SAND2014-15103PE

Using Close-Coupled Pilot Injections to Reduce Combustion Noise in a Small-Bore Diesel Engine

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This work is made possible through the support of the Office of Vehicle Technologies: Gurpreet Singh / Leo Breton and General Motors: Alok Warey (principal technical contact)

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Outline

- Introduction to Sandia National Laboratories
- Controlling combustion noise in a direct injection Diesel engine
- Engine testing
  - Small-bore Diesel engine
  - Pilot + main injection strategy
  - Trend in combustion noise with parametric variation
- Injection rate analysis
  - Injection profiles for parametric variation
- High speed fuel injection imaging
  - Image distortion correction
  - Preliminary results

Sandia National Laboratories

- "Exceptional service in the national interest"
- Largest national lab
  - ~10,000 employees
  - ~$2.2 B/yr
- Missions
  - Nuclear weapons engineering
  - Defense systems
  - Homeland security
  - Energy
- Locations
  - Albuquerque
  - Livermore
  - Also Nevada, Hawaii, DC

Sandia & CRF Leadership in Energy & Fuels Research

THOMSON REUTERS

scienceWATCH.com
TRACKING TRENDS & PERFORMANCE IN BASIC RESEARCH

Interviews | Analyses | Data & Rankings

FEATURED ANALYSIS, November/December 2008

"…Among institutions ranked by total citations, none surpasses Sandia National Laboratories, with more than 4,100 citations to its 395 papers"

Energy & Fuels: Institutions Ranked by Citations

Rank	Institution	Citations 1998-2008
1	Sandia National Labs	4,147
2	Natl. Renewable Energy Lab	3,773
3	CSIC (Spain)	3,678
4	Chinese Academy of Sciences	3,541
5	Indian Institutes of Technology	3,166

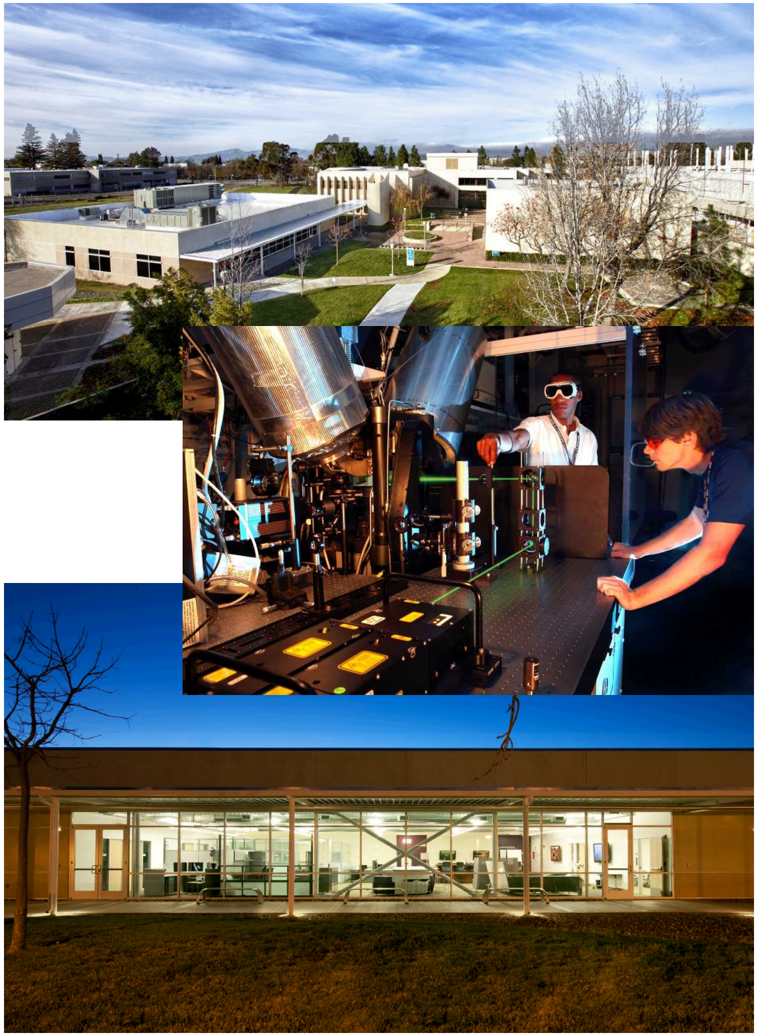
Approximately ½ of these citations are linked to the CRF.

http://sciencewatch.com/ana/fea/08novdecFea/

Combustion Research Facility

A DOE/BES Collaborative Research Facility dedicated to energy science and technology for the twenty-first century

- 82,000-square-foot office and laboratory facility
- 36 highly specialized labs
  - Lab building design accommodates
  - Laser-based diagnostics
  - Combustible and toxic gas handling
  - Computer-controlled safety system
- New 8000 square-foot computational laboratory



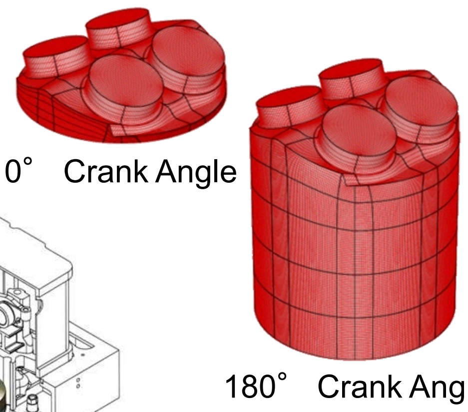
Engine Combustion Research – Overview

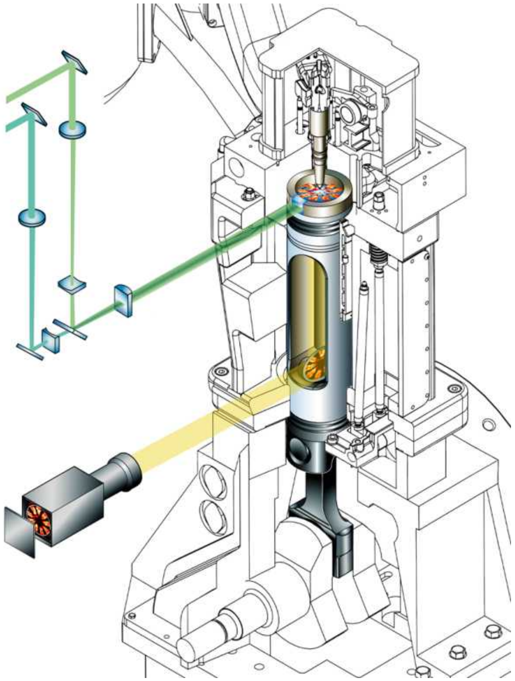
- Mission: Provide the combustion and emission science-base needed by industry to develop high-efficiency, clean engines for future fuels.
- Integral part of DOE/industry advanced engine and fuels programs.
- Sponsor is DOE Office of Vehicle Technologies ($8M)
  - Program managers: Gurpreet Singh and Kevin Stork
  - Program supports DOE engine targets
    - greatly improved efficiency
    - emission compliant
- Strong collaborations with industry, universities, and other national labs.
- Industry sponsors: GM, Caterpillar, Ford & Chevron ($1.3M).
- 25 staff, technologists and post docs; plus visitors

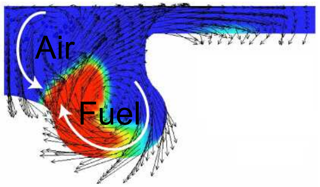
Research approach - closely coupled experiments and simulation

- Laser-based optical diagnostics.
- Optically accessible, realistic engine conditions:
  - pistons.
  - cylinder liner / spacer plates.
  - exhaust ports.
- Simulation
  - collaboration with partners
  - developing next-generation simulation tools for engines (Large Eddy Simulation - LES).
- Research has impacted engine design via two paths
  - provides accurate picture for engine designer
  - computational design tools

Time varying LES Grids
3-million cells, 137 blocks

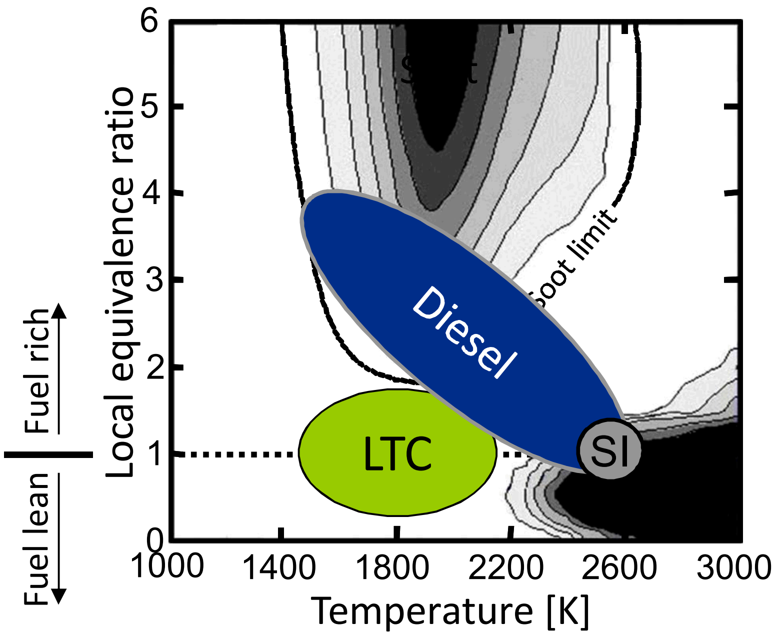






Advanced engine combustion research directions

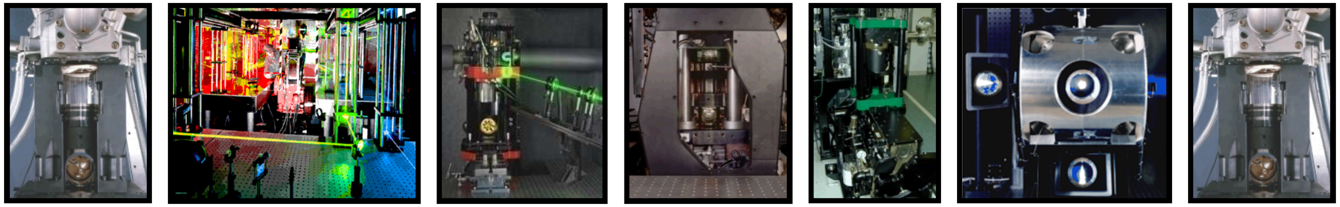
- Stratified DISI: Fuel-air mixing, ignition, flame propagation, misfire (fuel focused)
- Advanced diesel combustion: EGR, high-pressure and multi-pulse injection, lifted-flame combustion, post injections for aftertreatment, ...
- Low-Temperature Combustion (LTC):



  - Premixed-Charge Compression-Ignition (PCCI) (PPCI, PCI, MK, …)
  - Homogeneous-Charge Compression-Ignition (HCCI)
  - Challenges:
    - Combustion phasing
    - Load range
    - Heat release rate
    - Transient control
    - HC and CO emissions
    - Fuel characteristics

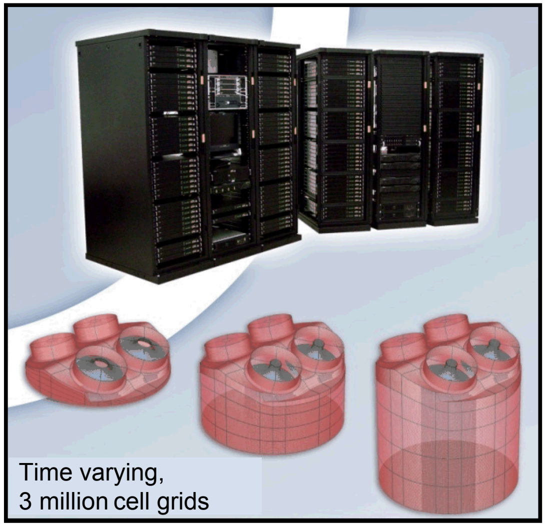
Working with industry to develop the science-base for next-generation engines for future fuels.

