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Effect of Close Pilot Spacing on Combustion Noise, Emissions, and Injection Rate Shape in a Small-Bore Diesel Engine

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Abstract: In this work, a pilot-main injection strategy is investigated in a small-bore DI Diesel engine. The dwell time between the pilot and the main injections is varied and its effect on combustion noise and exhaust emissions is measured for a moderate engine load and fixed combustion phasing (IMEPg = 9 bar; MFB50 = 13 CAD ATDC). A minimum in combustion noise occurs at a dwell time of 140 µs; but is not associated with a penalty in emissions. As a next step, injection rates are measured with a Moehwald HDA injection analyzer. The pilot injection is not affected by changes in dwell time, but the shape of the main injection ramp-up changes as dwell time decreases. Similar combustion noise trends have been observed by others, and heat release rate curves at the noise-optimized dwell time resemble those found in the literature. Future optical studies will provide more insight into the mixture formation and combustion processes as dwell time is varied.

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Outline

- Motivation and project objectives
  - Pilot – main injection strategy
- Measurements in the engine
  - Emissions (NO_x, CO, UHC, smoke)
  - Combustion noise
- Measurements on an injection rate analyzer
  - Moehwald HDA
  - Rate shapes
- Revisit combustion noise, comparison with literature
- Summary and outlook

Motivation and project objectives

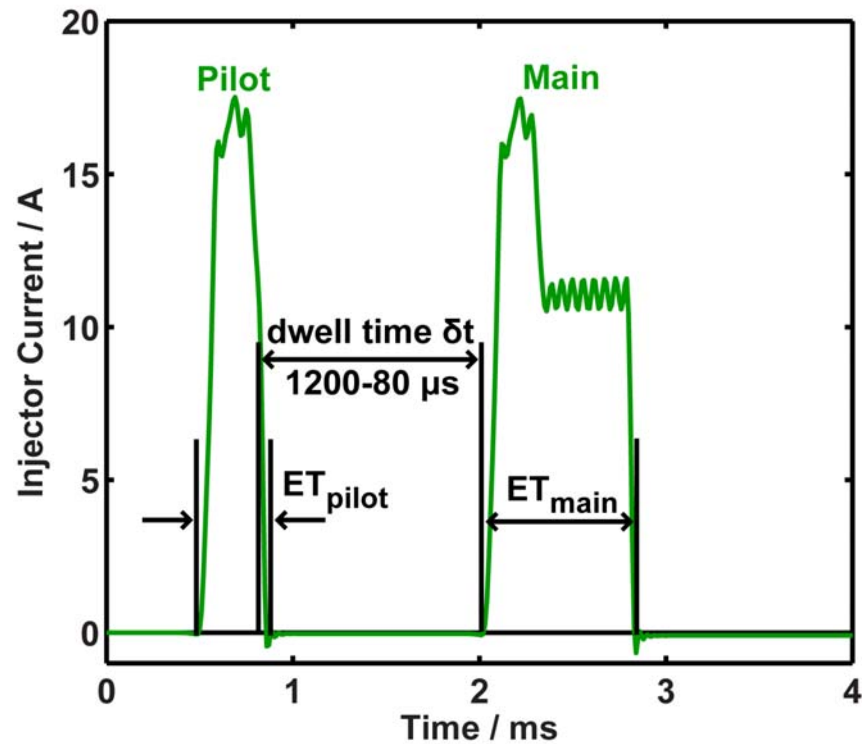
- Pilot injection
  - Typically a small quantity injected before the main
  - Shortens apparent ignition delay of main injection
  - Used to decrease combustion noise (compared to a single injection) but may have other benefits

- Project objective: Obtain a clearer understanding of how pilot injections impact mixture formation, ignition, combustion, and emissions
  - First steps: examine effects of changing dwell time on:
    - Combustion noise and emissions
    - Injection rate
    - Spray quality / mixture formation of main injection
    - Soot formation process

Injection strategy: pilot + main

- Injector control
  - Via GENOTEC control unit
  - Solenoid energizing time (ET) for each injection
  - Dwell time (δt)
- Injector
  - Bosch CRI 2.16 Multijet II
    - Pressure-balanced control valve
    - Fast acting → makes short dwell times possible

