SAND2014-1290P

COMBUSTION RESEARCH FACILITY

Effect of close pilot spacing on combustion and emissions

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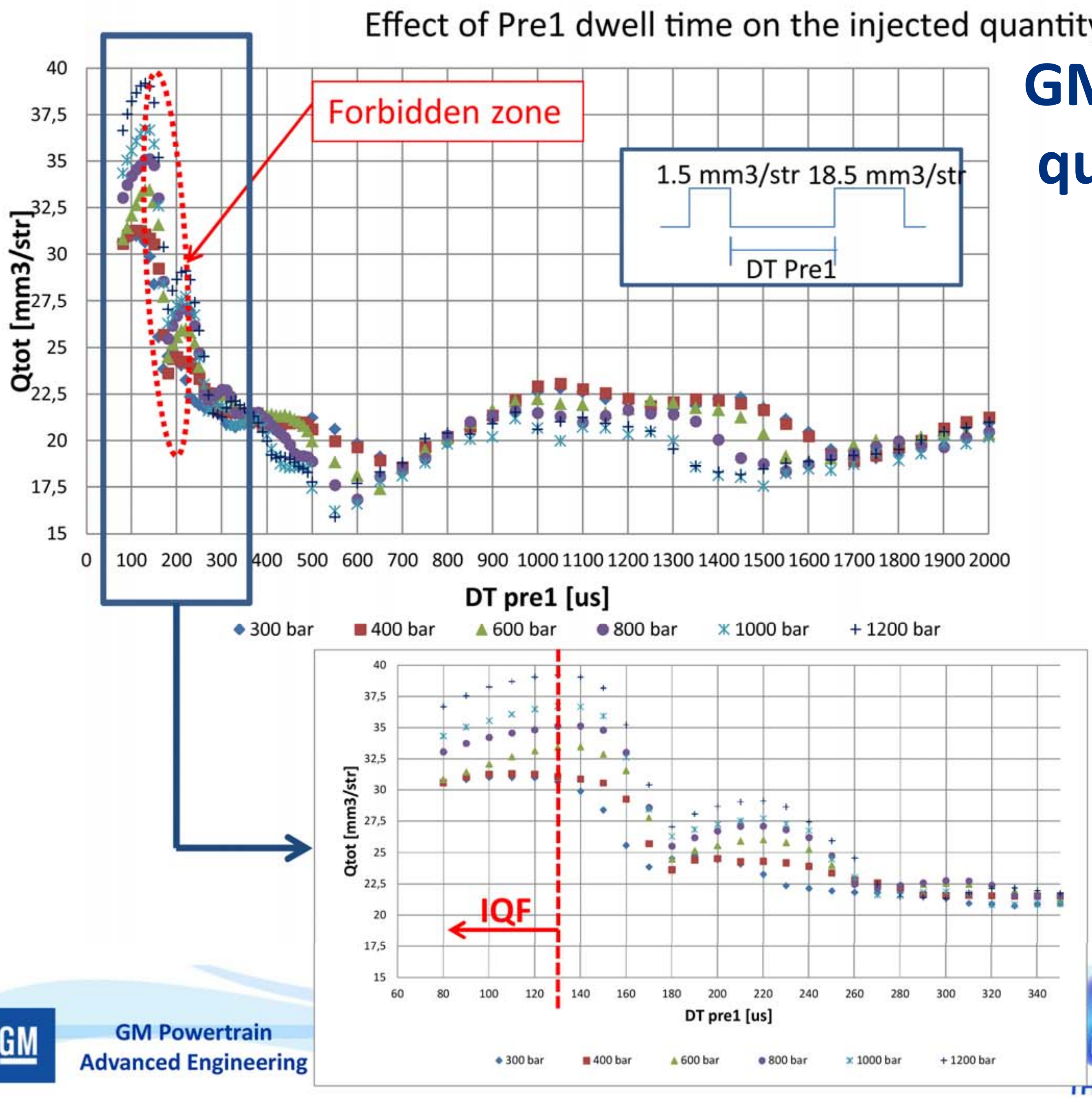
Testing Conditions

- Test 2: pilot + main: Repeat GM's conditions with HDA
  - Injector: CRI 2.16 Multijet II (SNL injector "B")
    - 7 holes
    - Ø: 139 μm
    - Conicity: 1.5
    - Included angle: 149°
  - Boundary conditions
    - Fuel: DPRF 58
    - $P_{rail:}$ 500, 750, 1000 bar
    - $P_{backpressure}$ = 50 bar
    - $T_{fuel, chamber}$ = 90 ℃
  - Injection train
    - Pilot: 1.5 mm^3 (1.1 mg) @ δt = 2500 μs
    - Main: 18.5 mm^3 (13.6 mg) @ δt = 2500 μs
    - $\tau_{pull\text{-}up}$ = 350 μs
    - δt = 80…10…160 μs, 160…20…300 μs

