High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines

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U.S. Department of Energy

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ACE016

HECC Project Overview

Activity evolves to address DOE challenges and is currently focused on milestones associated with Vehicle Technologies efficiency and emissions objectives.

Timeline

- **Consistent with VT MYPP**
- **Activity scope changes to address DOE *needs***

Barriers (MYPP 2.3 a,b,f)

- ***Lack of fundamental knowledge of AEC regimes***
- **Lack of effective engine controls**
- ***Lack of actual emissions data***
- ➡ **VT performance milestones**

Budget

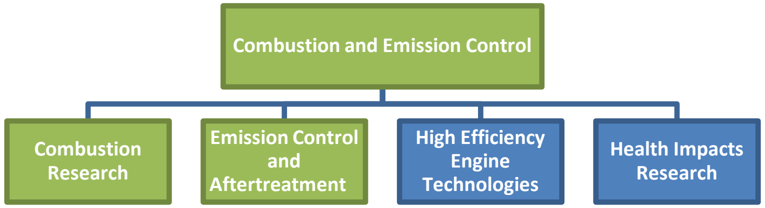
- **FY 2011 – Separate**
  - **$300k (HECC - ACE016)**
  - **$200k (Multi-Mode - ACE031)**
- **FY 2012 – Combined**
  - **$600k (HECC – ACE016)**

Partners / Interactions

- **Regular status reports to DOE**
- **Industry technical teams, DOE working groups, and one-on-one interactions.**
- **Industry: GM, MECA, Borg Warner**
- **University of Wisconsin-Madison**
- **CLEERS: Consortium**
- **ORNL fuels, emissions, and health impacts activities.**

Relevance

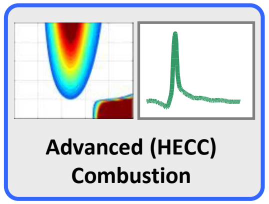
- **DOE VTP Milestones**
  - Addressing barriers to meeting VTP goals of reducing petroleum energy use (engine system) including potential market penetration with efficient, cost-effective aftertreatments.
- **Program Objectives (MYPP 2.3-3)**
  - **To develop and assess the potential of advanced combustion concepts, such as RCCI, on multi-cylinder engines for improved efficiency and emissions along with advanced emission control technologies (aftertreatments).**
  - Investigating high efficiency concepts developed on single-cylinder engines and addressing multi-cylinder engine/ aftertreatment implantation challenges.
  - Characterize emissions from advanced combustion modes and define the synergies and any incompatibilities with aftertreatments with the expectation that engines may operate in both conventional and advanced combustion modes including multi-mode.
  - Minimize aftertreatments and minimize fuel penalties for regeneration *(Tier 2 Bin 2 goal).*
  - Interact in CLEERS consortium and industry/DOE tech teams to respond to industry needs and support model development.



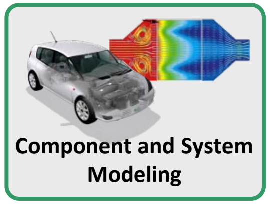
Adapted from: vtpn05_singh_ace_2011_o.pdf

Joule Milestones

- **FY 2012 Q3 – High Efficiency RCCI Mapping**
  - Develop RCCI combustion map on a multi-cylinder engine suitable for light-duty drive cycle simulations.
    - The map will be developed to maximize efficiency with lowest possible emissions with production viable hardware and biofuels as necessary.



- **FY 2012 Q4 – RCCI Vehicle Systems Modeling**
  - Demonstrate improved modeled fuel economy of 15% for passenger vehicles solely from improvements in powertrain efficiency relative to a 2009 PFI gasoline baseline.
    - The 2009 PFI gasoline baseline to be modeled using a representative engine map to ensure an accurate comparison.
    - Run Autonomie drive cycle simulations on same vehicle platform with AT.
      - **Fuel economy** and engine out emissions.

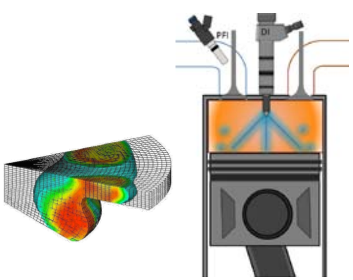


Approach: Multi-Cylinder Advanced Combustion with Production-Grade Hardware and Aftertreatment Integration

Modeling + Experiments + Analysis + Collaboration

- **Combine multi-cylinder advanced combustion and emissions control research to identify barriers to implementation and model feedback.**
- **Work with industry, academia and tech-teams to clearly define benefits and challenges associated with "real-world" implementation of advanced combustion modes including efficiency, controls and emissions.**

Integrative collaboration & feedback with partners



Gross indicated efficiency

- Fundamental combustion
- Simulated boundary conditions
- Modeling
- Single-cylinder engines
- Bench flow reactors

Brake (shaft) efficiency

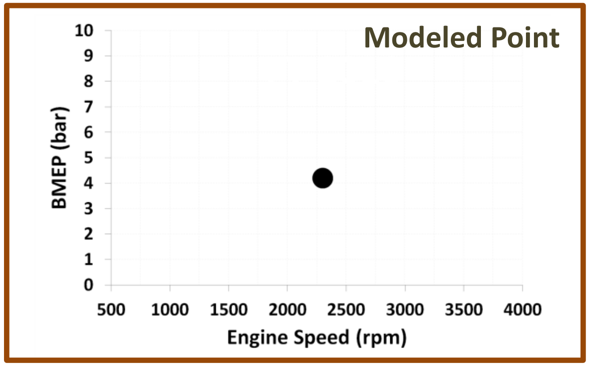
- Hardware limitations
- Aftertreatment integration
- Engine-system controls
- Instability mechanisms
- Cylinder imbalances
- Health impacts
- Auxiliary losses

Drive cycle efficiency

- Drive cycle emissions
- Fuel mix (tank sizes)
- Drive cycle mismatch
- Drive system optimization
- Vehicle system management

Accomplishments - Progression of Multi-Cylinder RCCI Experiments

Single Point

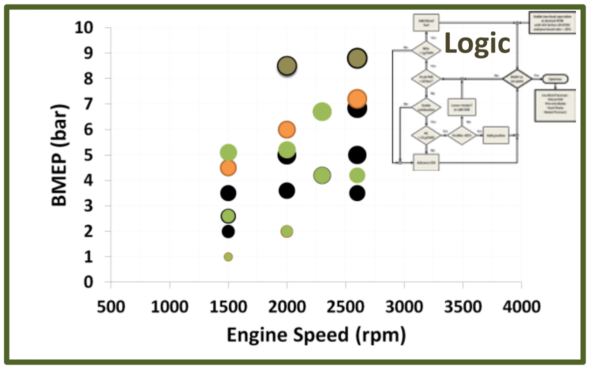


Initial Multi-Cylinder Experiments

FY 10

- Multi-cylinder challenges
- UW model comparison
- DOC effectiveness on HC & PM

Load Expansion

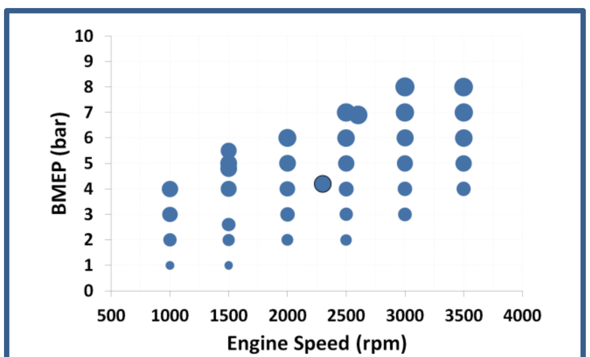


OEM Piston Experiments

FY 11-12

- Systematic approach to RCCI operation
- Operating map exploration and load expansion
- Effect of EGR and E85 on load expansion
- Modal point emissions estimates

Mapping



RCCI Optimized Piston Experiments

FY 12

- Engine mapping
- Fuel effects (E85, E20, B20)
- Piston effects
- Detailed emission and PM study (fuels/load)

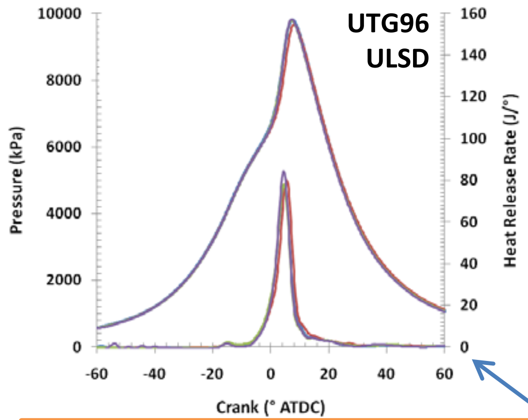
ORNL HECC Program Bridges Fundamental Combustion, Exhaust Emission Control System and Engine Systems R&D

Alternate

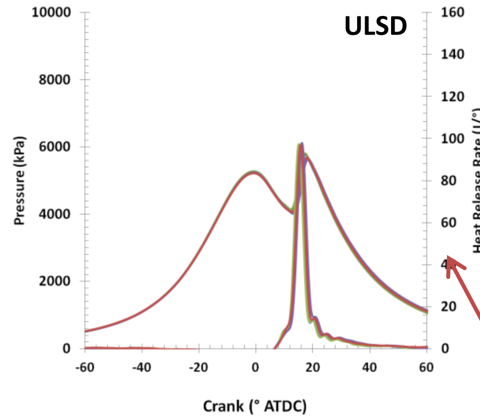
Advanced Combustion Techniques Present Different Emissions Challenges

LTC reduces burden of NOx and PM control on aftertreatment (thereby reducing cost and fuel penalty), but higher HC and CO emissions result

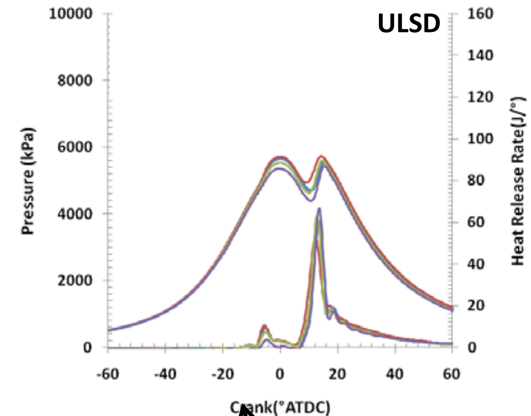
Reactivity Controlled Compression Ignition



