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Progress in understanding the combustion noise reduction mechanism with close-coupled pilot injections in a small-bore diesel engine

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Various pilot-main injection strategies are investigated in a single cylinder optical Diesel engine. As the dwell between a single pilot and the main injection is decreased towards zero, combustion noise passes through a minimum and a combustion noise reduction of 3 dB is possible. The mechanism responsible for this reduction in noise is investigated using a zero-dimensional thermodynamic simulation. Pre-defined heat release profiles are given as inputs to the model. The resulting simulated cylinder pressure traces are used to compute combustion noise values for various heat release profiles. The analysis of these simulation results reveals that the combustion noise reduction mechanism with close-coupled pilots is contained within this simple model. Furthermore, the mechanism is shown to be fundamentally independent of overall combustion phasing and main injection rate shaping effects. Frequency analysis reveals a frequency range of approximately 1-3 kHz in which sound pressure levels are most effected by this mechanism; analysis of measured cylinder pressure data has resulted in similar findings. The pilot and main heat release events are each associated with a specific pressure signature in this frequency band, and the superposition of these pressure signatures reveals the phase-dependent destructive interference mechanism in the time-pressure history.

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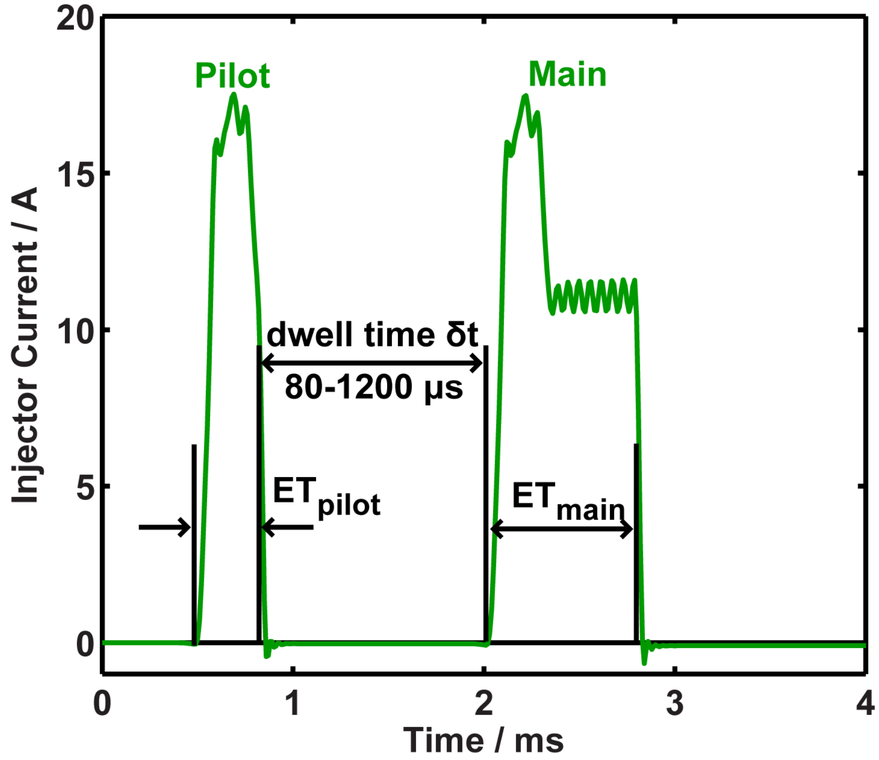
Progress Report Outline

- Review
  - Close-coupled pilot - main injection strategy
  - Reduction in combustion noise possible with close-coupled pilots
  - Theories about what may be responsible for reducing combustion noise with close-coupled pilot injections
- Zero-dimensional thermodynamic simulations
  - Pre-defined heat release profiles as inputs
  - Compute cylinder pressure traces
  - Combustion noise calculated for simulated traces
- Progress towards an explanation of the combustion noise reduction mechanism with close-coupled pilot injections
- Outlook / upcoming work

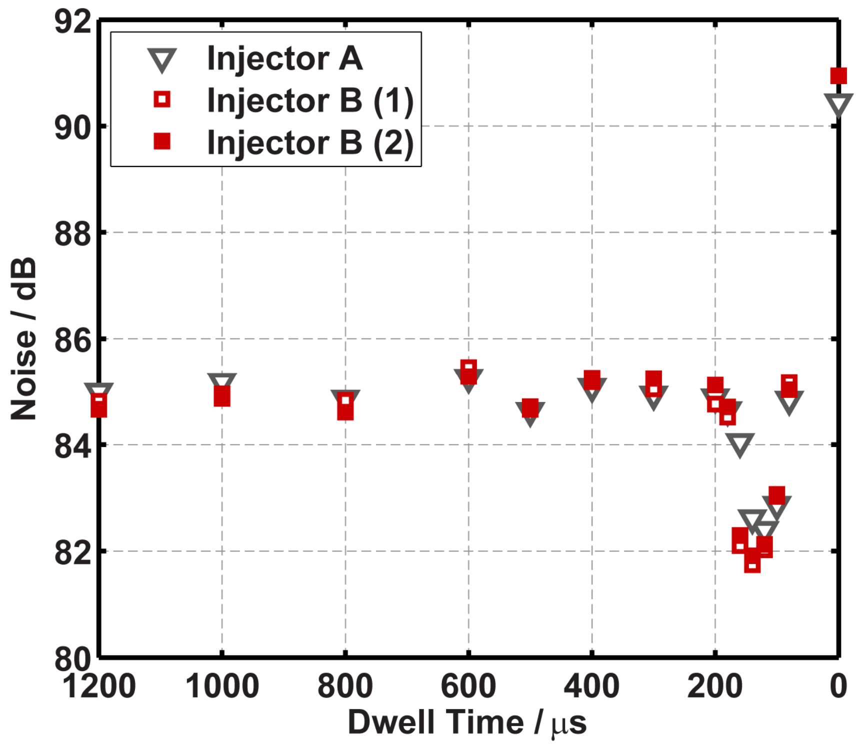
Pilot-main injection strategy

- Operating point:
  - 1500 rpm
  - Pilot mass: 1.5 mg/str
  - IMEPg: 9 bar
  - $P_{rail:}$ 800 bar
  - CA50: 13 CAD ATDC
  - Fuel: DPRF58 (58 vol% HMN, 42 vol% n-hexadecane)
- Vary energizing dwell between pilot and main injection
  - 1200 – 80 µs (10.8 CAD – 0.7 CAD)



Trend in combustion noise with changing pilot-main injection dwell

- Combustion noise with a pilot: ~6 dB quieter than without
- Further decrease in noise at dwell times near 140 µs
  - No penalty in pollutant emissions compared to longer dwells
- Last presentation: main injection rate shaping occurs but cannot explain the combustion noise trend



How can we test these theories of what is causing the trend in combustion noise?

