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

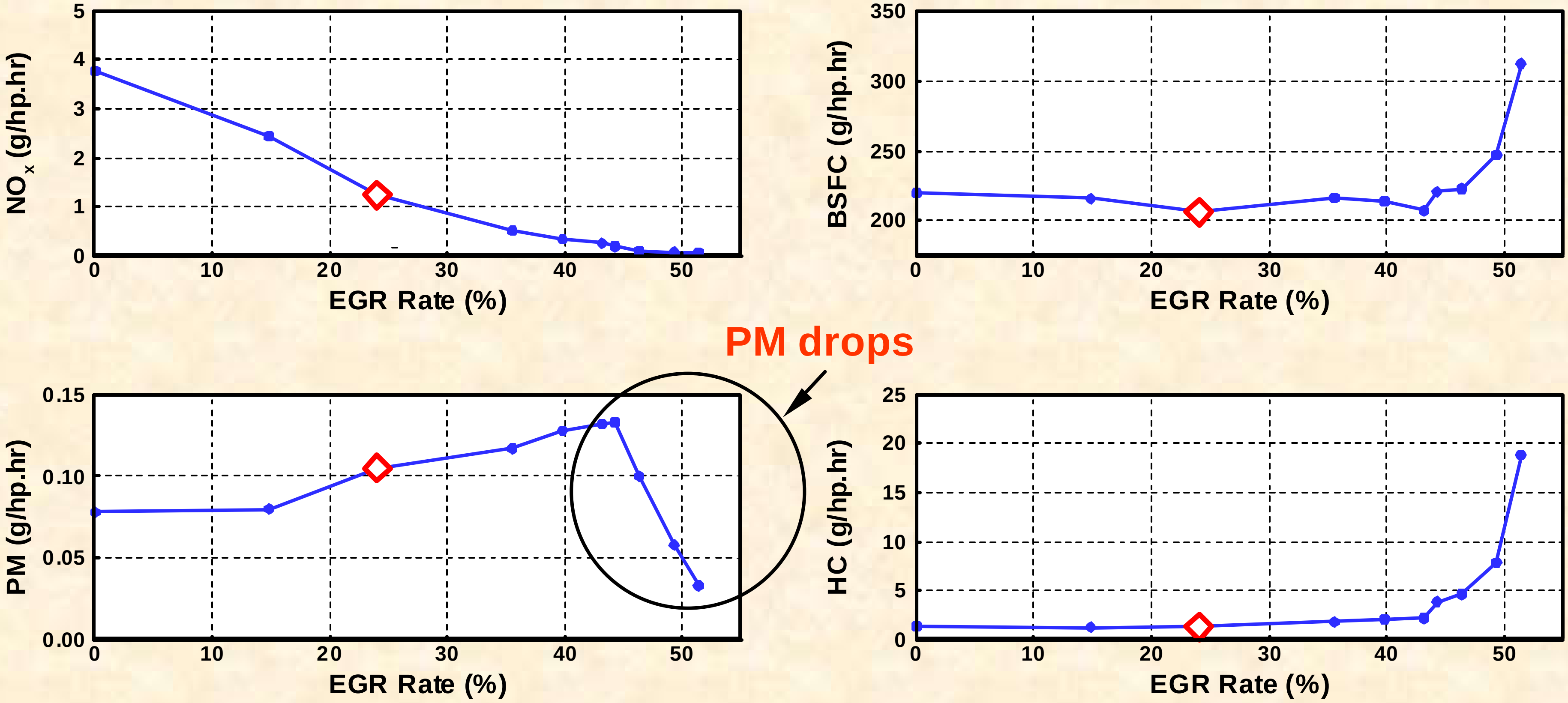
- **Engine Platform**
  - Mercedes 1.7 L common rail diesel engine with cooled EGR.
  - Full-pass control (modified SwRI RPECS system) of electronic throttle, EGR valve, and fueling parameters.
- **Instrumentation**
  (measurements for each individual cylinder)
  - In-cylinder pressure.
  - Regulated 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.

