Premix charge, compression ignition combustion system optimization

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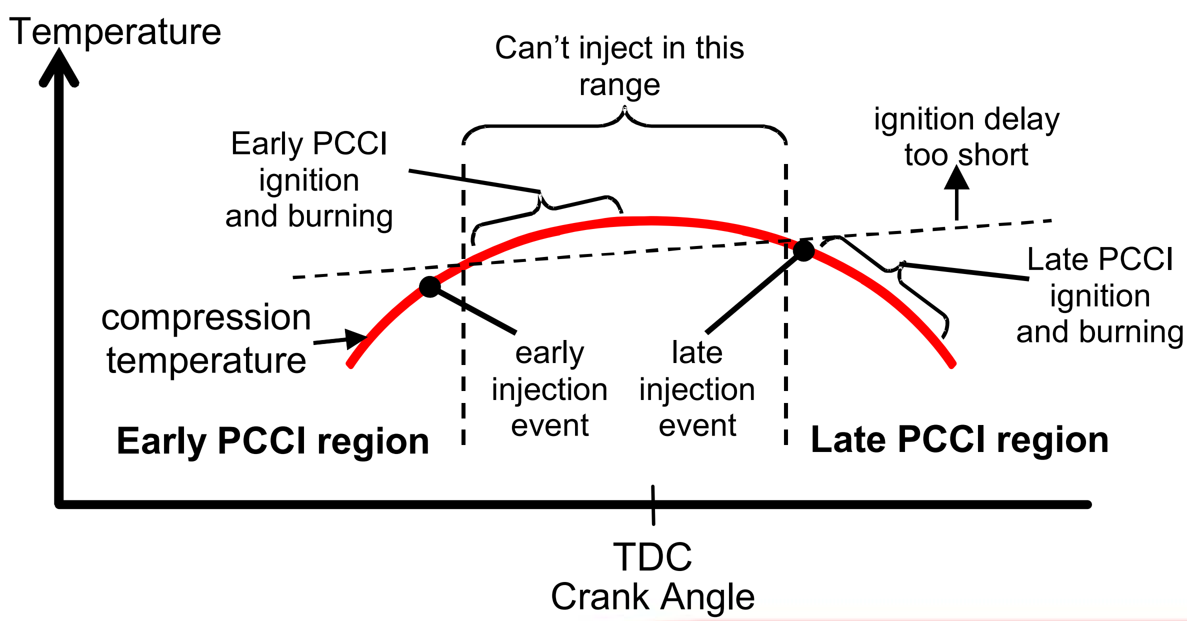
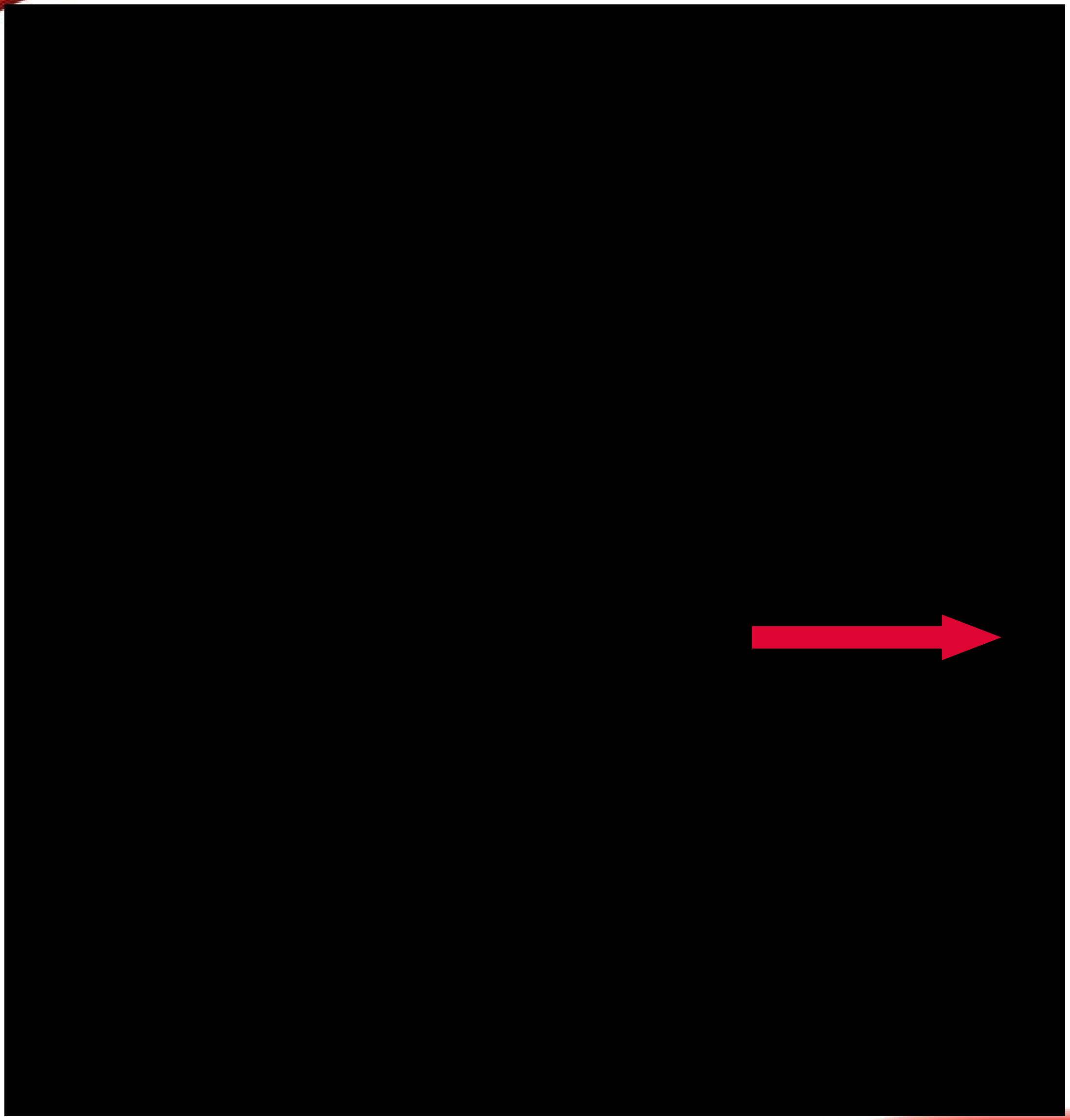
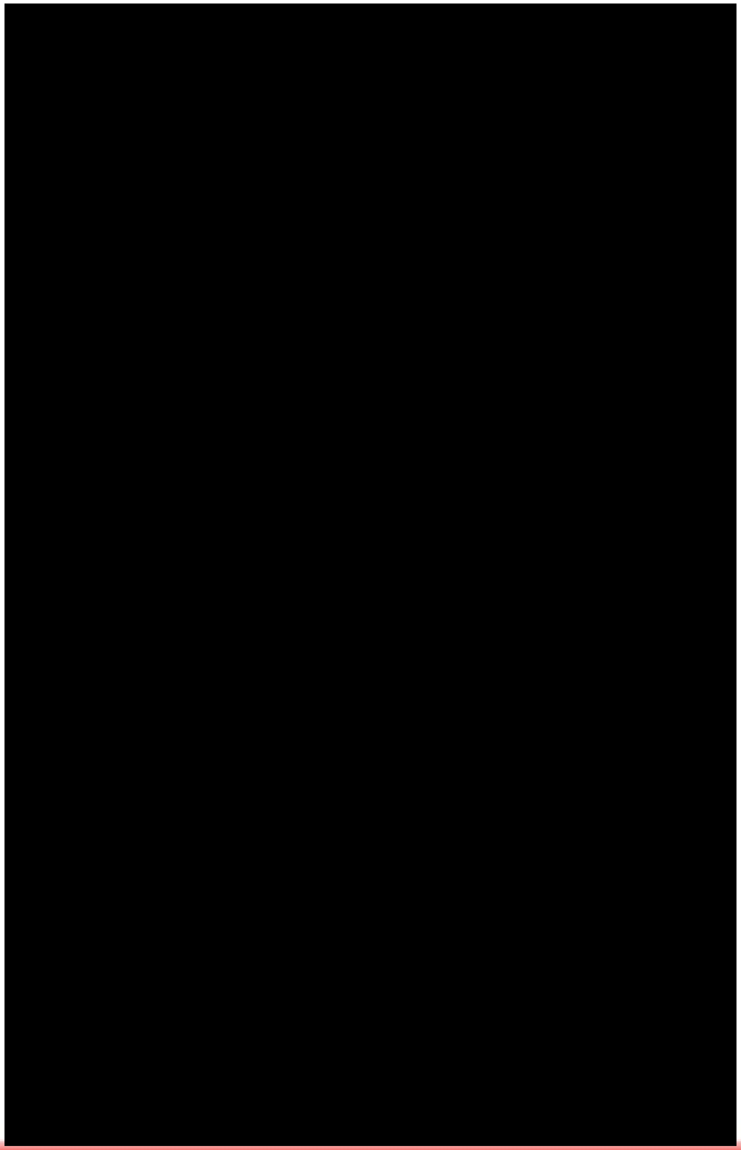
Project Goals

