Evaluation of High Efficiency Clean Combustion (HECC) Strategies for Meeting Future Emissions Regulations in Light-Duty Engines

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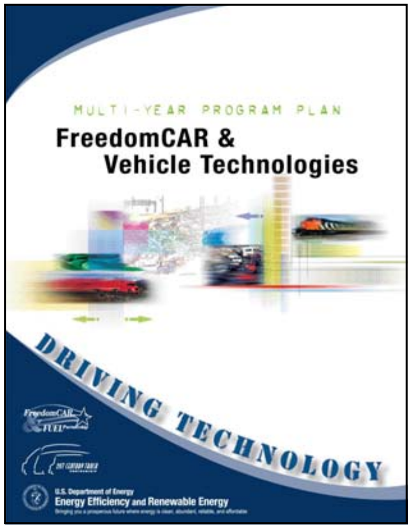
Project Overview



Motivation

Advanced combustion modes show promise as potential paths for meeting 2010 and beyond efficiency and emissions goals.

Objective of this Activity

Investigate potential near-term technologies for expanding usable speed-load range and to evaluate potential benefits and limitations for achieving HECC in light-duty diesel engines.

Complementary Activities:

- **Fuel property effects on diesel high efficiency clean combustion.** (parallel activity funded by Fuels Technology Subprogram, PI Scott Sluder)
- **Multi-Component Combustion Simulation Tools for Alternative Fuels.** (internally funded in collaboration with University of Wisconsin, PI Johney Green)

Comprehensive Research Approach

EGR Method & Composition	Low pressure, high pressure, N_2	↔
Injection Characteristics	Orifice size, fuel pressure, timing, duration, etc.	↔
Fuel Formulations	Oil-sands, bio-diesel blends, certification fuels, etc.	↔
Gaseous & PM Exhaust Analysis	HC speciation, PM precursor characterization , etc.	↔
Simulation	Injection & EGR strategies, efficiency & thermo analysis	↔

Multi-Cylinder Engine Platform

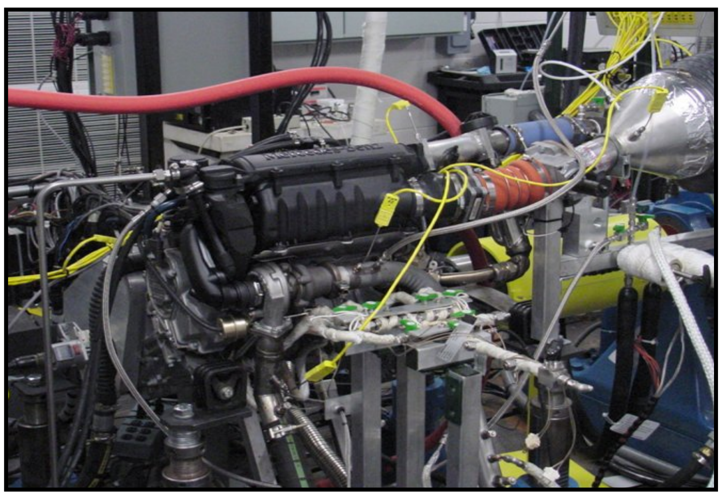
→

Improve understanding of HECC modes for enhanced multi-cylinder utilization

Show connection to light-duty certification cycles

Light-duty research engine

- Mercedes 1.7-L engine
  - Added EGR cooler, low pressure EGR loop, and throttle.
  - All other components are production.
- Equipped with rapid prototyping engine control systems.
- All four cylinders instrumented with pressure transducers.
- Extensive exhaust chemistry and PM analysis available.



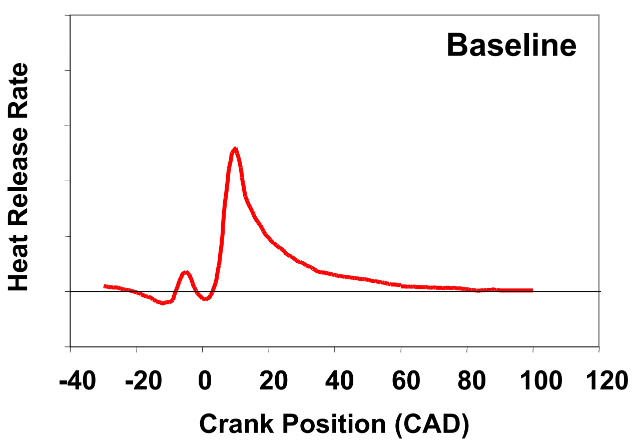
Number of Cylinders	4
Injector Holes	6
Injector Hole Diam, μm	169, 100
Bore, mm	80.0
Stroke, mm	84.0
Compression Ratio	19.0
Piston Geometry	Re-entrant bowl
Rated Power, kW	66
Rated Torque, Nm	180