GM's injection quantity data

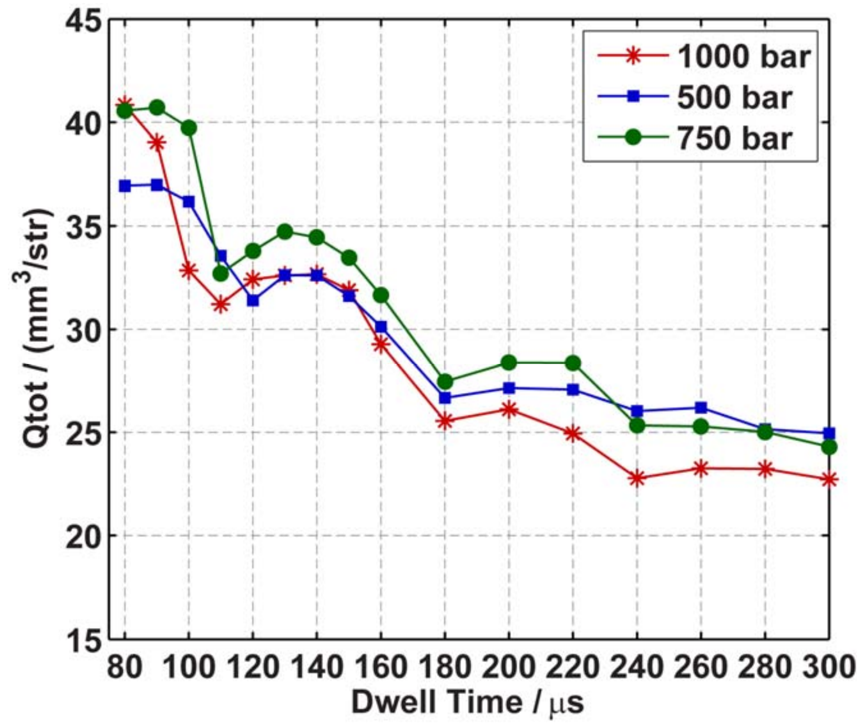


GM
GM Powertrain
Advanced Engineering

DESIGN BUILD SELL
THE WORLD'S BEST VEHICLES

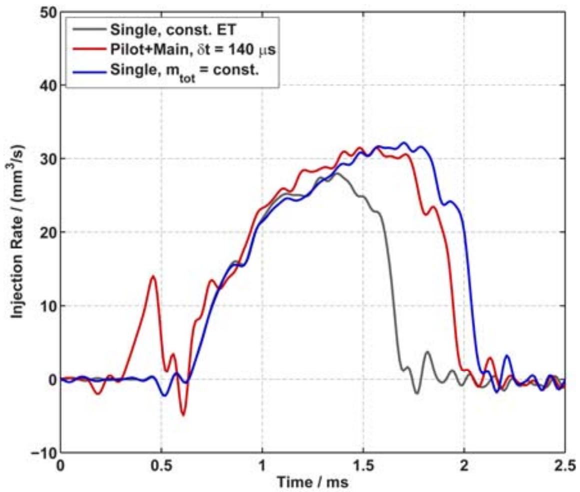
Total injected quantity vs. dwell time δt

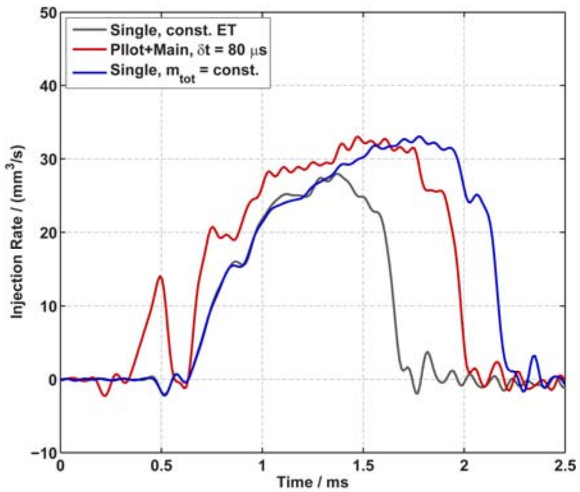
- Significant amplification of main injection for δt ≤ 300 μs
  - Amplification increases non-monotonically as δt decreases
- Maximum injection quantity slightly higher than for GM
- Little or no decrease in total quantity at very short dwell times
  - IQF as defined in previous slide



Comparison of Rate Shapes: P_{rail} = 500 bar

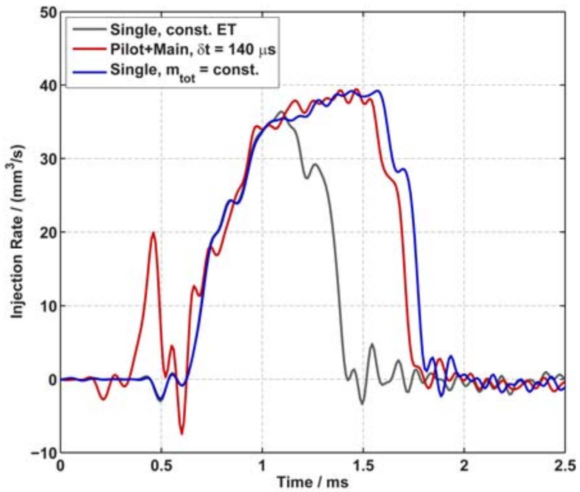
- Three traces
  - Red: pilot + main
    - δt = 140 μs (top)
    - δt = 80 μs (bottom)
  - Blue: single injection, same m_{tot}
  - Gray: single injection, same ET
- No significant rate shaping of main injection with a dwell time of 140 μs
- Noticeable main injection rate shaping with a dwell time of 80 μs
- Quantity increase for both dwell times(compared to single injection of equal ET)

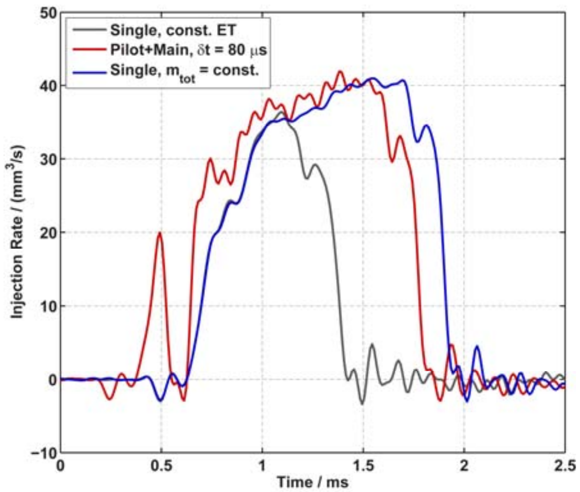




Comparison of Rate Shapes: P_{rail} = 750 bar

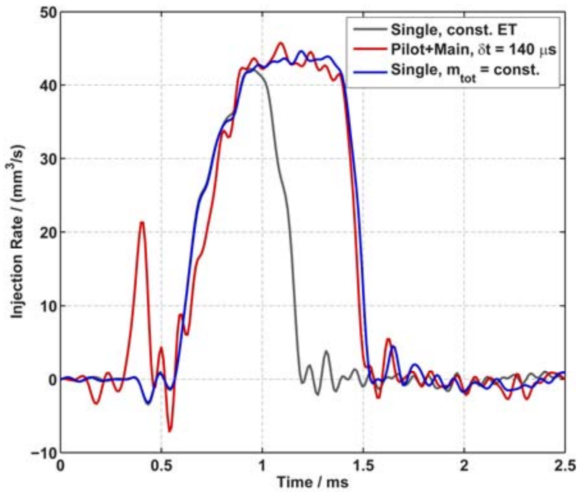
- Similar trends
  - No significant rate shaping of main injection with a dwell time of 140 µs
  - Noticeable main injection rate shaping with a dwell time of 80 µs
- Longer injection duration (and higher quantity) compared to single injection of equal ET

