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

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ACE016

High Efficiency Clean Combustion 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**
  - Q3 and Q4 milestones
- **Activity scope changes to address DOE & industry *needs***

Budget

FY 2012 – $600k

FY 2013 – $650k

Barriers (MYPP 2.3 a,b,f)*

Lack of fundamental knowledge of advanced combustion regimes

Lack of effective engine controls for LTC

Lack of actual emissions data on future engines

Partners / Interactions

Regular status reports to DOE

Industry technical teams, DOE working groups, and one-on-one interactions.

Industry: MAHLE, GM, MECA, others

Universities: Wisconsin-Madison

Consortia: CLEERS, DERC

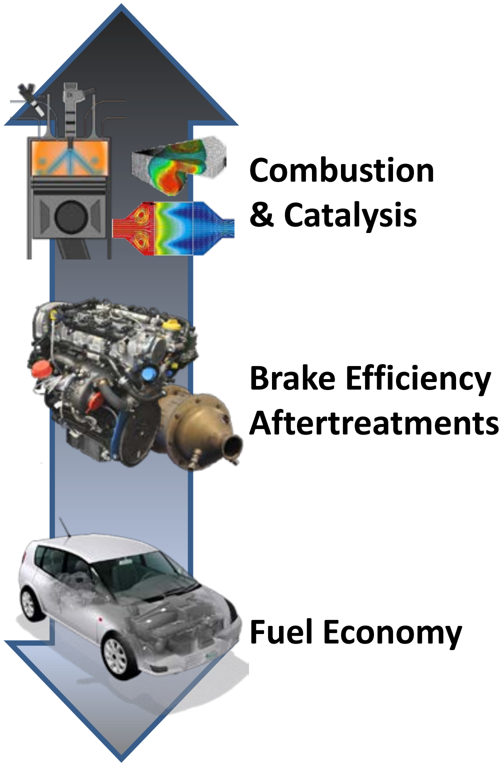
ORNL: fuels, emissions, vehicle systems, others

*http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

Relevance and Objectives

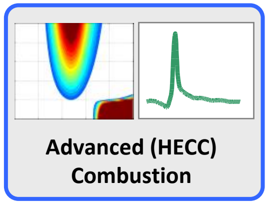
- **DOE VTP Milestones**
  - **Addressing barriers to meeting VTP goals of reducing petroleum energy use (engine system) including potential market penetration with efficient, cost-effective aftertreatments.**

- **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 industry/DOE tech teams** and CLEERS consortium to respond to industry needs and support model development.

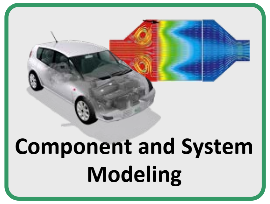


FY 13 JOULE Milestones On Track

- **FY 2013 Q3 – High Efficiency RCCI Mapping**
  - Develop engine map on a multi-cylinder engine which is suitable for light-duty drive cycle simulations. The map will be developed to maximize efficiency with lowest possible emissions with production viable hardware. Progress – **On track** (have received 3 new OEM PFI maps)



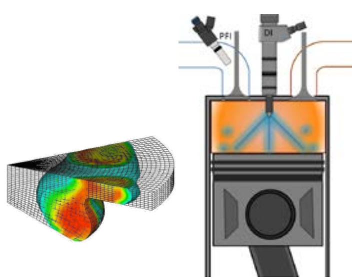
- **FY 2013 Q4 – RCCI Vehicle Systems Modeling**
  - Demonstrate improved modeled fuel economy of 20% for passenger vehicles solely from improvements in powertrain efficiency relative to a 2009 PFI gasoline baseline. Progress - **On track**



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

Systems level investigation into high efficiency combustion concepts on MCEs

- Combine multi-cylinder advanced combustion and emissions control research to identify barriers to LTC implementation and provide 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.



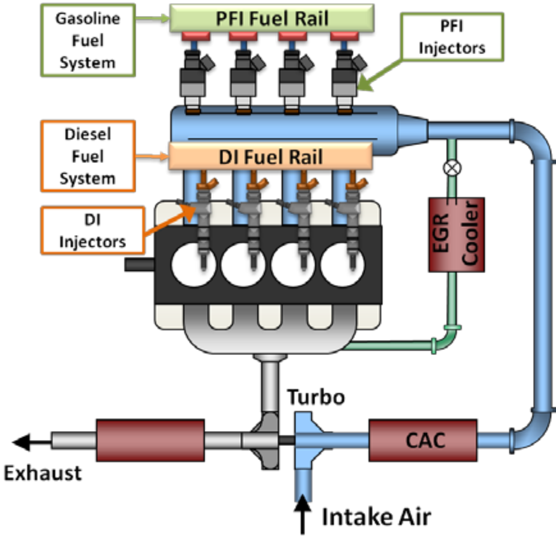
Combustion
Metric: Indicated efficiency

Engine System
Metric: Brake efficiency

Full Vehicle
Metric: Fuel Economy

ORNL's comprehensive approach to ACE research

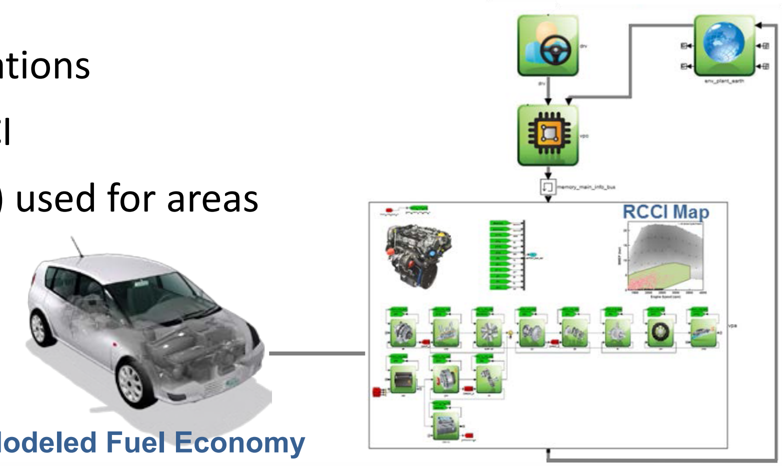
- **Two 2007 GM 1.9-L multi-cylinder diesel engines**
  - OEM (CR 17.5) and **modified RCCI** pistons (CR 15.1) (backup slide)
  - Dual-fuel system with PFI injectors
  - OEM diesel fuel system with DI injectors
  - Microprocessor based control system



ORNL RCCI Multi-Cylinder 1.9L GM

- **Aftertreatment integration & emissions characterization**
  - Modular catalysts / regulated and unregulated emissions
  - Particulate matter characterization
- **Vehicle systems simulations using Autonomie** (backup slide)
  - Midsize passenger vehicle
  - Experimental engine maps used for drive cycle simulations
  - Comparison between 2009 PFI, diesel and diesel/RCCI
  - Multi-mode (RCCI to conventional diesel combustion) used for areas of the drive cycle outside the RCCI operating range

AUTONOMIE Simulink/ Stateflow

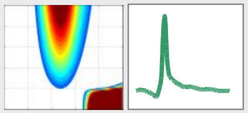


Modeled Fuel Economy

1 Autonomie, Developed by Argonne National Lab for U.S. DOE, http://www.autonomie.net/

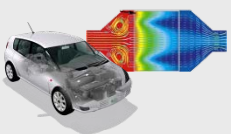
FY 12 Technical Accomplishments

- **Q3 Milestone – High Efficiency RCCI Mapping - Completed**
  – Developed RCCI combustion map on a multi-cylinder engine suitable for light-duty drive cycle simulations



Advanced (HECC) Combustion

- **Q4 Milestone – RCCI Vehicle Systems Modeling - Completed**
  – 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 drive cycle simulations on same vehicle platform
    - **Fuel economy** and engine out emissions over light-duty drive cycles



