Performance of Advanced Combustion Modes with Alternative Fuels: Reactivity Controlled Compression Ignition Case Study

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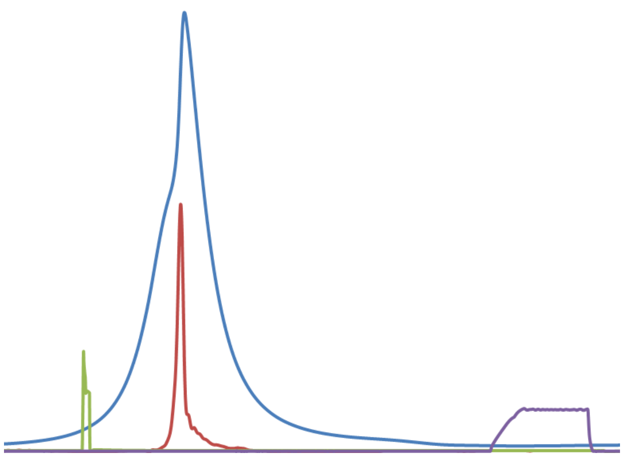
January 2012 CBES Forum



Reactivity Controlled Compression Ignition

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Overview – Multi-Cylinder RCCI Research

- **Fuels Engines and Emissions Research Center**
- **Advanced Combustion Primer**
- **Multi-Cylinder RCCI Results**
- **RCCI with Ethanol and Biodiesel Blends**
- **Implications for future RCCI work with Alt Fuels**

U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program

- **The mission of the VTP is to develop more <u>energy-efficient</u> and <u>environmentally friendly</u> highway transportation technologies that will:**
  - Meet or exceed performance expectations
  - Enable the United States to use significantly less petroleum
  - Reduce greenhouse gas and other regulated emissions

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

- **Fuel efficiency improvement is the overarching focus of this activity, but resolving the interdependent emissions challenges is a critical integrated requirement.**
  - The reduction of engine-out emissions is key to managing the extra cost of exhaust aftertreatment devices that can be a barrier to market acceptance.

Vehicle Technologies Program			
Advanced Combustion Engine R&D	Fuel Technologies	Hybrid Electric Systems	Materials Technology

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2010_adv_combustion_engine.pdf

Relevancy of Internal Combustion Engines and Biofuels

- **In terms of efficiency potential, market penetration projections and usability for IC Engines:**
  - 2011 2011 Directions in Engine-Efficiency and Emissions Research Conference (DEER) in Detroit

U.S. DEPARTMENT OF ENERGY
DEER 2011
DETROIT
DIRECTIONS IN ENGINE-EFFICIENCY AND EMISSIONS RESEARCH CONFERENCE

- ***"The future of the IC engine is bright and clear; I don't think that could be any more obvious to all of us,"***
- **Even while projecting to the future and talking about batteries and electric vehicles, he said, "*when you look at our actual analysis and you look to our projections for the future, 95% or more of the vehicles, all of the heavy-duty vehicles in our analysis are relying on IC engines.***
  - Byron Bunker, Director, Heavy Duty Engine Center, Office of Transportation and Air Quality, US Environmental Protection Agency -

- **Many other future of IC Engines presentations**
  - **EPA**
  - **Mahle Powertrain**
  - **Volvo**

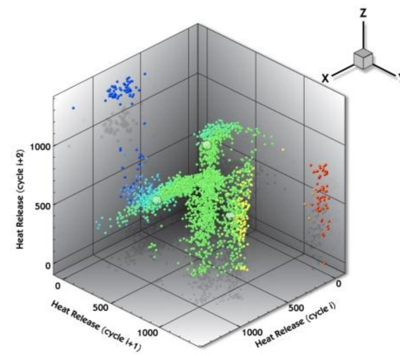
The rumors of the death of internal combustion engine have been greatly exaggerated!

http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/2011_deer_presentations.html
http://www.greencarcongress.com/2011/10/deer-20111005.html

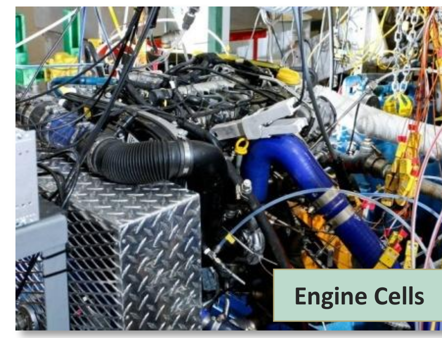
Fuels, Engines, and Emissions Research

…. a comprehensive laboratory for advanced transportation technologies

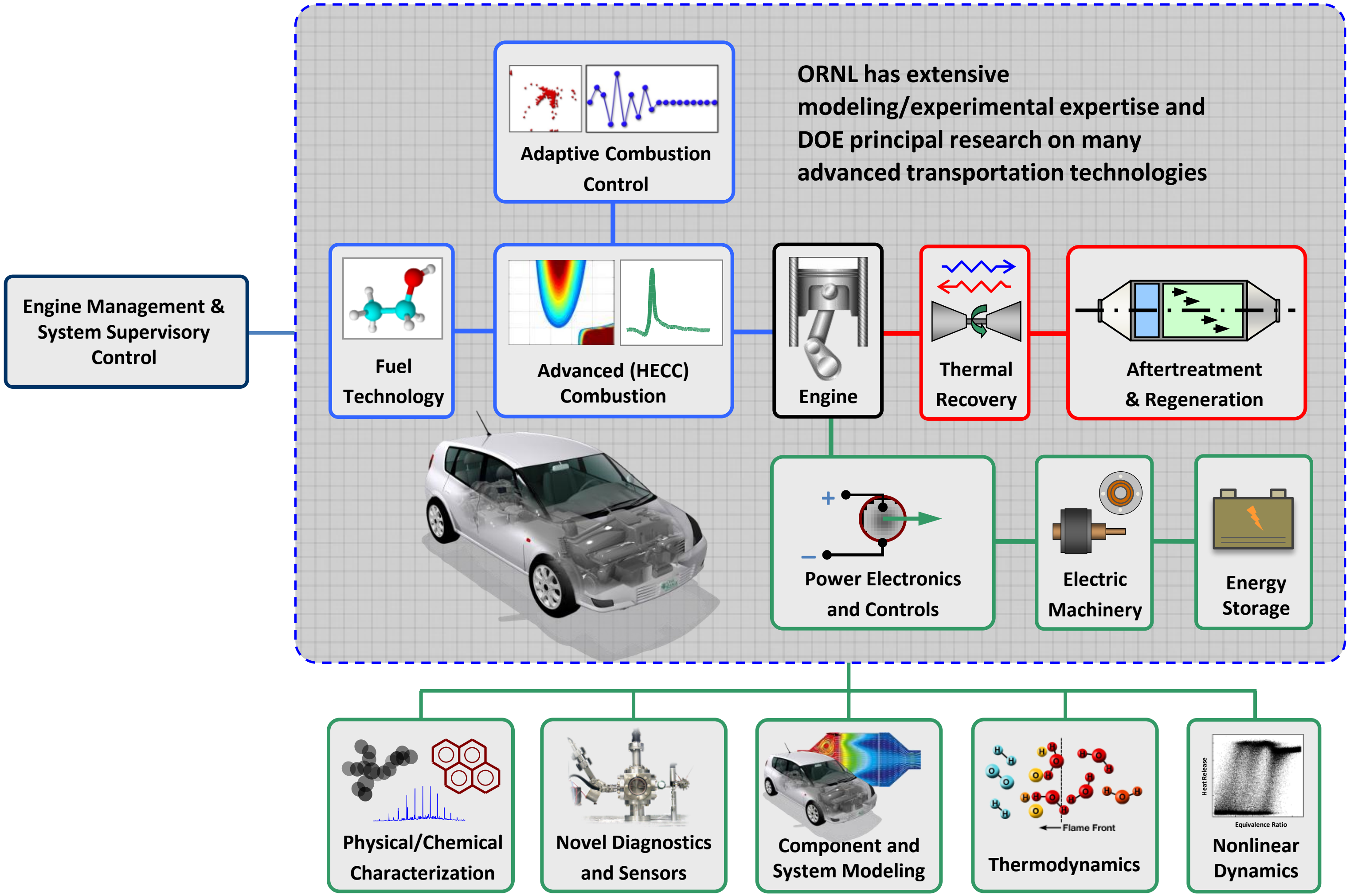
- **A DOE National User Facility**
- **Research and development to achieve key DOE milestones in transportation efficiency and emissions.**
- **Work with DOE and industry to resolve barriers to deployment of efficient vehicles and alternative fuels.**
  - High efficiency combustion concepts
  - Efficient emission control technologies
  - Alternative and renewable fuel technologies
  - Thermodynamic fundamentals and energy management
  - Enabling technologies including materials, diagnostics, etc.
  - Adaptive and self-learning controls
  - Fuel cell characterization
- **Vehicle systems integration for understanding potential and issues under real world conditions.**



Models and Controls



Research addresses wide range of advanced transportation technologies from fundamental to systems perspective

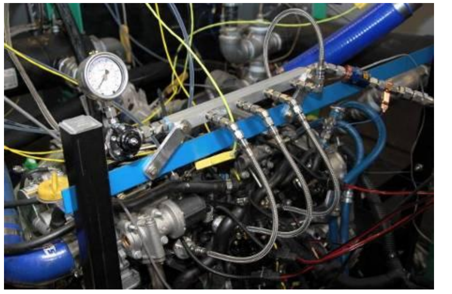


Unique tools and expertise used to understand, enable, and integrate critical technologies.