- Advanced combustion strategies for enabling high-efficiency, low-emission engines.
  - SI, Diesel, and Low-Temperature Combustion (HCCI, PCCI, …)



- Future fuels
  - adv. petroleum
  - bio-fuel,
  - gas-to-liquid,
  - oil sand and shale
  - natural gas & H_2
  - …

- Next generation computational tools
  - massively parallel machines



Controlling combustion noise in a direct injection Diesel engine

- Single fuel injection
  - Large amount of fuel injected into the cylinder during ignition delay
  - Fuel mixes with air, mixtures are heated to auto-ignition temperature
  - Significant amount of premixed heat release
  - Large rates of pressure rise – high combustion noise

- Short pilot injection before main injection
  - Small amount of fuel burns and raises gas temperatures
  - More of the main injection combustion is non-premixed
    - Lower rate of heat release
    - Lower rate of pressure rise
    - Quieter combustion

Controlling combustion noise in a direct injection Diesel engine

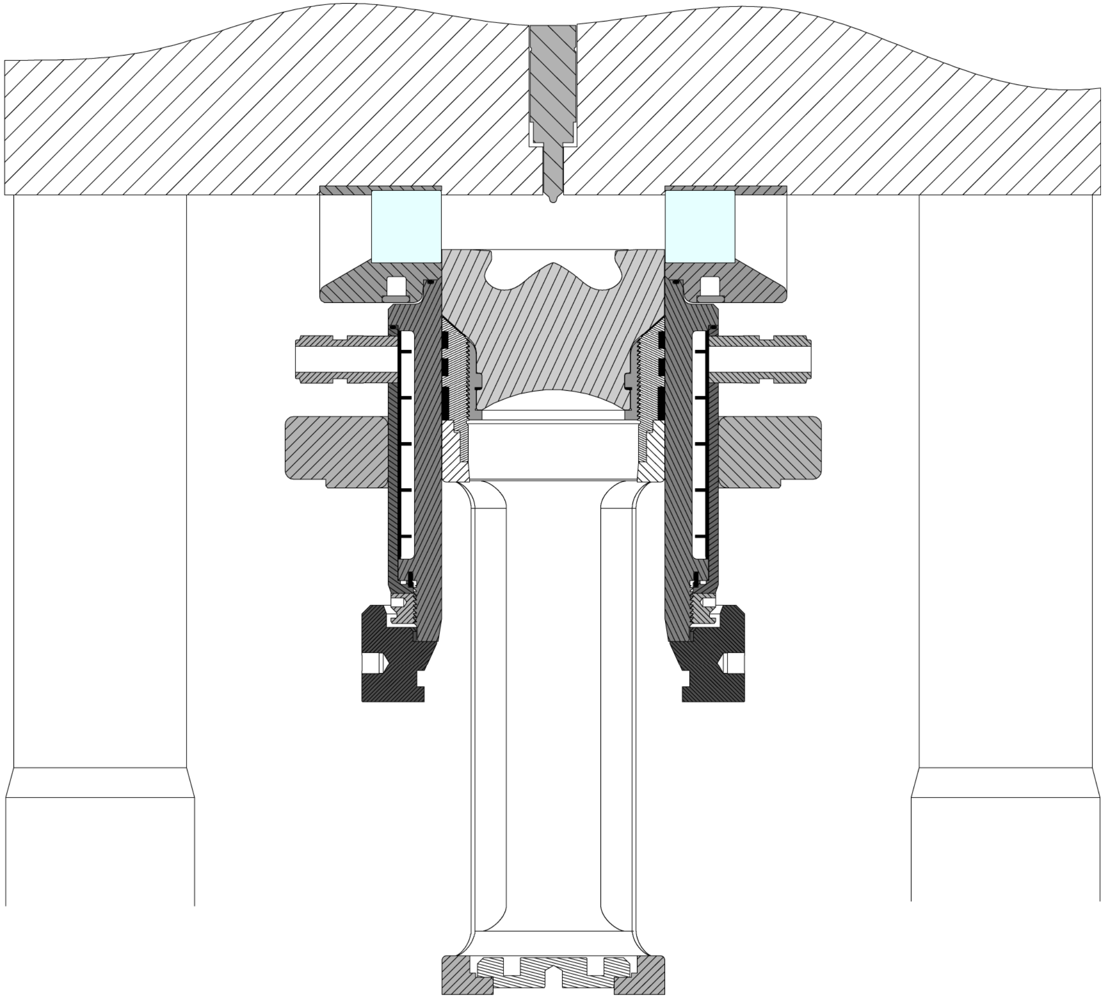
- Advances in fuel injection hardware have made multiple injection strategies robust and reliable
  - Common rail systems – control of fuel pressure and injection timing
  - Fast response injectors – up to 8 injections per cycle
  - Multiple injection strategies used in production engines for years
- Multiple injections provide many degrees of freedom
  - Injection timing and quantity (duration) for each injection
  - Difficult to optimize without a better understanding of the underlying mechanisms
- Close-coupled pilot injections
  - Very short delay (dwell) between pilot and main injections
  - Literature suggests that additional combustion noise benefits may be possible with close-coupled pilot injections

Engine testing: small-bore optical Diesel engine

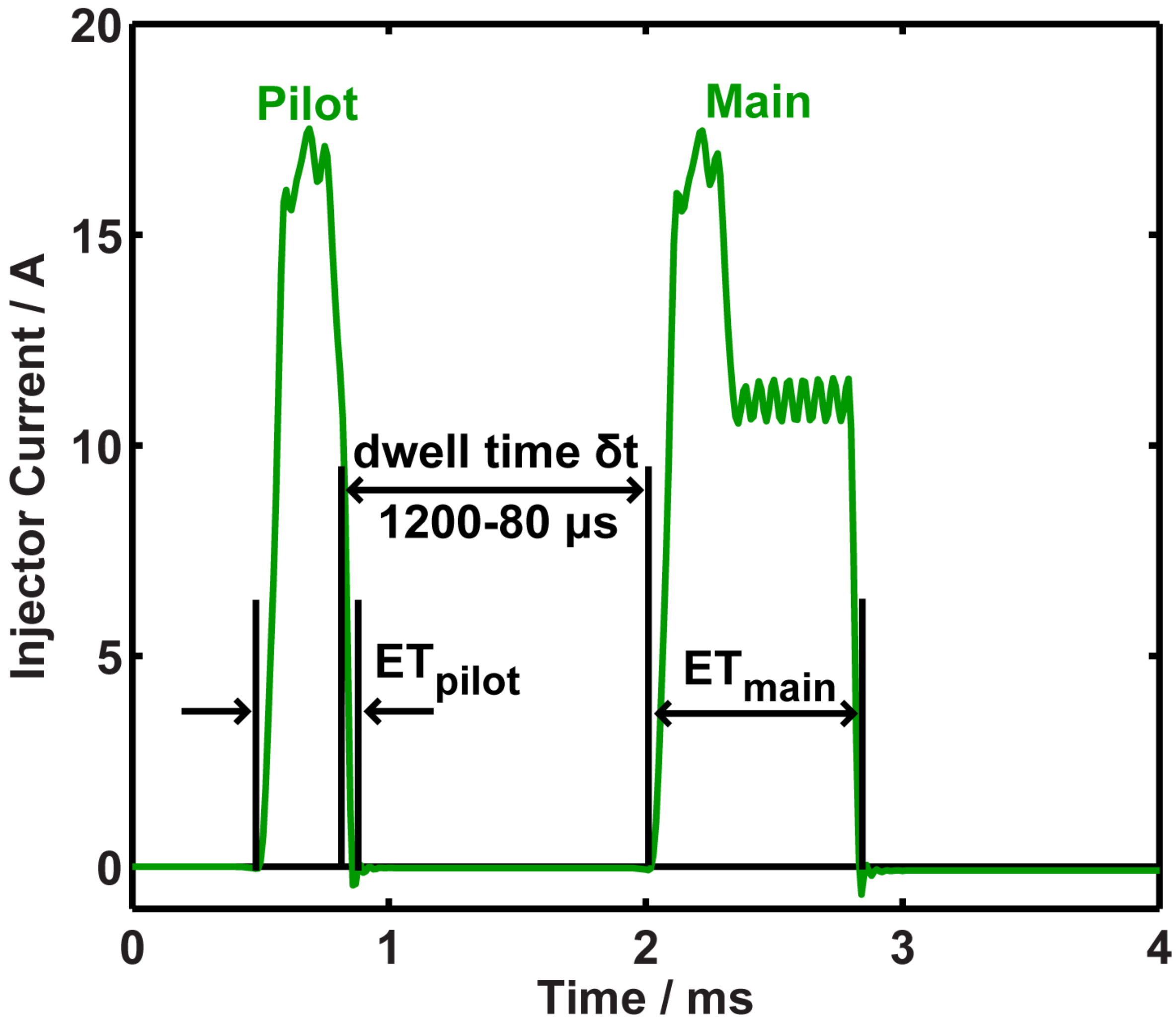
Single-cylinder engine data

Bore x Stroke	82 mm x 90.4 mm
Compression ratio	16.69:1
Valves	4
Piston geometry	Re-entrant bowl
Injector	Bosch CRI 2.16 Multijet II
Holes x Ø	7 x 139 μm
Conicity	1.5
Included angle	149°

- Bosch CRI 2.16 Multijet II
  - Pressure-balanced control valve
  - Fast acting → makes short dwell times possible

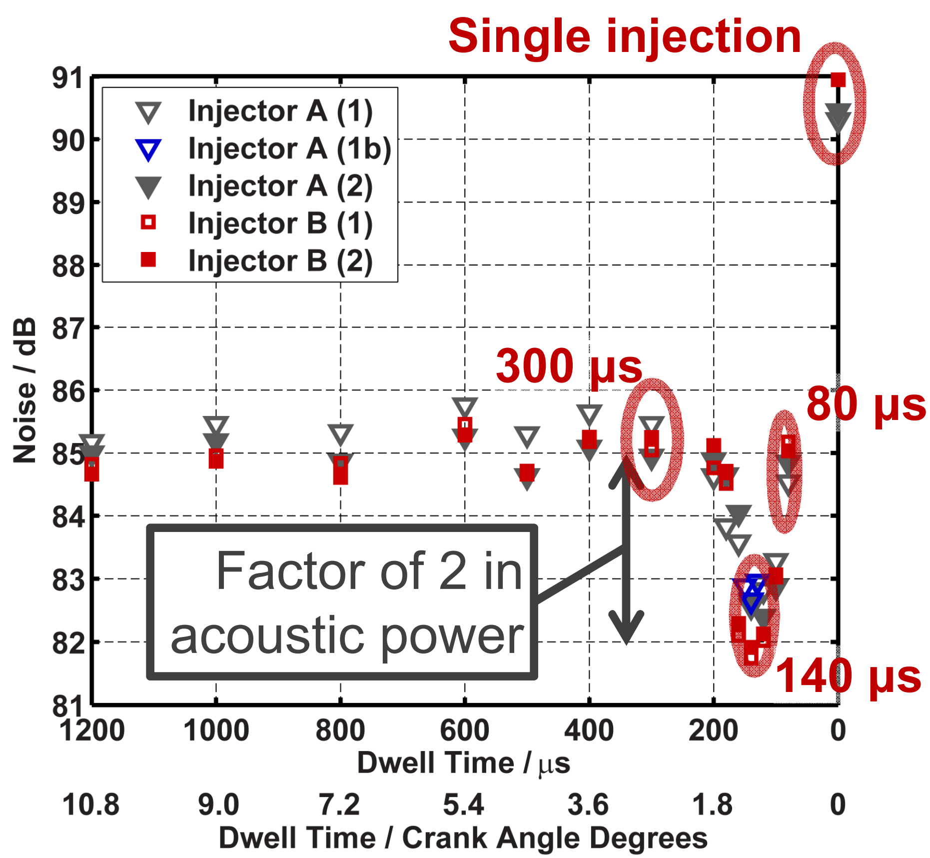


Pilot + main injection strategy



Trend in combustion noise with changing dwell time

- Computed combustion noise
  - Filtered, integrated cylinder pressure frequency spectrum
  - Normalized by threshold of human hearing; shown in dB
- Trend with changing dwell time repeats well
- Location of noise minimum is closely repeatable
  - Always near 140/120 μs
- Good agreement between injectors



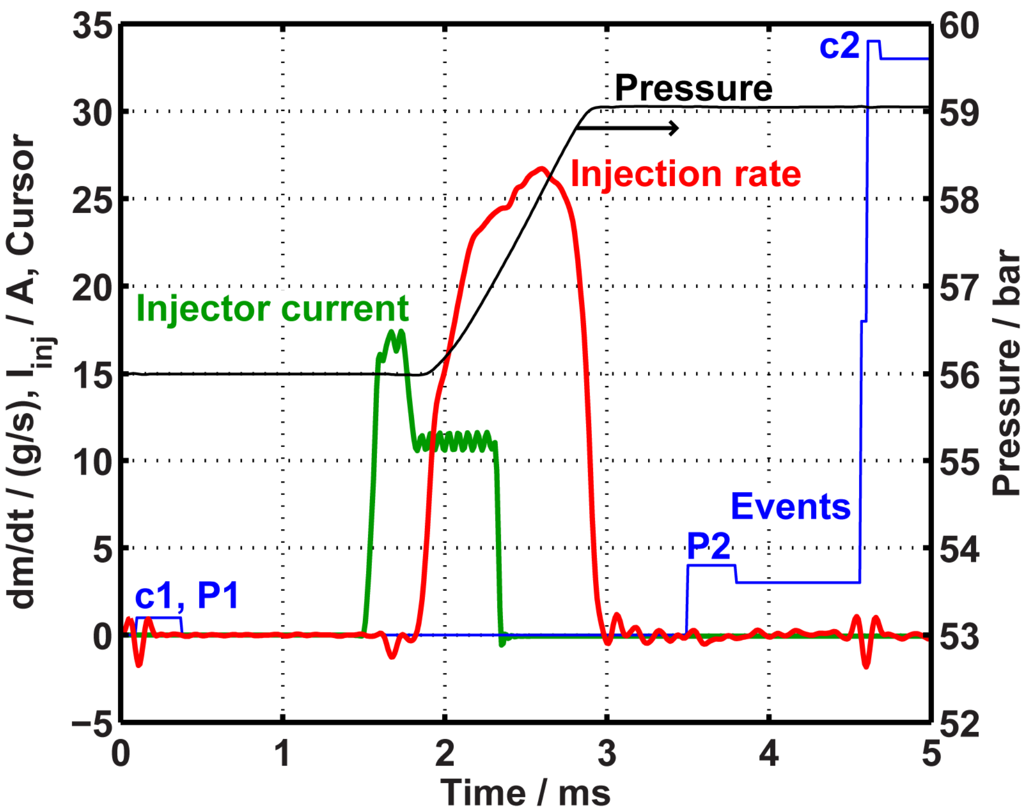
Combustion noise calculated according to:
Shahlari, A., Hocking, C., Kurtz, E., and Ghandhi, J., "Comparison of Compression Ignition Engine Noise Metrics in Low-Temperature Combustion Regimes," SAE Int. J. Engines 6(1):541-552, 2013, doi:10.4271/2013-01-1659.

