Addressing the Challenges of RCCI Operation on a Light-Duty Multi-Cylinder Engine

Presented by **Robert Wagner**

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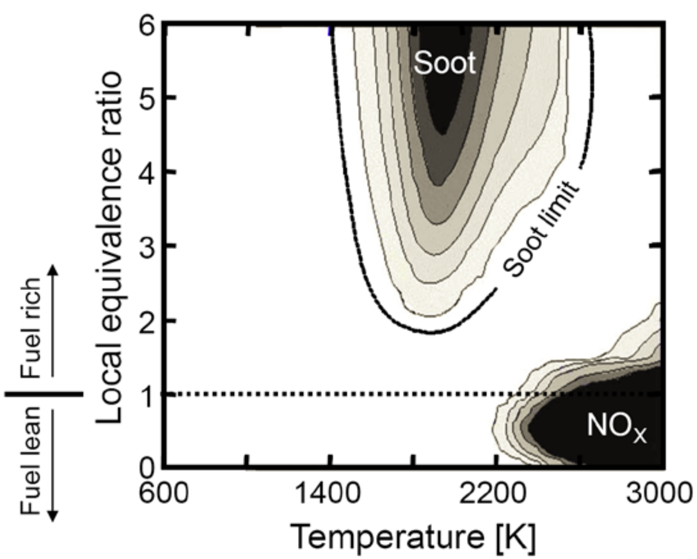
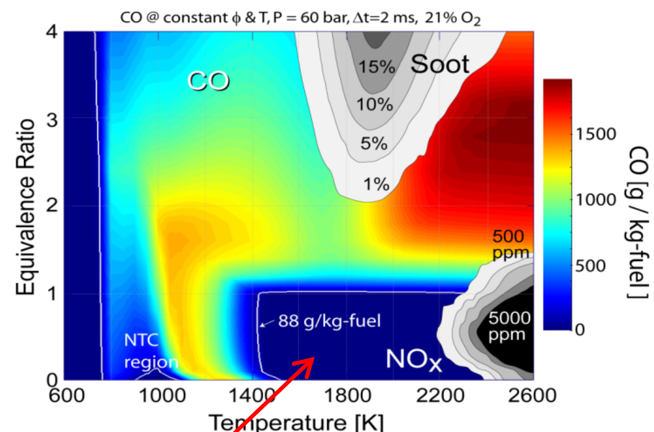
October 3, 2011
DEER 2011
DETROIT
Directions in Engine-Efficiency and Emissions Research Conference

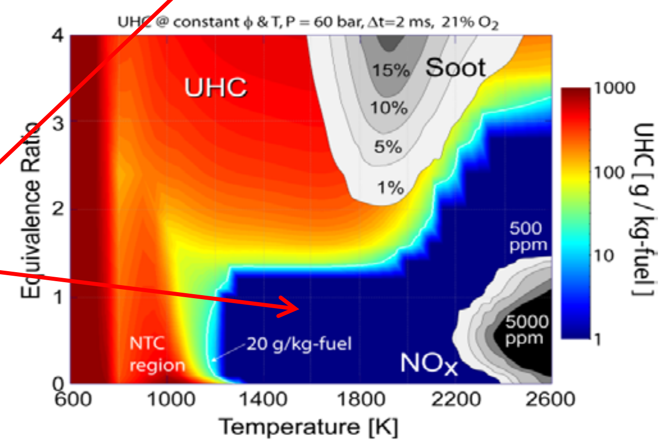
Simultaneous high efficiency with low emissions requires precise control of the combustion process

LTC creates reacting mixtures in-cylinder that avoid soot and NOx formation …



…while at the same time avoid CO and UHC emissions.



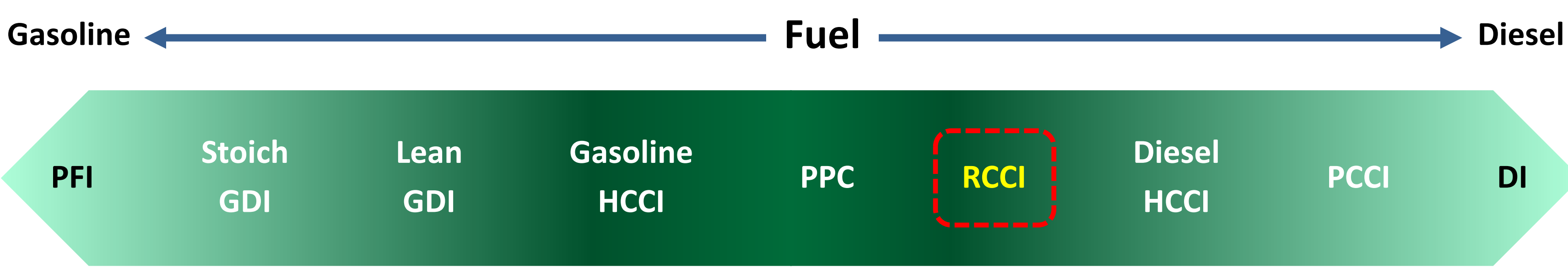


Charge must end up in this region after combustion is complete

Slide adapted from DOE presentation, Gurpreet Singh *et al.*

How does Reactivity Controlled Compression Ignition (RCCI) combustion compare to other approaches?

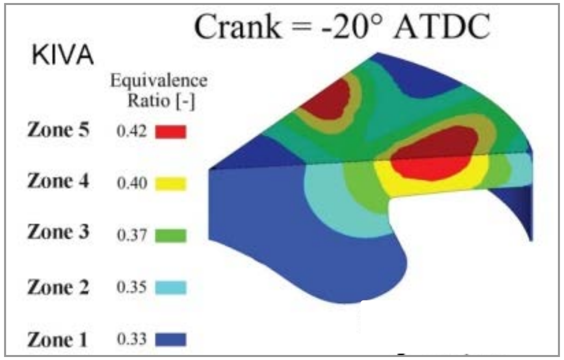
- **Advanced combustion approaches in general converging on technologies for maximum control of the combustion process.**
  - High compression ratio
  - High dilution
  - In-cylinder direct injection
  - Etc.
- **RCCI makes use of GASOLINE + DIESEL to add a new and powerful dimension to control in-cylinder charge conditions.**



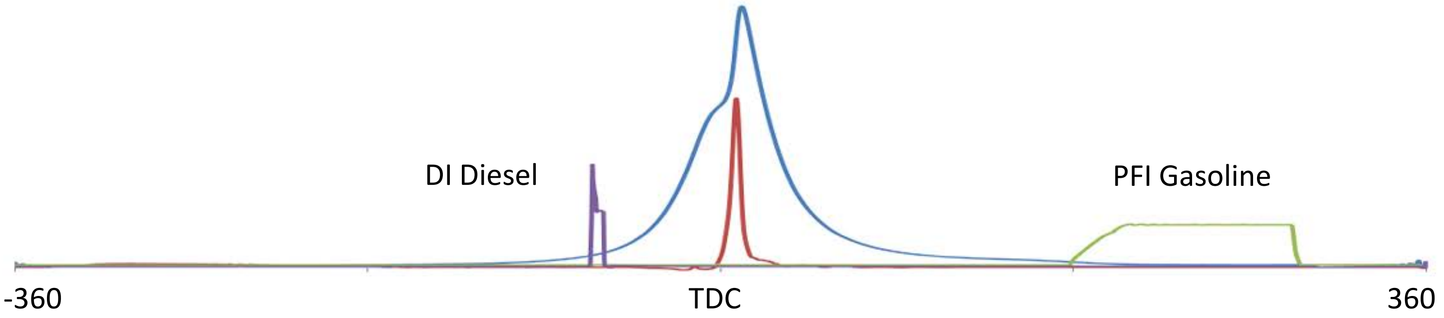
<u>Reference:</u> Adapted from Briggs et al., 2011 DOE Annual Merit Review.