Premixed Charge Compression Ignition

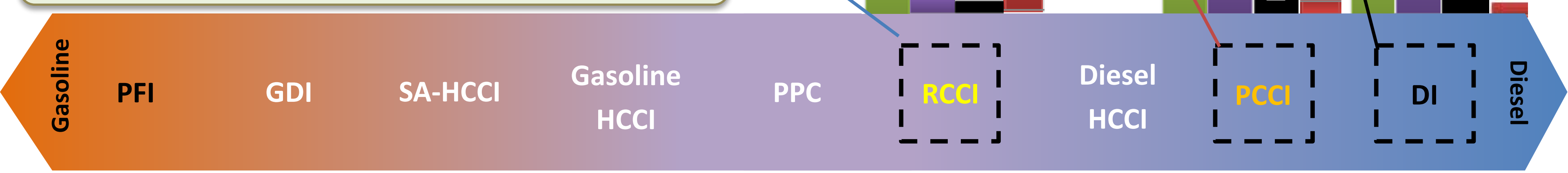


Conventional Diesel Combustion



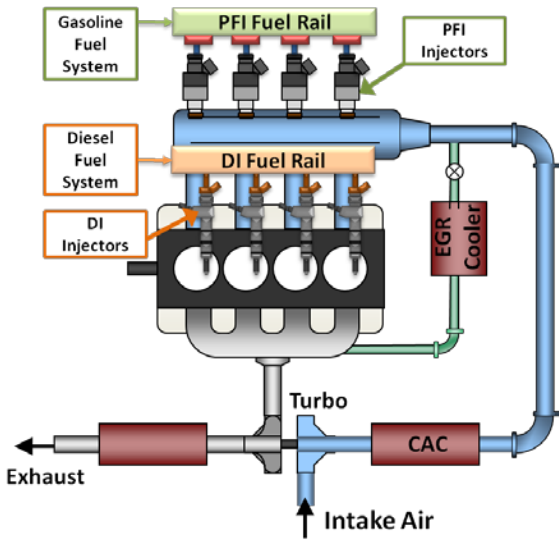
RCCI Background- backup slide

Results from multi-cylinder experiments at 2300 rpm, 4.2 bar BMEP
Curran et al. ASME - ICEF2011-60227



ORNL's Comprehensive approach to ACE Research

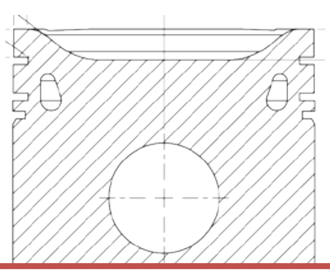
- **Two 2007 GM 1.9-L multi-cylinder diesel engines**
  - OEM (CR 17.5) and **modified RCCI** pistons (CR 15.1) (backup slide)
  - Dual-fuel system with PFI injectors
  - OEM diesel fuel system with DI injectors
- **DRIVVEN control system with DCAT**
  - Full control of DI & PFI fuel systems & emissions control
  - Cylinder-to-cylinder balancing
- **Aftertreatment integration & emissions characterization**
  - Modular catalysts / regulated and unregulated emissions
    - HC: Light HC Species, Semi-Volatiles, Carbonyl Species,
    - PM: Mass, Organic Fraction, Number-Size Dist, Morphology



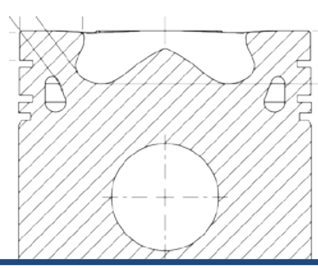
ORNL RCCI Multi-Cylinder 1.9L GM

Base Multi-Cylinder 1.9L GM CIDI

Number of Cylinders	**4**
Bore, mm	**82.0**
Stroke, mm	**90.4**
Compression Ratio	**17.5**
Rated Power, kW	**110**
Rated Torque, Nm	**315**



Modified RCCI Piston



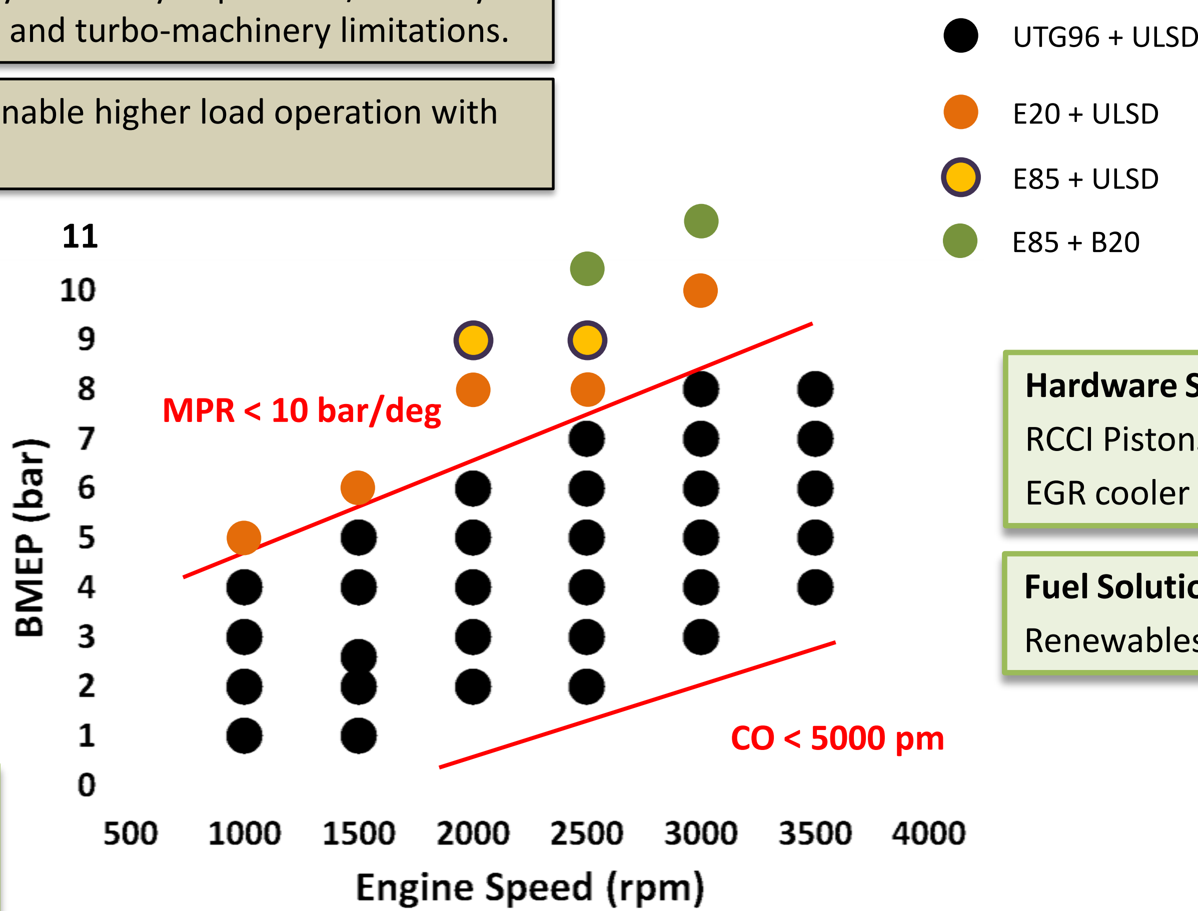
Stock GM 1.9 L piston

Self-Imposed Boundaries and Challenges to Load Expansion

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

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

B20 allows further expansion with E85.



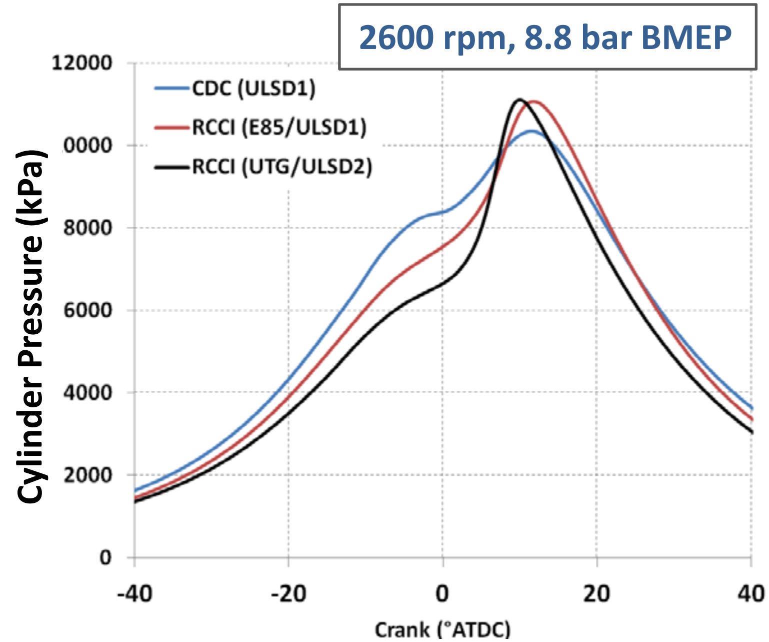
Hardware Solutions
RCCI Pistons
EGR cooler

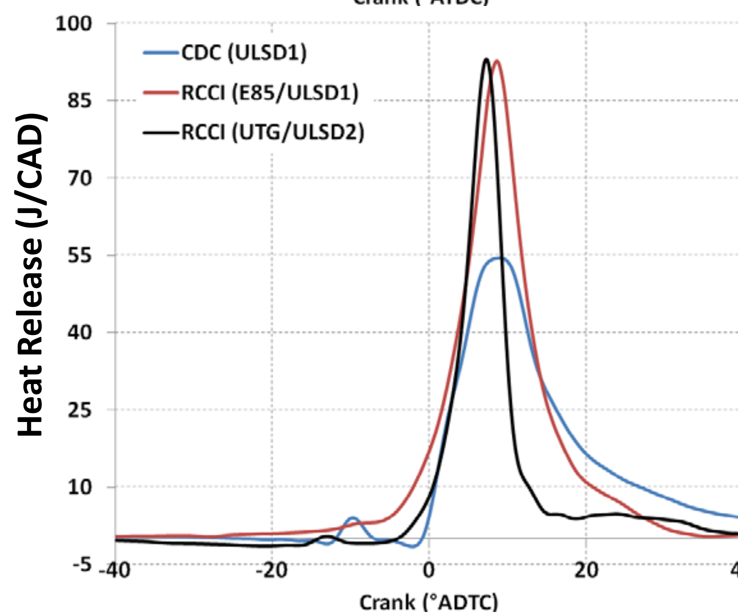
Fuel Solutions
Renewables

Future Hardware Solutions
LP EGR
2-stage turbo
Piston crevice/ ring pack
DI Nozzle

