# Simultaneous Low-Engine-Out NOx and PM with Highly Diluted Diesel Combustion

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# Improved EGR utilization in CIDI engines can lower the performance requirements for post-combustion emissions controls

- **Objectives**
  - Investigate potential for > 50% NOx reduction with minimal PM penalty via aggressive use of EGR in CIDI engines.
  - Develop diagnostic tools and/or feedback control strategies to allow closed-loop control of CIDI engines in low NOx and low PM regimes.
- **Challenges**
  - Actual EGR utilization is typically less than optimal because of PM and HC emissions.
  - Contributing factors are cycle-to-cycle and cylinder-to-cylinder variations in combustion, mixing, and EGR.
  - EGR contributes to corrosion.

# Summary of Accomplishments

- Performed extensive experiments under high EGR conditions with full-pass engine control.
- Explored potential for recovery of BSFC/BMEP penalty.
- Continued diagnostic tool development using data from recent experiments.
- Data reduction is ongoing and future experiments are planned.

# Experimental Platform

## Key improvements made since last year

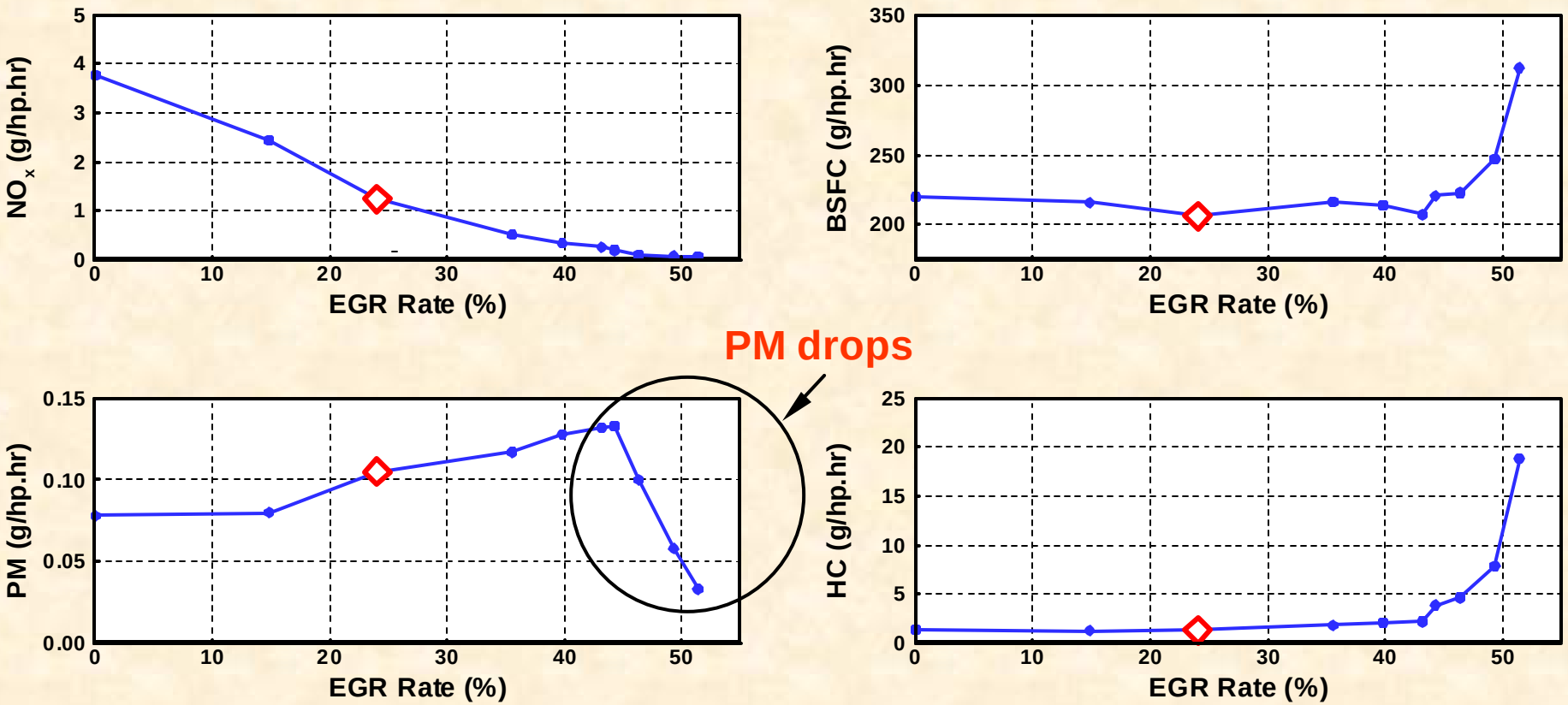
- **Engine Platform**
  - **Mercedes 1.7 L common rail diesel engine with cooled EGR.**
  - **Full-pass control (modified SwRI RPECS system) of electronic throttle, EGR valve, and fueling parameters.**
- **Instrumentation**
  **(measurements for each individual cylinder)**
  - **In-cylinder pressure.**
  - **Regulated steady-state gaseous emissions.**
  - **Fast HC emissions.**
  - **PM size and mass (TEOM, SMPS, Diesel Particle Scatterometer).**

# We explored two approaches for reducing engine-out NOx and PM at high EGR levels

- Approach One
  - Utilizing EGR valve control, sweep EGR rate until EGR valve fully open.
  - Employ intake throttling to further increase EGR rate with EGR valve fully open.
- Approach Two
  - Utilizing EGR valve control, sweep EGR rate until EGR valve fully open.
  - Retard injection timing with EGR valve fully open.