Combination of gasoline + diesel provides robust control of the combustion path

- **Multi-fuel approach makes use of desirable properties of both gasoline and diesel.**
  - Gasoline well suited for high loads (PFI).
  - Diesel fuel well suited for low loads (DI).
- **In-cylinder fuel blending in combination with in-cylinder charge conditions controls the combustion process.**
  - Gasoline port fuel injection with diesel direct injection.
  - Direct injection strategy spans single and multiple events depending on in-cylinder conditions.
  - Charge preparation is also very important.
- **Simulation and single-cylinder experiments demonstrate potential of this approach for very high efficiency with low emissions.**



References: Kokjohn et al. (SAE 2009-01-2647) and Hanson et al. (SAE 2010-01-0864) for more details on dual-fuel concept.



Next step is to transition RCCI combustion to production viable hardware to better understand real-world fuel economy potential

Gross indicated efficiency

- Fundamental combustion
- Simulated boundary conditions

Brake (shaft) efficiency

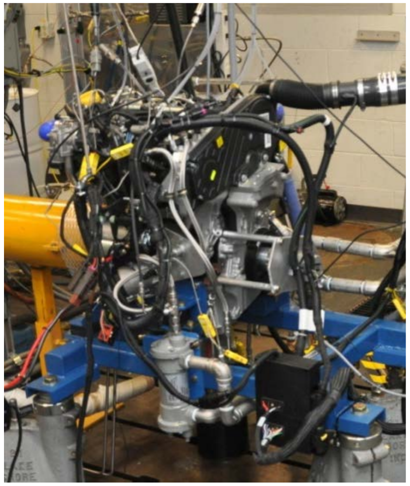
- Hardware limitations
- Engine-system controls
- Instability mechanisms
- Cylinder imbalances
- Aftertreatment integration
- Health impacts
- Auxiliary losses

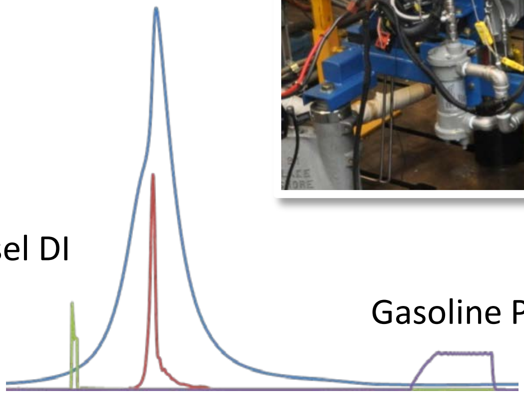
Drive cycle efficiency

- Drive system
- Fuel mix
- Drive cycle mismatch
- Vehicle system management

Experimental setup for multi-cylinder RCCI combustion

- **RCCI engine based on 2007 GM 1.9-L multi-cylinder diesel engine.**
  - Dual-fuel system with PFI injectors for gasoline
  - OEM diesel fuel system
  - OEM and **optimized** pistons
  - OEM variable geometry turbocharger
  - Expanded EGR heat rejection and control
- **Full pass DRIVVEN control system**
  - Full control of diesel & gasoline fuel systems
  - Cylinder-to-cylinder balancing capability
  - Next-cycle feedback control capability





Modified Intake Manifold with PFI Injectors

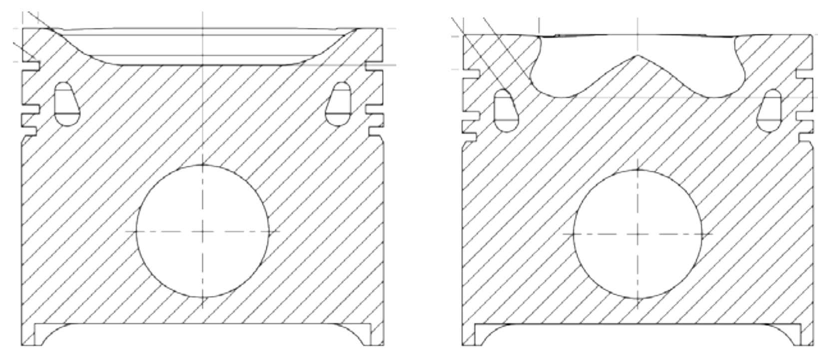
RCCI Optimized (left) and OEM (right) pistons

<u>Reference</u>: Curran et al. , "In-Cylinder Fuel Blending of Gasoline/Diesel for Improved Efficiency and Lowest Possible Emissions on a Multi-Cylinder Light-Duty Diesel Engine", *SAE Technical Paper Series* 2010-01-2206 (2010) – for more details on RCCI setup.

New piston design based on KIVA optimization at University of Wisconsin

- **UW design**
  - Based on heavy-duty RCCI piston
  - Reducing surface area primary consideration
  - Best HC emissions and Efficiency
  - Compromise for high and low loads
- **New design expectations**
  - Reduced heat transfer losses
  - Lower HC and CO
  - Higher load operation for RCCI
- **New design experimental observations**
  - Different injection strategies necessary to better match different mixing characteristics
  - HC, CO, and BTE similar for both designs
  - Crevice to be addressed in next iteration
  - Some load expansion possible with new design due to lower CR

