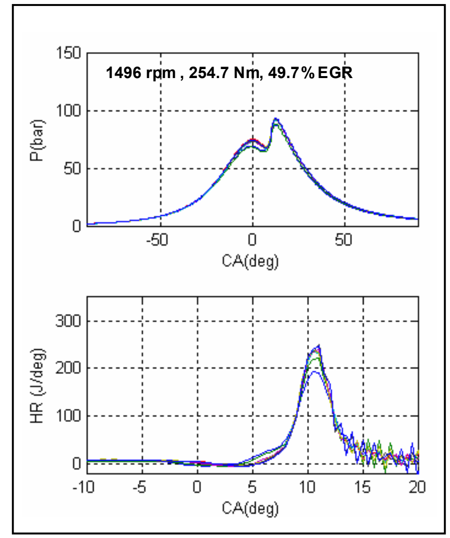


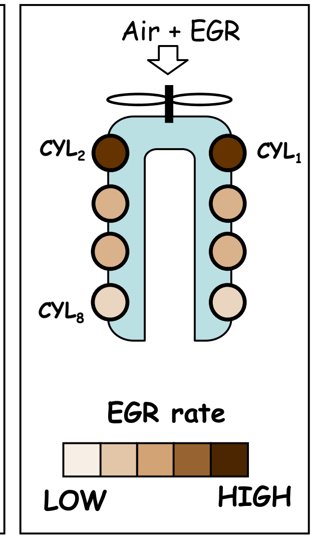
4.2 Control System Development

Stability of combustion System

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



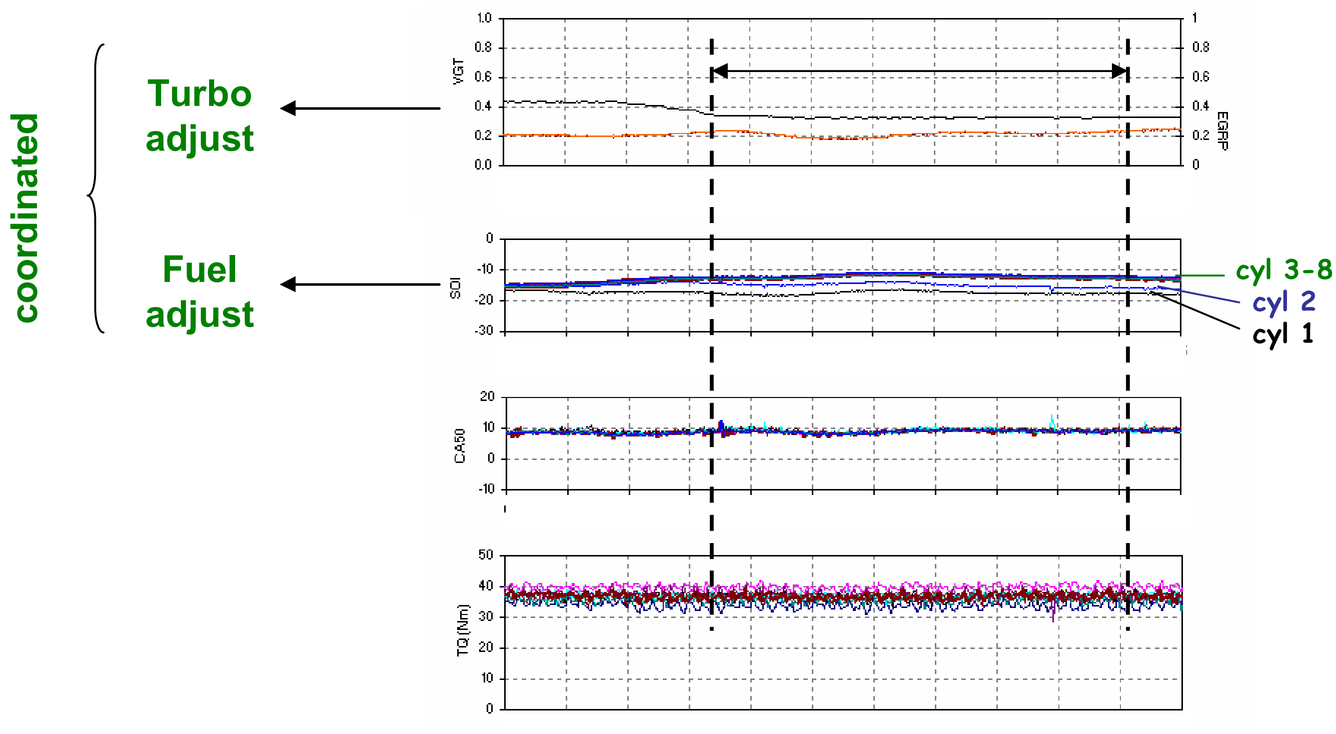




Cyl 1,2 have heavier EGR due to not-optimum mixing

Similar trends at higher speeds and loads