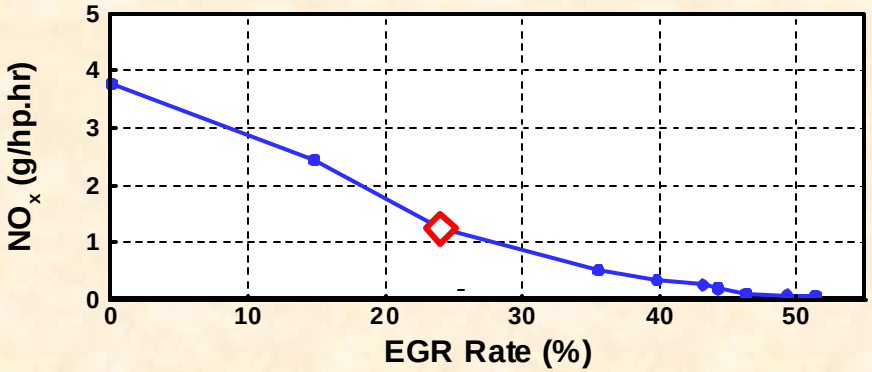
# Lower engine-out NOx and PM observed at higher EGR rates with throttling (Approach One)

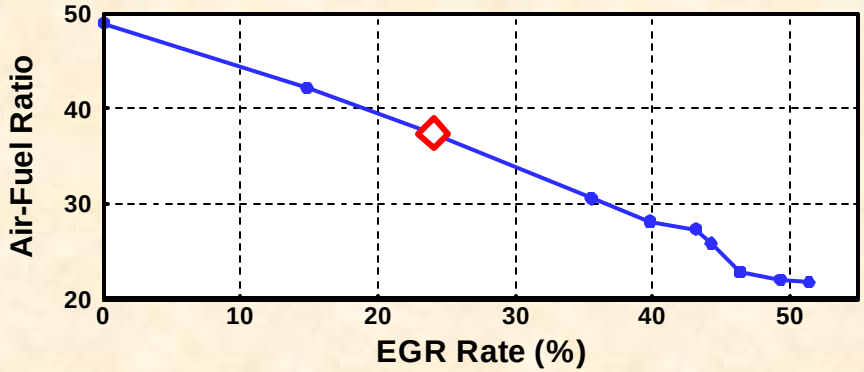
## 1500 rpm, 2.6 bar BMEP

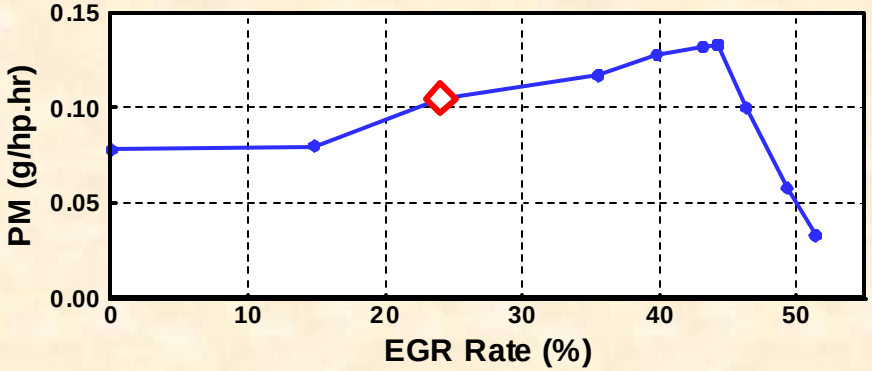


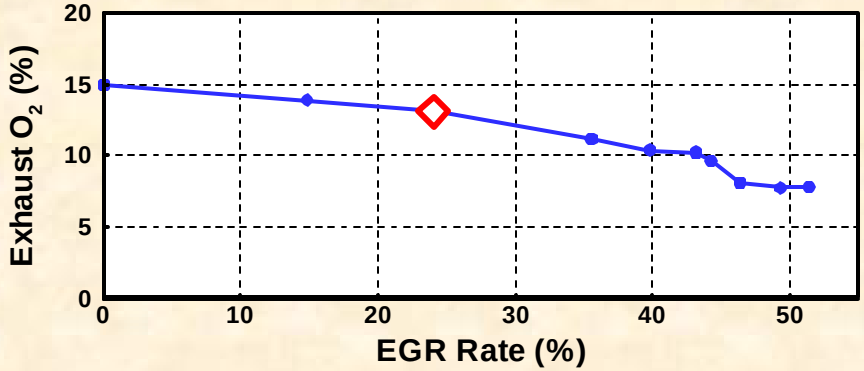

Production Calibration
(24% EGR)