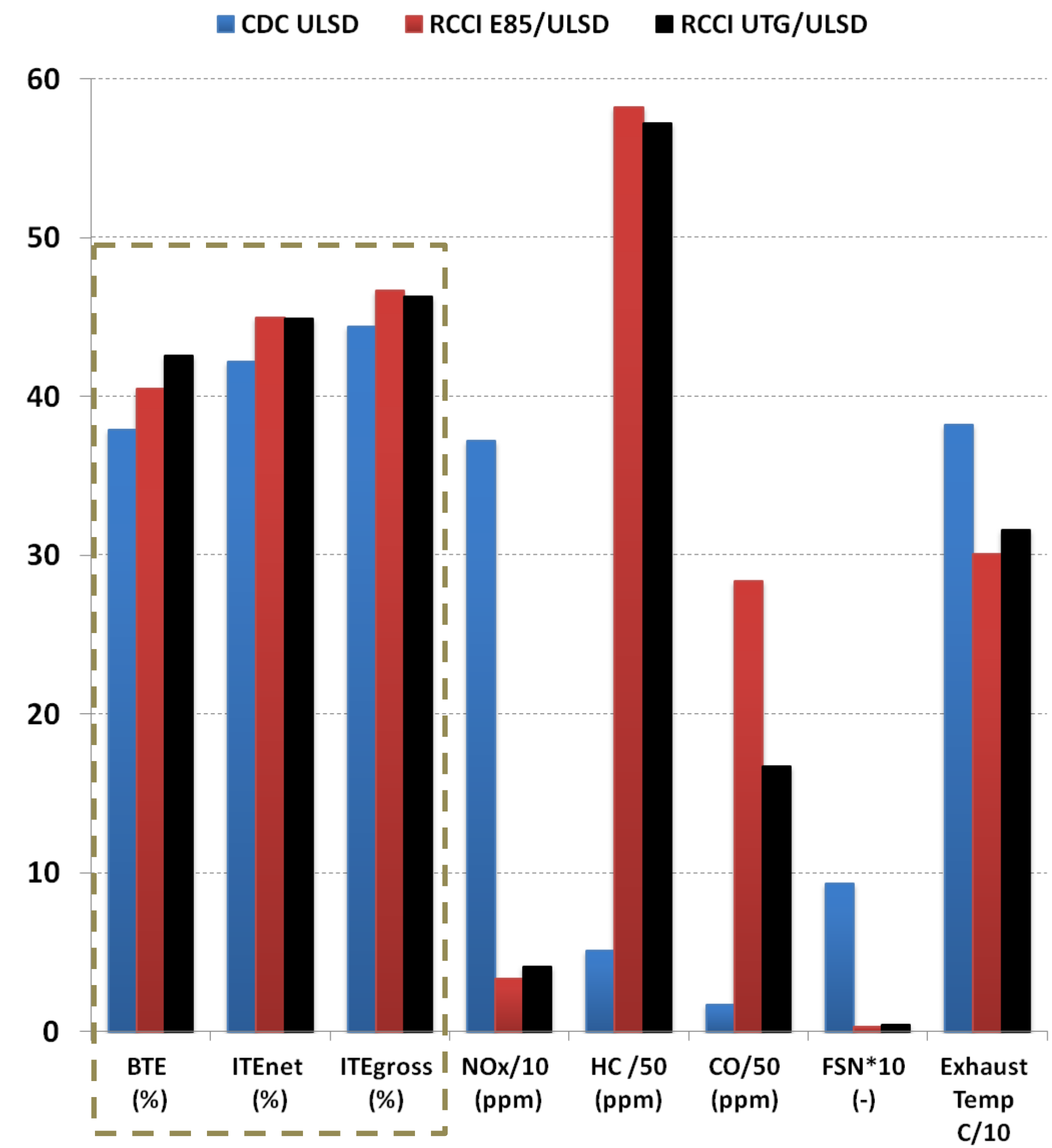
Comparison of RCCI and CDC 2600 rpm/8.8 bar BMEP

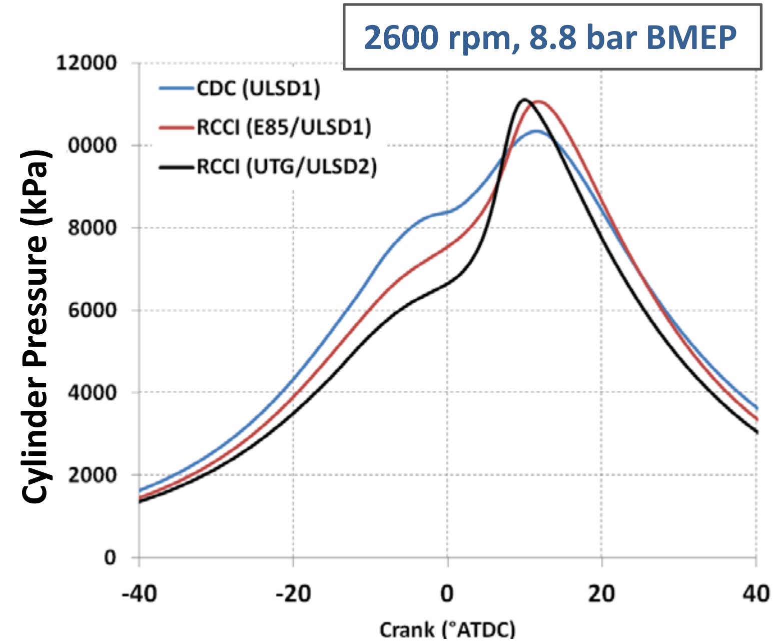
	OEM Piston		RCCI Piston
	CDC ULSD	RCCI E85/ULSD	RCCI UTG/ULSD
Gasoline ratio	NA	83	**88**
Boost (bar)	1.73	1.63	**1.54**
EGR Rate (%)	0	0	**0**
Rail Pressure (bar)	1200	500	**500**
CA50	11.2	7.5	**6.9**
BTE (%)	37.9	40.5	**42.6**
ITE_{NET} (%)	42.2	45.0	**44.9**
ITE_{GROSS} (%)	44.4	46.7	**46.3**
NOx (ppm)	744	66	**82**
HC (ppm)	254	2910	**2860**
CO (ppm)	84	1420	**835**
FSN (-)	0.93	0.03	**0.04**
Exhaust Temp (C)	382	301	**316**

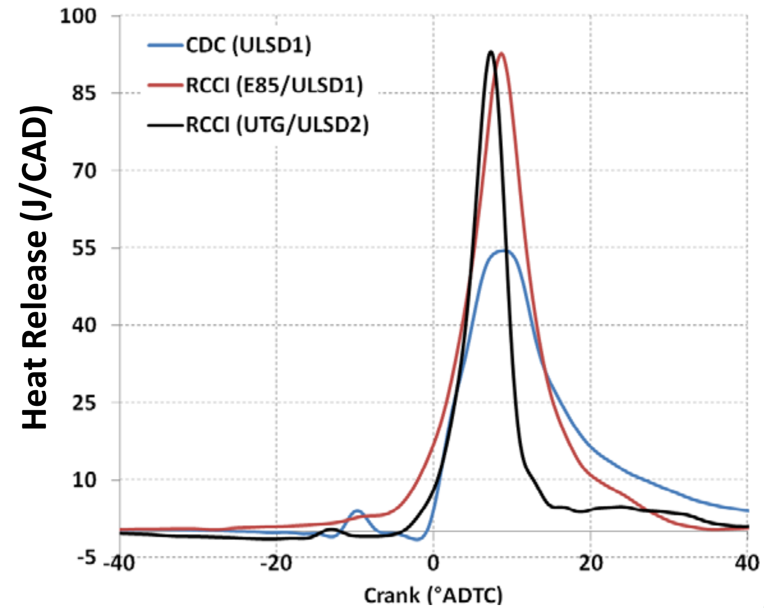




Comparison of RCCI and CDC 2600 rpm/8.8 bar BMEP

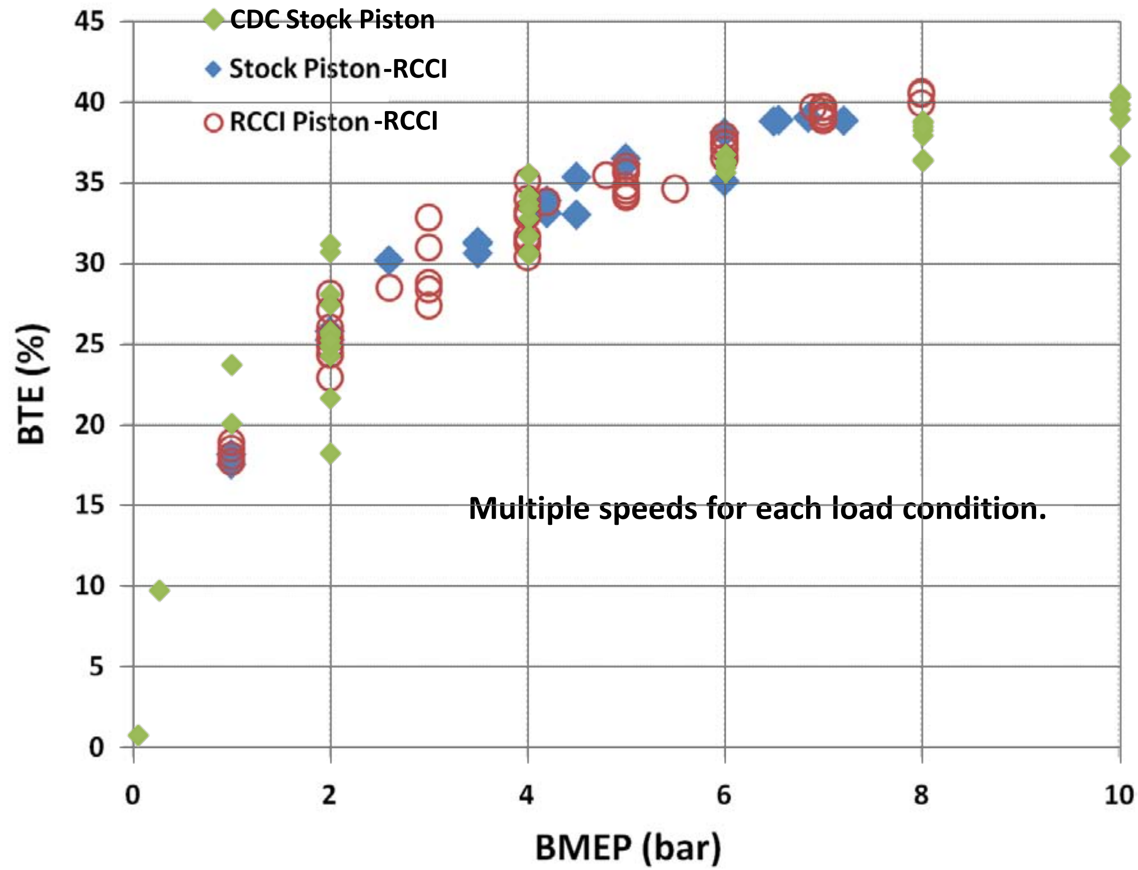






RCCI achieves diesel-like or better BTE across speed/load range

- **Piston geometry effects are compensated for with injection strategy.**
  - OEM pistons: mostly single-pulse injection schemes are sufficient
  - RCCI pistons: single and split injections explored
- **Lower CR of RCCI pistons allowed for higher load operation.**

