An Enabling Study of Diesel Low-Temperature Combustion via Adaptive Control

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LTC Enabling Prospects

1. Optimize control by separating the time scales of fuel air mixing and ignition
2. **Stabilizing LTC operations – on cliff operation of ultra low NOx emissions and acceptable fuel efficiency**
3. **Guide transient combustion control within LTC mode when major engine operating parameters such as boost, EGR, and engine speed varies**
4. Raise engine Load level in LTC
5. Mode shifts between conventional and LTC
6. Multi-cylinder EGR, fuel, and air distributions
7. Biodiesel Impact – Cetane, oxygen content, volatility, viscosity, biodegradation, high pressure compressed solid

Diesel LTC Challenges

1. The fuel efficiency of the LTC cycles is commonly mired by the high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions. The fuel-efficiency of HCCI engines is often compromised by the high levels of HC and CO emissions that may drain substantial amount of fuel energy (5~15% in low-load cases) from the engine cycle.
2. Moreover, the combustion process becomes less robust and enters into narrower operating ranges and with higher instabilities compared to conventional high temperature combustion (HTC) operations – LTC is closer to the flame-out limits than HTC.
3. The scheduling of early fuel delivery in HCCI engines has lesser leverage on the exact timing of auto-ignition that may even occur before the compression stroke completes when a high compression ratio of conventional diesel cycles is applied, which may cause excessive efficiency reduction and combustion roughness.
4. The high HC and CO emissions are attributed to the relatively low volatility of diesel fuels, the lowered combustion efficiency of the lean and/or EGR weakened cylinder charge, the non-homogeneity of the cylinder charge, and the fuel condensation and flame quenching on the surfaces of the combustion chamber.

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Diesel Low Temperature Combustion

- Heavy EGR and close to TDC burn – low IMEP
- Multiple early injection – homogenous lean/weak

- Late Injection – post TDC prolonged ignition delay
- Multiple early plus late main flame (HC post burn)

Prolonging of Ignition delay (mixing time)

from end of injection > 1.5 ms OR
50% prolonging from conventional

Ultra low NOx & near zero dry soot
(<5 ppm)

IMEP > 6bar

When IMEP<6bar,
ultra-low emissions
LTC can be enabled
with higher P_{inj},
EGR, & boost

Efficiency & Emissions
Power, Robustness & Roughness
After-treatment Readiness

Cylinder Charge
- Locally lean
- Halved intake O_2
- Increased CO_2

VVT
&
VCR

Trade-off

Burning Efficiency
CO & HC & SOF

Mode Switch

Load	HCCI	Diesel
Idle		High EGR
Low	Low EGR	
Mid	Medium EGR	
High	Heavy EGR	
Full		High EGR

Phasing
- Multi-pulse injection scheduling
- EGR, boost and T_{Intake} control
- Mixing improvement with Injector & piston bowl

Adaptive Control
- Navigate narrow operating corridors
- Model based heat release patterning
- Enable transients and mode switching
- Minimize cyclic variations to optimize fuel η

Research Platform – non compromised for control performance

The research platform consists of an advanced common-rail diesel engine modified for the intensified single cylinder research and a set of embedded real-time (RT) controllers, field programmable gate array (FPGA) devices, and a synchronized personal computer (PC) control and measurement system. Up to 12 fuel injection pulses per cylinder per cycle have been applied to modulate the homogeneity history of the cylinder charge in mixed mode combustion in order to improve the phasing and completeness of combustion under independently controlled exhaust gas recirculation (EGR), intake boost, and exhaust backpressure.

Experimental Setup

- Capable of multiple parallel 1st priority control tasks

Engine Type	4 Cylinder, Ford "Puma"
Displacement [cm^3]	1998
Bore x Stroke [mm]	86 x 86
Compression Ratio	18.2:1
Combustion System	Direct Injection
Injection System	Common-rail; $P_{Rail} \leq$ 160 MPa

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CONTROL & ACQUISTION HARDWARE

4 FPGA-RT Platforms

- Fuel Injection Control – up to 10 injections per combustion cycle
- Common-rail Pressure Control
- Combustion Characterization
  - Heat release analysis and pattern recognition
  - Motoring pressure estimation
  - Pmax, IMEP estimation for within-cycle control
  - Signal conditioning
- EGR Valve Control

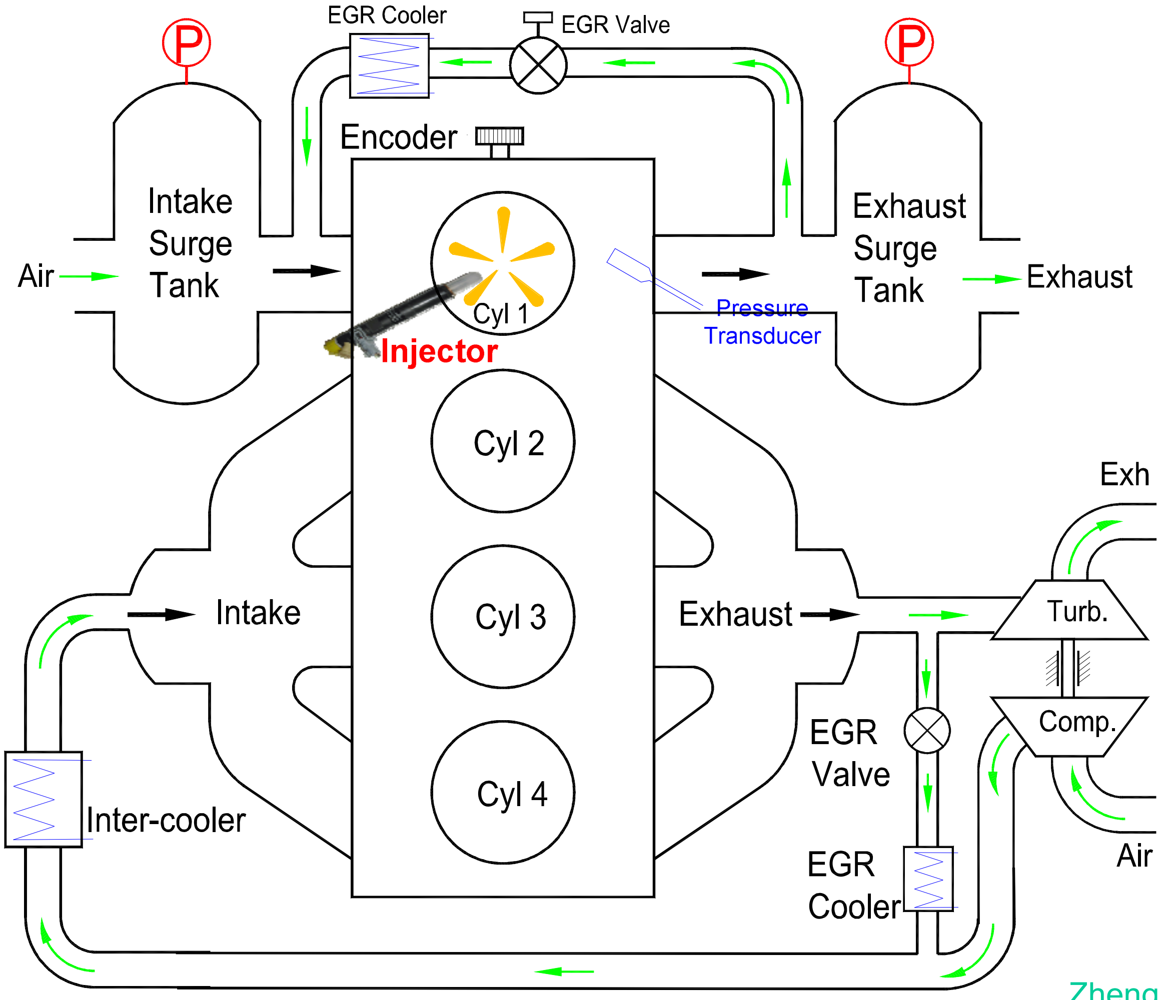
4 Injector Power Drives

- EV Driving Cycle
- Reconfigurable Conditioning

16 PC Systems

- 96 Simultaneous Temperature Measurements
- Continuous Cylinder Pressure Recording
- Engine Boost, Exhaust Back-pressure Control
- Online Heat Release Analysis
- Up to 128 Analog, 224 Digital Signal Acquisitions

Ford Puma Common Rail Diesel Engine



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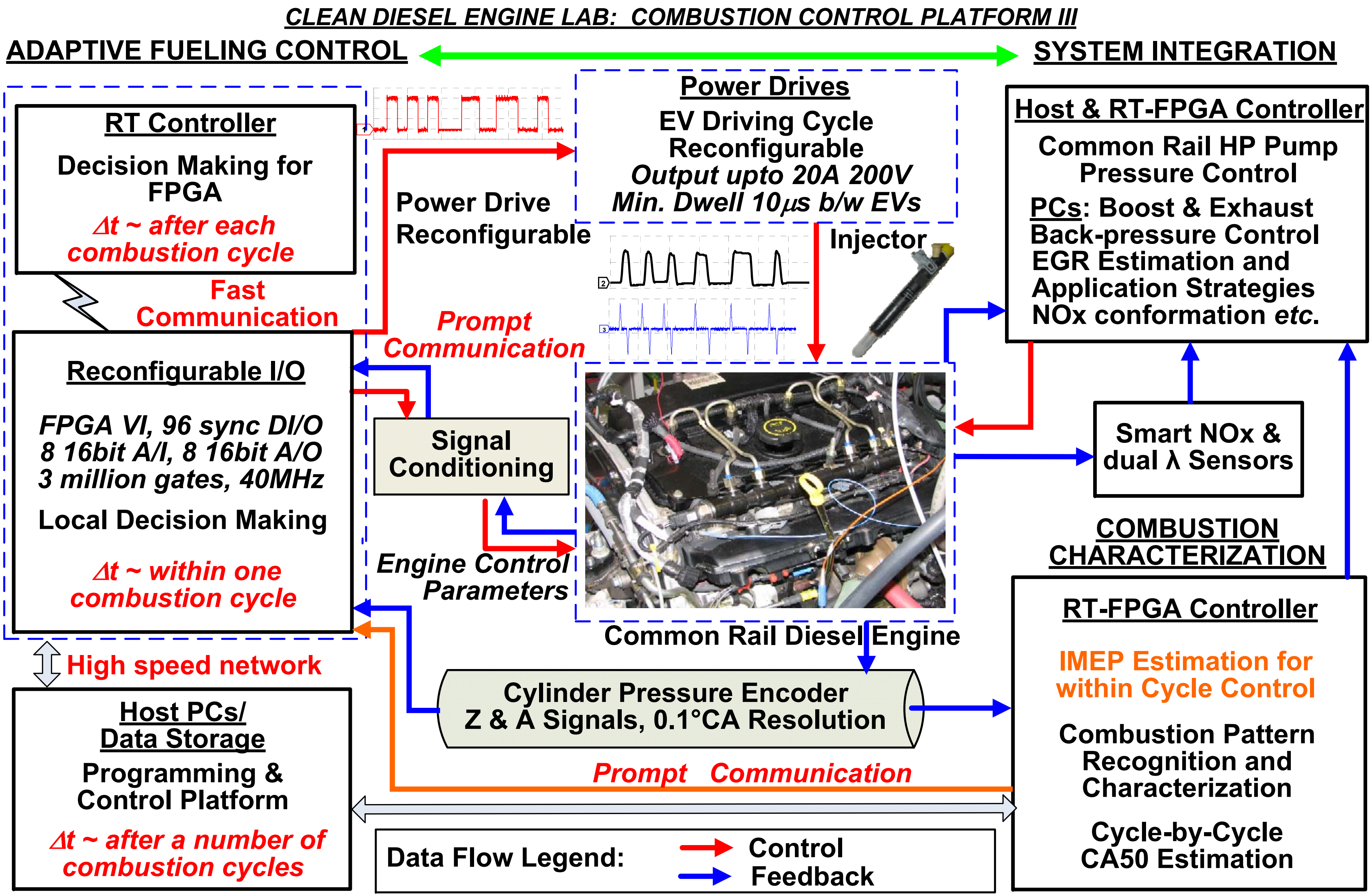
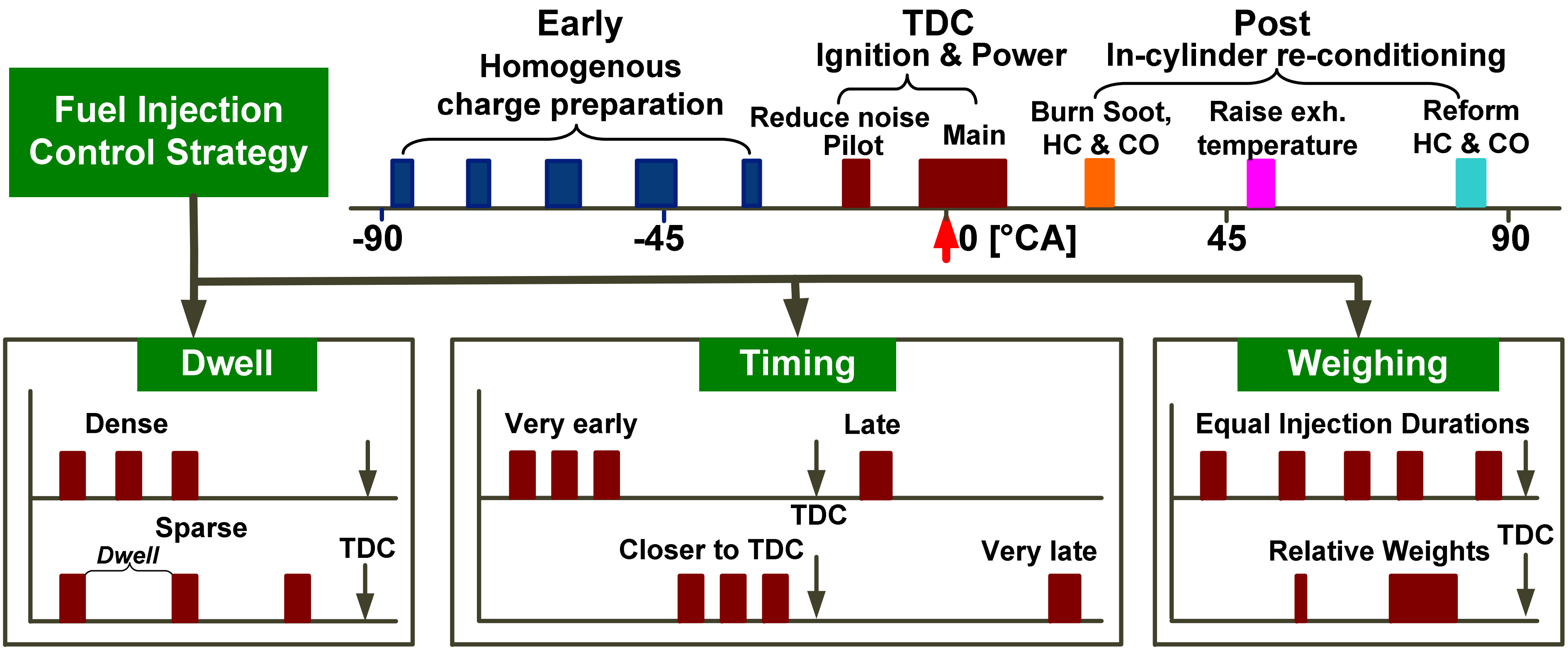
Adaptive Combustion Control Platform