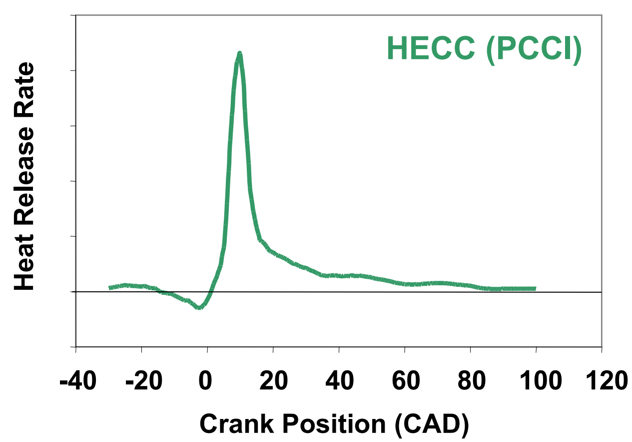
Premixed CI approach used to achieve HECC

Baseline conditions approximated OEM operating parameters.

HECC modes achieved with

- **Higher EGR rate**
- **Higher fuel rail pressure (400-1000 bar)**
- **Proper combustion phasing (single event, timing before but near TDC)**
- **Example heat release profiles at 1500 rpm, 2.6 bar BMEP**





Reminder: HECC is by definition high efficiency and low NOx & PM

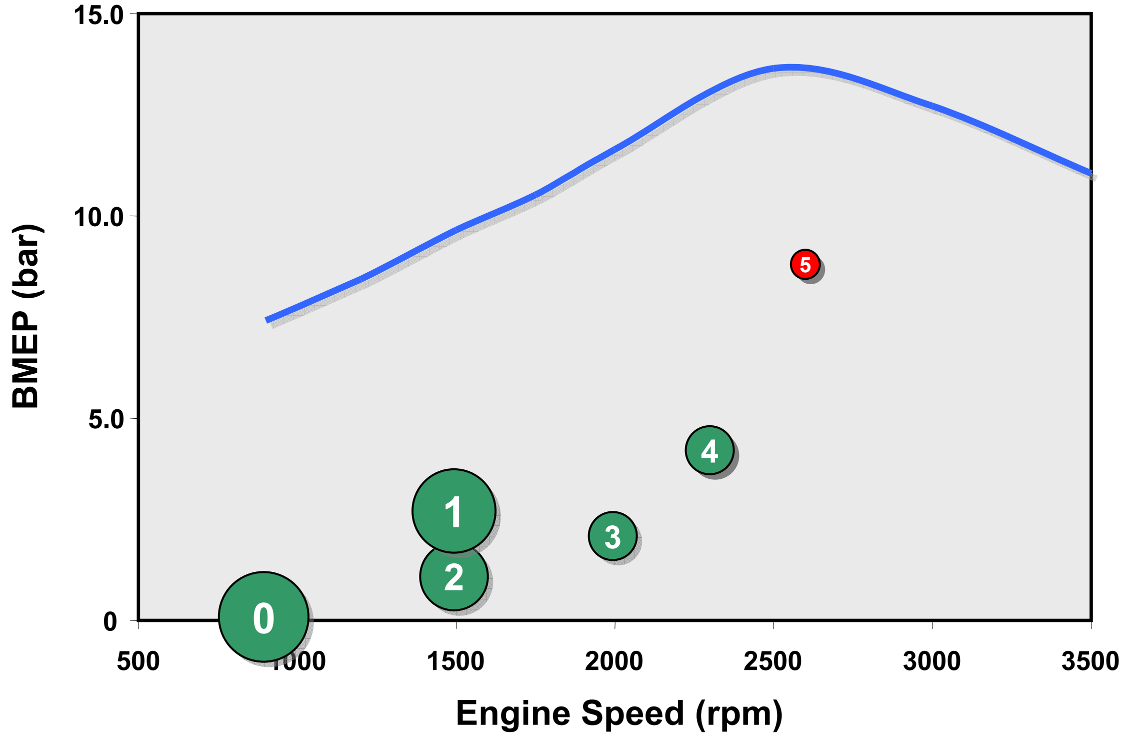
Experiments made use of engine conditions developed by Ad Hoc Working Group

- Considered representative speed-load points for light-duty diesel engines.
- Does not include cold-start or other transient phenomena.
- Represents method for estimating magnitude of drive-cycle emissions.

Point	Speed / Load	Weight Factor	Description
0	900 rpm / 0.1 bar	700	Idle
1	1500 rpm / 1.0 bar	400	Catalyst transition temperature
2	1500 rpm / 2.6 bar	600	Low speed cruise
3	2000 rpm / 2.0 bar	200	Low speed cruise with slight acceleration
4	2300 rpm / 4.2 bar	200	Moderate acceleration
5	2600 rpm / 8.8 bar	75	Hard acceleration