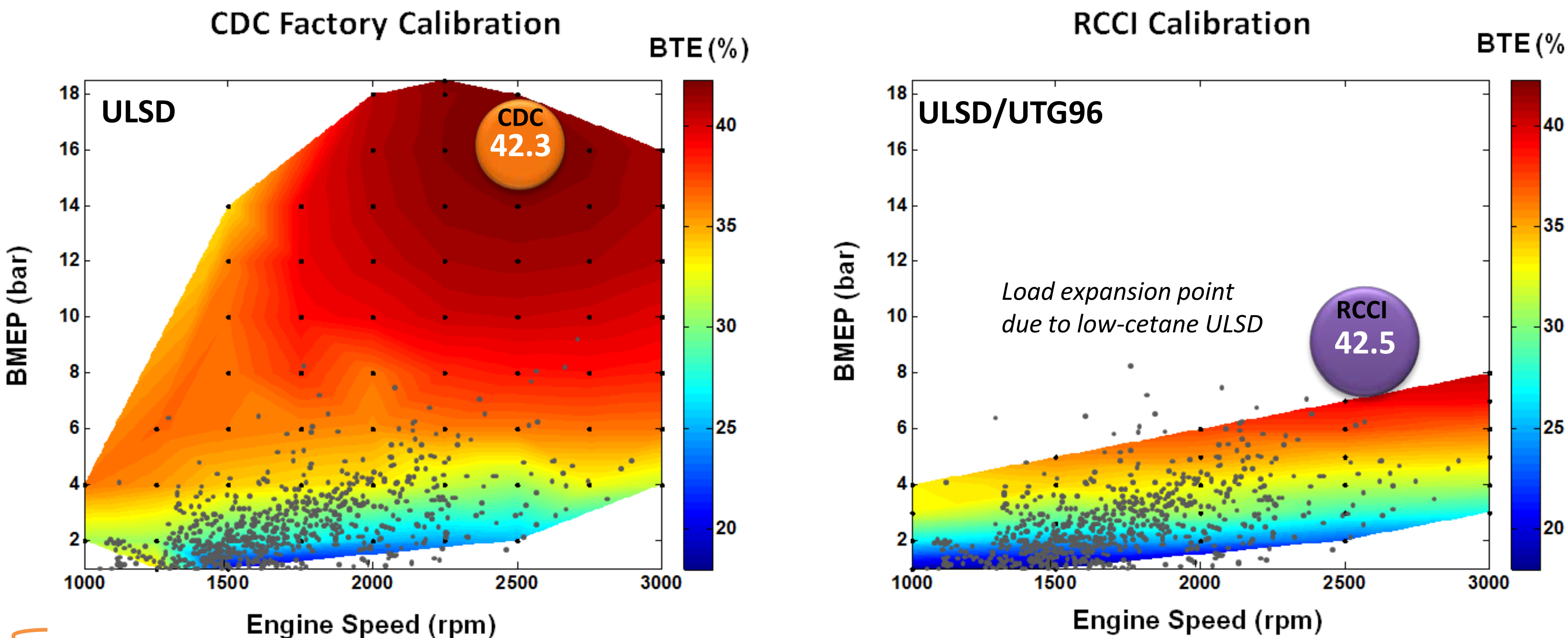


Modified RCCI pistons installed in GM 1.9-L diesel engine

BTE improvement increases with load - details in backup slide

HC & CO comparison - shown in backup slide

Current RCCI Operation Includes Most of LD Drive Cycle *(grey dots)*



Stock Piston: 42.3 — CDC ULSD

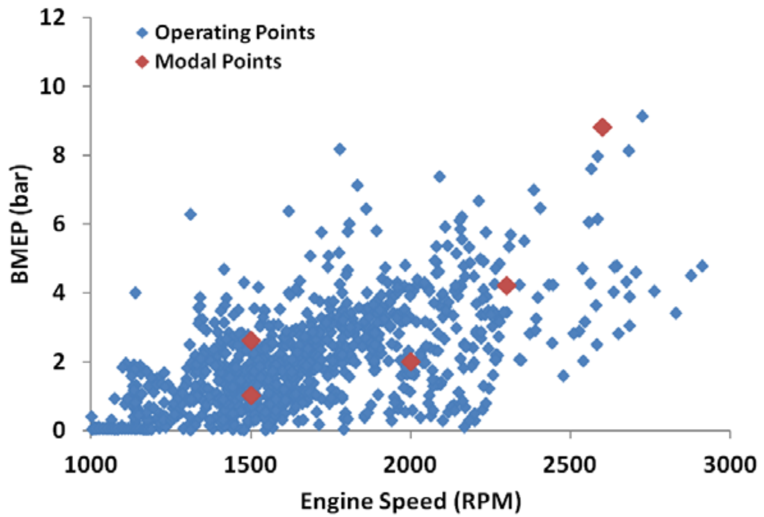
RCCI Piston: 42.5 — Lower Cetane RCCI UTG/ULSD$_{42}$

- **Initial mapping for certification diesel fuel (ULSD) and gasoline (UTG-96)**
  - Has provided clear trends and important emissions data for modeling
- **Load expansion challenges are under investigation**
  - Strong evidence of fuel effects *(reactivity controlled)*
  - Will be controls concern for full map operation
  - Also shows ability to compensate for market fuel property variation

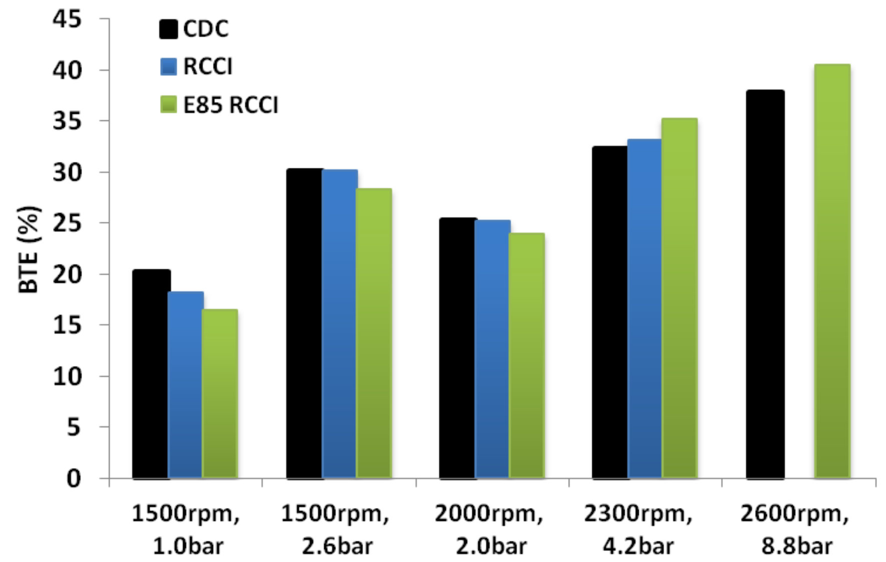
RCCI is able to be mapped

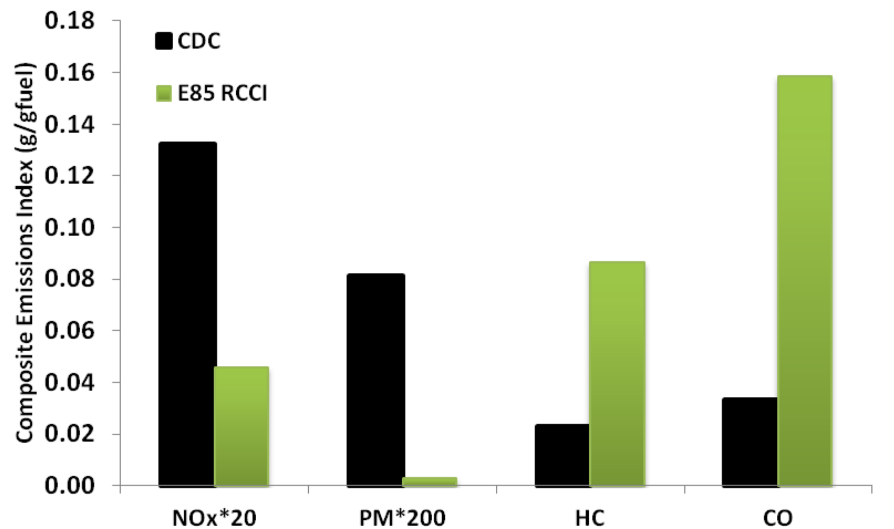
RCCI Drive Cycle Emissions Estimates – A more complete picture

- **RCCI with gasoline and E85** (2012 SAE Paper)
  - Higher BTE overall with RCCI
    - Weight of low-load hurts RCCI NOx index
    - High CO and HC with RCCI at all points