Fuel Injection Scheduling

1. Up to 12 fuel injection pulses per cylinder per cycle have been applied to modulate the homogeneity history of the HCCI operations in order to better phasing and completing the combustion process.
2. Empirical studies have been conducted under independently controlled exhaust gas recirculation (EGR), intake boost, and exhaust backpressure.



Challenges in Digital Combustion Control

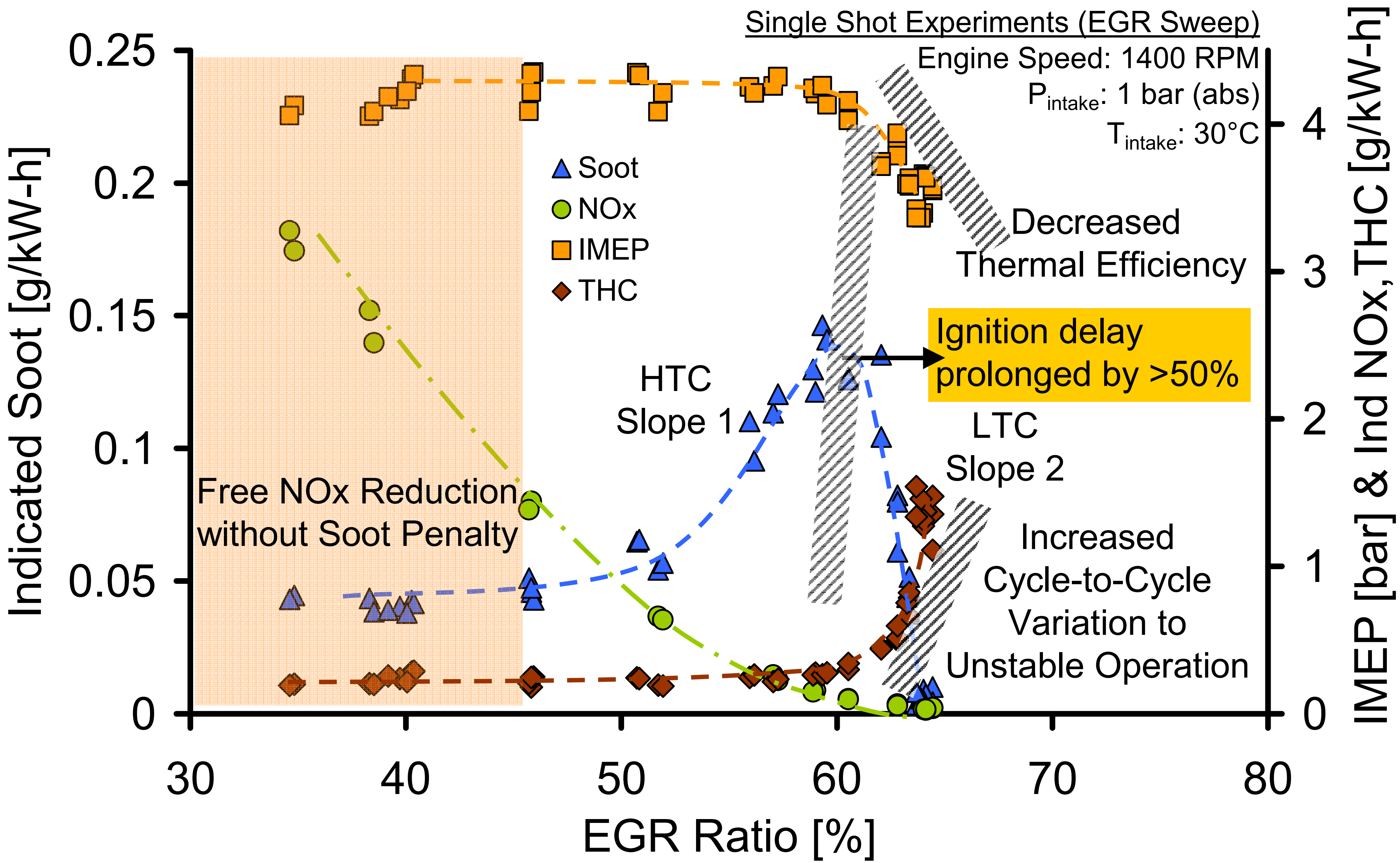
1. Adaptation step relaxation versus prompt performance modulation
2. Cylinder pressure noise filtration versus signal sharpness
3. Simplex feedback control versus model based forward control
4. Fuel injection pulse numbers versus total injection time window of the least condensation

Experimental Case Outline

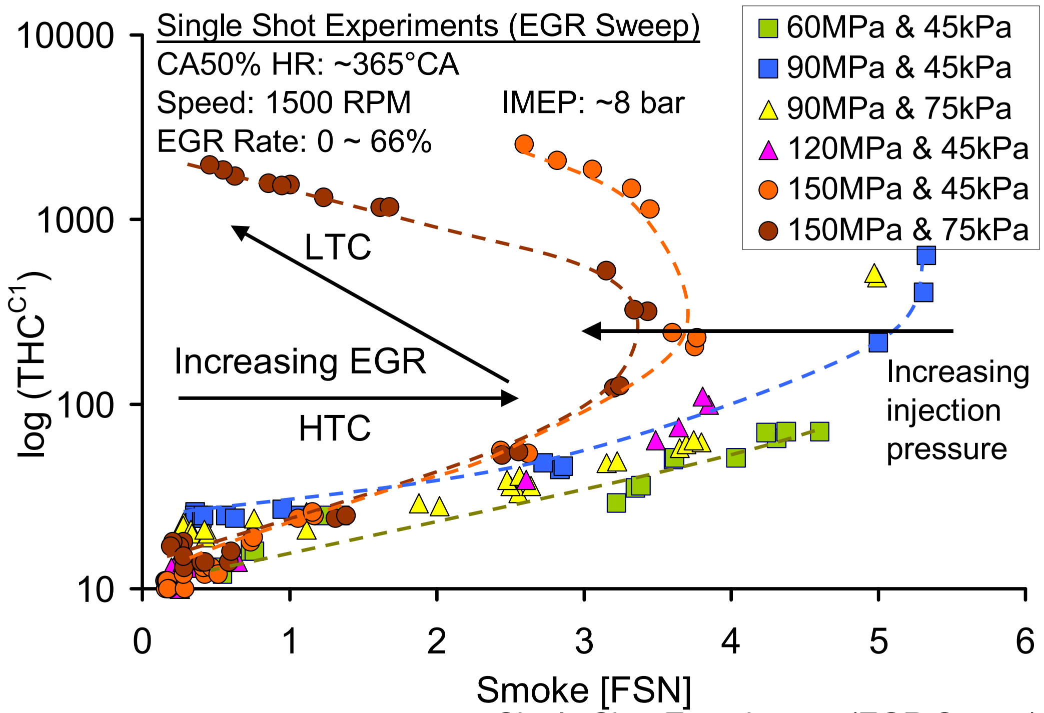
1. Single shot with heavy EGR to separate the time domains between injection and combustion
2. Multiple early shots with moderate EGR to improve homogeneity
3. Multiple early plus main to gain power output
4. Speed and boost transients