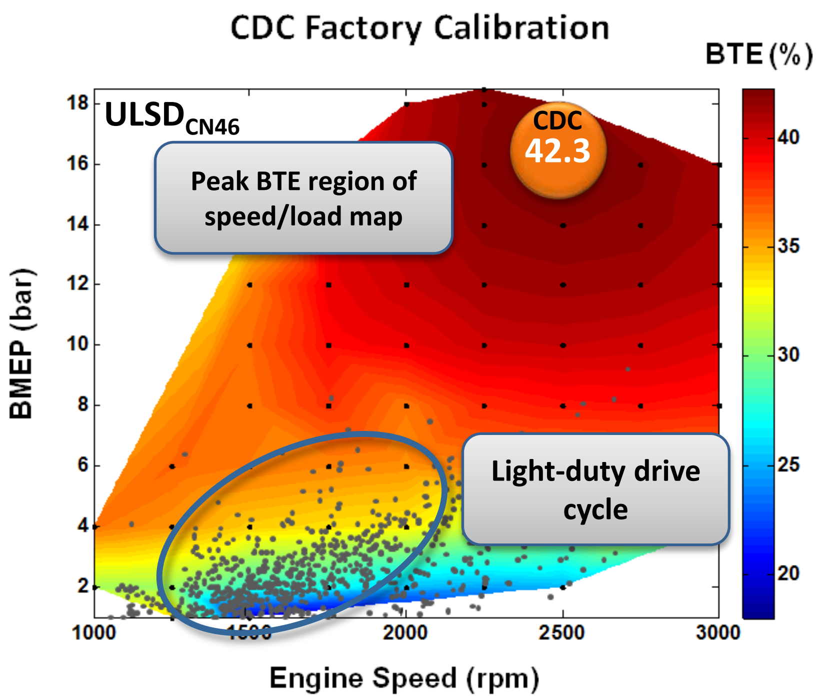
Component and System Modeling

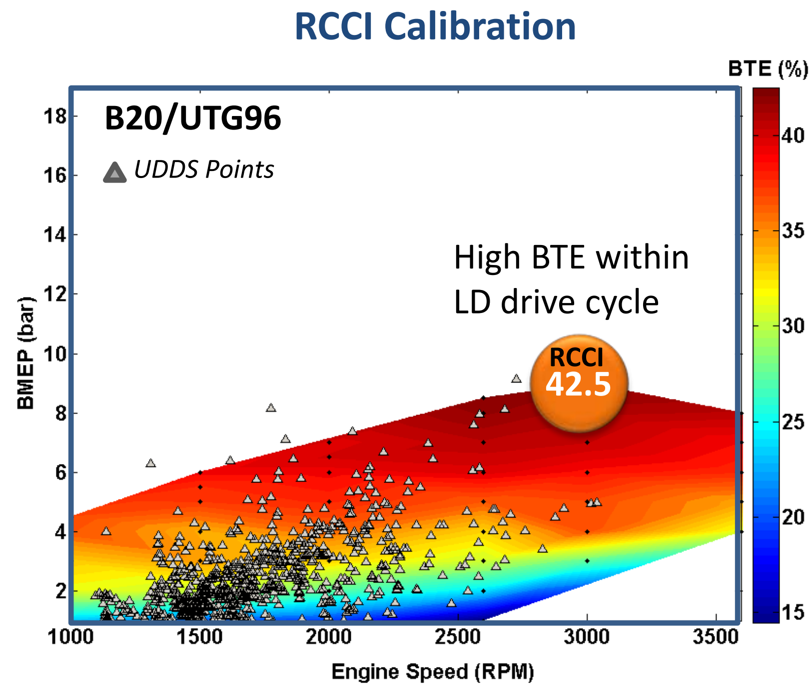
Relevance

RCCI has been shown in previous multi-cylinder experiments to have high brake thermal efficiencies with ultra-low NOx and soot emissions.

However, the benefits and challenges of RCCI on light-duty vehicles over federal driving cycles are still not well understood.

Current RCCI Operation Includes Most of Light-Duty Drive Cycle





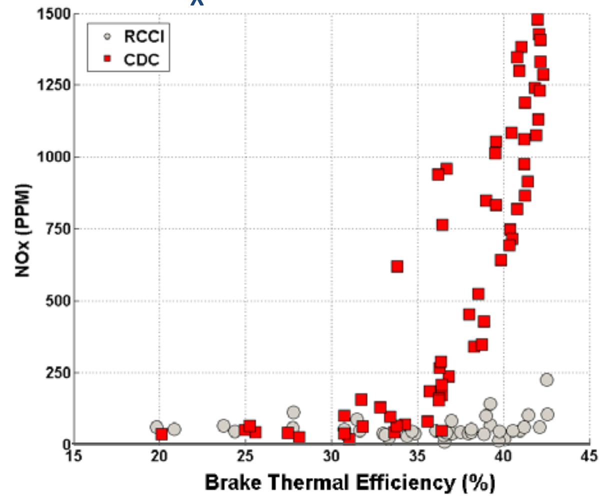
- **RCCI mapped with focus on efficiency and lowest possible emissions**
  - Peak BTE within light-duty drive cycle range (better than peak BTE of 1.9L GM diesel)
- **Detailed RCCI map shows insights into future development opportunities and challenges**
  - Aftertreatment integration (low exh T), drive cycle simulations (load coverage)
- **Load expansion challenges are under investigation for maximizing BTE**
  - Cyclic dispersion, exhaust residuals, thermodynamic analysis of loss mechanisms

RCCI – Benefits Include High BTE with Low NOx and Soot

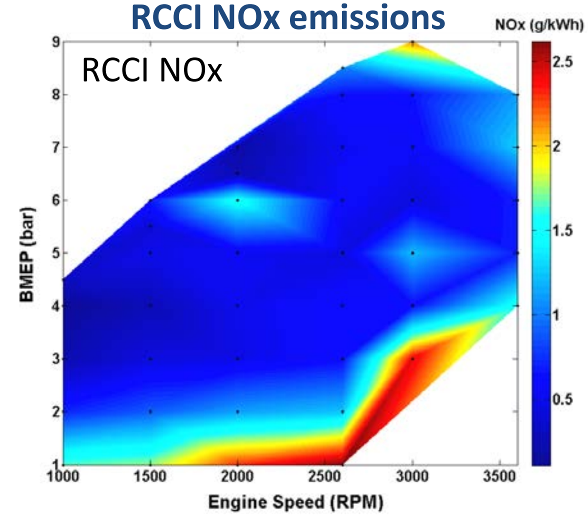
Low NOx across BTE
- Drive cycle simulations will provide insight into the level of NOx aftertreatment needed to address future emissions standards

Near zero smoke number
- Indicates very little elemental carbon in PM (Not zero PM)
- Implications for possible effectiveness of DOC to further reduce PM