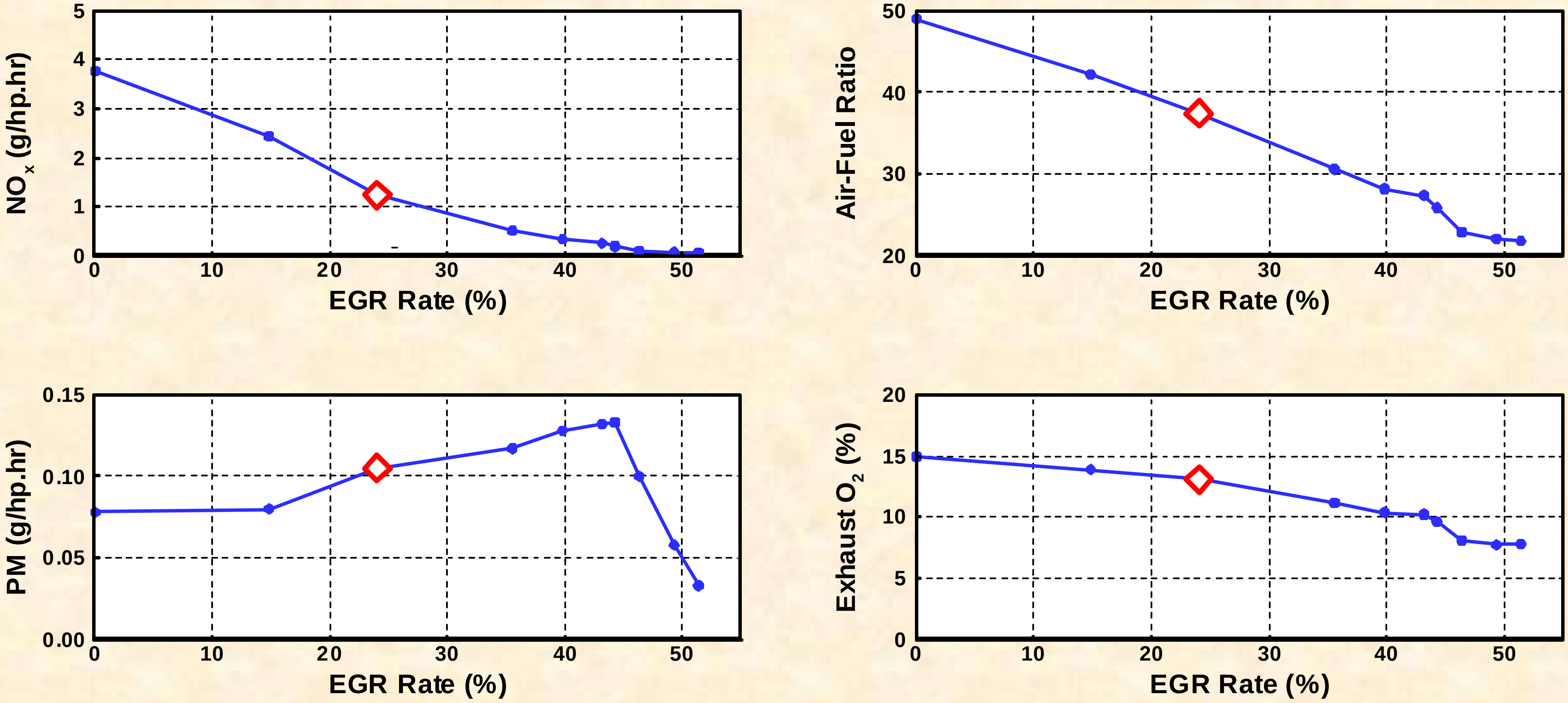
Lower engine-out NOx and PM observed at higher EGR rates with throttling (Approach One)

