Bringing the Low NOx Diesel Under Control

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Dispersion management is the greatest challenge facing the low-NOx diesel

- Dispersion management is critical at the lowest standards
- Sub-bin 5 emissions may require active dispersion management - even with effective aftertreatment
Roadmap to Low-NOx Combustion
Premixed Charge Compression Ignition (PCCI)

- Reduce charge temperature with cooled EGR and reduced compression ratio
- Enhance premixing through injection strategy
  - Early PCCI for light loads
  - Late PCCI for heavier loads

Issue
- Minimum achievable NOx levels are limited by the combustion quality and robustness
Combustion Mode Map over FTP for Chassis Certification HD Truck (8500 lb)

- **Early PCCI**: Noise and instability prone at higher loads
- **Late PCCI**: Reduced fuel economy and instability prone

- **Conventional**

**Axes**:
- **BMEP (Bar)**
- **Engine Speed (rpm)**
Combustion Feedback Control – The Promise

- Aggressive low-NOx calibration
- Extended PCCI calibrations
- Compensate for ageing and variation
- Early & accurate problem detection
Major Sources of Dispersion

Major players:
• Mass Air Flow Sensor (global)
• Injector variability (timing and quantity – esp. pilot)
• Compression ratio
• EGR distribution
• Fuel quality (cetane)
• Environmental factors
• Wear on everything

Tuning:
• Global EGR level (slow)
• Charge temperature control with sophisticated EGR system (slow)
• Individual injection quantity and phasing (fast)

Derived combustion quantities like the 50% burn rate provide good control parameters but require
- a powerful engine ECU
- robust sensors
Engine-Appropriate Sensor Considerations

Sensor Technology
- Research Grade
- High Quality Production Grade
- Moderate Quality Production Grade
- Low Quality Production Grade

Combustion Metric
- SOC, Ignition delay, Acoustics (Sampling: Burst, 0.5 deg)
- LPP, SOC, Max Pressure, Pressure Rise Rate (Sampling: Burst, 0.5 deg)
- IMEP, Heat Release (CA50, 0-90%) (Sampling: 1 deg)

Piezo
- Linearity: Excellent
- Calibrated: Yes

Optical/Diaphragm
- Linearity: Very Good
- Calibrated: TBD

Piezo-Resistive
- Linearity: Moderate/Good
- Calibrated: TBD

Piezo-Electric
- Linearity: Moderate/Good
- Calibrated: TBD

Ion-sense, Knock-sense, low-grade Piezo
- Linearity: Poor
- Calibrated: No
Simple Phasing and Fuel Balance Control
Using Pressure Feedback Control

**Conventional mode**

**Phasing Control**

**Fuel Balance Control**

**Early-PCCI mode**

**Phasing Control**

**Fuel Balance Control**

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Great! - But does it work?
• No NOx, HC or Smoke benefit observed due to linear emission response to the base engine cyl-to-cyl imbalance
**Procedure**

- Ran open and closed loop at each EGR
- For each EGR error, swept phasing target under C/L control
- C/L phasing uses “no EGR error” target as baseline

- HC and NOx emissions resulting in rich/lean shift due to EGR can be partially recovered through phasing correction
- **Requires individual cylinder pressure sensing**
Global EGR Correction with Phasing Control
Early-PCCI at 1400 RPM, 250 kPa BMEP

- Simulate EGR error through MAF error (+/- 11%)
- Closed-loop correction based on average combustion phasing
  - Feedback to EGR valve

- Effective in this case (but not in all cases)
Combustion Feedback Control Shows Promise for PCCI Operation

- Premixed combustion offers the potential to significantly reduce engine out emissions
- Comb feedback may be required due to production fleet variations and environmental factors
- Individual cylinder control combustion feedback shows potential for effective load balance and phasing control
  - Not all recoveries result in emission benefits
  - Works best in non-linear tradeoff regions
Thank you for your attention