For more information SAE 1999-01-3475, SAE 2001-01-0151, SAE 2002-01-2884

Combination of LP & HP EGR for achieving HECC

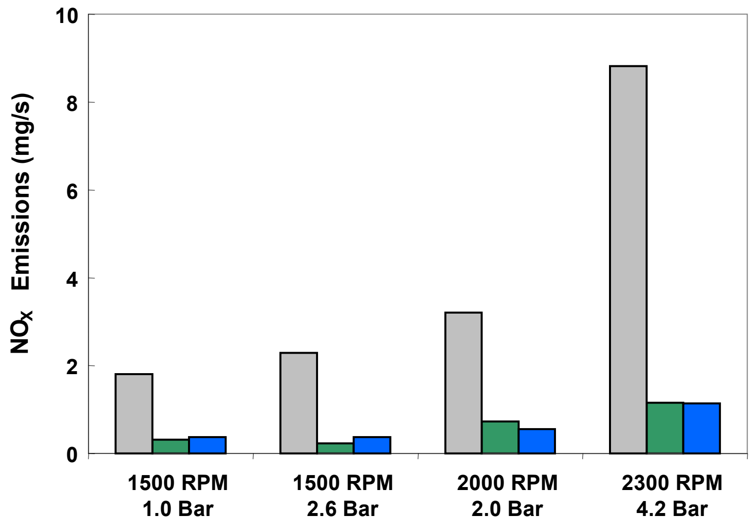


- HP EGR used to achieve Modes 0 to 3.
- LP EGR used to achieve Mode 4.
- BSFC equivalent to baseline operation.
- Emissions summarized in upcoming slide.

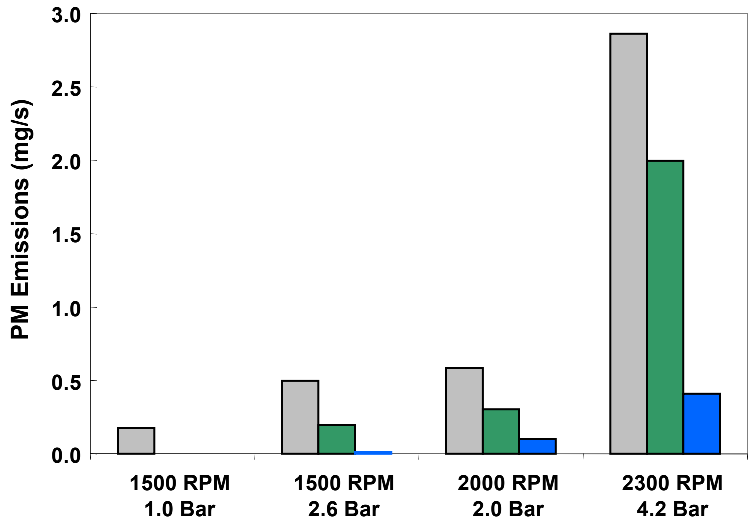
Injector orifice size (i.e., increased atomization & mixing) investigated at four modal conditions

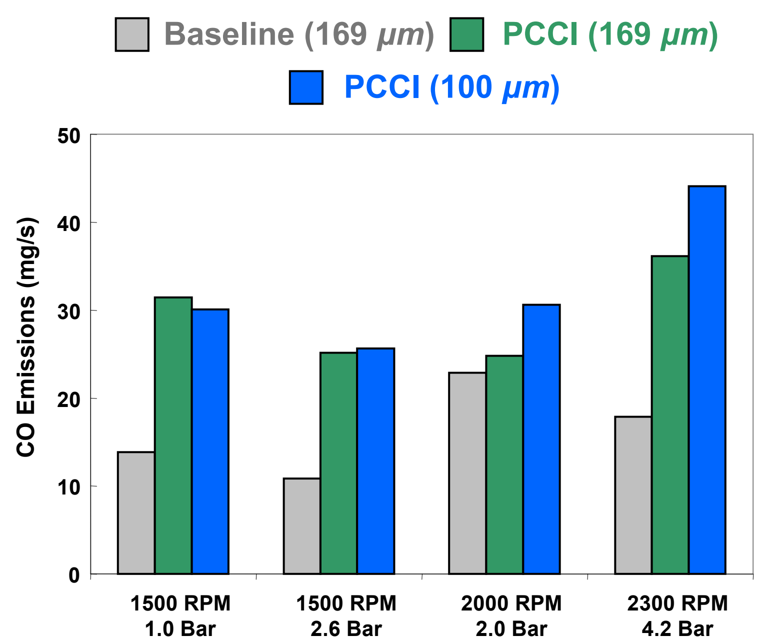
- **Injector nozzle sizes of 169 *µm* (OEM) and 100 *µm*, otherwise injectors were identical.**
- **Fuel pressure same for PCCI conditions with both orifice diameters – fuel pulse width adjusted to equalize fuel rate.**
- **PCCI injection pressures higher than OEM.**
- **EGR is combination of low & high pressure (combination enabled higher load points).**
- **BSFC is equivalent for all OEM, PCCI comparisons (*i.e.*, HECC).**