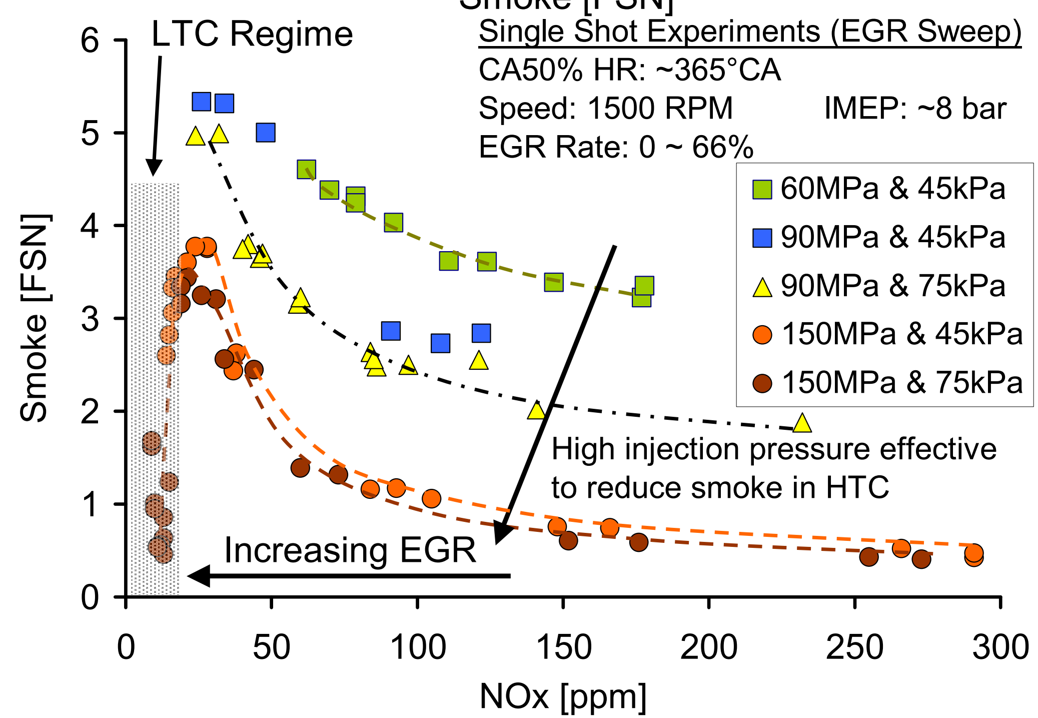
DIESEL LTC CHALLENGES

- Prolonged Ignition Delay to enable LTC

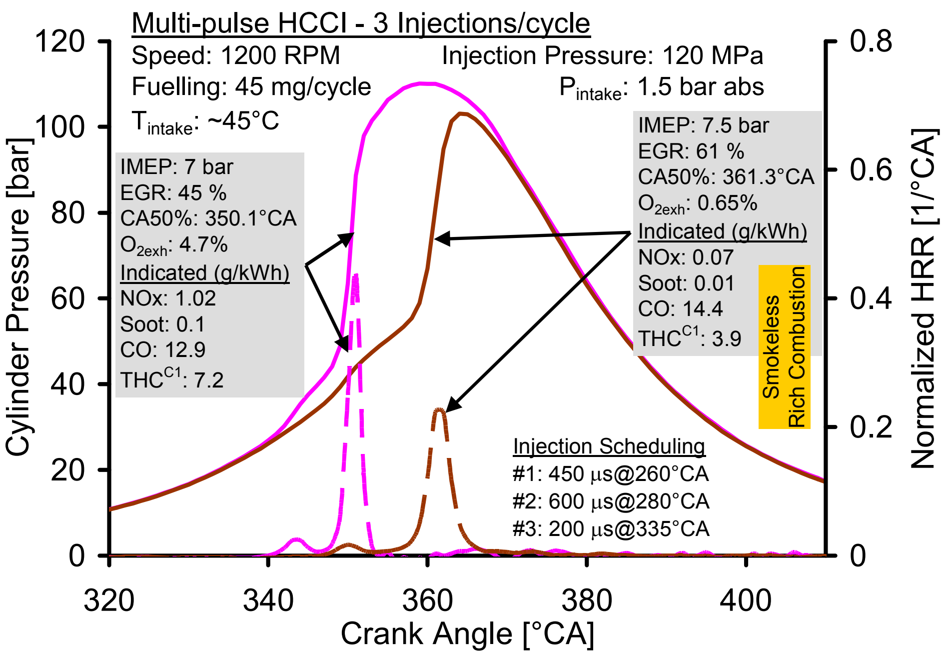


New LTC Emission Trade-off

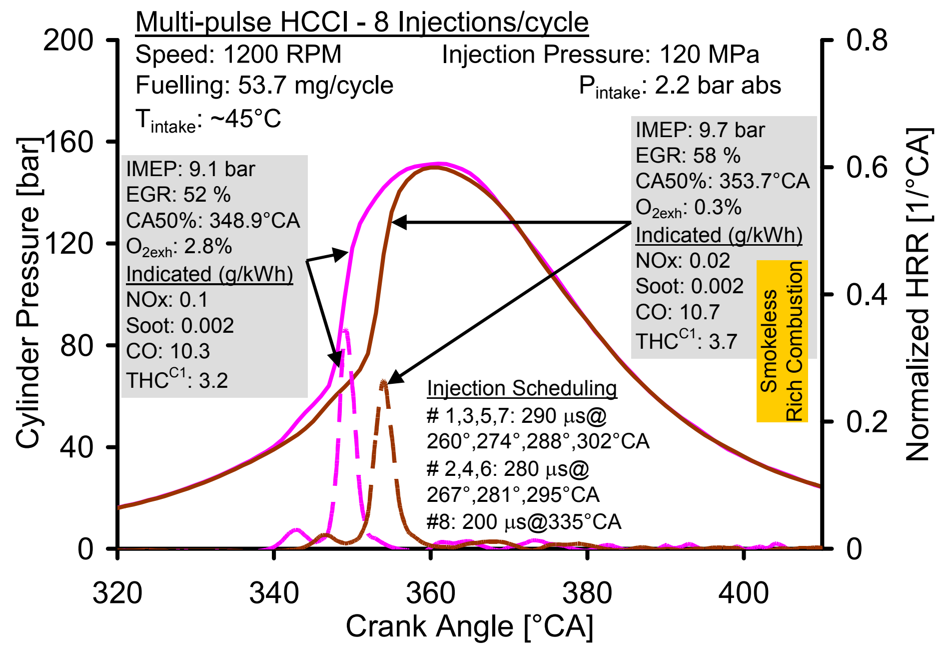




Diesel LTC vs. Engine Load



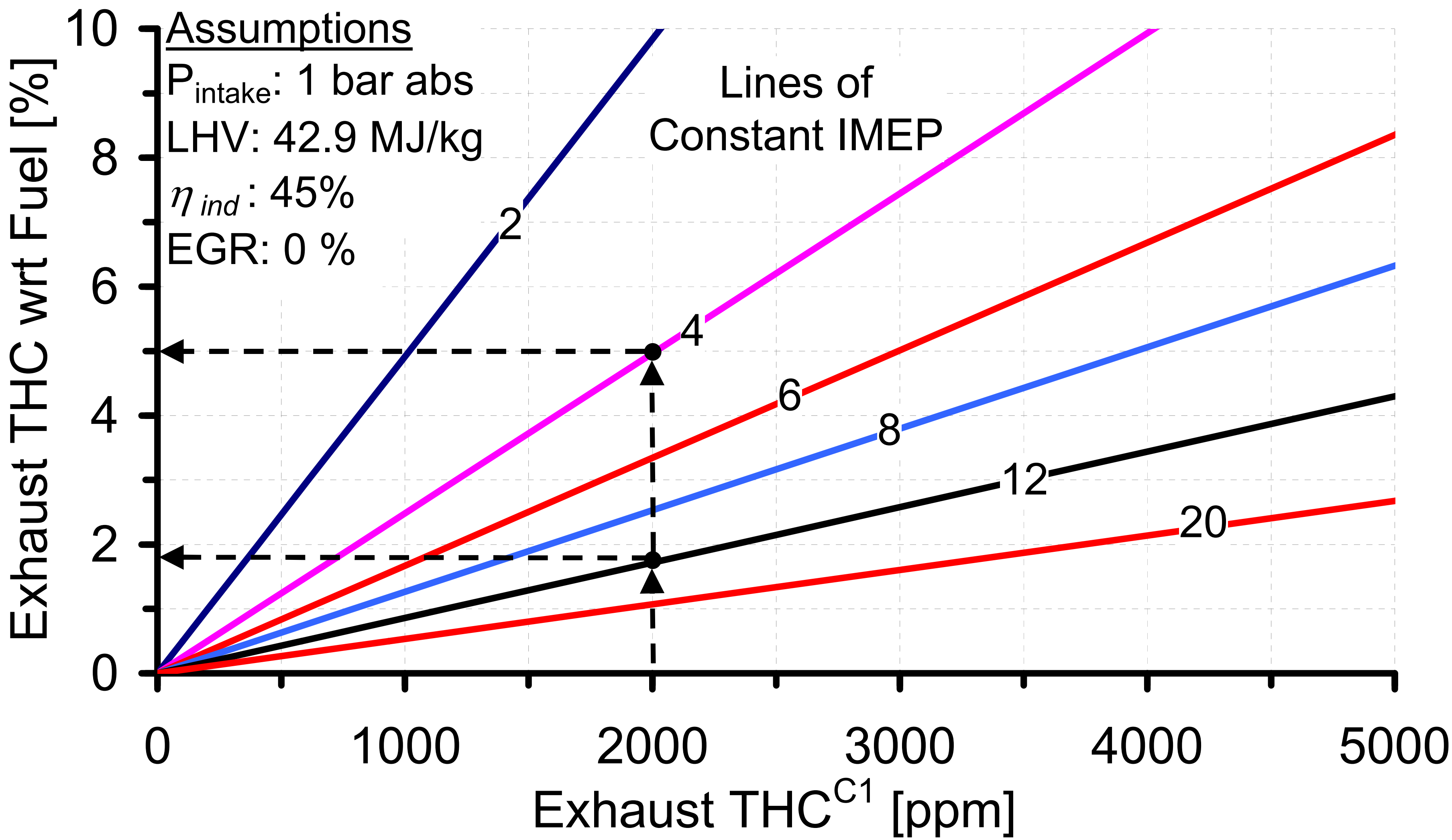
Relatively high CO & HC penalty due to large injection quantity/shot; Use of heavy EGR to improve combustion phasing



Reducing CO & HC penalty with 8 Injections/ cycle; Higher boost and heavy EGR to improve LTC

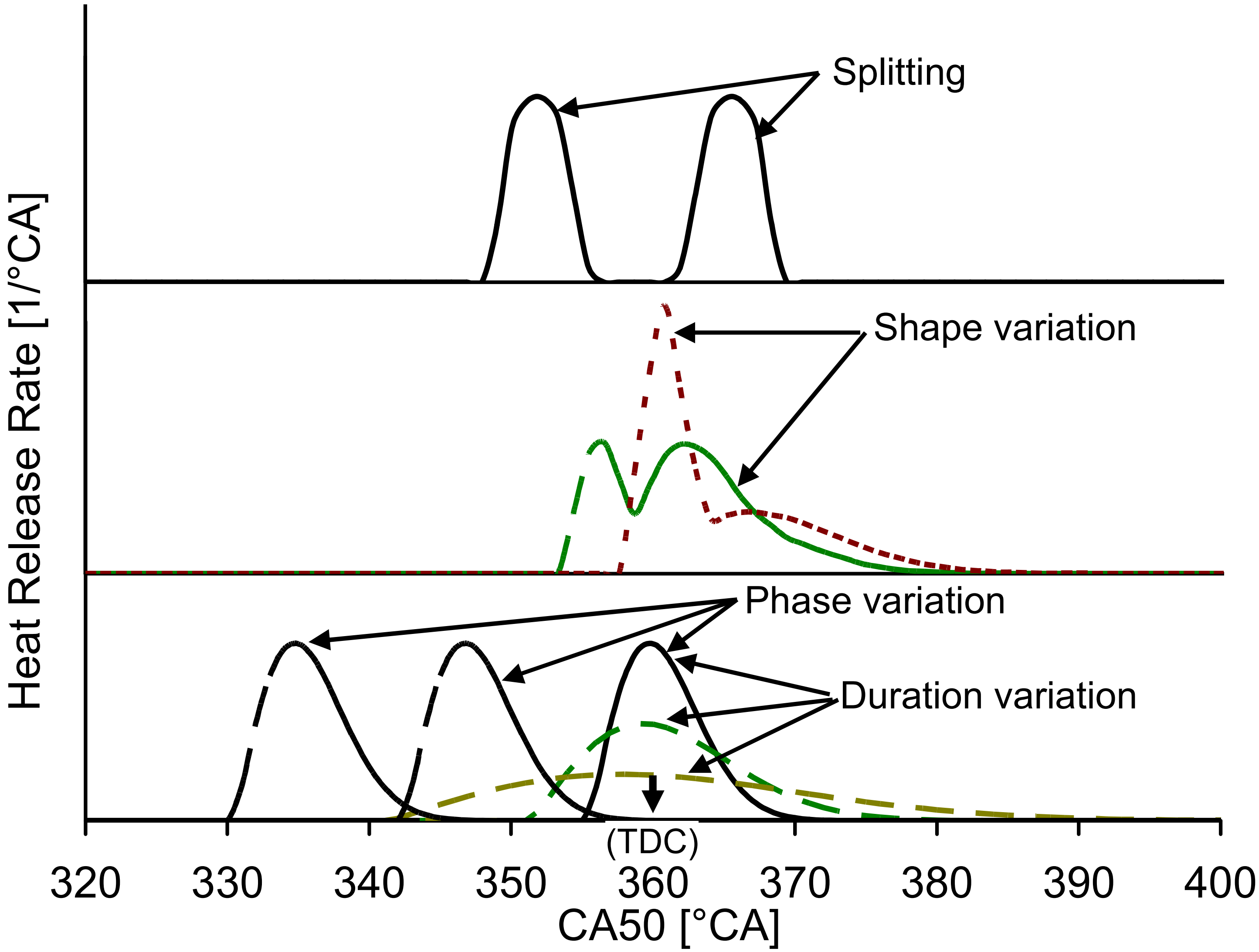
Combustion Cycle Efficiency Calculations

- Exhaust hydrocarbon energy with respect to fuel input at different engine loads