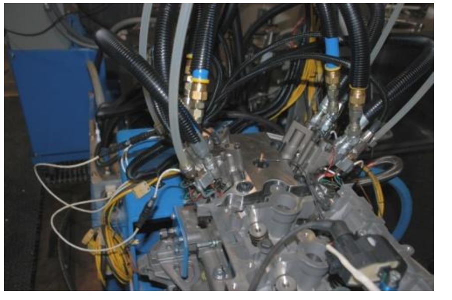
Example on-going combustion and efficiency activities

FEERC

- **Demonstration of DOE Vehicle Technologies efficiency and emissions milestones.**
- **High efficiency combustion concepts for diesel and gasoline platforms.**
  - Premixed Charge Compression Ignition (PCCI).
  - Homogeneous Charge Compression Ignition (HCCI).
  - High Dilution Gasoline Direction Injection.
  - Dual-Fuel Combustion (Gasoline/Diesel).
  - 6-stroke concept with thermal heat recuperation.
- **Nonlinear dynamics and information theory for adaptive controls for enabling or expanding operational range of HECC.**
  - Lean burn gasoline combustion.
  - High dilution stoichiometric GDI.
  - Identification and avoidance of Superknock.
- **Evaluation of high efficiency concepts for light-duty drive schedules.**
  - Integration with other advanced technologies including emissions controls and thermal energy recovery.
  - Suite of models for use with GT-Drive and PSAT.



Modified intake showing PFI injectors on-engine.



Variable valve system on GDI engine

GM 1.9-L diesel engine

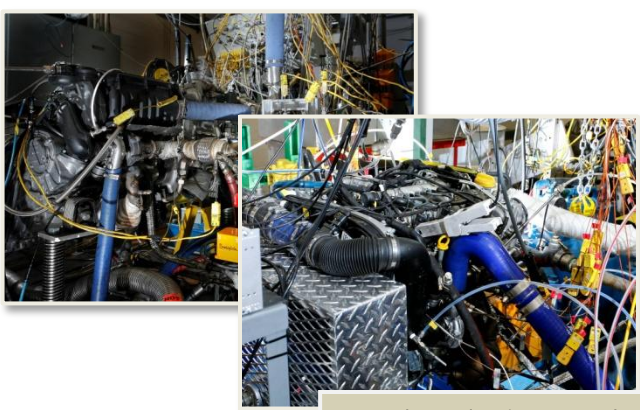
OAK RIDGE National Laboratory

Most comprehensive evaluation of fuel effects across national laboratory system – spans fundamental combustion to end-use production engines

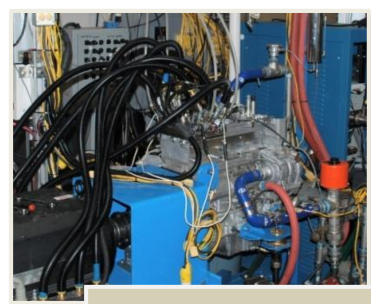
	2004	2005	2006	2007	2008	2009	2010
Conventional diesel fuels		•	•				
FACE diesel fuels					•	•	•
Oil sands derived				•			
Oil shale derived					•		
Biodiesels			•	•	•		
Conventional gasolines	•				•	•	
FACE gasolines							
Gasoline surrogates		•	•		•	•	•
Diesel surrogates					•		•
Ethanol blends					•	•	•
HVO, bio-algae, etc.							

Fully Premixed HCCI Single-Cylinder

VCR SI Two-Cylinder



Multi-Cylinder Diesel PCCI

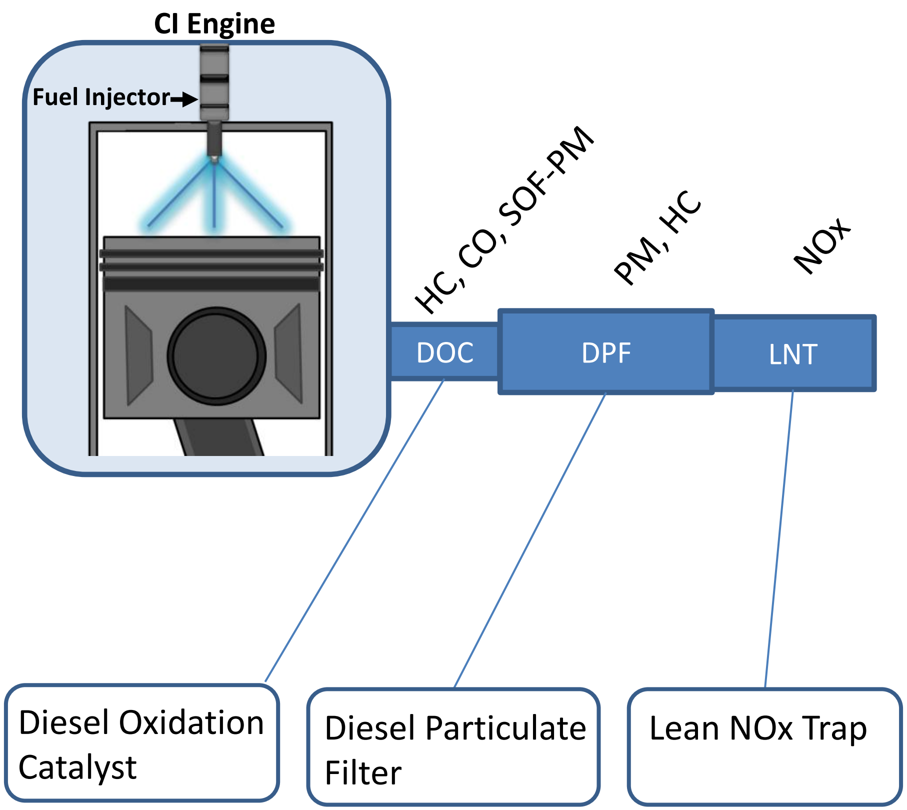


VVA Single-Cylinder

Managed by UT-Battelle
for the U.S. Department of Energy

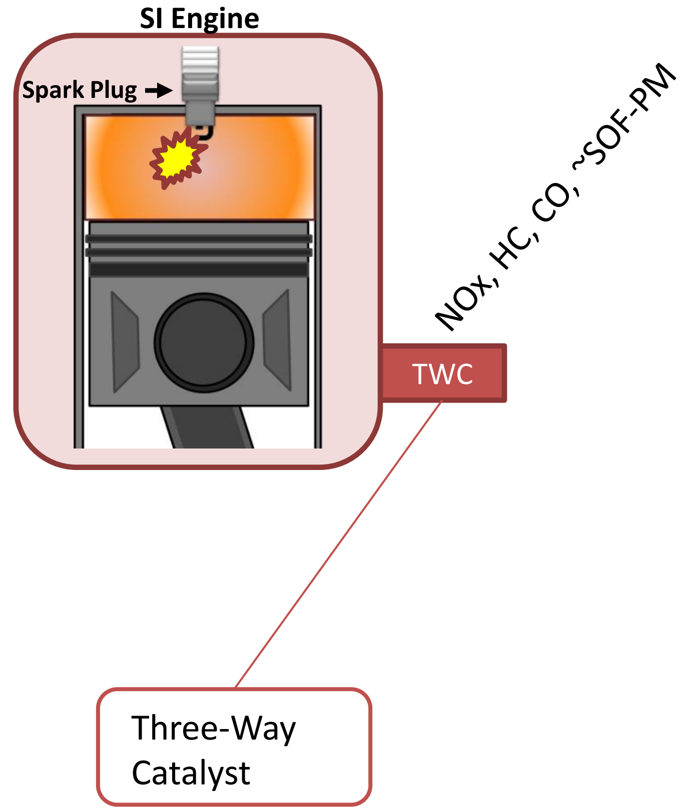
Motivation for Advanced Combustion

- **Diesel Engines**
  Compression Ignition (CI)



- **Gasoline Engine**
  Spark Ignition (SI)