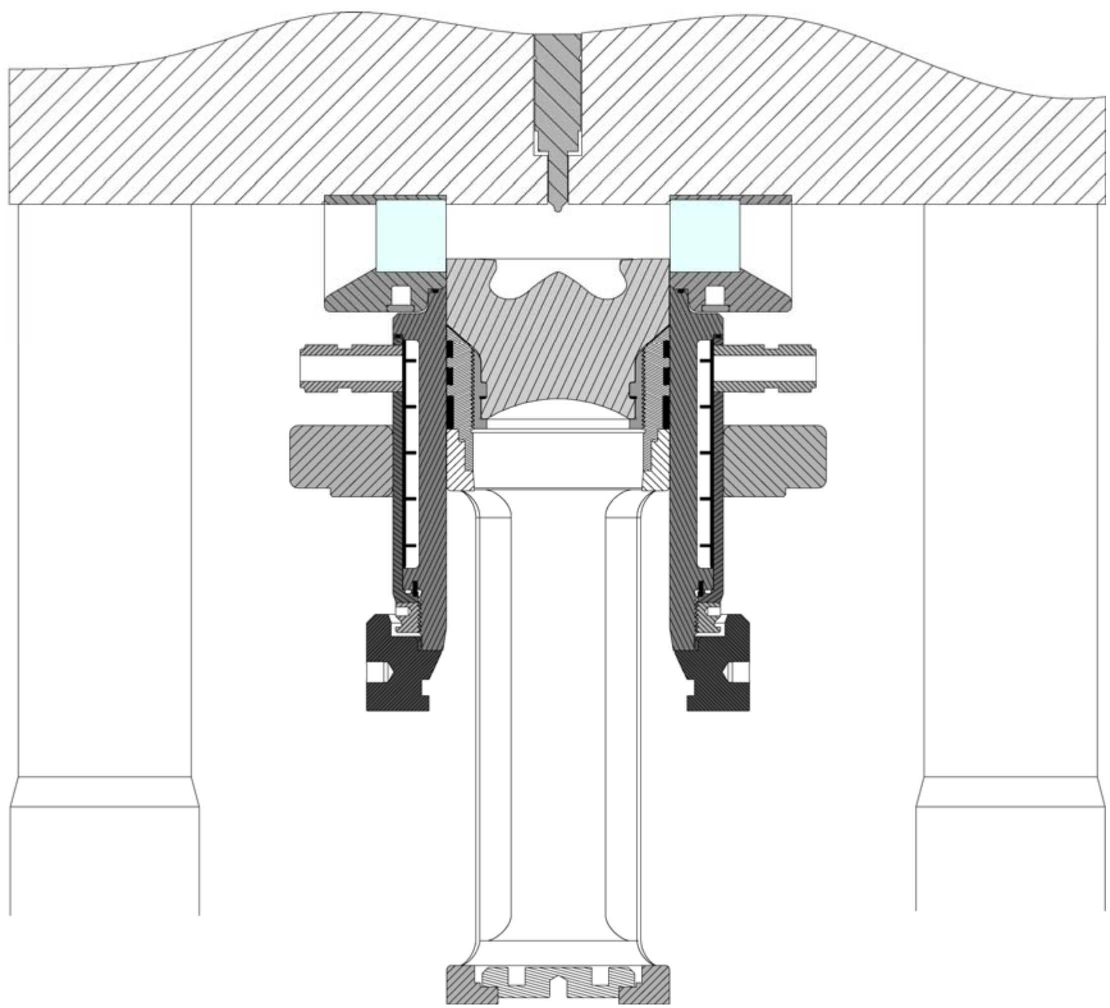
Injection train and naming convention



Small-bore optical Diesel engine

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°



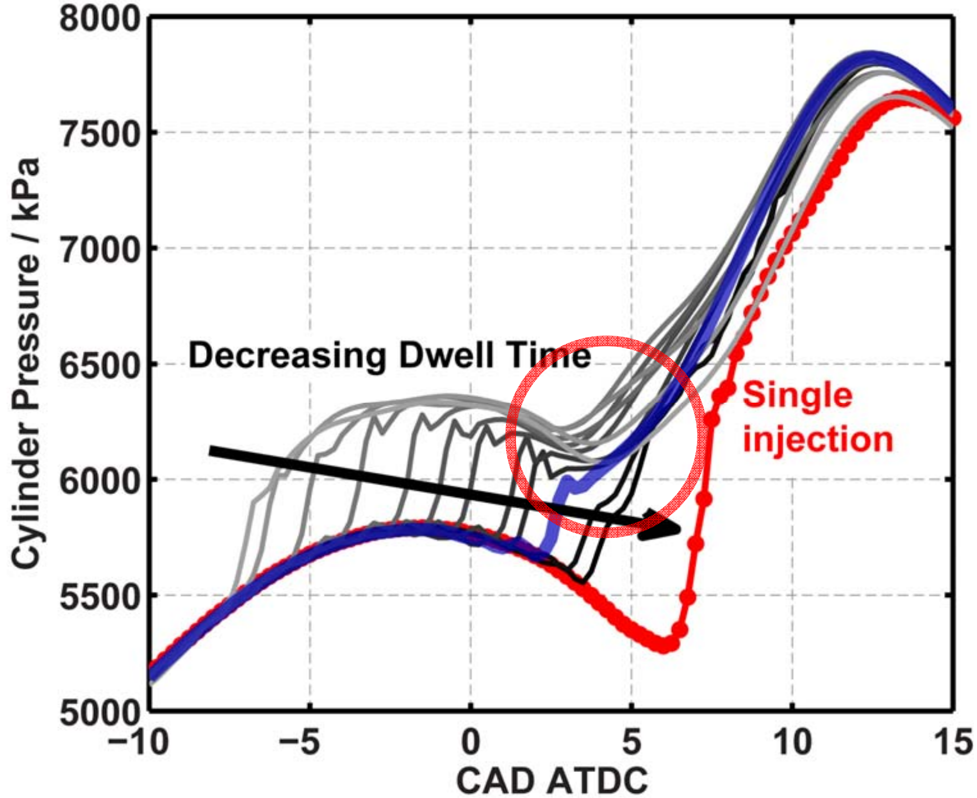
Engine operating conditions

Injection train	[-]	Single	Pilot + Main
Eng. speed	[rpm]	1500	
$IMEP_g$	[bar]	9.0	
P_{rail}	[bar]	800	
Q_{Pilot}	[mg/str]	-	1.5
δt_{Pilot}	[us]	-	1200…*200* ...600 600…*100* …200 200…*20* ...80
Boost pressure	[kPa abs]	~150	
Intake temp.	[°C]	~74	
TDC temp.	[K]	~925	
EGR nom.	[%]	~7 (10.3 accounting for residual fraction)	
MFB50	[CAD]	~13	
Fuel	[-]	DPRF 58 (CN 50.7) 58 vol% Heptamethylnonane 42 vol% n-Hexadecane	

Dwell time sweep: cylinder pressure traces

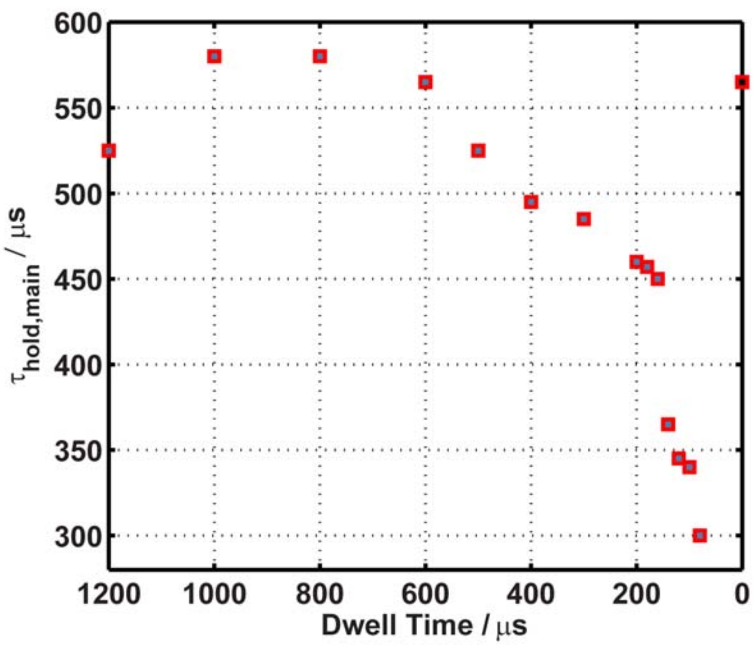
- MFB50 held constant
  - 13 CAD ATDC
- COV(IMEP) typically 1%
- Differences in initial rate of pressure rise due to main combustion

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



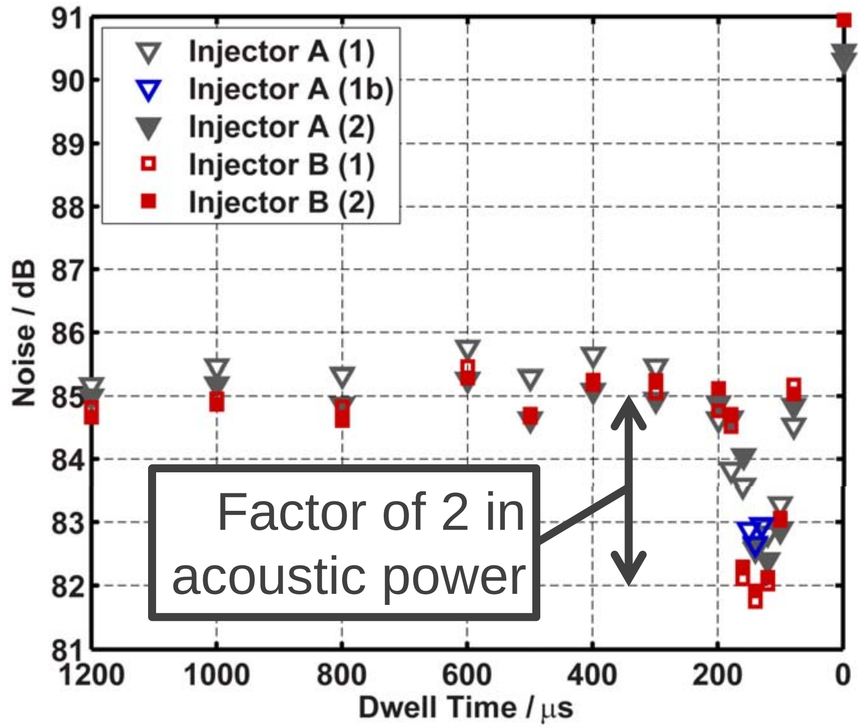
Dwell time sweep: main injection holding time