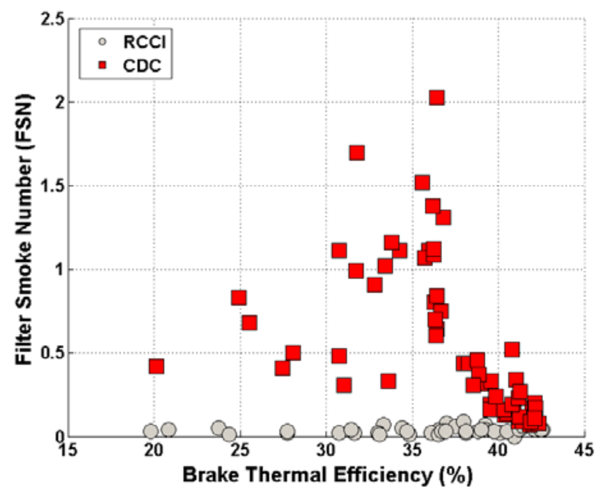
NO_X as Function of BTE



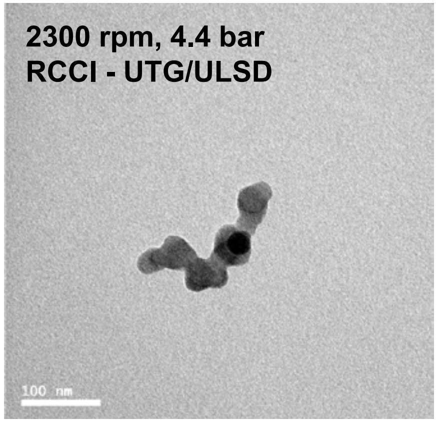
RCCI NOx emissions



FSN as Function of BTE



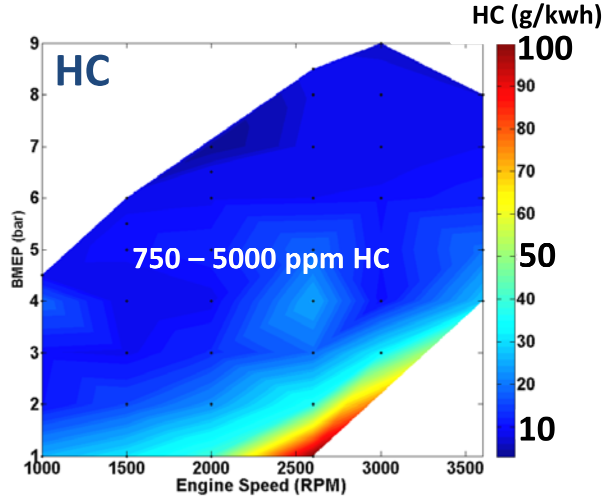
RCCI PM TEM Image

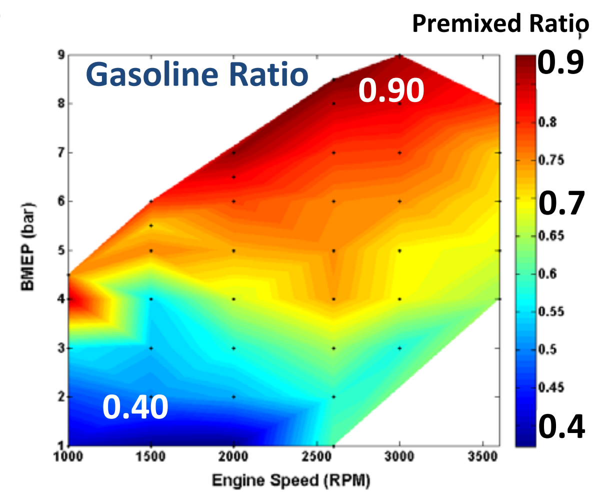


To be published Barone et al.

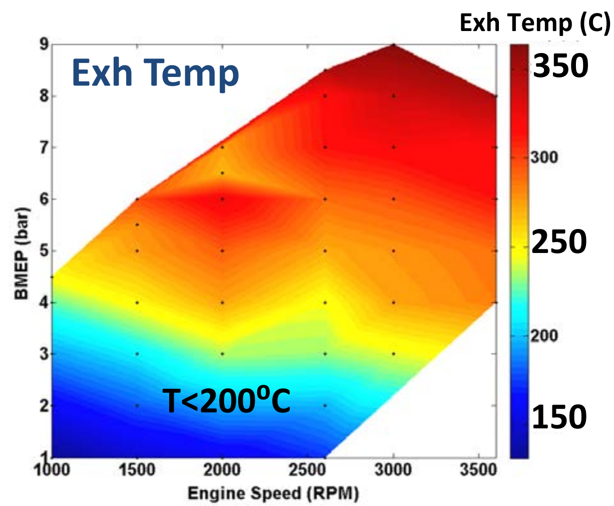
RCCI – Challenges Include Lower Exhaust Temps with High HC/CO emissions

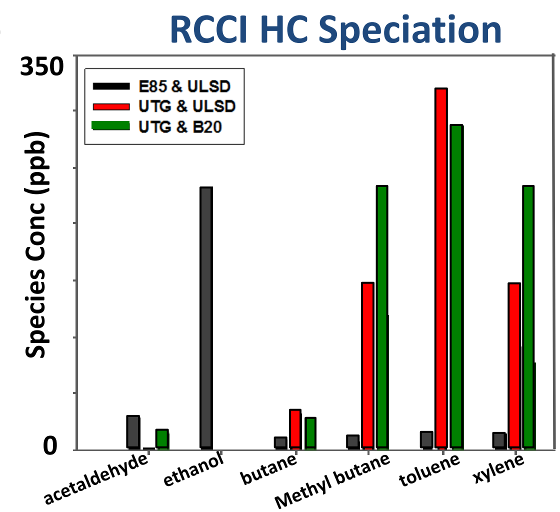
High HC and CO
- Similar to PFI engine out
- Fuel ratio varies over engine speed and load range meaning species will vary as well





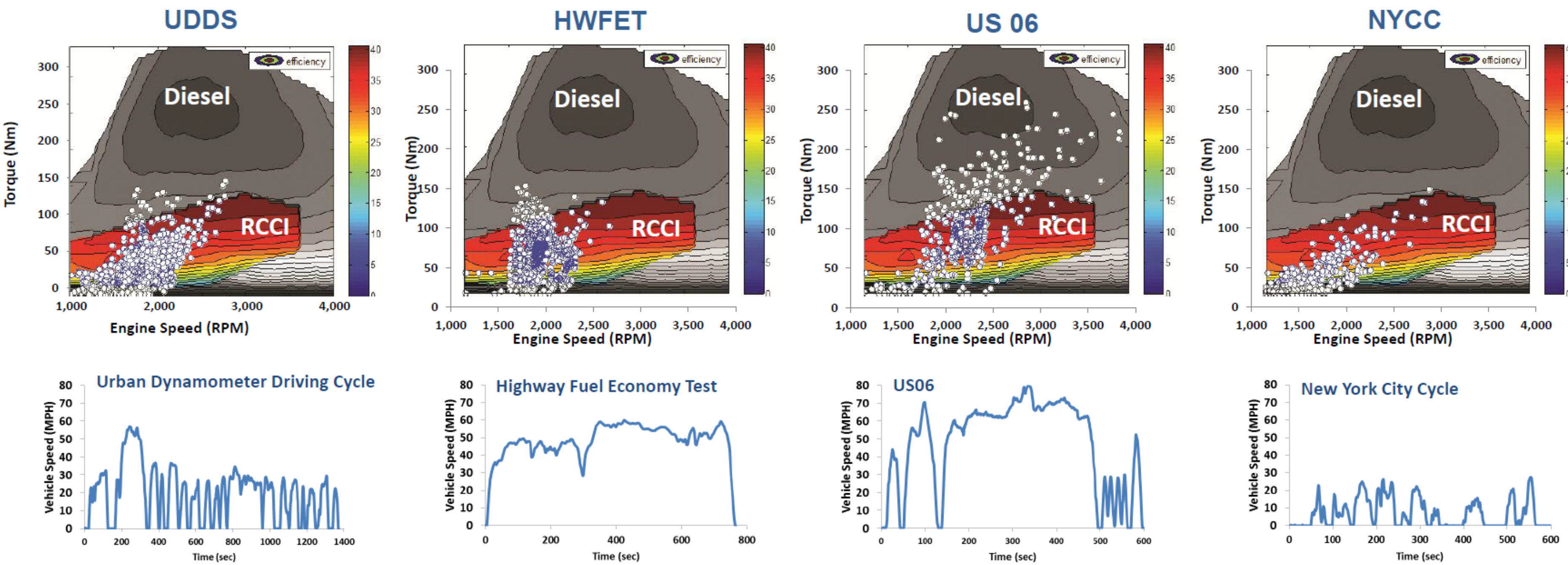
Low exhaust temperatures
- Areas < 200° C





Current RCCI Operation Includes Most of LD Drive Cycles

- **RCCI mapped with focus on efficiency and lowest possible emissions (Q3 Joule Milestone)**
- **Current RCCI map requires mode-switching to cover light-duty drive cycles**
  - 100% coverage of low temperature combustion is necessary to avoid mode-switching (RCCI to Diesel) and additional emissions controls which would have negative impacts on fuel economy and costs



Commonly called the "LA4" or "the city test" and represents city driving conditions

