Multicylinder Diesel Engine Design for HCCI operation

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Diesel Engine Development

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Industrial Partners: UCB, LLNL, Siemens, ConocoPhillips, BorgWarner, Mahle, Ricardo.

Goals and Objectives

- **Overall goal:**
  - Demonstrate the application of low temperature combustion (LTC) to minimize in-cylinder emissions using today's Diesel fuel.
  - The technology generated in project to be capable for production implementation.
- **Phase I:** Engine hardware simulation and design
- **Phase II:** Procurement and prove-out of main components:
  Fuel injectors, charge air-EGR system, control system with cylinder pressure feedback
- **Phase III:** Steady-state mapping
- **Phase IV:** Transient and vehicle installation
- **Key technical challenges addressed:**
  - Optimization of fuel and charge air mixture to sustain LTC conditions
  - Improve stability of combustion with control system / VVA system
  - Minimize hydrocarbon emissions and maintain or improve bsfc
  - Accommodate a range of fuel properties representative of US geography

Approach

Three pronged approach:

1. **Thermodynamic engine modeling** was done to select engine hardware to operate engine under LTC conditions (homogeneity, EQR) and deliver a max BMEP of 12.6 bar. The result is:
   a. two-stage turbocharger,
   b. dual-parallel EGR system,
   c. low compression ratio piston
2. **CFD-Kinetic combined modeling** (mainly performed at LLNL) to optimize the injection and combustion chamber geometries.
3. **Control Supervisor** is used to integrate fuel and air systems. Specially notable are:
   a. coordinated <u>boost/EGR</u> systems
   b. <u>fuel injection strategies</u> specific to speed and load
   b. development of a combustion <u>close-loop control</u> based on in-cylinder pressure measurements.
4. Still under design / procurement: these are considered as enablers of LTC:
   a. production like VVA system
   b. concept VCR