- 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



Dwell time sweep: combustion noise

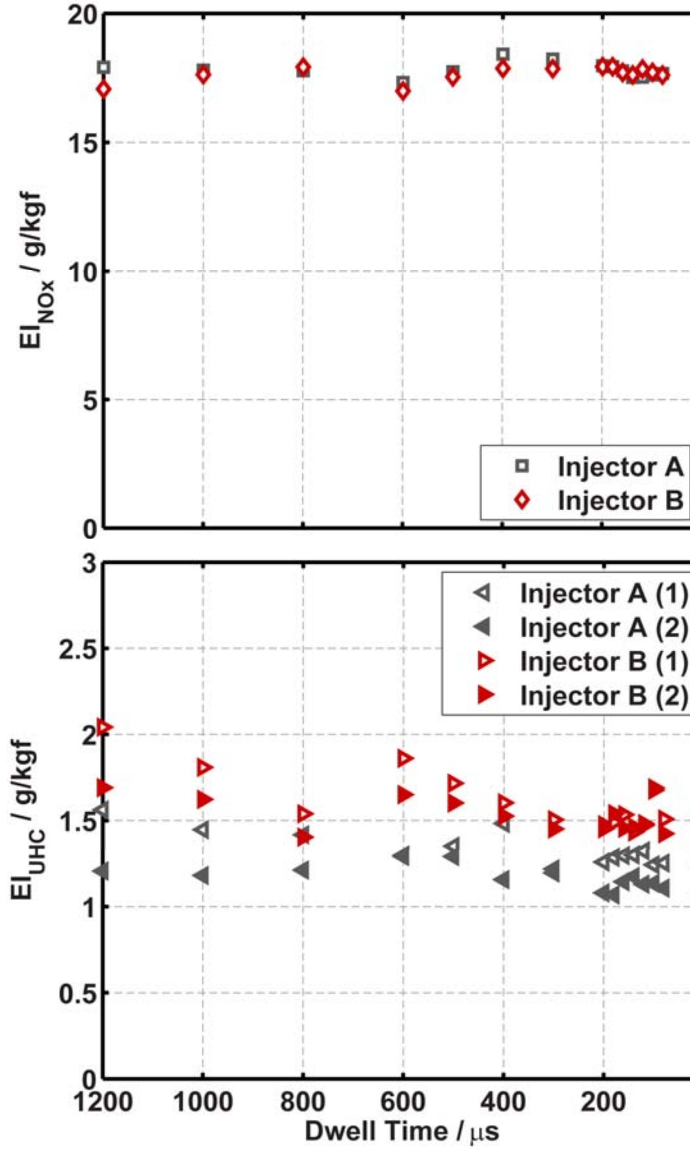
- Computed combustion noise
- Trend with changing dwell time repeats well
- Location of noise minimum is closely repeatable
  - Always near 140/120 µs
- Good agreement between injectors



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.