Smaller orifice diameter enhances PM benefits of PCCI

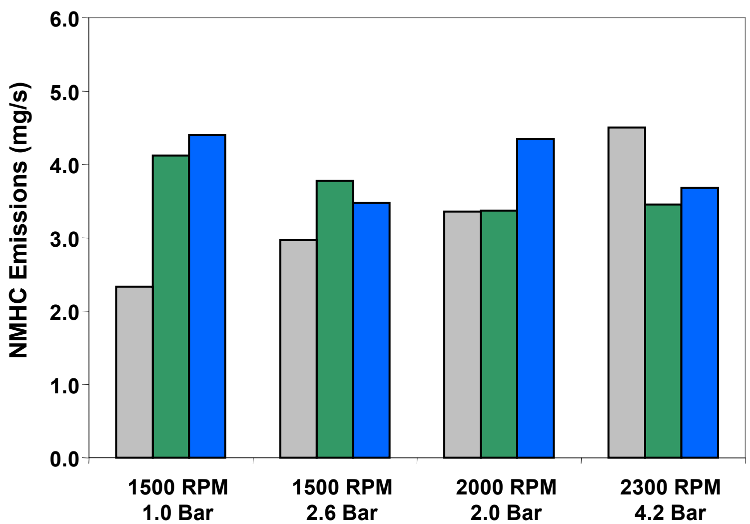


- NOx emissions similar for both injectors.
- PM emissions significantly lower for 100 *μm*.
- CO emissions similar.