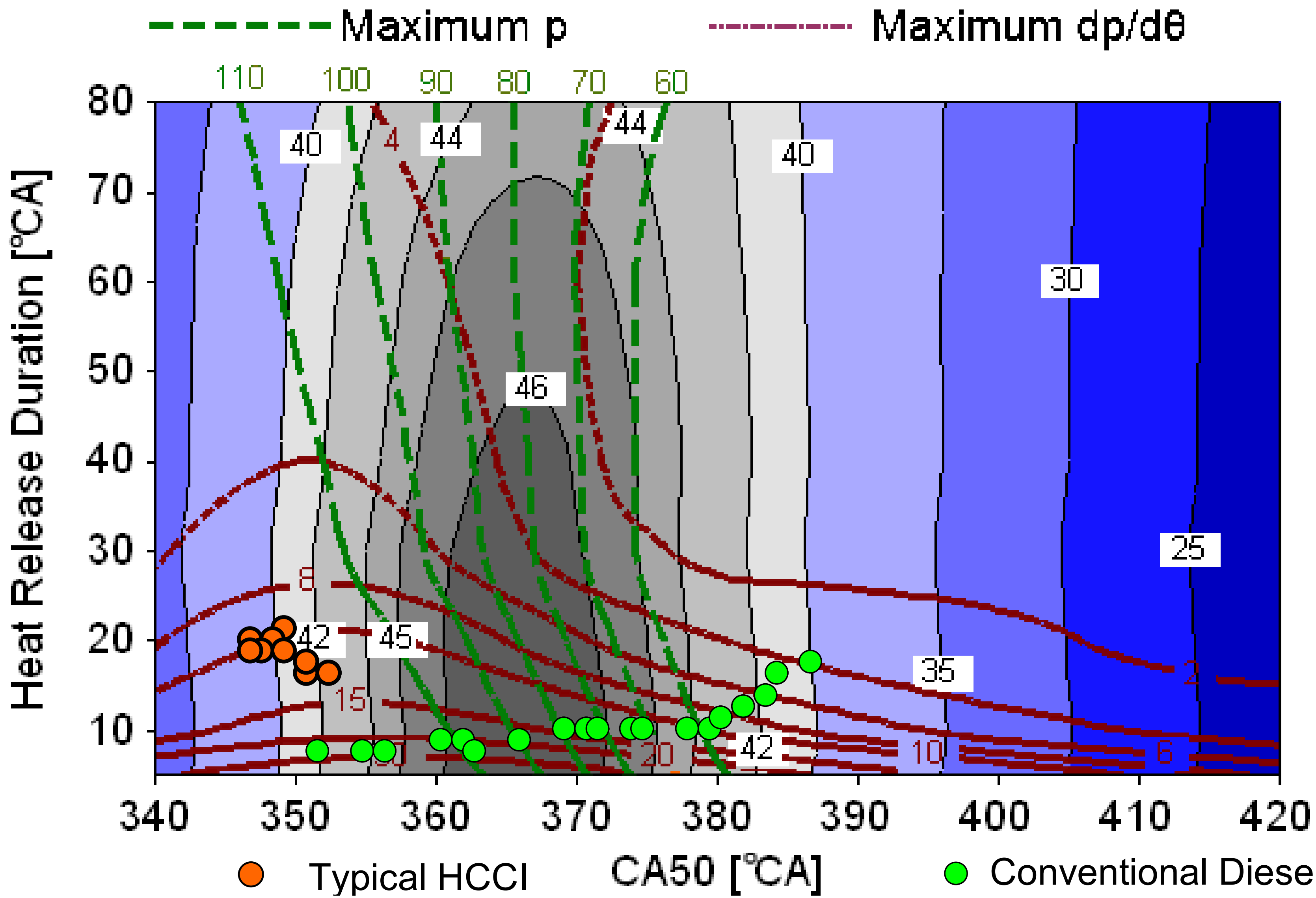
Engine Cycle Simulation

- Heat release rates used as input for simulations



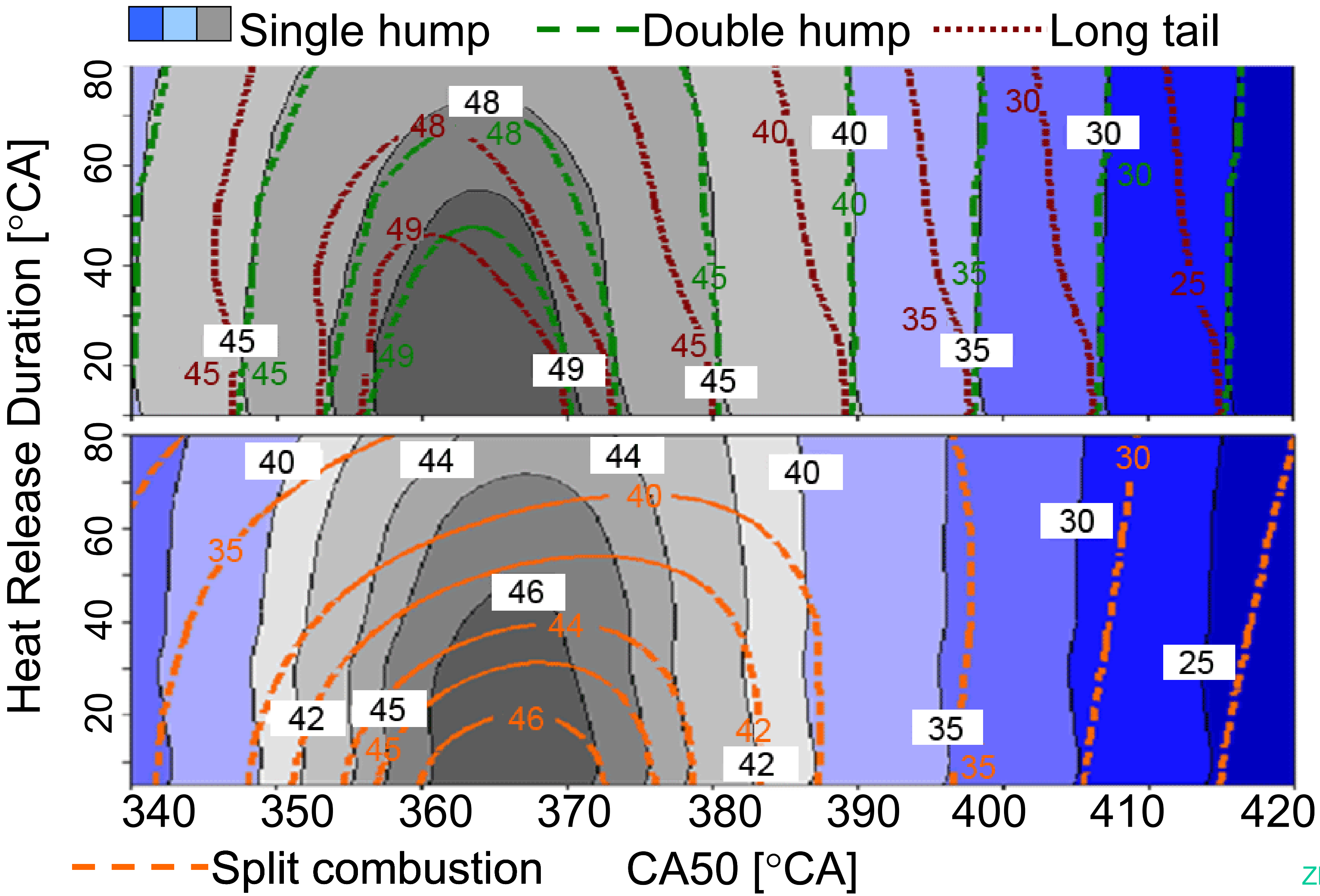
Engine Cycle Simulation Results

Effect of CA50 and combustion duration on η_{ind}, p_{max} & $(dp/d\theta)_{max}$ (1500 RPM, IMEP: 6 bar, P_{int}: 1.15 bar abs)



Engine Cycle Simulation Results

- η_{ind} comparison between – *Upper*: different heat release shapes; *Lower*: single hump and split combustion



Equivalent Combustion Cycle Deficiency Calculations

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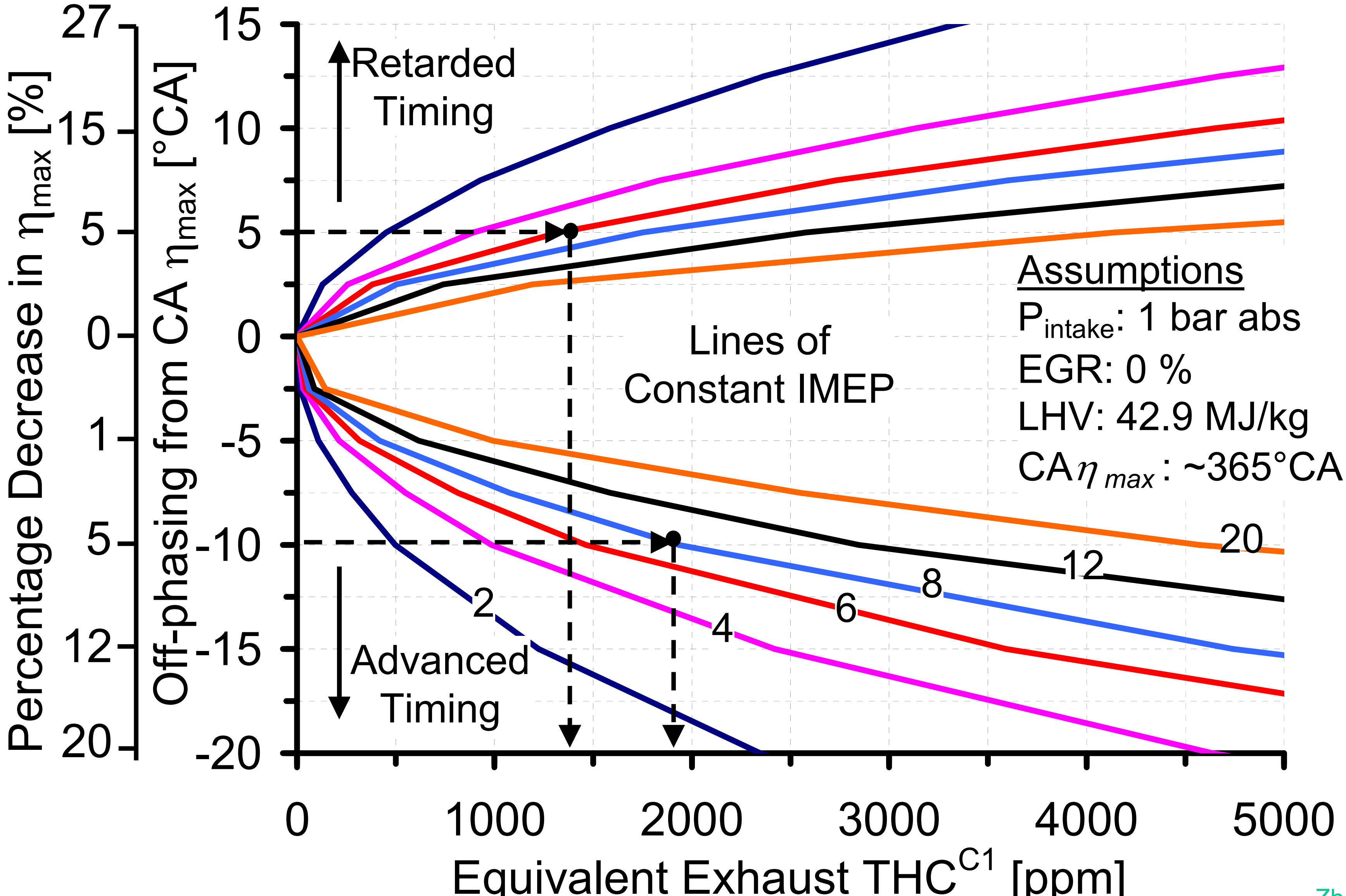
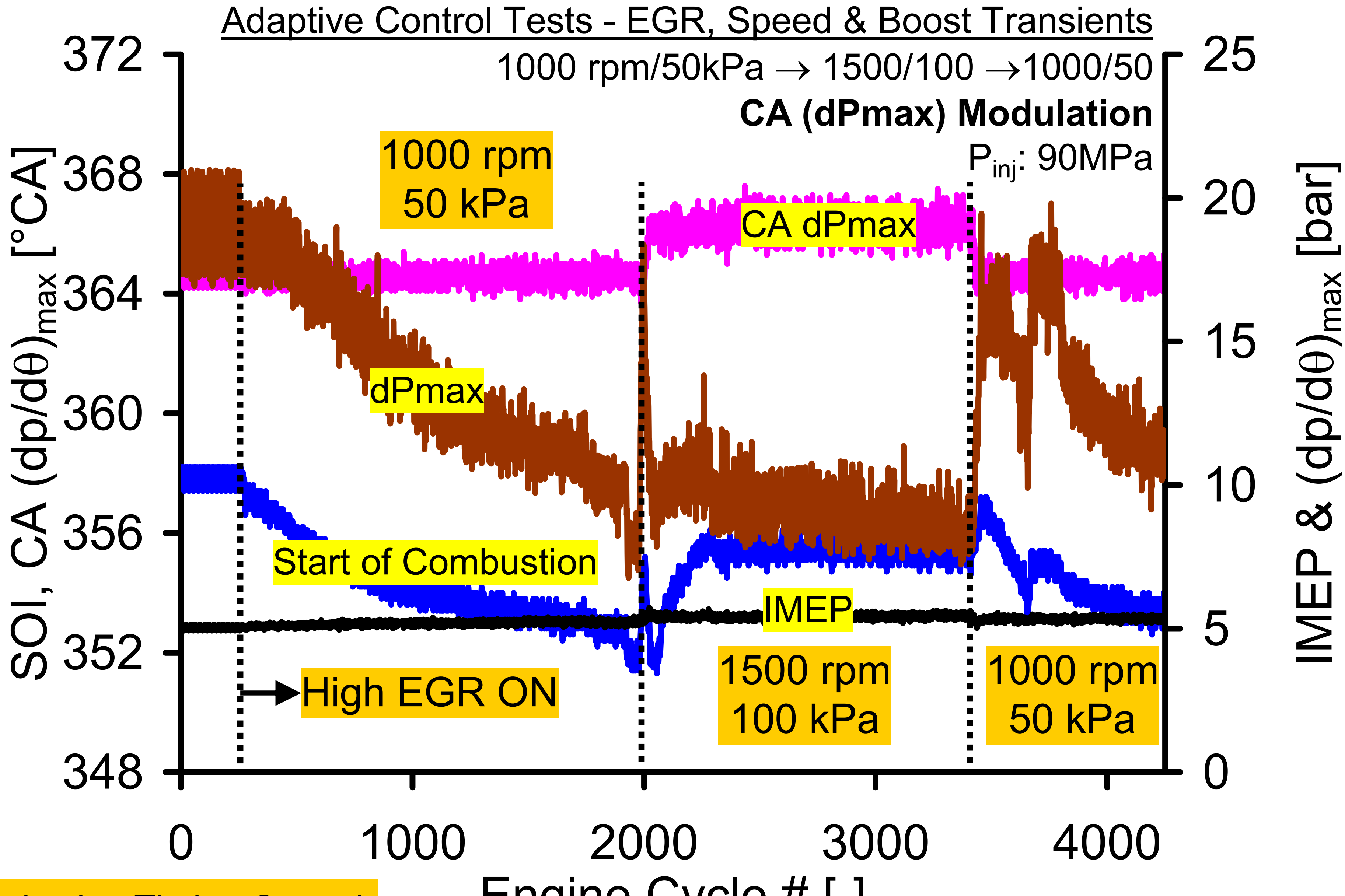
- Equivalent THC penalty with CA50 off-phasing