1500 rpm, 2.6 bar BMEP



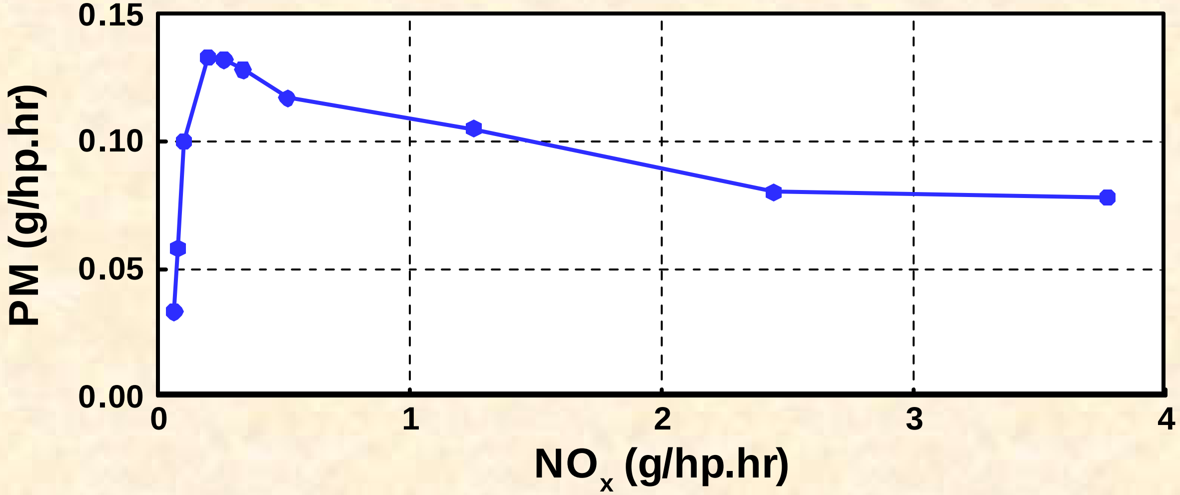
Production Calibration
(24% EGR)

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



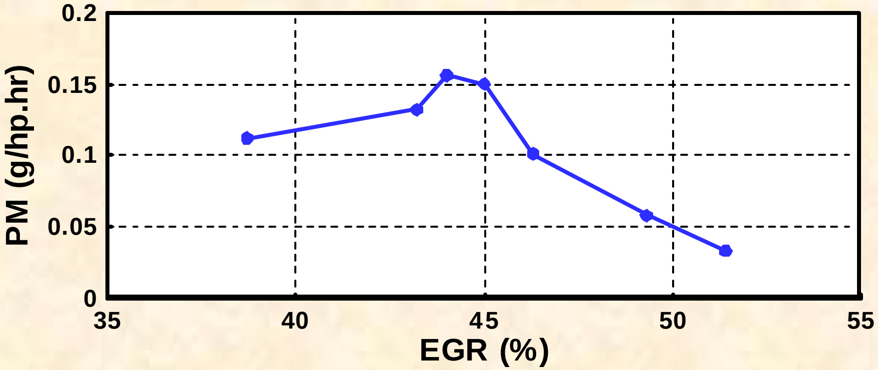
Approach One

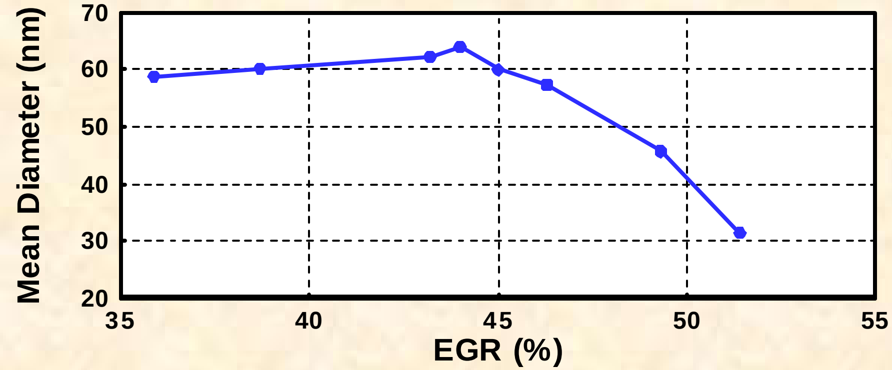
Not so "classic" PM and NOx tradeoff at 1500 rpm, 2.6 bar BMEP