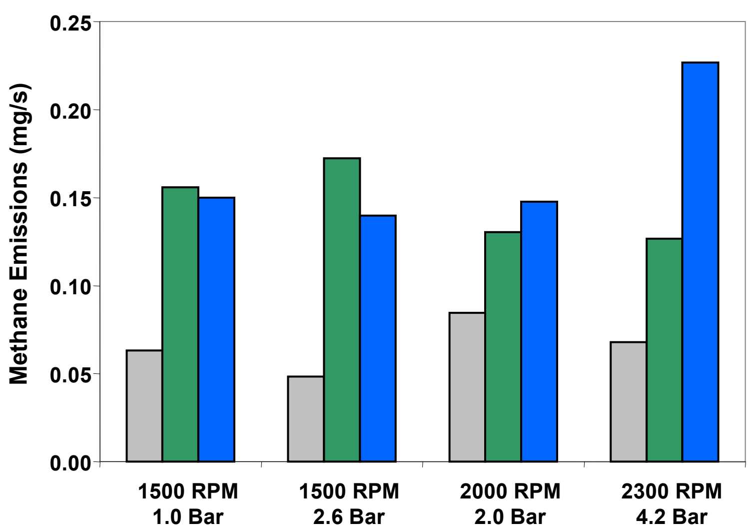


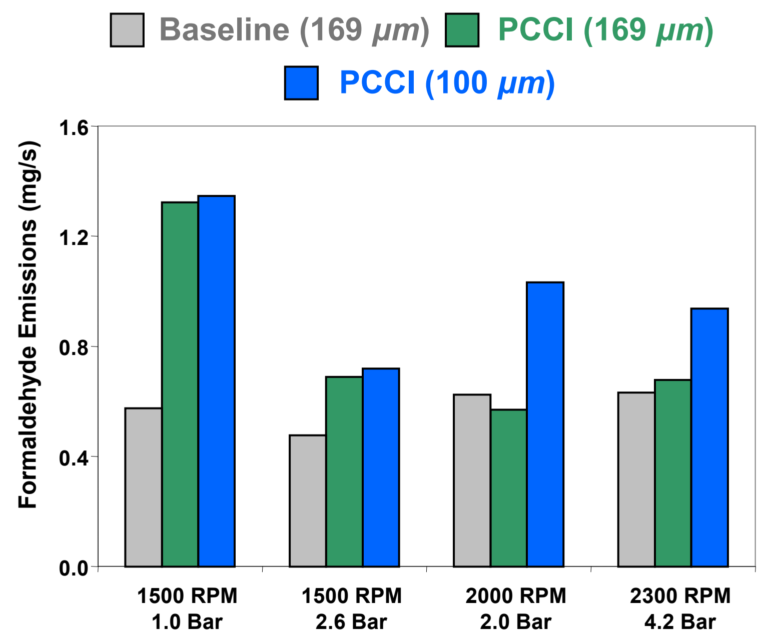


Smaller diameter orifice did not mitigate high HC characteristics of PCCI

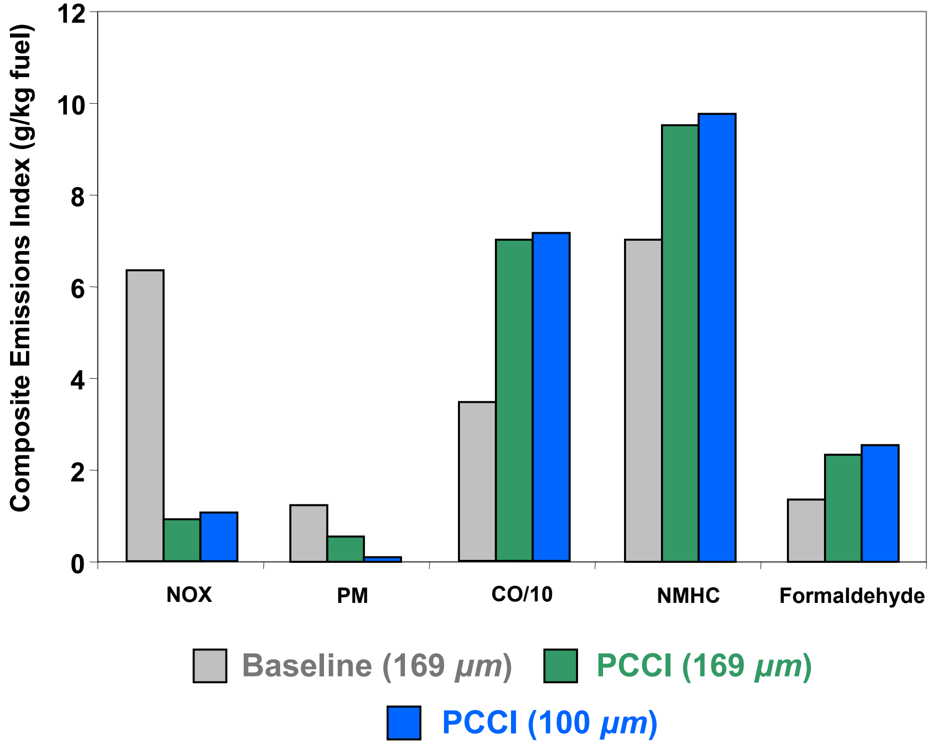


- Effect on HC emissions varies with speed-load condition.
- Overall much higher for PCCI operation.
- Can after-treatment take care of the HC emissions?





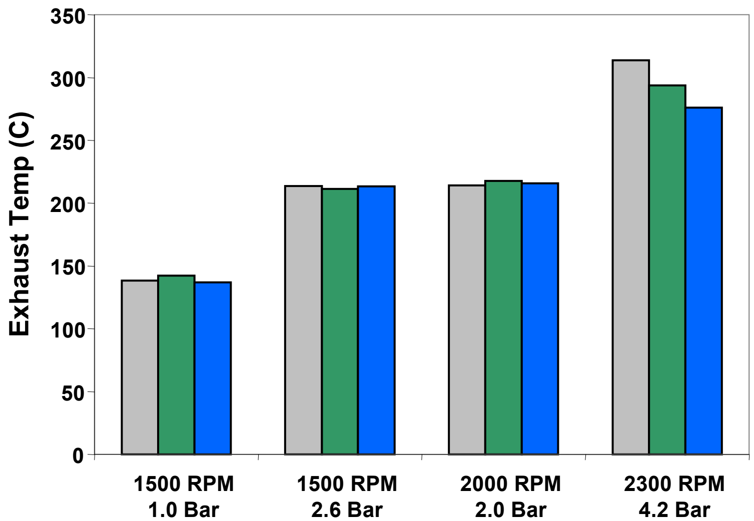
Composite indices highlight overall improvements in NOx and PM emissions at the expense of HCs and CO

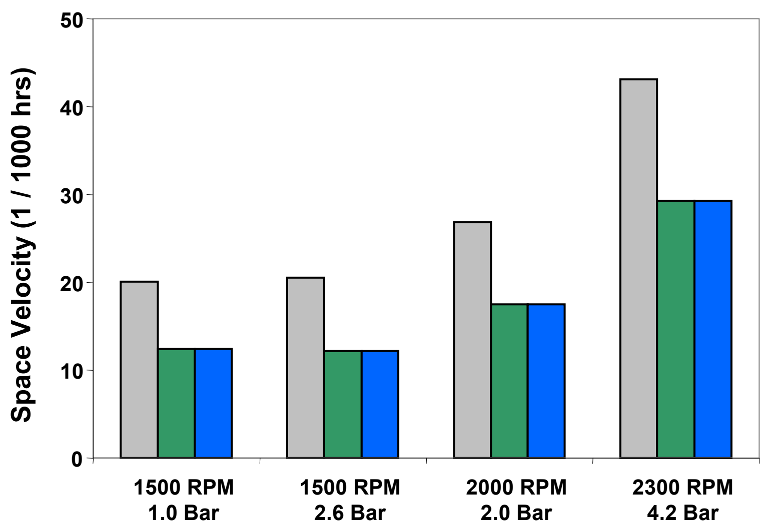


- **BSFC equivalent for baseline and PCCI modes.**
- **Significant reduction in PM observed for 100 *μm* injectors.**
- **Similar HC and CO levels for both orifice diameters.**
- **How do we deal with the high HCs and CO?**

Reminder – Purpose is to provide a metric indicative of cycle average results.

What does this mean with regards to after-treatment?



