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

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ACE016

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Oak Ridge National Laboratory

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**
- **Activity scope changes to address DOE & industry *needs***

Budget

FY 2013 – $600k

FY 2014 – $500k

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: Cummins, GM, MAHLE, and many others

Universities: U. Wisconsin-Madison, U. Minnesota

Consortia: CLEERS, DERC

VTO & DOE Labs: VSST, FLT, LANL, PNNL, SNL

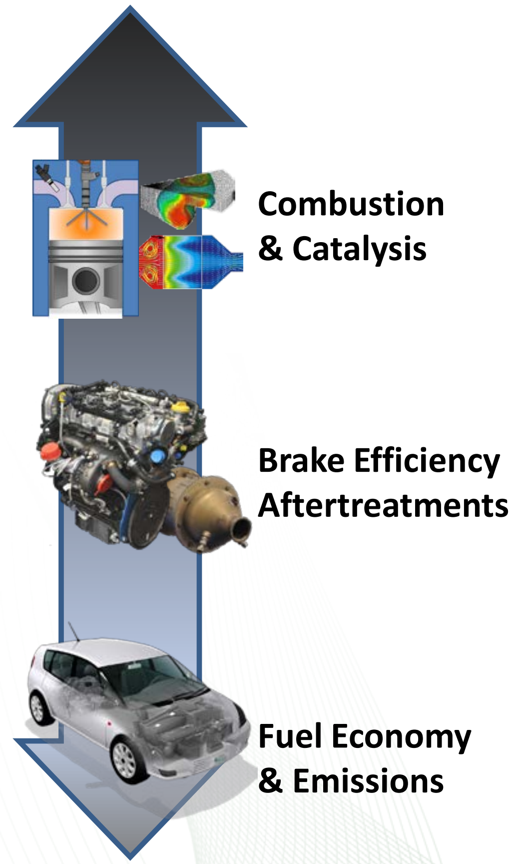
ORNL: fuels, emissions, vehicle systems, others

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

Relevance and Objectives

- **DOE VTO Milestones**
  - **Addressing barriers to meeting VTO 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).** (Backup slide on RCCI)
  - **Investigating high efficiency concepts** developed on single-cylinder engines and addressing multi-cylinder engine/ aftertreatment implementation 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 14 Milestones Met or On Track

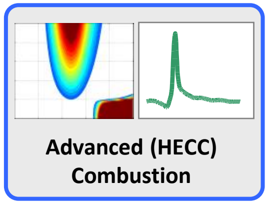
Month /Year	Milestone or Go/No-Go Decision	Description	Status
Dec 2013	Milestone	Demonstrate cylinder balancing control for RCCI operation	**COMPLETE**
Mar 2014	Milestone	Establish control authority on HD engine necessary for future RCCI operation	**COMPLETE**
June 2014	Milestone	Develop experimental RCCI map suitable for drive cycle simulations	ON SCHEDULE
Sept 2014	Milestone	Demonstrate 25% increase in modeled fuel economy with RCCI over LD drive cycles *	ON SCHEDULE
Sept 2014	Milestone	Demonstrate heavy duty RCCI on a MCE	ON SCHEDULE

** In collaboration with VSST support task*

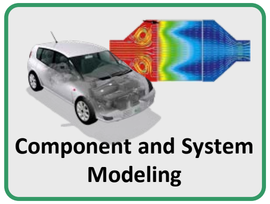
VSST 140 Impacts of Advanced Combustion Engines

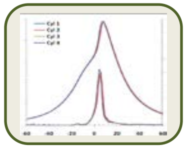
FY 14 Joule Milestones On Track

- **FY 2014 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**



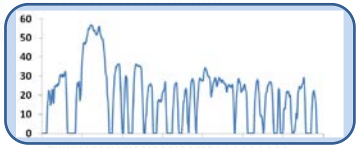
- **FY 2014 Q4 – RCCI Vehicle Systems Modeling**
  – Demonstrate improved modeled fuel economy of 25% for passenger vehicles solely from improvements in powertrain efficiency relative to a 2009 PFI gasoline baseline. Progress - **On track**
  – In collaboration with VSST support task
    - VSST 140 Impacts of Advanced Combustion Engines