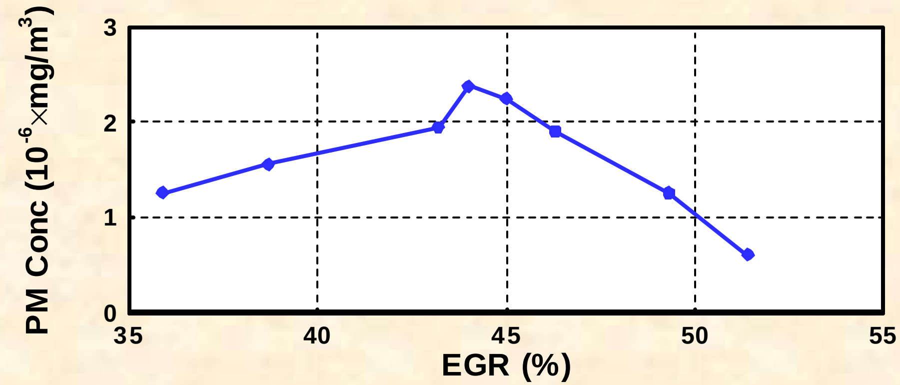


Approach One

PM size and concentration decreased at very high EGR levels



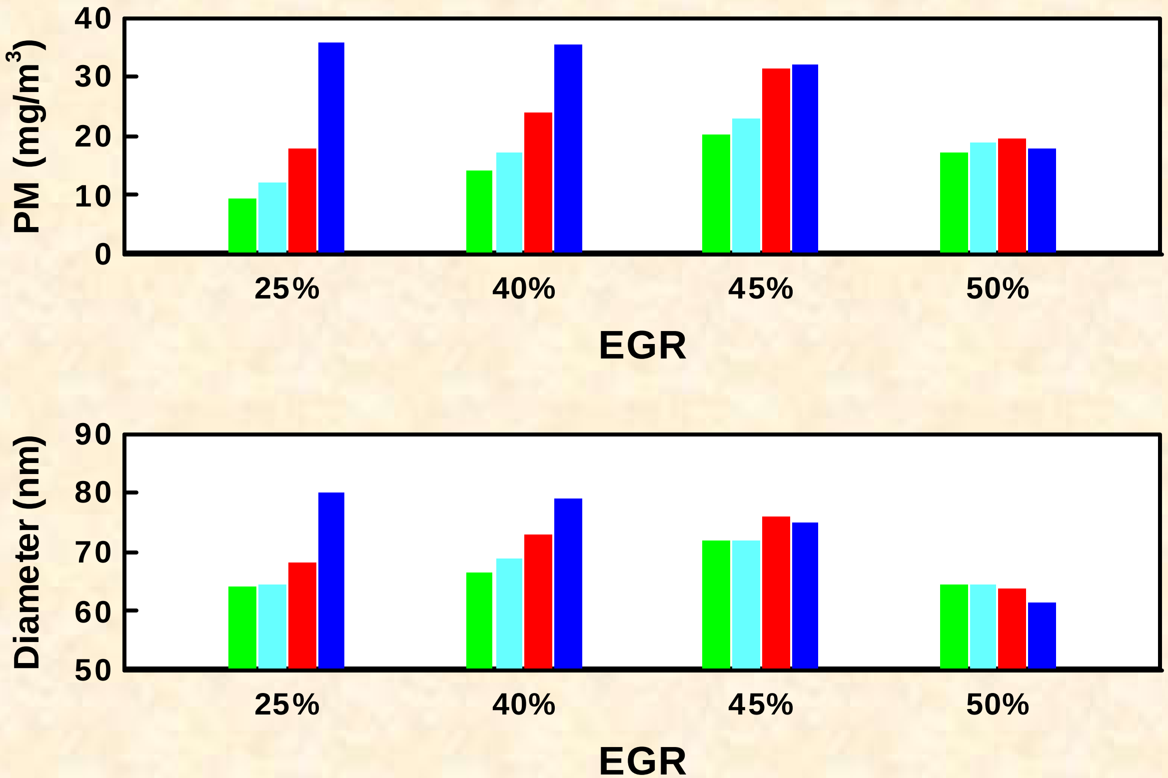