1. Main injection rate shaping
   - We have strong evidence that rate shaping isn't responsible for the noise reduction
2. Destructive interference of traveling waves (acoustics)
   - What would the mechanism be?
3. Suppression of pilot AHRR by the main injection
   - Highly repeatable trend (shown later)
4. Changing pressure time-history
   - May be significant, but what is the mechanism?

- A simple thermodynamic model is constructed to test (1-4)
  - By including / excluding the influence of these theories, their impact on combustion noise can be evaluated

Thermodynamic modeling to investigate the trend in combustion noise

- Calculation of combustion noise requires a cylinder pressure trace
  - Combustion noise can be computed from a simulated pressure trace
- Zero-dimensional modeling approach
  - Assume two independent heat release profiles represent the pilot and main combustion events, respectively
  - Temporally shift the heat release profiles and / or vary their shape to simulate various effects
  - Model gas exchange processes
  - Compute the resulting cylinder pressure trace for the complete cycle
  - Use the simulated pressure trace to compute combustion noise in the same way as for the measured cylinder pressure data:

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.

Zero-dimensional thermodynamic analyses

- First law of thermodynamics

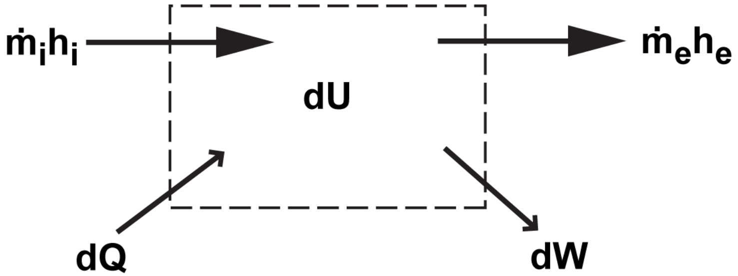
  $dU = dQ - dW + \dot{m}_i h_i - \dot{m}_e h_e$

- Idea gas law

  $PV = mRT$

- Continuity

  $dm = \dot{m}_i - \dot{m}_e$



- Differential equations (solved using 4th order Runge-Kutta method):

$$dP = \frac{(\gamma - 1)dQ - \gamma P dV + \frac{PV}{\gamma - 1} d\gamma + (\gamma - 1)(\dot{m}_i h_i - \dot{m}_e h_e)}{V}$$

$$dT = \frac{PdV + VdP}{mR} - T\frac{dm}{m}$$

$$dQ = dQ_{heat\ release} - dQ_{woschni}$$

$\gamma = 1.35 - 6 \cdot 10^{-5} T + 1 \cdot 10^{-8} T^2$ (Brunt and Platts, SAE 1999-01-0187)

Simulation of gas exchange process

- Compressible flow though valves (from Heywood, 1988)
  - Choked flow

if $\frac{P_{low}}{P_{hi}} \leq \left(\frac{2}{\gamma-1}\right)^{\gamma/\gamma-1}$

$$\dot{m} = \frac{C_D A_R P_{hi}}{\sqrt{RT_0}} \sqrt{\gamma} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)}$$

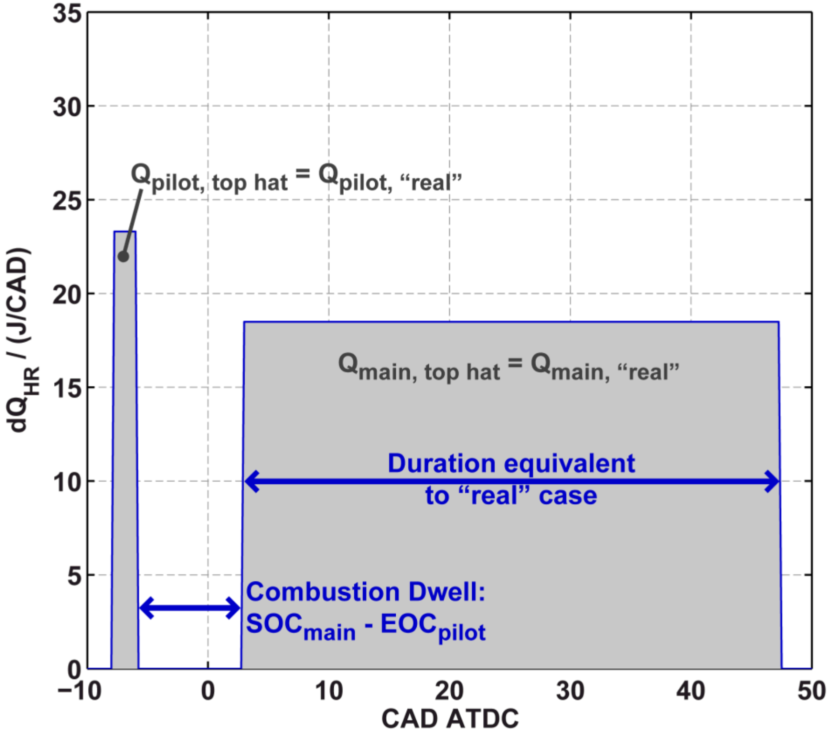
  - Non-choked flow

$$\dot{m} = \frac{C_D A_R P_{hi}}{\sqrt{RT_0}} \left(\frac{P_{low}}{P_{hi}}\right)^{1/\gamma} \sqrt{\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{P_{low}}{P_{hi}}\right)^{\gamma-1/\gamma}\right]}$$

- Valve lift and valve flow coefficient data have been measured
- Intake and exhaust pressures assumed to be constant
- Not as accurate as measured cylinder pressure during gas exchange, but adequate for a simple model

Heat release profiles: inputs to the zero-dimensional simulation

- Measured heat release for dwell of 1200 µs
  - Split into simplified pilot and main combustion events
  - Pilot and main heat release curves phased independently
  - Pilot and main heat release are added to each other if they overlap
- Assumption: pilot and main heat release shapes do not change with dwell
  - Effects of main injection rate shaping on heat release neglected
- Alternative heat release profiles