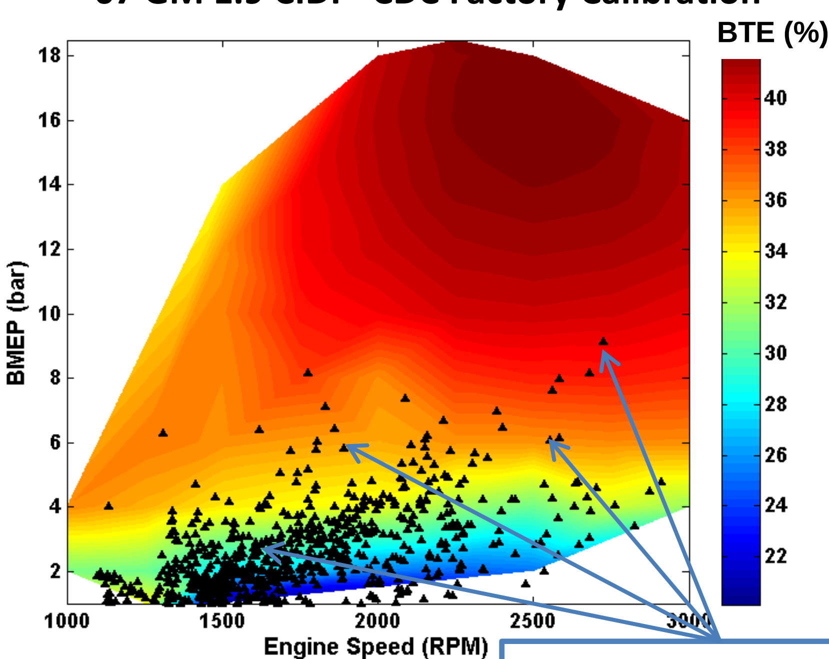
Stoich – PFI or DI Shown



Motivation for Advanced Combustion

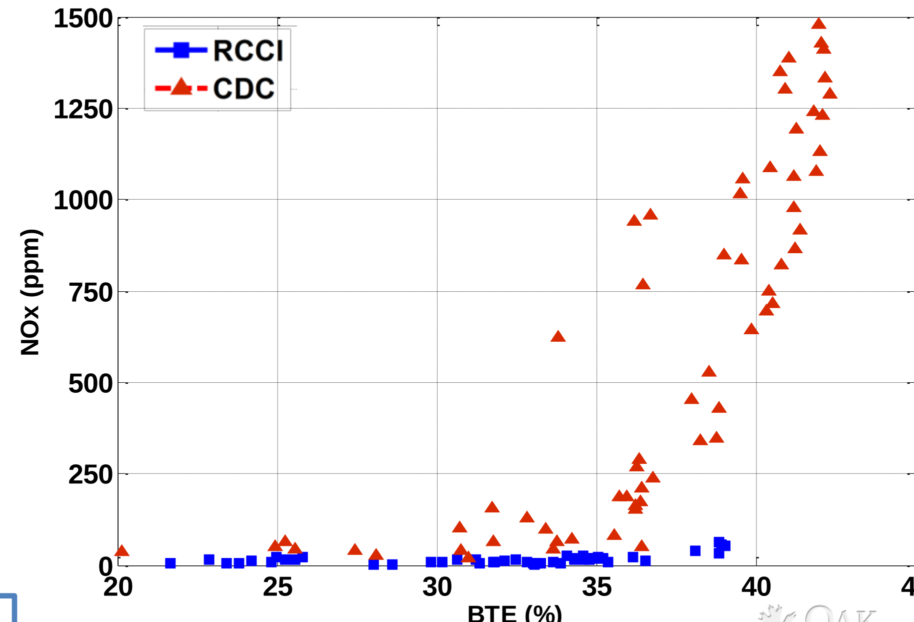
- **Peak efficiency is currently outside light-duty drive cycle**
  - Light-duty vehicle emissions subject to EPA/ CARB standards
- **Treating high NOx/ PM emissions reduces fuel economy**
  - Fuel Penalty: Lean NOx trap, SCR (reductant energy use), DPF regeneration
  - Lower compression ratio

'07 GM 1.9 CIDI - CDC Factory Calibration



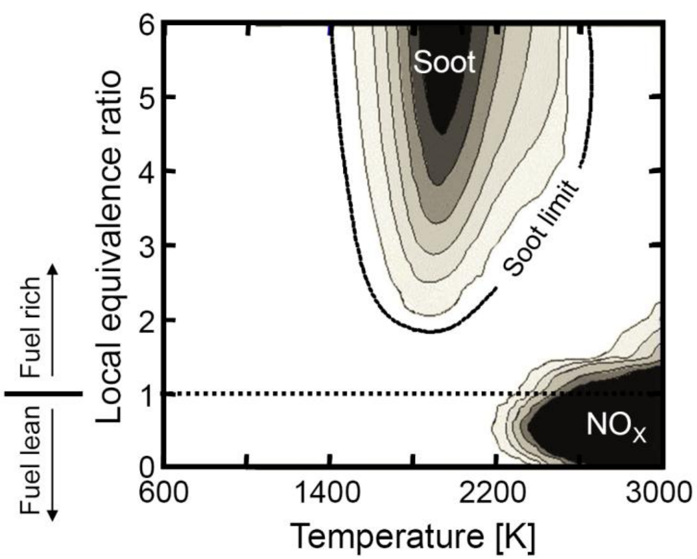
Engine speed and load points visited during FTP

NOx as a function of BTE on '07 GM 1.9

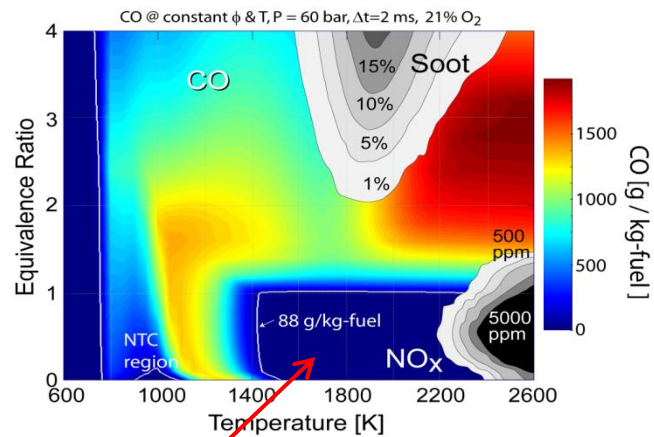


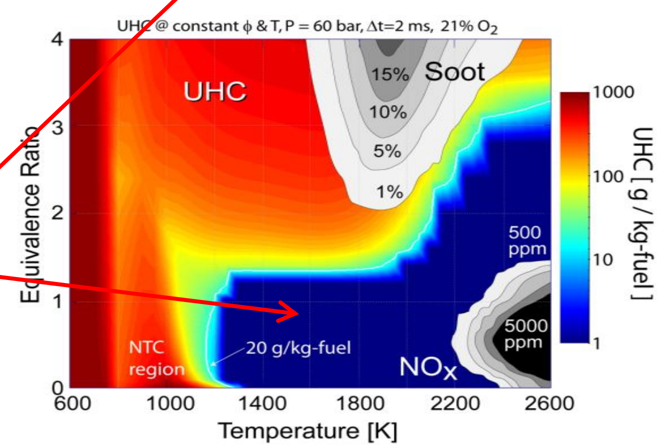
Simultaneous high efficiency with low emissions requires precise control of the combustion process

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



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



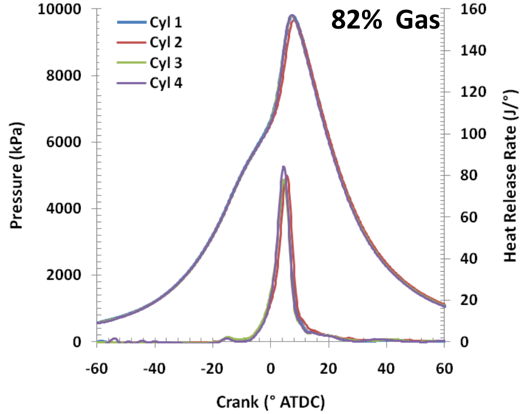


Charge must end up in this region after combustion is complete

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

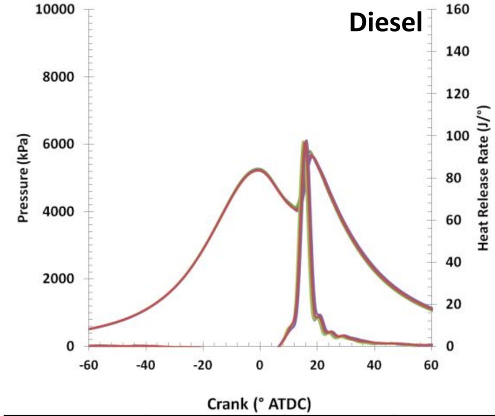
Advanced Combustion Strategies Converging on Hardware and Fuel

Reactivity Controlled Compression Ignition



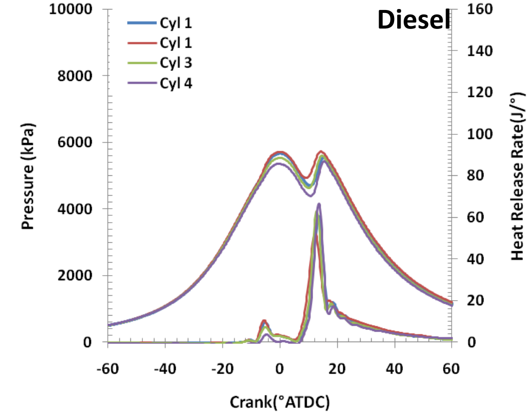
Main SOI (° ATDC)	Pilot SOI (° ATDC)	Inj P (bar)	EGR (%)
-60	NA	500	0