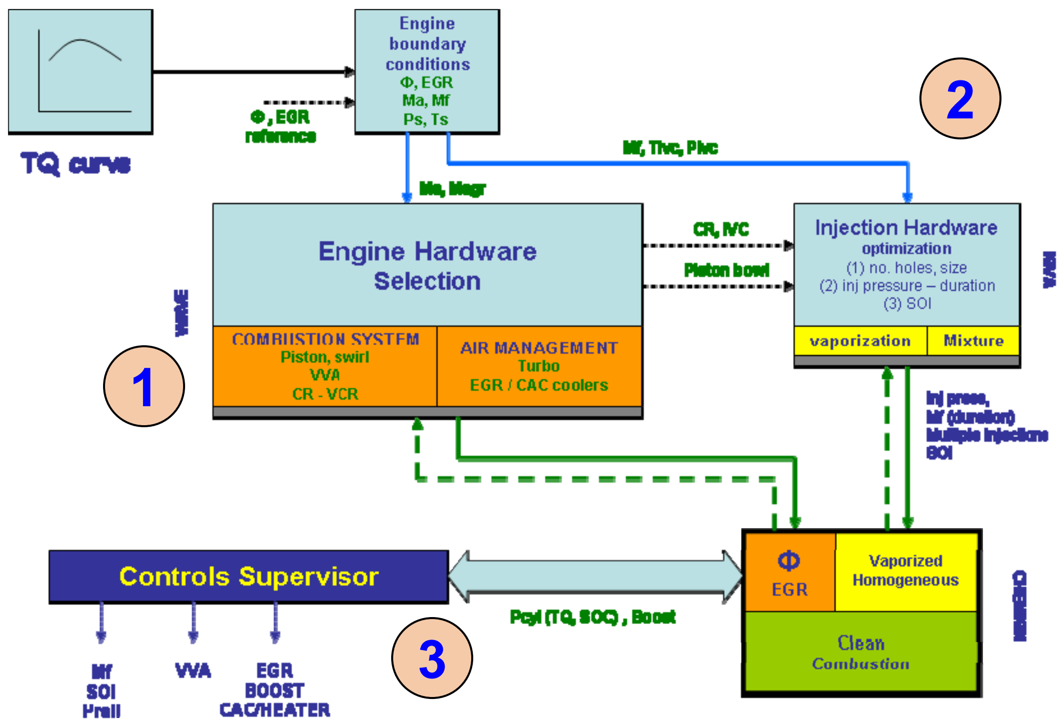


Illustration of engine design approach

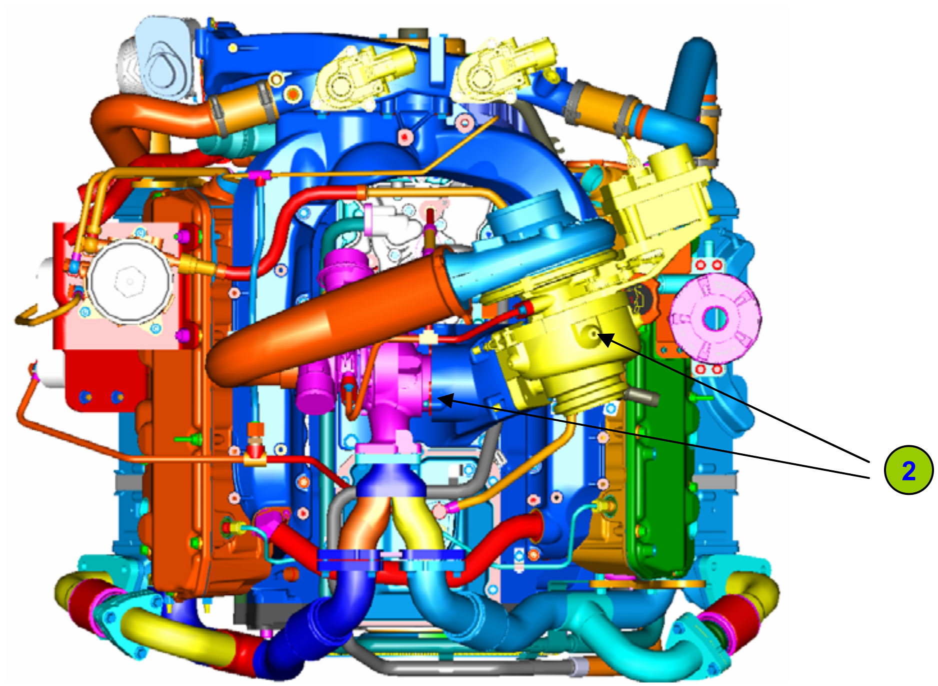
Engine Build

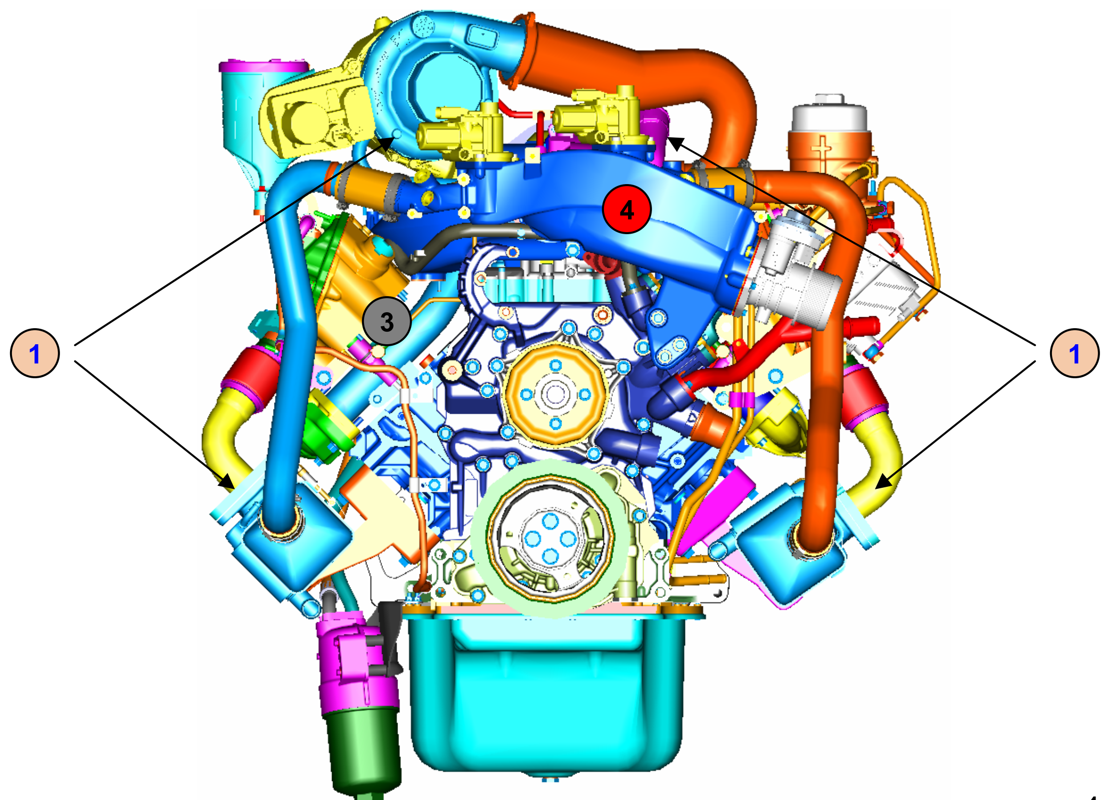
Base Engine:

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

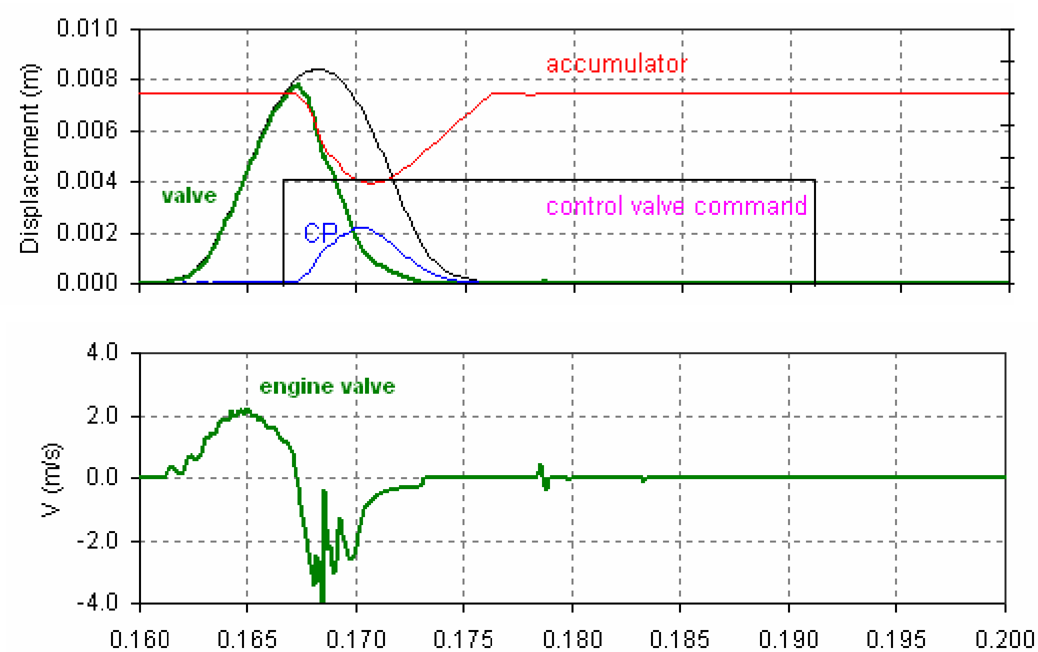




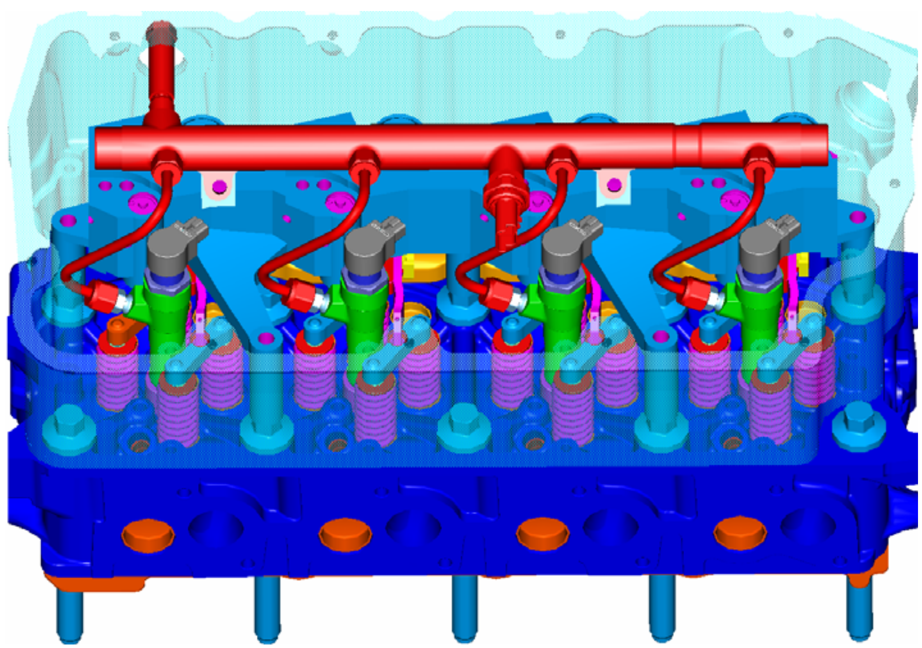
Next Engine Build: VVA system

Variable valve actuation system:

- Electro-hydraulic system can provide **flexible intake valve closing times**
- IVC is **applied to individual cylinders** and thus can provide effective “trimming” to balance cylinders.
- IVC can effectively reduce compression ratio and provide **control over ignition time**.