# Simultaneous low NOx and low PM were observed at lean air-fuel ratios



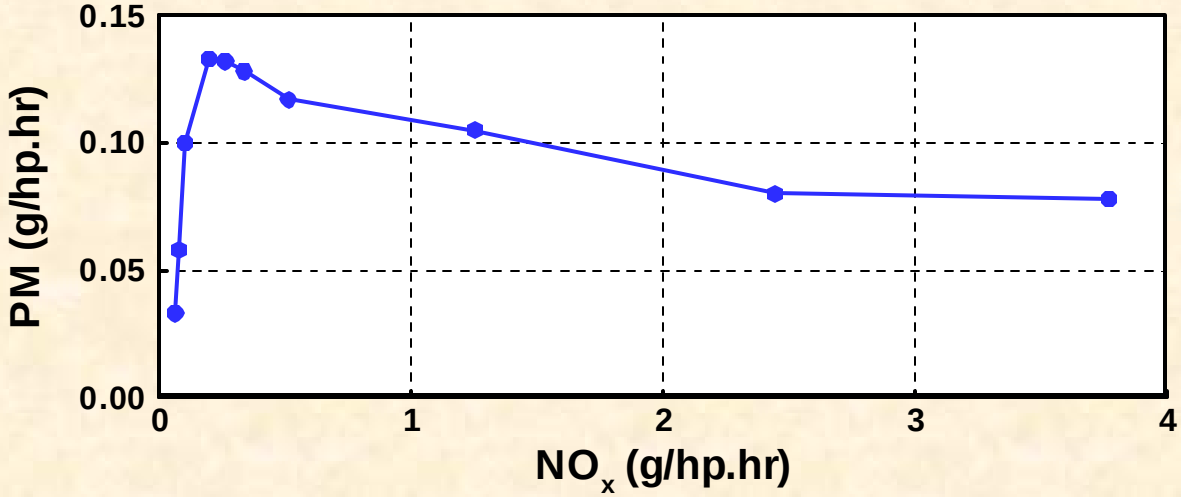






**Approach One**

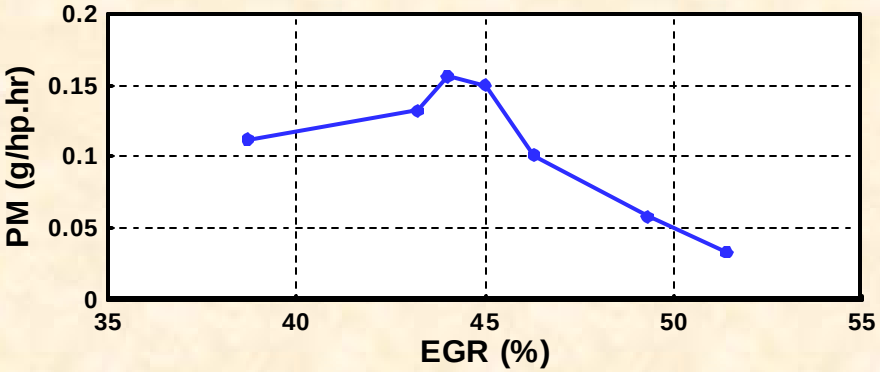
# Not so "classic" PM and NOx tradeoff at 1500 rpm, 2.6 bar BMEP