Cycle Based Adaptive Control to Improve LTC Transients

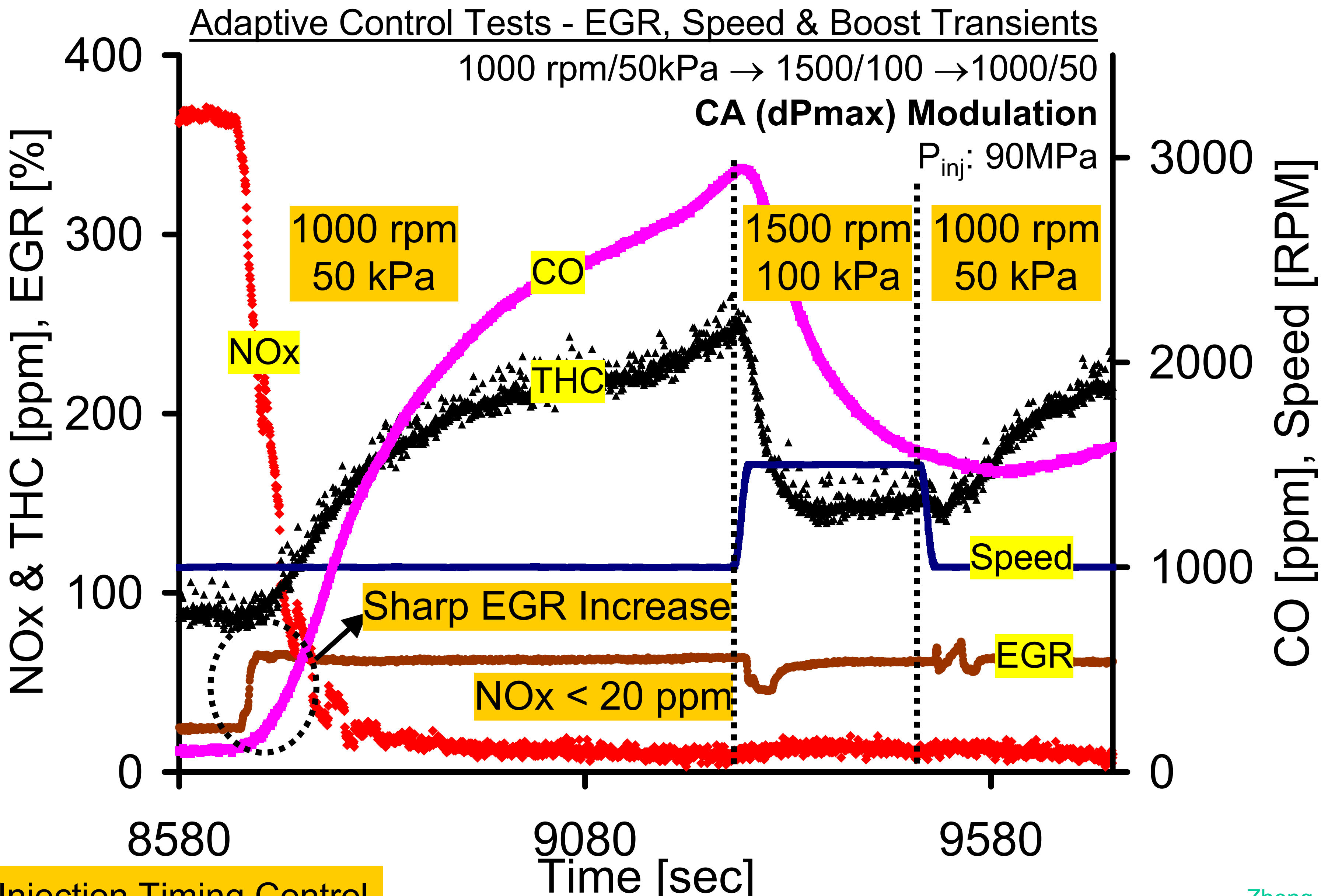
1. **SOI synchronized at optimized HR phasing via dPmax timing modulation**
2. **dPmax ceiling limitation via pilot quantity modulation**
3. **IMEP compensation via pilot and main modulations**
4. **IMEP top-up control via post quantity modulation**

Transient Peak Pressure Rise Timing Modulation after Entering LTC with High EGR (single shot)



Injection Timing Control

Emission Result when Entering LTC with High EGR under Peak Pressure Rise Timing Modulation



Injection Timing Control

Peak Pressure Rise Timing and Rate Modulation

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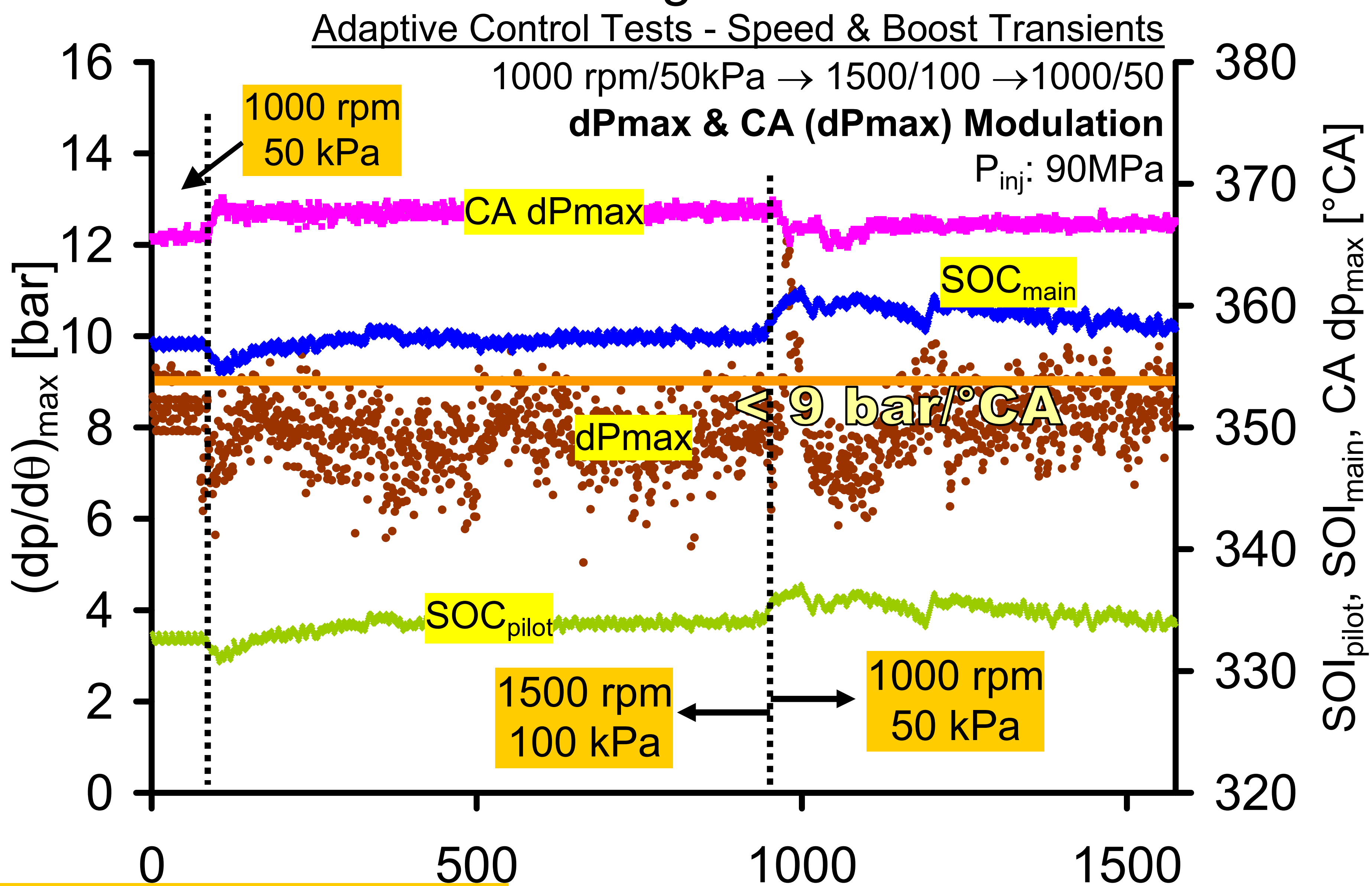
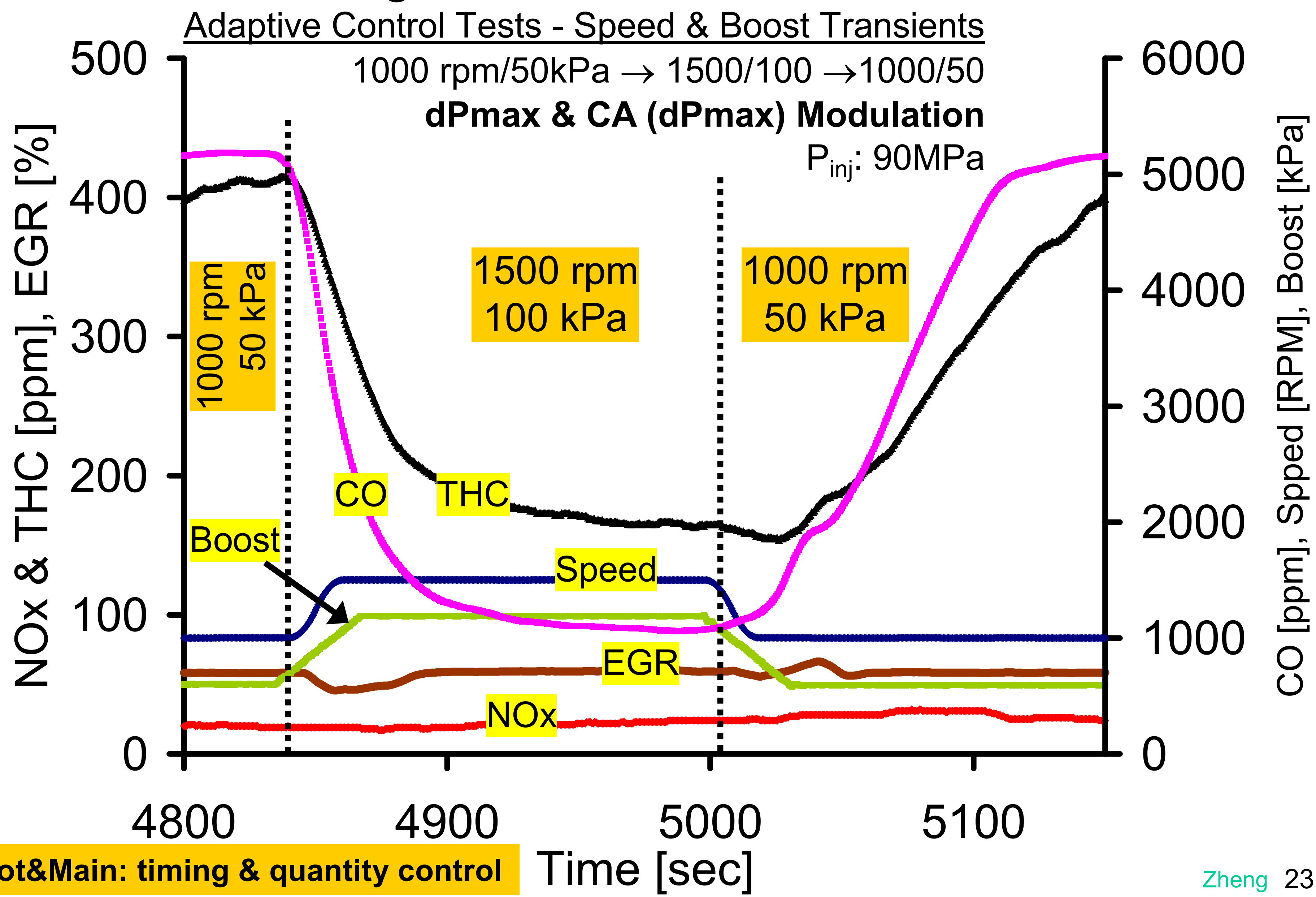