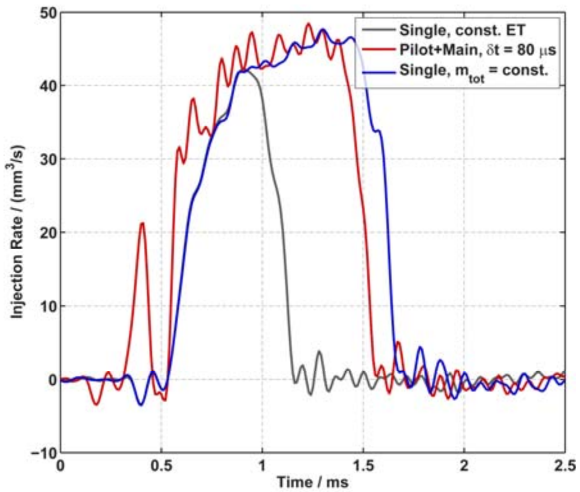




Comparison of Rate Shapes: P_{rail} = 1000 bar

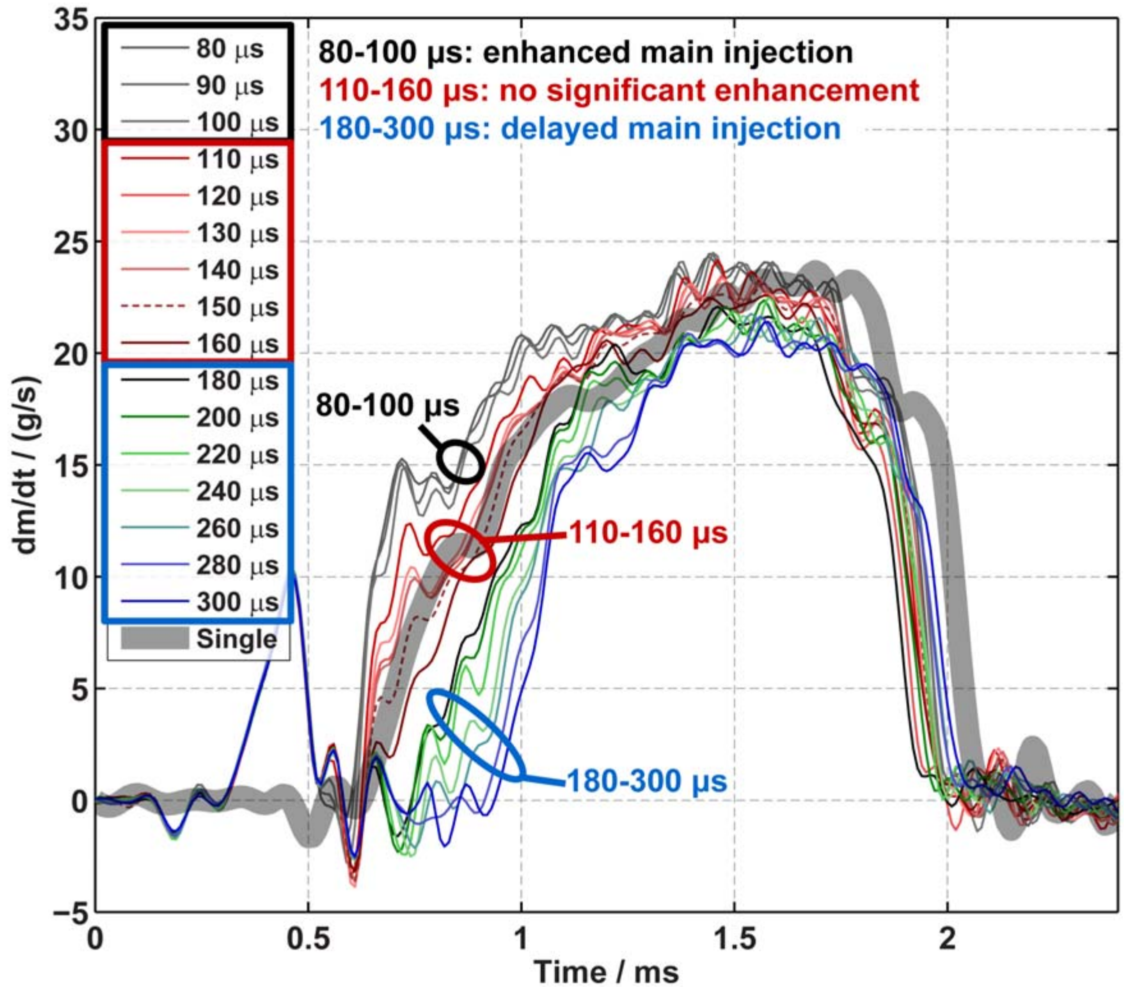
- Main injection ramps up slightly more slowly with a dwell time of 140 µs
- Noticeable main injection rate shaping with a dwell time of 80 µs
- Longer injection duration in both cases (compared to single injection of equal ET)