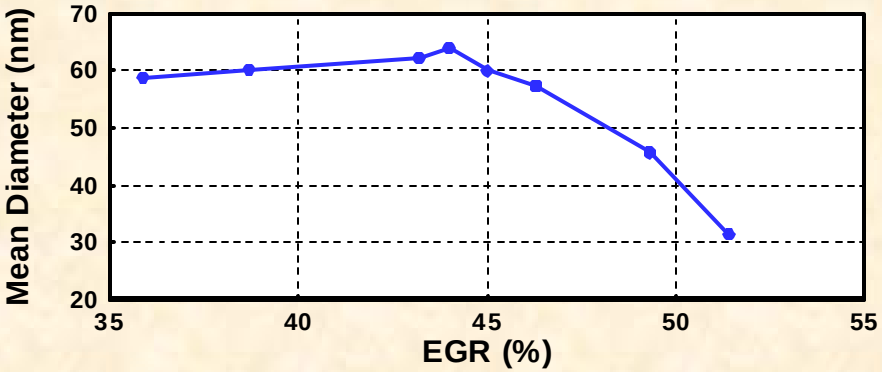




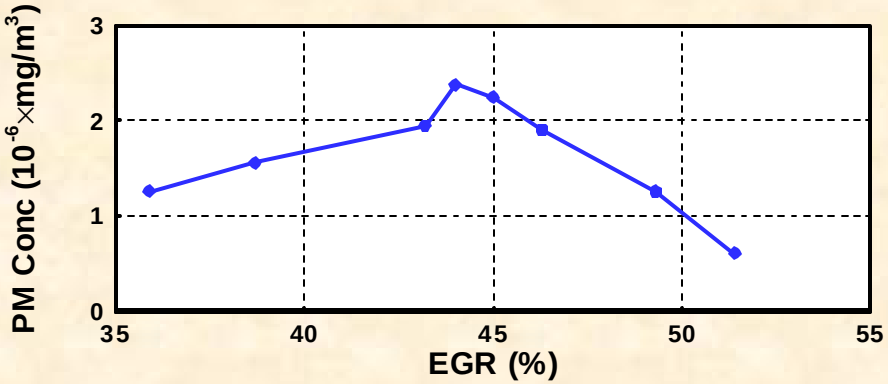

**Approach One**

# PM size and concentration decreased at very high EGR levels