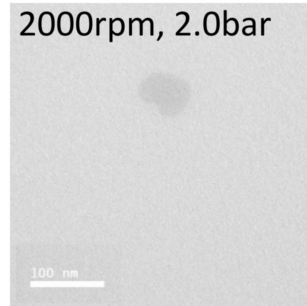
Point	*Speed / Load*	*Weight Factor*	*Description*
1	1500 rpm / 1.0 bar BMEP	400	Catalyst transition temperature
2	1500 rpm / 2.6 bar BMEP	600	Low speed cruise
3	2000 rpm / 2.0 bar BMEP	200	Low speed cruise with slight acceleration
4	2300 rpm / 4.2 bar BMEP	200	Moderate acceleration
5	2600 rpm / 8.8bar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

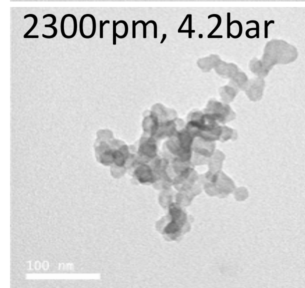


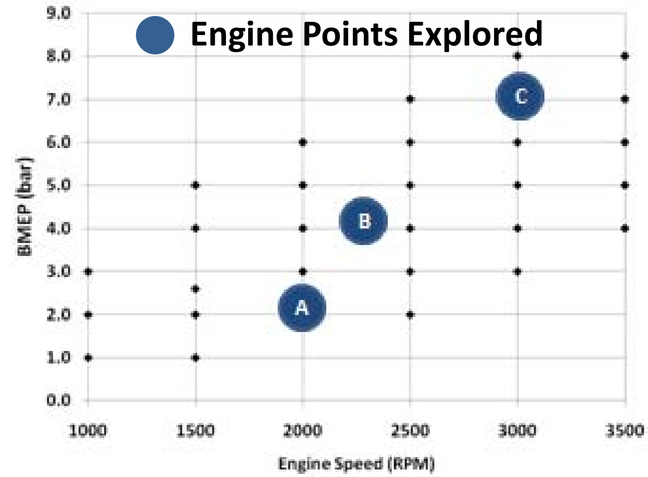


RCCI PM Size Distribution Mostly Independent of Fuel Choice

- **Detailed RCCI HC speciation and PM study**
  - For a given load, the size distributions did not depend significantly on fuel type
  - TEM analysis suggests volatile droplets were abundant and few soot particles were present. (surviving PMP (backup slide)
  - Thermal optical analysis showed that most PM was organic carbon (backup slide)
  - ⇒ DOC becomes effective at PM reduction
  - ⇒ PM is heavy hydrocarbons that could be counted as “solid” through European PMP standard

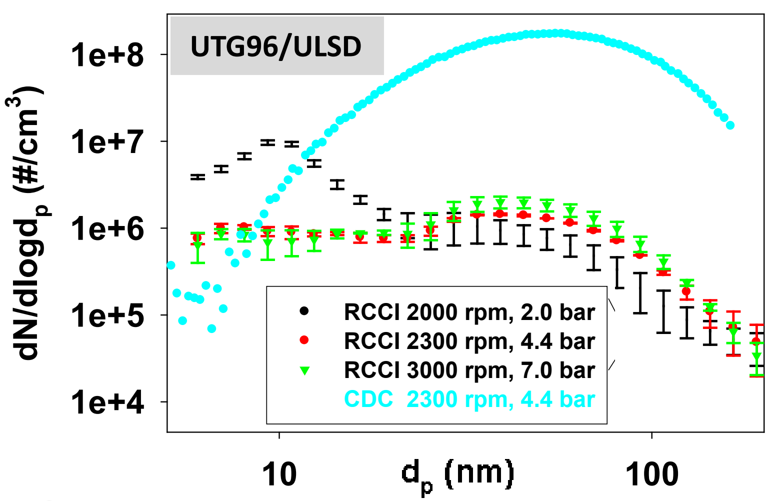


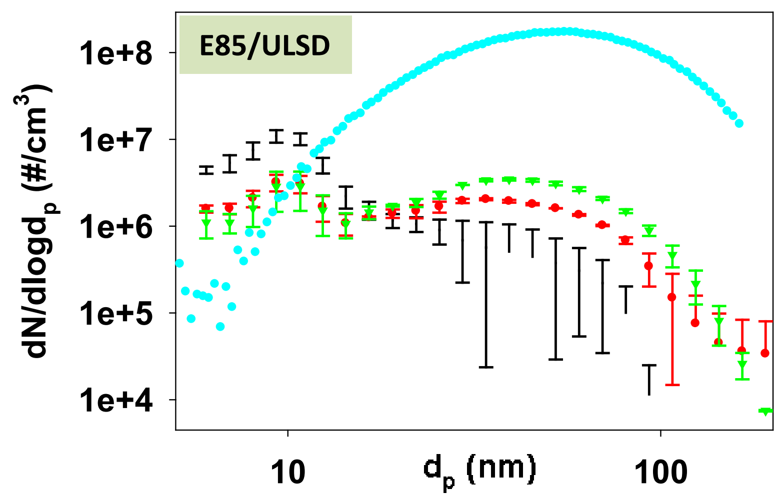




Fuel Combinations

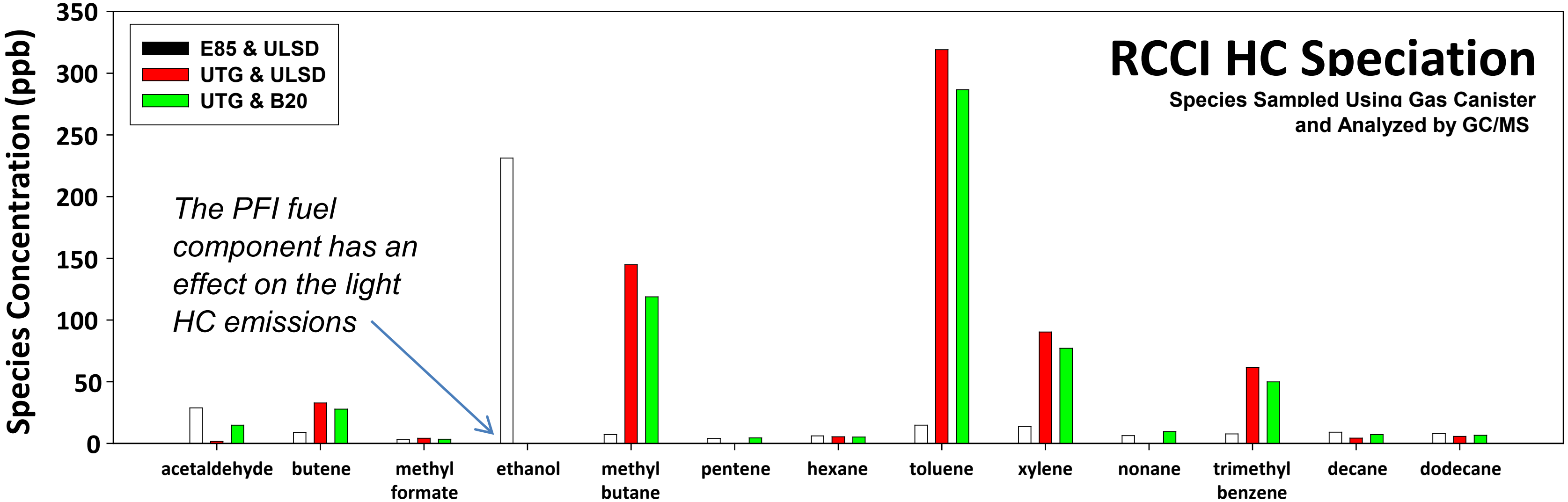
UTG 96 - ULSD	E85 - ULSD	UTG – B20

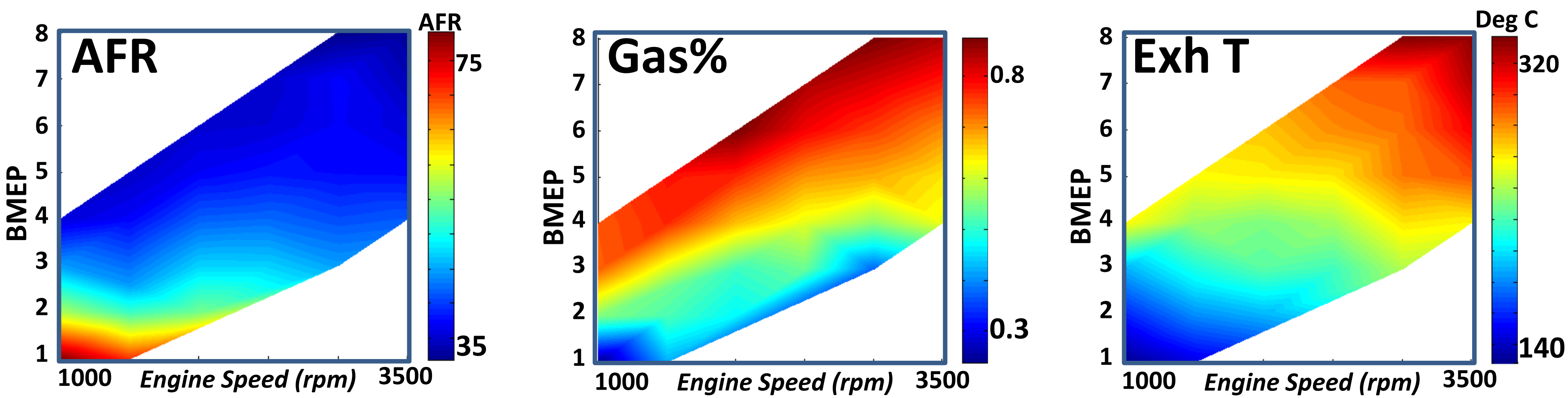




RCCI Emissions Trends Show Challenges for Aftertreatments

- High HC emissions along with lean operation and low exhaust temperature pose challenge
- HC species from RCCI are quite different that from CDC operation – fuel mix changes with speed & load