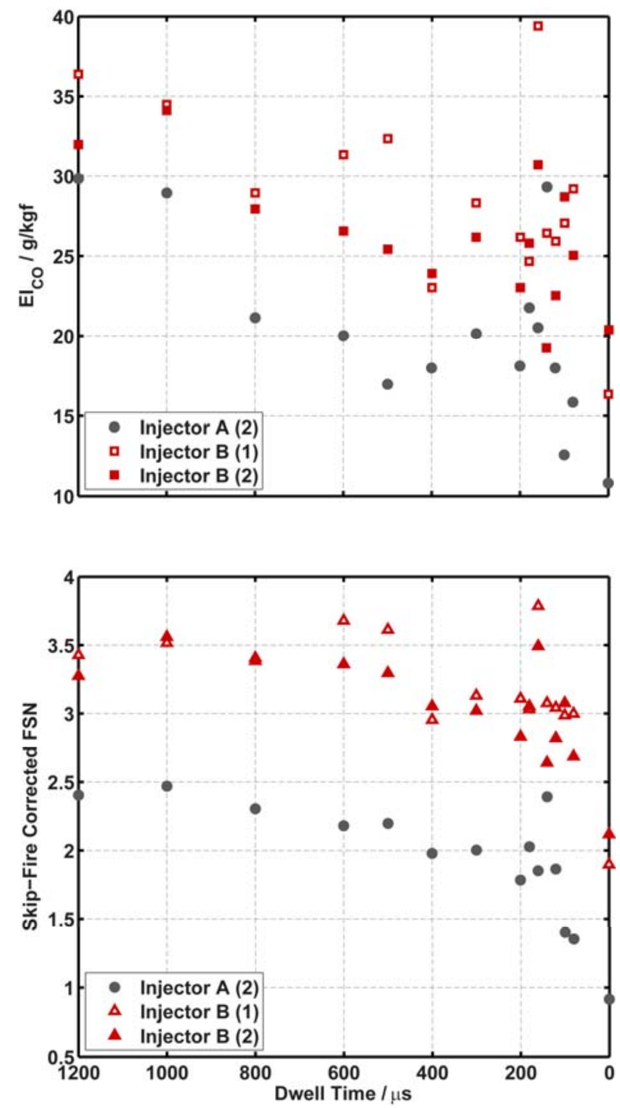
Dwell time sweep: NO_x and UHC

- 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



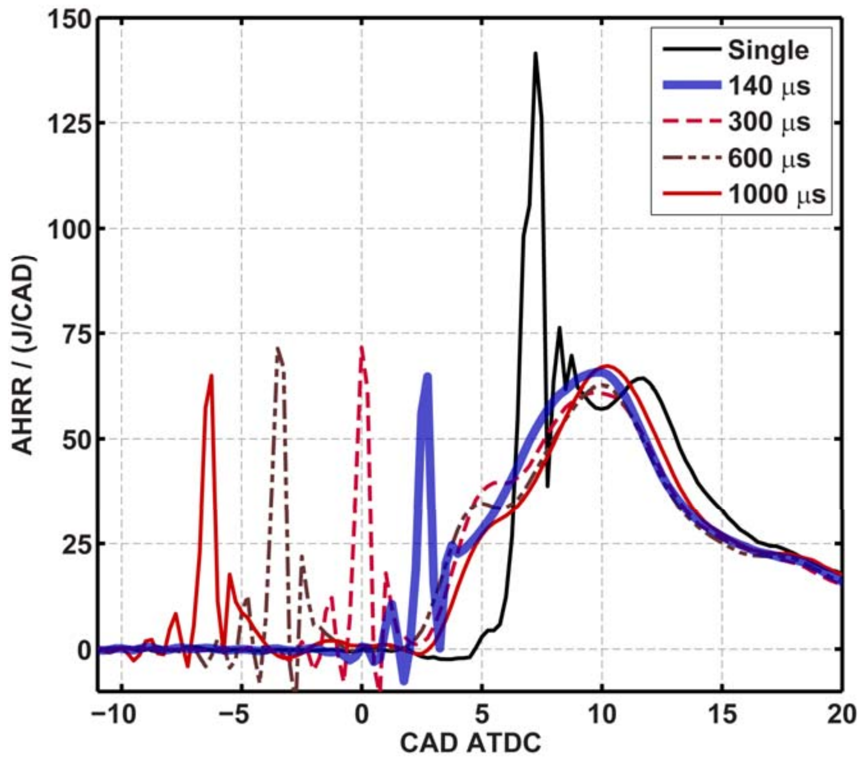
Dwell time sweep: CO and FSN

- 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



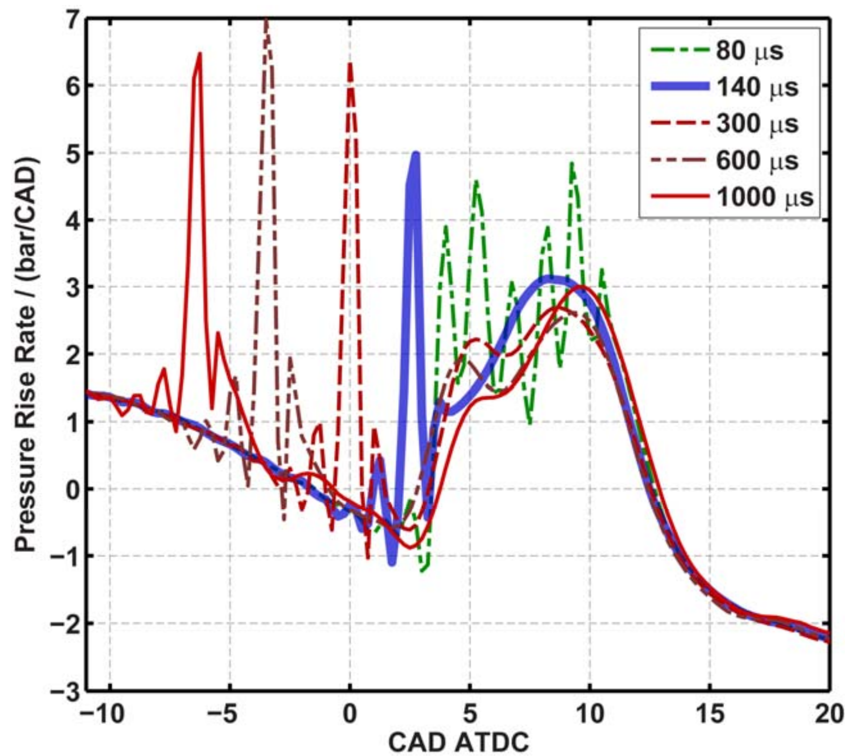
Dwell time sweep: apparent heat release

- 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 cylinder pressure 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?

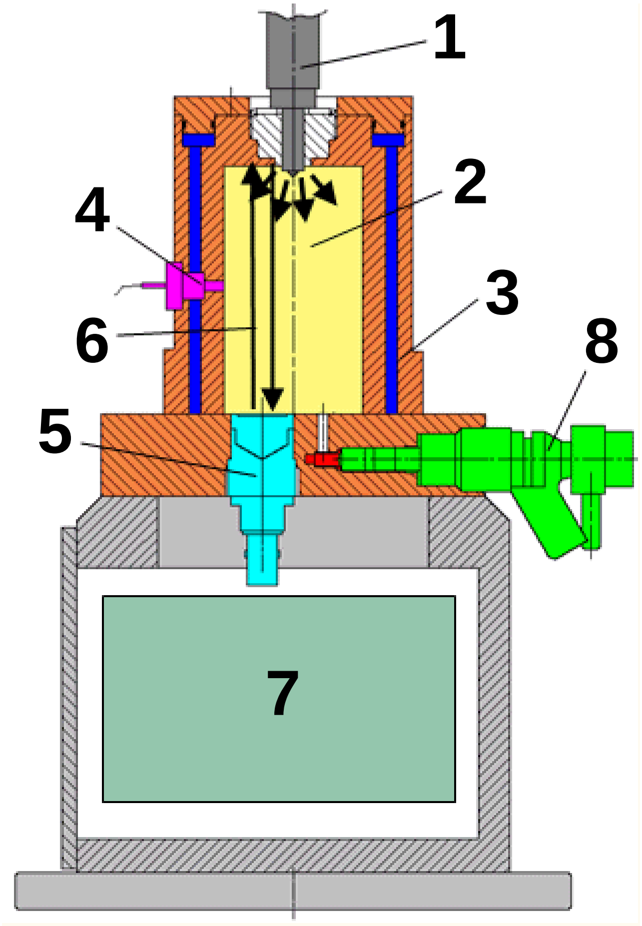


Recap: dwell time sweep

- Pilot-main: dwell time of 140 μs
  - Dramatic (~3 dB) decrease in combustion noise
  - No penalty in emissions
  - Peak rates of pressure rise for the pilot injection are lowest
- Is the noise minimum dependent on pilot combustion phasing or is it a matter of mixture formation?
- 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