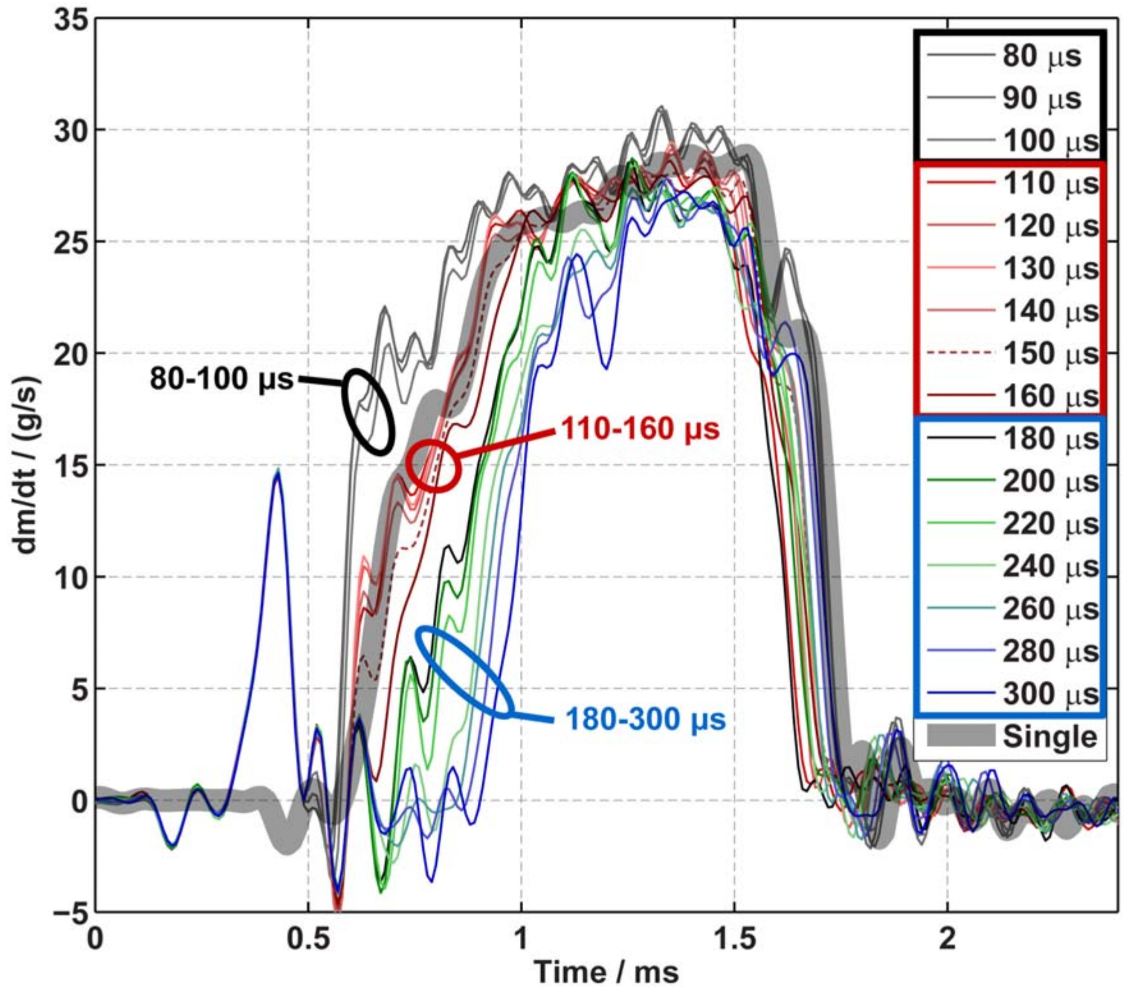
Injection Rate Summary: 500 bar

- 3 Regimes
  - Shortest δt, enhanced main injection
  - Intermediate δt, no significant enhancement
  - Slightly longer δt, delayed main injection
- Rapid increases in rate shape correspond to increases in total injected quantity