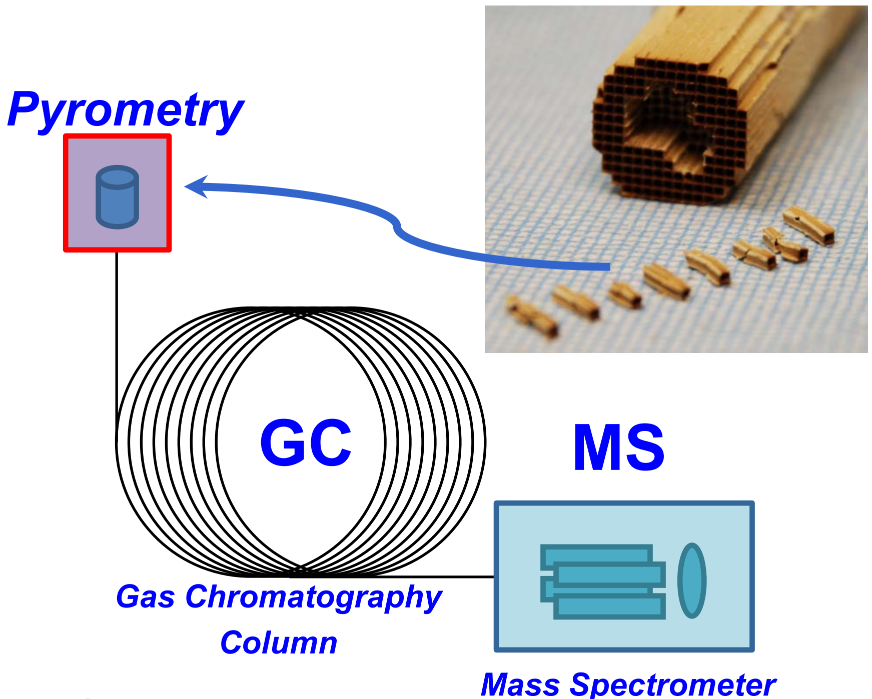


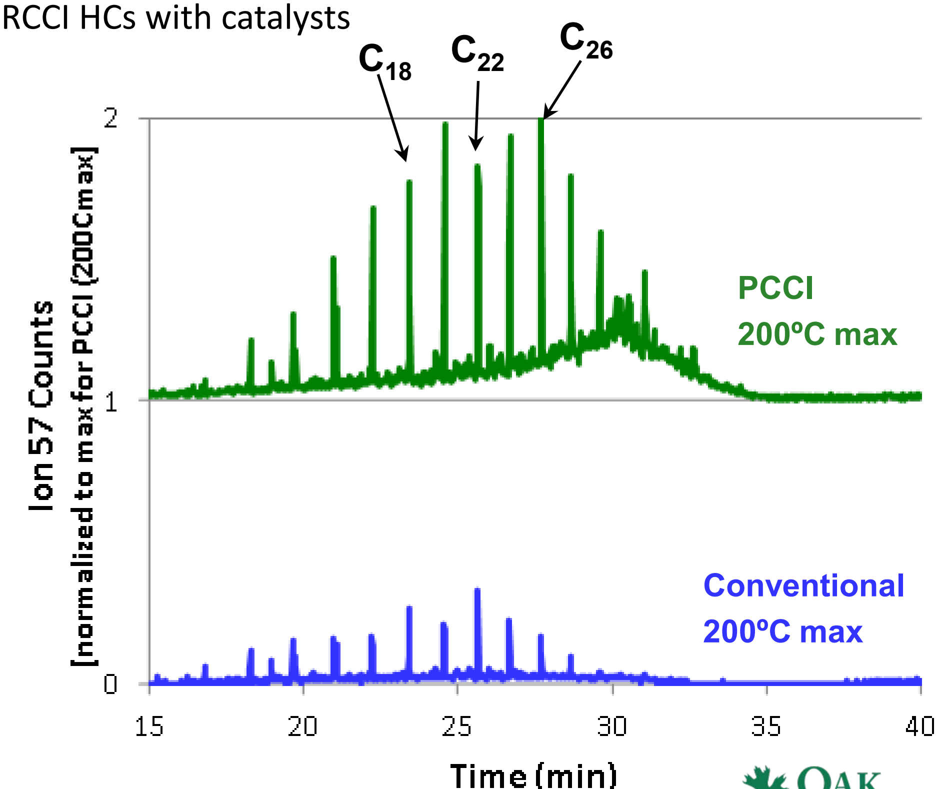


RCCI and CDC NOx comparison - shown in backup slide

HC Species from LTC Modes Can Foul Catalyst Performance

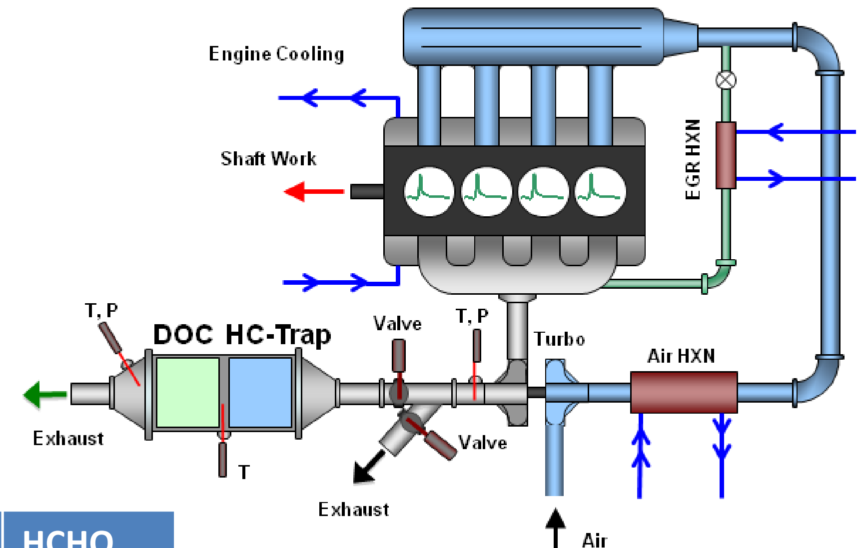
- **HCs desorbed from Cu Chabazite SCR catalysts after exposure to PCCI and conventional diesel exhaust show different degree of HC fouling**
  - Higher HC levels from PCCI can foul SCR more (implications for RCCI)
  - Specific HC species adsorbed may impact degree of performance loss and temperature of HC desorption (performance recovery)
- **Pyrolysis GC-MS technique directly measures HCs desorbed from catalysts**
  - Will utilize technique for analysis of interactions of RCCI HCs with catalysts





Aftertreatment Integration with RCCI

- **Looking towards Tier 2 Bin 2 emissions** *(Experiment planned for April 2012)*
- **Investigate the effectiveness of the HC-trap/DOC system to store/oxidize high levels of CO/HC from RCCI operation at Ad-Hoc modal points**
  - The experiments will determine the effectiveness each of the catalysts in storing/oxidizing CO/HC/PM emissions as a function of temperature
- **Measure exhaust species at engine-out, HC-trap-out and DOC-out locations**
  - Standard emissions benches (CO, HC and NOx)
  - FTIR + HC speciation
  - SMPS/ EEPS for PM
- **Results will be shared with CLEERS**
  - Results used for aftertreatment models
- **Autonomie simulations to estimate emissions**
  - Evaluate Tier 2 - Bin 5 & Bin 2 potential



Tier 2 (g/mile)	NOx	PM	CO	NMOG	HCHO
Bin 5	0.07	0.01	4.2	0.09	0.018
Bin 2	0.02	0.01	2.1	0.01	0.004
Reduction	**71%**	**--**	**50%**	**89%**	**78%**

SULEV30 – CARB LEV III

Adapted from: epa.gov/otaq/standards/light-duty/tier2stds.htm

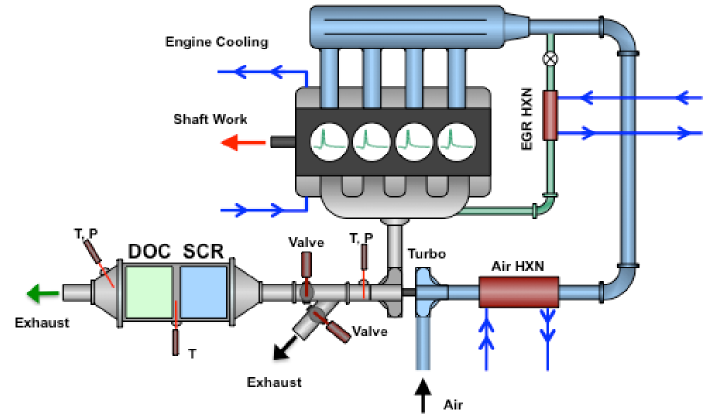
Collaborations

- **University Partners**
  - The University of Wisconsin-Madison – RCCI modeling
    - Student researcher over summer incorporated multi-cylinder work into thesis
- **Automotive OEM Partners**
  - GM - Discuss GM 1.9 – Hardware and LTC noise discussion
  - Borg Warner – Hardware
  - MECA – Catalysts supply and industry feedback
  - Energy Company– Possible fuel effects collaboration for LTC
  - Chrysler – Data for Q4 milestone
- **DOE Working Group Partners**
  - Research is shared with DOE's AEC/HCCI working group meeting twice a year
- **CLEERS (**Cross-Cut Lean Exhaust Emissions Reduction Simulations)
  - Universities/ Industry/ Other National Labs
- **Other ORNL-DOE Activities**
  - Fuel Technologies, Health Effects, Vehicle Systems
- **ACE briefs to ORNL Bioenergy Researchers/ Local Clean Cities/ Universities**

Future Work

FY 12

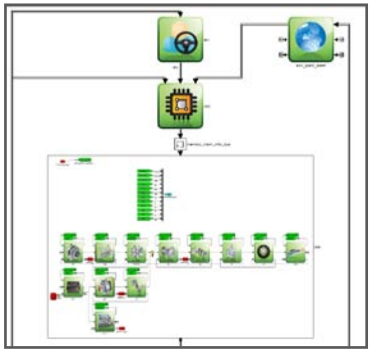
- **Q3 and Q4 DOE Milestones – RCCI**
  - Publish results of ACE milestones and related research
- **RCCI aftertreatment integration studies** (couple to mapping)
  - DOC and SCR – data into CLEERS database
  - Publish study on RCCI PM and HC speciation



FY13

- **Address multi-cylinder challenges**
  - Instability, load range limitations, dilution challenges
  - Combustion stability / Controls for LTC on MCE
  - Thermodynamic analysis of LTC to identify losses/ opportunities
- **Minimizing secondary fuel system in dual-fuel LTC**
- **Drive cycle considerations including transient challenges and tank sizing**
- **Aftertreatment integration research including low-temp catalysts**
  - RCCI aftertreatment performance mapping and feedback to CLEERS

AUTONOMIE



Summary – On track to meet FY 2012 Milestones

Advanced combustion techniques such as RCCI can increase engine efficiency and lower NOx and PM emissions. Comprehensive approach to help meet VTP goals and milestones.