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

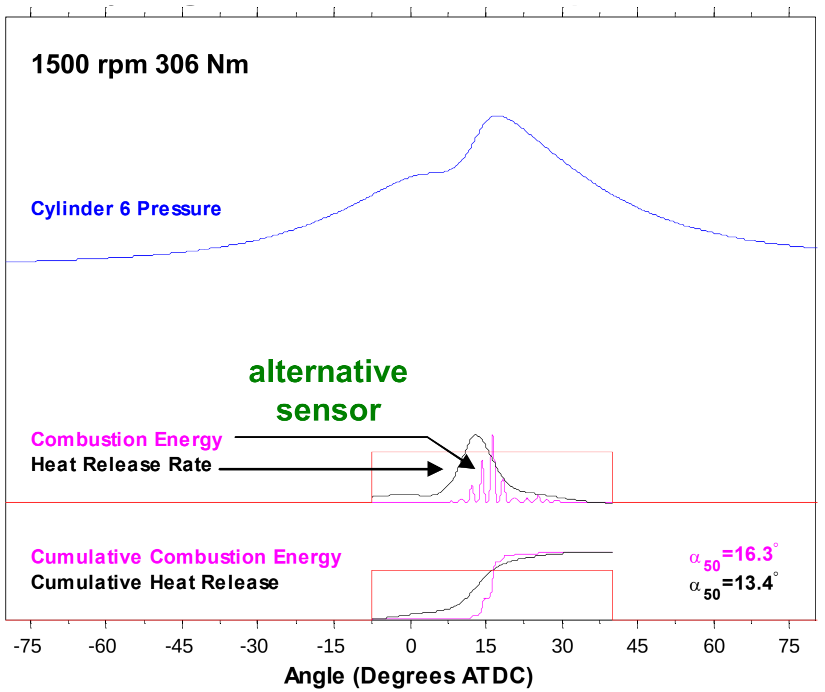


4.2 Control System Development

Production Feasible Combustion Diagnostics

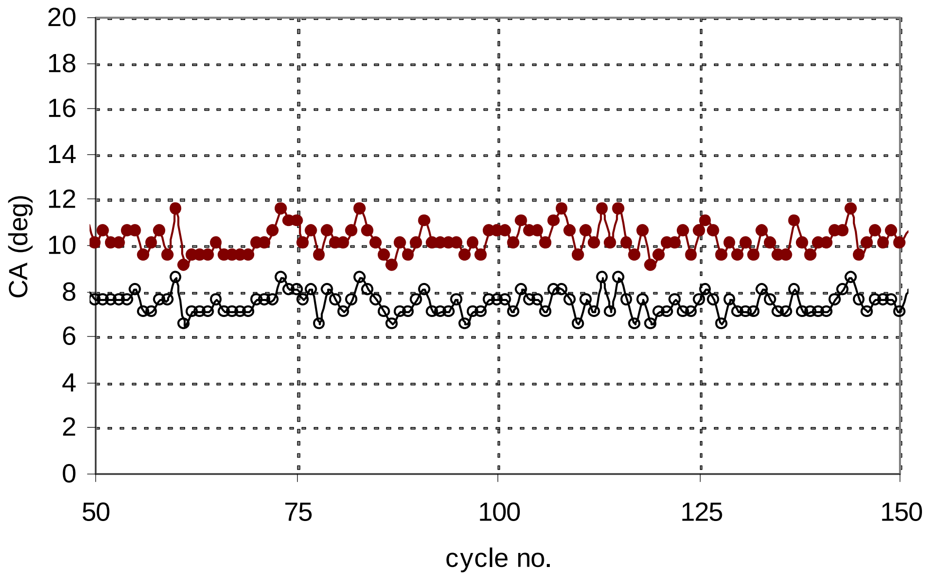
Most of the combustion diagnostics work has been performed with in-cylinder pressure transducers.