Approach One

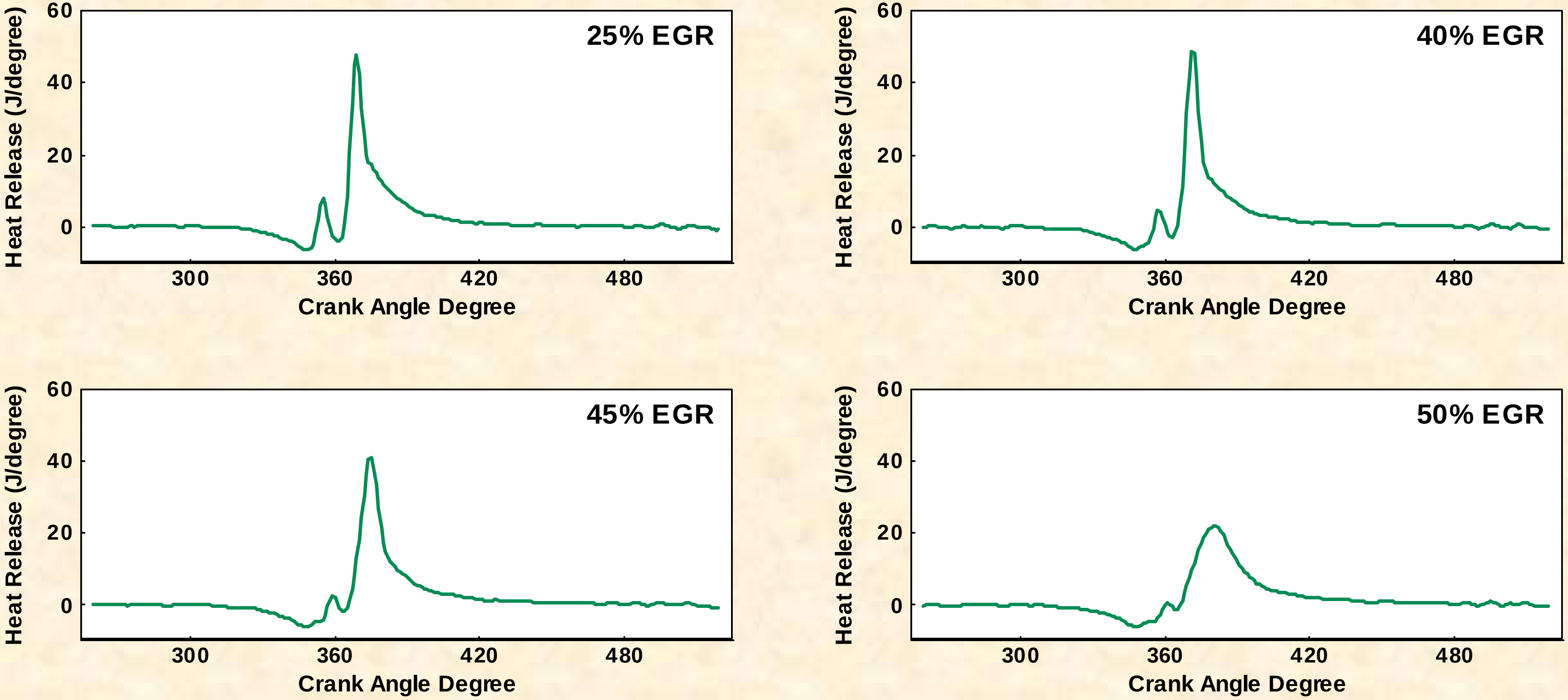
Cylinder-to-cylinder variations in PM emissions decreased at higher EGR levels