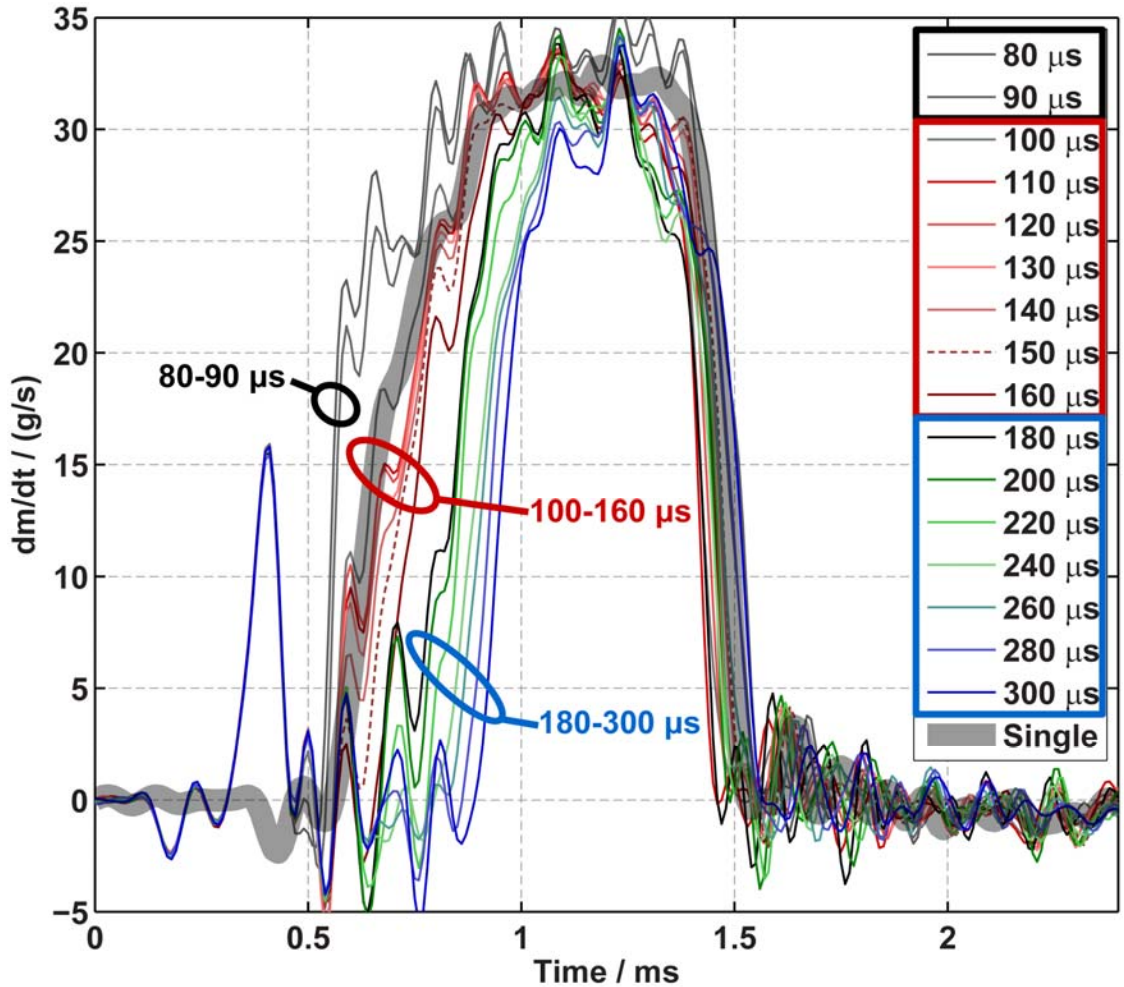
Injection Rate Summary: 750 bar

- Similar trend to P_{rail} = 500 bar
- Faster ramp-up of injection rate, higher maximum rates than for P_{rail} = 500 bar



Injection Rate Summary: 1000 bar

- Dwell time of 100 µs no longer associated with main injection enhancement
- Fastest ramp-up of injection rate, highest maximum rates

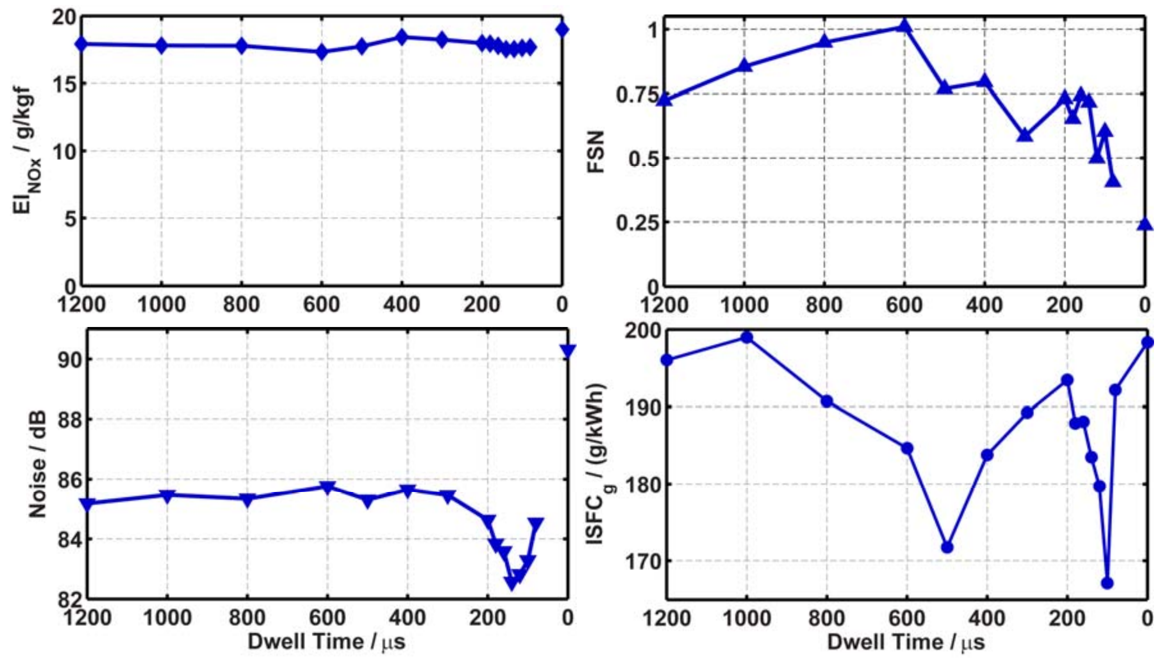


Recap

- SNL's injector seems to behave differently than GM's
  - Different nozzle diameters / flow rates
  - Different hydrodynamic behavior
  - Nozzle likely affects hydrodynamics inside the injector
  - No IQF observed at any rail pressure with SNL's injector
- Rate shaping can occur to enhance or delay the start of main injection and to change the initial rate at small dwell times
- Injection quantity enhanced for all rail pressures and dwell times shown here
  - Quantity increase over a single injection with the same ET
  - Combination of ramp-up shaping and injection duration
- What can we find in the literature?

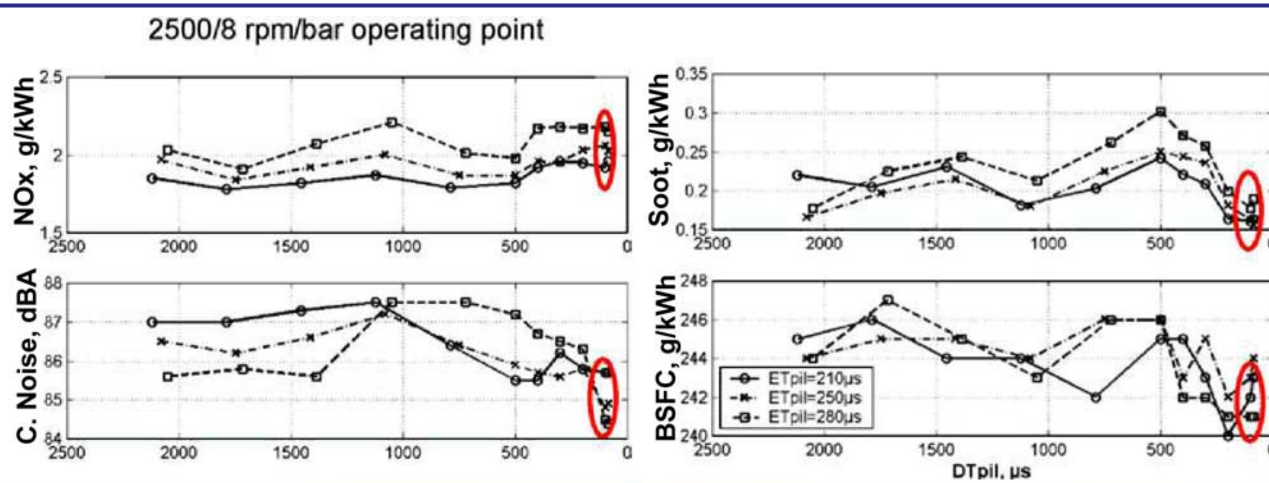
Comparison: SNL vs. Torino (2001/2003)