Engine Efficiency

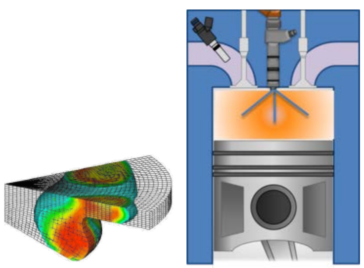
Fuel Economy



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

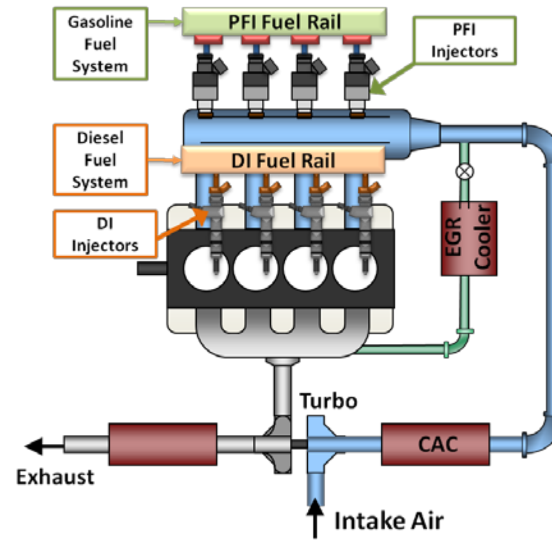
Engine System
Metric: Brake efficiency

Full Vehicle
Metric: Fuel Economy

ORNL's comprehensive approach to ACE research

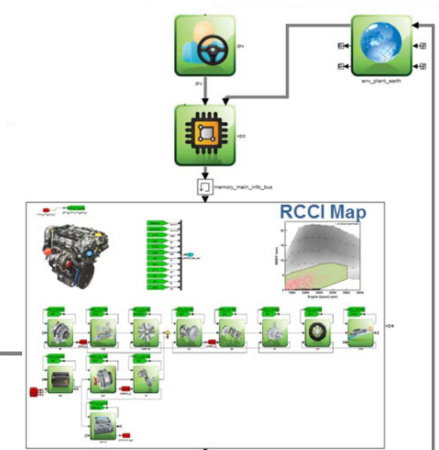
APPROACH (2/2)

- **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
- **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



ORNL RCCI Multi-Cylinder 1.9L GM

AUTONOMIE Simulink/ Stateflow



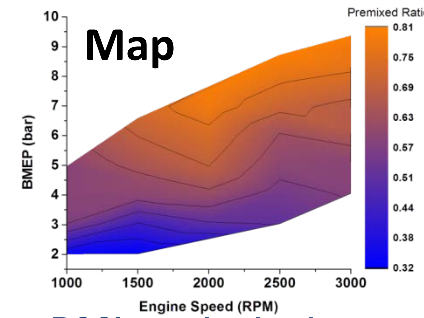
Modeled Fuel Economy

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

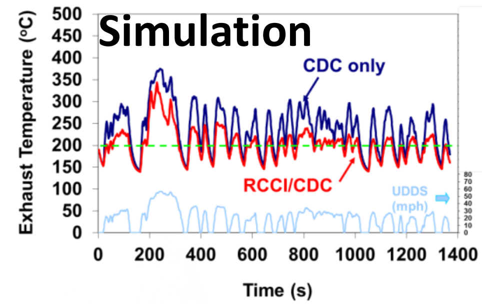
FY 13 Technical Accomplishments

Accomplishments (1/8)