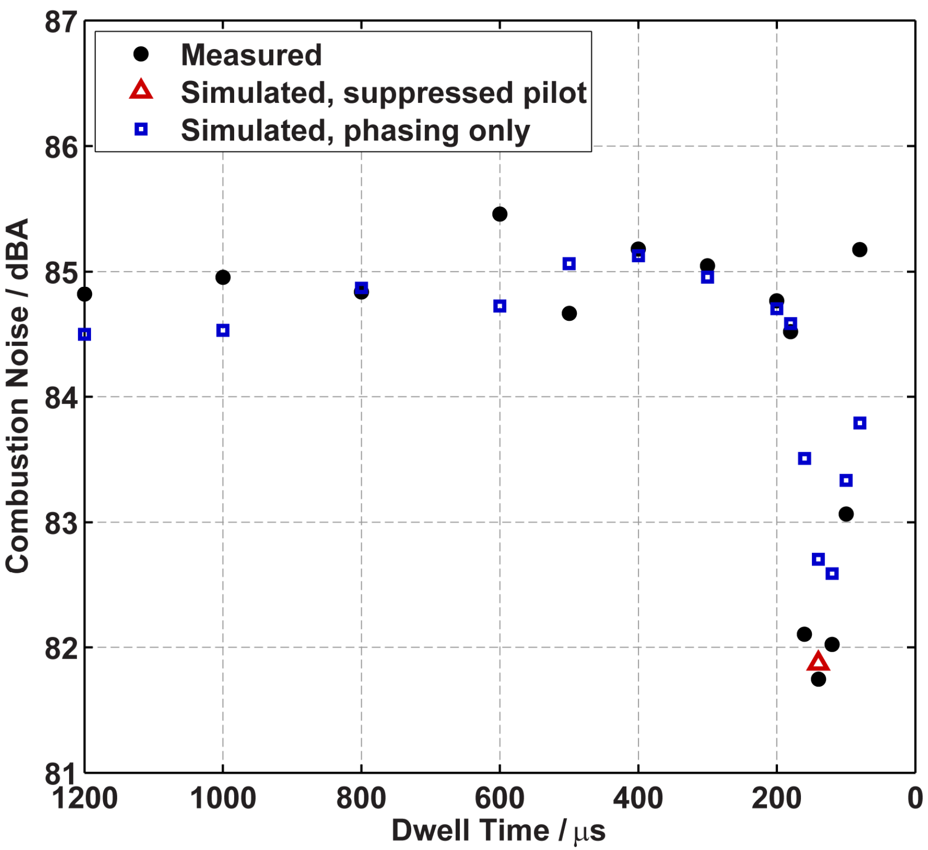
Numerical integration / initial simulation

- Equations for dP, $dP_{motored}$, dm, and dT are integrated in time
  - 4^{th} order Runge-Kutta algorithm
  - Initial and boundary conditions taken from test bench data or assumed based on values found in the literature
- Step size: 0.25 CAD (simulation is relatively insensitive to step size)
- Result: traces of P, $P_{motored}$, m, and T vs. crank angle

- Initial simulation: pilot and main combustion phasing chosen to represent the measured data for the dwell sweep
- Plot of combustion noise vs. dwell
  - Can this simple model reproduce this noise trend and capture the underlying noise reduction mechanism?

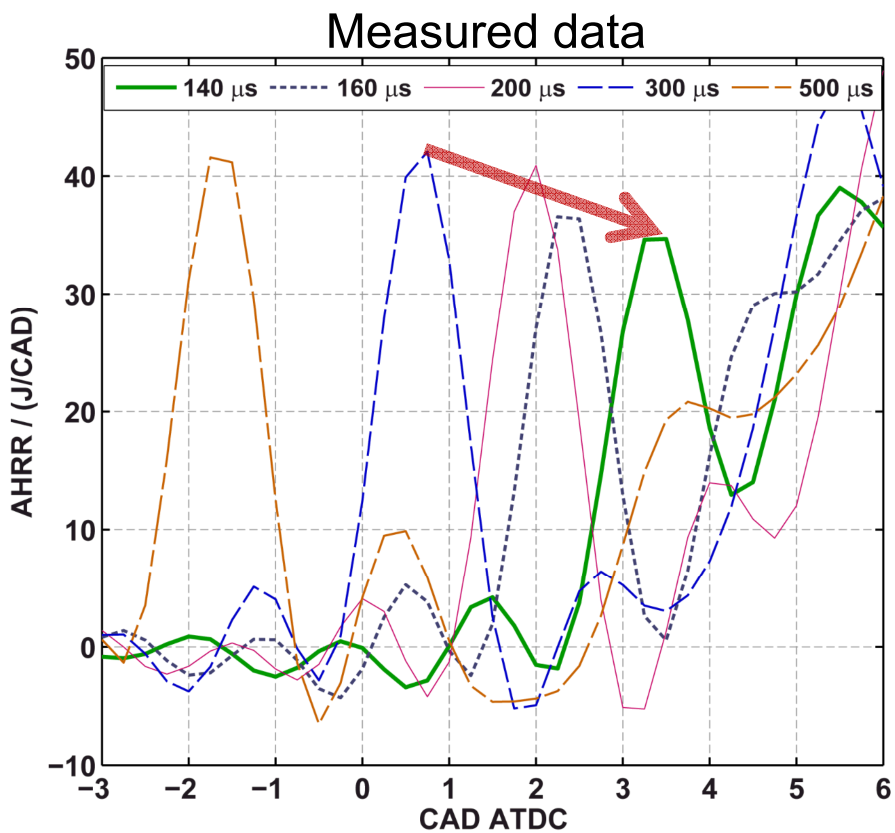
0-D simulation results: combustion noise

- The noise reduction mechanism is captured within this simple model
- Trend can be explained by:
  - Suppression of pilot AHRR (by the main injection?)
    - Next slide
  - Changing pressure waveform shape with changing dwell
    - Requires further explanation and analysis



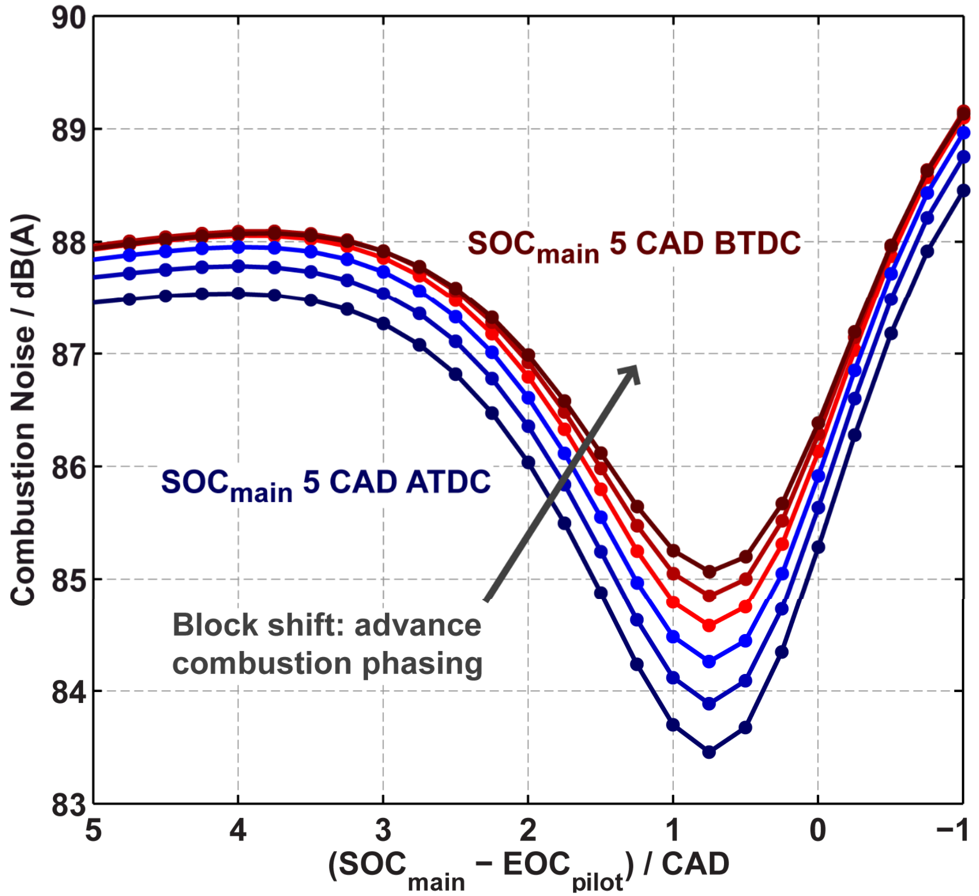
Suppression of pilot AHRR due to heating and vaporization of the main injection