Premixed Charge Compression Ignition

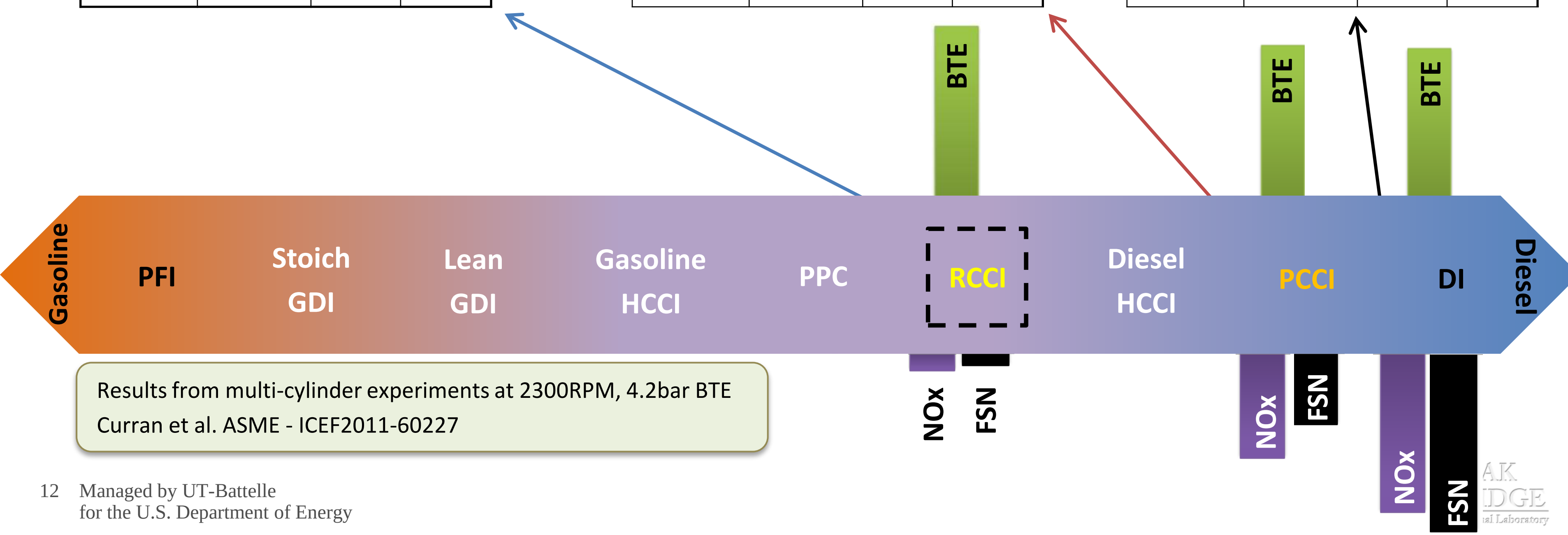


Main SOI (° ATDC)	Pilot SOI (° ATDC)	Inj P (bar)	EGR (%)
4.5	NA	1222	28.2

Conventional Diesel Combustion



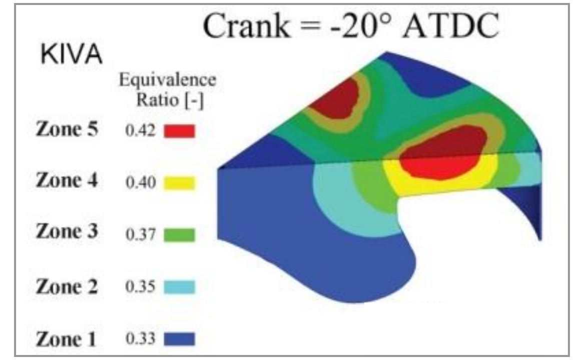
Main SOI (° ATDC)	Pilot SOI (° ATDC)	Inj P (bar)	EGR (%)
1.7	-27.5	1026	24.8

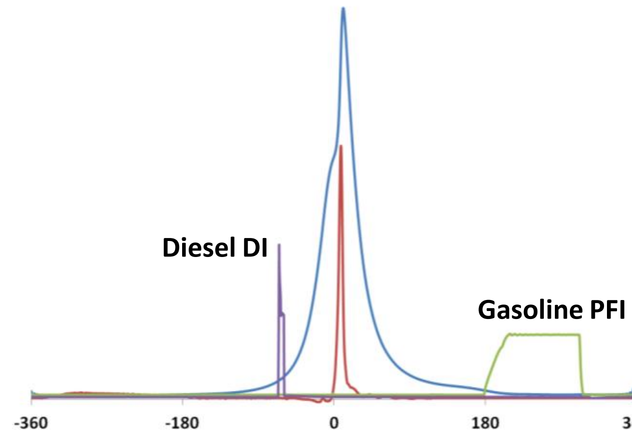


Results from multi-cylinder experiments at 2300RPM, 4.2bar BTE
Curran et al. ASME - ICEF2011-60227

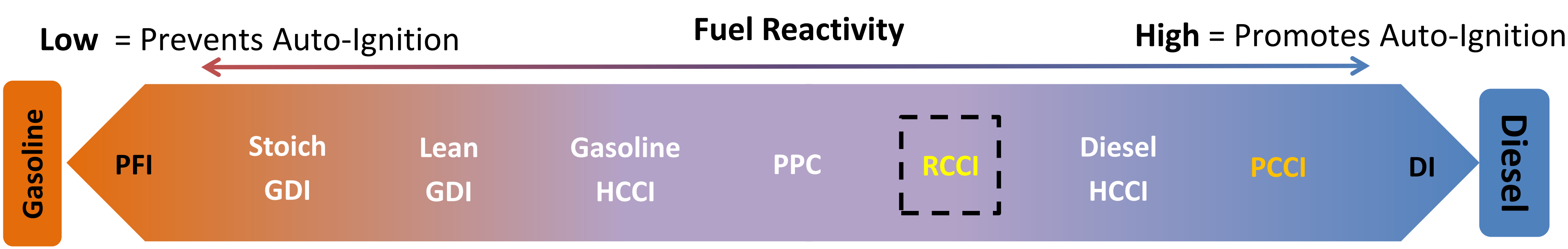
RCCI – Premixed combustion load expansion through fuel reactivity stratification

- **Dual-Fuel Reactivity Controlled Compression Ignition (RCCI) provides high level of control of combustion process**
  - In-cylinder fuel blending for reactivity stratification
  - Gasoline port fuel injection with diesel direct injection
- **Reactivity: the ability to autoignite** (High cetane number)
  - Gasoline is flammable but not kinetically reactive
    - Octane prevents autoignition (knock)
- **Controlling reactivity allows for wide range of HECC operation**
  - Gasoline well suited for high loads (high octane)
  - Diesel fuel well suited for low loads (high cetane)





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



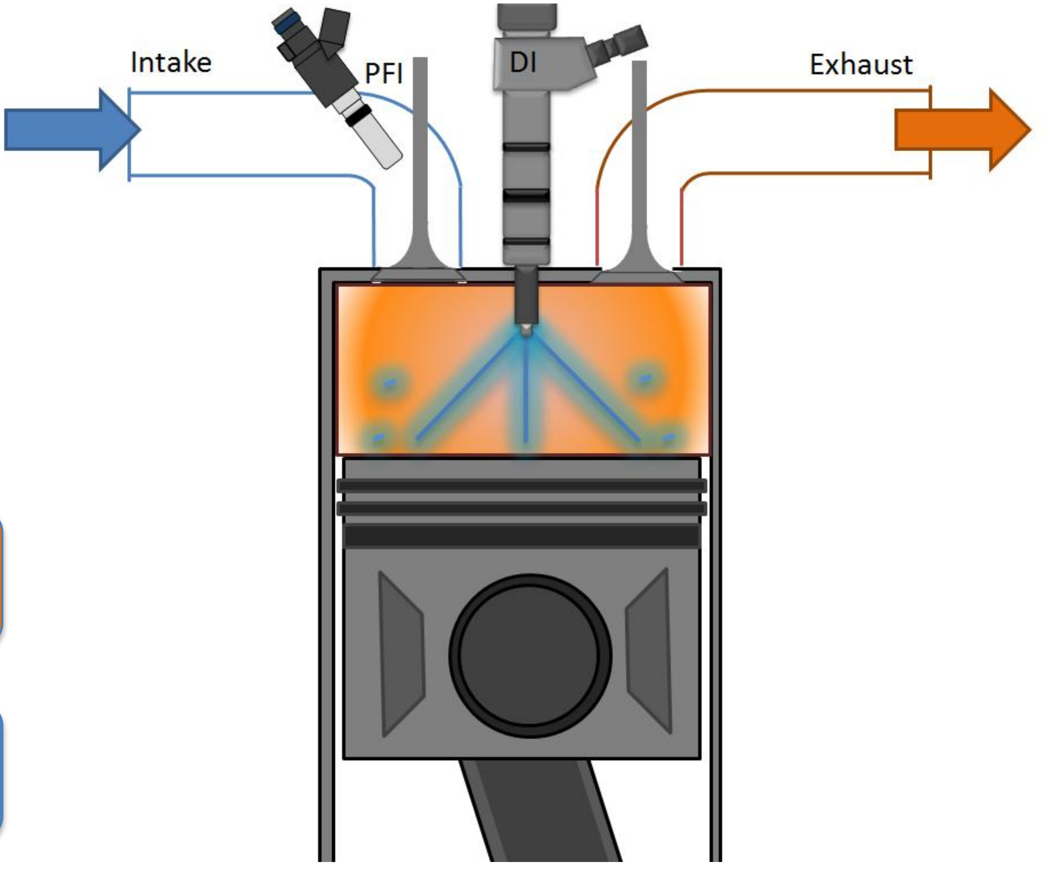
Dual-fuel RCCI concept

Allows increased engine operating range for premixed combustion through:

- Fuel reactivity gradients
- Equivalence ratio stratification
- Temperature stratification

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

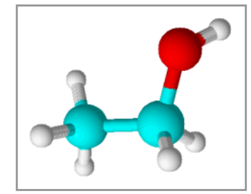
Direct injection of high reactivity fuel, i.e. Diesel/ B20 (blue)



Adapted from Hanson, UW-M Engine Research Center

Effects of Renewable Fuels on Advanced Combustion

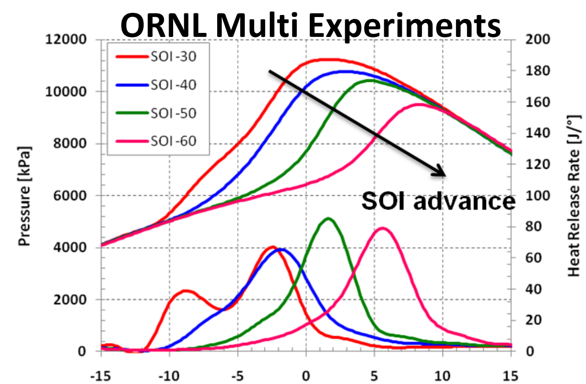
- **Many renewable fuels have unique properties which enable expanded operation of advanced combustion methods for higher engine efficiency and lower energy requirements for emissions control devices.**
  - Fuel composition and chemistry including oxygen content
  - Reactivity
    - Ethanol higher octane than gasoline,
    - Biodiesel/ FT Diesel higher cetane than most diesel fuel
  - Low temperature reaction kinetics (ability to serve as OH radical sink)

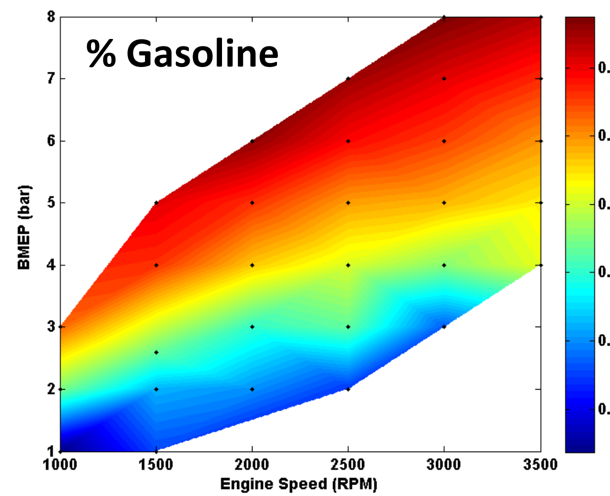


- **Project goal**
  - Addresses the implementation of advanced combustion concepts with production viable engine systems to further petroleum displacement through the combination of direct displacement and improved engine-system efficiency.