- **Q3 Milestone – High Efficiency RCCI Mapping -Completed**
  - **Developed RCCI combustion map on a multi-cylinder engine** suitable for light-duty drive cycle simulations (E30/ ULSD)
- **Q4 Milestone – RCCI Vehicle Systems Modeling -Completed**
  - **Demonstrate improved modeled fuel economy** of <u>20%</u> for passenger vehicles solely from improvements in powertrain efficiency relative to a 2009 PFI gasoline baseline
    - Multiple 2009 PFI baselines examined
      - Provided by industry partner
    - **Fuel economy** and engine out emissions over drive cycles



RCCI premixed ratio as a function of engine speed and load



Modeled RCCI/CDC exhaust temperatures compared to CDC operation

Relevance

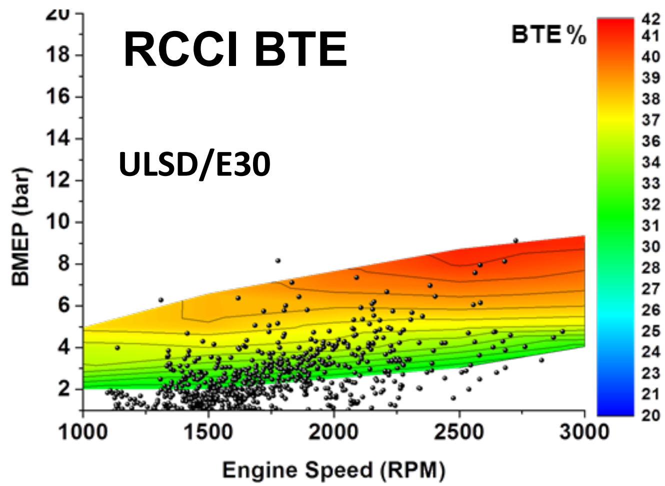
RCCI has been shown in previous multi-cylinder experiments to have high brake thermal efficiencies with ultra-low NOx and soot emissions.

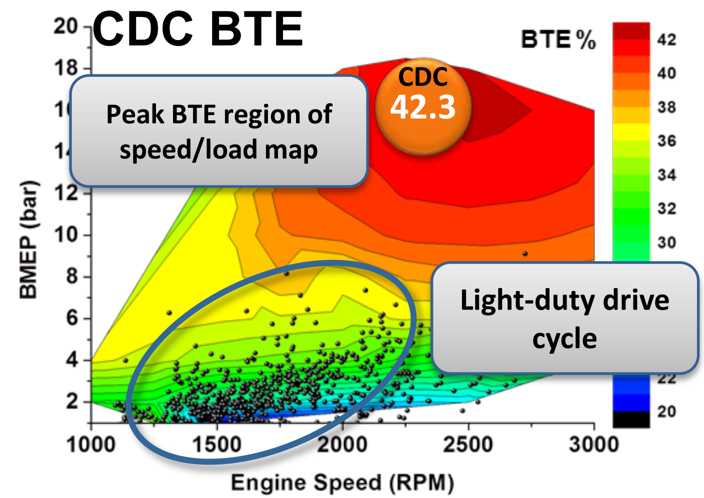
However, the benefits and challenges of RCCI on light-duty vehicles over federal driving cycles are still not well understood.

E30/ULSD RCCI mapping focused on efficiency and load expansion

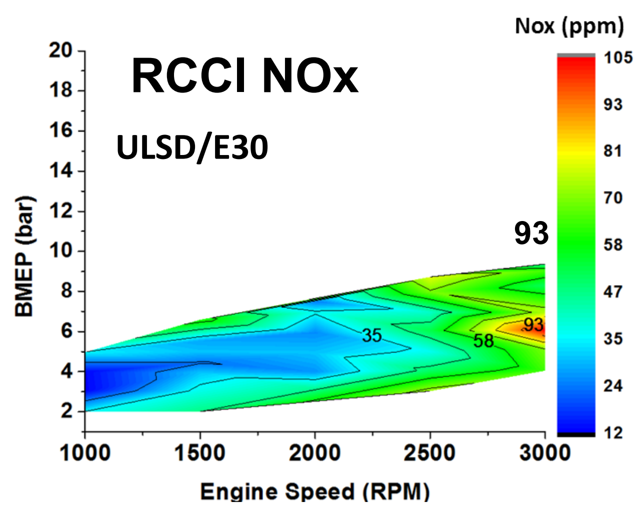
ACCOMPLISHMENTS (2/8)