- Peak AHRR rate for pilot combustion decreases for dwells shorter than ~300 μs
- Maximum decrease in apparent heat release is on the order of 3 J
- Sensible enthalpy is removed from the cylinder contents to heat and vaporize the fuel injected during the main injection
  - Consideration of fuel injected while pilot heat release occurs
  - Estimated energy required for heating/vaporization: 3-4 J
- Energy required to heat and vaporize fuel decreases the impact of the pilot heat release



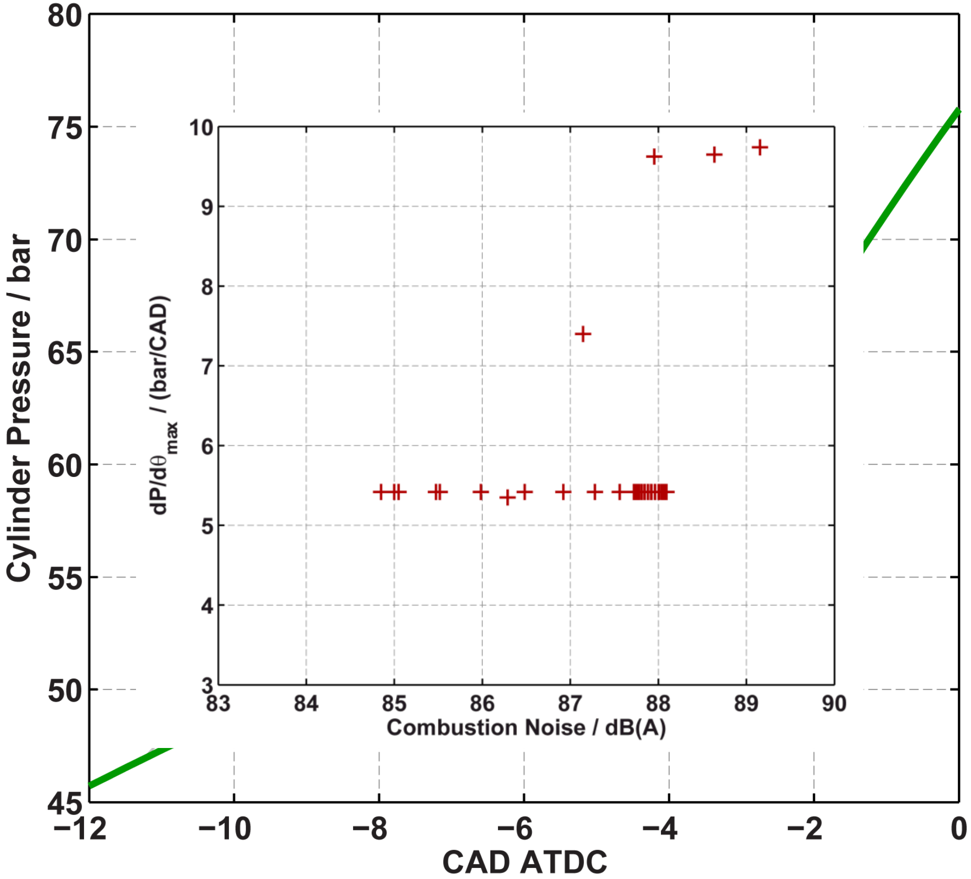
Effect of combustion phasing on combustion noise with top hat heat release profiles

- Combustion dwell is defined as: $(SOC_{main} - EOC_{pilot})$
- Noise reduction occurs with top hat heat release profiles
- Combustion noise increases with advanced combustion phasing
- The combustion dwell for minimum noise does not change as the heat release events are block shifted
- Do cylinder pressure traces help explain this trend?



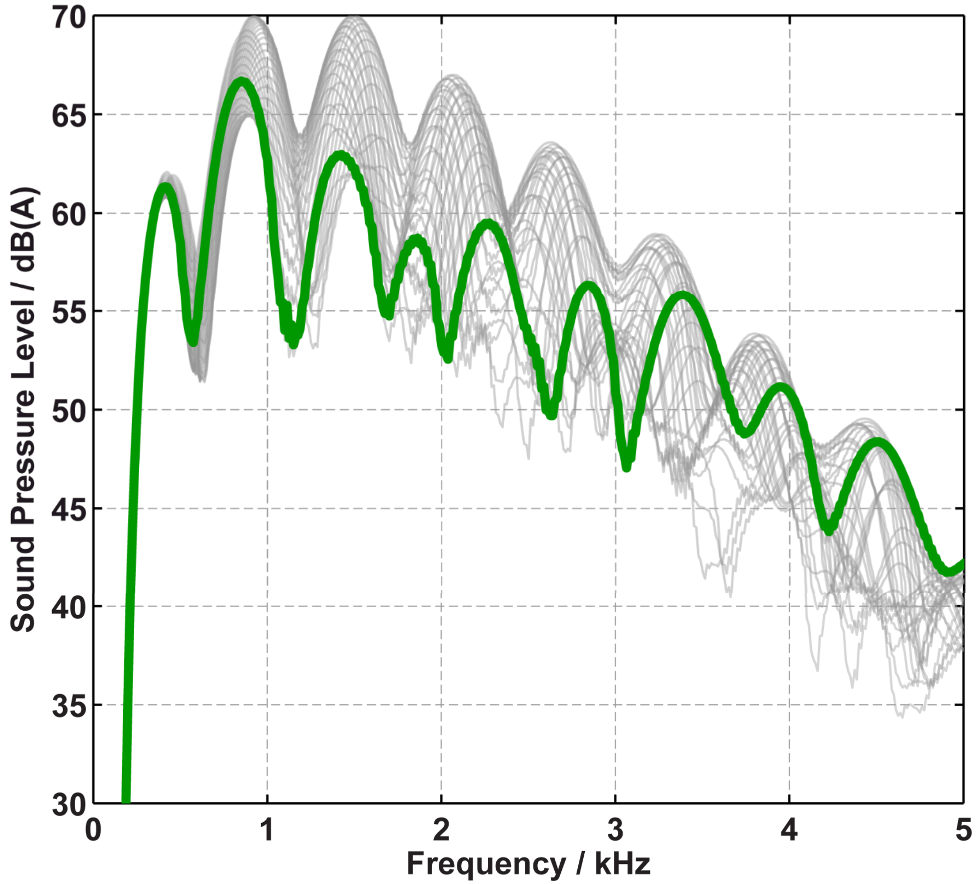
Large changes in combustion noise can occur with subtle changes in pressure traces

- SOC_{main} = 3 CAD BTDC (top hat heat release profile)
- $dP/d\theta_{max}$ does not correlate with combustion noise
- What does a spectral analysis tell us?