- Utilize PCCI combustion technology to optimize fuel economy while meeting EPA 2010 emission targets and customer requirements for noise and drivability

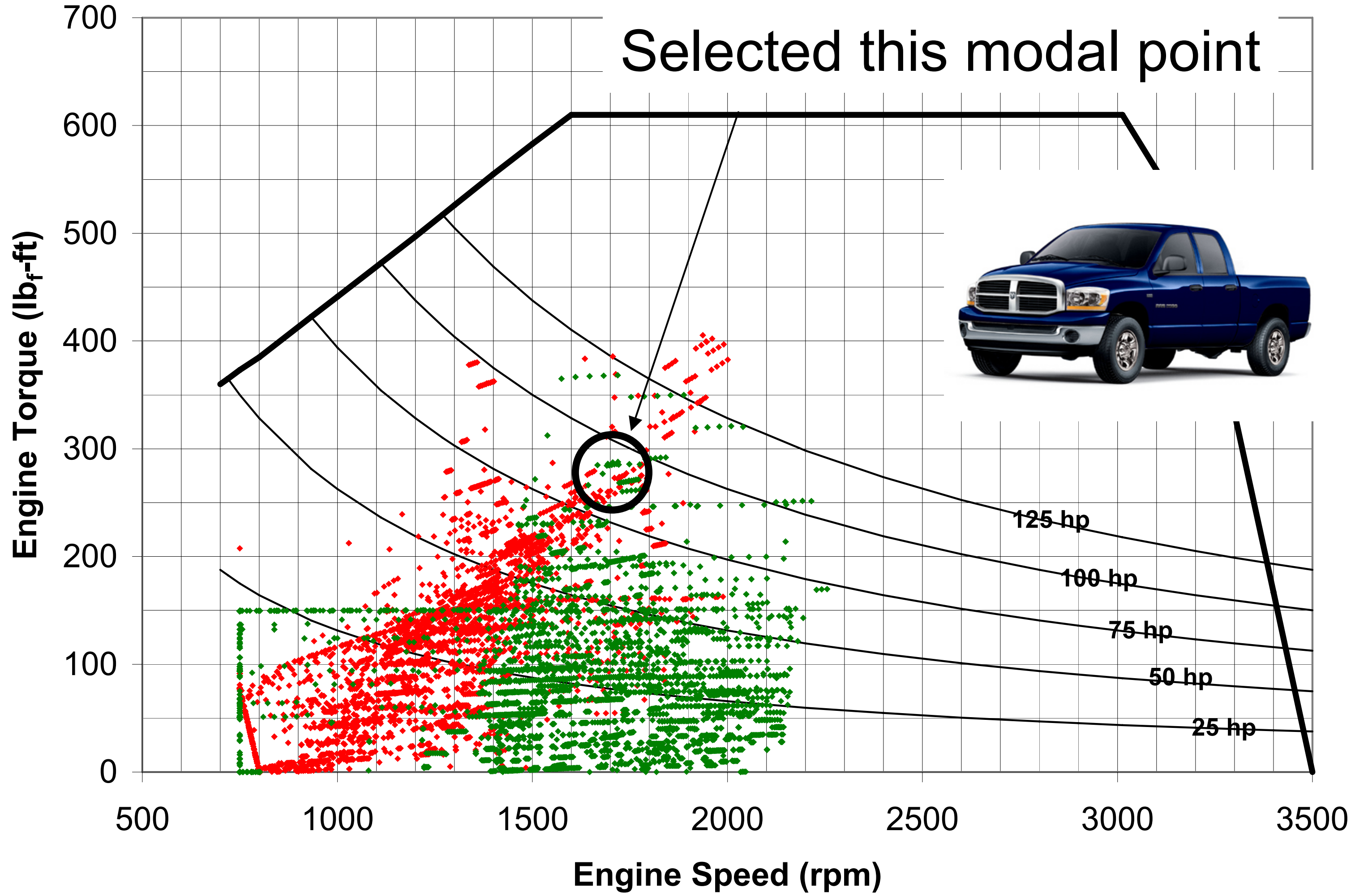


Critical Parameters





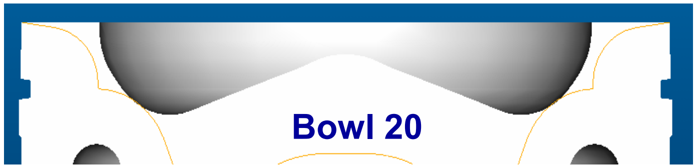
Narrowing Domain ...



Narrowing Domain …

- Speed
- IMT (effective)
- Swirl
- Nozzle
  - # holes
  - Angle
  - Flow
  - AFM (hydro-grind)
  - L/D – K factor
- Injection
  - Rail P
  - Shape
  - Pilots
  - Post
  - Main

- Fresh A/F (λ)
- Intake O_2 fraction
- Residual
- Piston Bowl
  - Geometric compression ratio
  - Bowl shape
- ….