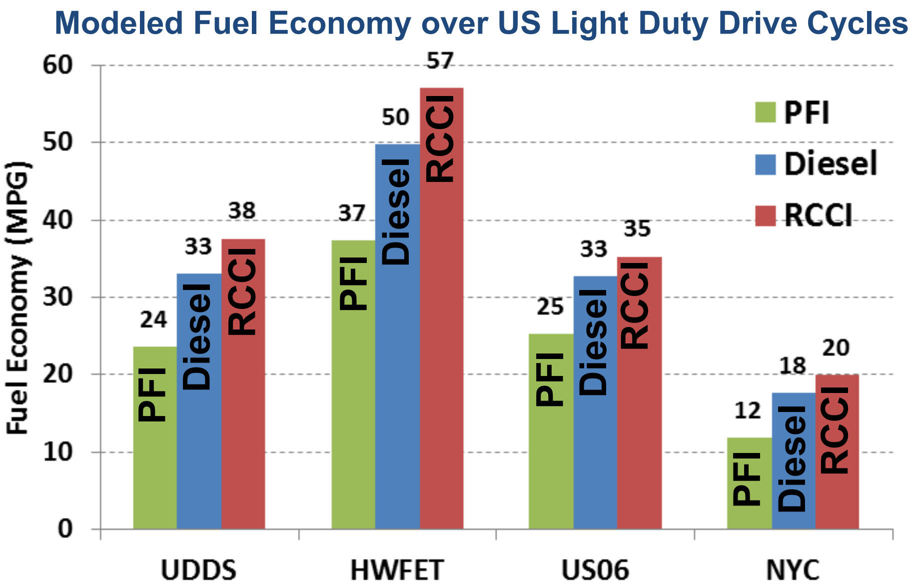
Represents highway driving conditions under 60 mph

High acceleration aggressive driving schedule – also called the "Supplemental FTP"

Features low speed stop-and-go traffic conditions

Modeled RCCI Drive Cycle Fuel Economy

- **Modeling results show up to a to 59% improvement in fuel economy with RCCI over UDDS compared to 2009 PFI (SI) baseline on same vehicle** (4.0L PFI baseline)



Modeled Fuel Economy Improvements

% Fuel Economy Improvement With RCCI	Vs. PFI	Vs. Diesel
UDDS (city)	**+ 59%**	+ 14%
HWFET (highway)	**+ 53%**	+ 15%
US06 (high speed)	**+ 39%**	+ 8%
NY City (stop and go)	**+ 67%**	+ 13%

- **RCCI fuel economy improvements despite lack of complete drive cycle coverage**
  - Further development underway *(fuels, hardware, controls)*
- **Results based on steady state engine data**
  - Does not address transient operation
- **Does not address aftertreatment effectiveness**
  - On going research at ORNL

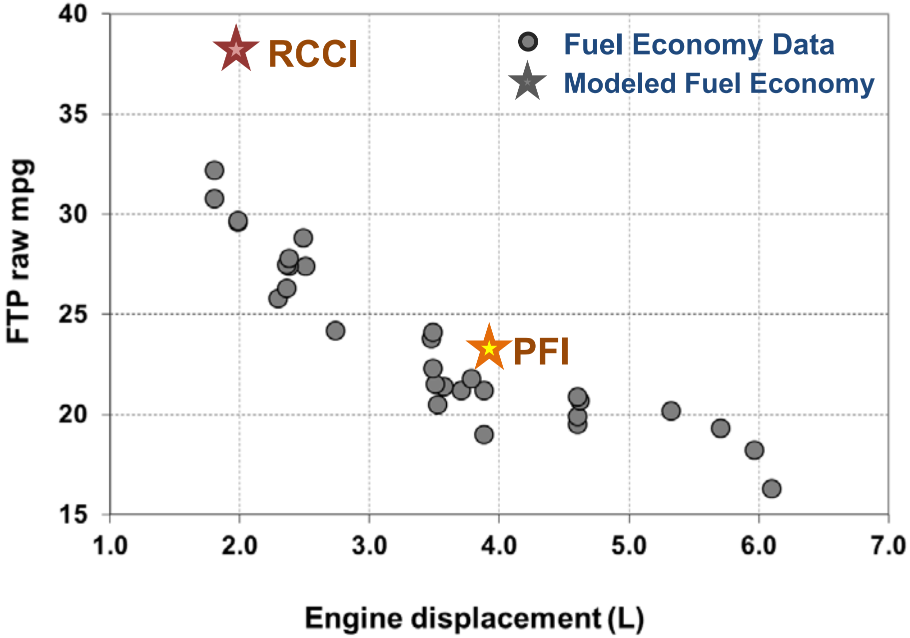
Modeling provides insight into fuel needs under mixed-mode RCCI operation

- Amount of drive cycle spent in RCCI mode
- Total amount of diesel fuel used (or secondary fluid)
- Fuel split during RCCI operation

RCCI offers >15% Improvement Over Best-in-Class PFI

- **4.0L PFI map matches torque of 1.9L diesel engine**
  - Diesel torque characteristics make matching PFI size difficult
- **ORNL vehicle laboratory and EPA fuel economy data mined for other PFI engine sizes**
  - Figure shows how city (UDDS/FTP) fuel economy trends with displacement
  - More complete comparison against best-in-class PFI engines

ORNL and EPA FTP (UDDS) 2009 PFI Fuel Economy Data



Data for small to full-size passenger cars with varying vehicle weight

RCCI Improvements compared to smaller PFI engines

RCCI MPG improvement vs.	4.0L PFI Baseline Comparison	2.4L PFI	2.0L PFI	1.8L PFI
UDDS RCCI Improvement	**59%**	33%	22%	15%
PFI UDDS_mpg	**23.6**	27.5	29.6	32.6
HWFET RCCI improvement	**53%**	34%	30%	19%
PFI HWFET_mpg	**37.5**	42.6	43.9	48.1

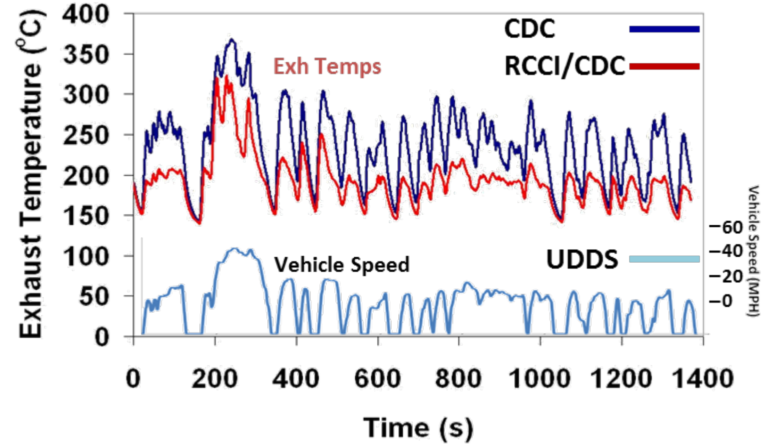
Corollary Study: Aftertreatment Integration with RCCI

- **Drive cycle simulations help illustrate challenges**
  - Estimate emissions and exhaust temperatures over drive cycles

Modeled engine out emissions reductions compared to Diesel

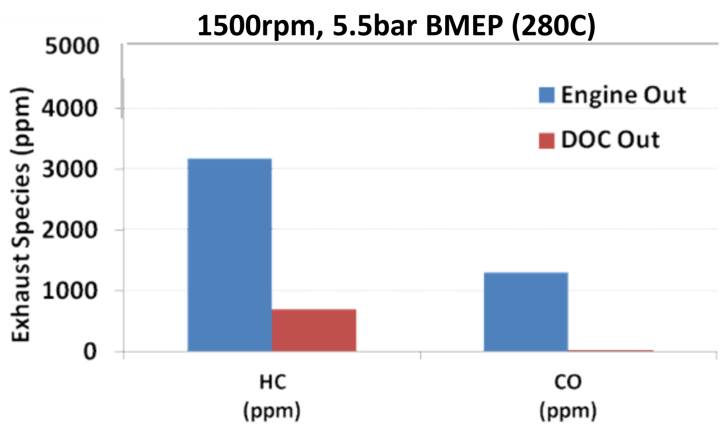
Reductions With RCCI	NOx	HC	CO
UDDS*	17%	+ 240%	+ 150%
HWFET	21%	+ 300%	+ 140%
US06	8%	+ 310%	+ 140%
NY City	+4%	+ 220%	+ 150%