The use of other more feasible sensors (cost effective, robust) are being considered. Preliminary results show:



- **Correlation between alternative sensor and pressure data is good;**
- **Comparisons hold at LTC conditions.**
- **Results will eventually quantify alternative vs. heat release data and associated uncertainties.**

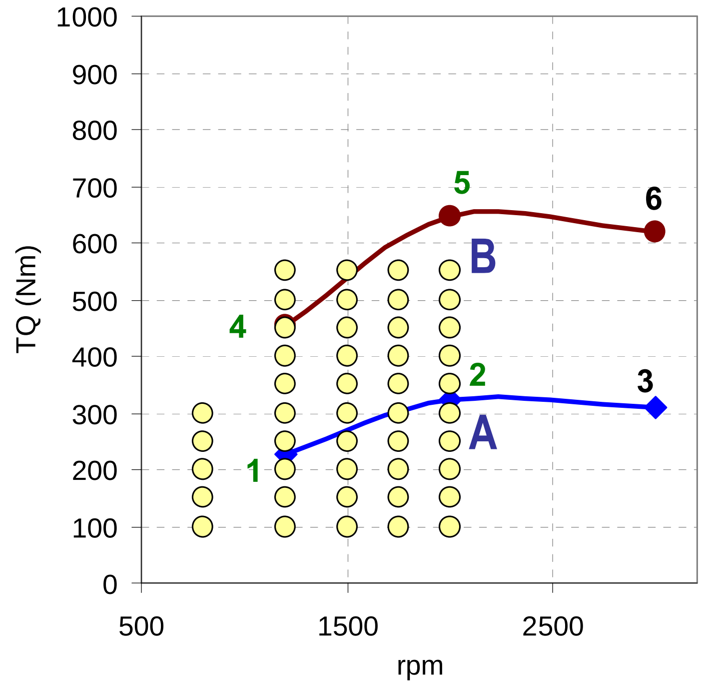
Typical cycle data shows excellent locking between heat release combustion phasing and alternative excitation signal