Piston bowl and nozzle characteristics recommended by KIVA computational analysis

Experimental Method

- Utilized Cummins single cylinder 6.7L test engine
- Used a space filling test plan
  - Rail pressure
  - Two pilot injections
  - Main injection
  - Post injection
  - O_2 intake fraction
  - Fresh A/F ratio

→ Analysis with response surface quadratic fits (reduced models)

Experimental Results

- fsNOx
- fsPM via smoke (FSN)
- HC
- Fuel consumption
- Combustion noise → Extremely important parameter for the pickup truck and SUV market – difficult technical hurdle for PCCI combustion

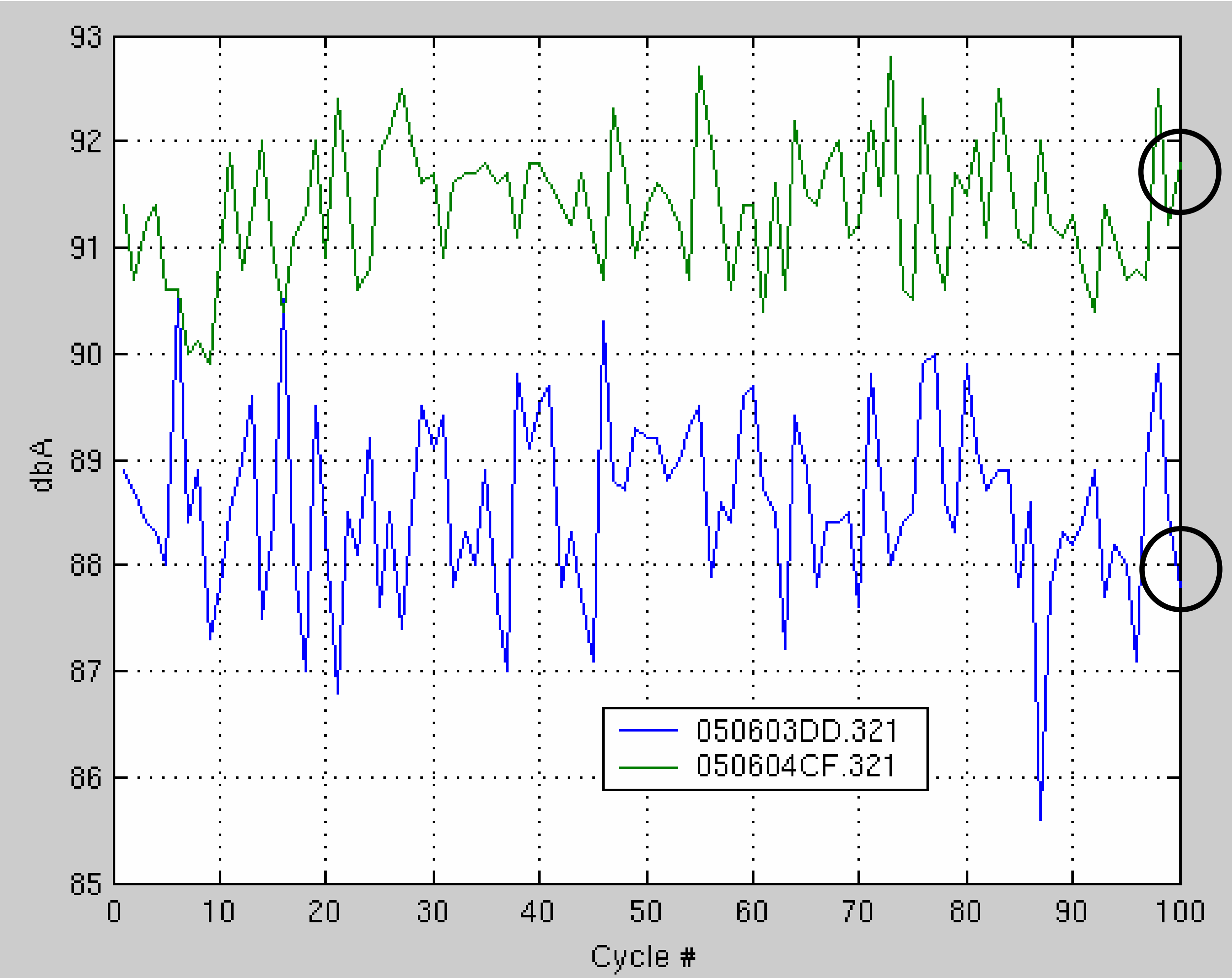
Noise Measurement, Calculation …

- Simulation of noise meter analyzes each of 100 total cycles per data point, results are tabulated as average of these noise calculations plus deviation
- Method: FFT of cylinder pressure → filtered gains applied → inverse FFT → RMS noise power calc → customer acceptance criteria

Sound Pressure Level:

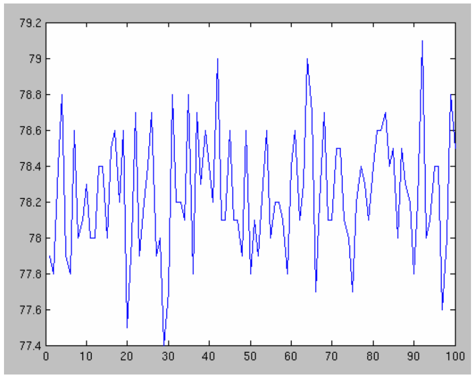
$$SPL = 10\log\left(\frac{p_{RMS}^{2}}{p_{ref}^{2}}\right) \quad \text{OR} \quad SPL = 20\log\left(\frac{p_{RMS}}{p_{ref}}\right) \qquad p_{ref} = 2 \times 10^{-5}\ \text{Pa}$$