Recap: dwell time sweep

- Pilot + main: dwell time of 140 μs
  - Dramatic (~3 dB) decrease in combustion noise
- What is happening to the rate of injection as dwell time changes?
  - Measurements with Moehwald HDA
  - HDA: similar to Zeuch's method
    - Injection into a pressurized, fuel-filled chamber
    - Measured chamber pressure
    - Measured speed of sound (fuel compressibility and density)
    - Provides instantaneous rates of mass injection

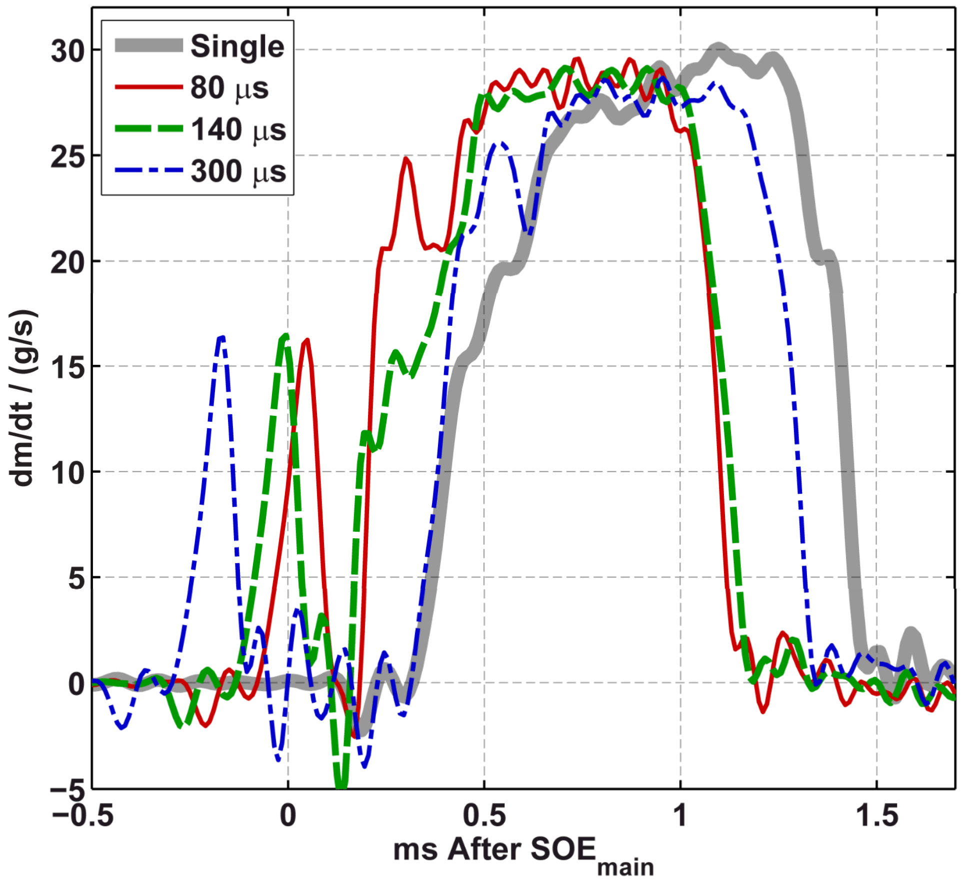
HDA timing example: single injection

- Measured quantities
  - Chamber pressure (P): continuously sampled (100 kHz)
  - Speed of sound (c): twice per injection train



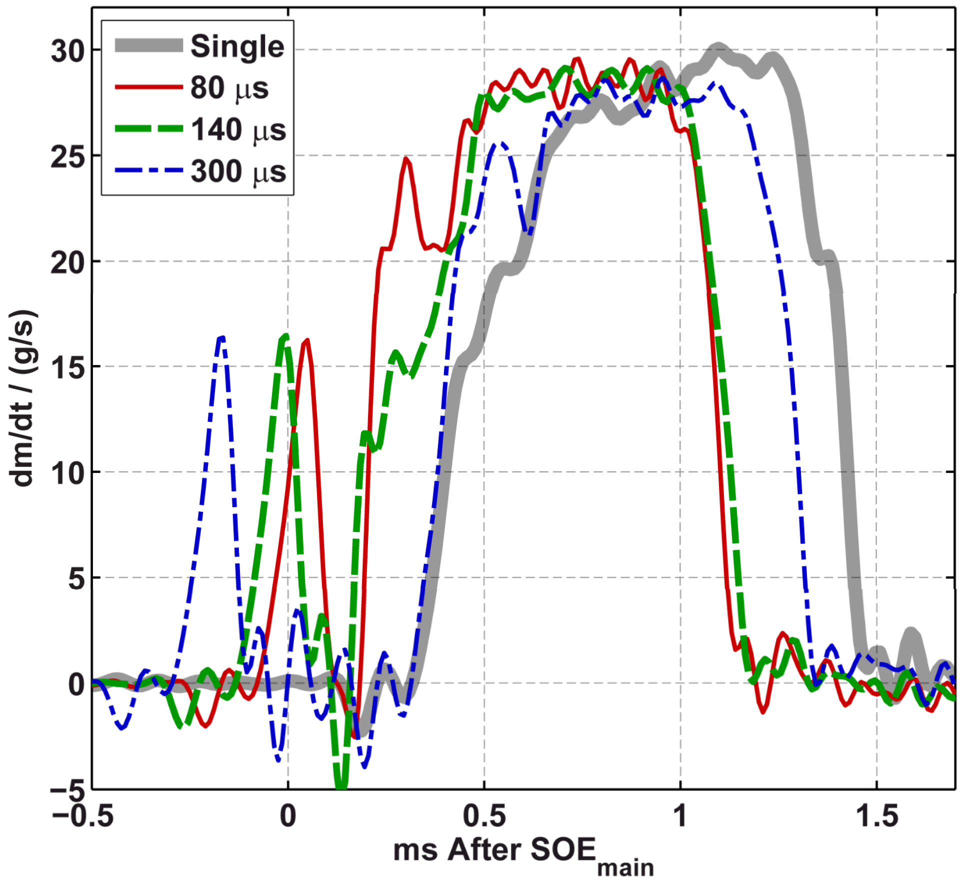
Dwell time sweep: injection rates

- Main injection rate shaping
  - Depends strongly on dwell
  - Trends shown are repeatable
- **Short dwell (80-90 μs)**
  - Start of main is advanced, has steepest ramp up
- **Intermediate (110-160 μs)**
  - Start of main is advanced, ramp up is enhanced
- **Long dwell (180-300 μs)**
  - Start of main not advanced; only slight rate shaping occurs
- Dwell time doesn't affect shape of pilot injection



Recap: injection rate measurements

- Recall: noise minimum at dwell of 140 µs
- Questions
  - Do these rate shapes represent what happens in the engine?
  - How does changing the dwell time affect:
    - The mixture formation process?
    - Ignition and combustion?
    - Pollutant formation?
    - Combustion noise?



High speed fuel injection imaging setup

- Imaging and illumination through the bottom of the piston
- Illumination via high-intensity pulsed LED
  - Focusing optics
- Beam splitter
  - Improves radial symmetry of illumination
  - Illumination highly non-uniform due to piston form
- Side illumination
  - Much higher signal levels
  - Uneven illumination due to signal trapping

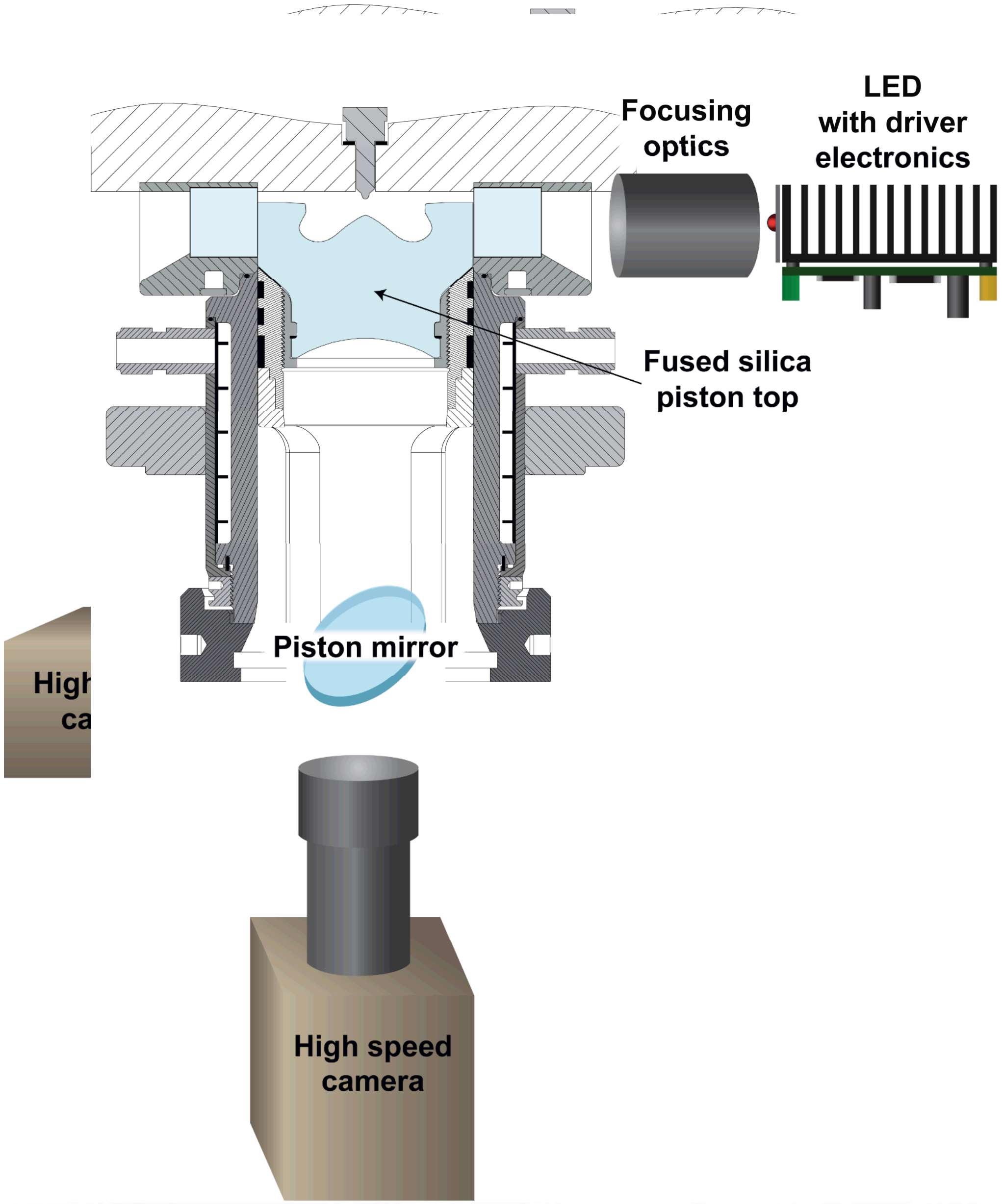


Image distortion occurs when looking up through the piston

- Area of interest: inside the piston bowl
- Image distortion
  - Complicates analysis of images
  - Changes with crank angle
  - Distortion can be corrected, but this is time consuming
- High speed imaging: the de-warping process needs to be automated!
  - New approach based on ray tracing