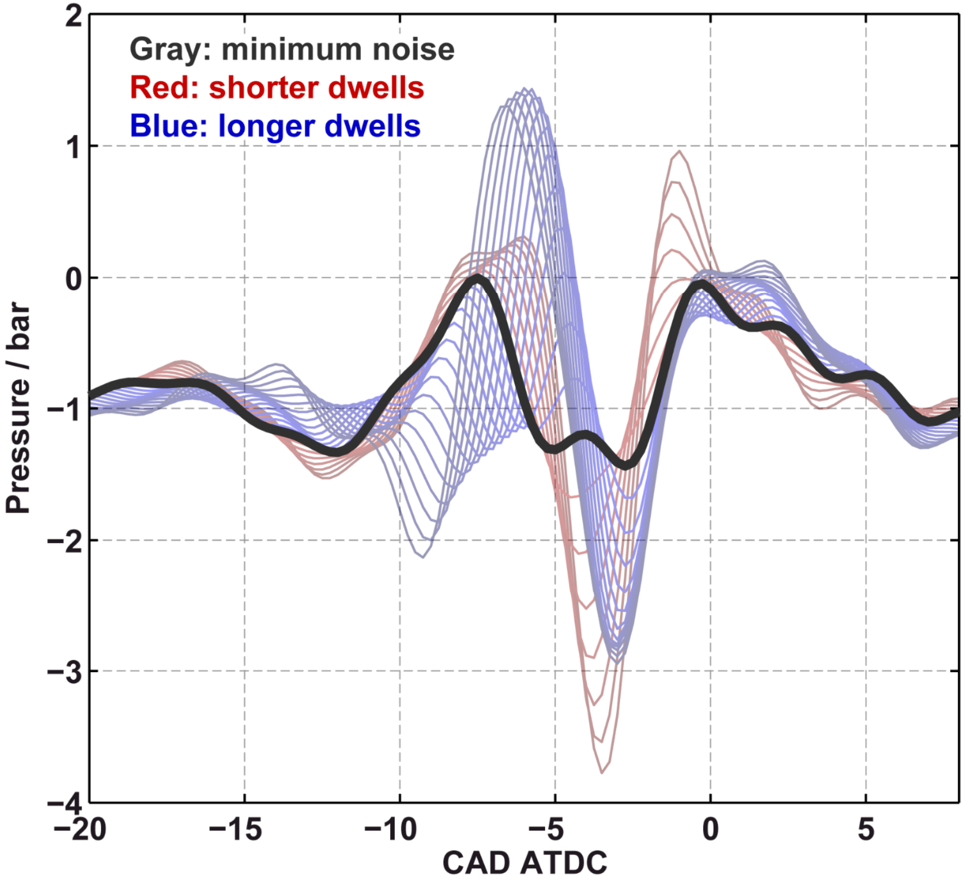
Spectral analysis indicates which frequencies contribute to the combustion noise minimum

- Examine sound pressure spectra for all combustion dwells
  - Indicator of how much each frequency contributes to noise
  - SOC_{main} 3 CAD BTDC
- Pressure frequency components responsible for noise minimum: 1 kHz – 3 kHz
- What does a band pass filtered pressure trace tell us?
  - Pass band: 1 kHz – 3 kHz



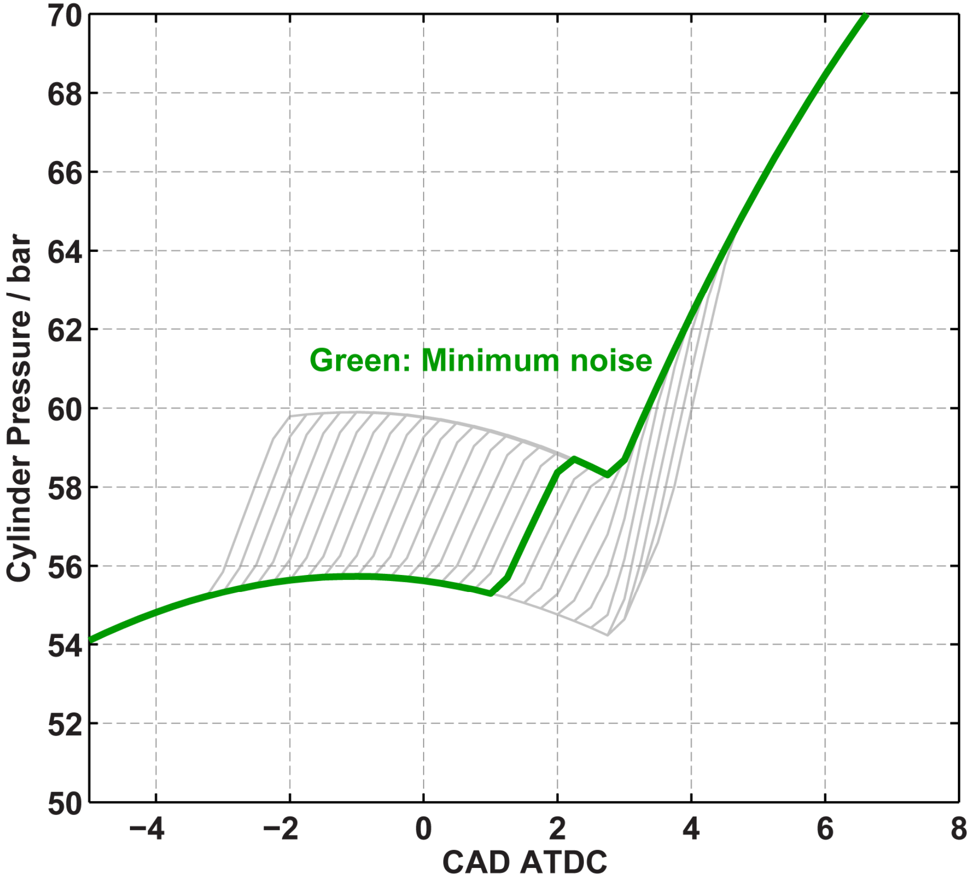
Band pass (BP) filtering between 1 and 3 kHz shows

- Examine BP-filtered cylinder pressures for all combustion dwells
  - SOC_{main}: 3 CAD BTDC
- Oscillation amplitude minimized for minimum noise case
- How does this look for a case in which main combustion starts after TDC?