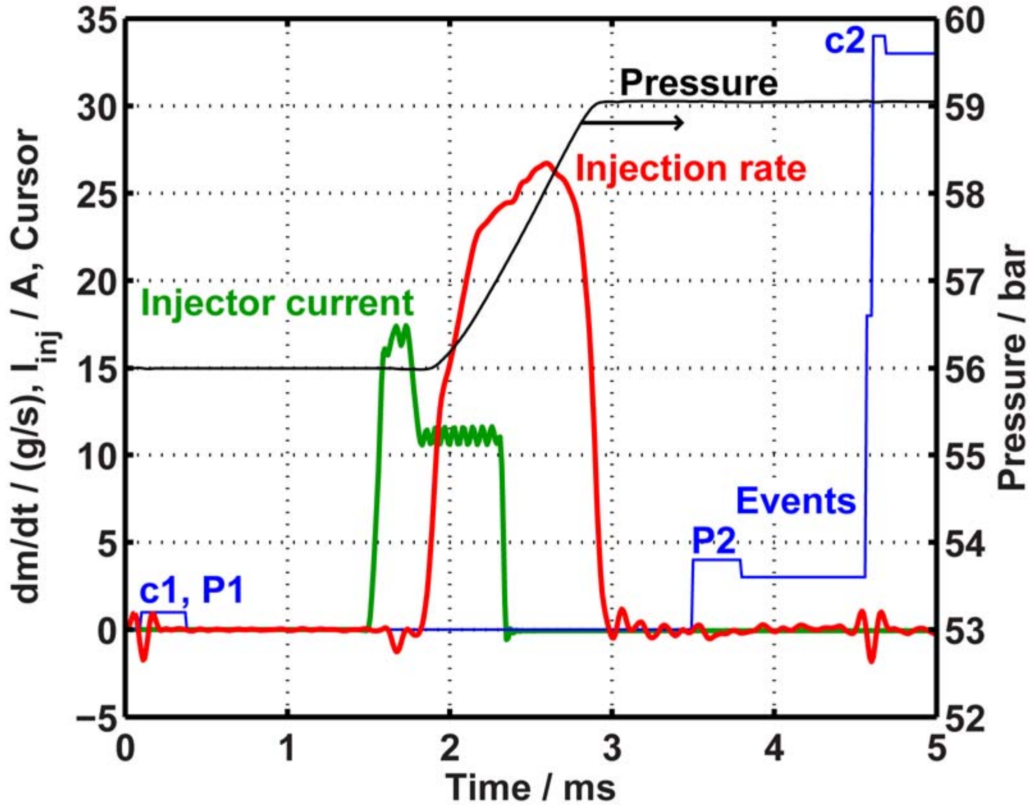
HDA components

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



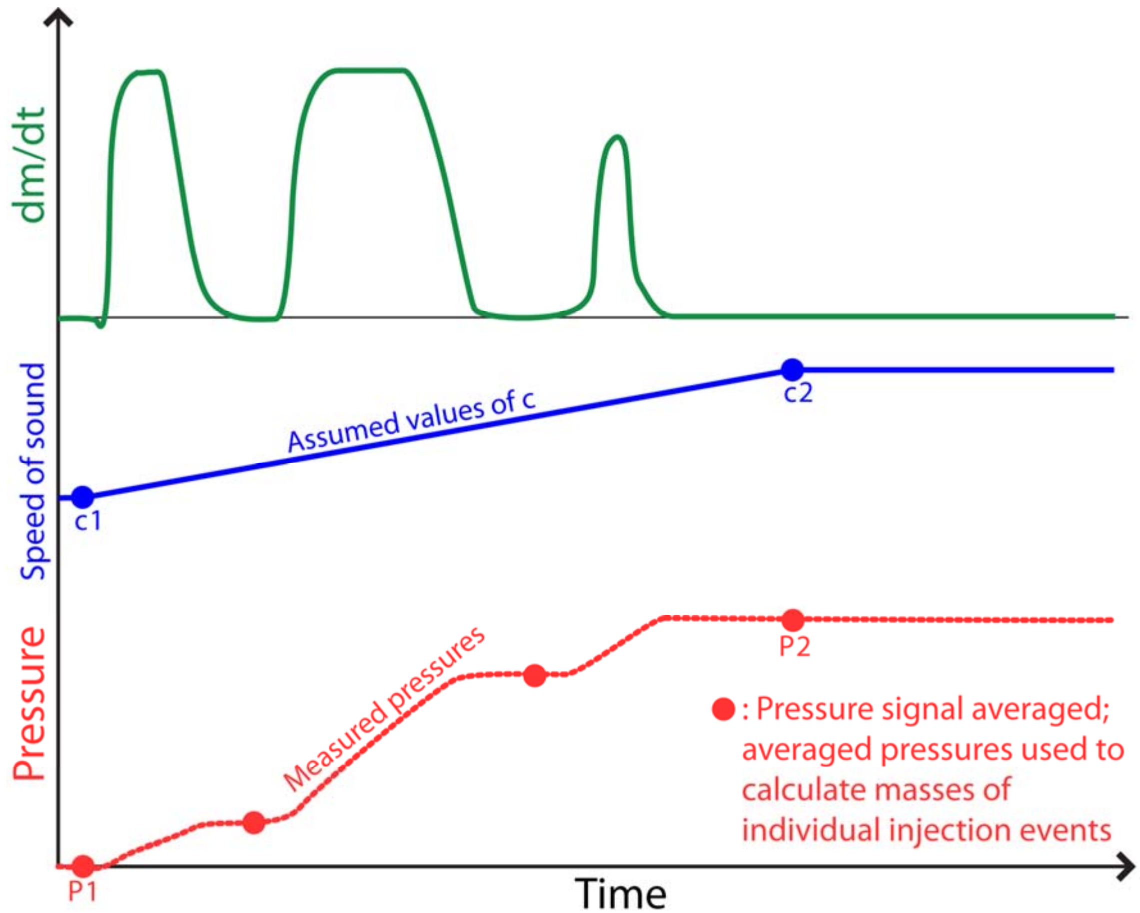
HDA timing example: single injection

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



HDA measurement principle

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

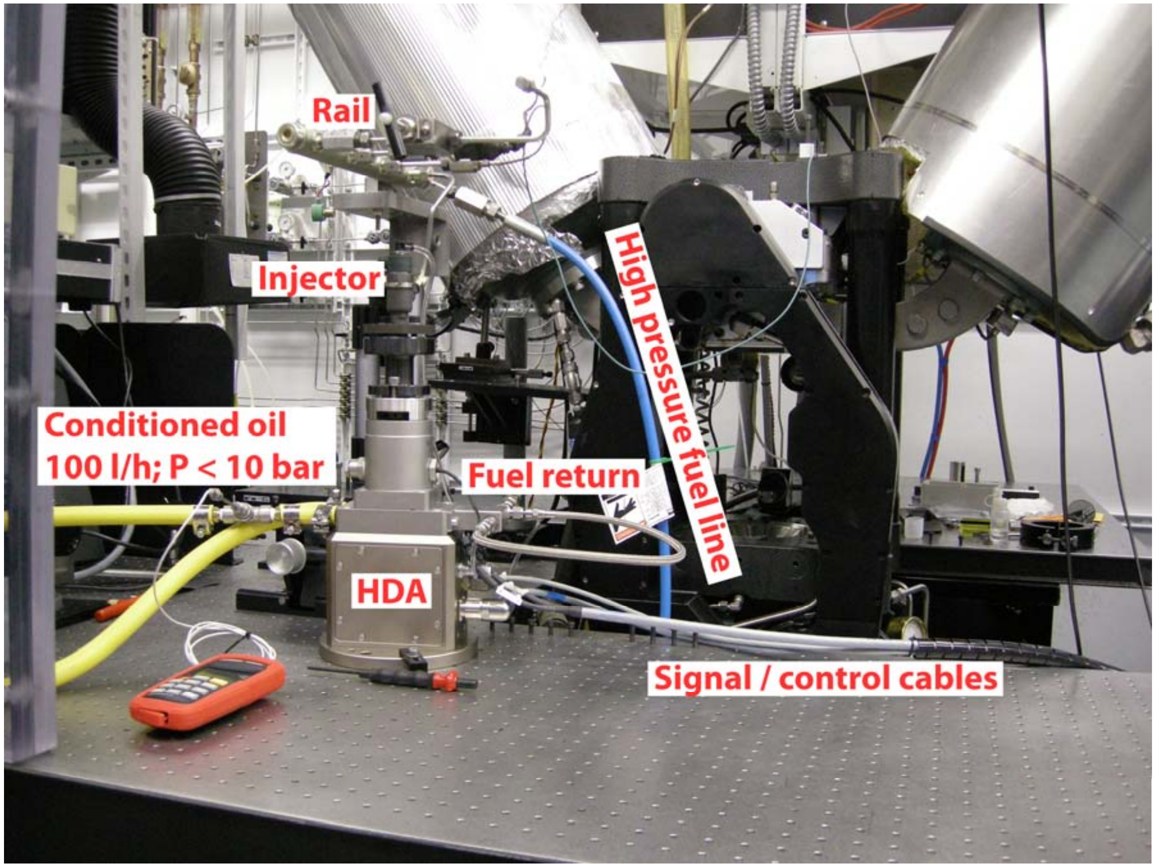


HDA testing conditions

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

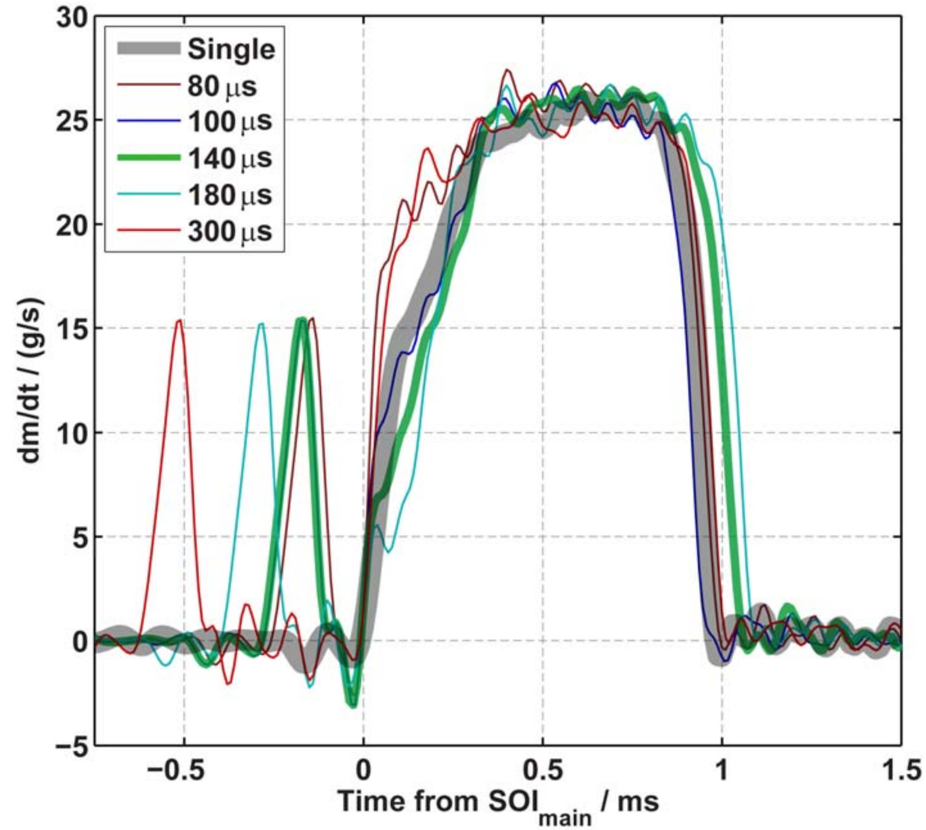
- Multiple injection events measured for each operating point
  - Data shown here is a 50-shot ensemble average
  - Rate shapes are highly repeatable



Dwell time sweep: injection rates

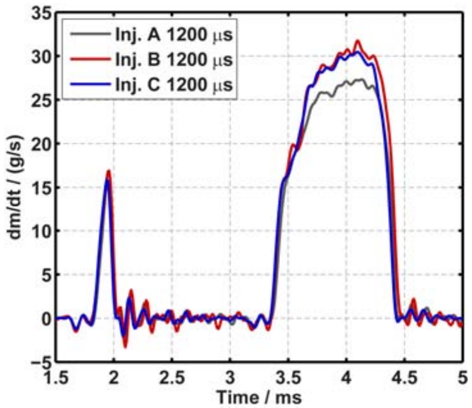