Calibration target with stationary engine

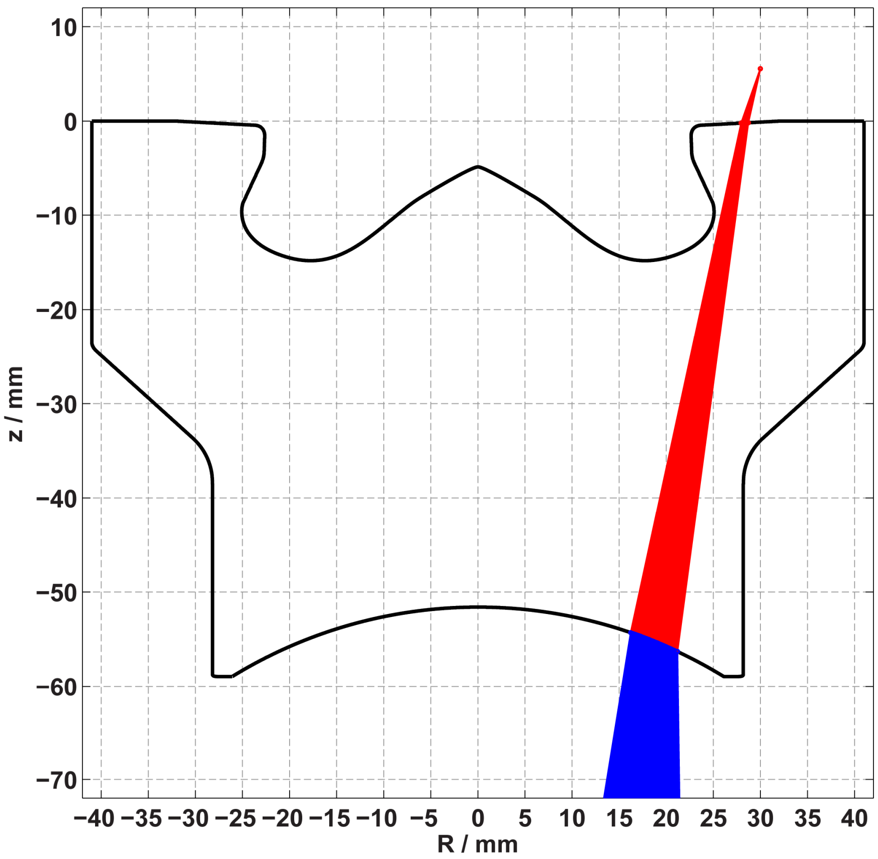


Image de-warping with ray tracing

- Rays start above piston at a given point and propagate through the piston
- Virtual image forms where the exiting rays intersect
- Any ray can be traced in this manner
- Only the rays that reach the mirror can be seen by the camera
- The point in real space is mapped into a virtual image point

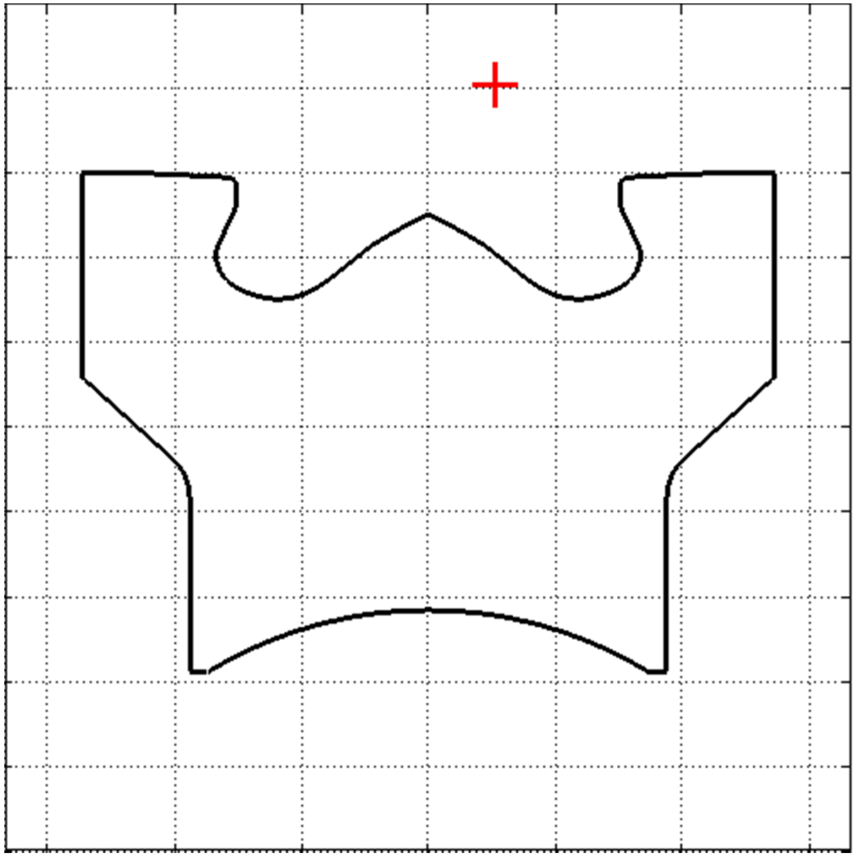
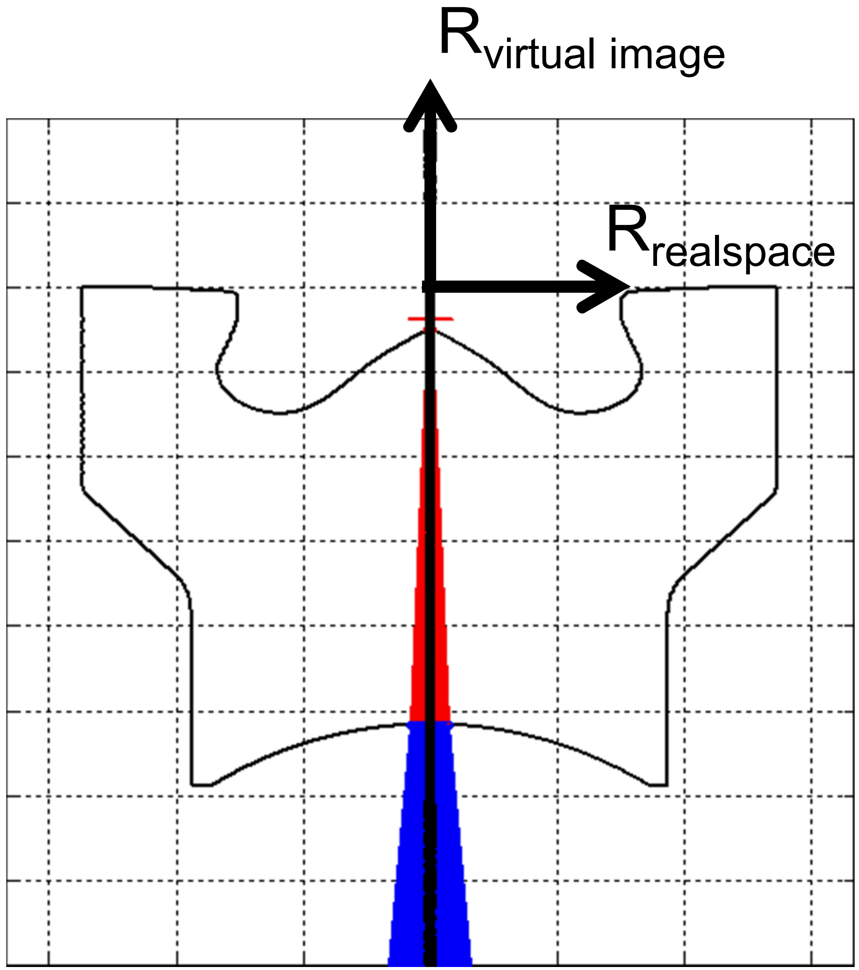
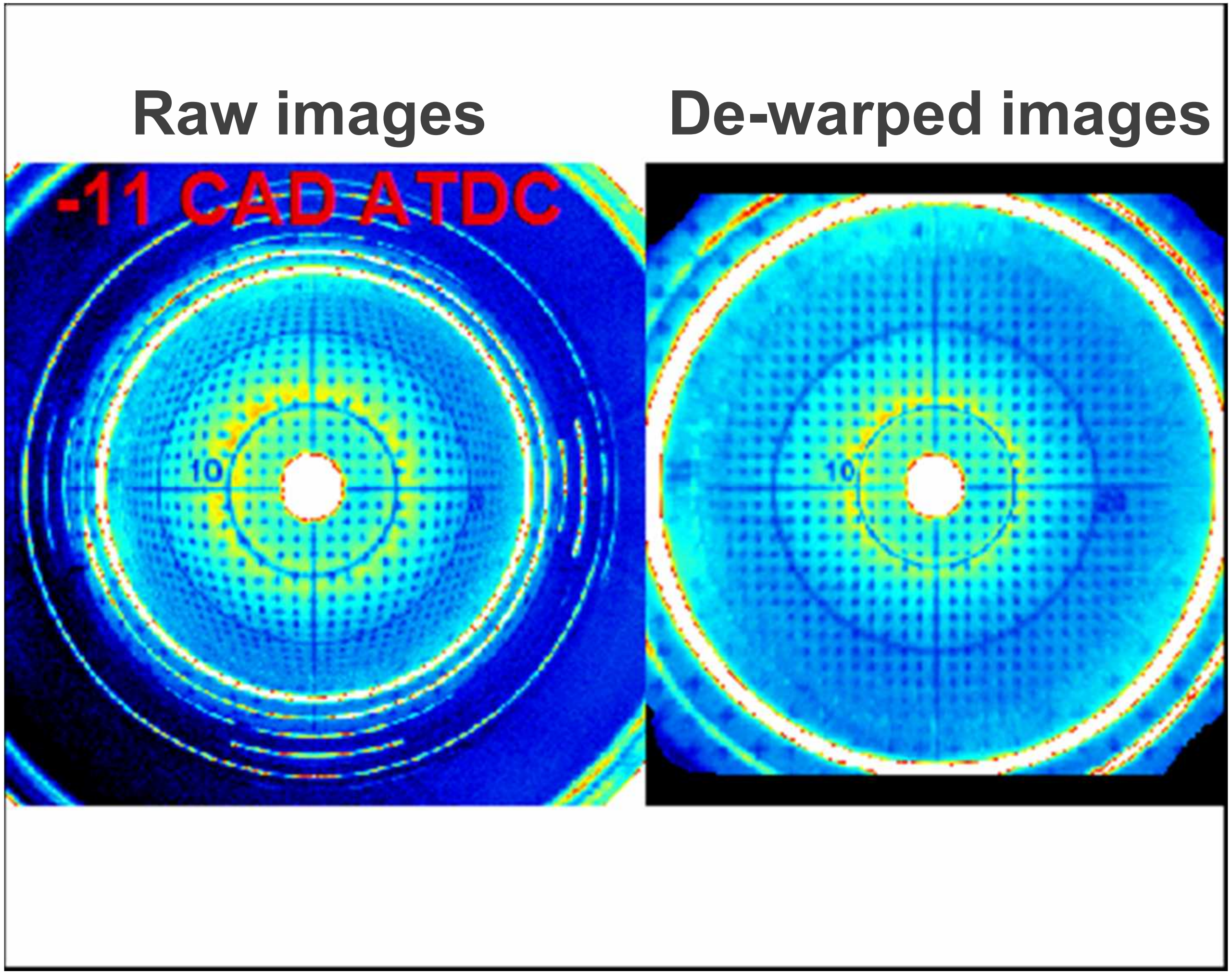


Image de-warping with ray tracing

- For a given crank angle and plane in real space (5 mm below the head)
  - Perform ray tracing for many radial positions
  - Determine mapping function between real space and the virtual image
- Radial mapping functions are used to de-warp images taken at a known crank angle