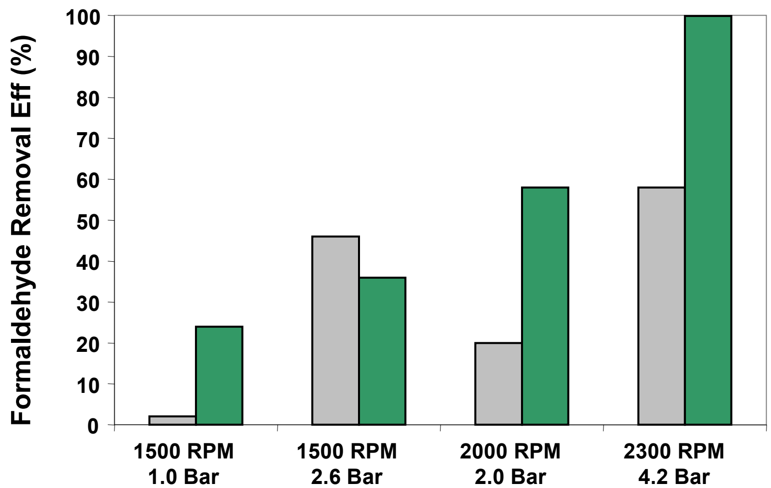


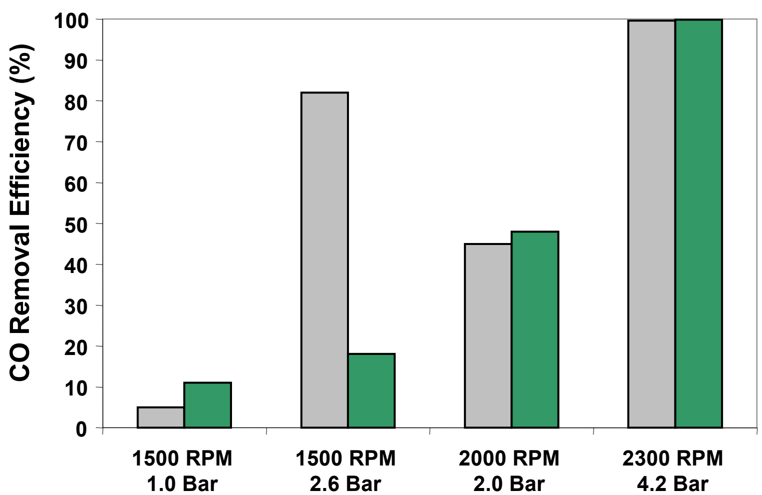
Baseline (169 *μm*) PCCI (169 *μm*) PCCI (100 *μm*)

- **Exhaust temperatures comparable for all modes.**
- **Achieving high oxidation effectiveness may be a challenge due to low temperatures.**
- **Space velocity lower for PCCI modes due to high EGR.**

Formaldehyde removal not sufficient for baseline or PCCI

(Factory MB silicon-carbide DPF for A-Class)

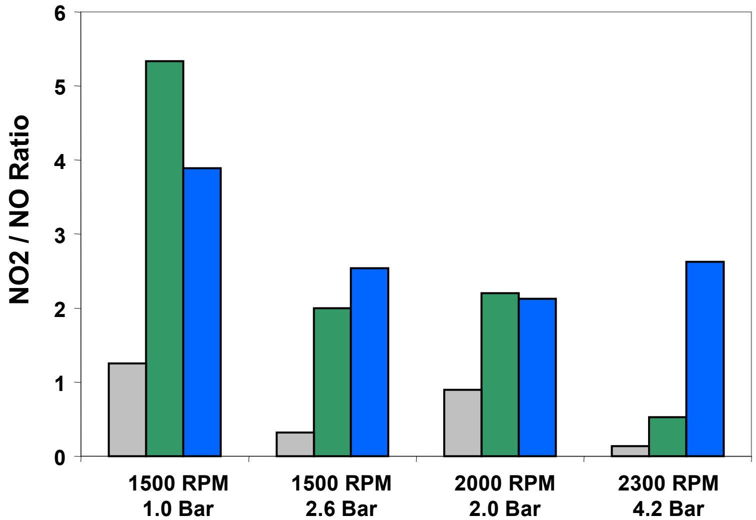




Baseline (169 *μm*) PCCI (169 *μm*)

- Formaldehyde removal is not sufficient for baseline or PCCI.
- CO removal sufficient for baseline and PCCI.
  - Standard relatively high as compared to other pollutants
- Any other issues?

What are implications for NOx after-treatment?



- **NOx in PCCI modes dominated by NO_2.**
- **Shift toward NO_2 is consistent with lower flame temperature.**
- **May be beneficial to NOx adsorbers, especially at lower exhaust temperatures.**
- **May not be beneficial to SCR due to high N_2O production for ratios > 1.**
- **After-treatment may need to accommodate wide variation in ratio (especially if mode switching is required).**

Fuel formulation investigated for achieving HECC operation

- **Certification fuel (CPChem)**
- **Low-aromatic Tier 2 certification fuel (CPChem)**
- **Oil Sands fuel (from Shell Canada)**
- **SME bio-diesel (World Energy) 5% blends with certification and low-aromatic**