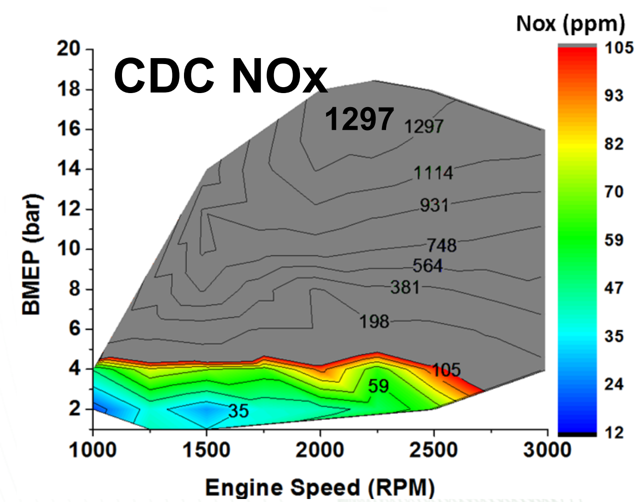
Focus on higher **BTE** operation with limits on PRR (high) and CO emissions (low)





NO_X emissions reductions are generally on the order of 50% to 92%





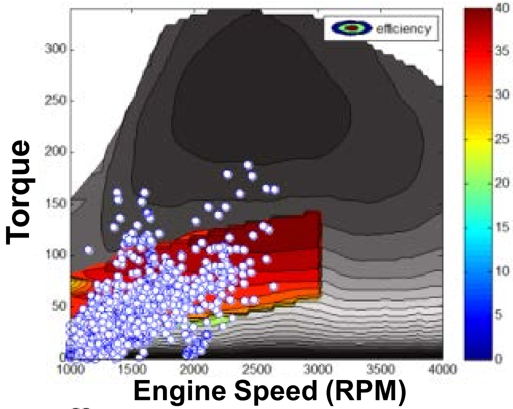
Mapping - Curran, et al., *SAE Int. J. Engines* 7(2):2014

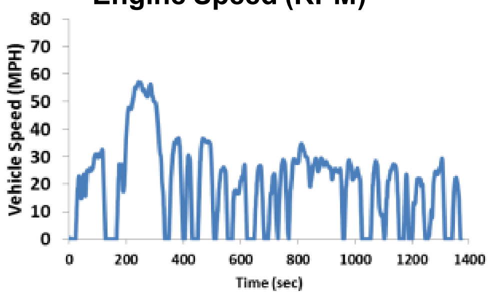
Previous Mapping - Curran, et al., SAE Technical Paper 2013-01-0289

Current RCCI map requires mode-switching to cover light-duty drive cycles

- **RCCI coverage of engine speed and load over the different drive cycles and illustrates need for multi-mode operation with the current RCCI map for both low load operation and high load operation.**
  - 100% coverage of low temperature combustion is necessary to avoid mode-switching