Modified RCCI Piston | Stock GM 1.9 L piston

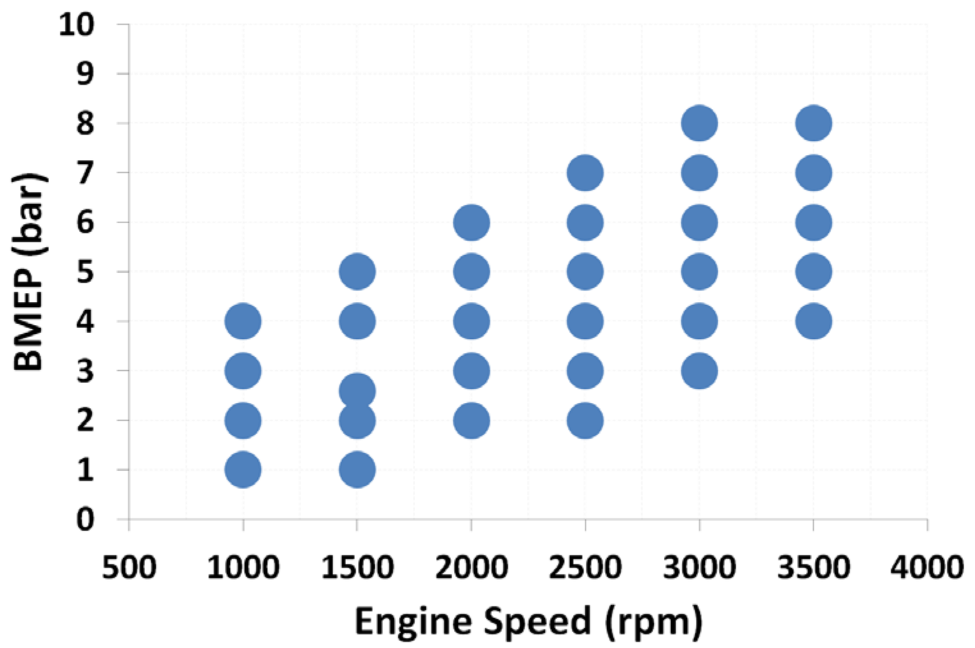


CR = 15.1:1 | CR = 17.5:1

Reference: Abstract accepted: Hanson et al. 2012 SAE World Congress - 12PFL-0950

RCCI operation demonstrated for majority of LD drive-cycle

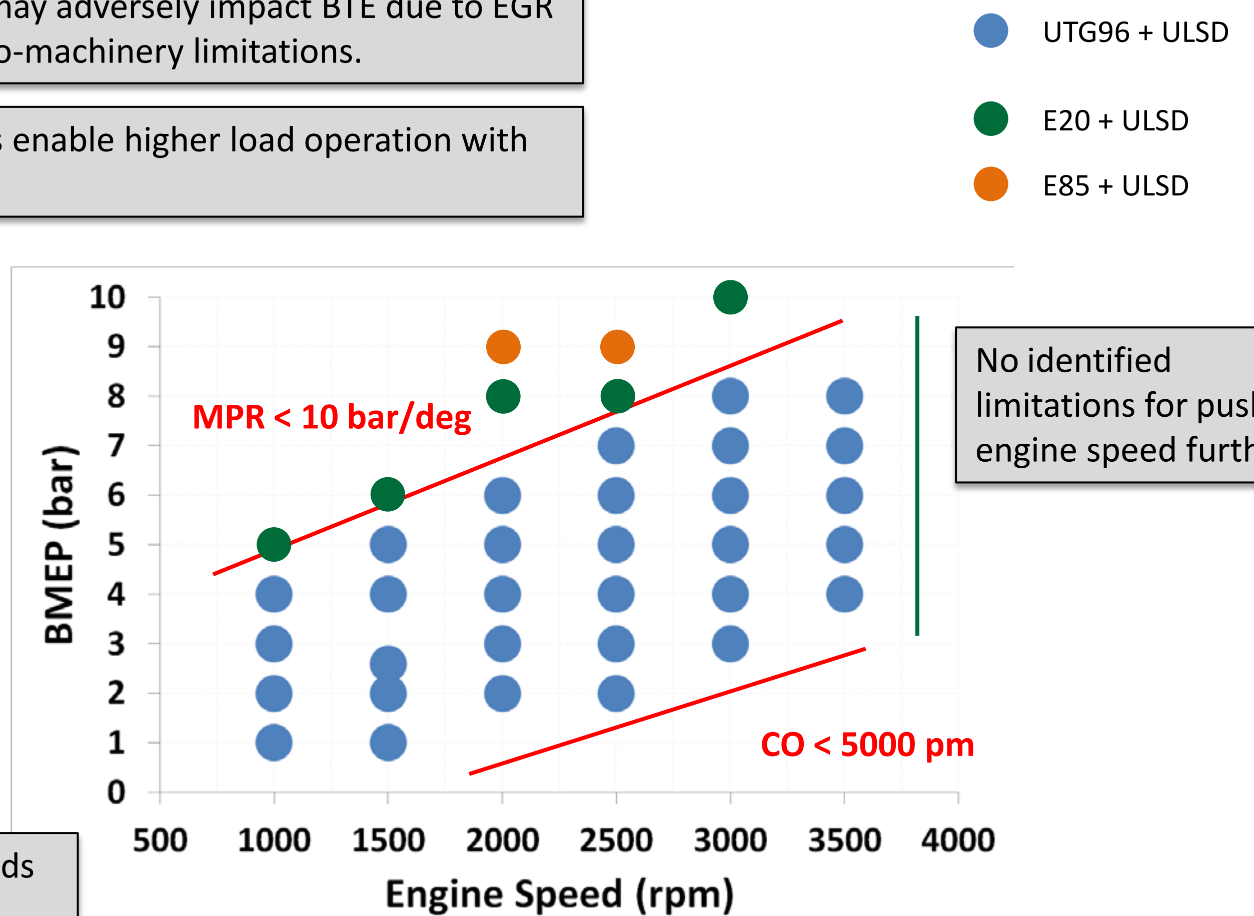
- **Exploration of engine parameters, hardware, and fuel chemistries.**
  - Gasoline/diesel ratio, dilution, charge temperature, swirl, boost, etc.
  - DI injection strategy.
  - CDC and RCCI-optimized piston designs.
  - Conventional and bio-renewable fuels.
- **Detailed characterization of emissions and performance.**
  - HC speciation, PM characterization, thermodynamic loss analysis, instability mechanism characterization, etc.
- **Estimation of LD drive-cycle fuel economy and emissions.**



Self-imposed boundaries and challenges to load expansion

EGR controls MPR but may adversely impact BTE due to EGR heat rejection and turbo-machinery limitations.

Ethanol-gasoline blends enable higher load operation with reduced or zero EGR.



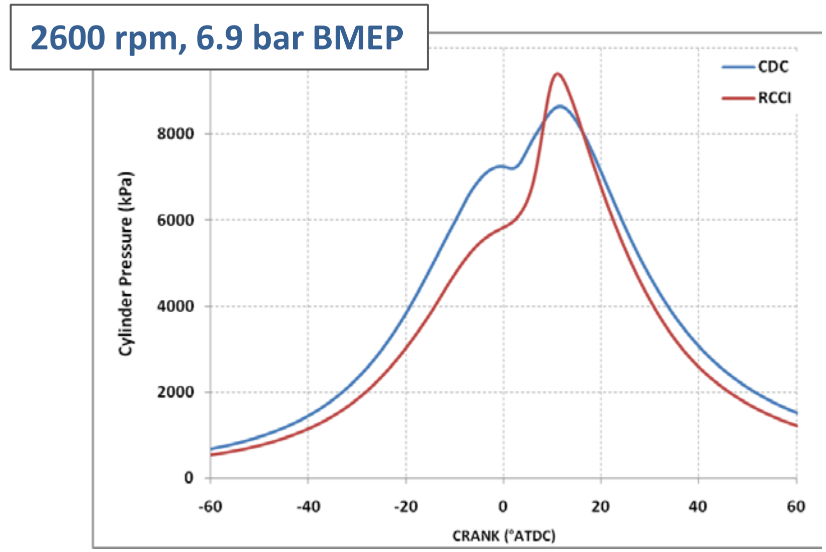
No identified limitations for pushing engine speed further.

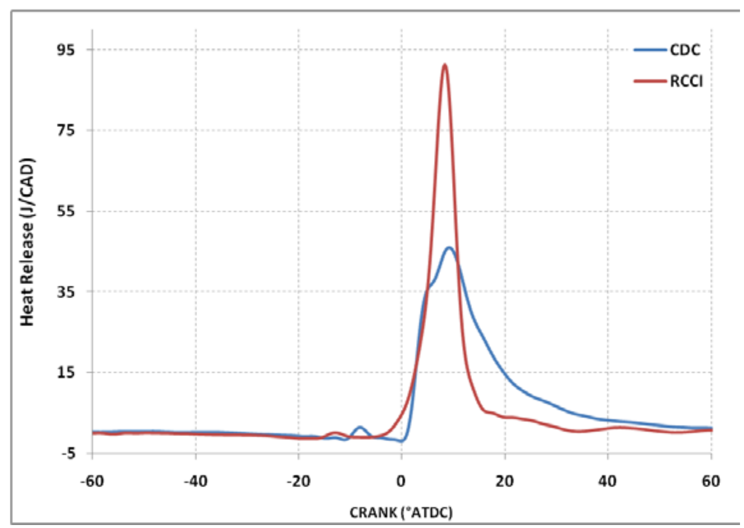
EGR required at low loads to maintain suitable air/fuel ratio and charge temperature.

Poor turbocharger performance limits low-load performance at higher speeds.