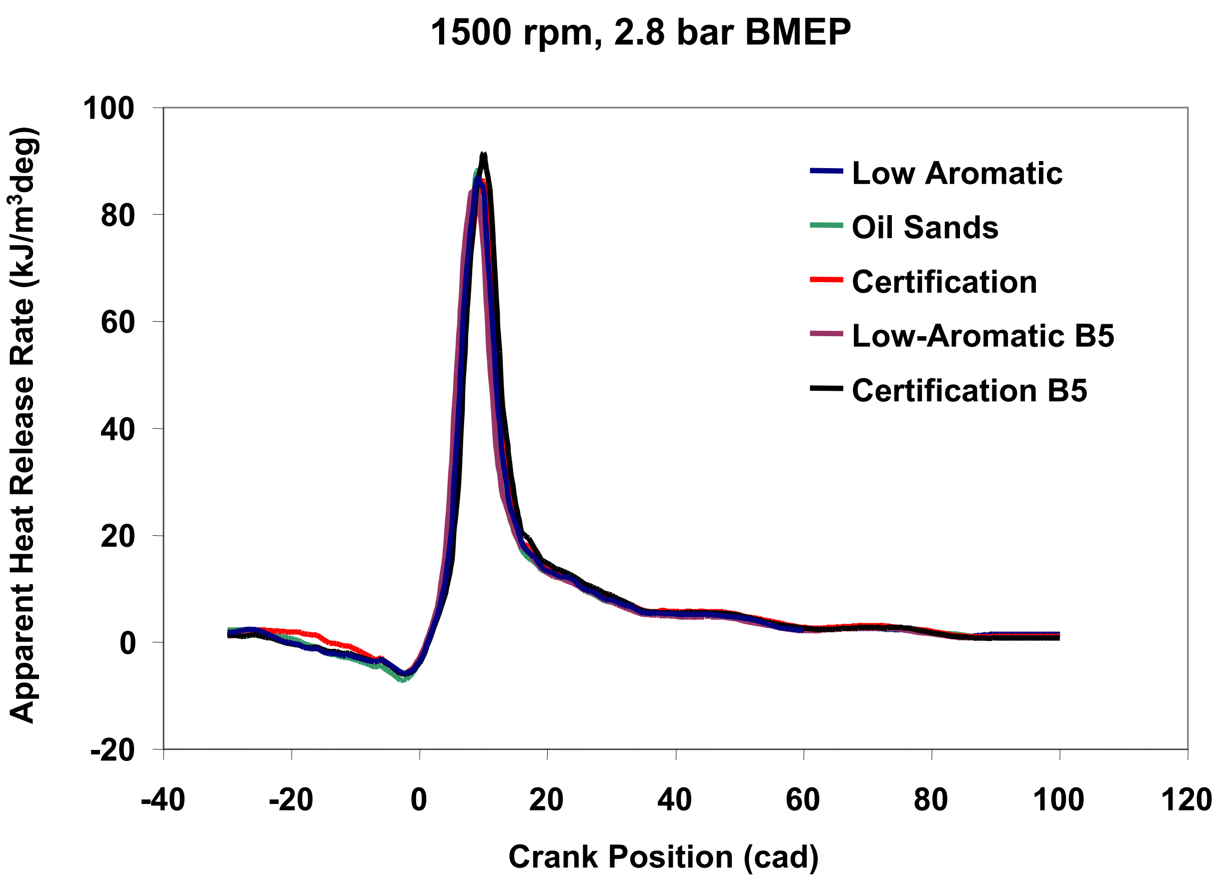
Fuel "Similarities"

- **Cetane**
  47.3 – 49.9
- **Heating Value**
  42.8 – 43.1 MJ/kg
- **Specific Gravity**
  0.830 – 0.845
- **Viscosity**
  2.27 – 2.32 cs