Urban Dynamometer Driving Cycle

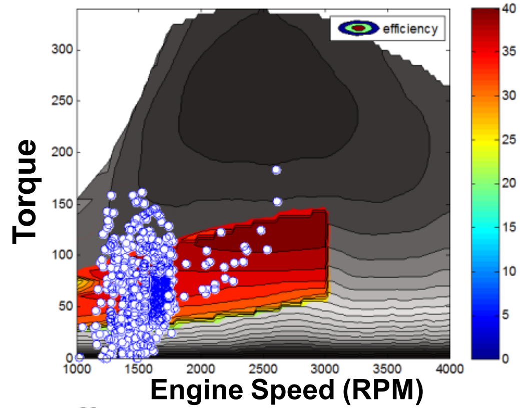


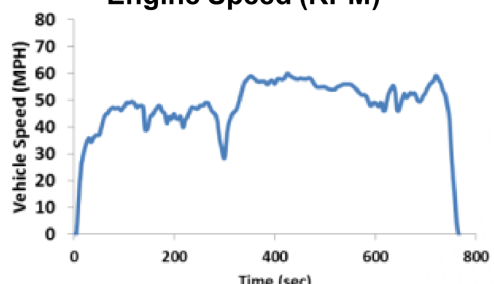


Represents city driving conditions

RCCI Coverage*= 51.8%

Highway Fuel Economy Test

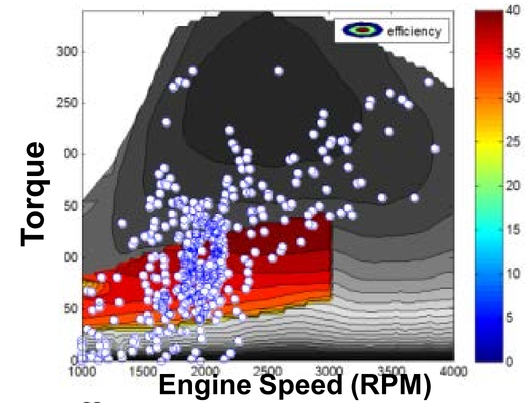


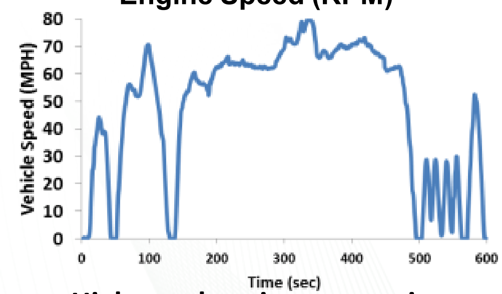


Represents highway driving conditions under 60 mph

RCCI Coverage*= 74.3%

US06 - Supplemental