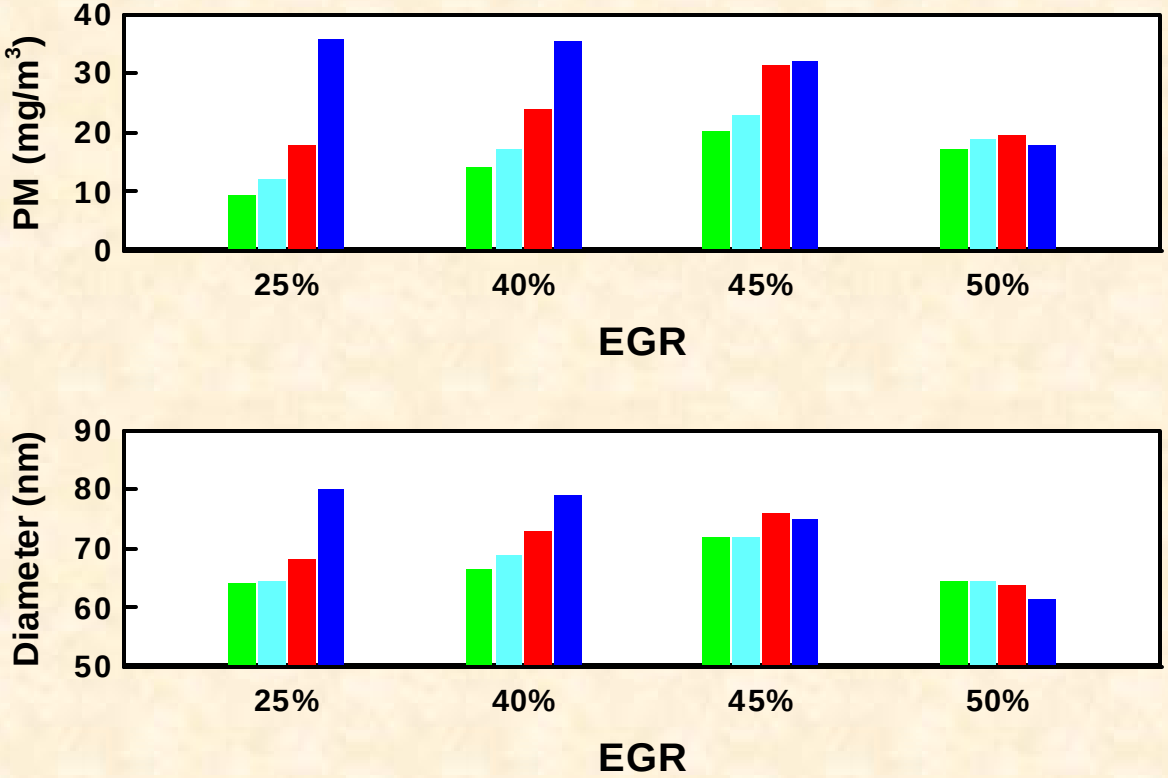




**Approach One**



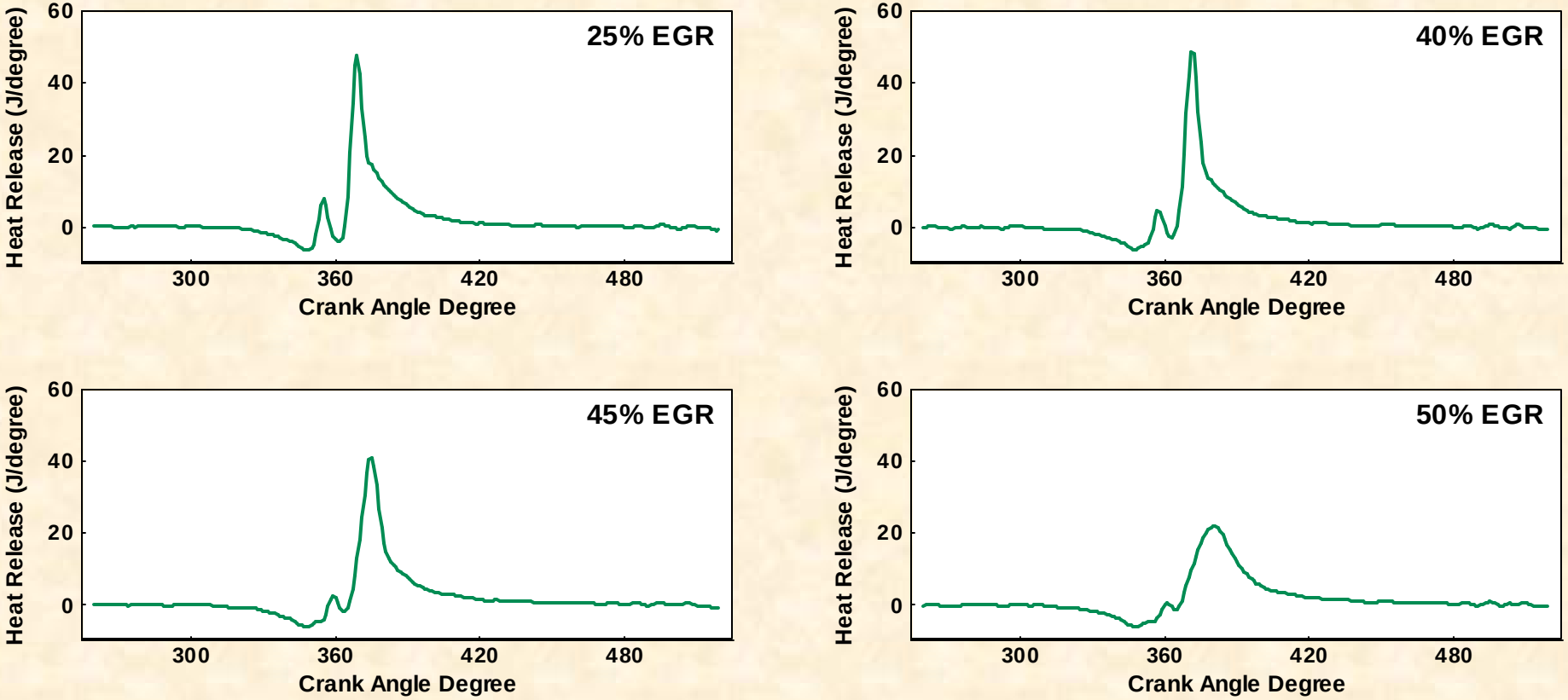
# Cylinder-to-cylinder variations in PM emissions decreased at higher EGR levels