- Pilot quantity highly repeatable as dwell time changes
- Main injection rate shaping
  - Depends strongly on dwell
  - Trends shown here are repeatable
- Dwell time of 140 µs
  - Slower main injection ramp-up could explain noise trends
  - Less fuel injected during early phase of main injection
  - **Dwell time of 180 µs should result in the lowest combustion noise, but it does not!**

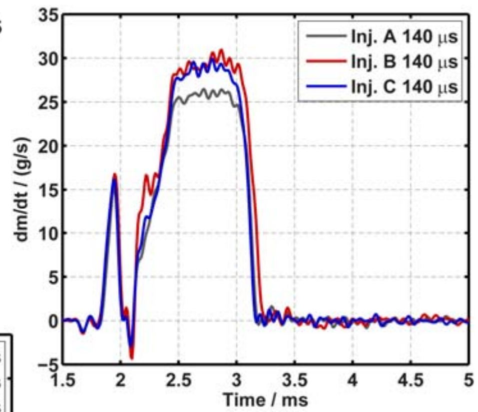
Single injection shown with comparable Q_{main}; longer holding time required

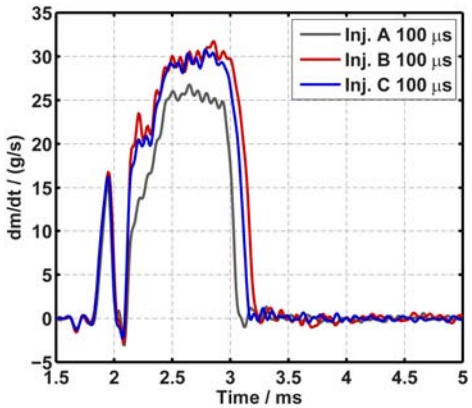


Dwell time sweep: variation between injectors

- Three injectors tested
  - Theoretically identical
- 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
- Significantly different maximum flow rates