Example comparison of RCCI vs conventional diesel combustion (CDC)

	CDC	RCCI
Gasoline ratio	NA	88%
Boost (bar)	1.58	1.22
EGR Rate (%)	15.3	0
Diesel SOI (BTDC)	7	65
BTE (%)	36.4	39.0
ITE_{NET} (%)	41.7	43.4
ITE_{GROSS} (%)	44.5	44.8
NOx (ppm)	417	53
HC (ppm)	140	3207
CO (ppm)	140	1099
FSN (-)	1.51	0.01
COV IMEP (%)	2.26	1.58
COV MB50 (%)	3.56	14.3
Exhaust Temp (C)	370	334





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2600 rpm, 6.9 bar BMEP

- **Boost limited by turbo-machinery**

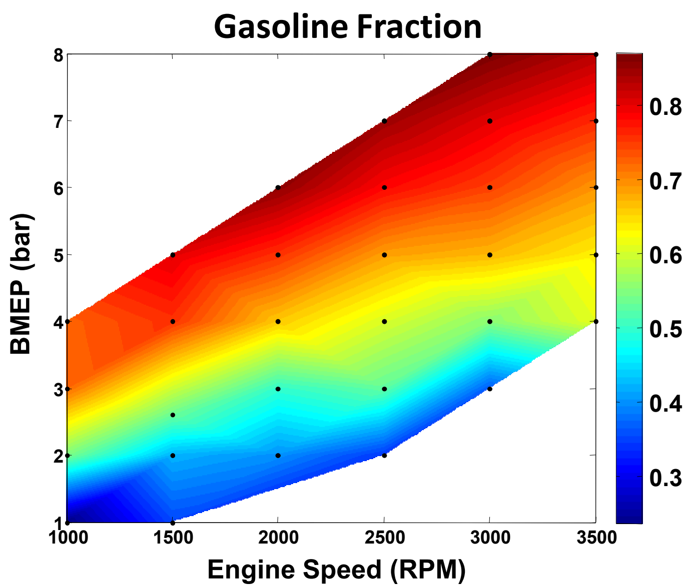
- **Gross ITE similar for two approaches.**
- **Net ITE higher for RCCI → reduced pumping and heat losses with zero EGR.**

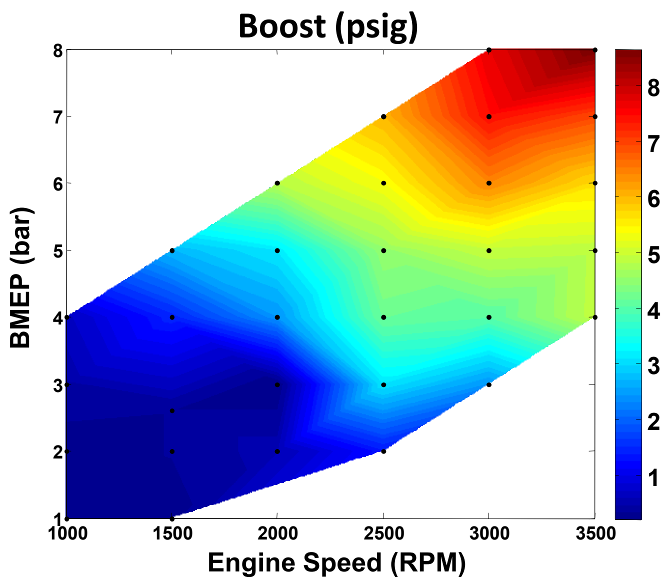
- **Very low NOx, PM with increase in HC, CO**

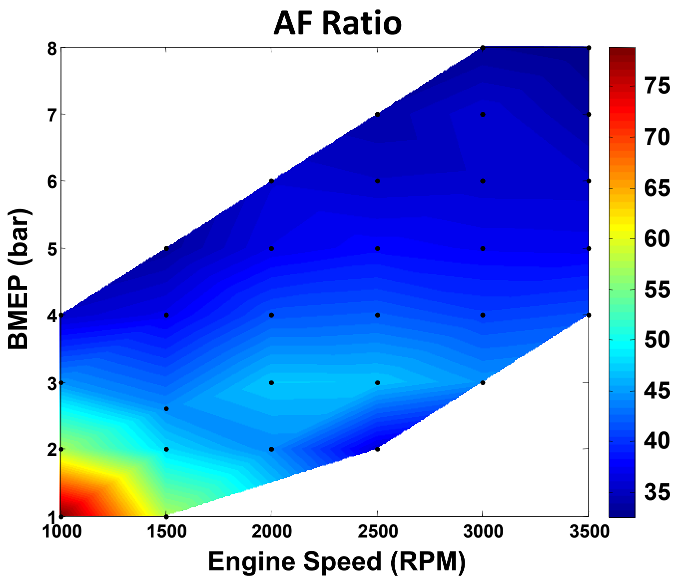
- **Acceptable COV IMEP. High COV MB50 could be control challenge**

- **Lower exhaust temperature challenge for HC/CO oxidation catalysts**

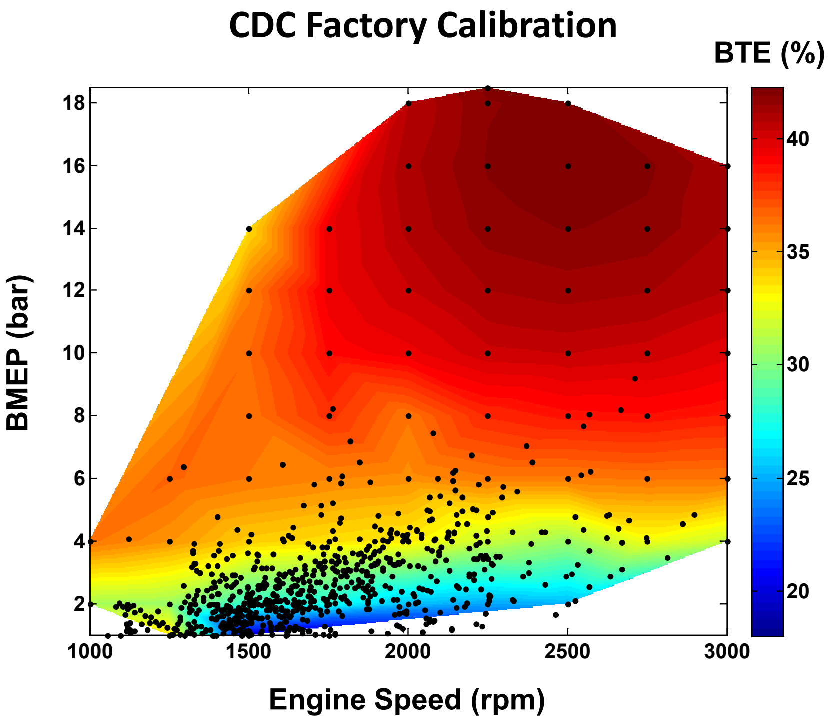
Major engine parameters used for controlling RCCI combustion process