- Cylinder 1
- Cylinder 2
- Cylinder 3
- Cylinder 4




**Oxygen emissions were significantly lower for cylinder 4 for all conditions.**

# Significant shift in heat release observed at higher EGR levels

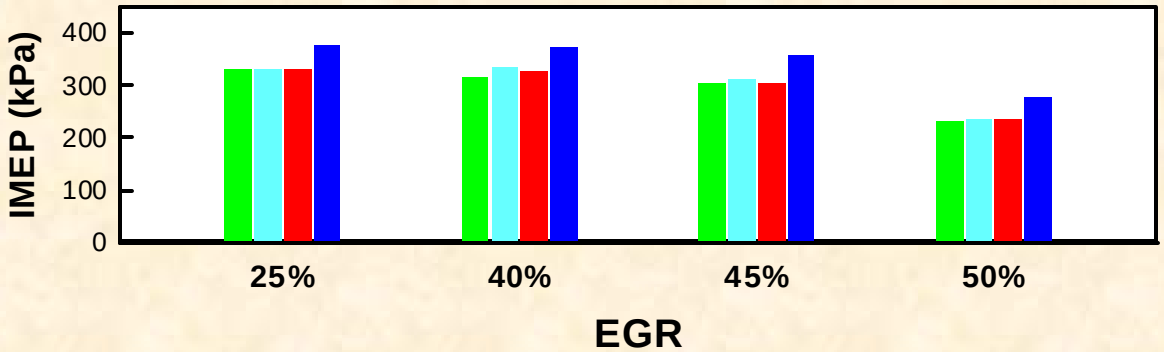


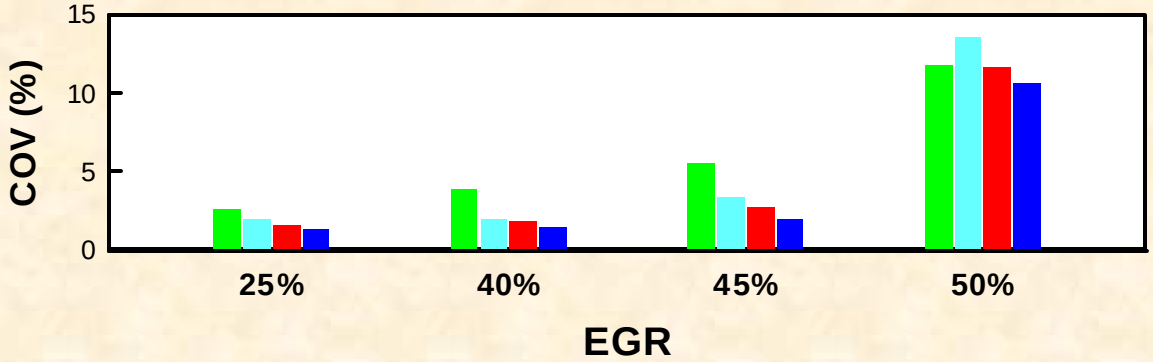



**Approach One**

# Cylinder-to-cylinder variations in combustion were significant for all EGR levels

- Cylinder 1
- Cylinder 2
- Cylinder 3
- Cylinder 4



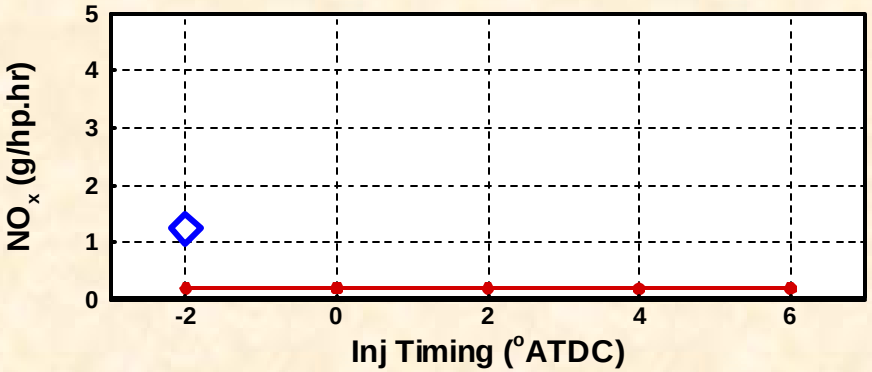

**Oxygen emissions were significantly lower for cylinder 4 for all conditions.**

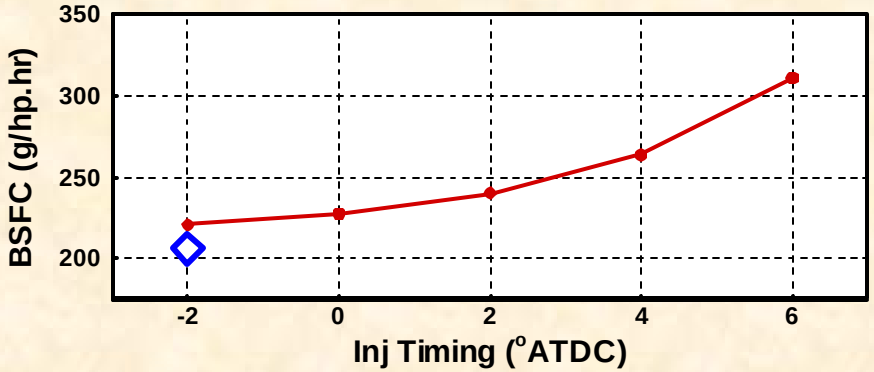
# ORNL explored two approaches to reduce engine-out NOx and PM at high EGR levels

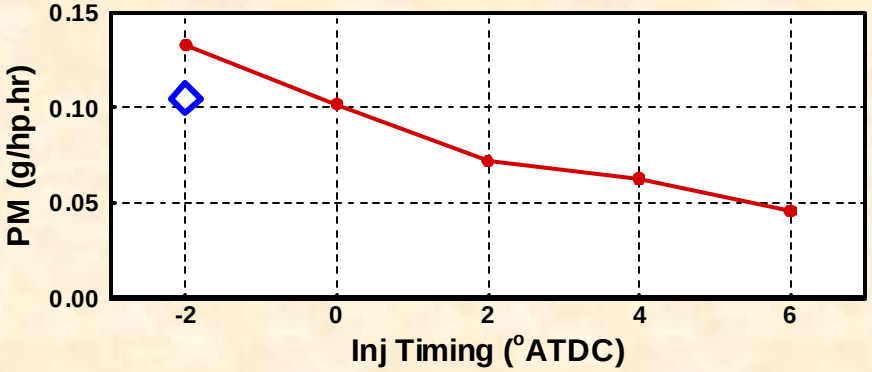
- Approach One
  - Utilizing EGR valve control, sweep EGR rate until EGR valve fully open.
  - Employ intake throttling to further increase EGR rate with EGR valve fully open.
- Approach Two
  - Utilizing EGR valve control, sweep EGR rate until EGR valve fully open.
  - Retard injection timing with EGR valve fully open.

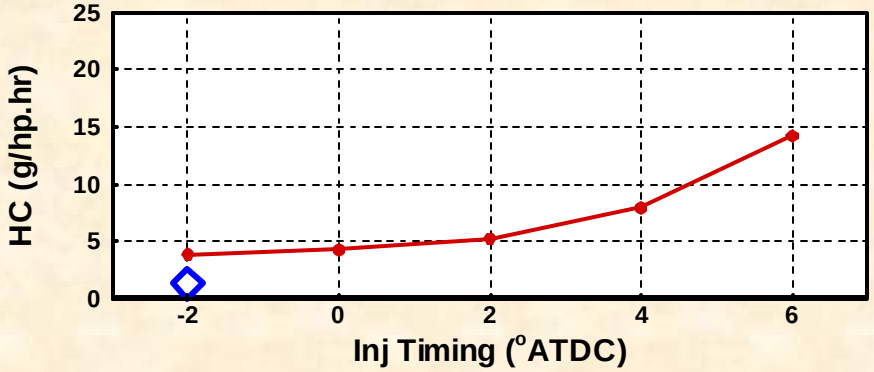
# Lower engine-out NOx and PM also observed using retarded injection timing (Approach Two)