Multi-Cylinder RCCI Experiments at ORNL

- **Background**
  - Verification and exploration of RCCI concept on multi-cylinder light-duty diesel engine with production viable hardware
- **Previous Results** *(Gasoline & Diesel Fuel)*
  - RCCI operation at 2300 RPM, 4.3bar BMEP
    - Point modeled by UW
  - Indentified real-world and multi-cylinder challenges
    - Cylinder balancing, limits of turbo-machinery and EGR
  - Detailed combustion and emissions results [1,2]
    - Pre and post-DOC emissions including HC speciation and PM
  - Developed systemic approach for RCCI operation
    - Based on modeling and previous multi-cylinder work





1. 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)

2. Prikhodko et al. , "Emission Characteristics of a Diesel Engine Operating with In-Cylinder Gasoline and Diesel Fuel Blending", *SAE Technical Paper Series* 2010-01-2266 (2010)

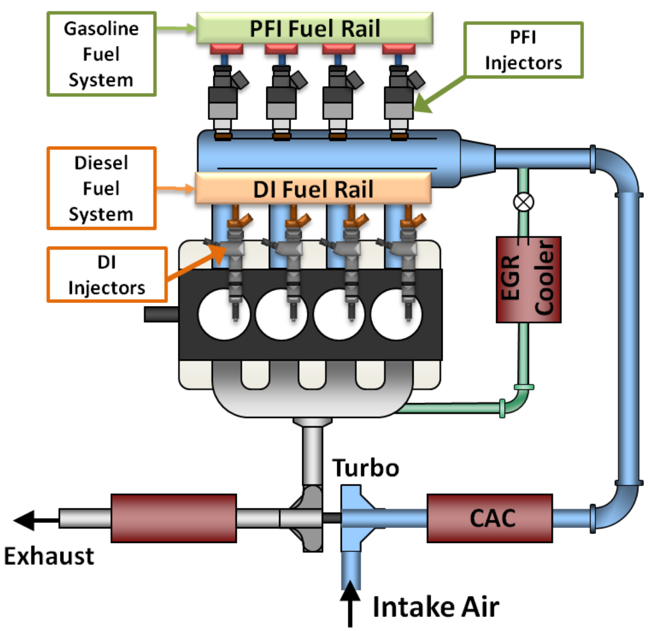
ORNL Light-Duty Multi-Cylinder RCCI Setup

- **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
- **DRIVVEN control system with DCAT**
  - Full control of diesel & gasoline fuel systems
  - Cylinder-to-cylinder balancing capability

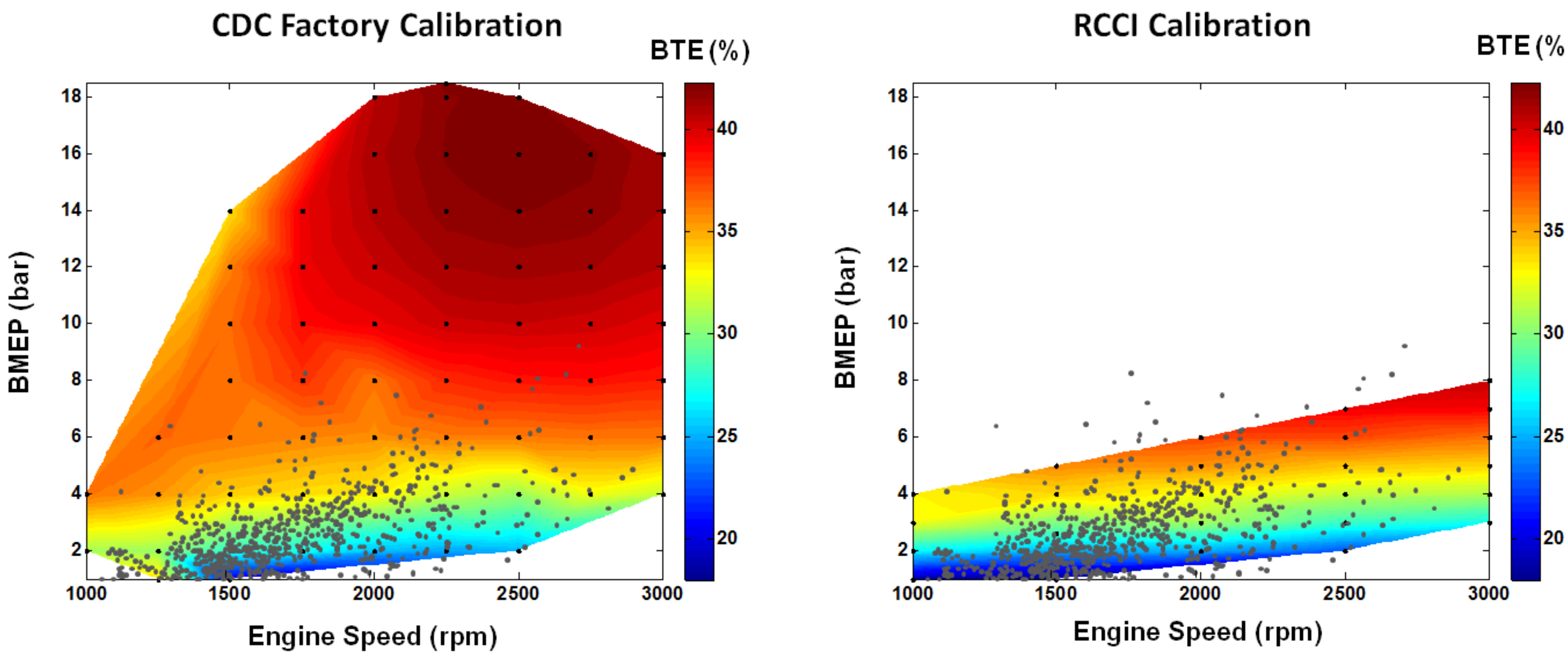
ORNL Multi-Cylinder 1.9L GM CIDI

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 Intake Manifold with PFI Injectors

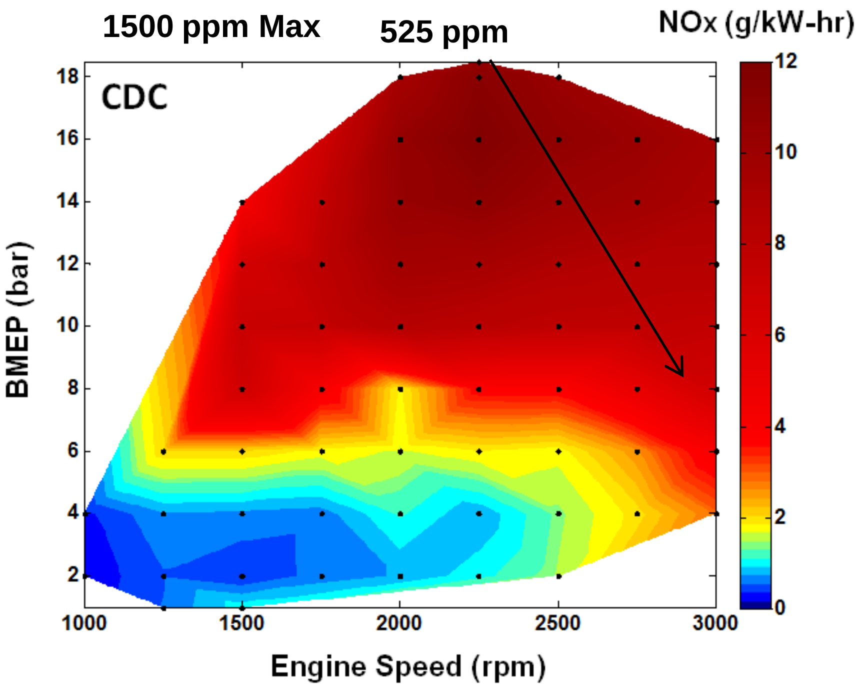


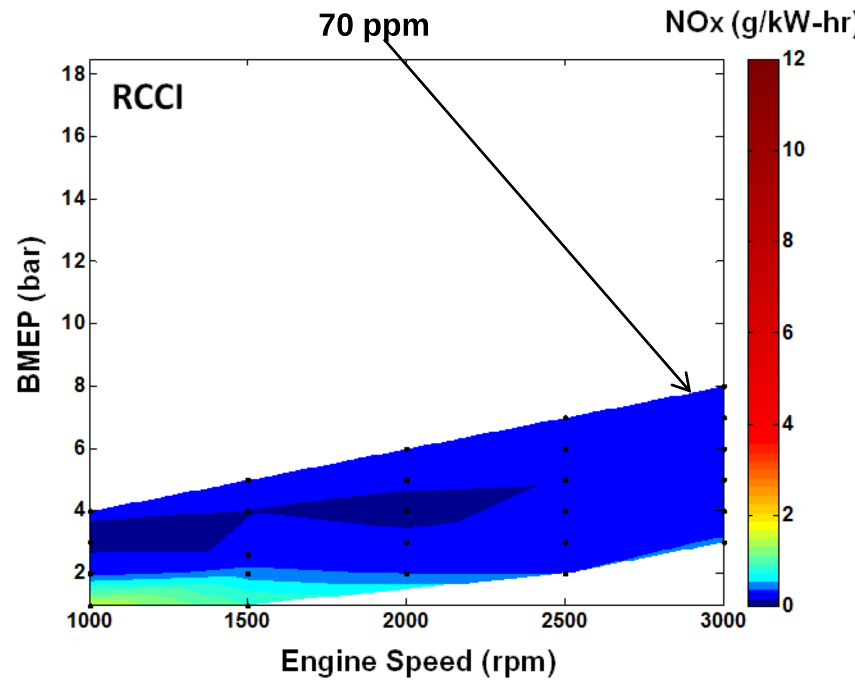
Current RCCI Operation Includes Most of LD Drive-Cycle *(grey dots)*