4.3 Steady State Mapping

Test matrix

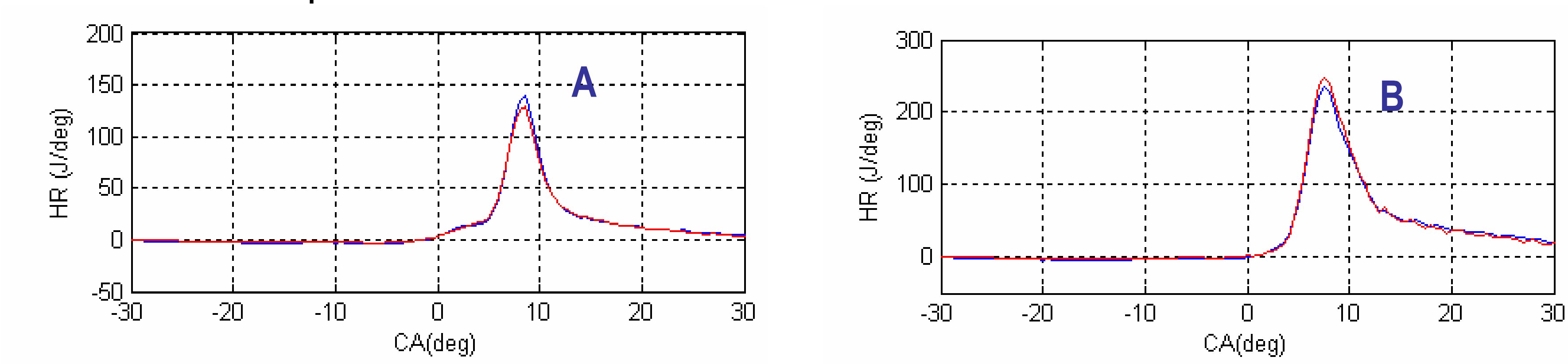
- Target region for operating with LTC,
  - Peak BMEP = 12.6 bar (point 5)
  - Rated speed = 3000 rpm (point 6)
- Steady state engine benchmark completed for (point B):
  - BMEP ~ 11bar
  - N = 2000 rpm
- Developing strategy of combustion approach based on
  - **Injection timing to optimize "premixed" mixture**
  - **Avoid wall impingement (minimize HC and BSFC penalties)**
  - **High EGR rates to maintain ignition delay**
  - **Adequate homogenization of fuel with charged air**



Present operating map **(yellow symbols)** and program test points 1,2,3 represent 50% load, points 4,5,6 represent 100% load.

Combustion traces in from cyl 1 and 8 at two different loads

and its effect on low temperature combustion



4.3 Steady State Mapping

Fuel Efficiency Optimization

Optimization of the combustion system can lead to a stable operation of LTC as is illustrated here

① **At a high CR High EGR levels are effective in reducing NOx**

In the process however the following trends are observed…
(a) SOOT is increased by ~ 0.5FSN
(b) BSFC is increased by 5 to 8%

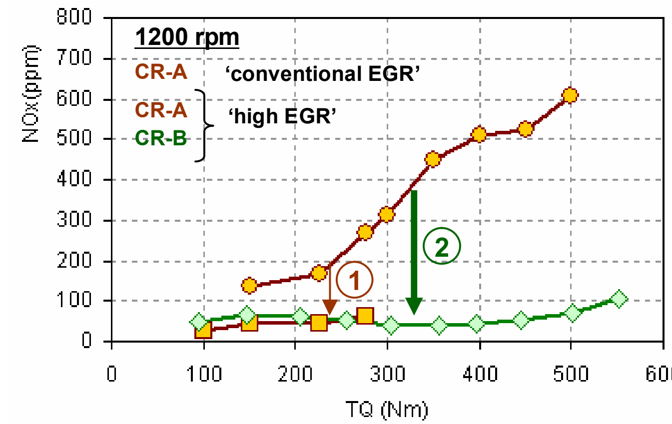
② **Low CR in addition to reducing NOx has the following advantage *over the lower portion* of the load range:**

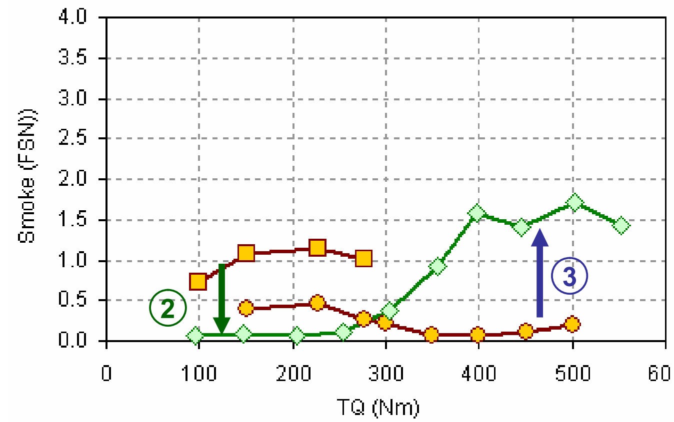
(a) BSFC improves 2-3% over a range of load
(b) Significant soot reduction, approximately 1 FSN