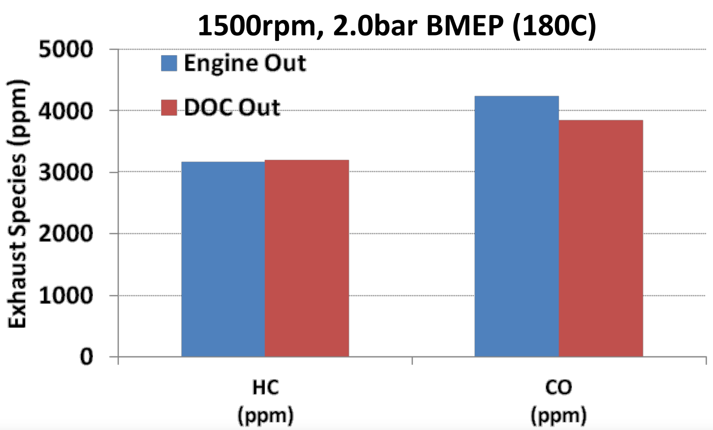
Modeled CDC and RCCI-Mixed-Mode Exhaust Temps over UDDS



- Examples 1500 RPM, 5.5bar and 2.0bar BMEP **[Model DOC (1.25 L, 100g/Ft^3 Pt, 400 csi)]**

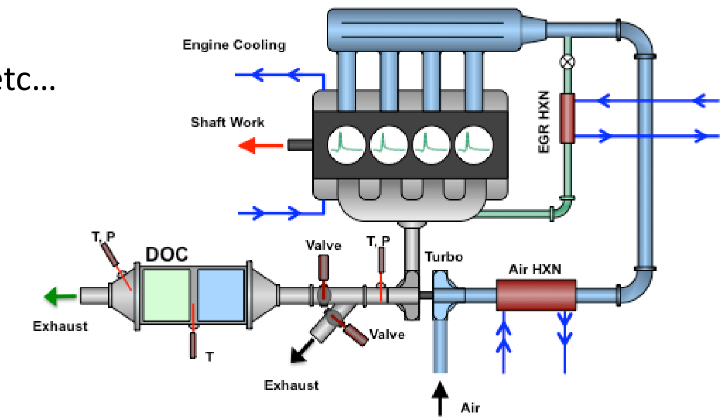
Experimental Data Showing Challenges with Low Temperature Aftertreatment

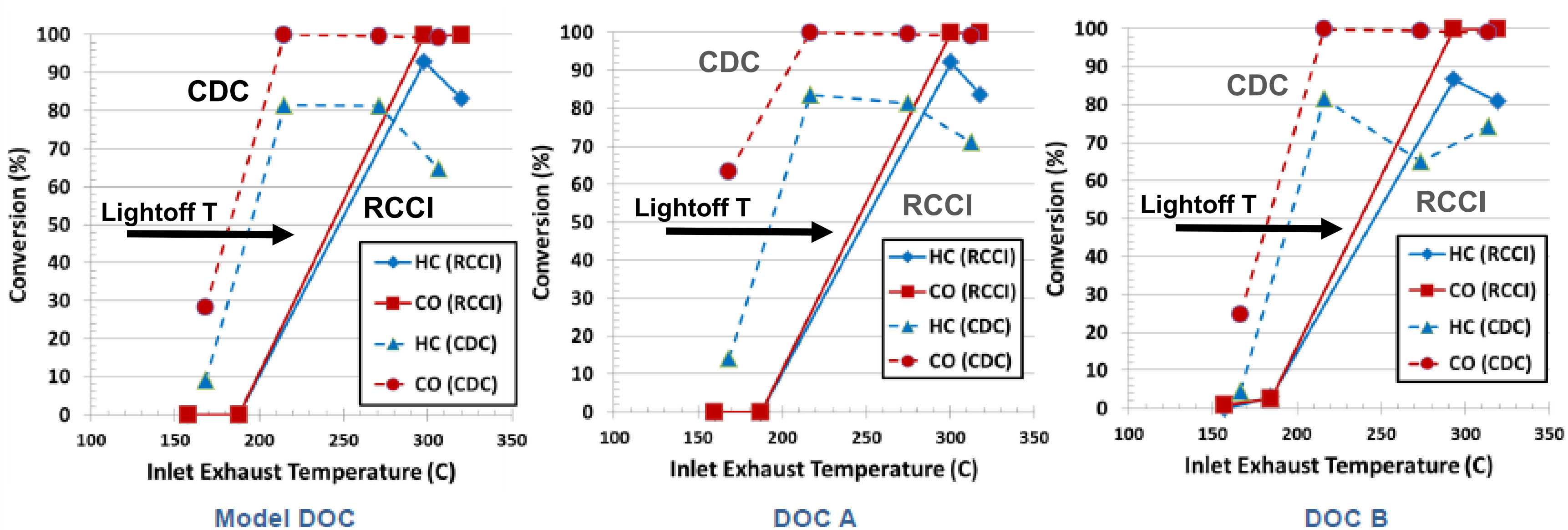




DOC Effectiveness with RCCI HC and CO emissions

- **HC species with RCCI have previously been determined to be quite different than CDC**
  - SAE 2010-01-2266 (Prikhodko et al.)
  - Gasoline range and diesel range species with increased aldehydes etc…
- **RCCI results in shift in HC and CO light-off temperature**
  - Higher CO and HC concentrations from RCCI
  - Different HC species also playing a role
  - SAE 2013-01-0515 (Prikhodko et al.)



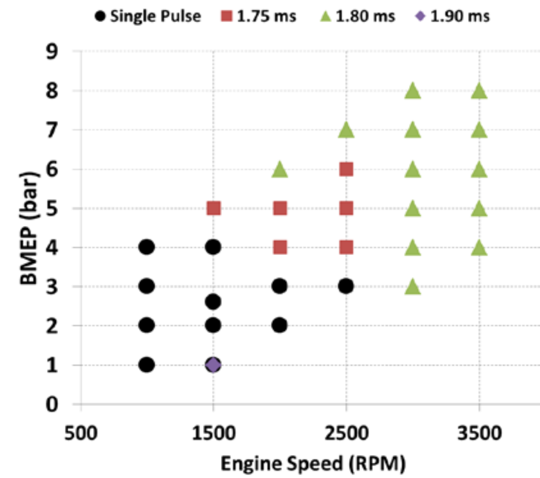


RCCI Data Being Shared with Community via CLEERS

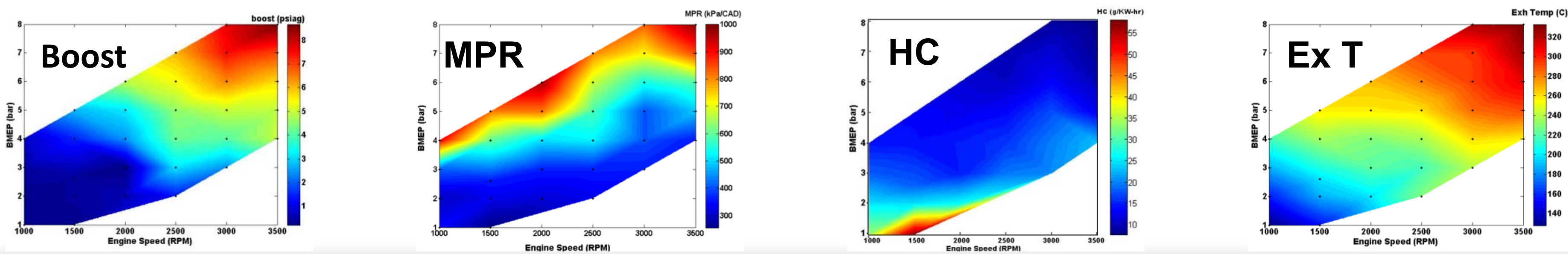
- **RCCI mapping data uploaded to CLEERS database**
  - Allows sharing with research community
  - Many requests for data – allows for standard form