- **Mapping data for certification diesel fuel (ULSD) and gasoline (UTG-96)**
  - Sparse map completed for E20 and ULSD
- **Load expansion challenges are under investigation**
  - Biofuels play important role

RCCI Reduces Engine-out NOx and Soot Emissions Significantly

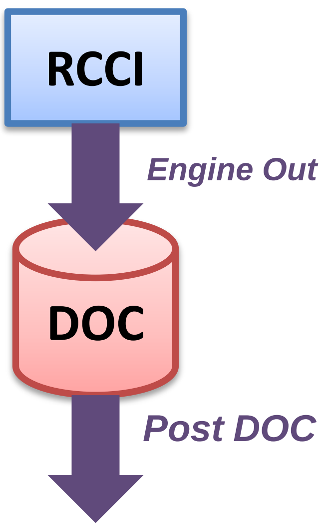


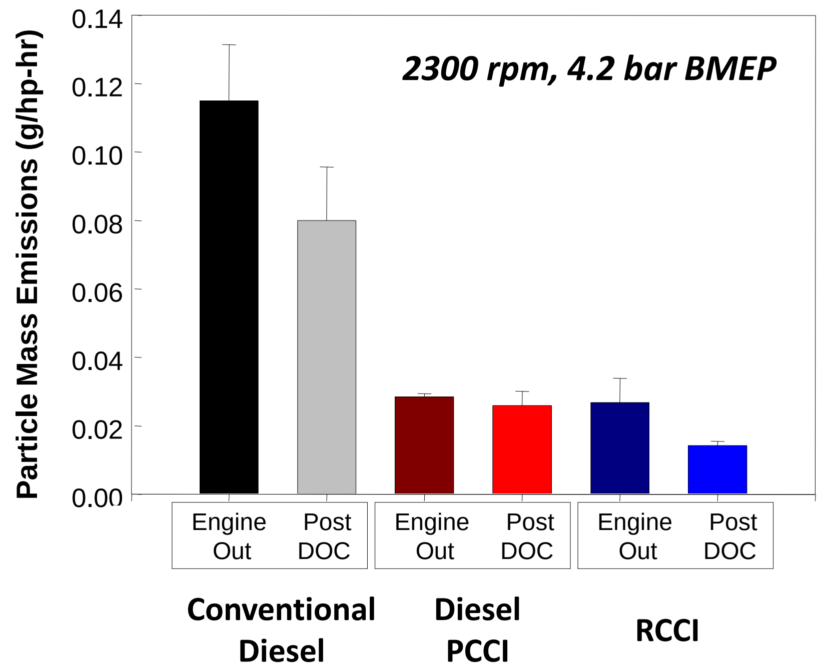


- **RCCI produces ~order of magnitude reduction in NOx**
- **Soot emissions (not shown) less than 0.05 FSN for all RCCI conditions**
  - Smoke number not sufficient to understand PM characteristics
  - Under investigation after recent experimental campaign

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.**
  - Found to be > 98% organic carbon at some conditions
- **DOC reduces RCCI PM mass significantly.**



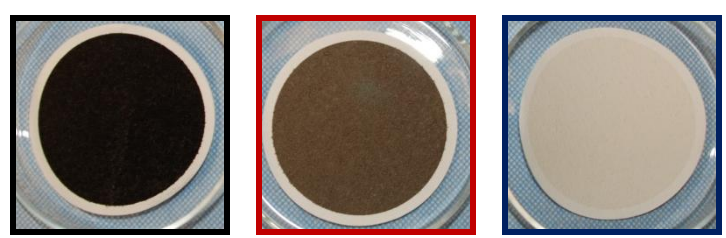


Exhaust Temperature

Conventional	415ºC
PCCI	420ºC
RCCI	250ºC

DOC effective for RCCI PM even though exhaust temperature lower

PM filter samples at Engine Out

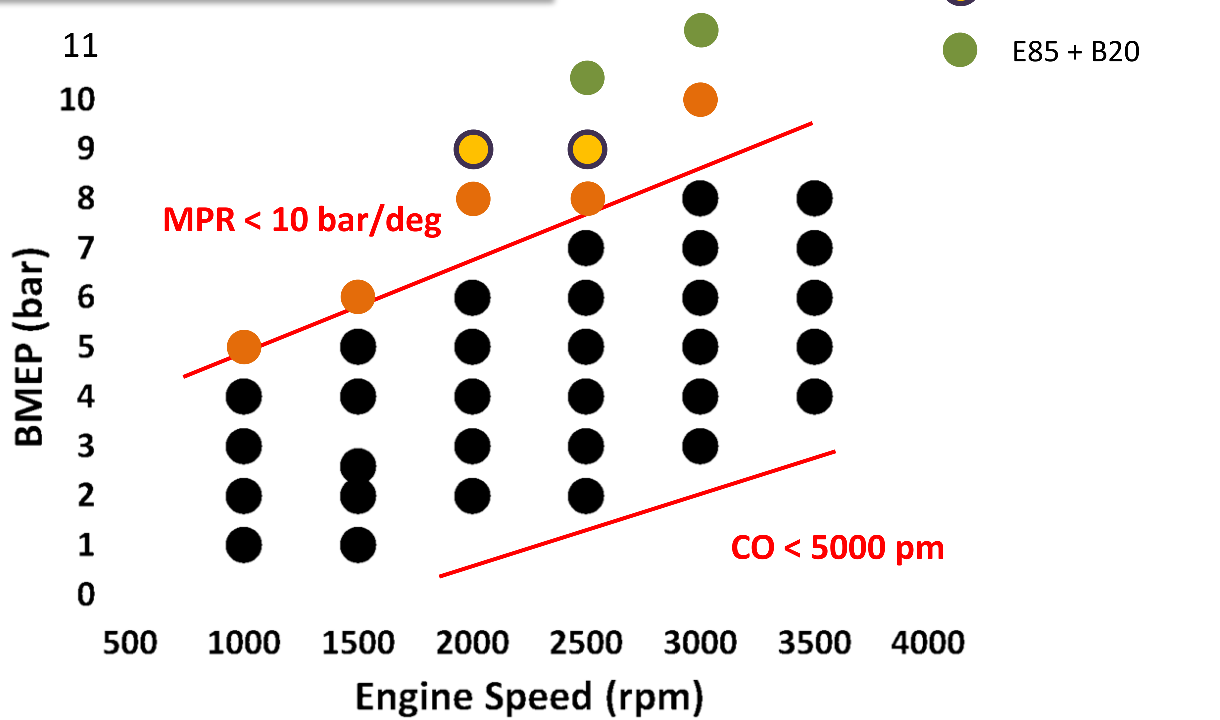


Self-Imposed Boundaries and Challenges to Load Expansion

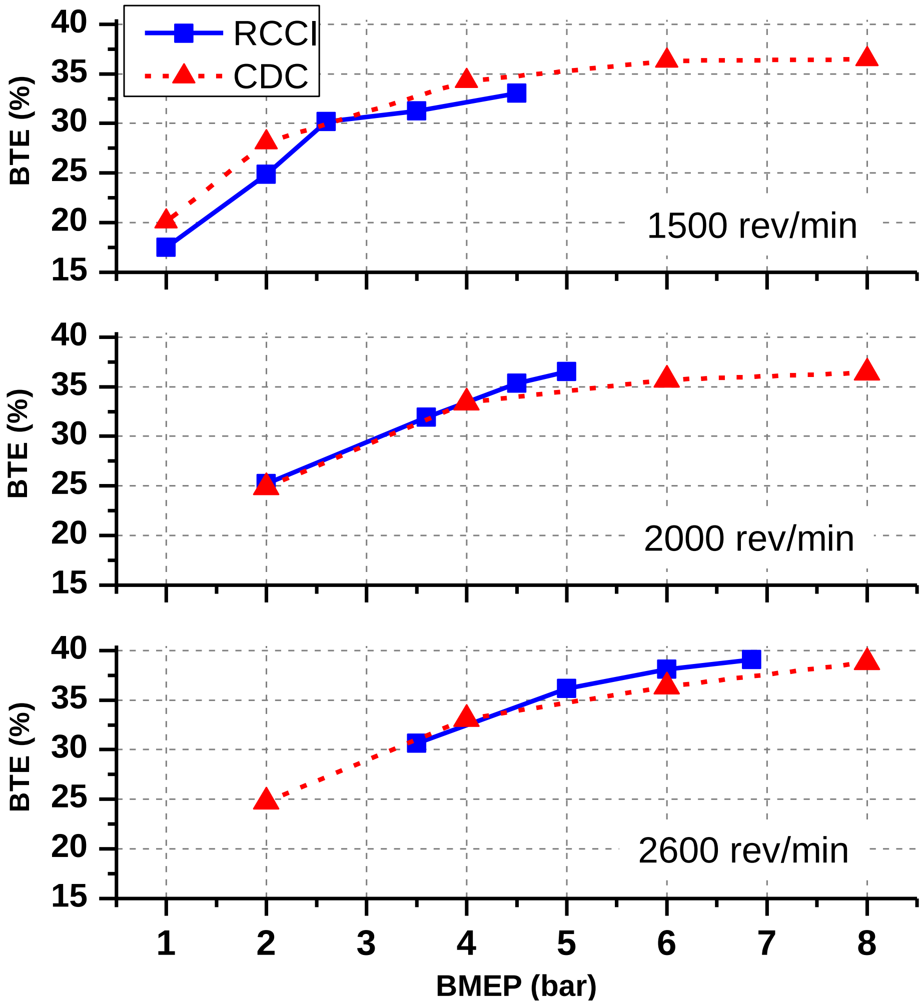
EGR controls MPR but may adversely impact BTE due to EGR heat rejection and turbo-machinery limitations.