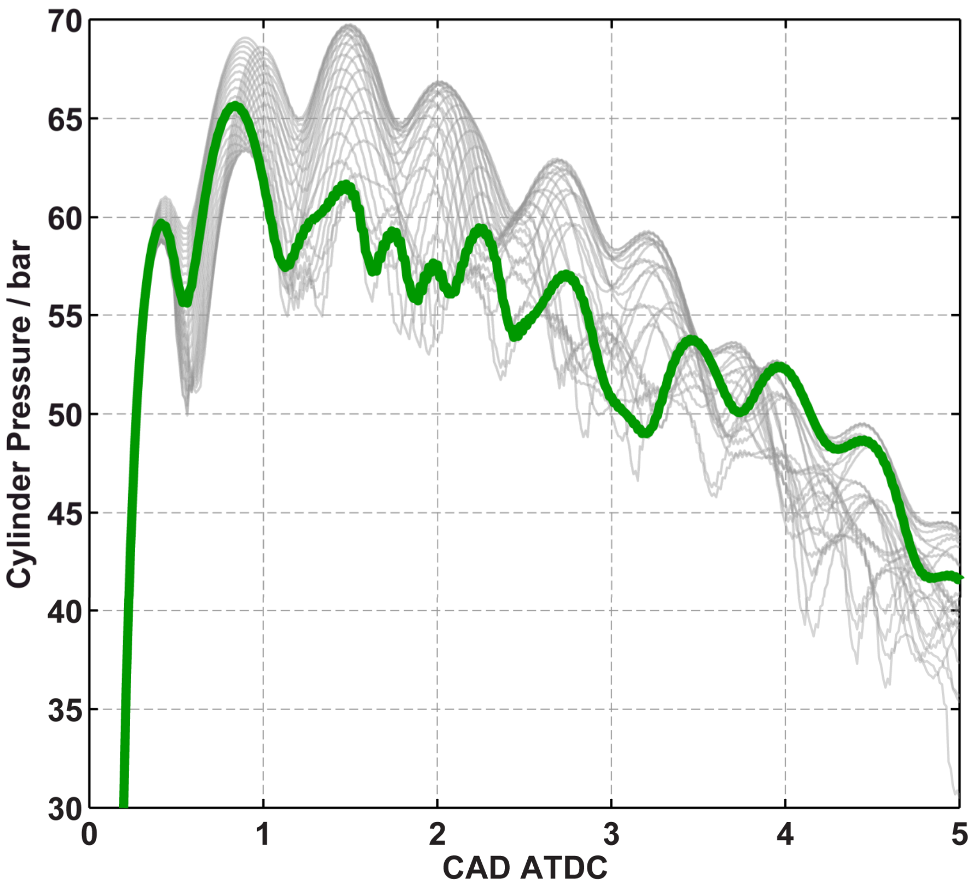
Large changes in combustion noise can occur with subtle changes in pressure traces

- SOC_{main} = 3 CAD ATDC (top hat heat release profile)
- Better approximation of measured trend in the engine



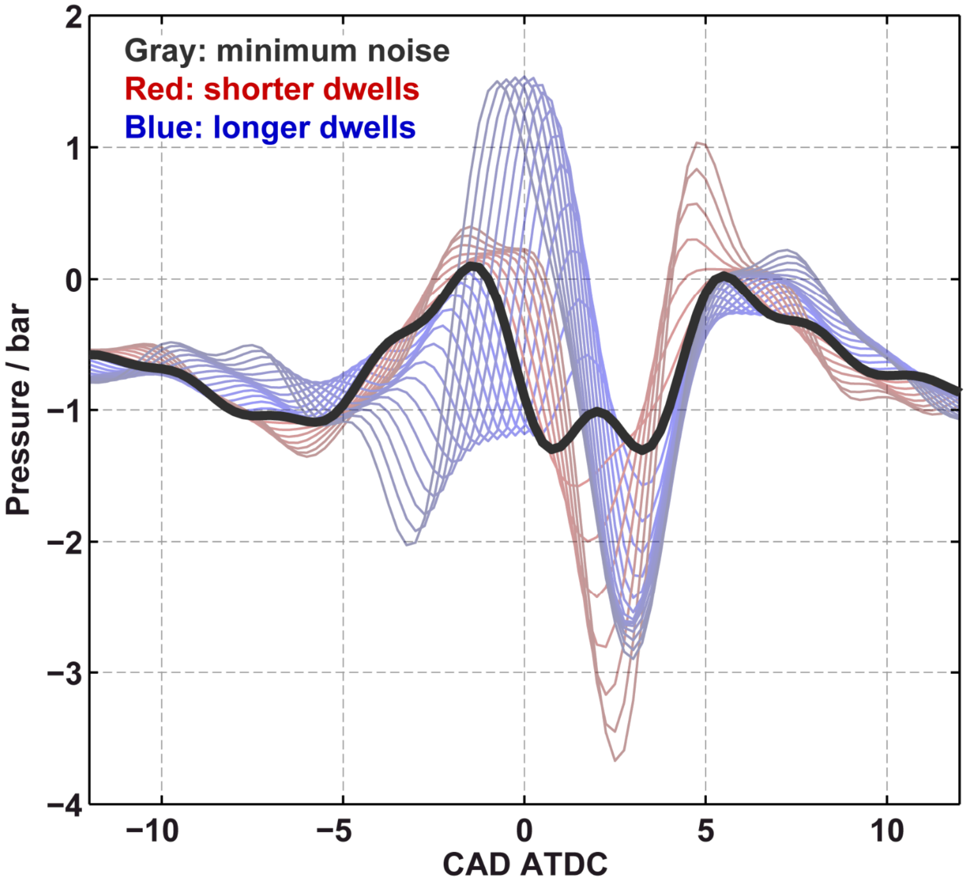
Spectral analysis indicates which frequencies contribute to the combustion noise minimum

- Examine sound pressure spectra for all combustion dwells
  - SOC_{main} 3 CAD ATDC
- Pressure frequency components responsible for noise minimum: 1 kHz – 3.2 kHz
- What does a band pass filtered pressure trace tell us?
  - Pass band: 1 kHz – 3.2 kHz