## 1500 rpm, 2.6 bar BMEP (EGR fixed at 44%)



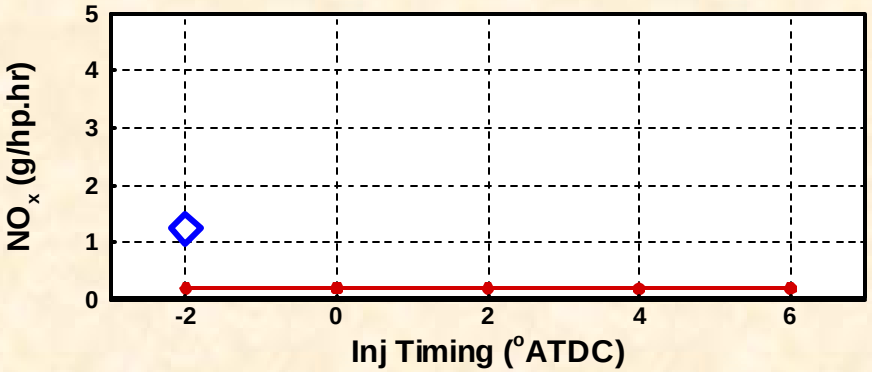



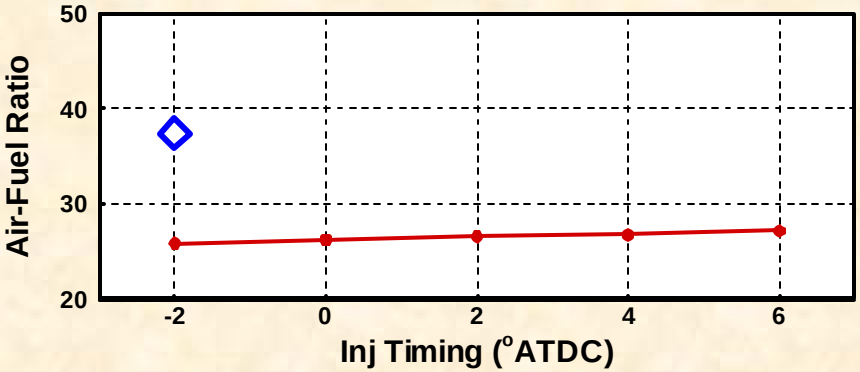



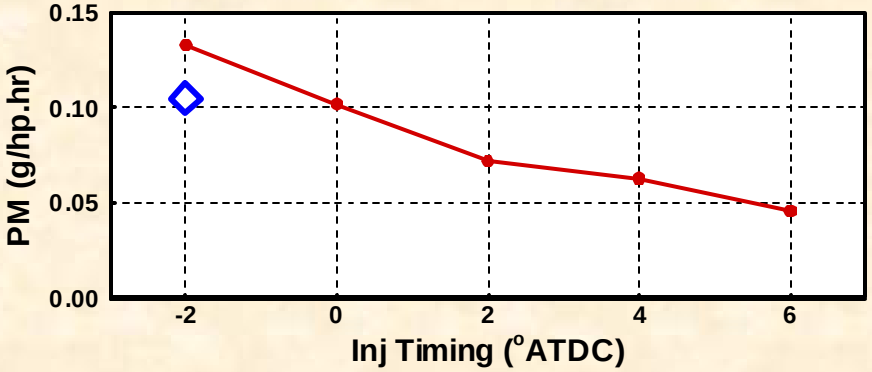



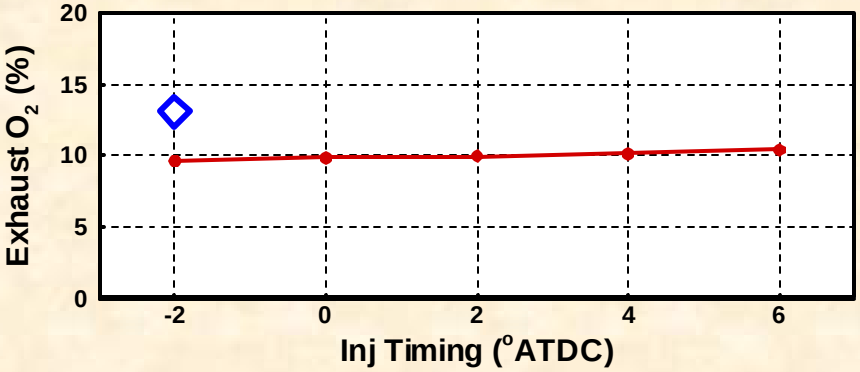

◇ **Production Calibration**
**(24% EGR)**

# Simultaneous low NOx and low PM were observed at lean air-fuel ratios



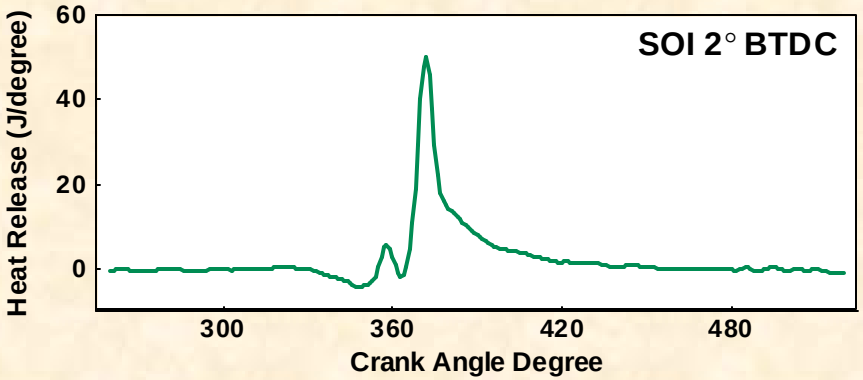



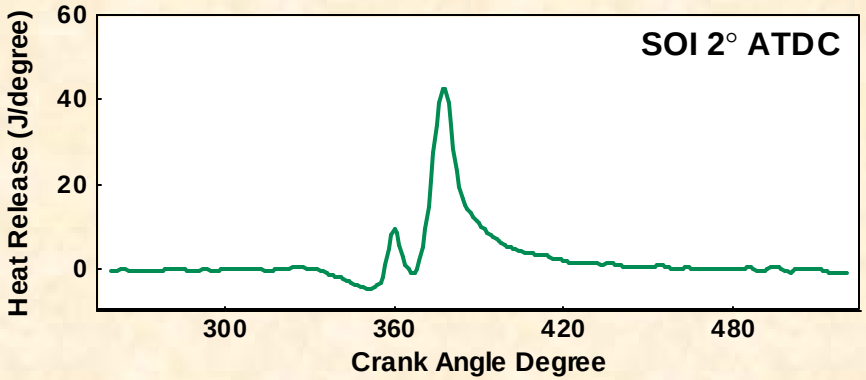



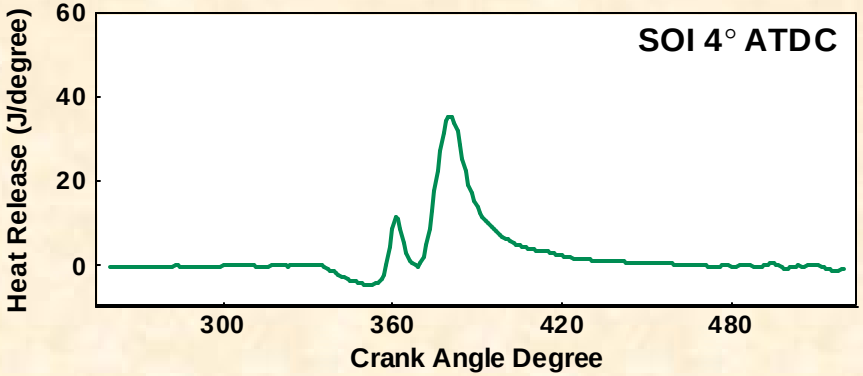


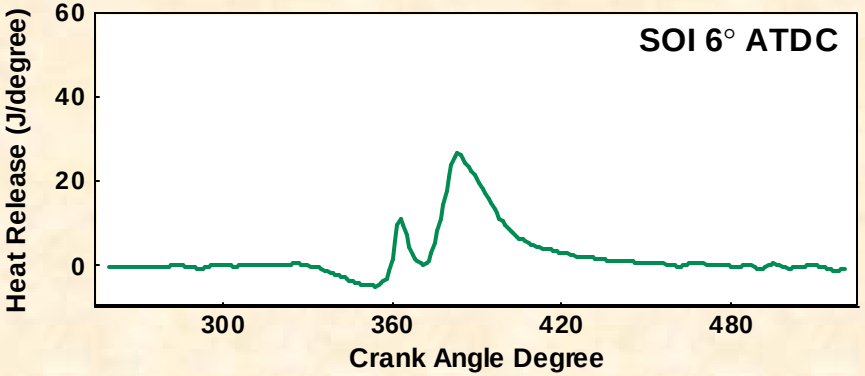

**Approach Two**

# Significant shift in heat release observed at retarded injection timings



# Trends in combustion and emissions were similar to those seen for Approach One

- Effect of retarding injection timing similar to increasing EGR via intake throttle.
- PM and NOx emissions decreased to levels below those observed for production EGR condition.
- BSFC/BMEP penalty observed for both approaches in low NOx and PM region.

# Preliminary Attempts to Recover Load at High EGR Rates Reveal Significant NOx and PM Reduction with Some Fuel Penalty

**2000 rpm, 2.0 bar BMEP**

| | EGR (%) | SOI (°ATDC) | BSFC (g/hp.hr) | NOx (g/hp.hr) | PM (g/hp.hr) | HC (g/hp.hr) | Exh Temp (°C) | Recovery Approach |
|---|---|---|---|---|---|---|---|---|