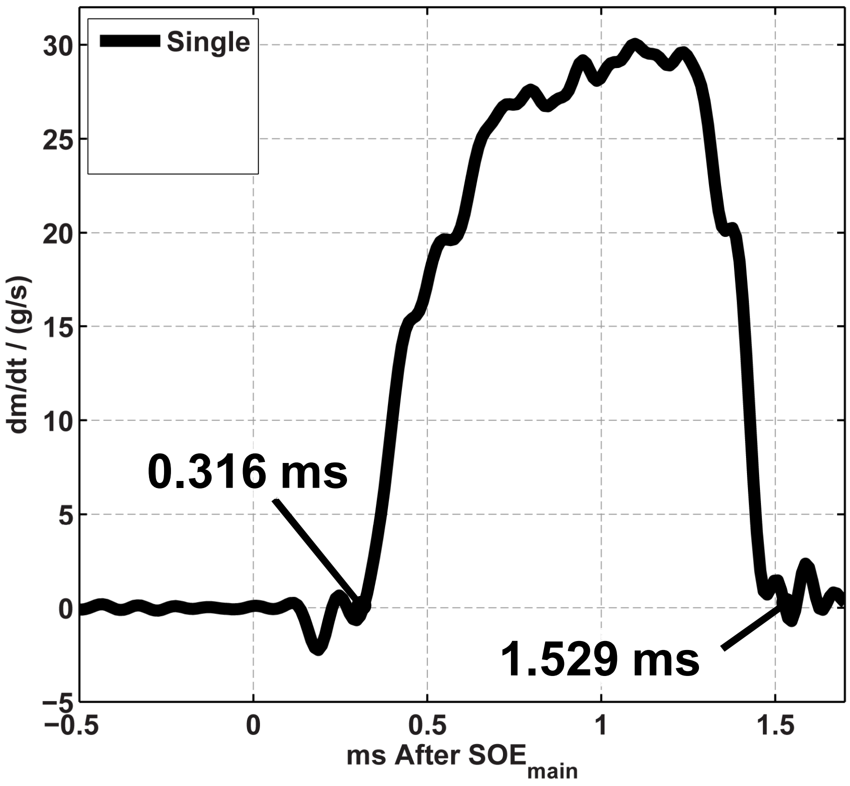
Testing the ray tracing approach

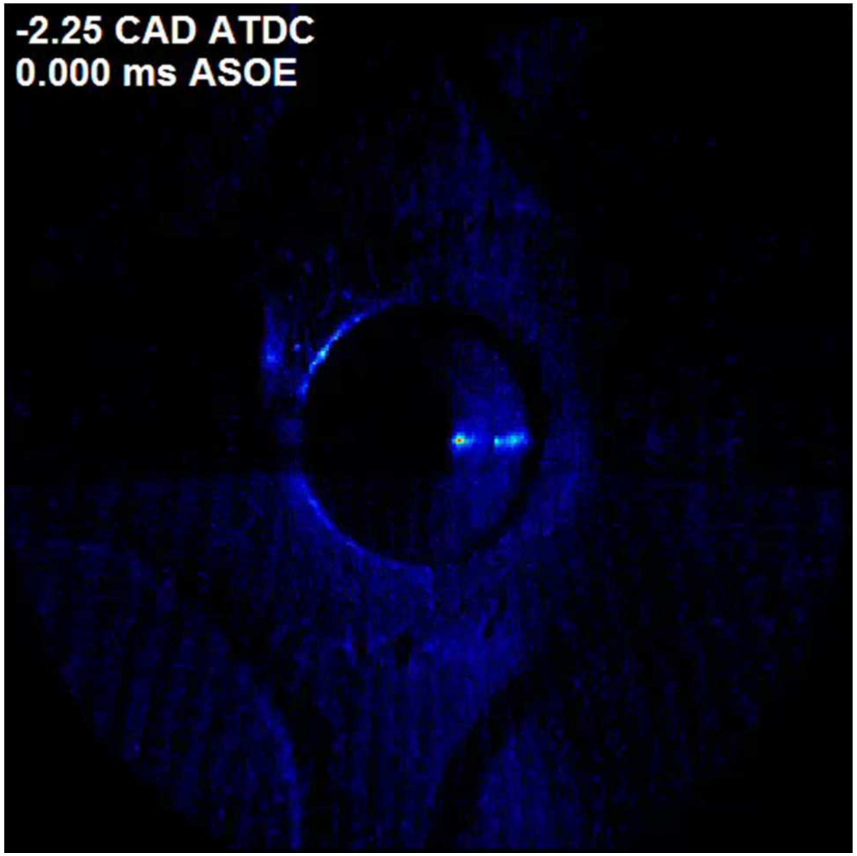


High speed fuel injection imaging

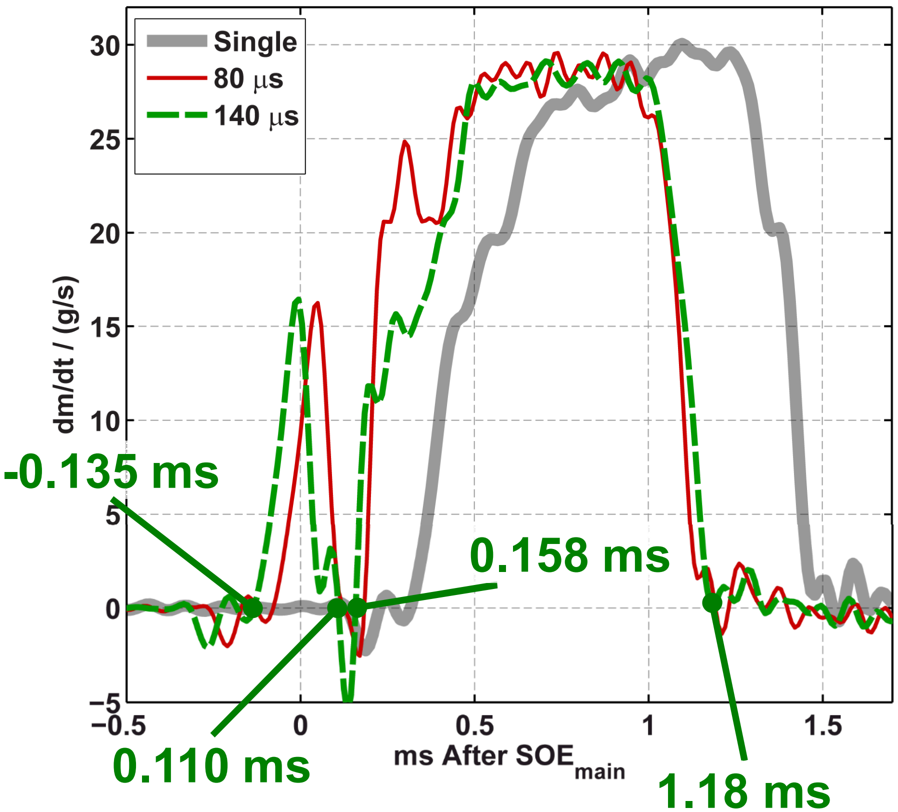
- Engine operation
  - Same injection trains as for the combustion noise testing
  - Air replaced with nitrogen – no combustion
- Dwell times tested
  - Single injection
  - 90 µs
  - 140 µs
  - 300 µs (not shown)
- Imaging at 120 kHz
  - 8.33 µs between images
  - 0.075 crank angle degrees at 1500 rpm
- LED
  - 1.5 µs pulse width
  - ~45 A peak current

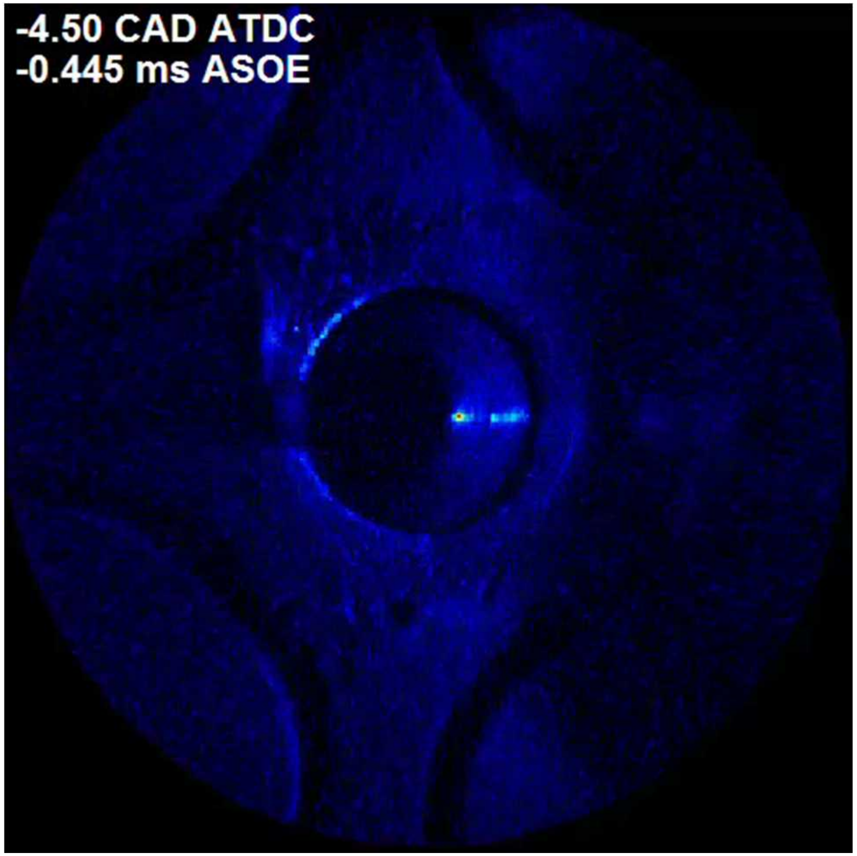
Initial imaging results: single injection



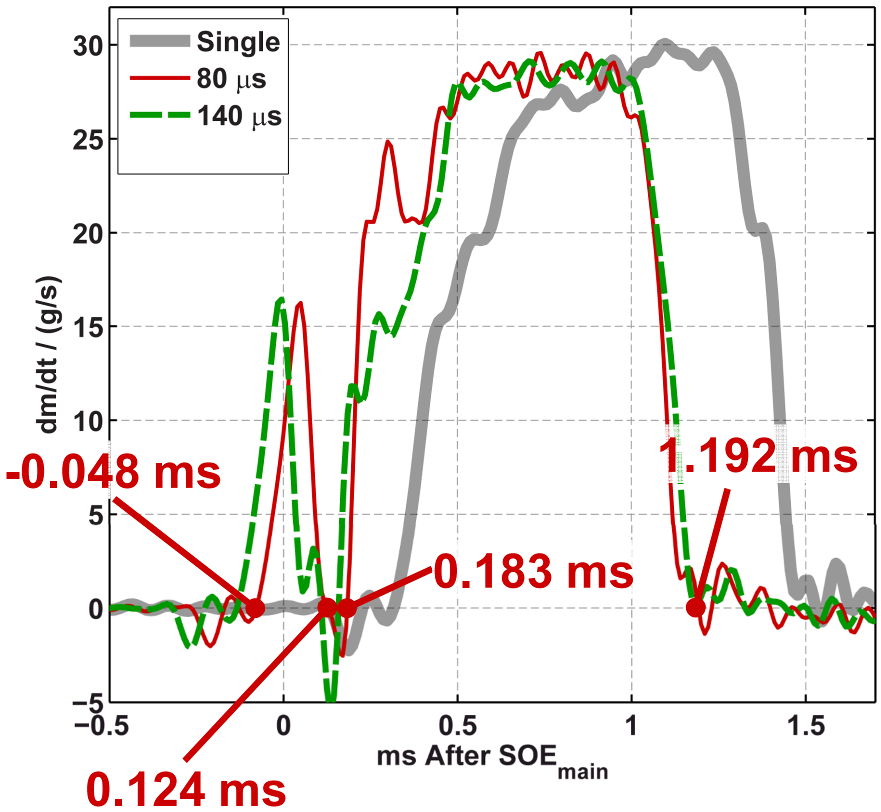


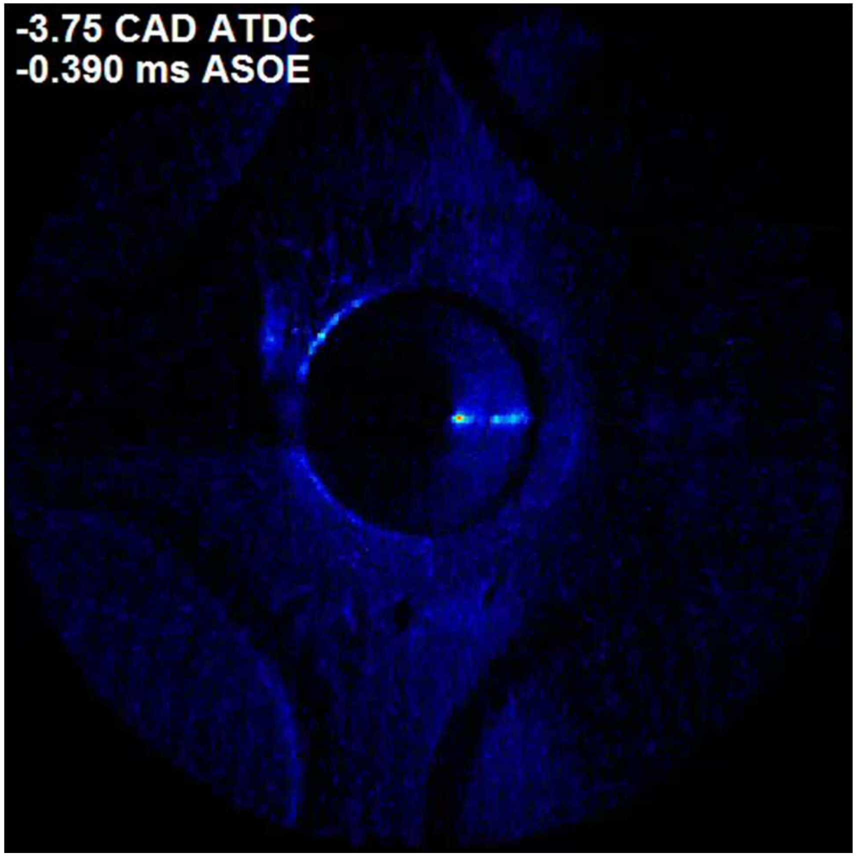
Initial imaging results: dwell 140 µs





Initial imaging results: dwell 90 µs





Summary

- Pilot + main injection strategy
  - Lower combustion noise than for a single injection
  - Combustion noise depends on dwell between pilot and main
    - Minimum at dwell time of 140 μs
- Injection rate measurements
  - Show significant rate shaping as dwell changes
  - Shortest dwells lead to steepest ramp-ups in main injection rate shape
- High speed injection imaging
  - Automated image de-warping routine developed
  - Imaging at 120 kHz possible
  - Further analysis to follow…

THANK YOU FOR YOUR ATTENTION!