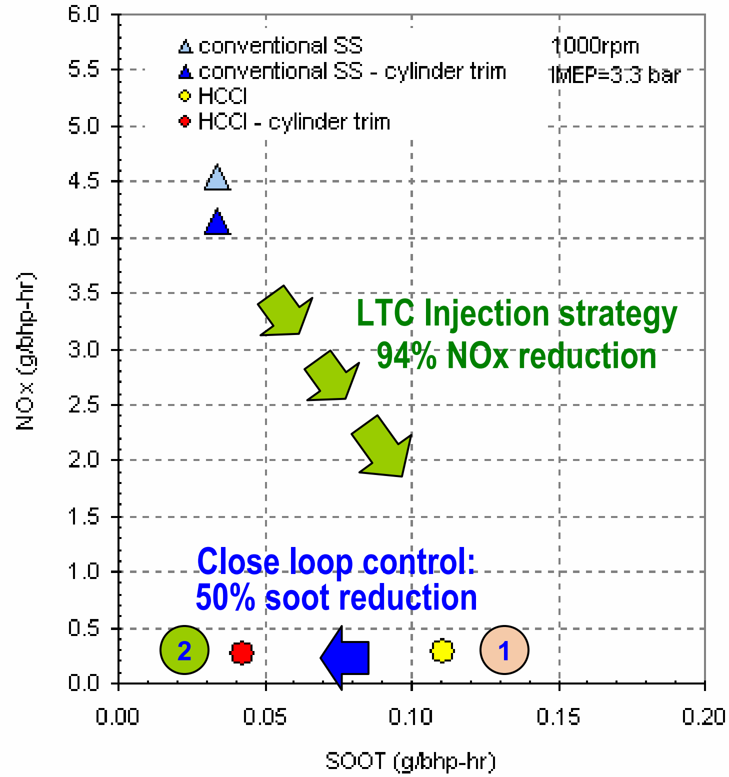
Simulation of VVA system at 3000rpm

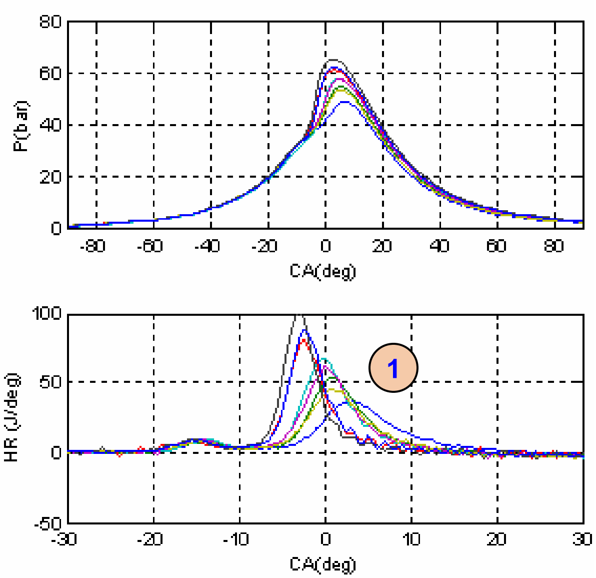


Proposed layout of VVA system

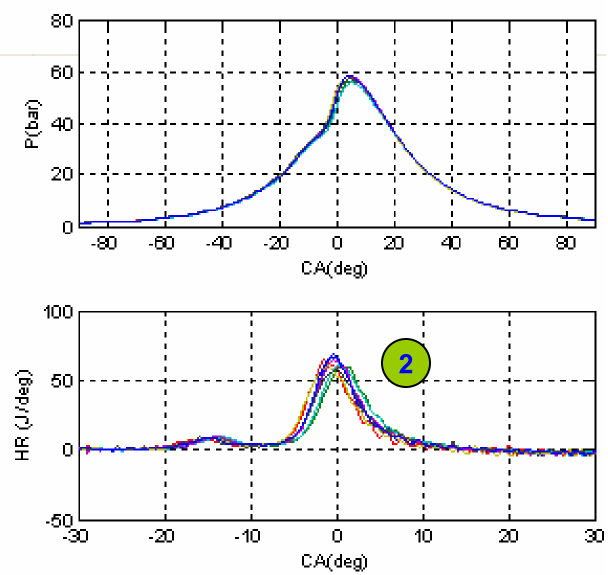
Close-Loop-Control
to control combustion with multiple cylinders

- Control system is based on cylinder pressure measurements
- System is applied to conventional combustion and to LTC like conditions. It is effective in reducing overall emissions by trimming fuel to each cylinder.
- Under conventional combustion, emissions improve only slightly. **Under LTC conditions** the effect is more pronounced, data shows soot may be reduced by up to 50%





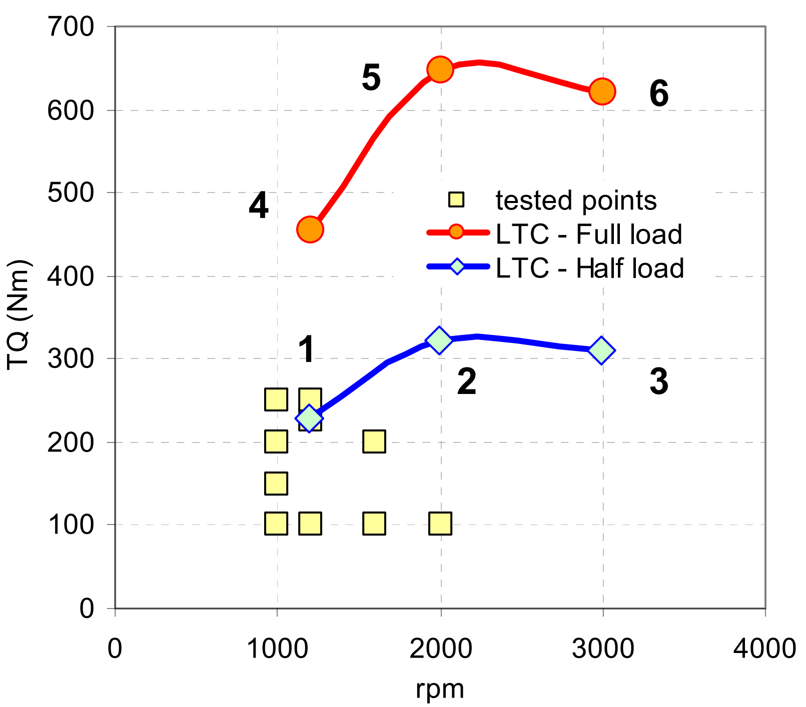
Pressure and heat release traces **without** close feedback under HCCI operation



Pressure and heat release traces **with** close feedback under HCCI operation

Steady State Mapping

- Began steady
- Developing strategy of combustion approach based on emissions and fuel economy performance. Keys are:
  - **Provide homogenization of fuel with charged air** via FIE injection pattern (holes and size), single/multi-shot injections, injection timing.
  - **Target specific dilute conditions (equivalence ratio targets)** via turbocharger hardware.
  - **Target EGR levels to suppress combustion** via EGR cooler / valving system
  - **Avoid wall impingement** (key to minimize HC and BSFC penalties)



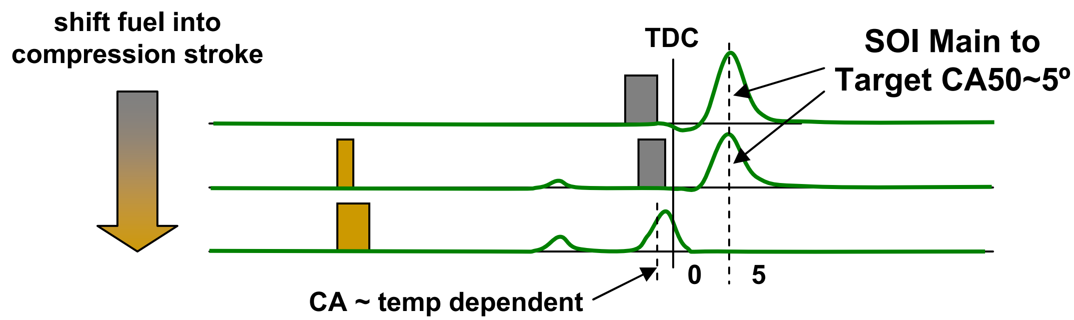
Present operating map (squares) and test points.