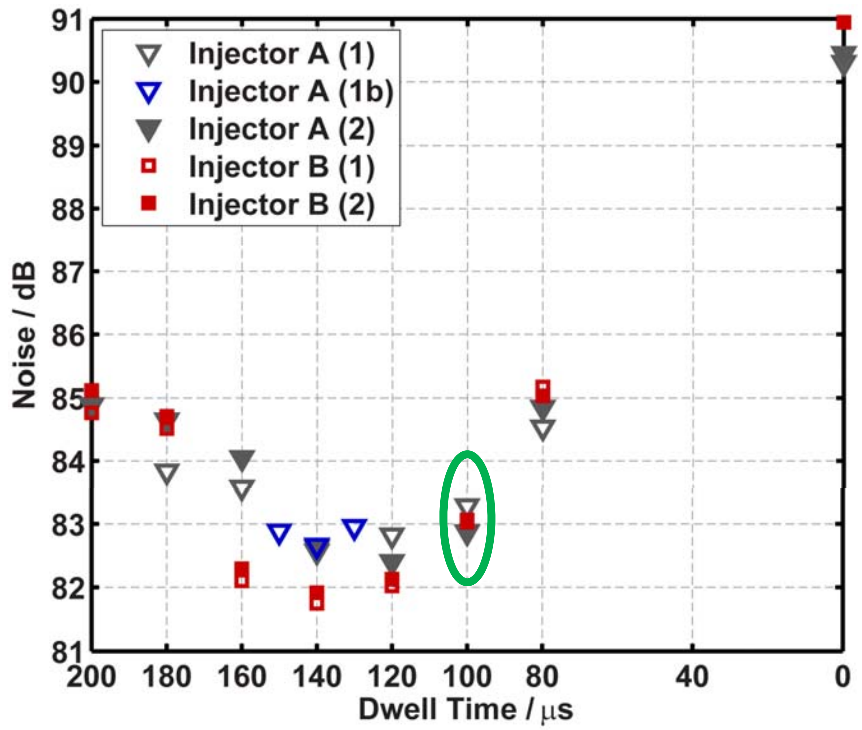






Combustion noise revisited

- 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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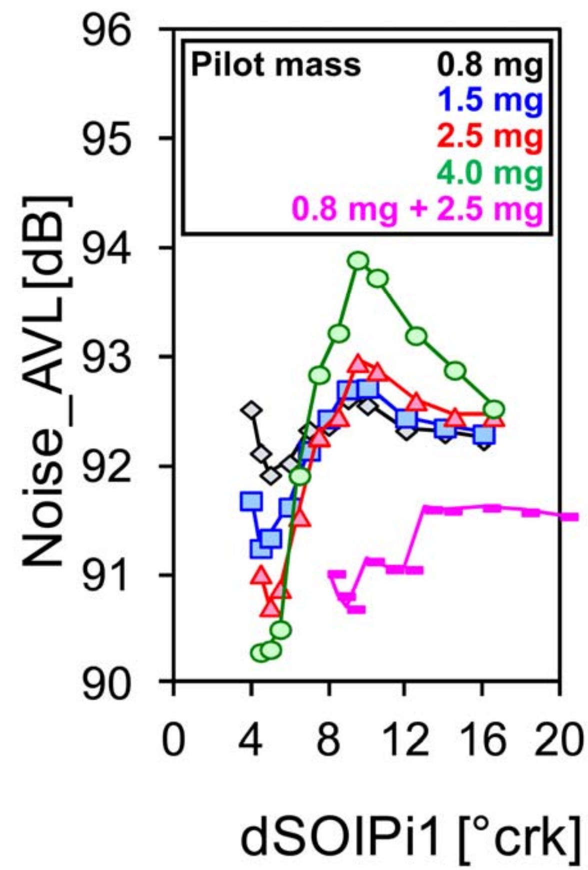
Combustion noise data from Continental (2012)

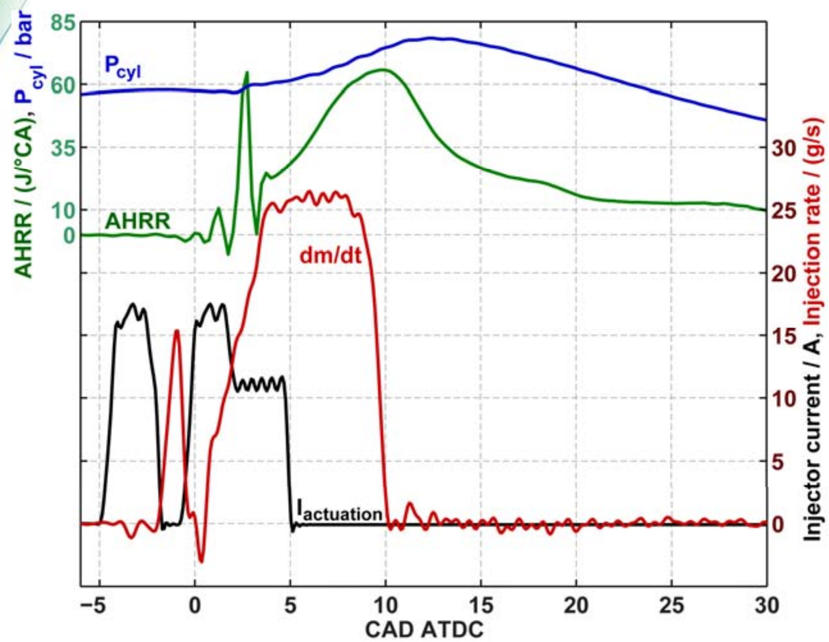
- Pilot – main – post injection strategy
- Piezoelectric injector actuation
- IMEP = 14 bar; n = 2280 rpm; P_{rail} = 1600 bar; MFB50 = 12 CAD ATDC