100 Cycle Noise PCCI Combustion

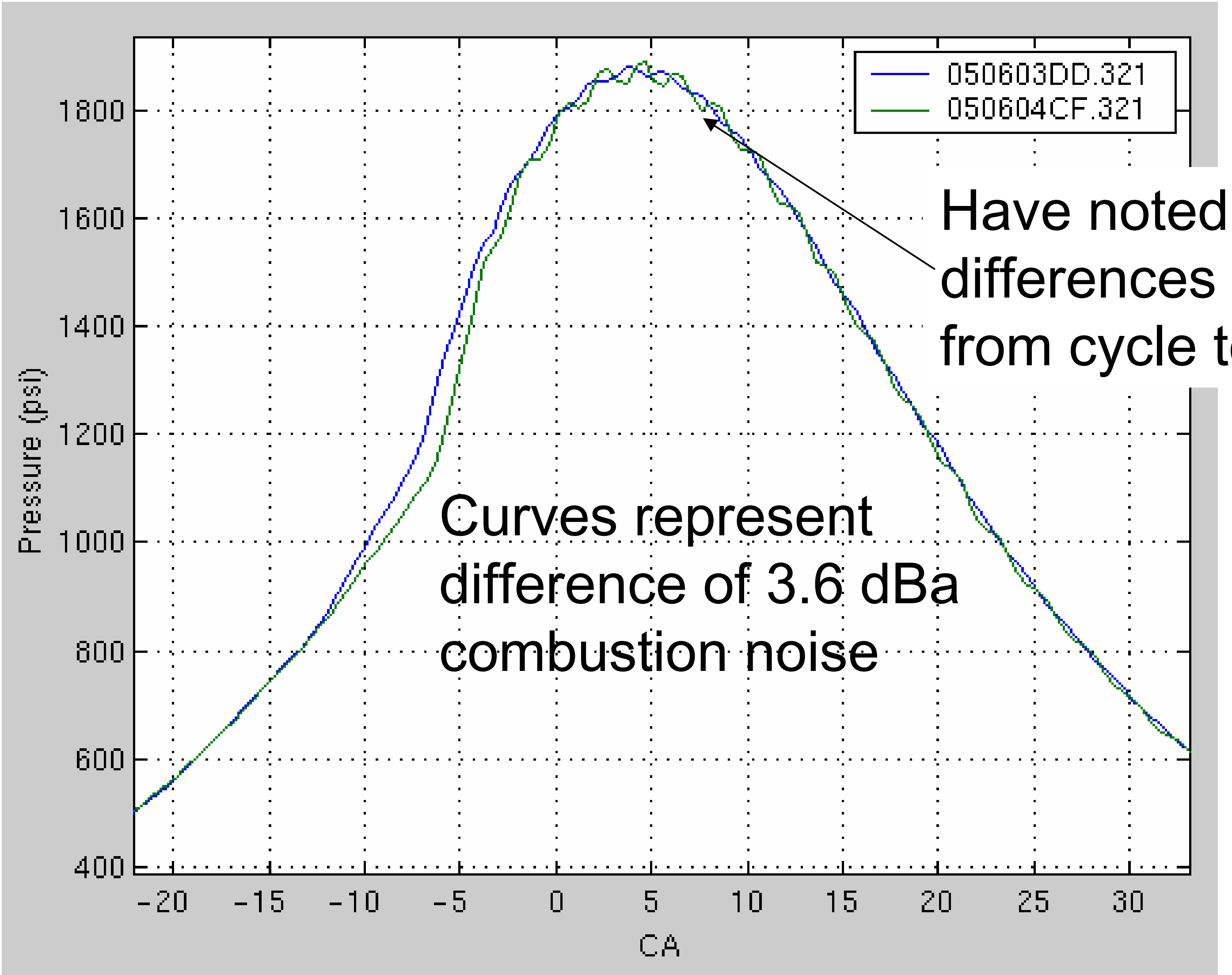


More detailed analysis of these last two cycles

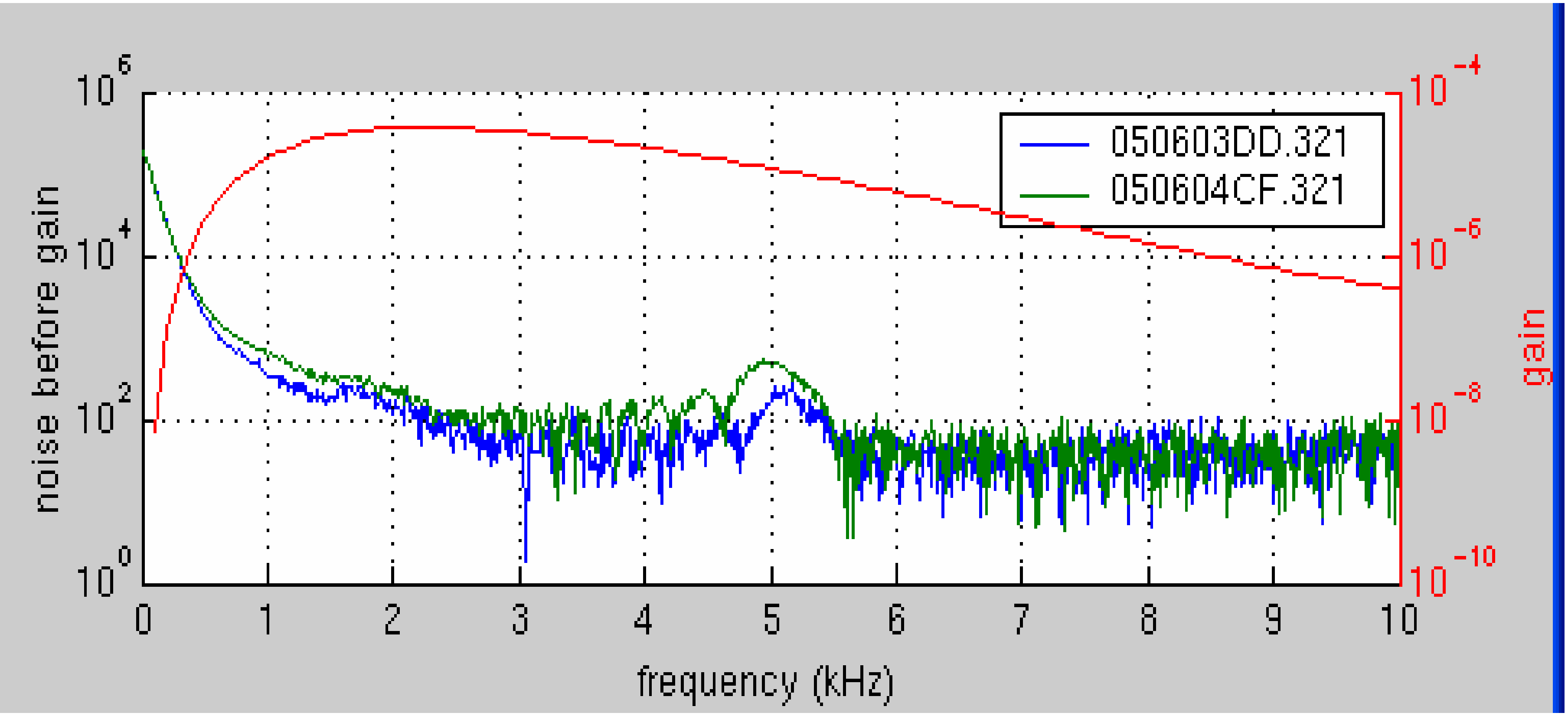
Motoring noise is ~78 dBa