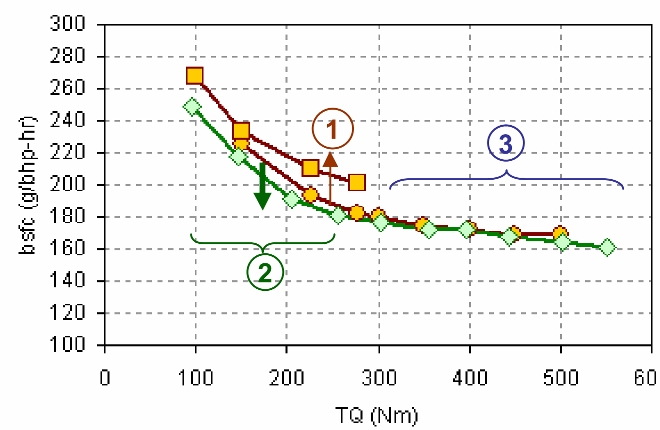
③ **Low CR in addition to reducing NOx shows the following *trends at higher loads*:**

(a) BSFC is comparable to the base engine
(b) Runs into high soot, approximately 0.5 FSN over CASE 1.

The soot is being addressed through KIVA simulations for a better bowl – injector match







4.3 Steady State Mapping

Extending the limits of LTC

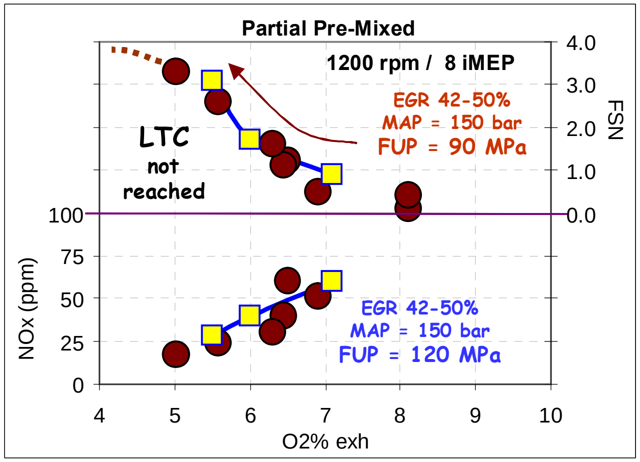
2008 DOE Merit Review

Extending the range of LTC

CR	**Confirmed**
EGR	Confirmed !
Injection strategy	***Explore in SCTE (shown here below)***
. . .	

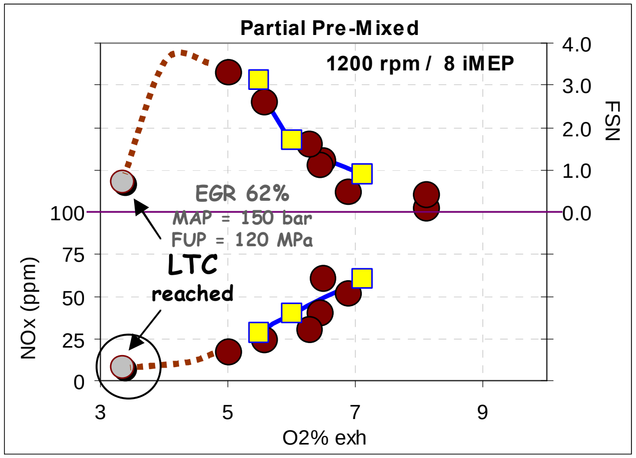
LTC not attained at iMEP of 8 bar (277Nm)

- Injection strategy: single shot
- Requires extra EGR rates
- FUP pressure not 'significant'