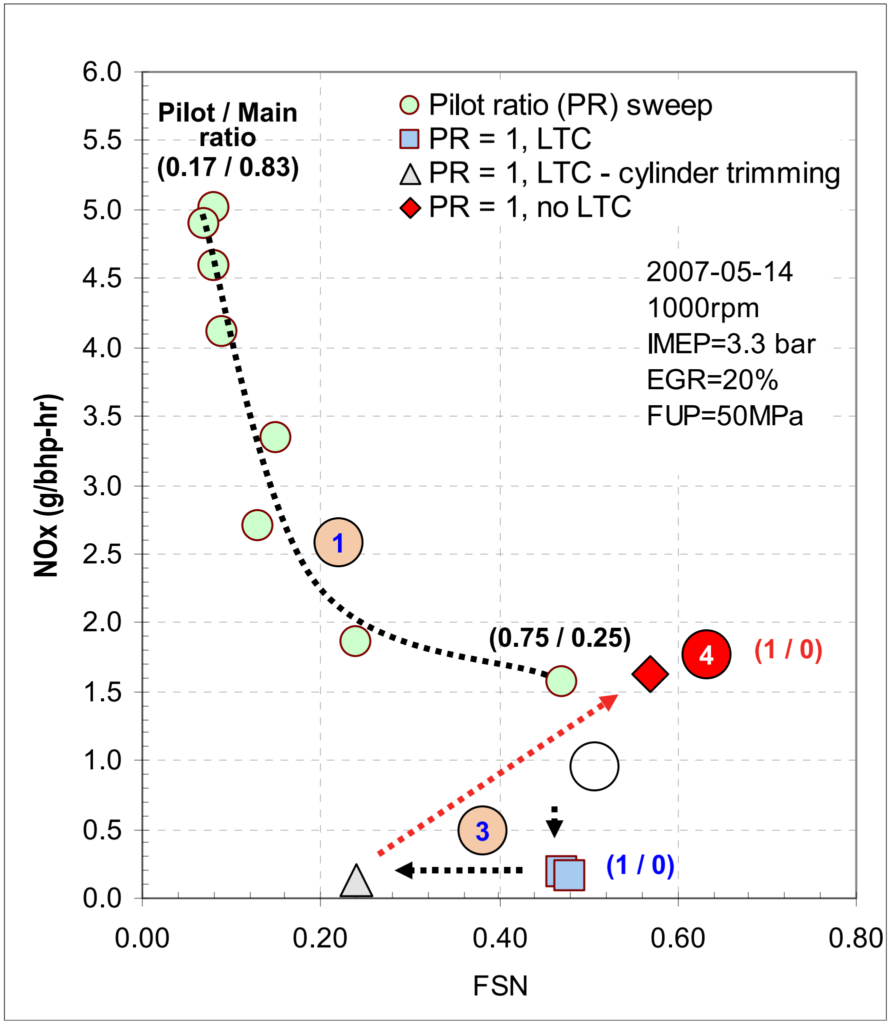
Points 1,2,3 represent 50% load
Points 4,5,6 represent 100% load.

Test Methodology

Highlighted is the achievement of LTC (low NOx/SOOT) with modest EGR levels and low injection pressure relying on fuel-charge air mixing:

1. Fuel transfer from "main" near TDC to early "pilot" shows the traditional NOx/SOOT tradeoff.
2. Fully premixed fuel reduces NOx by ~85% ("cliff-event")
3. The effect of close-loop fuel trimming is illustrated
4. Injection timing is key to ensure fuel-charge air homogeneity as shown in the loss of LTC from (3) to (4). Latter injection timing returned combustion system to non-LTC like conditions with high NOx and soot.