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



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

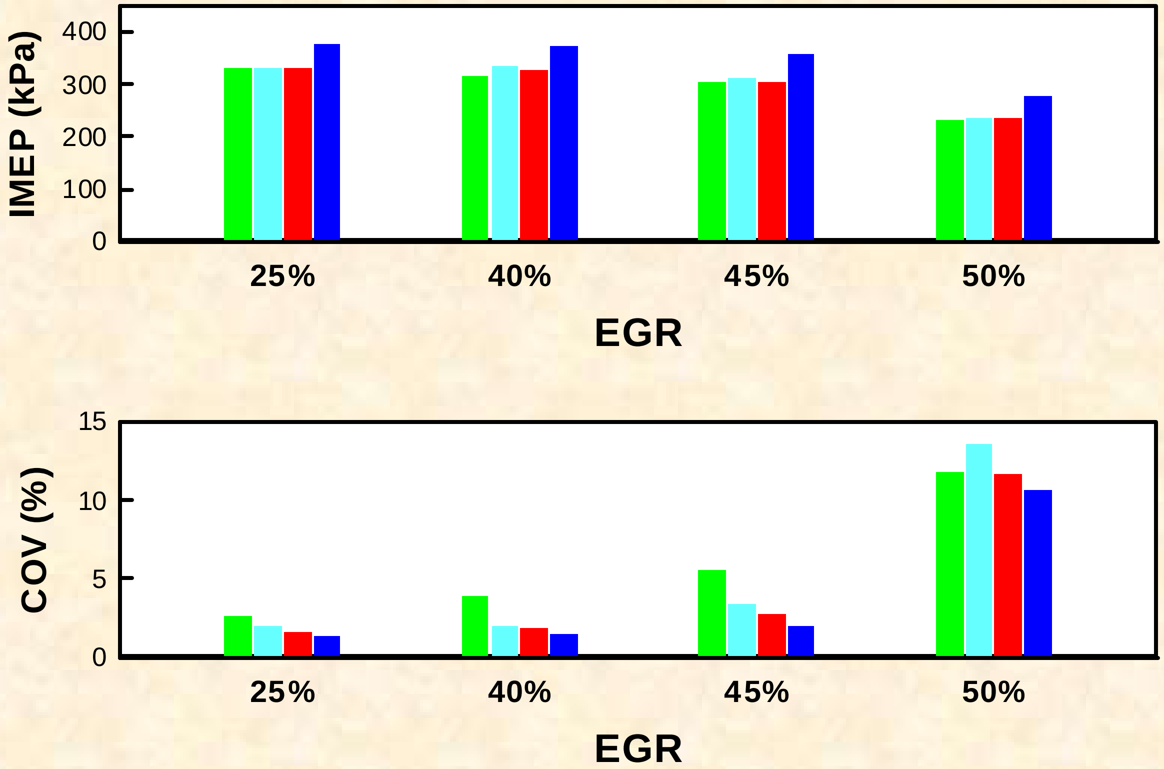
Significant shift in heat release observed at higher EGR levels



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.