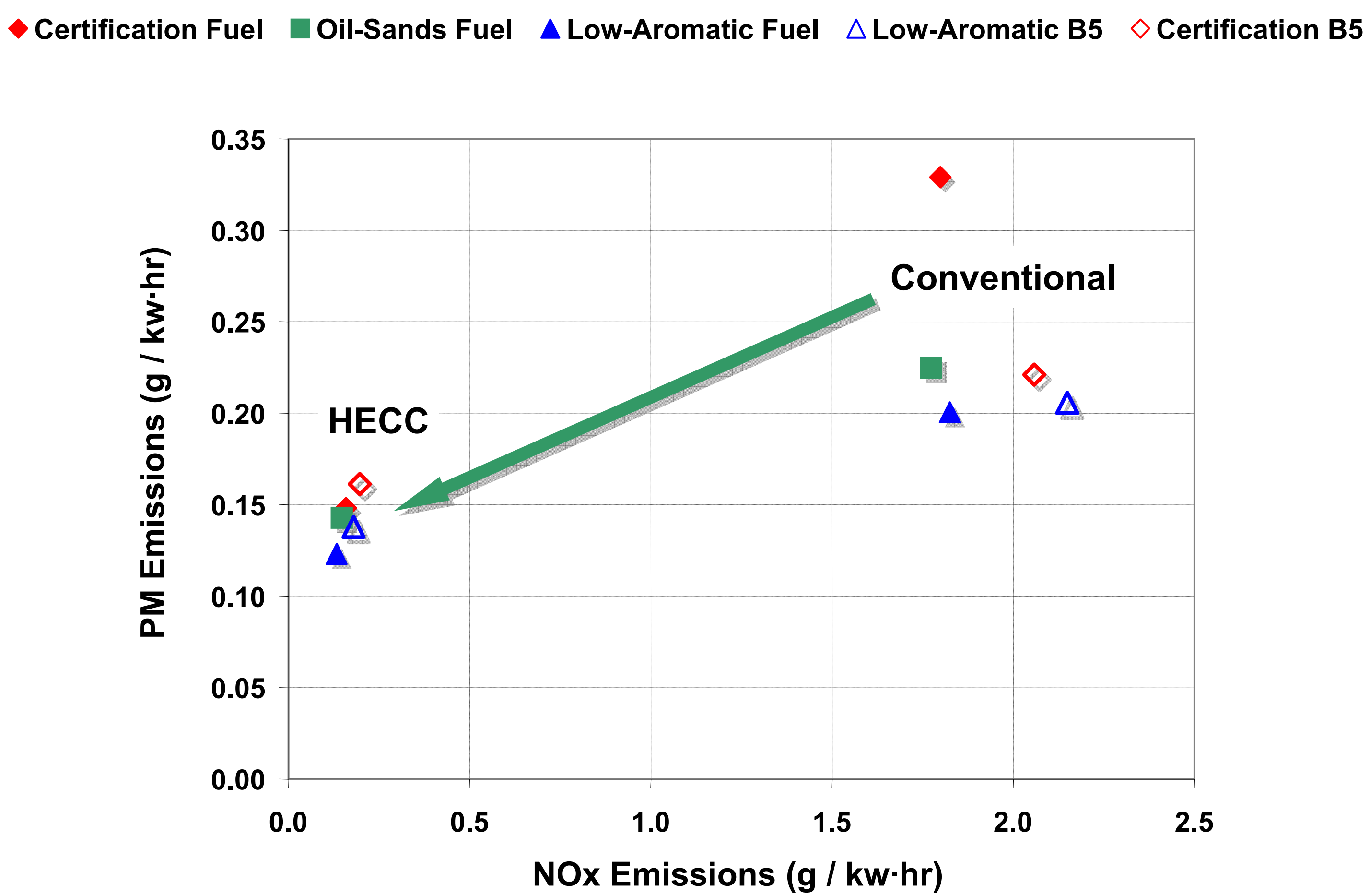
Fuel "Differences"

- **Sulfur**
  13 – 386 PPMw
- **Aromatics**
  9.0 – 30.6 Vol%
- **Polynuclear Aromatics**
  0.7 – 10.0 Wt%
- **Olefins**
  0.3 – 2.0 Vol%
- **Oxygen**
  0.0, 0.6% B5 Blends

Heat release profiles and SOC similar for all five fuels



HECC operation achieved for all five fuels for this operating condition



Fuel formulation observations

- Combustion characteristics and engine efficiency similar for the five fuels in this study.
- Maximum HECC BMEP similar – no obvious opportunity for significant load expansion.
- Difficult to separate effects arising from differences in aromatics and distillation with small number of fuels.
- PM benefit of low-aromatic and 5% bio-diesel low-aromatic blend observed for HECC operation.
- Reductions in HC, H_2CO, and CO emissions possible in HECC modes through fuel reformulation (not shown).

Conclusions

- Low pressure EGR offers PM emissions and load expansion benefits.
- PCCI operation efficiently reduces NOx and PM emissions at expense of CO, HC, and formaldehyde emissions.
- Smaller injector orifice diameter is effective at enhancing PM reduction for PCCI operation.
- After-treatment oxidation will be a challenge for reducing higher HC and CO emissions observed with PCCI operation.
- NOx after-treatment systems used with PCCI operation will need to be more tolerant of wider range of NO_2/NO ratios.
- Fuel formulations investigated did not have a significant effect on ability to achieve HECC operation or HECC speed-load envelope.

On-going and future work

Further understanding of potential efficiency and emissions benefits, as well as enablers, of advanced combustion strategies on multi-cylinder operation and after-treatment technologies.

- **Remainder FY 2006 continuation of research shown in this presentation.**
- **Installation of GM 1.9-L and porting of advanced controller.**
  - **OEM hardware include EGR cooler, VGT, and throttle.**
  - **Same geometry investigated at U-Wisconsin and Sandia National Laboratory.**
- **Installation of variable compression ratio (VCR) version of MB 1.7-L.**
  - **Potential of CR and dilution for achieving HCCI and PCCI over extended speed-load range in multi-cylinder engine.**
- **More detailed thermodynamic and exhaust chemistry analysis as well as computer simulation for improved understanding of efficiency opportunities with simultaneous emissions reduction.**
- **Fuel properties as enablers for HECC operation (ongoing parallel activity funded by Fuels Technology Subprogram).**