Pilot and Main Injections: Timing and Quantity Control

SOC: Start of Combustion

Emission Results under Peak Pressure Rise Timing and Rate Modulation

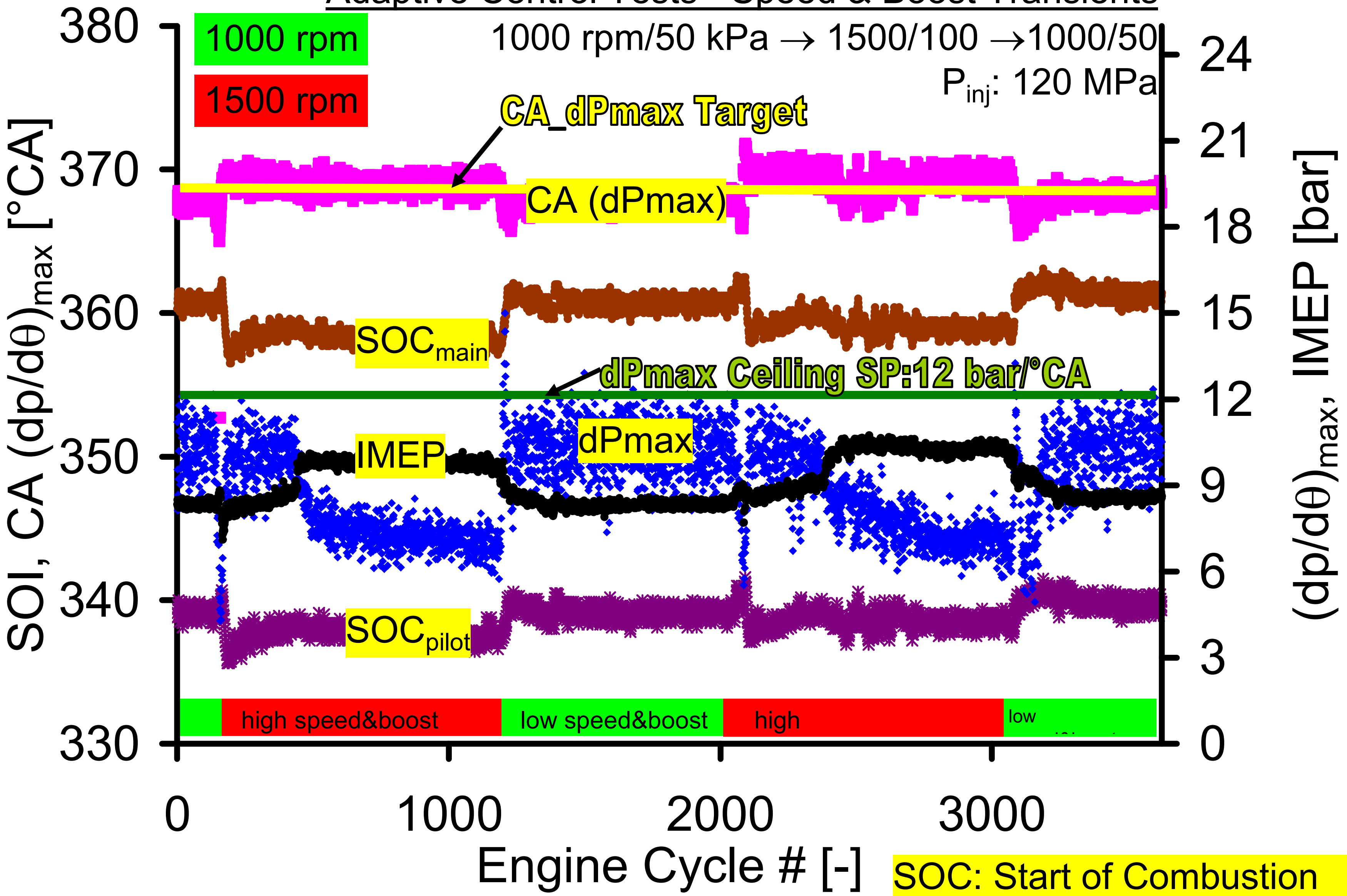


Pilot&Main: timing & quantity control

Peak Pressure Rise Timing and Rate Modulation under High EGR (NOx ~30ppm) Transients

dPmax & CA (dPmax) Modulation

Adaptive Control Tests - Speed & Boost Transients



Transient Low NOx Confirmation with NOx Sensor

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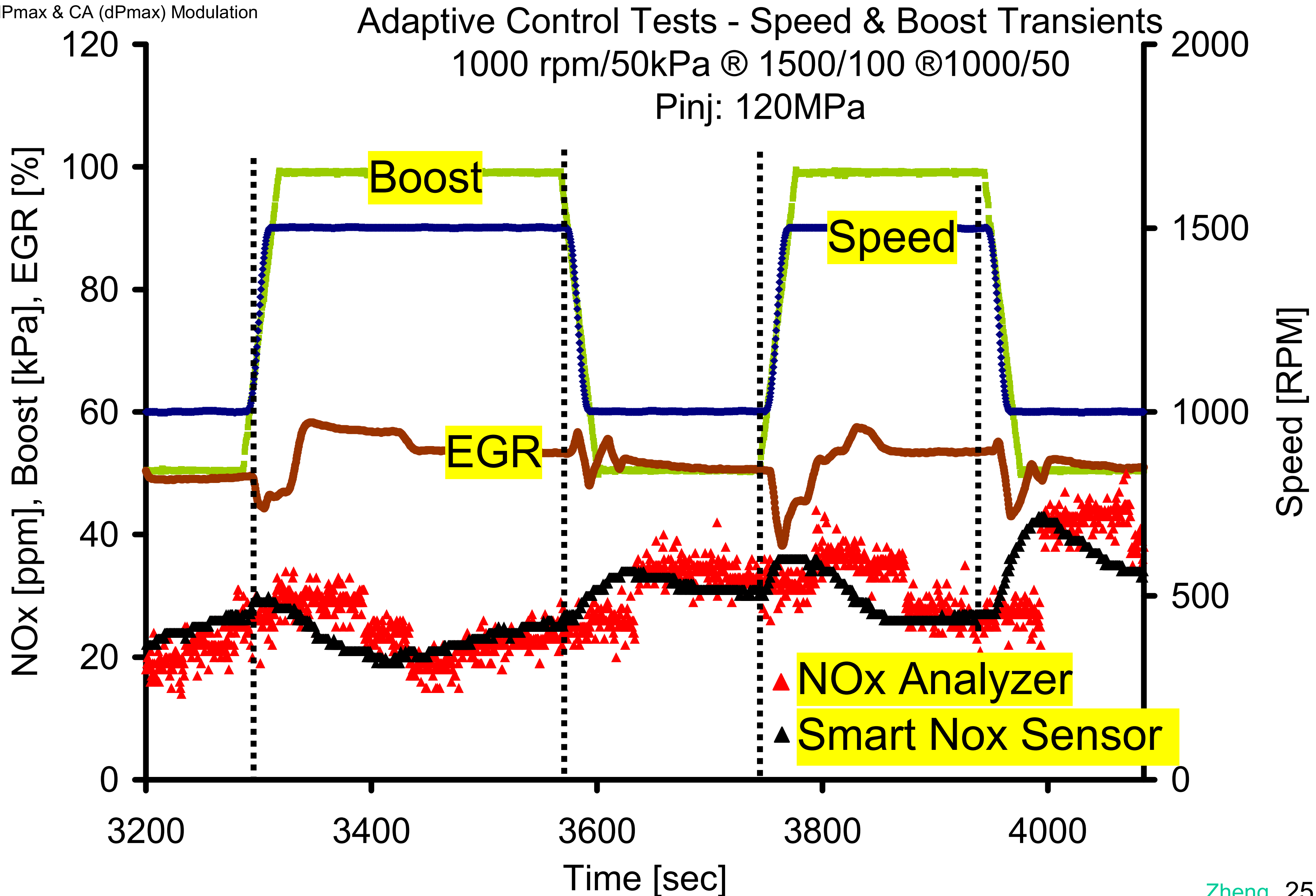
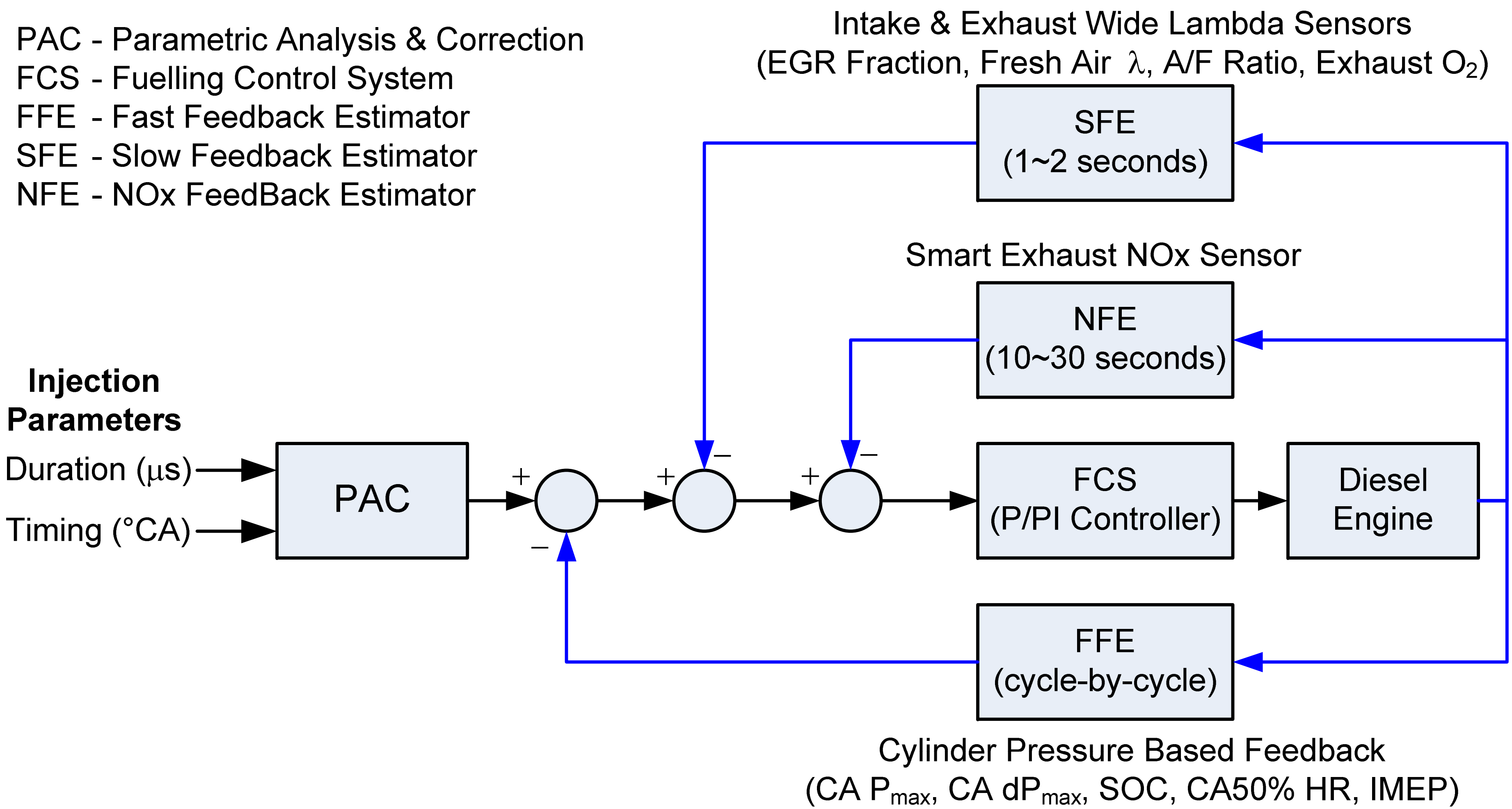
dPmax & CA (dPmax) Modulation