- SNL: Injector A, Test2
  - NO_x: no strong dependence
  - FSN: maximum near dwell time of 600 μs
  - Noise: minimum at dwell time of 140 μs
  - $ISFC_g$: two local minimums



- Torino, 2003

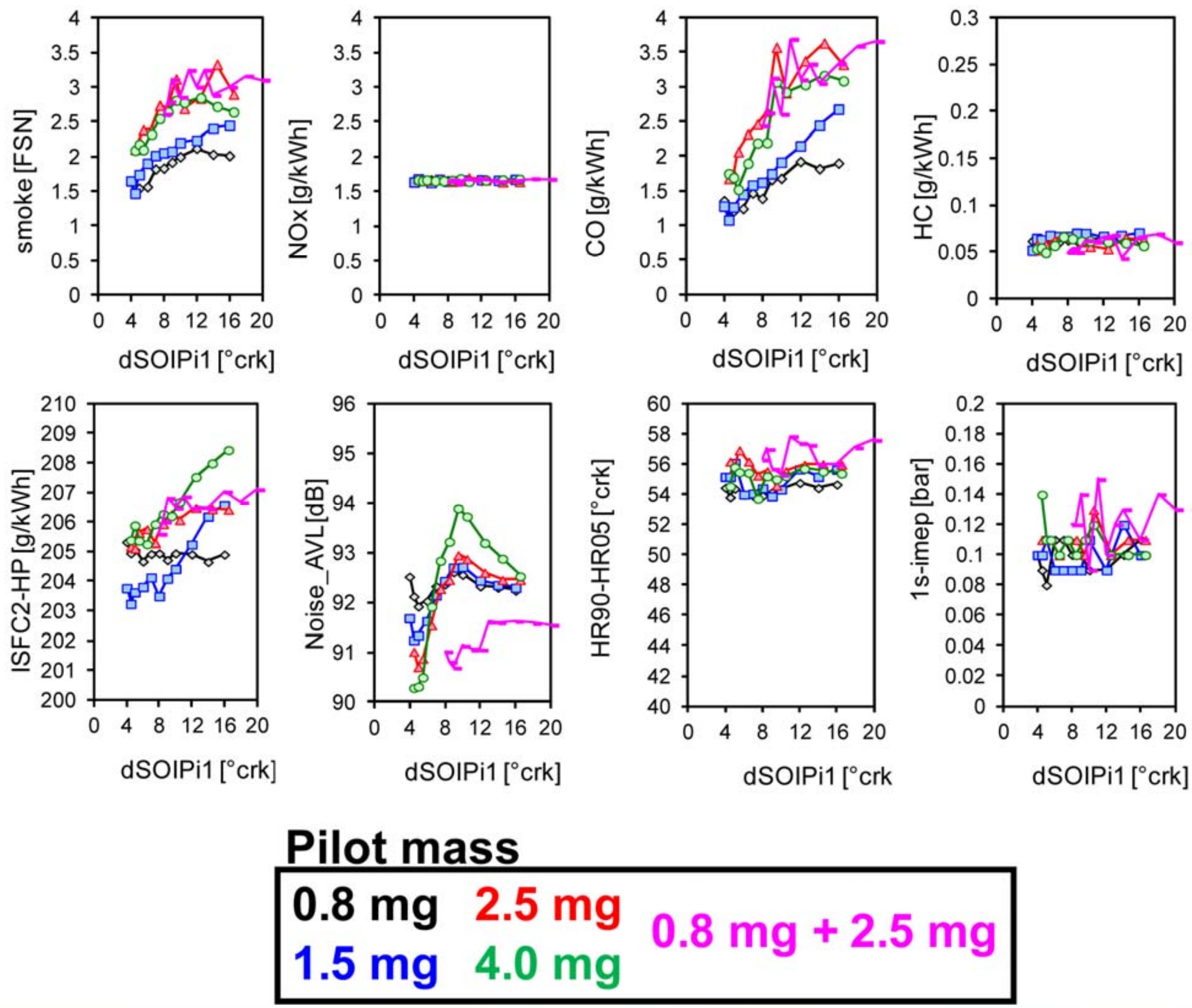
Taken from: Badami, M., Mallamo, F., Millo, F., Rossi, E.E., *Experimental Investigations on the effect of multiple injection strategies on emissions, noise and brake specific fuel consumption of an automotive direct injection common-rail diesel engine.* Int. J. Engine Research, Vol. 4, No. 4, 2003.



Comparison: SNL vs. Continental (2012)

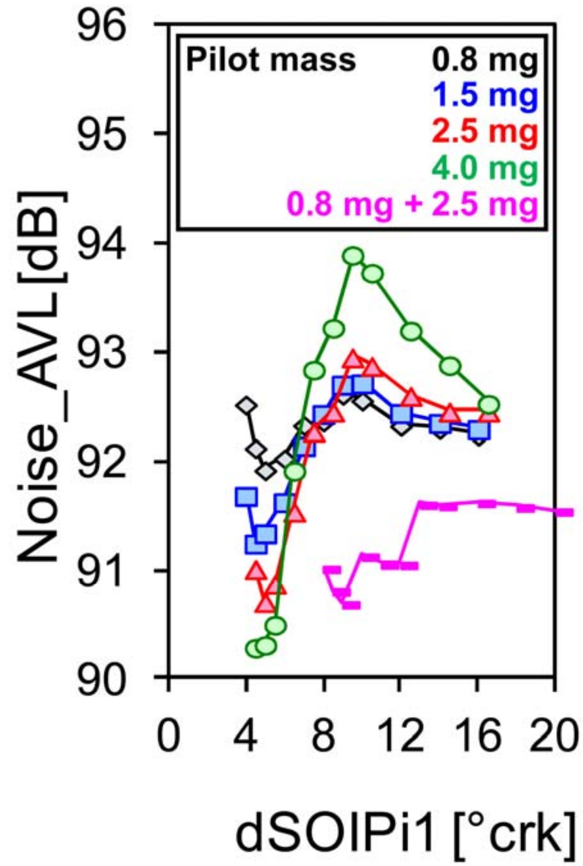
Direct-acting piezo; IMEP = 14 bar ; n = 2280 rpm; P_{rail} = 1600 bar; P_{boost} = 2000 mbar, MFB50 = 12 CAD ATDC; pilot+main+post