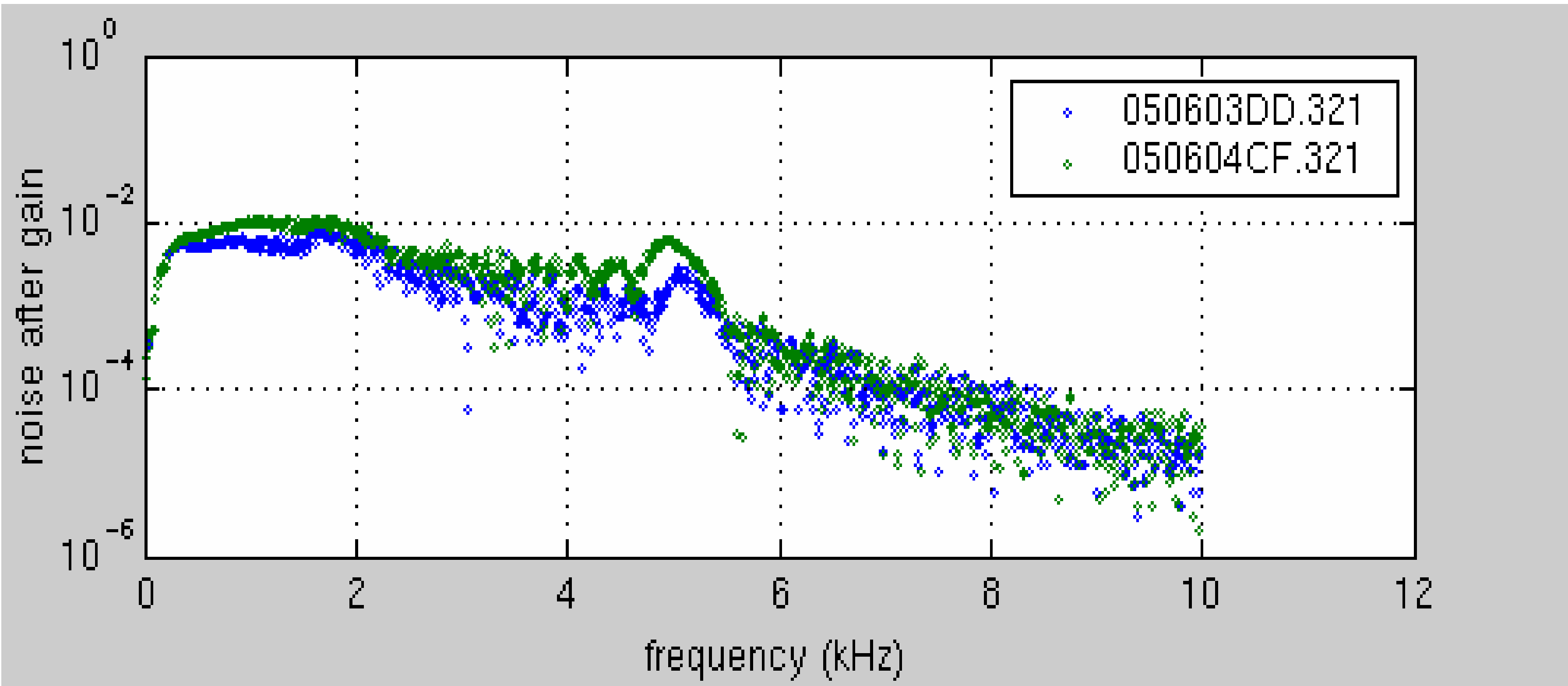
Cylinder Pressure Comparison



FFT and Meter Gains

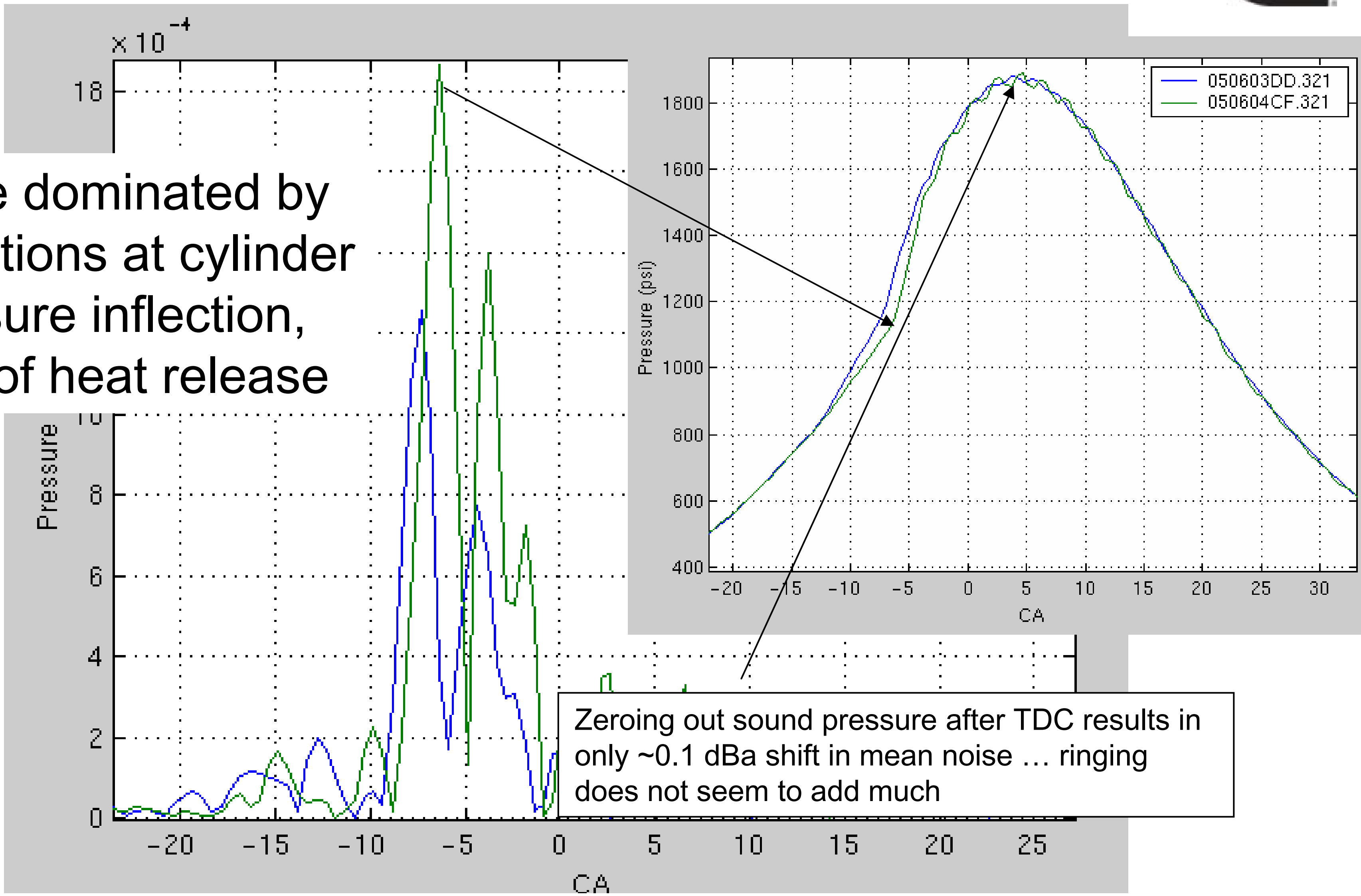


Sound Pressure (after gains)