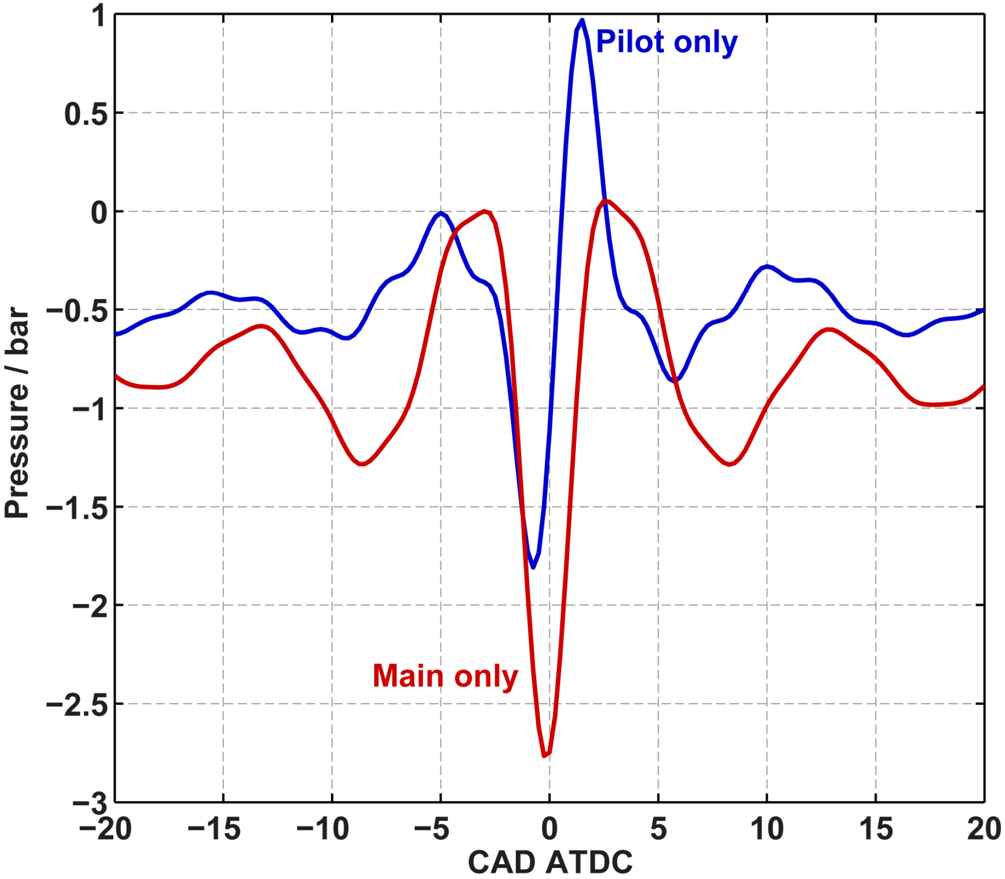
Band pass (BP) filtering between 1 and 3 kHz shows

- Examine BP-filtered cylinder pressures for all combustion dwells
  - SOC_{main}: 3 CAD ATDC
- Behavior is very similar to SOC_{main} 3 CAD BTDC case
- These curves appear to undergo a smooth transition with an optimum shape in the middle…



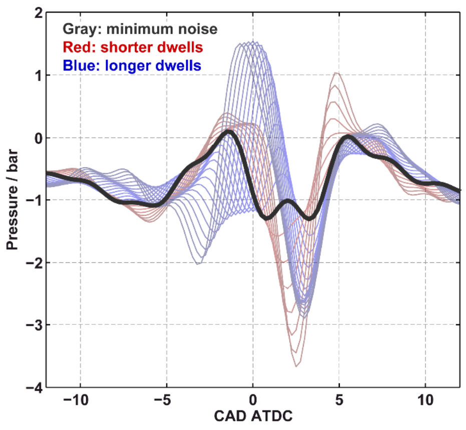
What do the pilot and main contribute to the frequency range between 1 and 3.2 kHz?

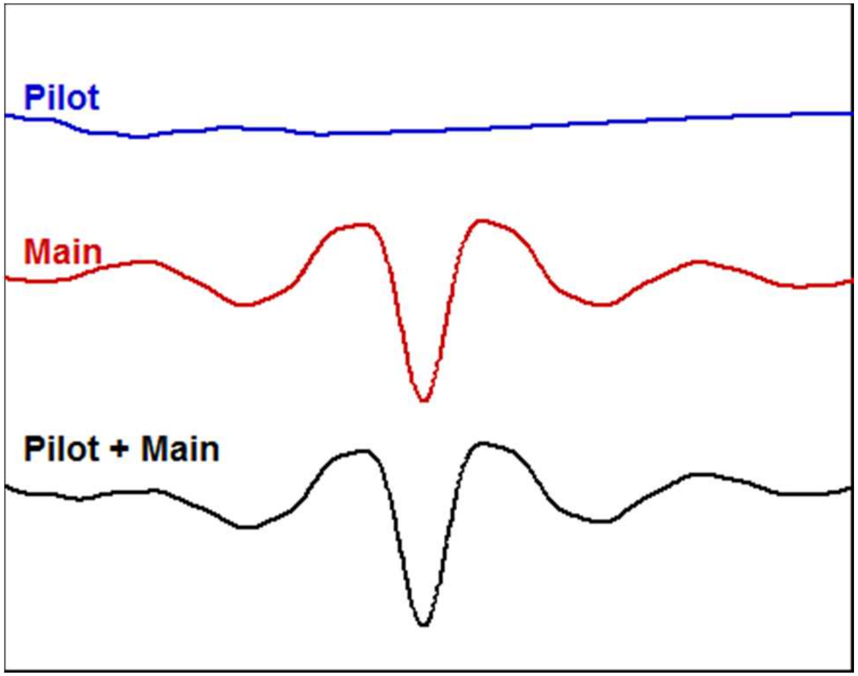
- Simulate pilot and main separately
- Compute cylinder pressure for each case
- Band pass filter between 1 and 3.2 kHz
- Superimpose these two waveforms on one another with variable delay…



Superposition of two waveforms to create a noise-minimum waveform

- Superposition of two waveforms ("pressure signatures"):
  - Waveform resulting from pilot heat release
  - Waveform resulting from main heat release
- These waveforms represent the amplitudes and phases of the frequency components responsible for the combustion noise reduction





Summary: combustion noise reduction via close-coupled pilot injections

- Mechanism has been captured with a zero-dimensional model
- Simple metrics ($dP/d\theta_{max}$) cannot predict or explain this phenomenon
- Mechanism occurs in addition to combustion phasing effects
- Noise reduction occurs for many pilot and main injection heat release profiles (not all results were shown today)
- Two factors seem to play a role
  - Heating and vaporization of fuel injected during the main injection can suppress the *apparent* heat release of the pilot injection and decrease combustion noise further for short dwells (briefly discussed in this presentation)
  - Superposition of pressure signatures due to pilot and main heat release events create pressure waveforms with reduced amplitudes in the frequency range of ~1-3 kHz (when properly phased)