| Production | 14 | – 5 | 257.8 | 2.20 | 0.13 | 3.19 | 201.9 | NA |
| Approach One | 47 | – 7 | 253.1 | 0.24 | 0.07 | 6.28 | 224.2 | Adv Timing |
| Approach Two | 43 | 0 | 268.6 | 0.25 | 0.04 | 8.92 | 250.6 | Increased Rail Press |

**COV of IMEP comparable for all cases**

**Similar results at the 1500 rpm, 2.6 bar BMEP point.**

# General Observations

- Simultaneous reduction in PM and NOx observed using two approaches at several engine conditions.
- Reduction in PM and NOx possibly due to premixed combustion and/or premature quenching.
- Cylinder-to-cylinder variations in emissions and combustion are significant and change with EGR rate.
- Preliminary attempts to recover BSFC/BMEP at high EGR rates showed promise.

# Future Plans

- Data analysis and interpretation:
  - Massive data sets, many for individual cylinders: pressure, TEOM mass data, SMPS size data, gaseous emissions, diesel particle scatterometer, and fast response FID data.
  - Continue development of virtual sensor for closed-loop feedback control.
  - Determine mechanisms behind low NOx and PM emissions in high EGR combustion regime, why different from prior reports.
- Recovering BSFC/BMEP penalty.
- HC speciation.
- PM characterization.
- EGR distribution effects.