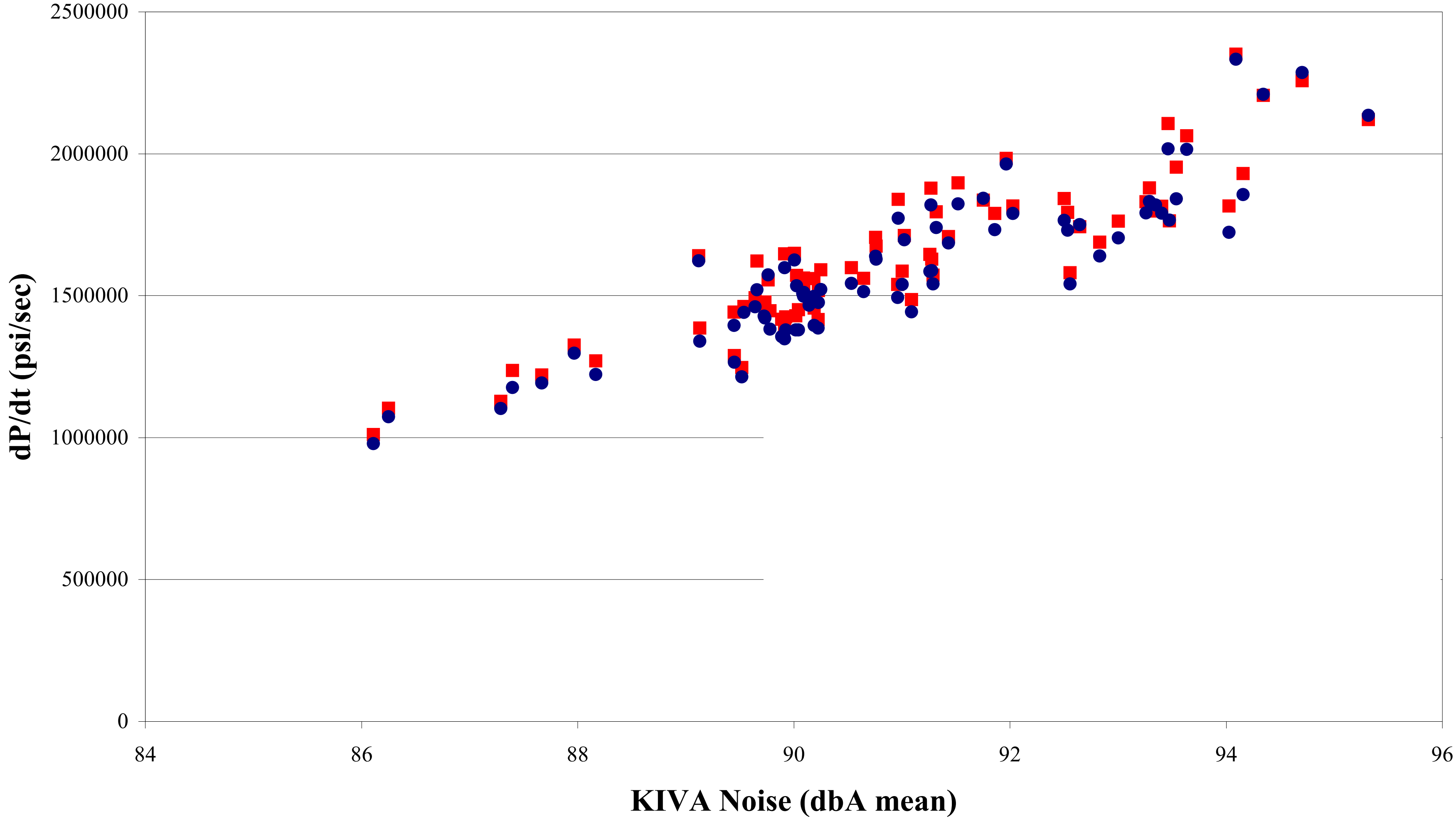
Inverse FFT

Noise dominated by conditions at cylinder pressure inflection, start of heat release

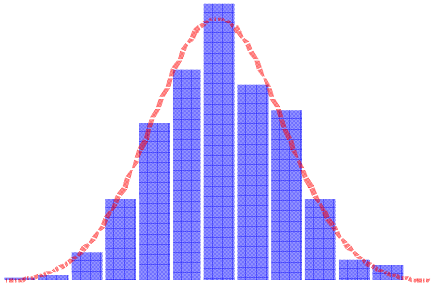


Zeroing out sound pressure after TDC results in only ~0.1 dBa shift in mean noise … ringing does not seem to add much

Rate of Pressure Change

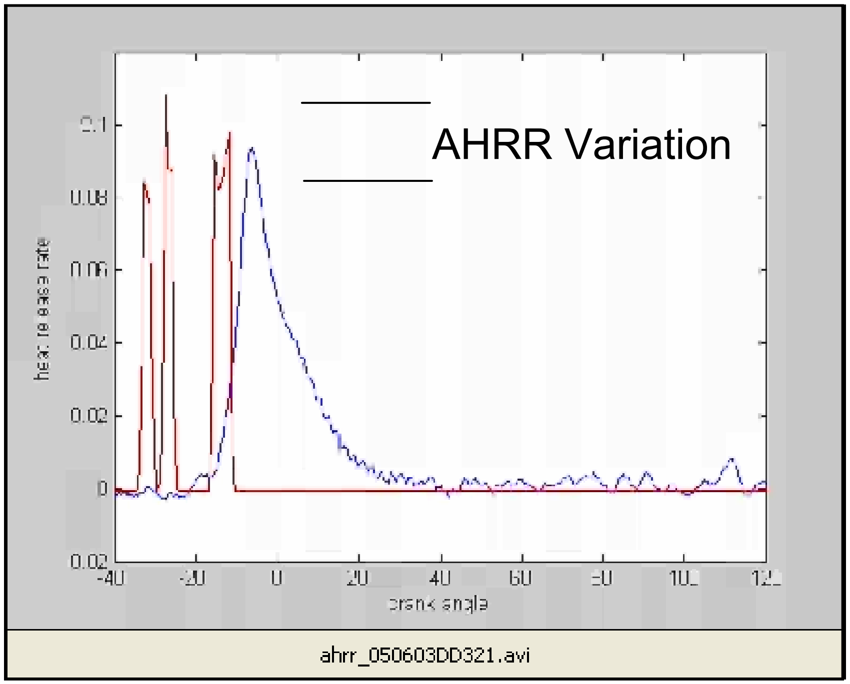


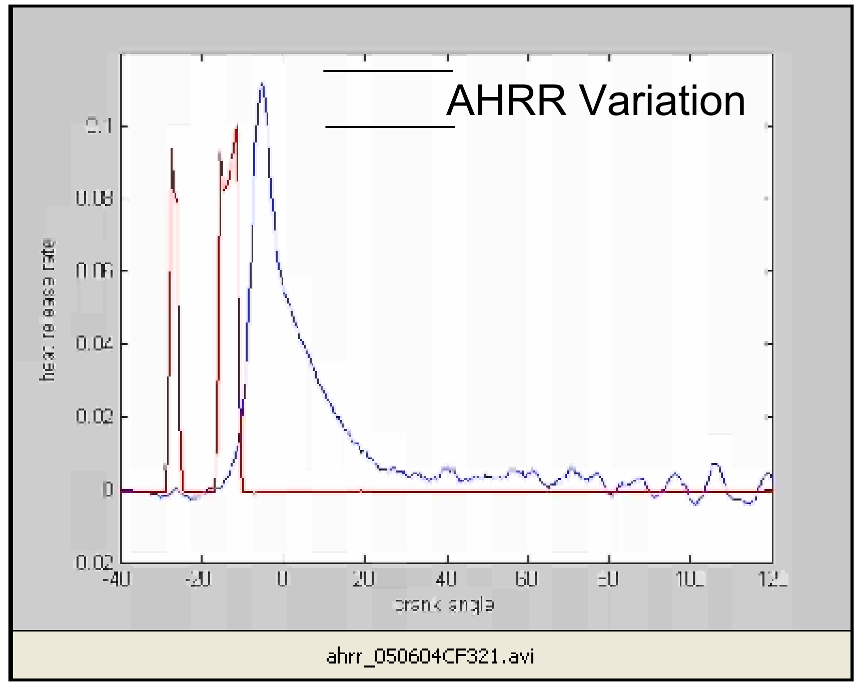
Repeatability of Noise



- Engine test repeat points also showed substantial variation of *mean* noise levels ~ 1 dBa, cycle/cycle variation was also of this order
- Analysis of fuel system and air charge conditions did not account for observed noise variation