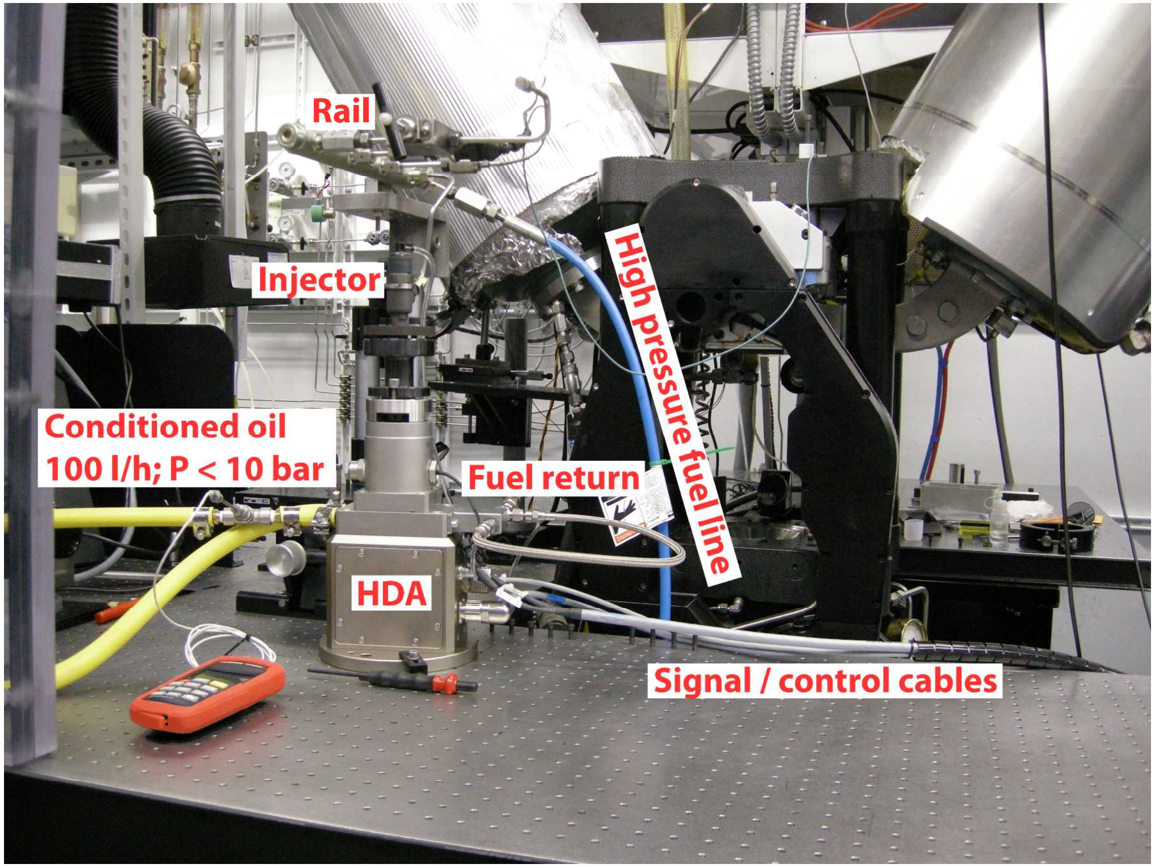
Questions?

HDA testing conditions

Parameters

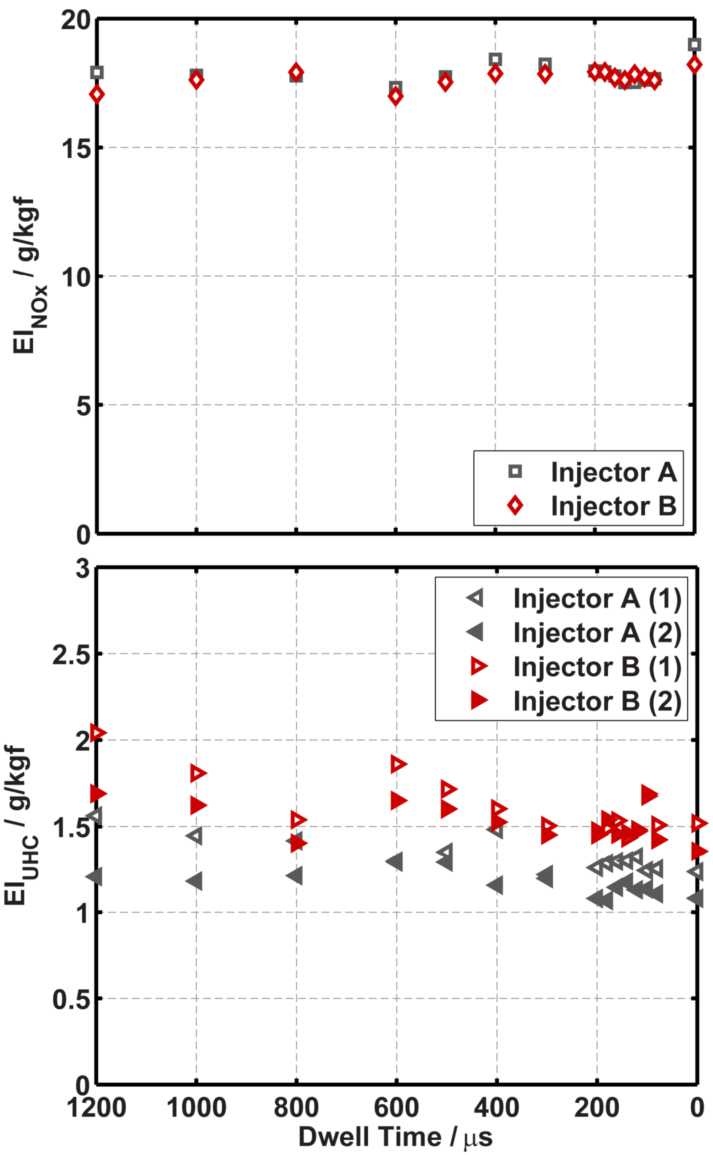
P_{rail}	[bar]	800
$T_{fuel/chamber}$	°C	90
$P_{chamber, base}$	[bar]	56
Repetition rate	[Hz]	2.5
Digital filter f_c	[kHz]	10
Fuel	[-]	DPRF 58

- Multiple injection events measured for each operating point
  - Data shown here is a 50-shot ensemble average
  - Rate shapes are highly repeatable



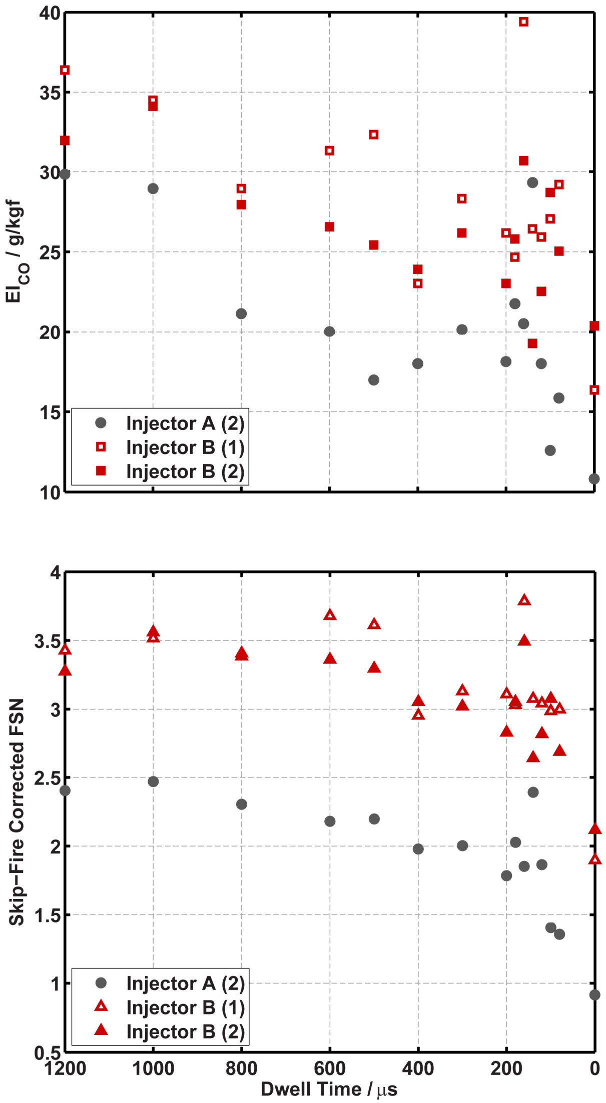
Dwell time sweep: NO_x and UHC

- NO_x
  - Emissions decrease slightly with the presence of a pilot
  - Relatively insensitive to dwell time
- UHC
  - Low level (~0.2% of fuel)
  - Slightly higher at longer dwell times
    - Suspected overmixing of far pilot



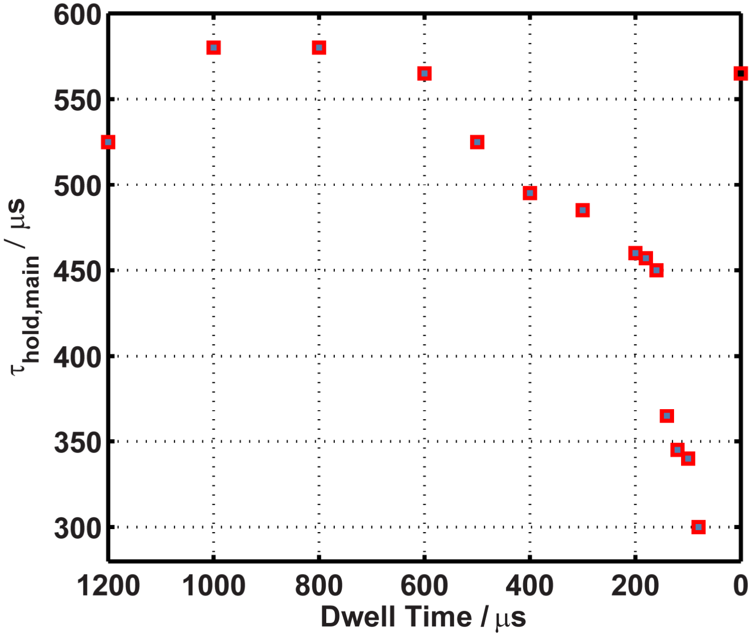
Dwell time sweep: CO and FSN

- CO
  - Increase at longer dwell times attributed to overly lean mixtures
  - Local maxima at dwell times shorter than 200 µs
- FSN
  - Local maximum at dwell times of 500-600 µs
  - Overall trends similar to CO trends
    - Rich mixtures as a source of CO



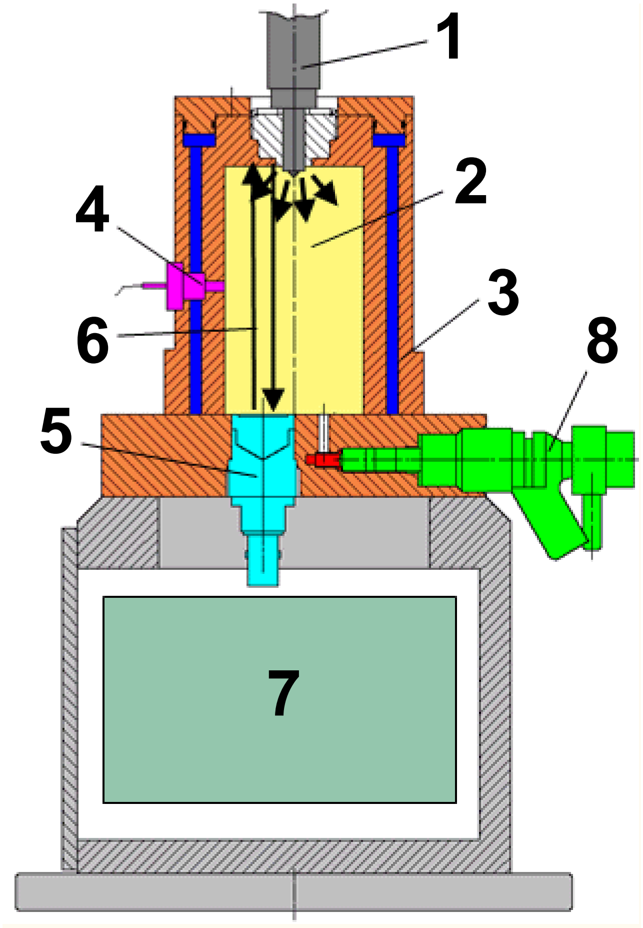
Dwell time sweep: main injection holding time

- Main injection duration adjusted to maintain constant load
  - Duration depends strongly on dwell time
- Demonstrates significant hydrodynamic coupling within the injector between injection events
  - Main injection quantity is amplified by a close pilot
  - For given actuation time, main injection lasts longer with a pilot than without