CLEERS Database

http://www.cleers.org/databases/

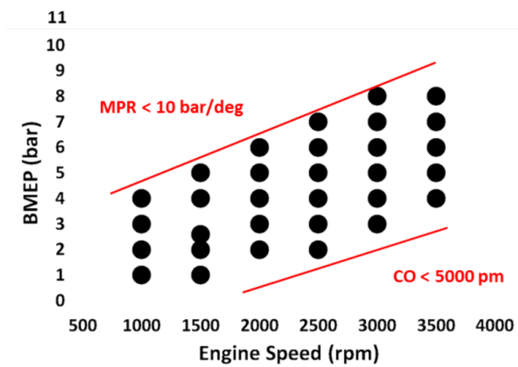


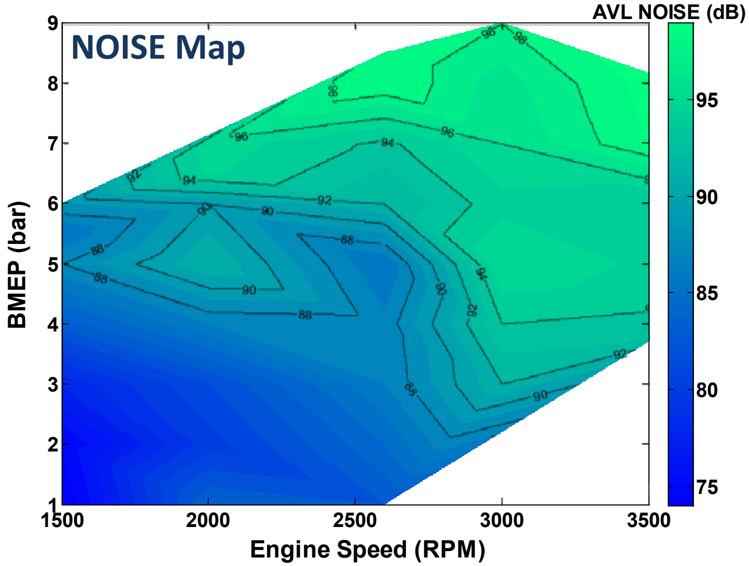
BMEP (bar)	Speed (RPM)	Torque (ft-lb)	Diesel Rate (g/s)	Gasoline rate (g/s)	Max COV (%)	Gas % (mass)	BTE (%)	Raw BSFC (g/kwhr)	D_eq BSFC (g/kwhr)	BaroP (InHg)	AirMassFlow (g/s)	EGR Rate (%)		AFR mass	HC (ppm)	NOx (ppm)	CO (ppm)	CO2 Intake (%)
1.0	1000	11.526	0.1537	0.04770	10.4	0.2369	**18.90**	443.0	443.4	28.91	15.91	4.53	0.05	79.00	1992.3	26.84676	5086.4	0.096
2.0	1000	22.772	0.1240	0.15309	2.8	0.5525	**27.11**	308.5	309.2	28.91	15.90	3.51	0.05	57.37	2882.1	10.24139	5244.6	0.105
3.0	1000	34.429	0.0930	0.25252	4.0	0.7309	**32.85**	254.4	255.1	29.05	15.42	2.85	0.03	44.63	3225.4	7.471395	2010.4	0.113
4.0	1000	45.384	0.1193	0.33133	1.5	0.7352	**33.19**	251.8	252.5	28.91	16.06	4.29	0.07	35.64	3228.0	16.59825	1412.8	0.237
1.0	1500	11.97972	0.1906	0.13741	5.7	0.4189	**18.08**	462.8	463.6	28.93	23.25	3.25	0.04	70.89	3630.9	21.92095	5015.9	0.065
2.0	1500	22.973	0.2111	0.22608	4.2	0.5171	**26.00**	321.7	322.3	28.93	22.73	2.10	0.05	52.00	3034.6	27.03704	4845.1	0.065
2.6	1500	29.609	0.2365	0.27792	4.0	0.5403	**28.48**	293.6	294.3	28.92	22.87	1.78	0.01	44.47	2852.7	9.790642	3579.5	0.069
4.0	1500	45.495	0.1550	0.50697	2.4	0.7659	**33.97**	245.9	246.7	28.92	24.67	1.75	0.02	37.26	3118.1	12.51186	1834.2	0.088

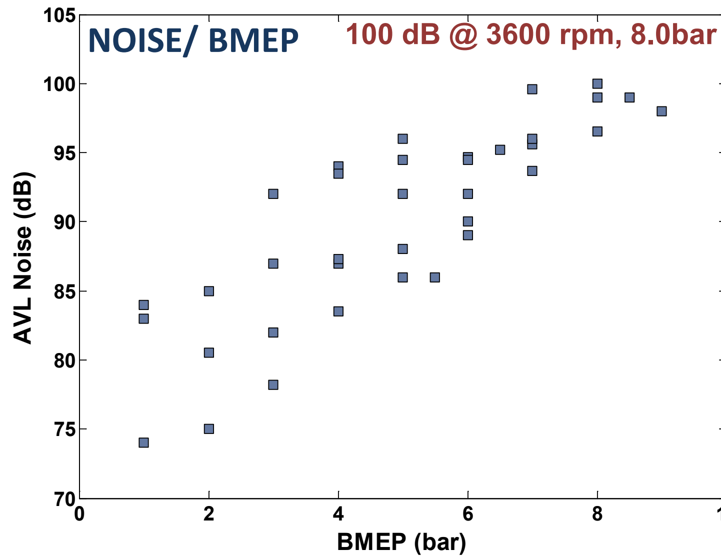


Combustion Noise From MCE RCCI Under Investigation

- **Mapping results from 10bar/deg limit map**
  - Noise not initially primary consideration
- **Combustion Noise**
  - AVL Combustion Meter – AVL 4050A1
    - Now using AVL FLEXIFEM & Drivven







- **ACEC guidance being developed**
  - Working with Eric Kurtz (Ford/ACEC) and others (GM, ORNL, UW-M) to investigate combustion noise with RCCI

To be presented at ASME ICEF Fall 2013

Collaborations and Industry Feedback

- **University Partners**
  - The University of Wisconsin-Madison – RCCI modeling
- **Industry Partners**
  - ACEC/ USDRIVE – Goal Setting, Noise and Drive Cycle Estimates
  - GM - GM 1.9 – Hardware and LTC noise discussion
  - Chrysler – Engine Data for Q4 milestone
  - MAHLE – Premixed Compression Ignition Piston Design
  - Drivven – Same/ next cycle controls
  - Cummins / FORD– Sharing RCCI data and RCCI discussions
  - MECA – Catalysts supply and industry feedback
  - Energy Company– Fuel effects collaboration for LTC
- **DOE AEC/ HCCI working Group**
  - Research is shared with DOE's AEC/HCCI working group meeting twice a year
- **Consortia**
  - CLEERS (Cross-Cut Lean Exhaust Emissions Reduction Simulations)
  - UW- DERC (Direct-injection Engine Research Consortium)
- **Other ORNL-DOE Activities**
  - Fuel Technologies, Vehicle Systems and others
  - ACE briefs to ORNL Bioenergy Researchers/ Local Clean Cities/ Universities

Model Development and Refinement

Hardware for LTC

Feedback and Data Sharing

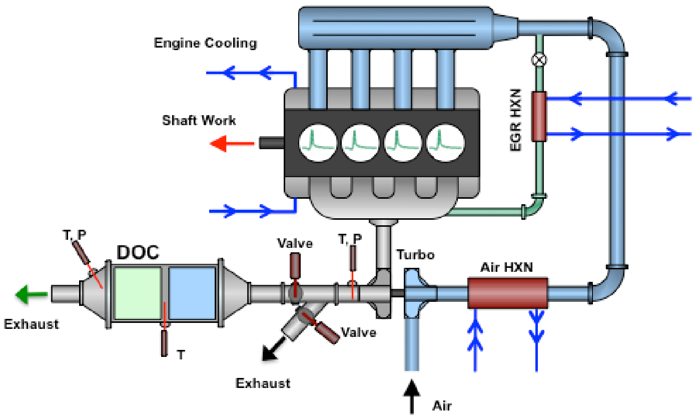
Goal Setting

Leveraging and Outreach

Future Work

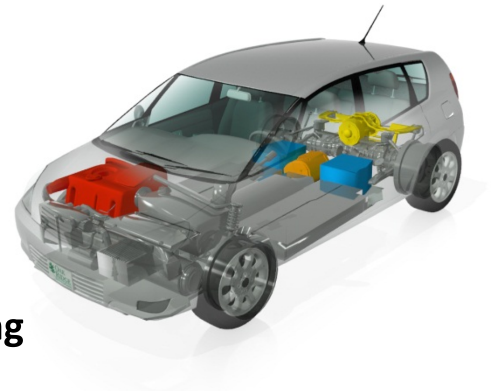
FY 13

- **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



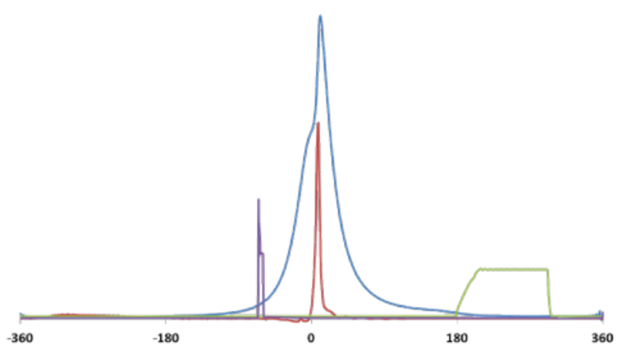
FY14

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



Summary

- **Advanced combustion techniques such as RCCI shown to increase engine efficiency and lower NOx and PM emissions demonstrating potential for increased fuel economy**
- **Comprehensive engine systems approach**
  - Multi-cylinder advanced combustion experiments
  - Aftertreatment integration
  - Vehicle systems level modeling
- **Current research focused on investigated fuel economy potential of LTC**
  - RCCI engine mapping to provide data
  - Aftertreatment studies to understand interdependency of emissions control and system efficiency
  - Related research into loss mechanisms, combustions noise and controls
- **Interactive feedback and collaboration**
  - Industry and Tech Teams
  - University and National lab partners
- **Future work includes progressive milestones**
  - Transient operation
  - Low temperature catalysts