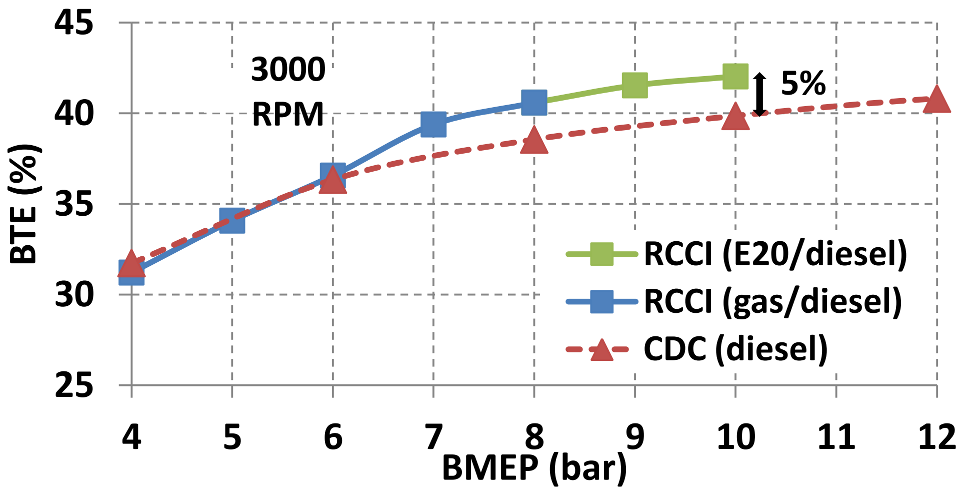
Ethanol-gasoline blends enable higher load operation with reduced or zero EGR.

B20 allows further expansion with E85



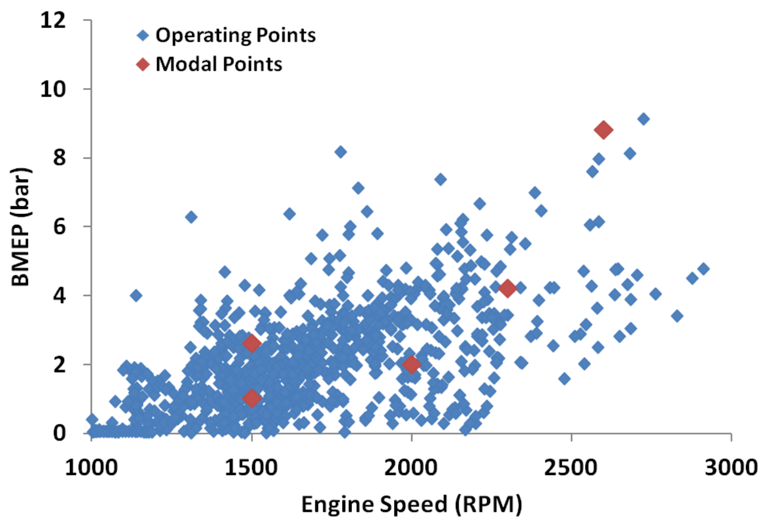
Ethanol Blends Allow for Load Expansion



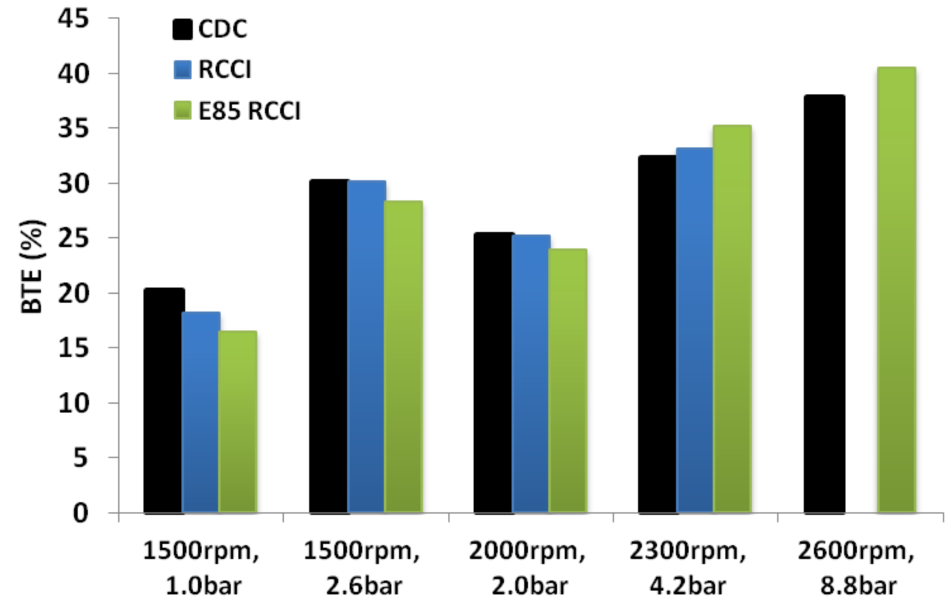


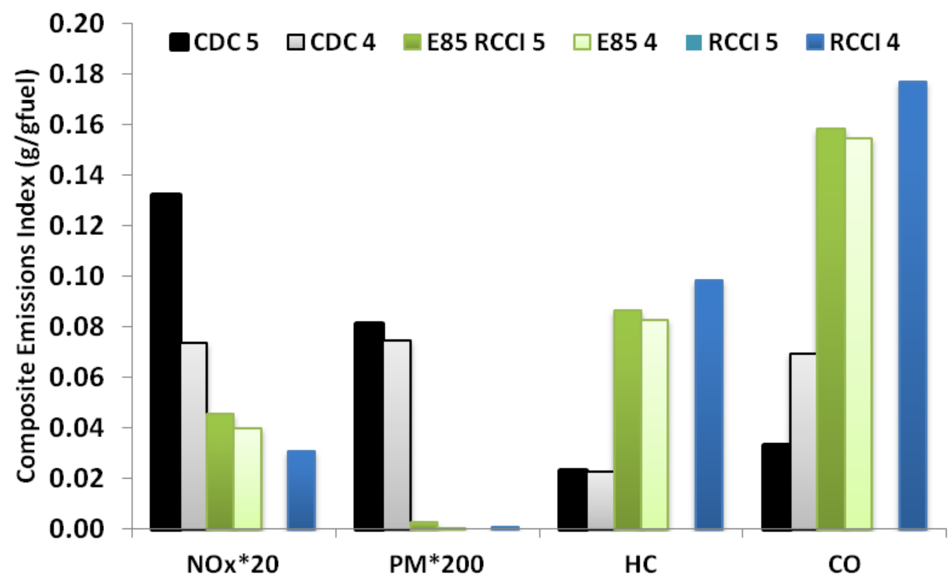
RCCI Drive Cycle Emissions Estimates– A more complete picture