LTC attained at iMEP of 8 bar (277Nm) by an HCCI strategy

- Injection strategy involves multi-shots (~5-7)
- Requires further extra EGR rates
- FUP pressure contributes to mixing
- Combustion time depends on temperature and can affect cycle efficiency
- Low combustion temperatures may yield excess CO and impact combustion efficiency



5. Publications, Presentations, Patents

- “Development of a Fuel Injection Strategy for HCCI in a Diesel Engine”, William de Ojeda, Phil Zoldak, Raul Espinosa, Raj Kumar, 2008-01-0057, SAE 2008 World Congress and Exhibition

- “Multicylinder Diesel Engine Design for HCCI operation”, William de Ojeda, Raj Kumar, Raul Espinosa, Phil Zoldak, Chunyi Xia, Diesel Engine Development, DEER 2007, August 12-16, Detroit Michigan

- “Development of a Multi-Cylinder Diesel Engine for HCCI Operation”, William de Ojeda, Homogeneous Charge Compression Ignition Symposium, 24-26 September 2006, San Ramon, California

- “Multi-cylinder Diesel Engine Design for HCCI operation”, William de Ojeda, Alan Karkkainen, Diesel Engine Development, DEER 2006, August 20-24, Detroit Michigan

6. Collaborations/Interactions

- Partners:
  - Ricardo: engine design support (cylinder head optimization)
  - ConnocoPhillips: test fuels at varying CN
  - Mahle: piston design
  - Borg Warner: turbo charger mapping
  - Siemens: injector design, knock sensor technology
  - University of California – Berkeley: Ion sensing
  - LLNL
    - Modeling engine conditions to understand and optimize system
    - Piston and injector optimization
    - Track sources of emissions

- Collaborations:
  - SWRI
  - University of Windsor: SCTE
  - SANDIA

7. Activities for Next Fiscal Year

- Extend steady state mapping to higher loads (above 11 bar bMEP)
- Development of Model and controls towards transient operation
- Reduce Heat Rejection, HC/CO and PM through Combustion System Optimization:
  - Impact of Hardware: continue with modeling and experiments to refine the interaction among piston / bowl / injector to support LTC (collaboration with LLNL's and Univ. of Windsor). *Develop fundamentals of the combustion process.*
  - Implementation of VVA hardware and start of engine testing.
  - Continue with VCR hardware design
  - Selection of mature start of combustion sensing technology.
- ECU development
  - Capable to sustain in-cylinder pressure feedback.
- Next Milestones:
  - July 1st 2008: Report on VVA impact
  - August 1st 2008: Report on fuel property effects (ConnocoPhillips)
    Impact of combustion detection technology
  - November 1st 2008: PHASE III REPORT: Complete full N-TQ mapping with LTC
  - March 1st 2009: Preliminary transient results
  - May 1st 2009: Vehicle installation

8. Summary

- Applied low temperature combustion (LTC) to the ITEC 6.4L V8 production engine.
  - ✓ Significant progress was made to extend operation to 11 bMEP
  - ✓ Special focus on engine efficiency at or better than the base engine
  - ✓ Technology path outline: (1) Compression Ratio, EGR, Injection strategy (2) Air System, Combustion Bowl
- Engine testing coupled to combustion fundamentals:
  - ✓ Testing is accompanied by chemical kinetic simulations
  - ✓ Testing is coordinated with better controlled single-cylinder engine tests.
- Capable for production implementation:
  - ✓ The application of non-pressure based a combustion diagnostics have been benchmarked with in-cylinder pressure sensors and early results give promising results.
  - ✓ Controls development has been effective to stabilize the combustion system in (1) coordinated control among air/EGR/fuel systems, and (2) in preventing misfire.
- Successful collaborations: The approach targets 2010 emissions without after treatment using today's Diesel fuel.
  - ✓ ConnocoPhillips follow the combustion data and impact of fuel formulation
  - ✓ LLNL support the KIVA simulations matching engine test points
  - ✓ Control development in conjunction with Univ of Windsor.
- Next Milestones outlined