Noise Variations and Apparent Heat Release …

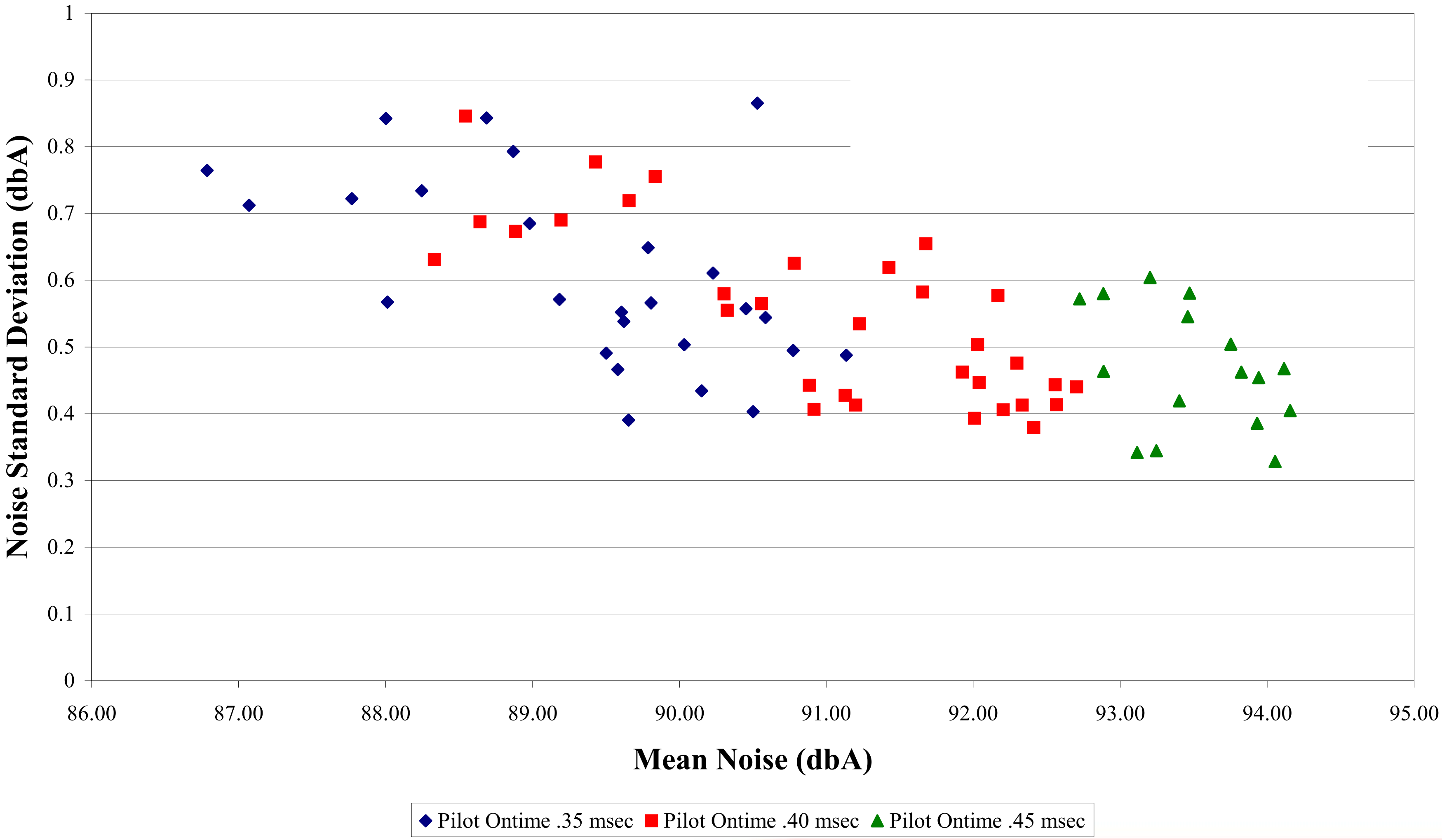




Mean noise = 88.6 dBa
Std Dev = 0.9 dBa

Mean noise = 91.4 dBa
Std Dev = 0.6 dBa

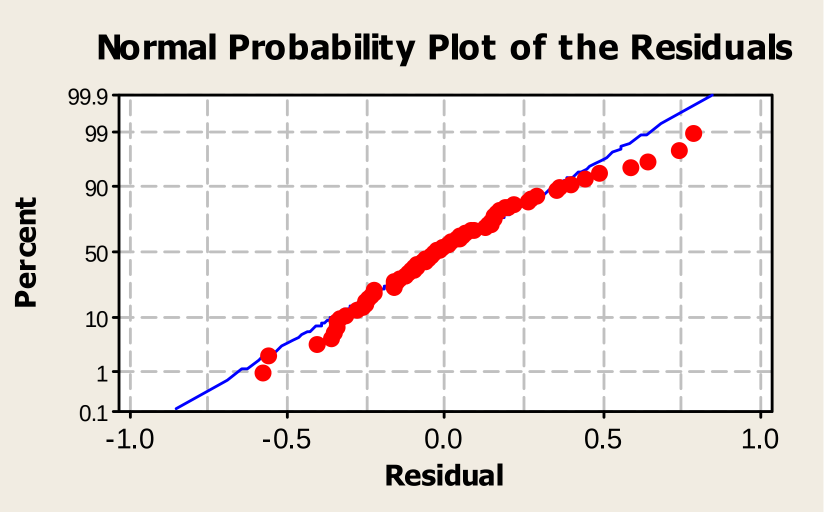
Cycle to Cycle σ



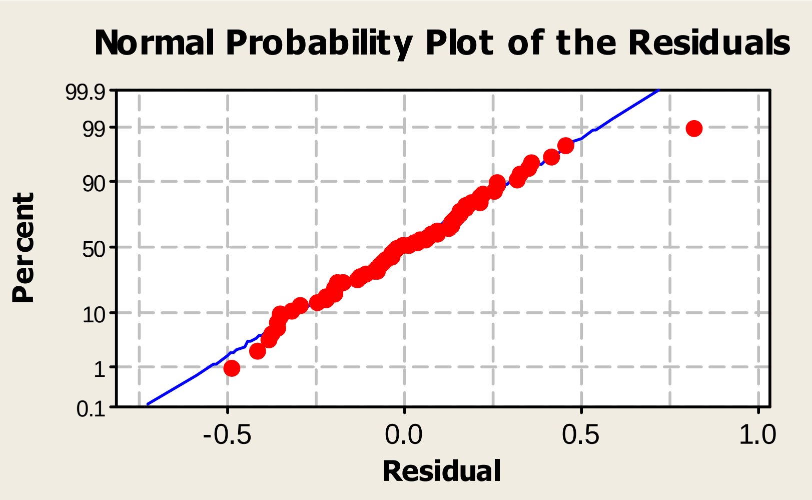
Combustion Noise Conclusions

- Substantial cycle to cycle and mean variation was noted for early PCCI combustion with multi-pulse injection
- Analysis of fuel system and air charge inputs did not account for variation
- Analysis technique appears to be capturing fundamental noise phenomena
- Early PCCI heat release process may have inherently higher variation causing observed noise variation … longer ignition delay has more variation in subsequent heat release … more investigation required

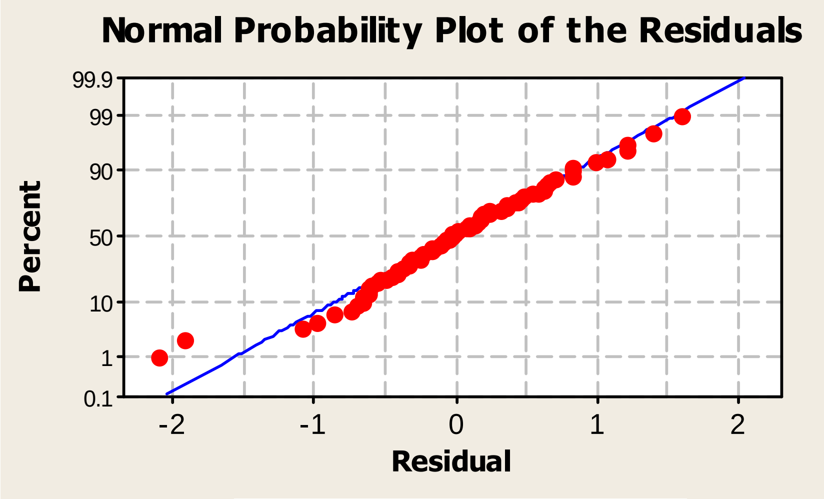
Design of Experiment Fits



fsNOx, g/kg