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



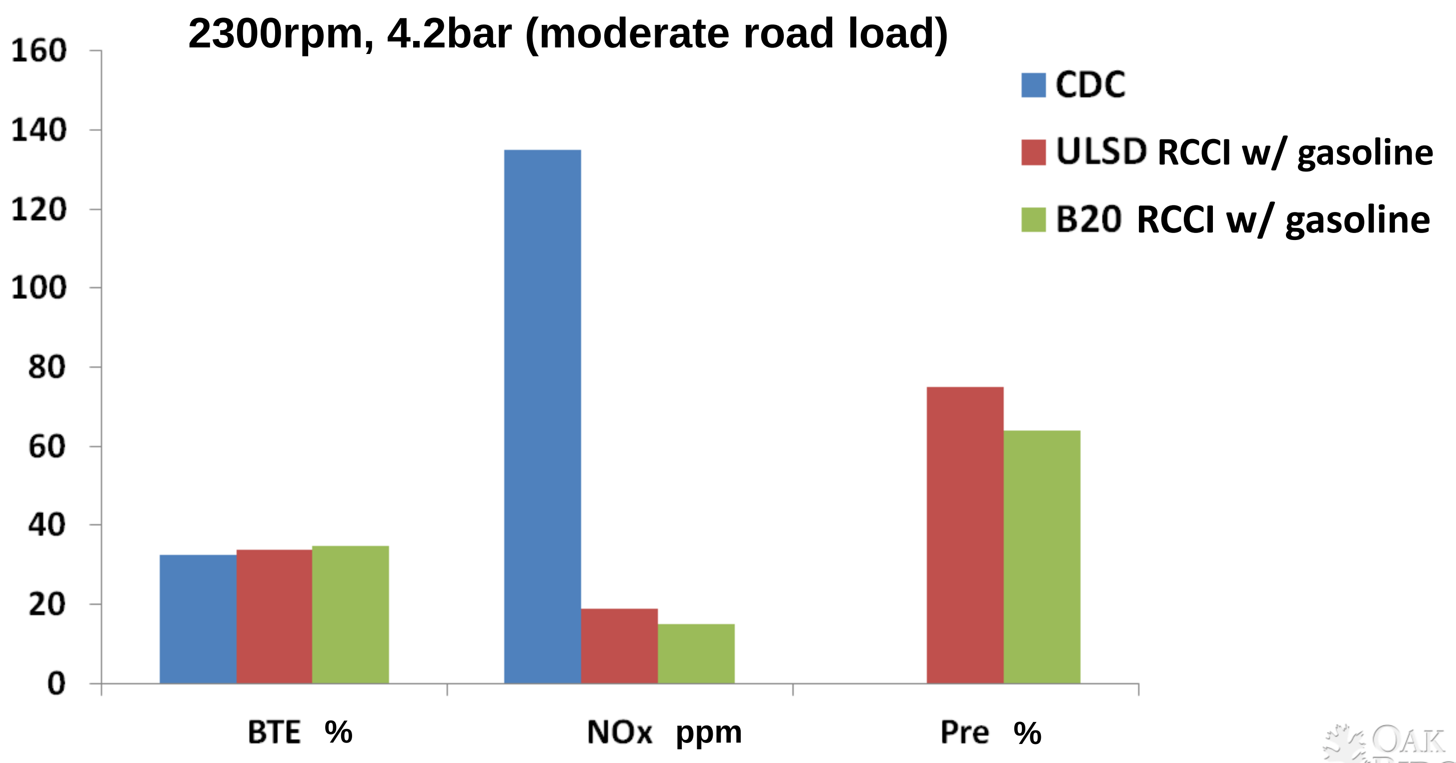
Point	Speed / Load	Weight Factor	Description
1	1500 rpm / 1.0 bar BMEP	400	Catalyst transition temperature
2	1500 rpm / 2.6 bar BMEP	600	Low speed cruise
3	2000 rpm / 2.0 bar BMEP	200	Low speed cruise with slight acceleration
4	2300 rpm / 4.2 bar BMEP	200	Moderate acceleration
5	2600 rpm/ 8.8bar BMEP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





RCCI operation with B20

- **B20 allows lower pre-mixed ratio**
  - Can allow higher BTE with gasoline
  - For E85 important for maintaining stability at high loads
- **B20 effect not just a reactivity effect**
  - ~ Same cetane as cert-grade ULSD (46.5)



RCCI Combustion Takeaways

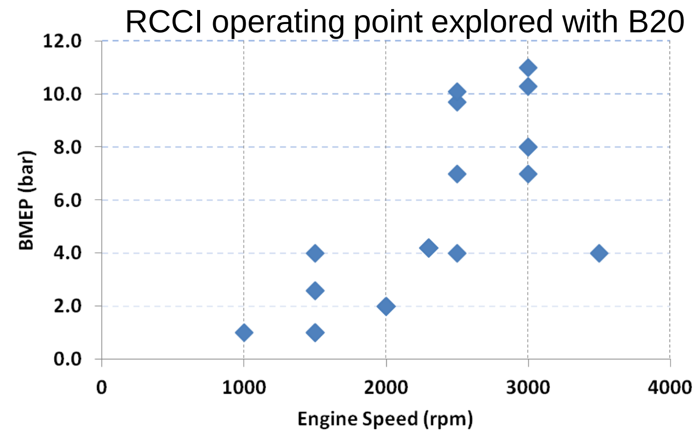
Advanced combustion techniques such as RCCI can increase engine efficiency and lower NOx and PM emissions.

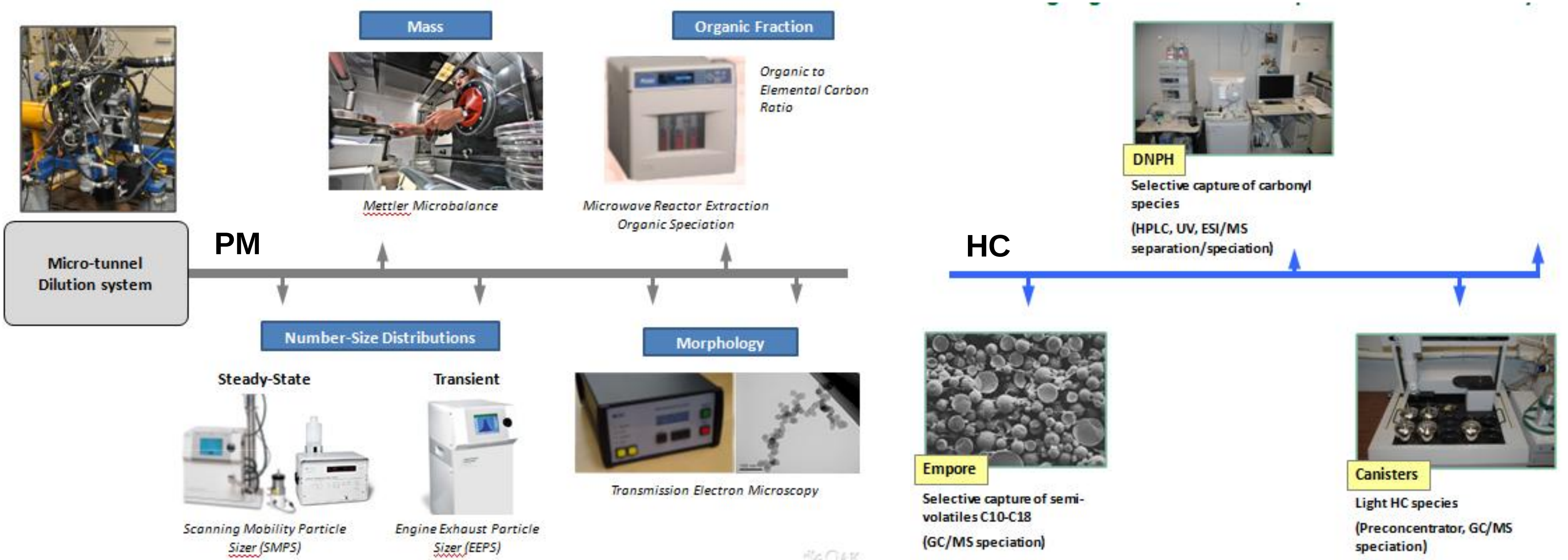
Many renewable fuels have unique properties which enable expanded operation of advanced combustion methods and improve performance as compared to conventional fuels.

- **RCCI uses in-cylinder blending of two fuels with different fuel reactivity (octane/cetane) to allow increased control over combustion compared to other advanced combustion methods that use a single fuel**
  - i.e. 20% gasoline/ 80% diesel at low load and 85% gasoline/ 15% diesel at high load
- **Ethanol blends allows for higher load operation with RCCI without the use of EGR**
  - Combination of higher octane, radical sink and additional intake cooling effect
- **Biodiesel blends lower pre-mixed ratio needed for meeting emissions and performance targets**
  - Important for maintaining combustion stability at high loads requiring high pre-mixed ratio

Current and near-term biofuel RCCI research

- **Wide speed and load operating range with focus on load expansion**
- **Detailed HC speciation and PM study 3 points, 3 fuel combinations**
  - ULSD, gasoline
  - ULSD, E85
  - B20, gasoline
- **Next: Examine effectiveness of DOC with biofuel blends**
  - Higher biodiesel blends are of interest





RCCI - 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.

Q2 Milestone (Fuel Technologies): Characterize the potential of bio-fuels to enable and expand the operating range of reactivity controlled compression ignition (RCCI) combustion in a multi-cylinder engine with diesel-like or higher brake thermal efficiency and an order of magnitude decrease in engine-out NOx and soot emissions.

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Next FEERC CBES presentation

Jim Szybist
March 15
How advanced combustion and emerging technologies (i.e. waste heat recovery) fit into the larger picture of reducing petroleum consumption.

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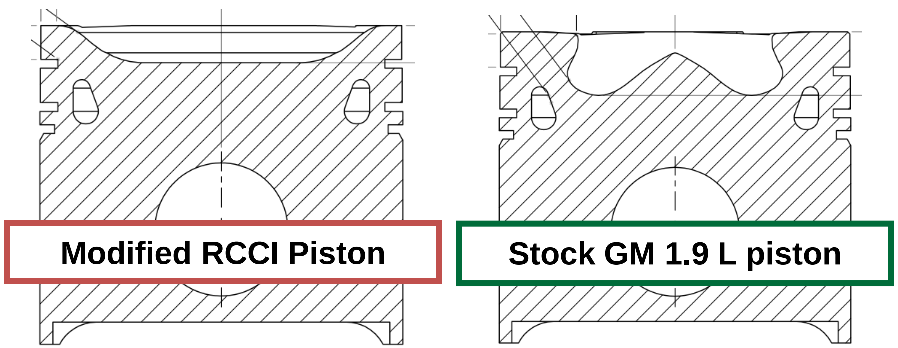
RCCI Optimized Pistons

- **UW design**
  - Based on heavy-duty RCCI piston
  - Reducing surface area main consideration
  - Best HC emissions and Efficiency
  - Compromise for high and low loads

- **Experiments with optimized piston**
  - Should allow for higher loads
  - Reduce heat transfer losses
  - Minimized squish region



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