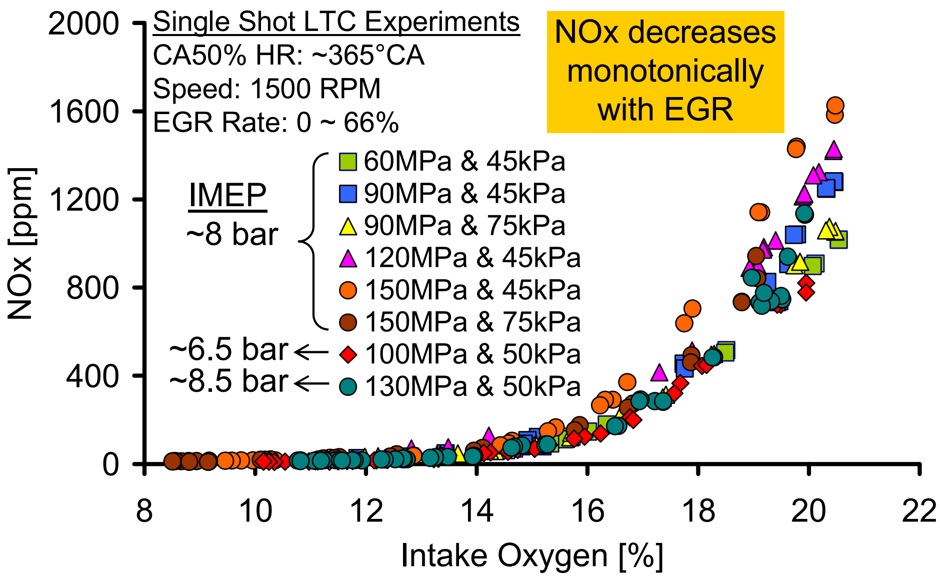


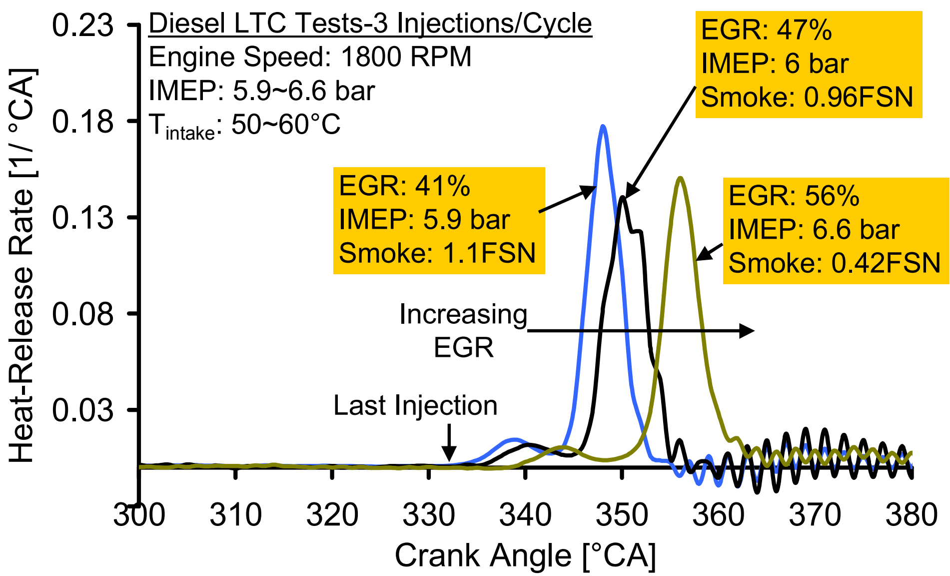
- Structure of the CDEL Adaptive Control System

PAC - Parametric Analysis & Correction
FCS - Fuelling Control System
FFE - Fast Feedback Estimator
SFE - Slow Feedback Estimator
NFE - NOx FeedBack Estimator



SYSTEMATIC AND ADAPTIVE CONTROL RESULTS

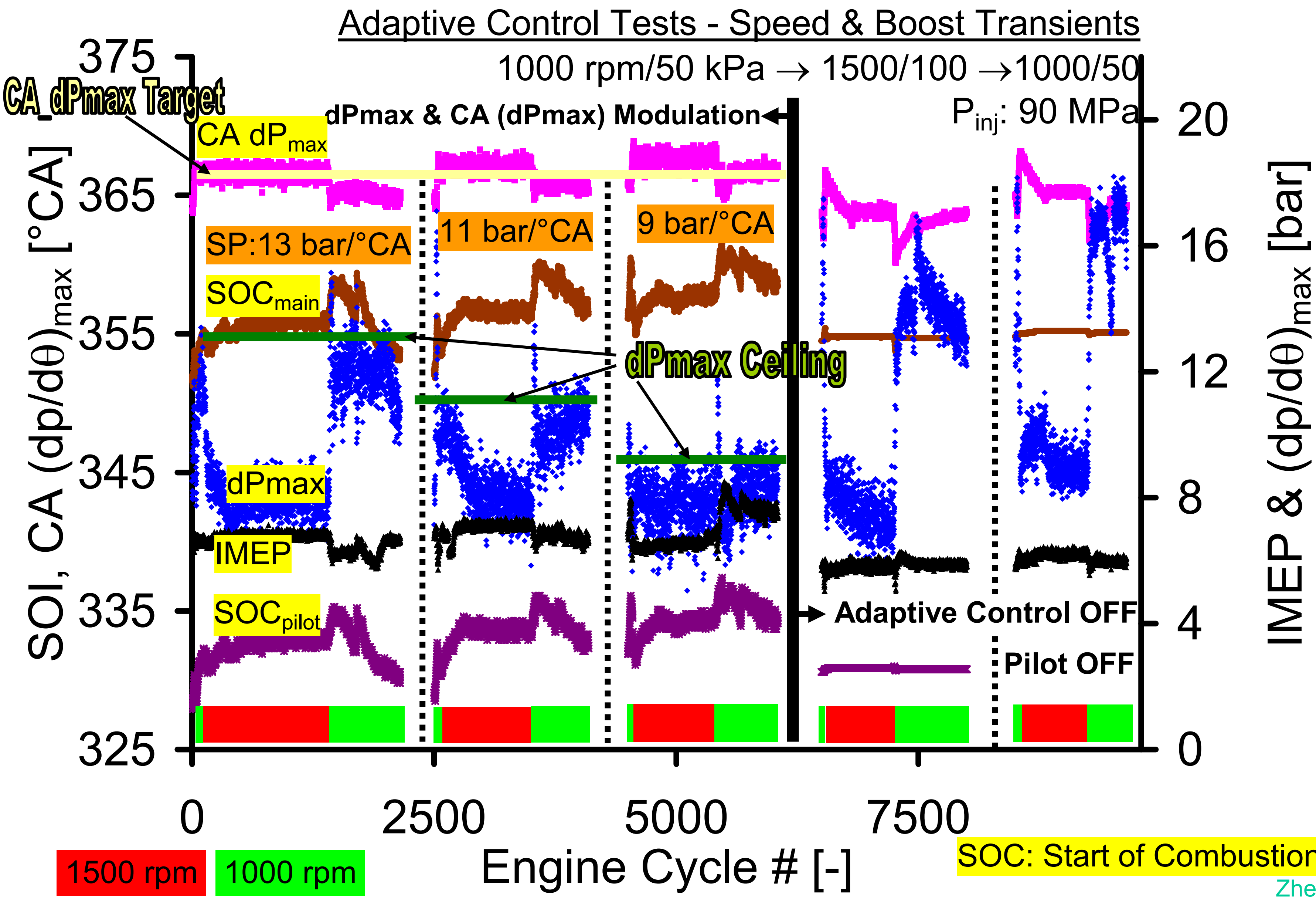




NOx as function of intake oxygen

Heat-release rate for soot reduction

Adaptive Control ON/OFF Comparison (High EGR, NOx ~20pm)