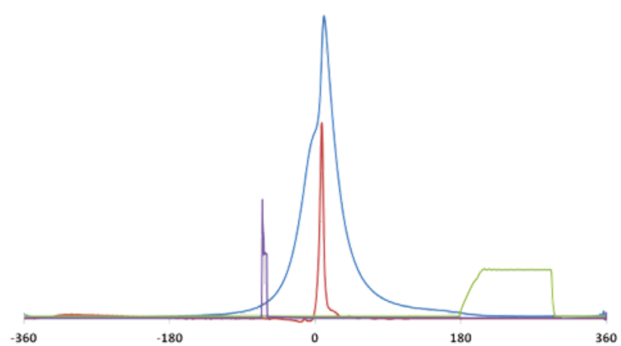
In-cylinder blending of two fuels with different fuel reactivity (octane/cetane) allows increased control over combustion compared to single fuel advanced combustion techniques.

Increased HC/CO emissions will be a challenge and will require progress in low temperature aftertreatment *(On-going research for FY 2012).*

LTC techniques challenge catalysts with lower exhaust temperatures… the species-specific interactions with the catalyst pore structures must be considered for system design

Multi-Cylinder RCCI Challenges Identified

- Matching turbomachinery to low-load operation
- EGR and combustion stability
- Sensitivity of combustion to intake temperature
- Aftertreatment integration with LTC with high HC/ low temp



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Technical Back-Up Slides

Backup 1 - RCCI – Premixed combustion load expansion through fuel reactivity stratification

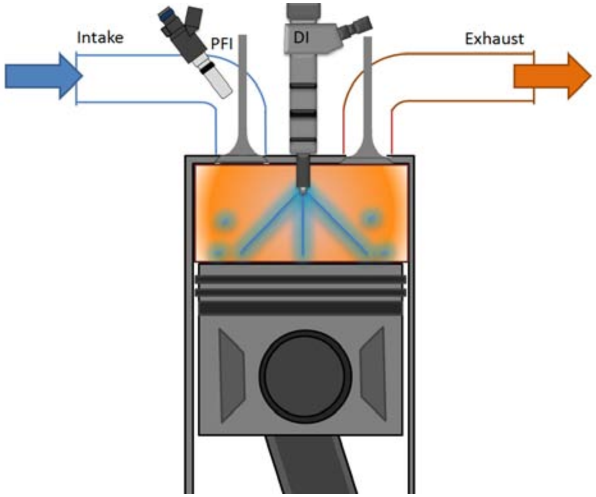
- **Dual-Fuel Reactivity Controlled Compression Ignition (RCCI) provides high level of control of combustion process**
- **In-cylinder fuel blending for reactivity stratification**

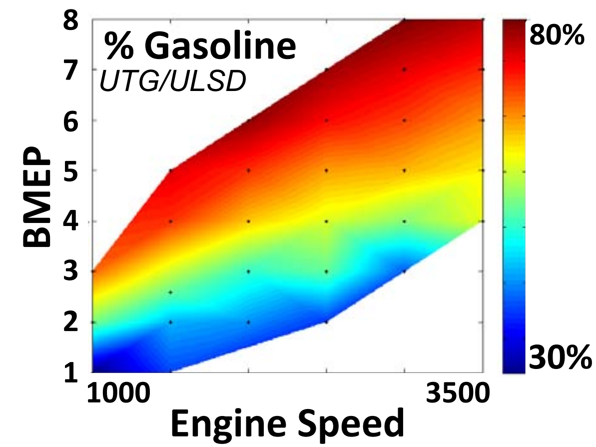
Port injection of low reactivity fuel, i.e. Gasoline/ E85 (orange)

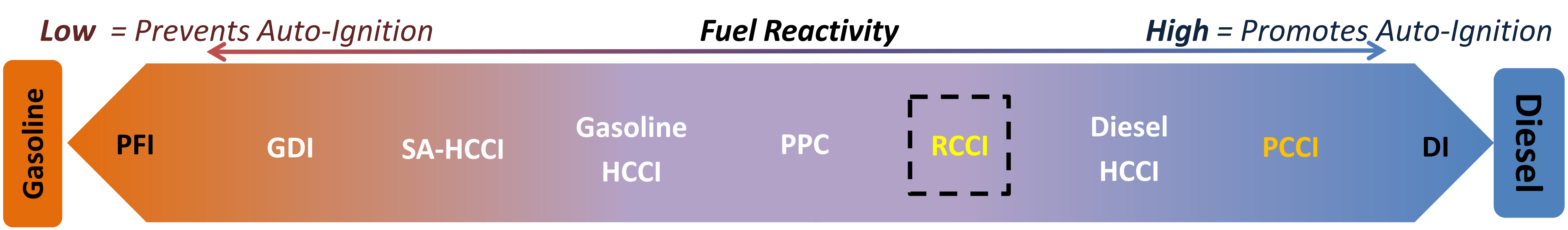
Direct injection of high reactivity fuel, i.e. Diesel/ B20 (blue)

  – Global fuel reactivity (combustion phasing)
  – Fuel reactivity gradients (pressure rise rate)
  – Equivalence ratio stratification
  – Temperature stratification

- **Controlling reactivity allows for wide range of HECC operation**
  – Gasoline/ ethanol well suited for high loads (high octane)
  – Diesel/ biodiesel well suited for low loads (high cetane)







Backup - RCCI Optimized Pistons

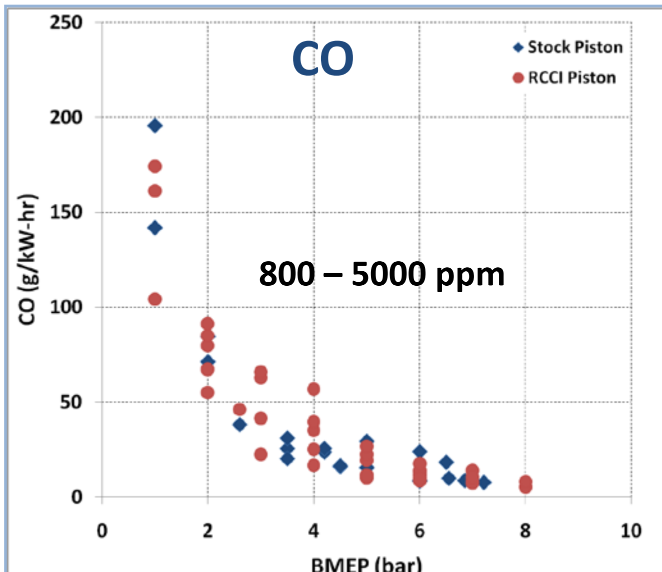
- **UW design (CFD modeling)**
  - Based on heavy-duty RCCI piston
  - Reducing surface area main consideration
  - Best HC emissions and Efficiency
  - Compromise for high and low loads
  - Reduce heat transfer losses
- **HC and CO emissions mostly insensitive to piston bowl geometry** (Inline with PFI engine-out).
  - Possibly due to crevice effects – same for both piston designs.