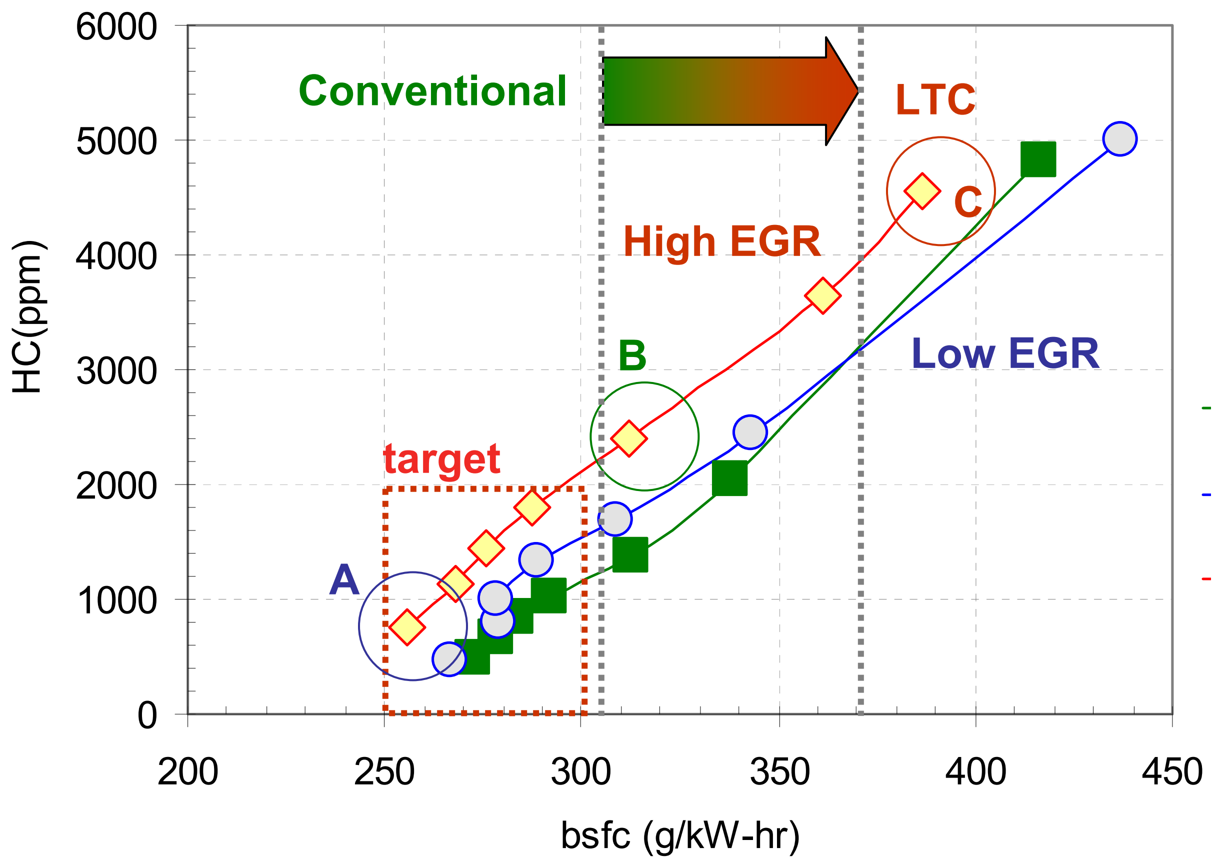


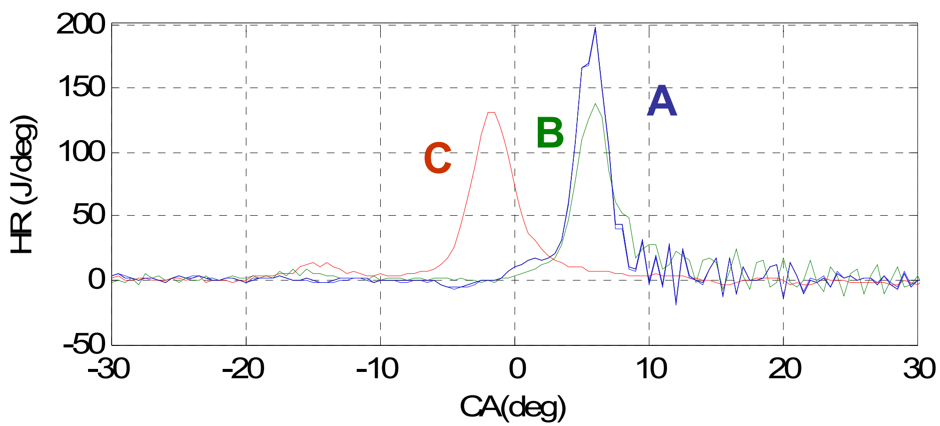
The HC and BSFC Challenge

The challenge of poor fuel economy and high HCs is illustrated here.

LTC like conditions are attained by shifting fuel into the compression stroke.

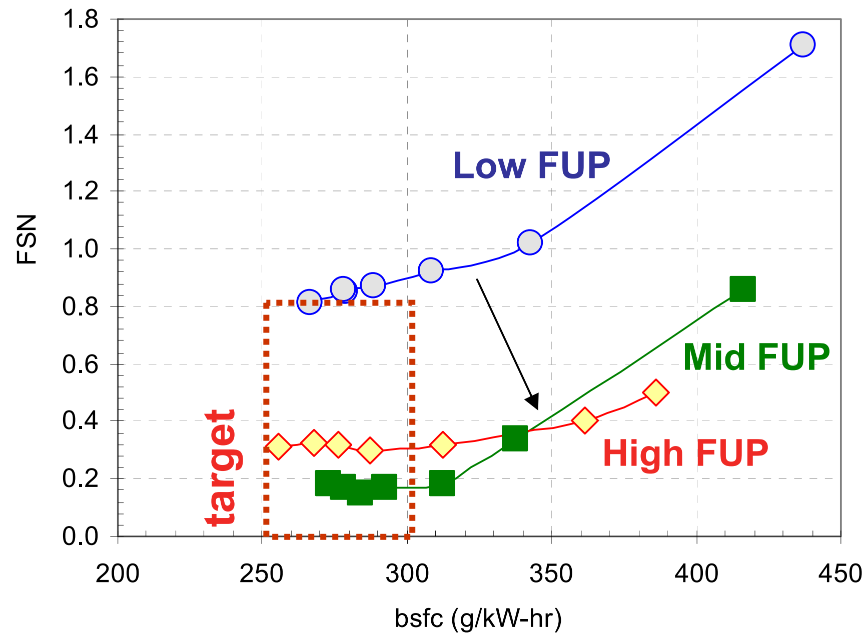
Low temperature conditions are attained as shown in **case C**. The characteristic "cool" flame chemistry appears. However HCs and BSFC increasingly deteriorate.