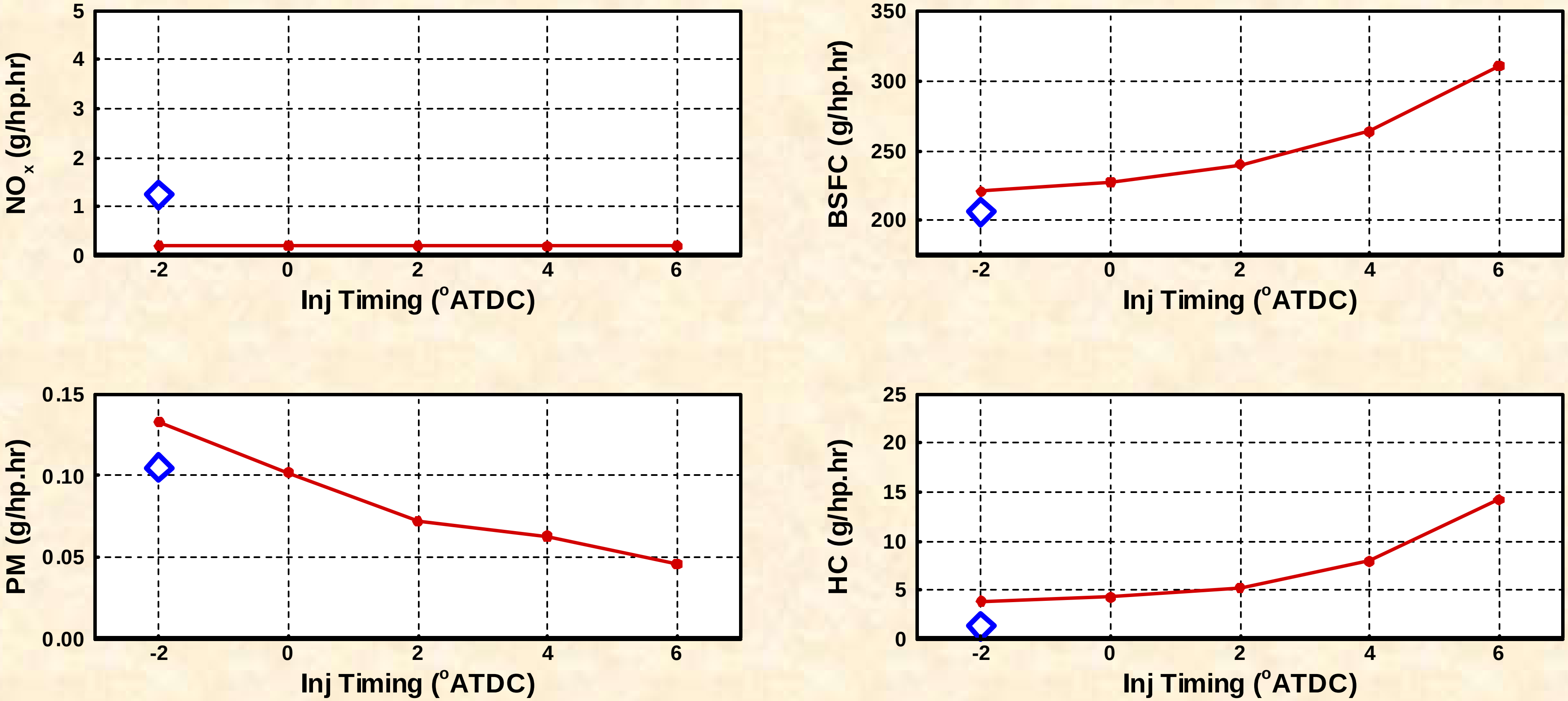
Approach One

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.

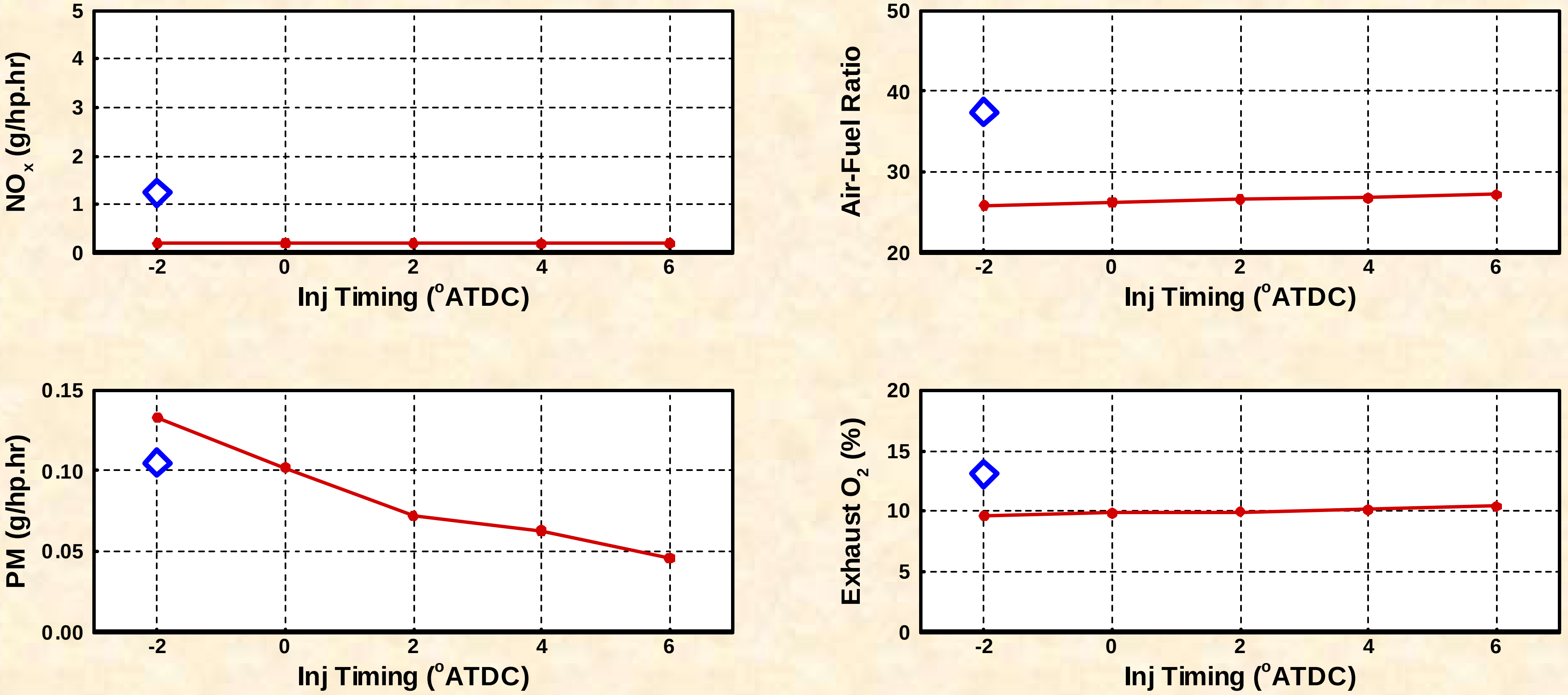
Lower engine-out NOx and PM also observed using retarded injection timing (Approach Two)