Outlook / upcoming work: close-coupled pilot injections

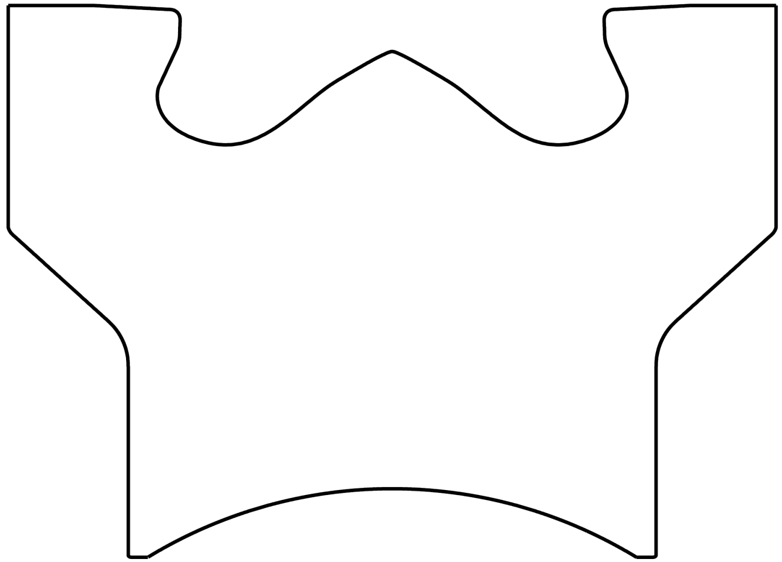
- A thorough, theoretical explanation of the combustion noise reduction mechanism with close-coupled pilots is being published (intended for ASME ICEF)

- Further investigations: the effect of close-coupled pilot injections on mixture formation and combustion
  - Fuel tracer PLIF (motored operation with N_2)
    - How does changing dwell impact the distribution and composition of mixtures near the start of main combustion?
  - High speed natural luminosity imaging (skip-fired)
    - How does dwell impact the flame structure?
    - How does the ignition / inflammation of the main mixture field change with dwell?
    - How might changing dwell impact soot emissions?

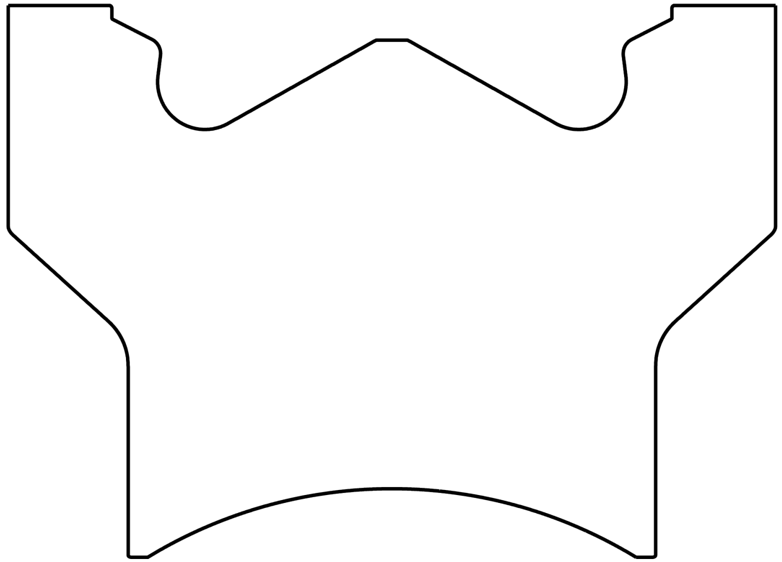
Outlook / upcoming work: piston bowl geometry variation

- Comparison of two piston geometries
  - No valve cutouts
  - Same bowl volume / compression ratio

“Conventional” re-entrant piston bowl geometry



“Stepped-lip” piston bowl geometry



Outlook / upcoming work: piston bowl geometry variation

- Planned investigations:
  - Swirl plane PIV, comparison of the two bowl geometries
    - Does the change in bowl geometry affect swirl center position / flow asymmetry during the intake and compression strokes?
  - Vertical plane PIV, comparison of the two bowl geometries
    - How is the squish flow impacted by the change in geometry?
    - How does the flow topology change?
  - Comparison of mixture formation and combustion processes
    - LTC operating point
    - Other operating points (will be developed)

Outlook / upcoming work: current status

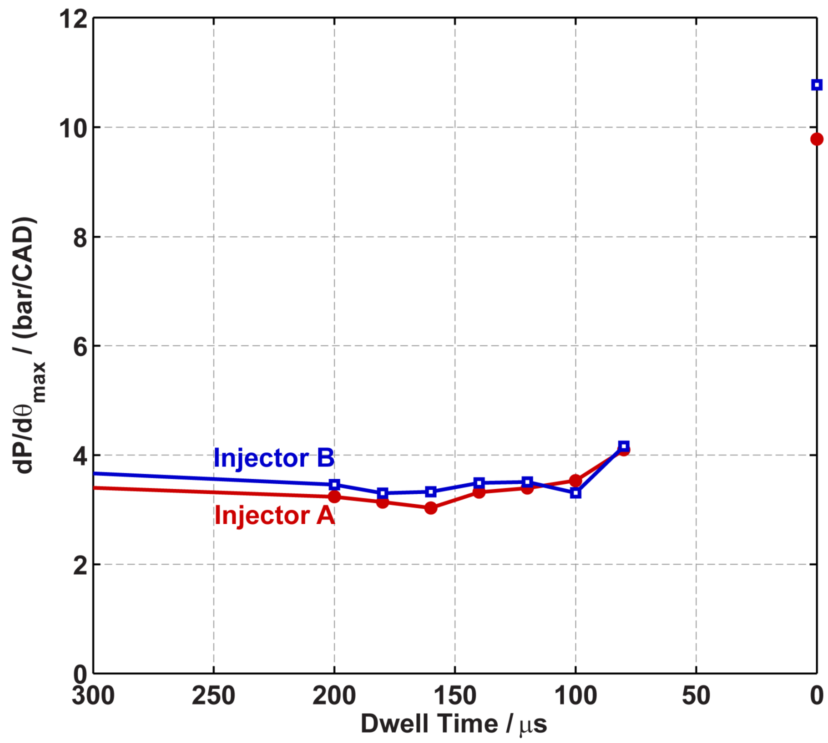
- Failure of first stepped-lip piston (last year)
  - Was the first test of a new piston retainer design
  - Problem with assembly / break in process has been identified
  - The second piston was successfully tested last week
- PIV measurements will commence in the coming weeks
- Working with partners at Ford and GM to define new operating points and research objectives
  - Experimental parameters and measurement techniques will be defined to meet experimental goals

THANK YOU FOR YOUR ATTENTION!

Questions?

Can maximum rate of pressure rise be used to predict the combustion noise trend?

- Maximum rate of pressure rise for filtered cylinder pressure
- Trend in $dP/d\theta_{max}$ does not reflect the noise behavior for short dwell times
- What else could be causing this noise minimum?



Can staged heat release lead to interference of pressure waves within the cylinder?

- For destructive interference:
  - delay = 2.25 CAD → 0.250 ms
  - n = 0; T = 2x delay = 0.50 ms
- Destructive interference expected at a frequency near 1/0.5 ms = 2 kHz