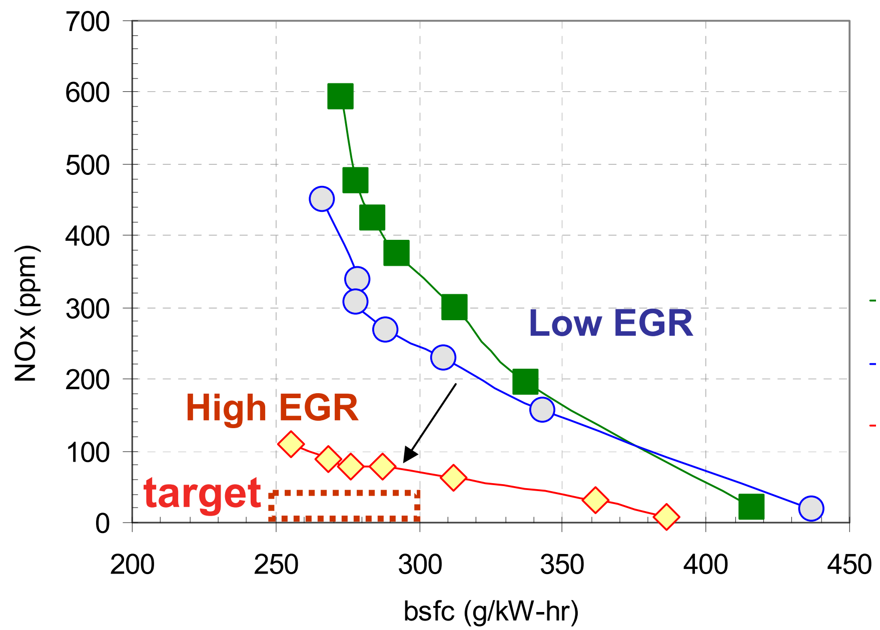


General Trends

Injection pressure is effective in reducing smoke / soot generation.



EGR is effective in reducing NOx.



NEXT:

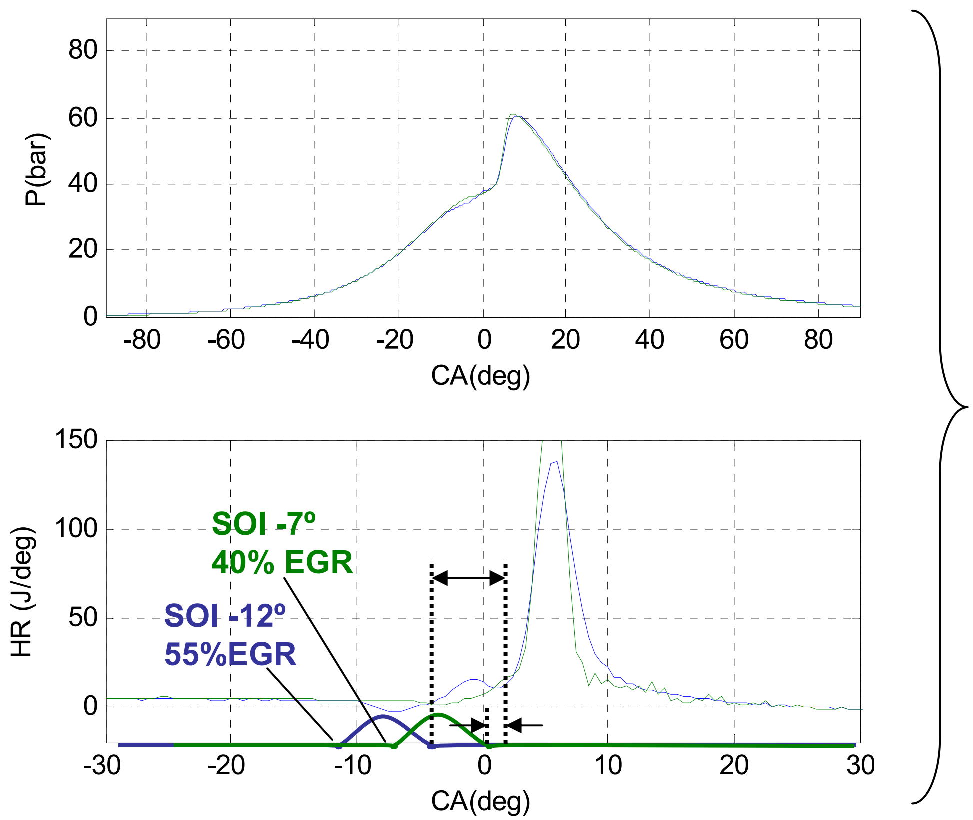
EGR in combination with injection pressure and **OPTIMUM COMBUSTION TIMING AND VAPORIZATION** can lead to optimizing emissions and HC/BSFC tradeoff to acceptable levels.