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



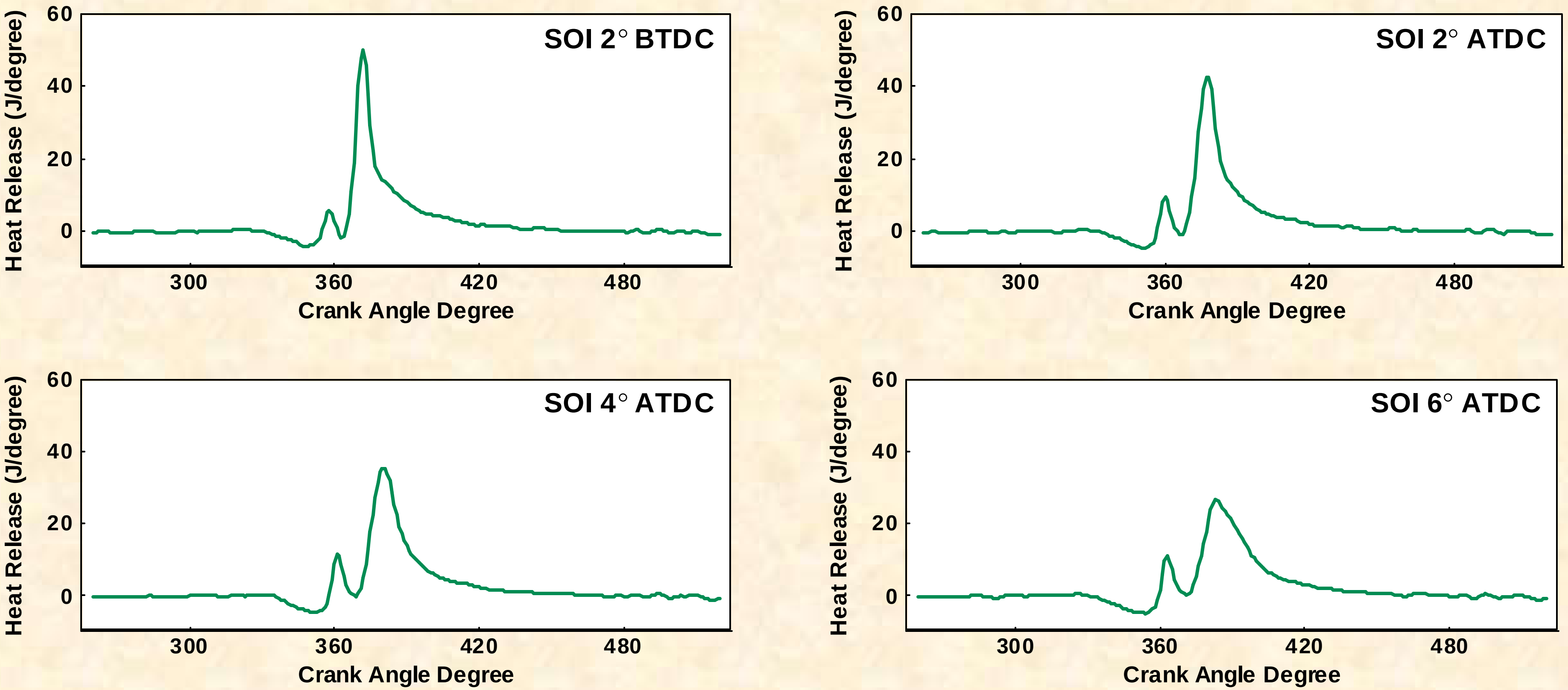
◇ **Production Calibration**
(24% EGR)

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.