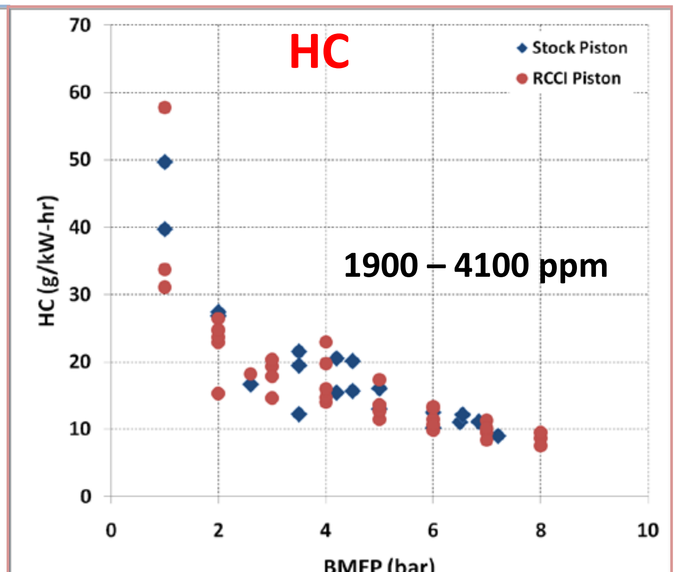
Modified RCCI Piston

CR = 15.1:1

Stock GM 1.9 L piston

CR = 17.5:1

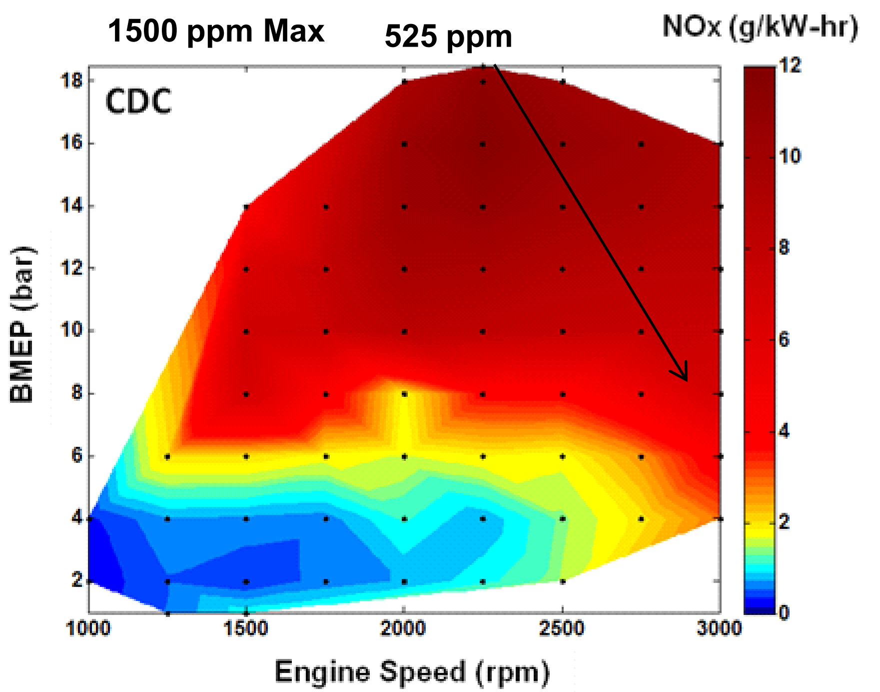


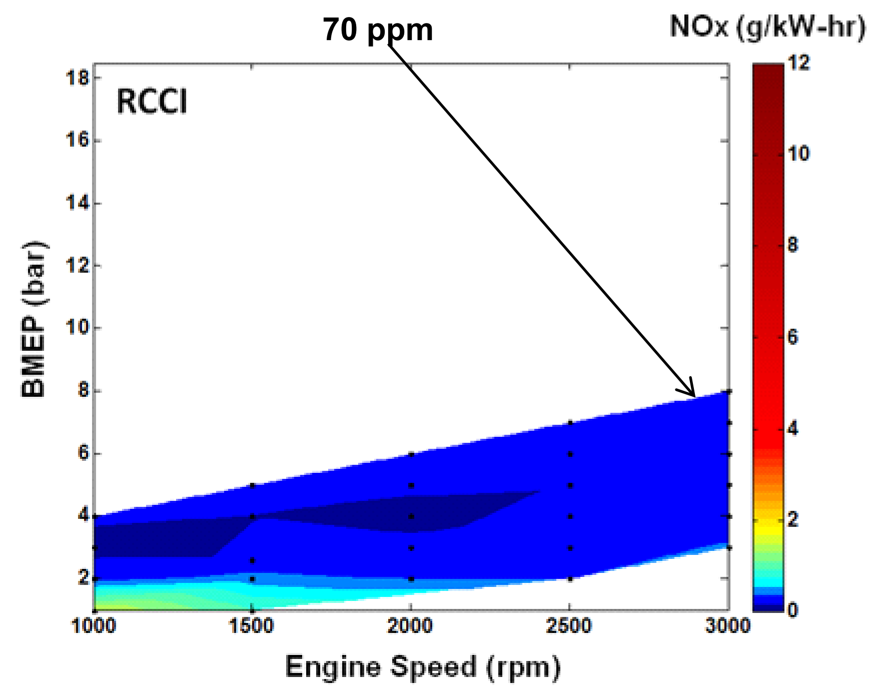


Hanson, et al. 2012 SAE Paper 2012-01-0380

OAK RIDGE National Laboratory

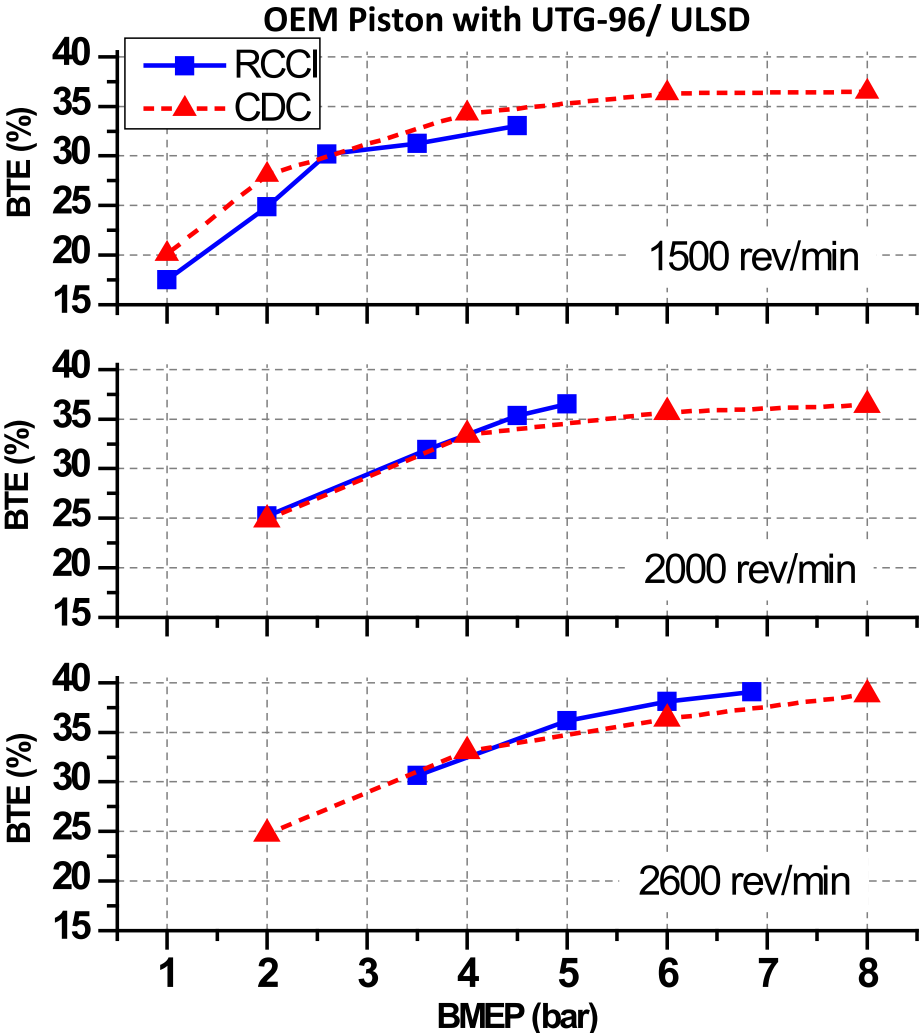
Backup - RCCI Reduces Engine-out NOx and Soot Emissions Significantly Compared to CDC





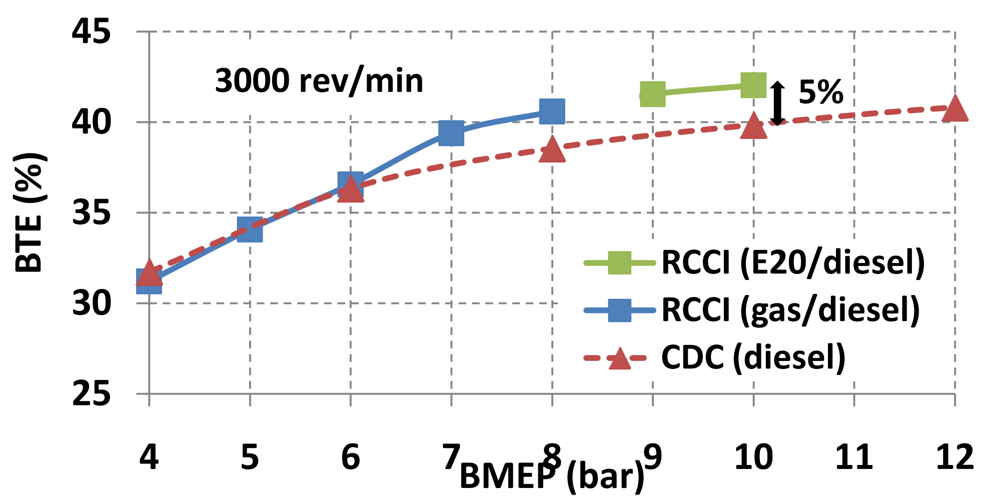
- **RCCI produces ~order of magnitude reduction in NOx**
- **Soot emissions (not shown) less than 0.05 FSN for all RCCI conditions**
  - Smoke number not sufficient to understand PM characteristics
  - Under investigation after recent experimental campaign

Backup - Motivation for Load Expansion is Efficiency



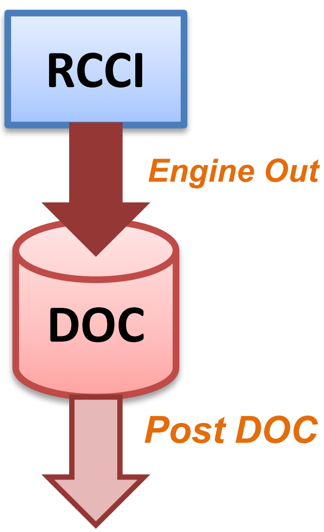
Diesel-like efficiency at low-mid loads

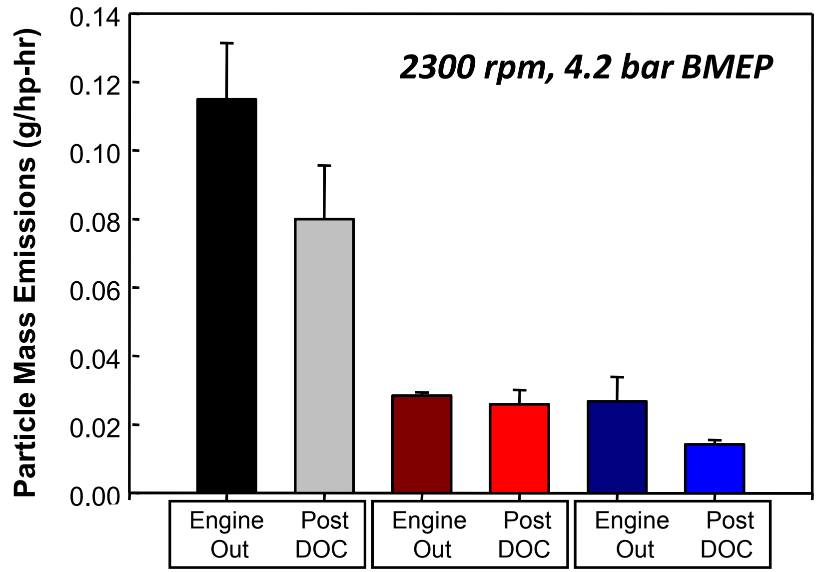
>5% improvement at higher loads



Backup - Mass Based RCCI PM Measurements (High OC content)

- **PM filter images and size distribution data suggested high organic content in PM from RCCI.**
  - Found to be > 98% organic carbon at conditions examined
- **DOC reduces RCCI PM mass significantly.**





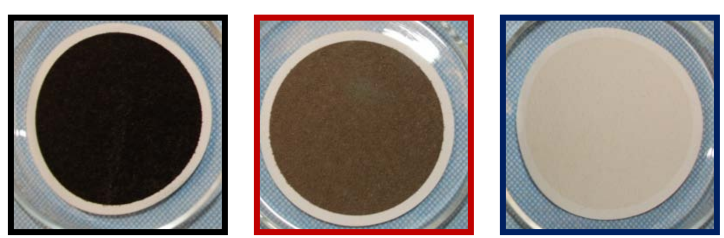
Exhaust Temperature

Conventional	415 C
PCCI	420 C
RCCI	250 C

DOC effective for RCCI PM even though exhaust temperature lower

Conventional Diesel **Diesel PCCI** **RCCI**

PM filter samples at Engine Out



Prikhodko, et al.
2011 ASME ICEF Paper