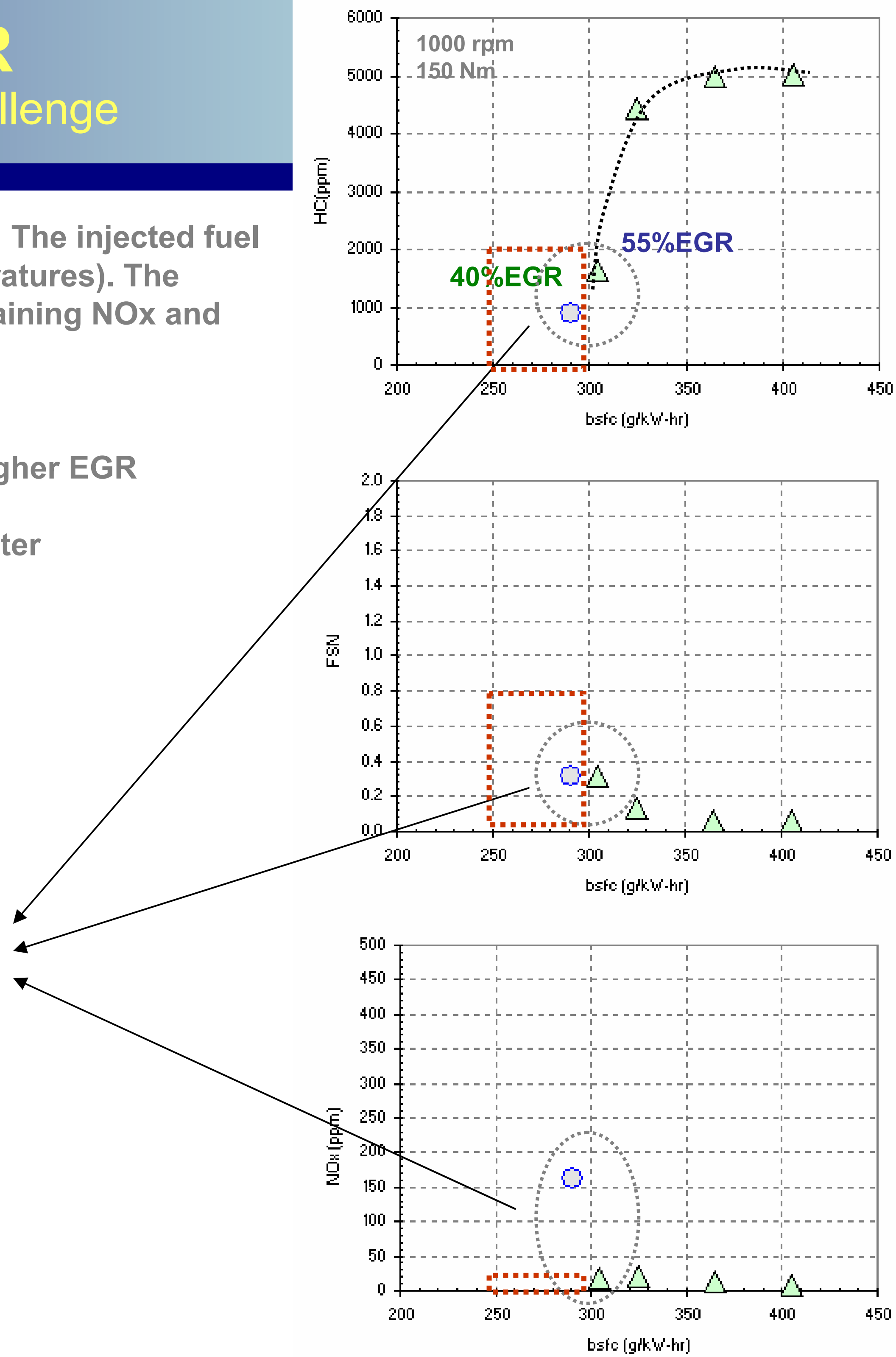
Optimizing Timing and EGR

Helping to resolve the HC and BSFC challenge

The Effect of SOI in preparing the mixture is key: The injected fuel must vaporize (thus it must be injected at higher temperatures). The impact is great in minimizing BSFC and HC while maintaining NOx and soot emissions.

Effect of EGR in ignition delay and emissions: higher EGR rates allow earlier injection timings (while holding CA50 constant). The longer ignition delay correlates with greater mixing times typical of LTC operation.





Summary

- **Applied low temperature combustion** (LTC) to minimize engine out emissions using today's Diesel fuel.
- **Approach for engine design** combined thermodynamic engine modeling (based on prescribed EGR and EQR targets) to deliver a max BMEP of 12.6 bar, CFD-kinetic modeling to optimize the injection and combustion chamber geometries, and a control supervisor to integrate fuel and air systems.

  The technology gathered is capable for production implementation: especially designed fuel injectors, pistons, EGR system, turbocharger were procured.

  A VVA version of the engine is underway.
- **LTC** was achieved with high EGR levels as well as more modest EGR and injection pressures by relying on generating a fuel - charge air homogenous mixture.

  Key technical challenges addressed are optimization of fuel and charge air mixture to sustain LTC conditions; limit engine out emissions, improve stability of combustion with control system, minimize hydrocarbon emissions and gain in bsfc

  The effects of EGR, intake manifold temperatures, injection pressures and injection timing were documented.
- **A close-loop-control** WAS successfully applied to conventional combustion and to LTC conditions to equalize cylinder torque and start of combustion. Data to date showed reduction of soot over 50%.
- Next steps is to extend the steady state mapping. The region currently being study extends between 6 – 12.6 bar.