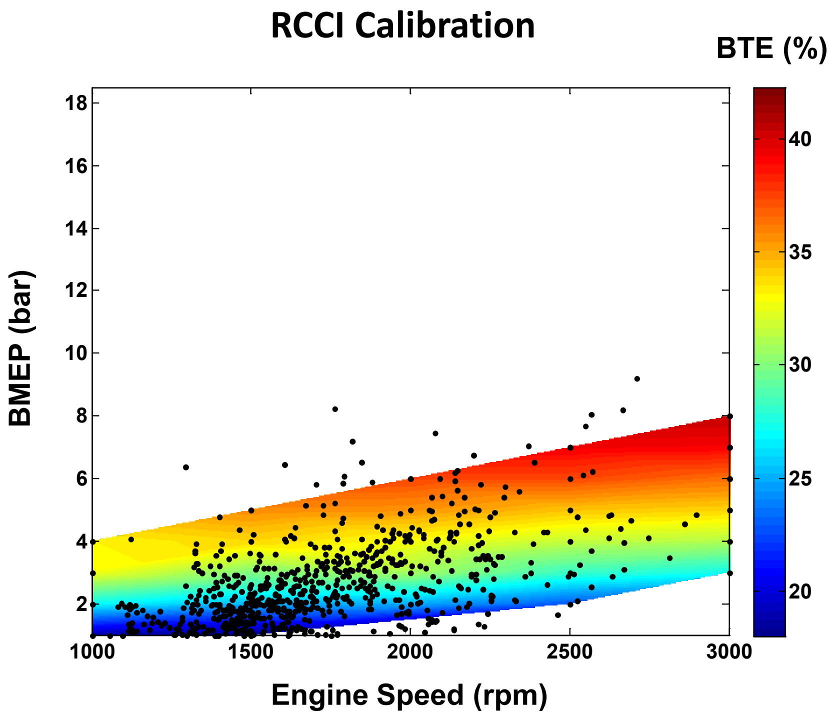






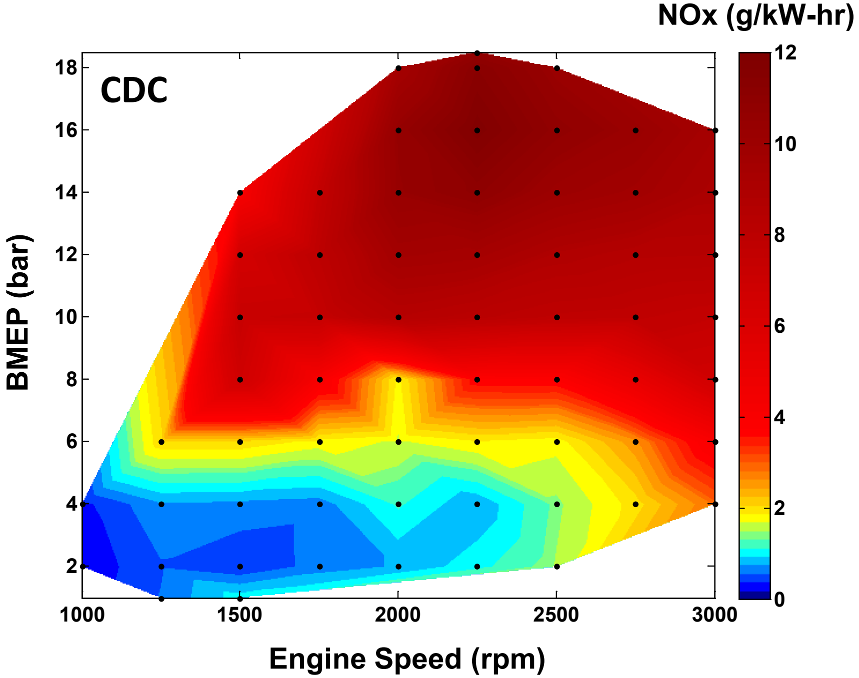
Current RCCI operation includes most of LD drive-cycle (black symbols)

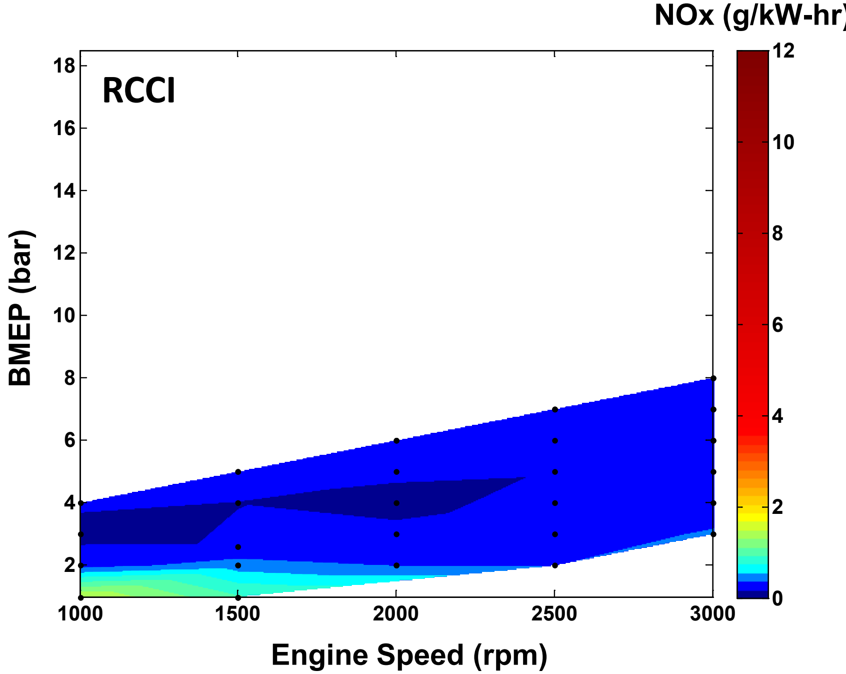




- Data shown for certification diesel fuel (ULSD) and gasoline (UTG96)
- Load expansion challenges are under investigation.

Engine-out NOx and soot emissions significantly reduced for RCCI combustion

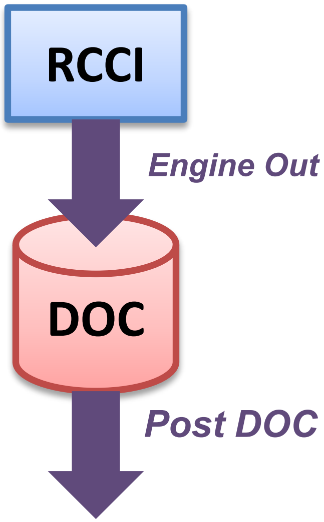


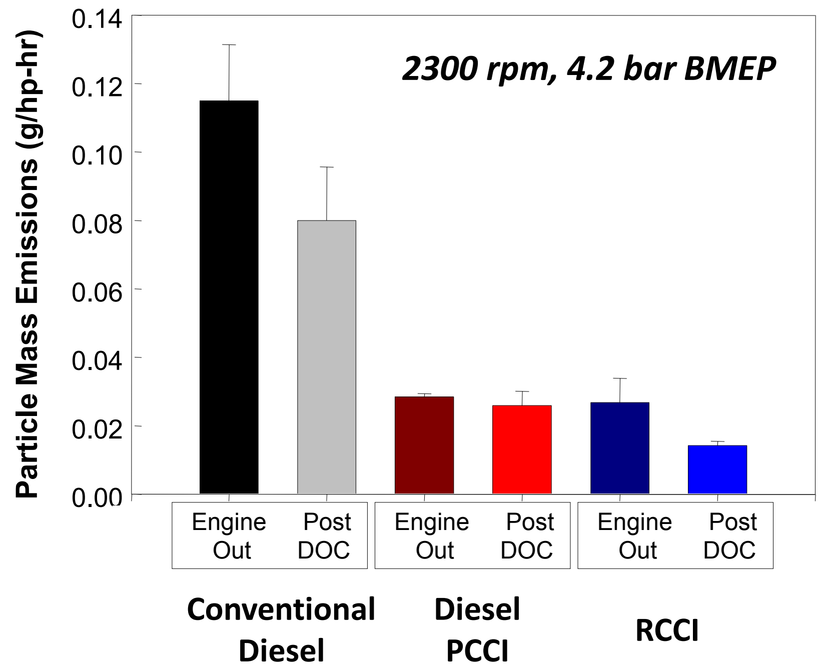


Soot emissions (not shown) less than 0.05 FSN for all RCCI conditions.
Smoke number not sufficient to understand PM characteristics.