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Oak Ridge National Laboratory

Technical Back-Up Slides

Background: Dual-fuel Reactivity Controlled Compression Ignition (RCCI)

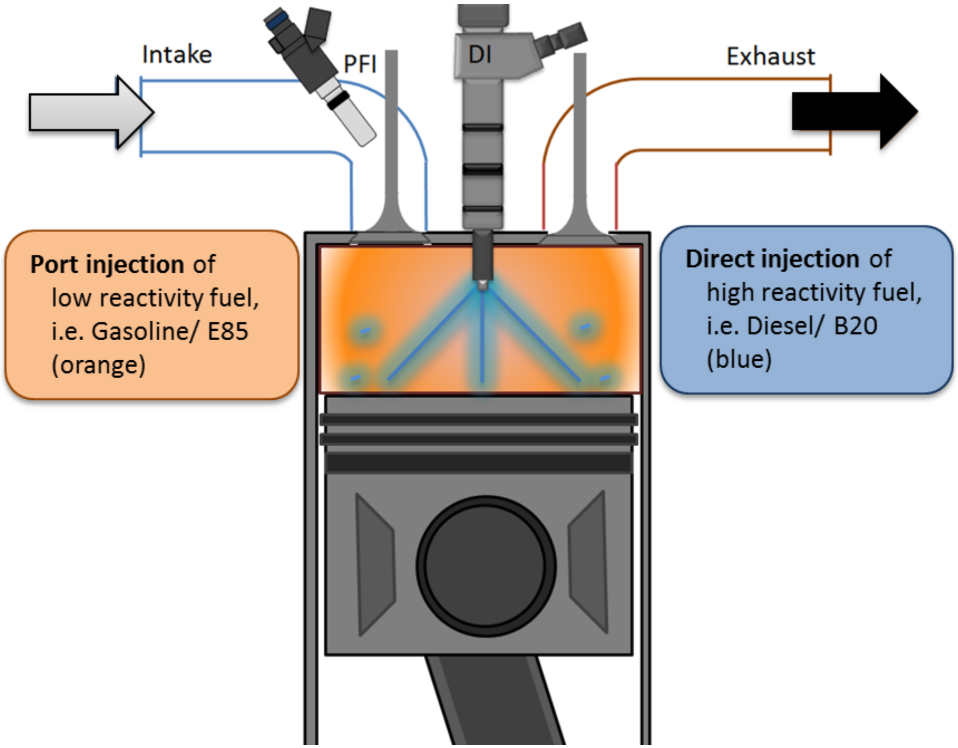
Back-Up 1

RCCI allows increased engine operating range for premixed combustion through:

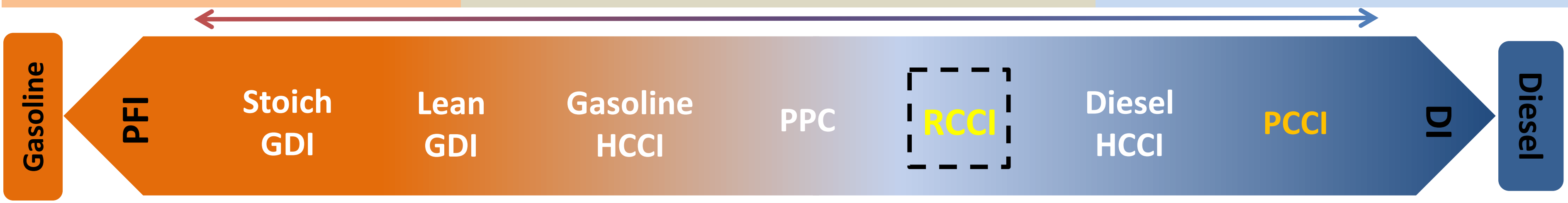
- Global fuel reactivity (phasing)
- Fuel reactivity gradients (pressure rise)
- Equivalence ratio stratification
- Temperature stratification

RCCI offers both benefits and challenges to implementation of LTC

- Diesel-like efficiency or better
- Low NOx and soot
- Controls and emissions challenges



Low = Prevents Auto-Ignition | **Fuel Reactivity** | **High** = Promotes Auto-Ignition

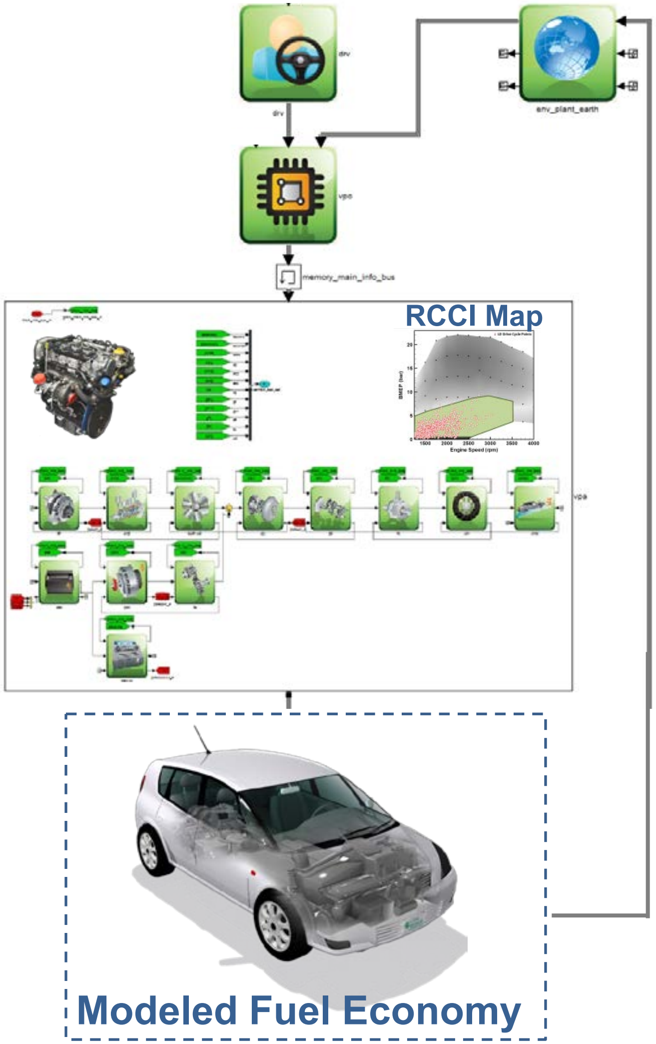


Vehicle system modeling using experimental/ industry engine maps on same vehicle in Autonomie [1]

Back-Up 2

- **Autonomie* used for model based simulation**
- **Base vehicle - Mid-size passenger sedan**
  - 1580kg, Automatic transmission
  - Used for all simulations only changing engine maps
- **Engine maps based on steady state experimental data**
  - 1.9L RCCI Map –*Experimental ORNL map*
  - 4.0L 2009 PFI Map – *Automotive OEM supplied*
  - 1.9L Diesel Map – *Experimental ORNL map*
- **Multi-mode RCCI/Diesel strategy used**
  - Mode-switching (RCCI to Diesel) used for areas of the drive cycle outside the RCCI operating range
    - *Gao et al., "A proposed methodology for estimating transient engine-out temperature and emissions from steady state maps", International Journal of Engine Research, Vol 11, pp 137, 2009.*
    - *Gao et al., "Simulating the impact of premixed charge compression ignition on light-duty diesel fuel economy and emissions of particulates and NOx", Journal of Automobile Engineering 0(0), 1-21, 2012.*