Pressure Rise Curves under Peak Rise Timing and Rate Control

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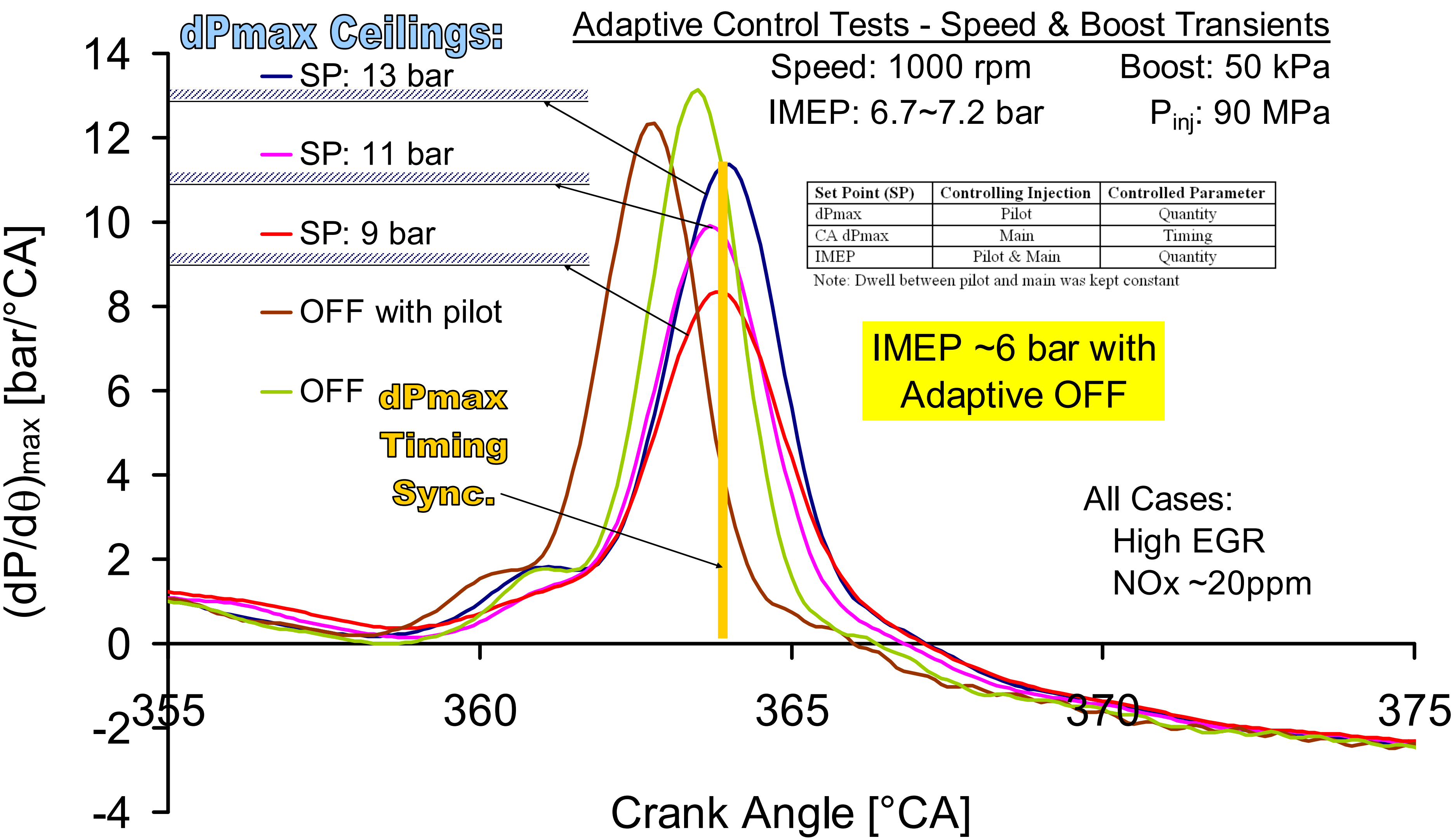
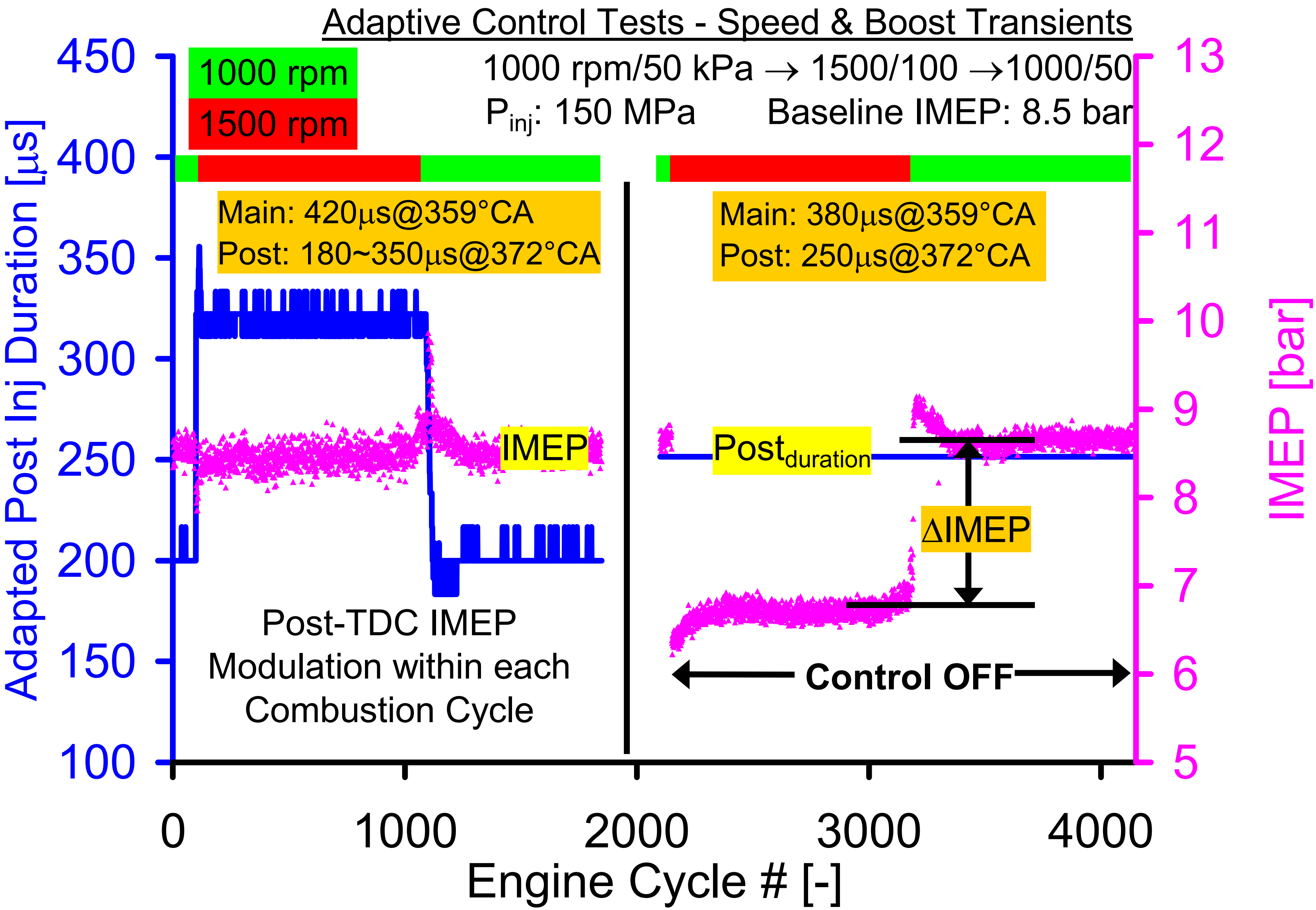


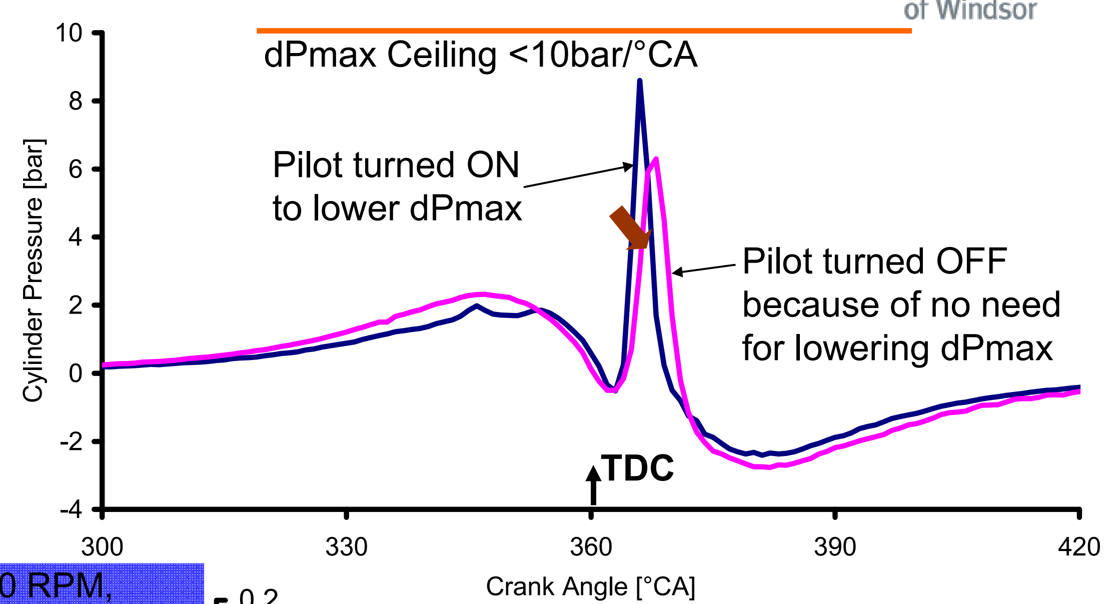
Set Point (SP)	Controlling Injection	Controlled Parameter
dPmax	Pilot	Quantity
CA dPmax	Main	Timing
IMEP	Pilot & Main	Quantity

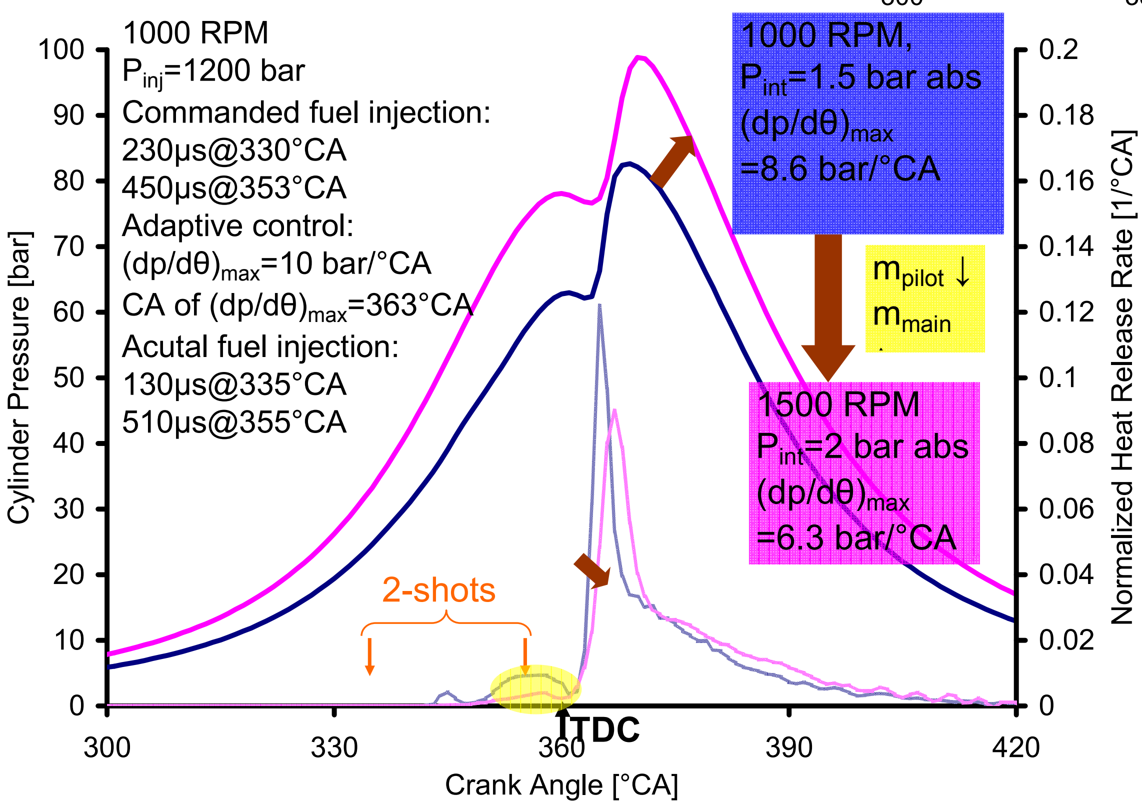
Note: Dwell between pilot and main was kept constant

IMEP Compensation (high EGR, NOx ~30ppm)



Sample cylinder pressure and heat release characteristics with adaptive control





Progresses in LTC Control
- Reduce reliance on de-NOx after-treatment

1. The simulations and empirical results indicate that the combustion phasing dominates the maximum attainable fuel efficiency of the engine. However, the phasing domination cedes to high HC when the fuel efficiency is severely deteriorated such as by excessive EGR.
2. The energy deficiency of typical LTC heat release patterns has been further quantified by comparing with HC and CO emissions with combustion phasing deficiency across the engine load spectra.
3. Adaptive control strategies based on cylinder pressure and heat release characteristics are implemented to stabilize and enable the low-temperature combustion from mid to high loads especially when high boost and EGR are applied.
4. Further, oxygen and NOx sensors at the intake and exhaust of the engine are devised to comprehend the transient impacts of EGR, boost, and load variations.
5. The multi-pulse scheduling is effective to prevent premature ignition and elevated NOx and soot.

Prospective LTC Load Control Improvements

1. The mode of ***EGR enabled LTC*** is suitable for low load operations, in which a single shot of fuel is delivered close to the top dead center (TDC). The heat release phasing is fully controllable via injection timing control and thus high energy efficiency in attainable.
2. The mode of ***early injection HCCI*** is suitable for mid load operations, in which the fuel is delivered in multiple events and by milliseconds prior to TDC and thus the heat release phasing is not directly controllable. EGR is commonly applied suppress premature ignition and combustion noise.
3. The mode of ***split burning LTC*** is suitable for high load operations, in which a partial amount of fuel is delivered to produce HCCI combustion and the remaining for post TDC late combustion. The latter may be benefited from the virtual EGR produced by the prior HCCI burning and timed to best eliminate combustibles and raise power output.

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