RCCI PM found to be very different from CDC and PCCI

- **PM filter images and size distribution data suggested high organic content in PM from RCCI.**
- **DOC reduces RCCI PM mass significantly.**



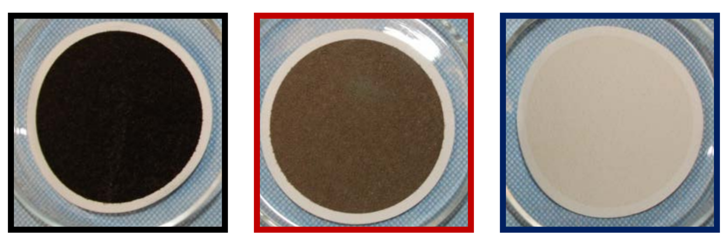


Exhaust Temperature

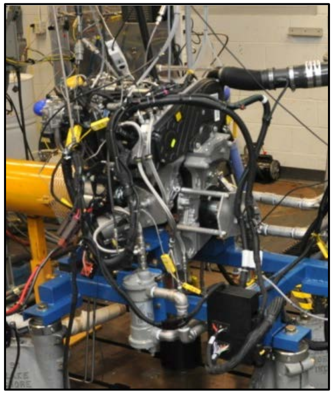
Conventional	415ºC
PCCI	420ºC
RCCI	250ºC

DOC effective for RCCI PM even though exhaust temperature lower

PM filter samples at Engine Out



A wide range of PM data has been collected and is undergoing analysis



Micro-tunnel Dilution system

Mass

Tapered Element Oscillating Microbalance (TEOM)

Mettler Microbalance

Organic Fraction

Organic to Elemental Carbon Ratio

Microwave Reactor Extraction
Organic Speciation

Number-Size Distributions

Steady-State

Scanning Mobility Particle Sizer (SMPS)

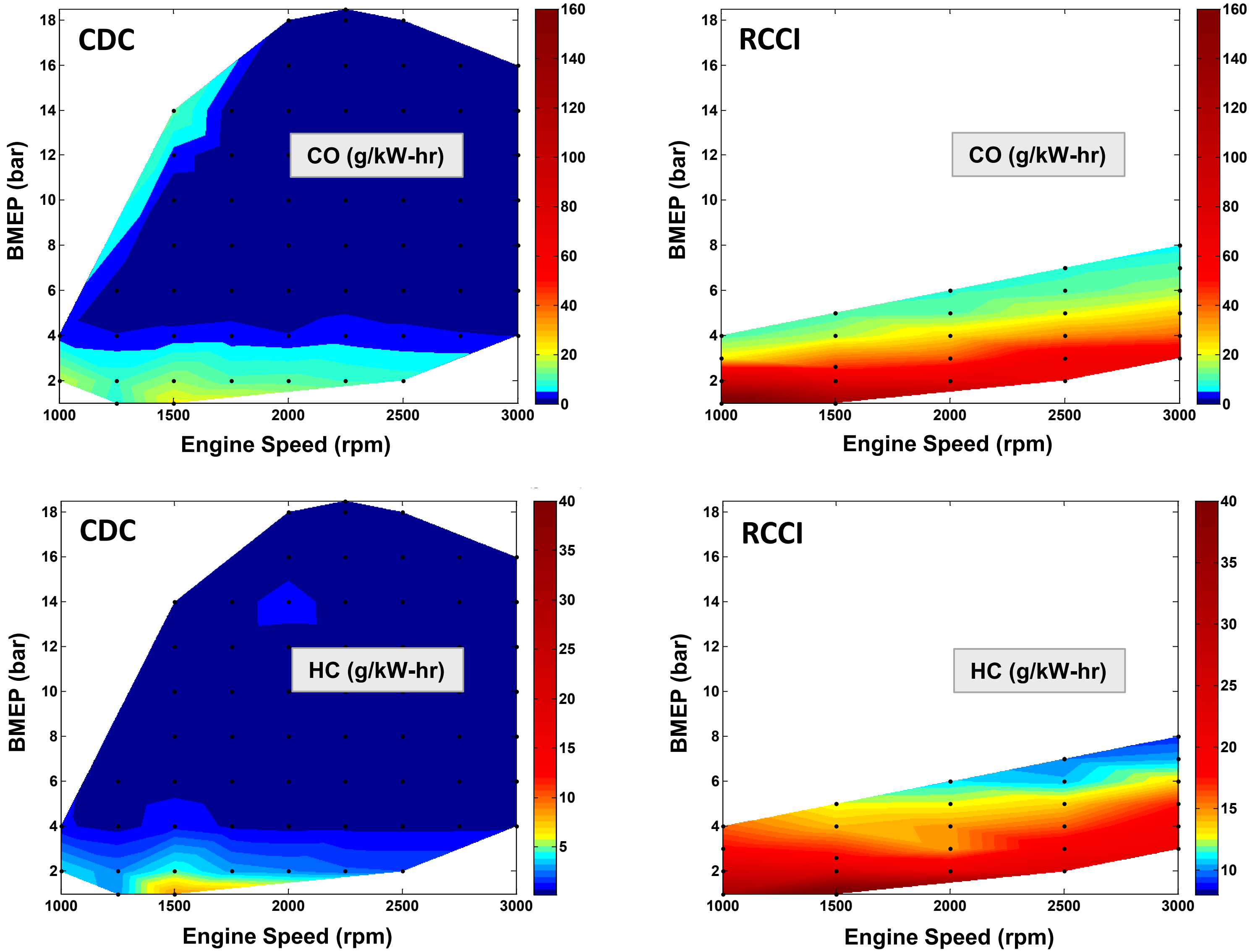
Transient

Engine Exhaust Particle Sizer (EEPS)

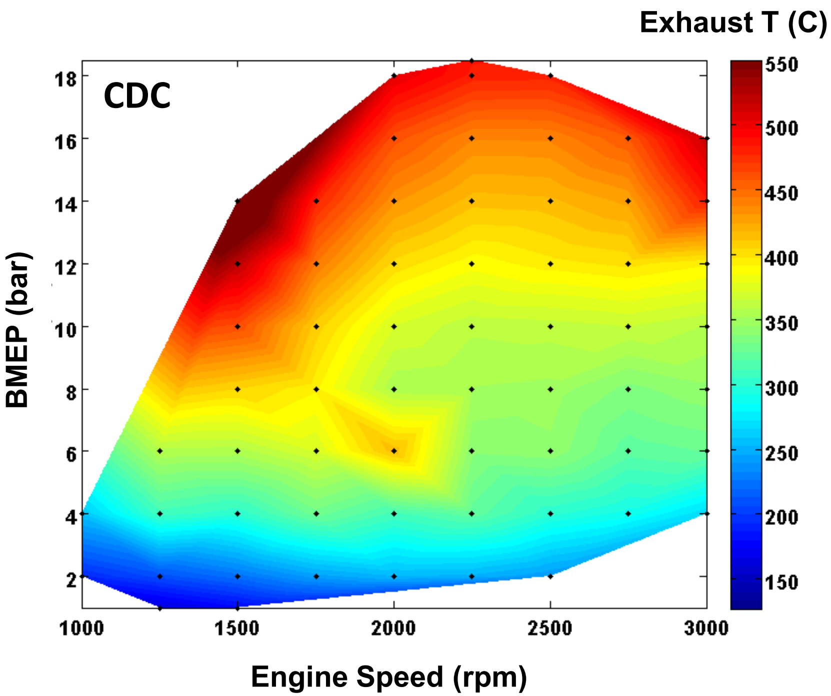
Morphology

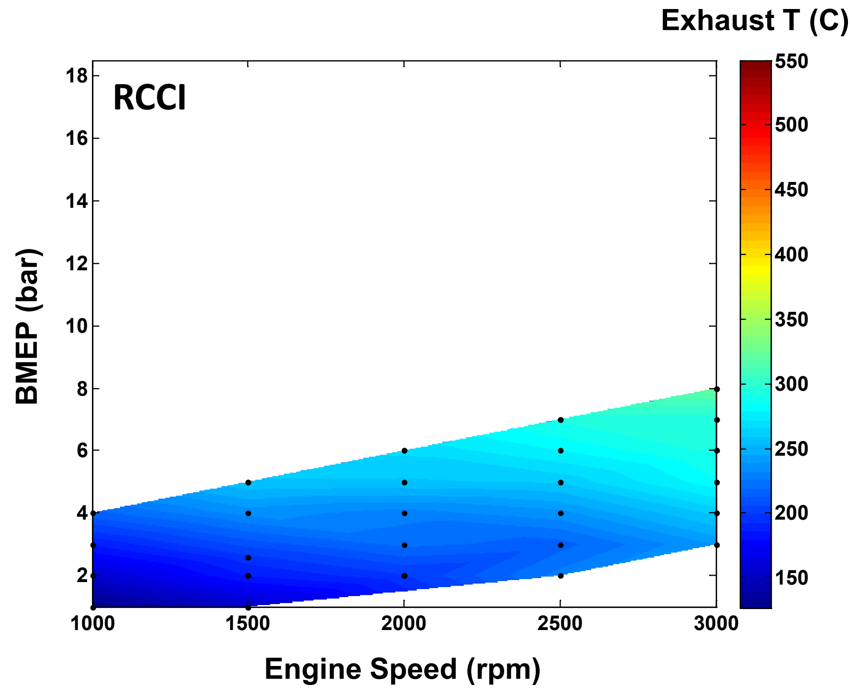
Transmission Electron Microscopy

Engine-out HC and CO emissions are high and more in-line with gasoline applications