- Soot / CO
  - Trends don't match well with SNL data
  - Closely spaced pilots may reduce formation of over-rich mixture
- Noise
  - Comparable trends
- NO_x / HC
  - No strong dependence on dwell time
- ISFC
  - Optimum at shorter dwell times



Combustion noise data from Continental (2012)

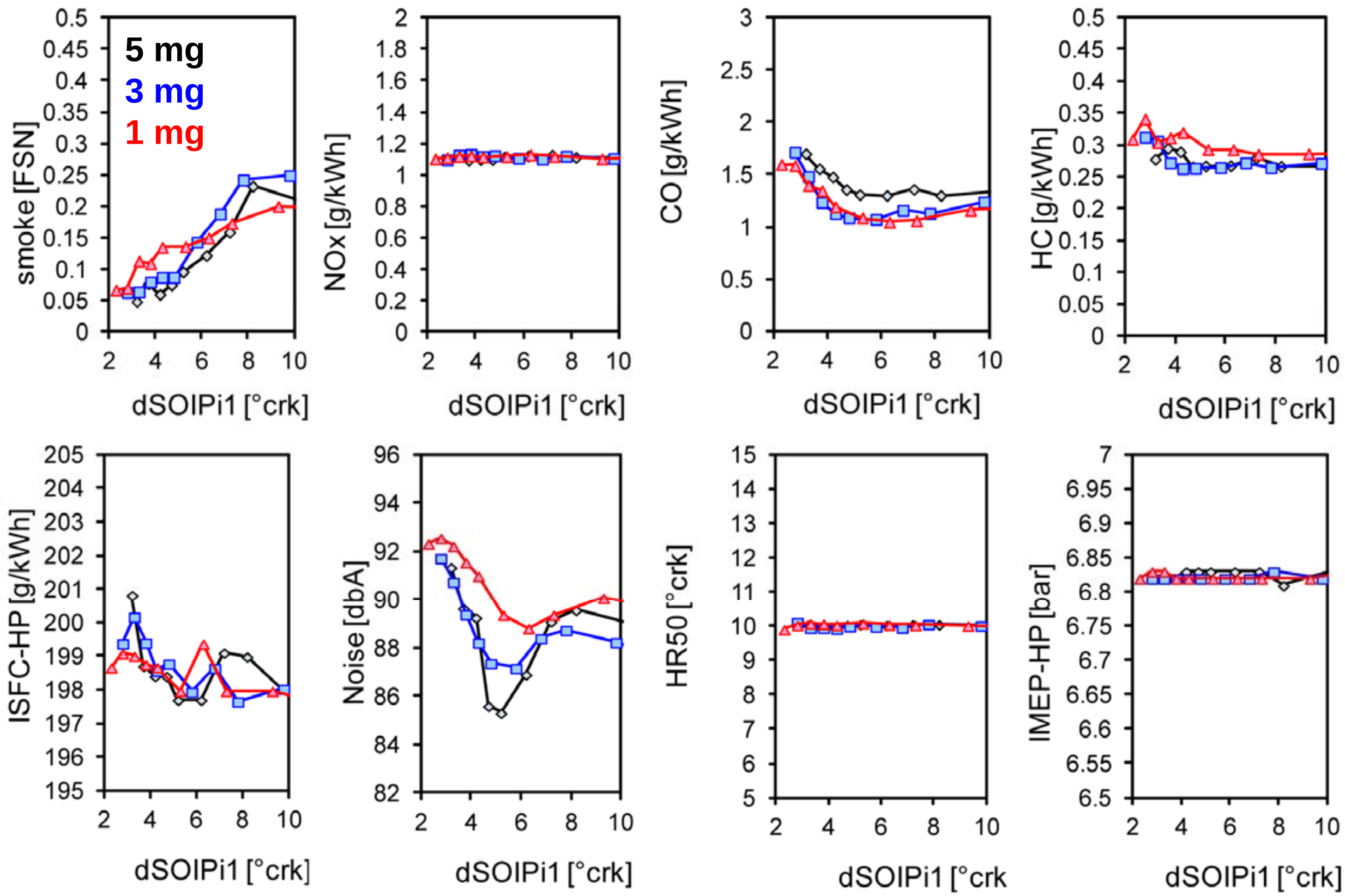
- For varying pilot injection quantities, noise passes through a minimum as dwell time decreases
  - Minimum occurs at a hydraulic dwell (EOI-SOI) of 110 µs (1.5 mg pilot)
  - Hydraulic dwell for current study (δt = 140 µs): ~60 µs
  - Decrease in noise depends on pilot injection quantity
- Significantly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