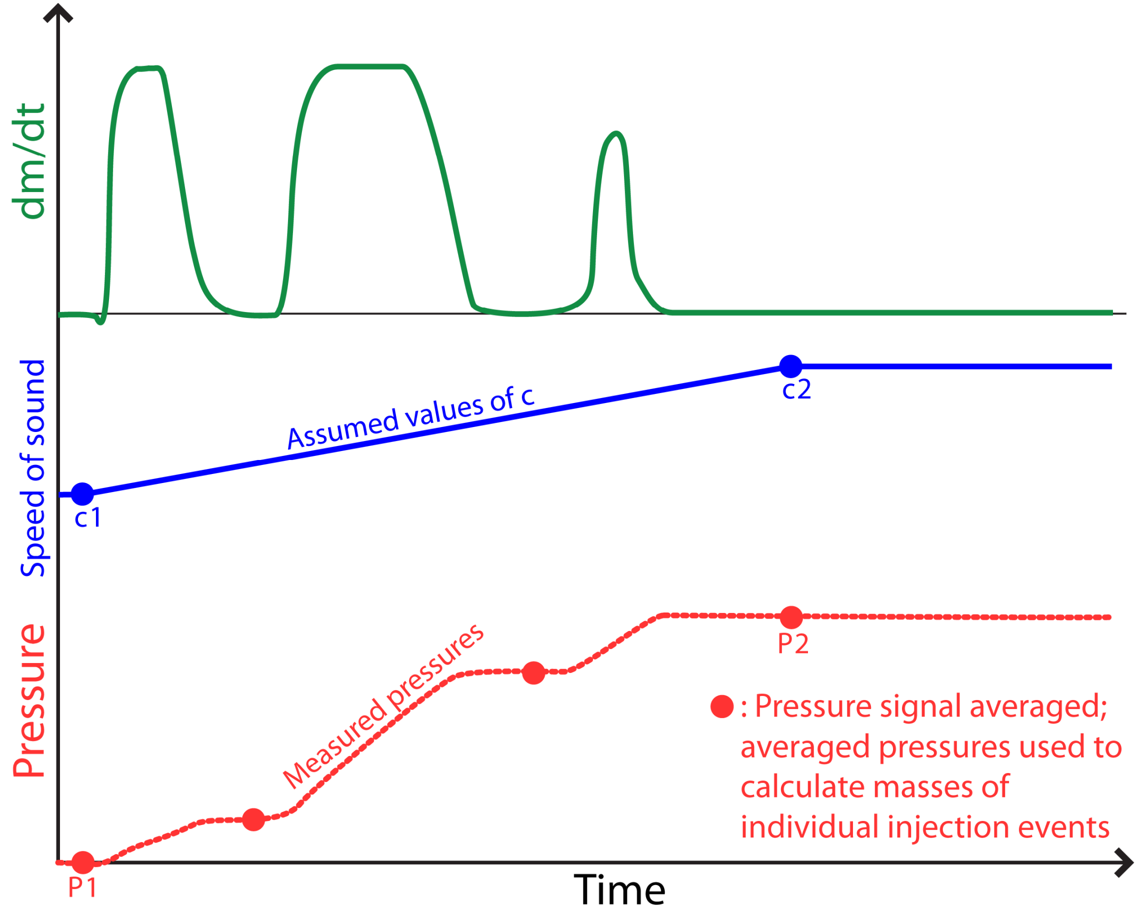
HDA components

1. Injector (mechanically isolated)
2. Temperature controlled SS chamber, V = 128 ml
3. Heat transfer fluid channels
4. Piezoresistive pressure sensor, 0-100 bar; located halfway up the chamber wall
   - Location at node helps attenuate pressure oscillations
5. Piezoceramic ultrasonic sensor
6. Ultrasound path
7. HDA base with electronics
8. HDEV backpressure control valve



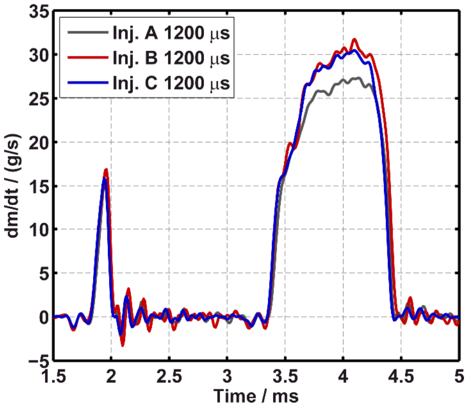
HDA measurement principle

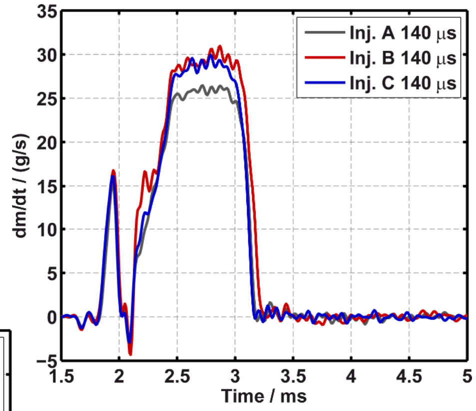
- $\Delta m = V_{MK} \int_{p_1}^{p_1+\Delta p} \frac{1}{c(p)^2} dp$
- $m_i = V_{MK} \frac{\Delta P}{c^2}$

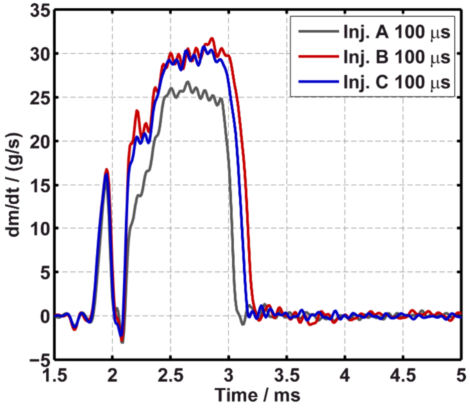


Dwell time sweep: variation between injectors

- Three injectors tested
  - Theoretically identical
- Significantly different maximum flow rates
- Differences in main injection can be substantial as dwell time decreases
  - Not a monotonic trend
  - Differences most significant at a dwell time of 100 µs

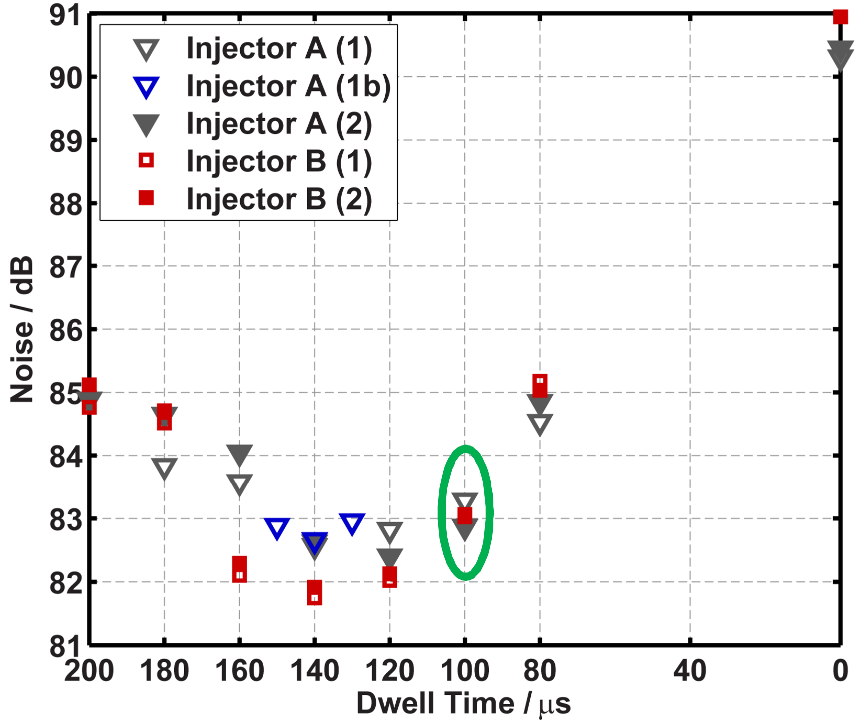






Combustion noise revisited

- Dwell time of 100 µs
  - Small dispersion in noise levels between injectors A and B
  - Largest differences in main injection rate shaping between injectors A and B
- Is the injection rate data reliable?
  - Nothing in the literature to suggest otherwise
- What about other pilot-main dwell studies in the literature?
  - Different injection hardware



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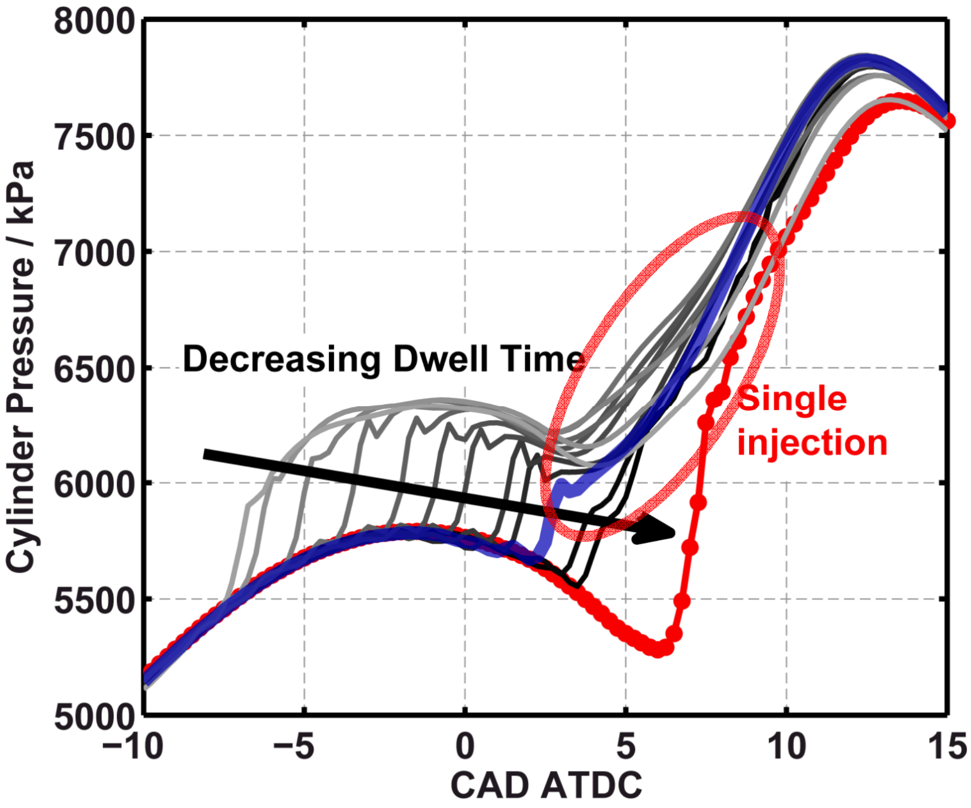
Dwell time sweep: cylinder pressure traces

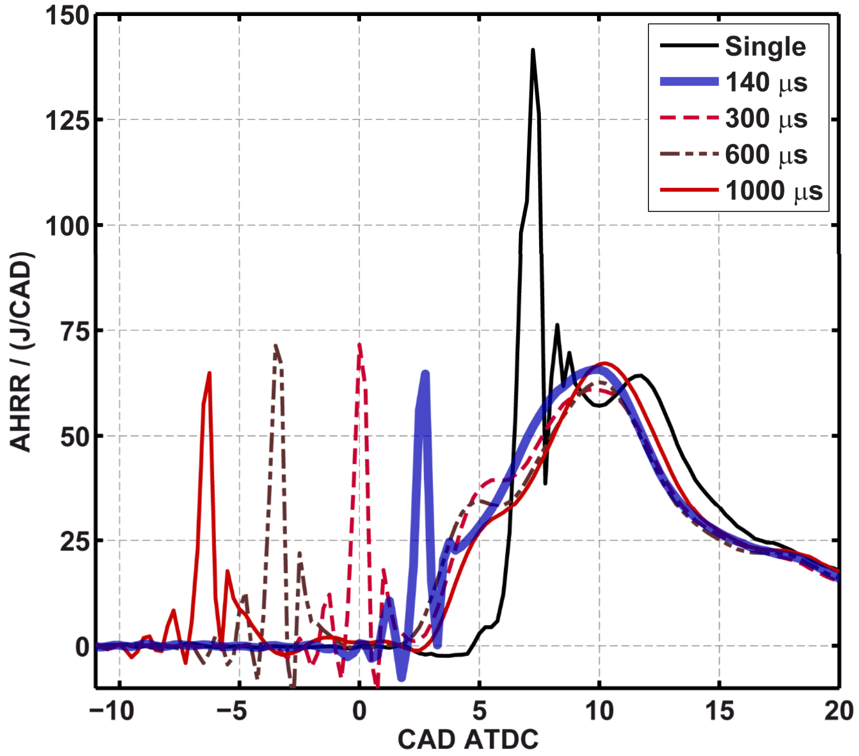
- MFB50 held constant
  - 13 CAD ATDC
- COV(IMEP) typically 1%
- Differences in initial rate of pressure rise due to main combustion