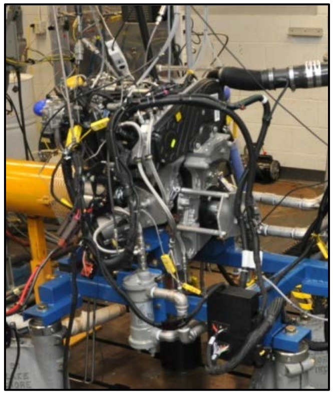
Low exhaust temperatures will make oxidation of HC and CO more difficult



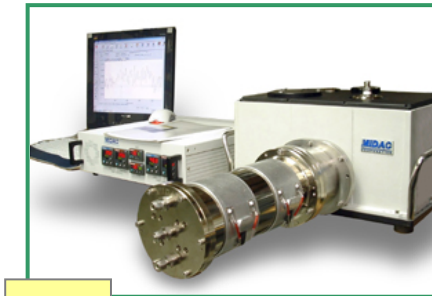


HC speciation and aftertreatment paths are under investigation.

HC speciation also ongoing with extensive samples collected in recent weeks

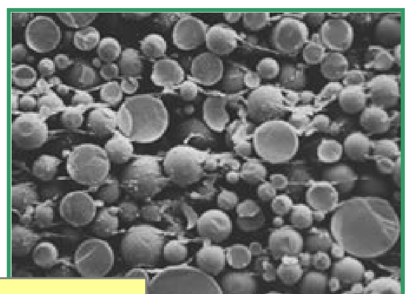


Micro-tunnel Dilution system



FTIR

C1-C4 species



Empore

Selective capture of semi-volatiles C10-C18

(GC/MS speciation)

DNPH

Selective capture of carbonyl species

(HPLC, UV, ESI/MS separation/speciation)

Canisters

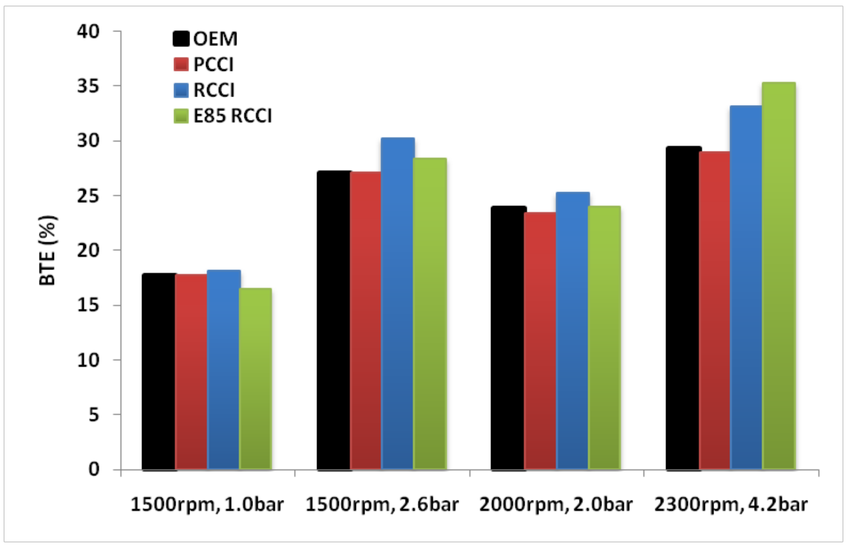
Light HC species

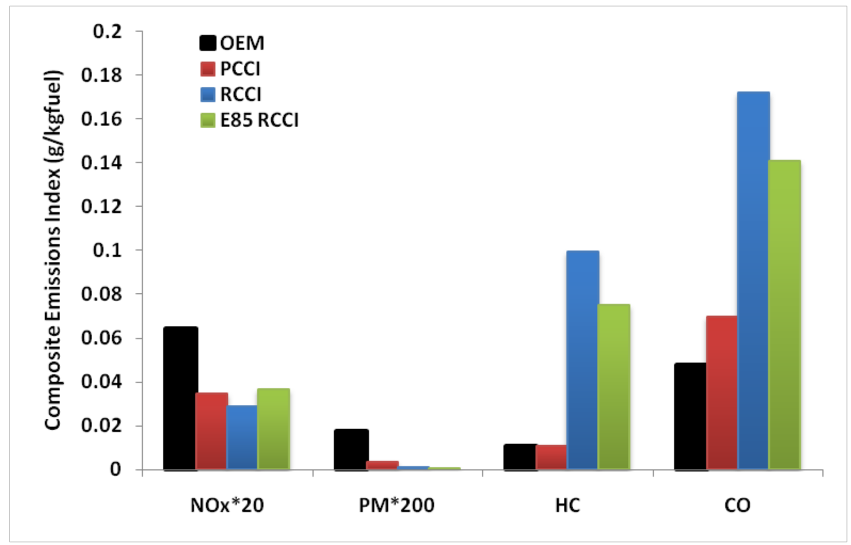
(Preconcentrator, GC/MS speciation)

Drive-cycle estimations show efficiency potential and emissions benefits/challenges

- **Comparisons with PCCI and RCCI.**
- **Higher efficiency for RCCI for most modal conditions.**
- **Higher HC and CO for RCCI for all conditions.**
- **E85 showed reduced PM, HC, and CO emissions.**

Point	Speed / Load	Weight Factor	Description
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





Sufficient data is now available to perform full vehicle simulations with Autonomie.

RCCI Combustion Takeaways

- **Meets or exceeds diesel-like efficiencies with very low NOx and PM emissions.**
- **HC and CO emissions similar level to modern gasoline engine but with added challenge of very low exhaust temperatures (i.e., CO/HC oxidation more difficult).**
- **Very robust to different piston geometries, operating conditions, and transients – additional DOF from gasoline/diesel mix.**
- **Ethanol-gasoline blends enable higher load operation with reduced or zero EGR.**
- **EGR path to higher load has control, heat rejection, and turbo-machinery challenges.**
  - Dilution important to manage maximum pressure rise rate for higher load operation.
  - Higher heat rejection capacity and better turbo-charger matching critical to preserve dilution benefits.

Next Steps

- **Vehicle level simulations of RCCI based on extensive RCCI combustion map**
- **Hardware modifications**
  - Low pressure EGR system
  - Re-designed pistons with focus on crevice
- **Emissions characterization and aftertreatment matching**
  - Detailed gaseous and PM characterization.
  - Supports model development.
- **Control challenges**
  - Continued investigation of transient operation.
  - Characterization and control of cyclic/cylinder dispersion instability mechanisms.
- **Fuel effects including bio-renewable gasoline and diesel fuels.**

UW will be installing an RCCI engine in a series-hybrid vehicle to showcase the efficiency and emissions potential of this combustion strategy.

Acknowledgements

Gurpreet Singh, Ken Howden
Advanced Combustion Engine R&D

Kevin Stork, Steve Przesmitzki
Fuel Technologies R&D

UNITED STATES DEPARTMENT OF ENERGY

Questions?