AUTONOMIE Simulink/ Stateflow



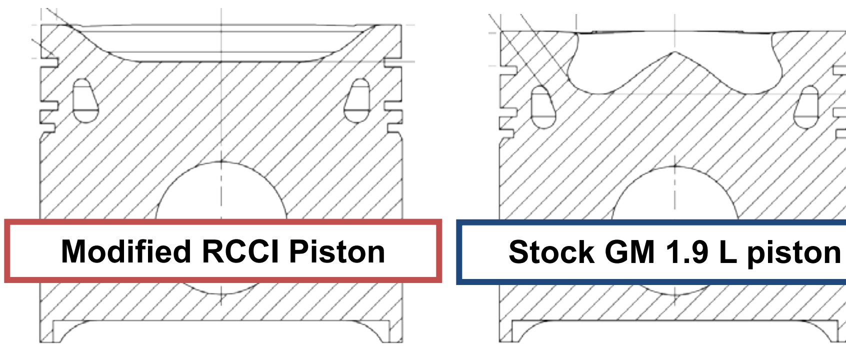
* *Autonomie, Developed by Argonne National Lab for U.S. DOE, http://www.autonomie.net/*

RCCI Optimized Pistons

Back-Up 3

- **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**
  - Allows for higher loads
  - Reduce heat transfer losses
  - Minimized squish region

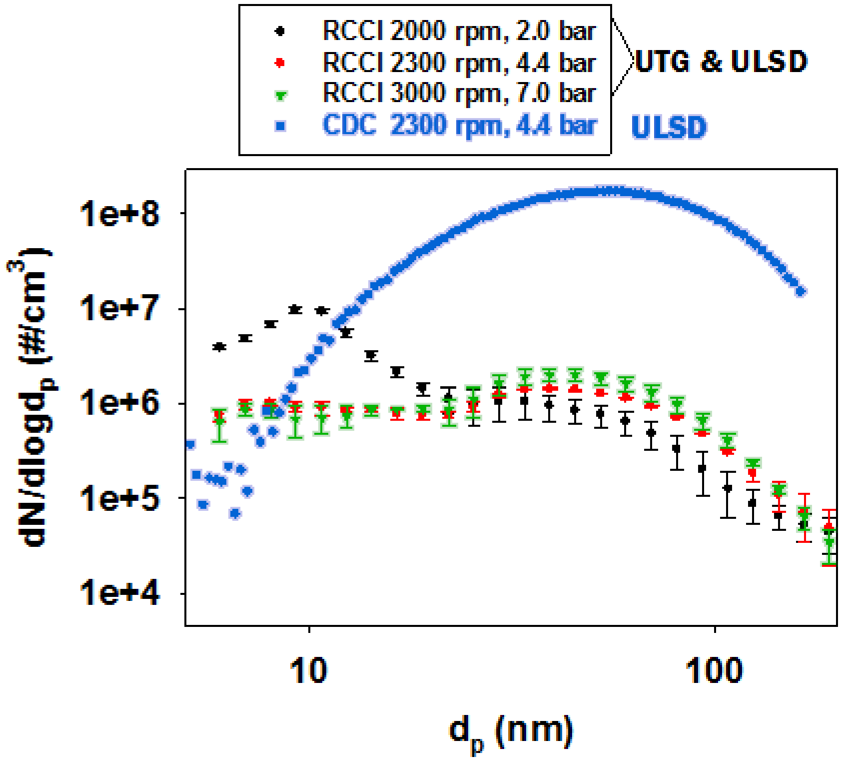


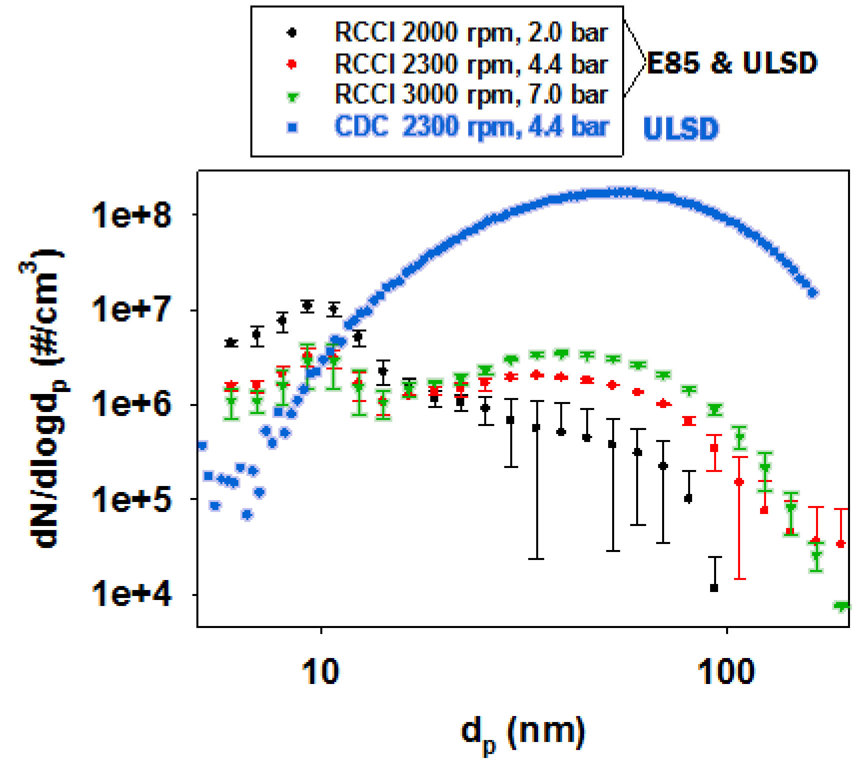
Hanson, et al. 2012 SAE Paper

RCCI PM Size Distribution Mostly Independent of Fuel Choice

Back-Up 4

- **Near Zero Smoke Number for RCCI – Not Zero PM**
  - Thermal optical analysis showed that most PM was organic carbon



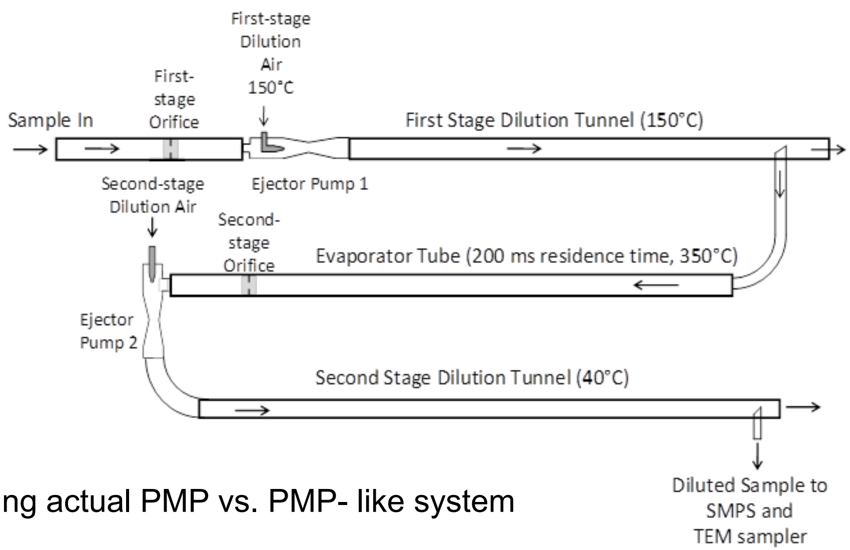


PMP-Style Dilution Used for PM Measurements

Back-Up 5

PMP-Style PM Measurements

Dilution Ratio
1st stage: 10
2nd stage: 20
=> overall: 200



Dilution system similar to European Particle Measurement Programme but with ejector pumps rather than rotating disc diluter. Reduces gas to particle conversion or the formation of liquid hydrocarbon droplets.

Future: Evaluate RCCI PM using actual PMP vs. PMP- like system