- Blue trace: lowest noise
  - Dwell time 140 µs
  - Moderate rise in pressure early during the main combustion



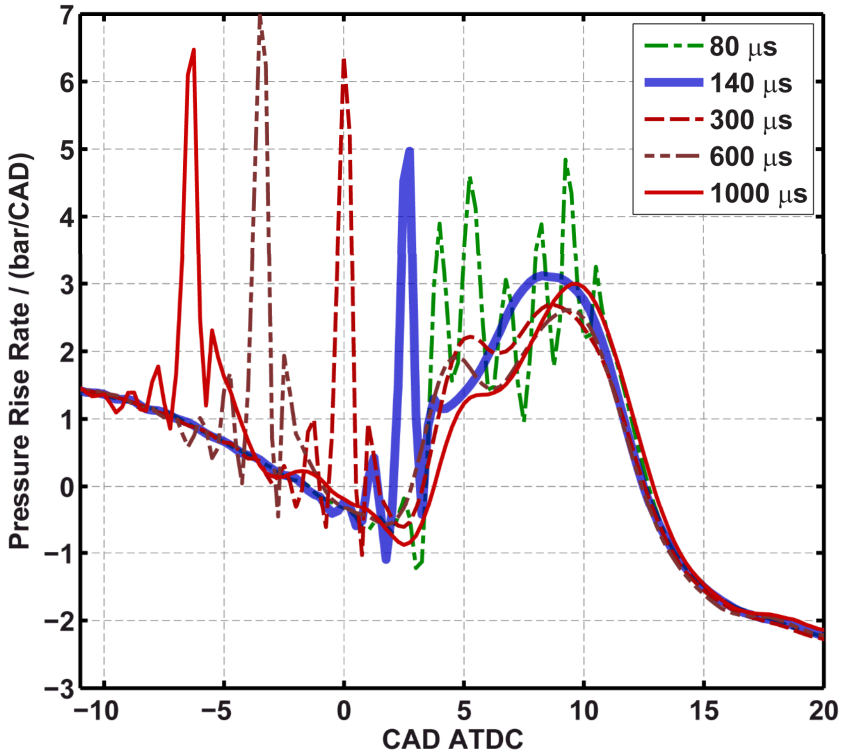
Dwell time sweep: apparent heat release

- Clear separation between pilot and main combustion
- Peak pilot heat release rate similar in magnitude to peak main injection heat release
- Differences in main heat release difficult to quantify
- Need more information to understand the trend in combustion noise



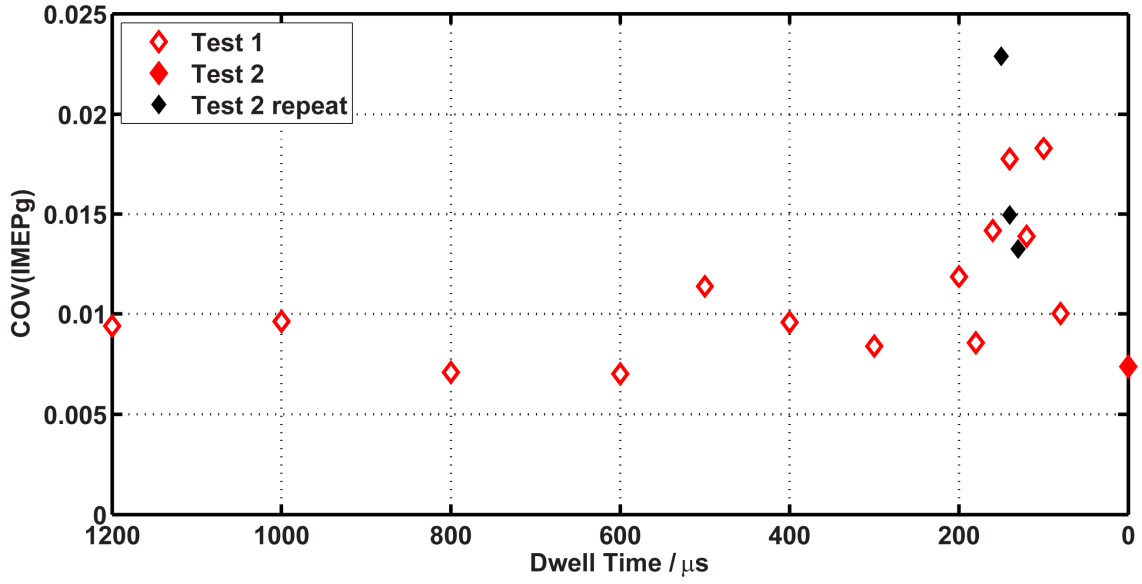
Dwell time sweep: pressure rise rate

- Peak rate of pressure rise tends to decrease with decreasing dwell time
- For dwell times shorter than 140 µs, the dP/dCA trace becomes erratic
  - Adaptive filter cannot adequately filter out pressure fluctuations
  - No separation between pilot and main heat release
- Does the noise minimum occur at a dwell time of 140 µs because of retarded combustion phasing or is it related to mixture formation?



Dwell time sweep: COV(IMEPg)

- COV(IMEPg) typically near 1%
- Increases at dwell times less than 200 µs
- Peaks near dwell time with large scatter in CO/smoke

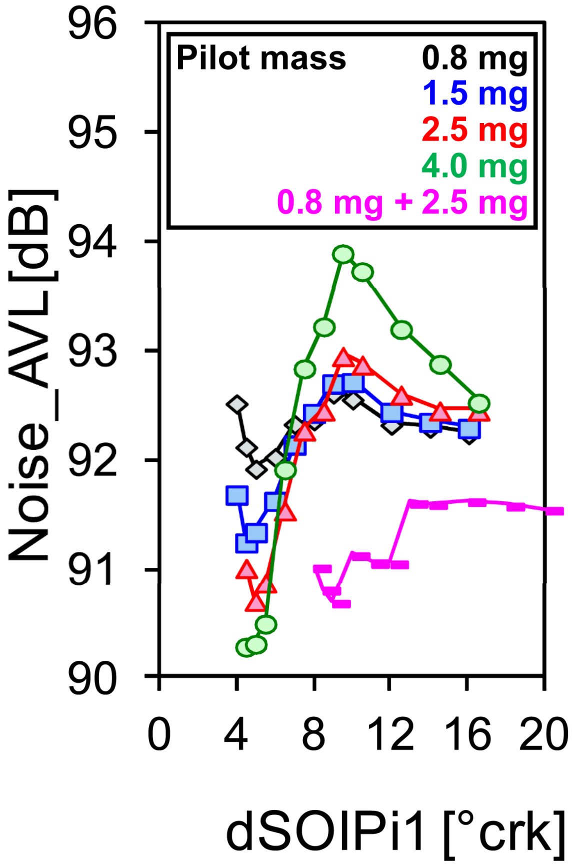


Combustion noise data from Continental (2012)

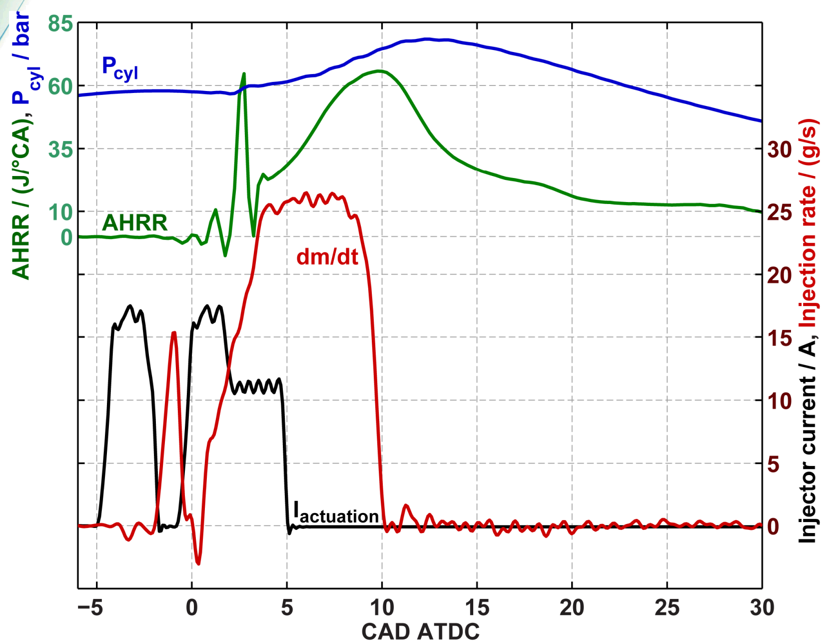
- Pilot – main – post injection strategy
- Piezoelectric injector actuation
- IMEP = 14 bar; n = 2280 rpm; P_{rail} = 1600 bar; MFB50 = 12 CAD ATDC

- For varying pilot injection quantities, noise passes through a minimum as dwell time decreases
  - Minimum occurs at a hydraulic dwell (EOI-SOI) of 110 µs (1.5 mg pilot)
  - Hydraulic dwell for current study (δt = 140 µs): ~60 µs
  - Decrease in noise depends on pilot injection quantity

- Significantly different hardware, different operating point, but the trend in combustion noise with changing dwell time is remarkably similar
  - Continental: noise minimum achieved with decreased soot

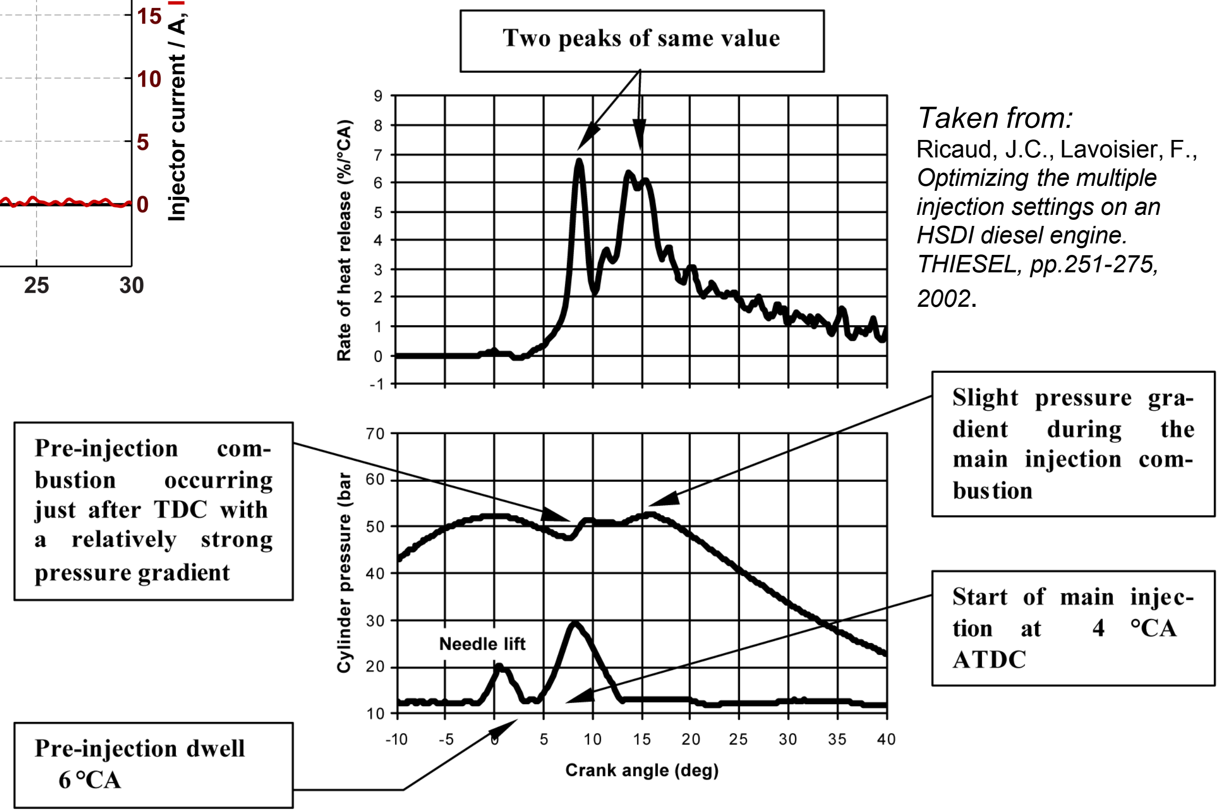


Comparison with noise-optimized operation in the literature



- SNL: dwell time 140 µs
  - Lower pressure rise rates during main combustion
  - Similar relationship between pilot and main heat release
  - Comparable phasing of main injection relative to pilot heat release

- Renault 2002
  - Piezoelectric injector, low load, retarded combustion phasing
  - Maximum heat release rates similar for pilot and main for minimum noise



Taken from:
Ricaud, J.C., Lavoisier, F., *Optimizing the multiple injection settings on an HSDI diesel engine. THIESEL, pp.251-275, 2002*.