- 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

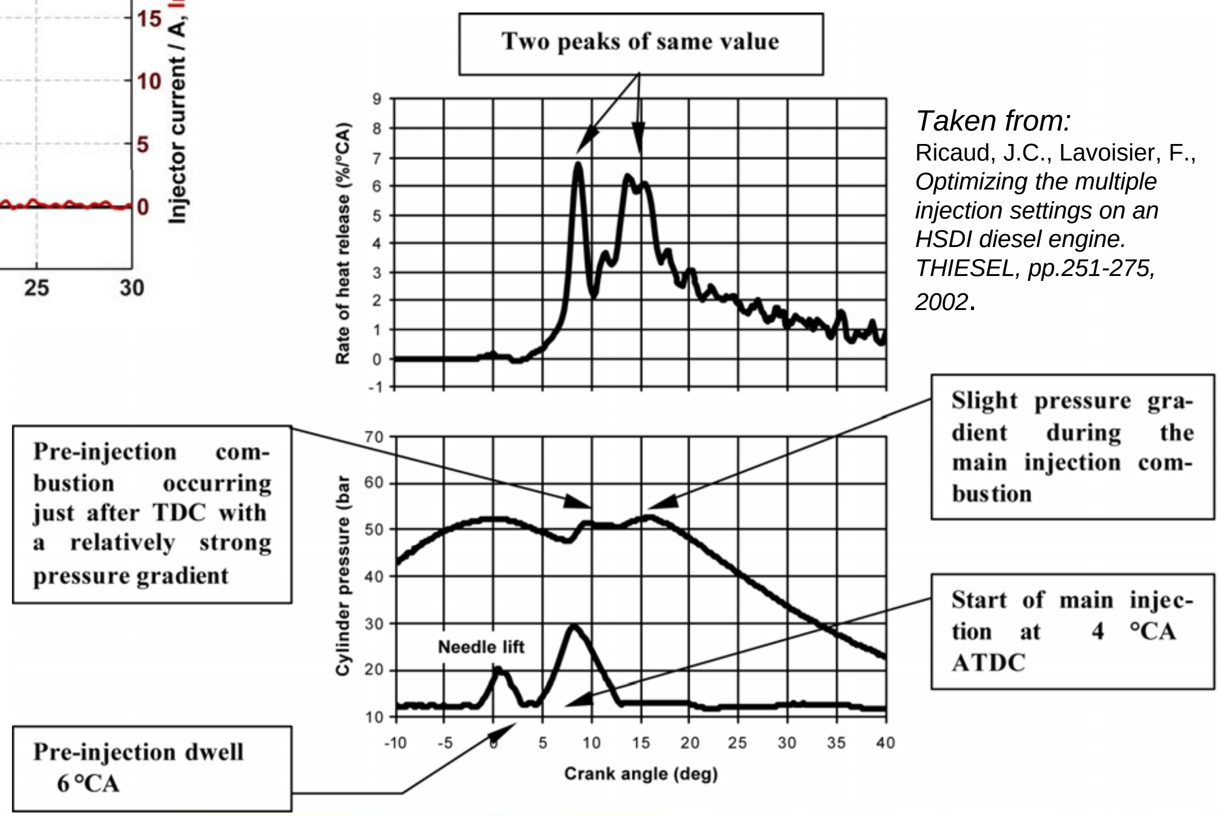


Comparison with noise-optimized operation in the literature



- 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*.

Summary

- Pilot – main injection strategy with varying dwell time
- Parameters held constant
  - Load: $IMEP_g$ = 9 bar
  - Engine speed: n=1500 rpm
  - Combustion phasing: MFB50 = 13 CAD ATDC
  - Pilot mass: m_{pilot} = 1.5 mg
- Minimum combustion noise with a dwell time of 140 µs
  - 2.5-3 dB decrease in noise compared to longer dwells
  - ~8 dB improvement in noise compared to single injection
  - No penalty in emissions
- Injection rate data show that dwell time affects the main injection rate shape, but more research is needed to determine how this contributes to the minimum in combustion noise at δt = 140 µs

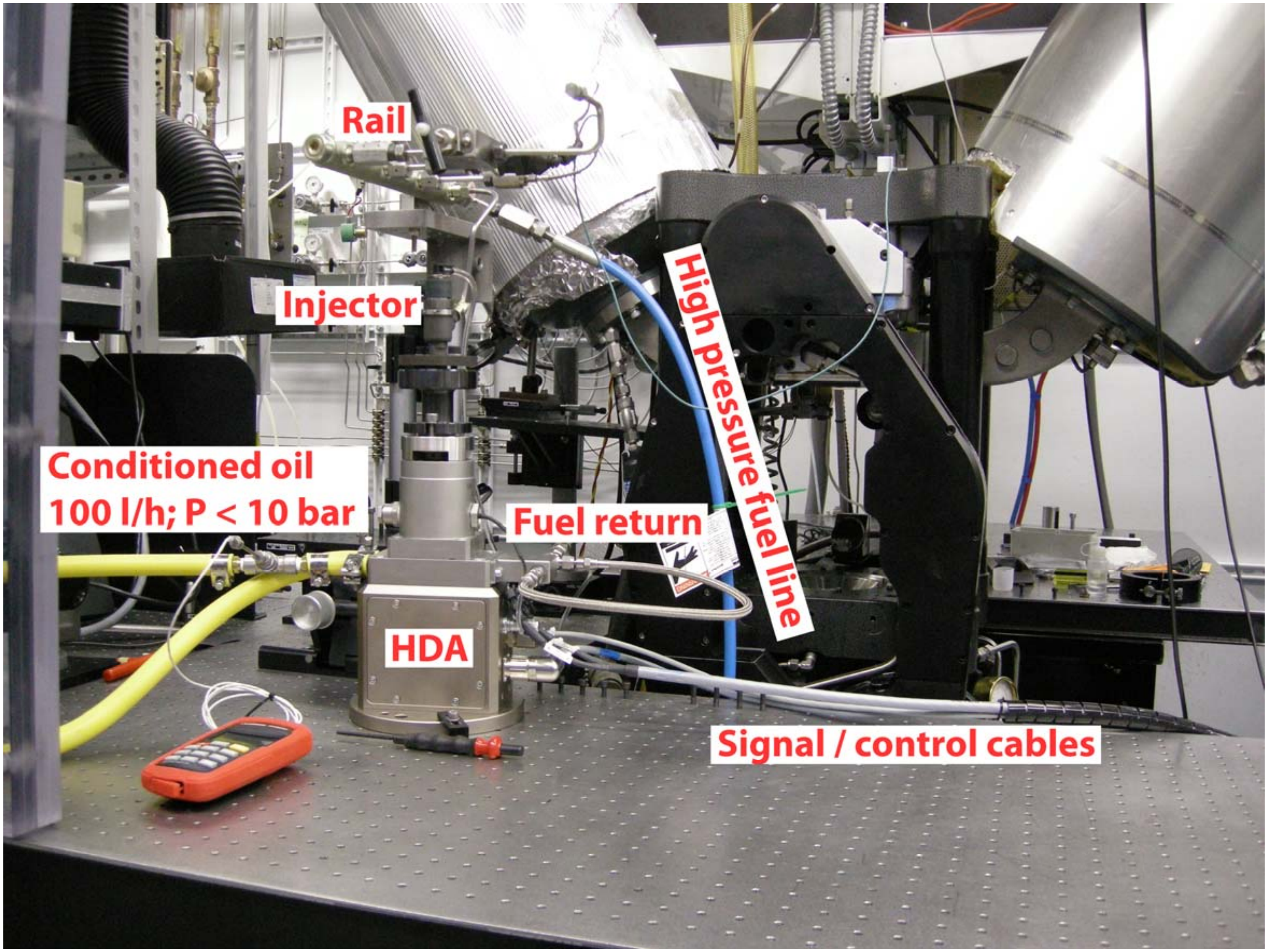
Outlook & future work

- Combustion phasing variation
  - How does overall combustion phasing affect the dwell time-combustion noise relationship?
- Understanding pilot spacing's effect on mixture formation
  - High speed spray visualization
    - Will observations correlate with the rate shapes measured with the HDA?
    - Can any interaction be observed between the pilot and main injections?
  - High speed combustion visualization
    - Are there observable trends in the initial combustion luminosity and later soot radiation as dwell time changes?
  - Tracer-LIF
    - What is the nature of the interaction between pilot and main mixture fields?
    - How could this impact ignition, heat release rates, CO/HC/soot emissions, and ultimately noise?

THANK YOU FOR YOUR ATTENTION!

Questions?

HDA components



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