Related DEER Presentations

- Monday, 3:30 pm: Kokjohn, "In-cylinder mechanisms of PCI heat-release rate control by fuel reactivity stratification"
- Monday, P-04: Dempsey, "Characterization of dual-fuel reactivity controlled compression ignition (RCCI) using hydrated ethanol and diesel fuel"
- Wednesday, 9:30 am: Splitter, "Effect of compression ratio and piston geometry on RCCI load limit"

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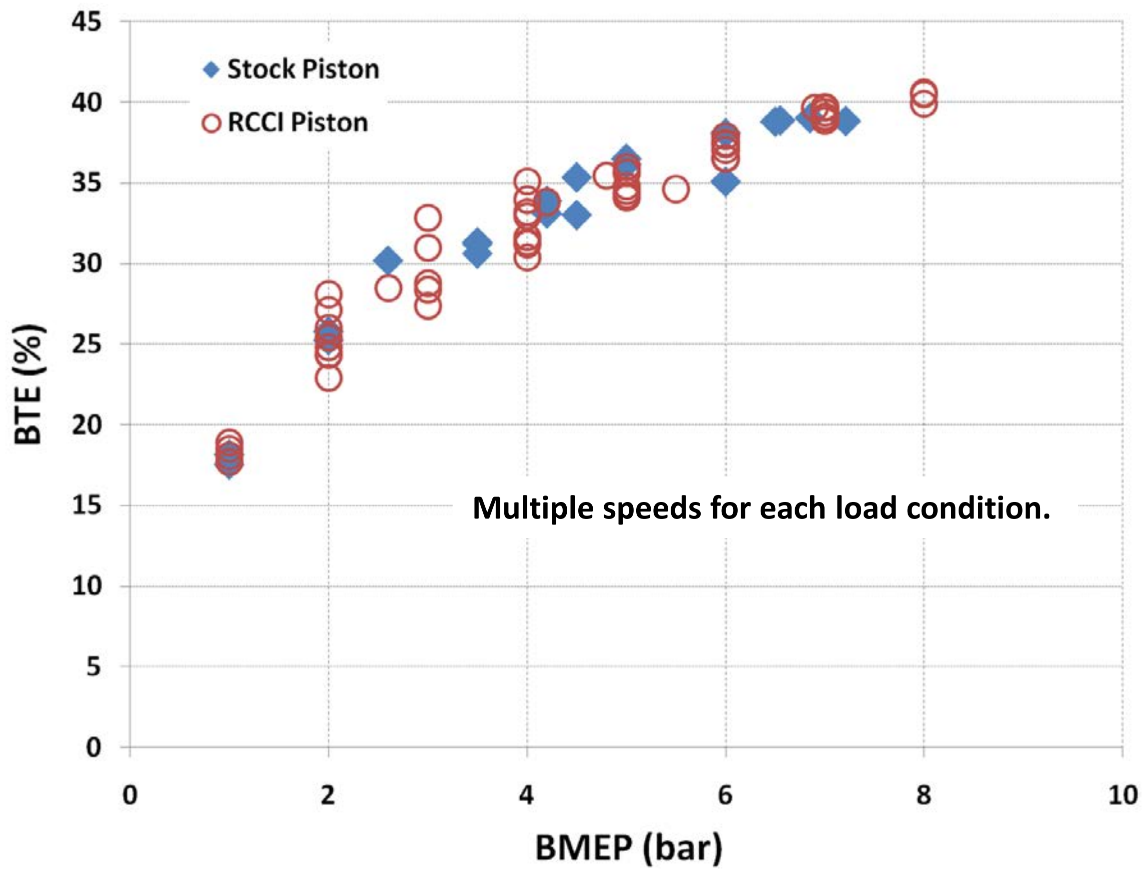
Extra Slides

RCCI achieves diesel-like or better BTE across speed-load range

- **Piston geometry effects are compensated with injection strategy.**
  - OEM pistons: mostly single-pulse injection schemes are sufficient.
  - RCCI pistons: requires dual-pulse injection for most conditions.
- **Lower CR of RCCI pistons allowed for higher load operation.**

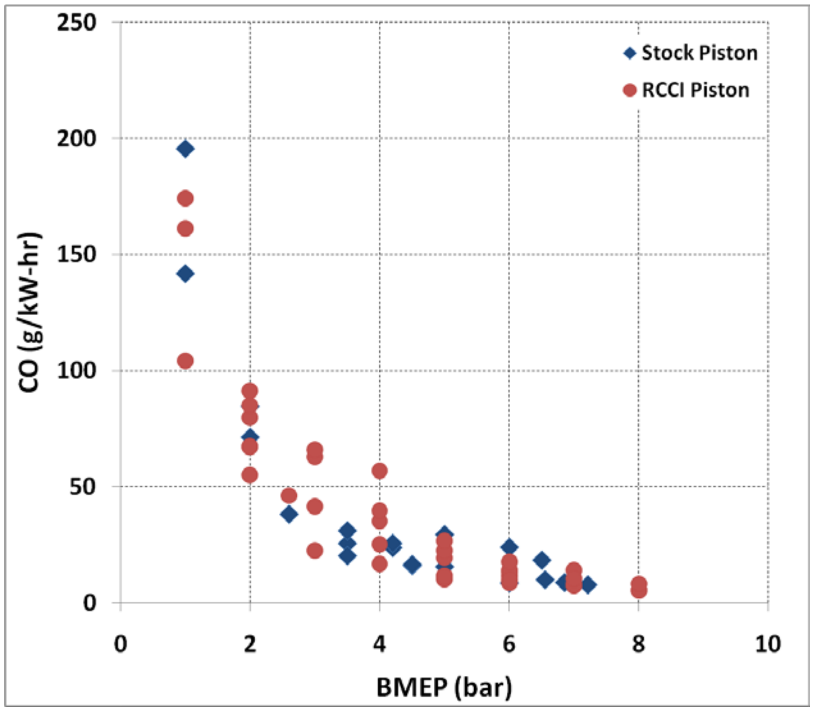


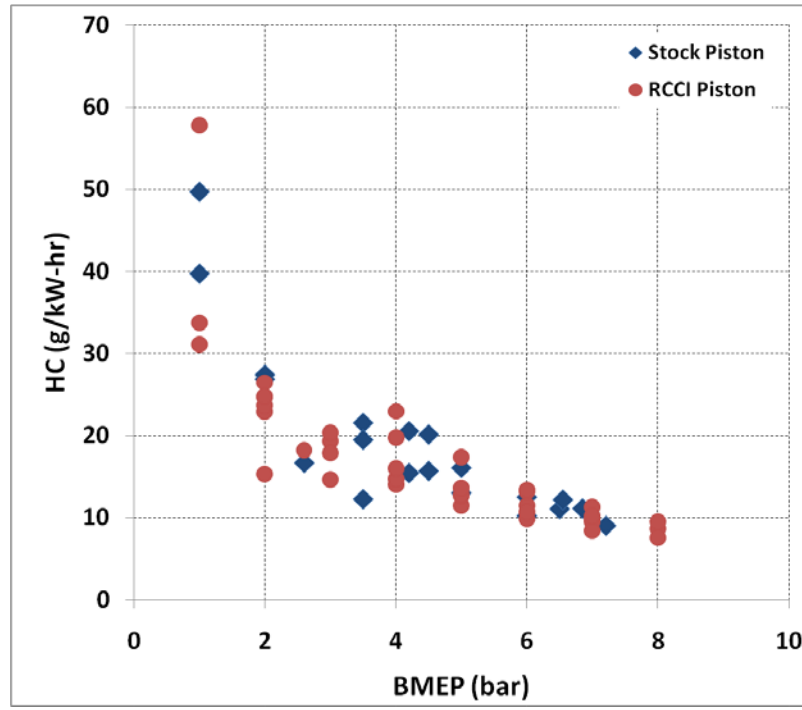
Modified RCCI pistons installed in GM 1.9-L diesel engine

OAK RIDGE
National Laboratory

HC and CO emissions higher than diesel and more in-line with gasoline engines

- **HC and CO emissions mostly insensitive to piston bowl geometry (this was a surprise).**
- **Possibly due to crevice effects – same for both piston designs.**





Multiple speeds for each load condition.