Smoke, FSN

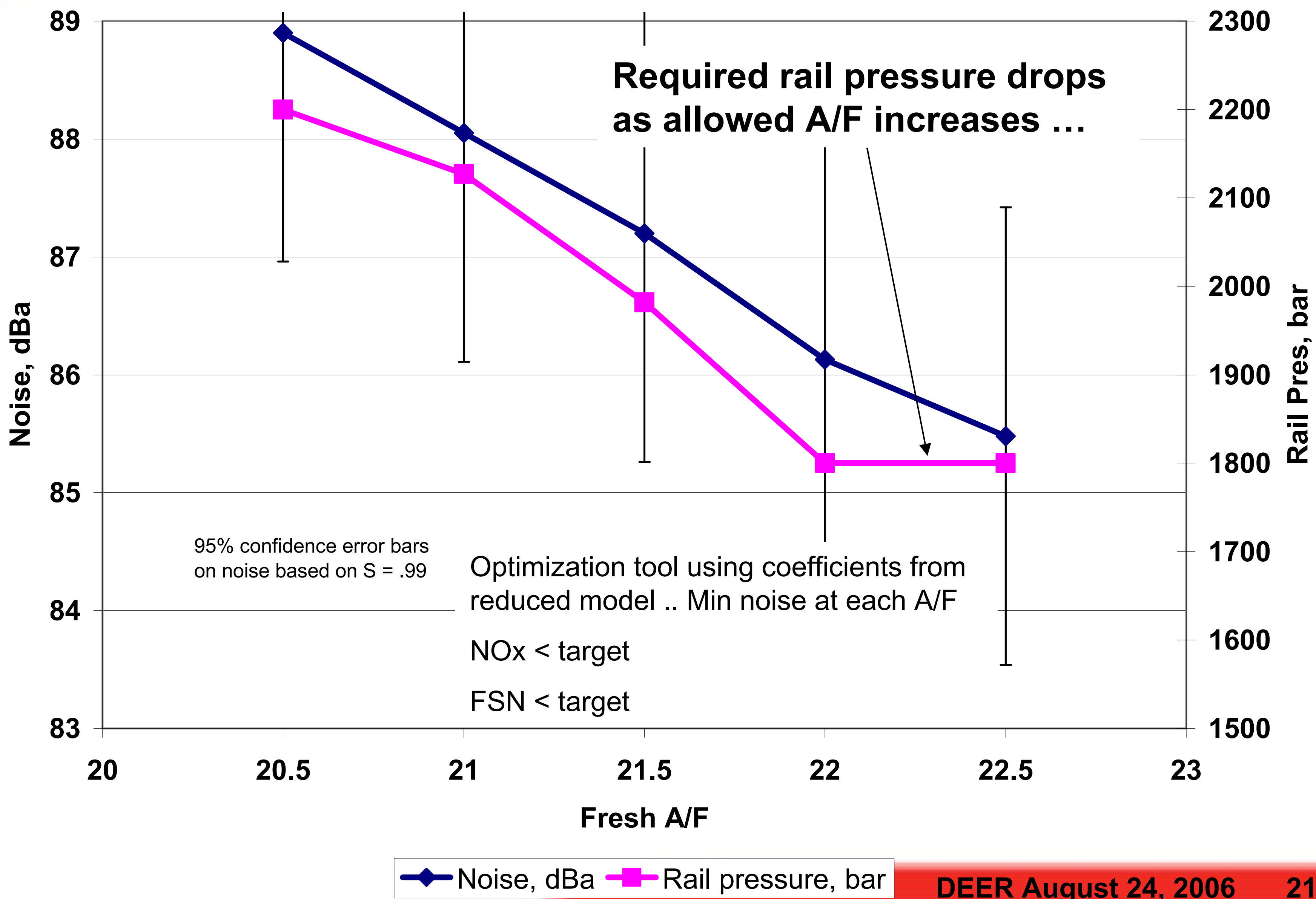


Noise, dBa

Optimization …

- The correlation of experimental results were adequate with noted variation in combustion noise
  - Rail pressure
  - Two pilot injections
  - Main injection
  - Post injection
  - O_2 intake fraction
  - Fresh A/F ratio
- Resulting reduced quadratic models were incorporated in an optimizing software code
- Results for minimum combustion noise meeting emission constraints were obtained for various A/F ratio limits …

PCCI Noise optimization …



Summary

- Experiments indicate that high A/F and EGR rates are critical for meeting emission and noise targets
- Injection pressure requirements are reduced with higher A/F
- Noise targets are difficult to obtain with early PCCI combustion, significant variation noted with multi-pulse pilot with early main injection