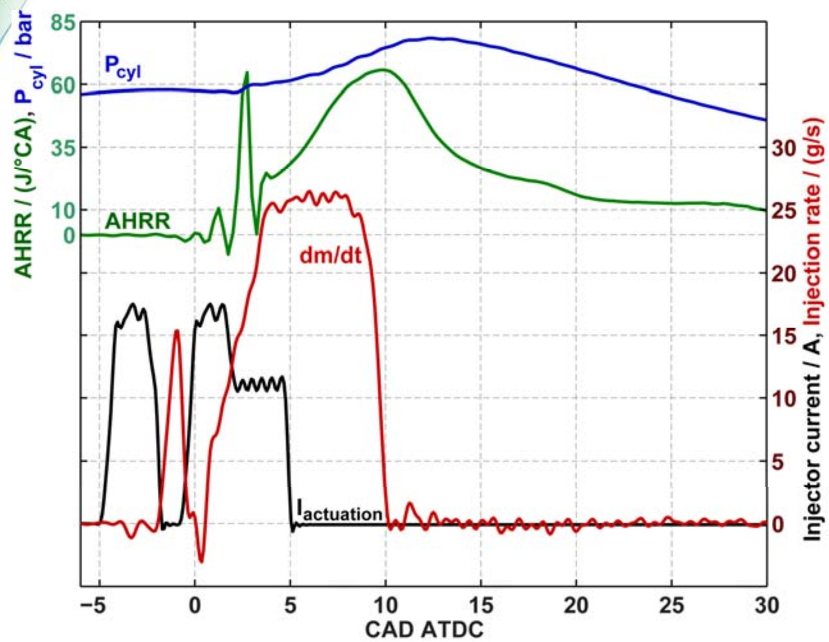
Comparison: SNL vs. Continental (2012)

Direct-acting piezo; IMEP = 6.5 bar ; n = 1500 rpm; P_{rail} = 900 bar; P_{boost} = 1250 mbar, MFB50 = 10 CAD ATDC; pilot+main+post

- Soot / CO
  - Behave differently
  - Lean sources of CO?
  - Seems unrelated to noise
- Noise
  - Trend dependent on pilot quantity
- ISFC
  - Different trend than at higher load

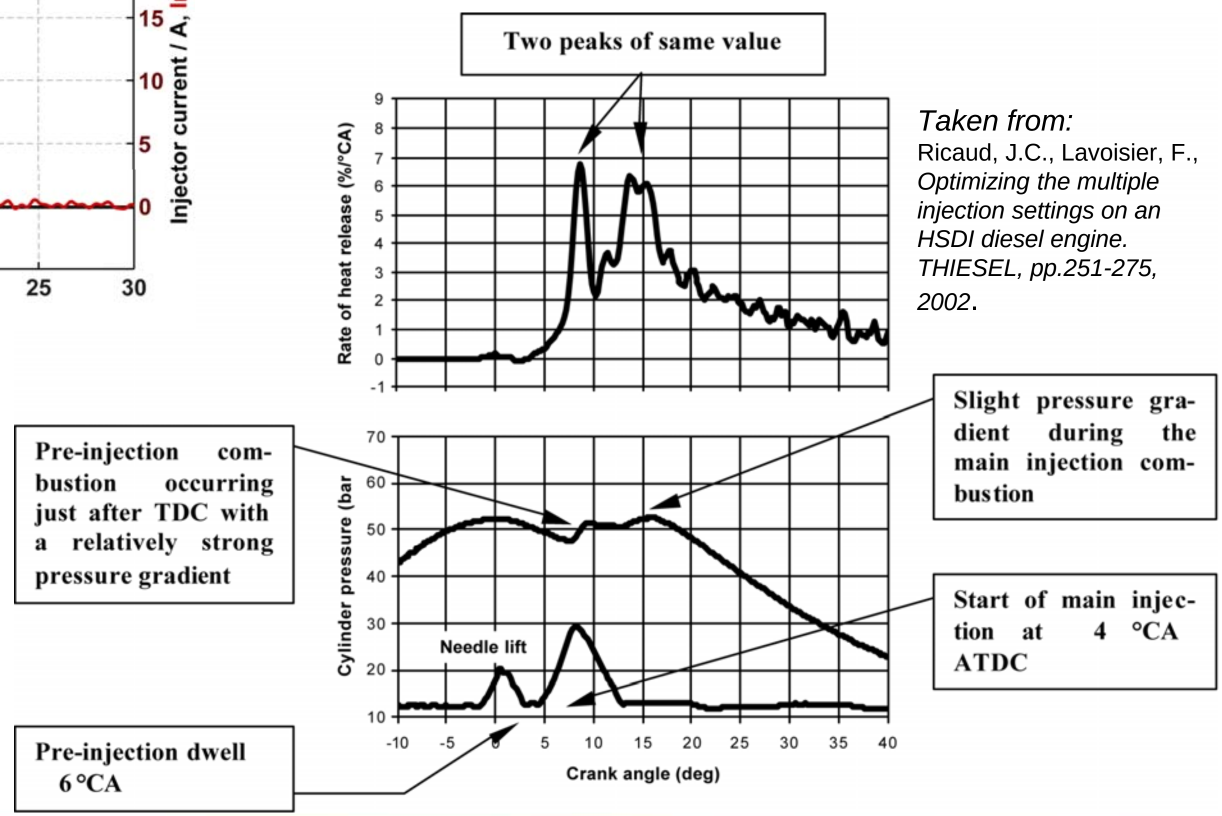


Comparison with noise-optimized operation in the literature



- 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*.

What do we know?

- Investigation of combustion noise (GM vs. SNL): agreement in noise-dwell time relationship, discrepancy in injection rate shapes as dwell changes
  - Are the HDA measurements somehow unreliable?
    - No evidence in the literature to refute HDA results
  - Perhaps rate shapes are not the decisive factor for combustion noise
    - GM and SNL: two different engines, two different fuels, two different injector nozzles with different rate shaping tendencies
    - **Very similar trend in combustion noise as dwell time changes**
    - Brief literature survey: decreasing dwell time often results in very similar trends in noise, even with different injection hardware and different operating parameters
- Still no clear understanding of what's responsible for our 3 dB decrease in noise as dwell time approaches its noise-optimized value
  - Hypothesis 1: the retarded phasing of the pilot injection is primarily responsible for the noise decrease at this optimum dwell time
  - Hypothesis 2: the decrease in noise at shorter dwell times results primarily from modulation of the heat release rate due to changing mixture formation processes within the engine

How do we proceed?

- Effects of rail pressure, pilot mass, engine load, pilot combustion phasing, and (injector nozzle?) for pilot-main case

- 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 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 emissions, and ultimately noise?

THANK YOU FOR YOUR ATTENTION!

Questions?