High acceleration aggressive driving schedule

RCCI Coverage*= 56.5%

* Non-idling portion of drive cycle covered in RCCI mode

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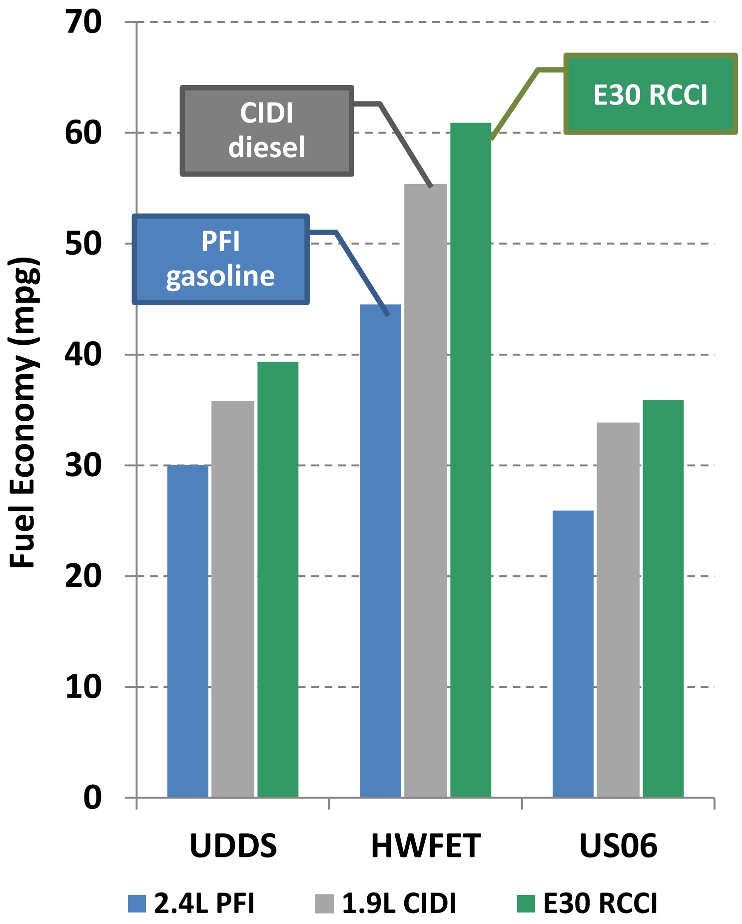
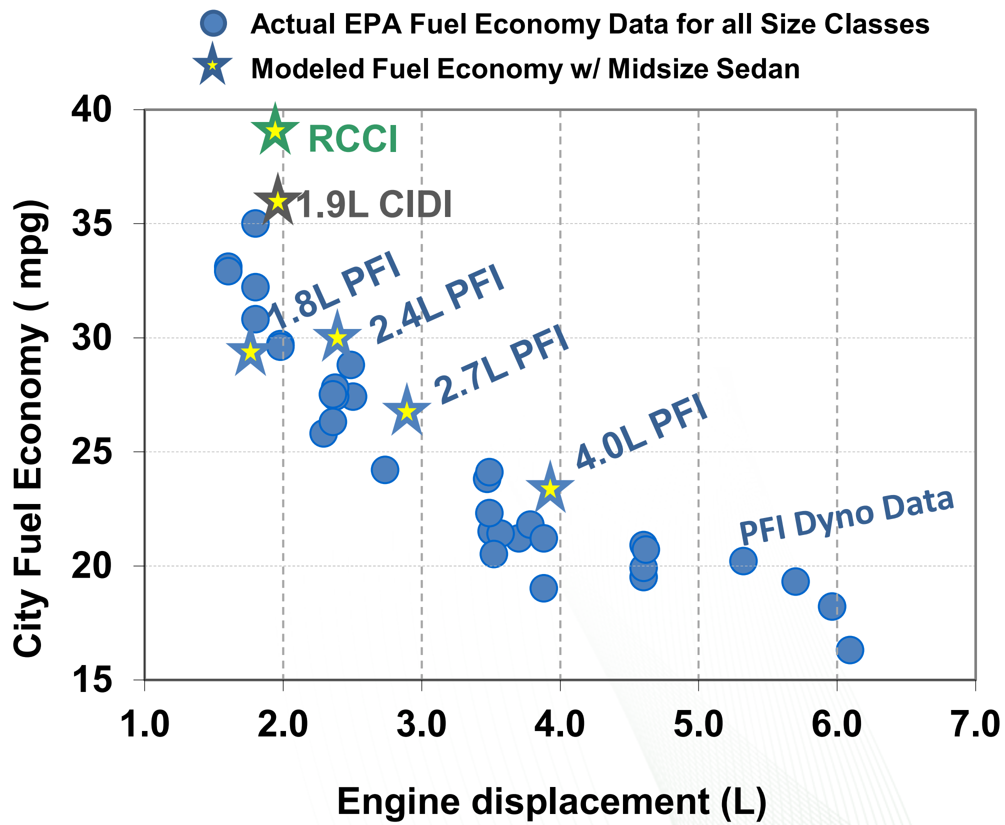
RCCI offers >20% improvement all 2009 PFI engines evaluated

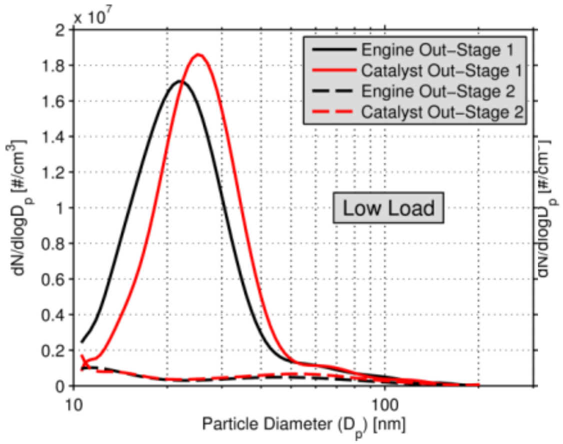
- **Modeling results show up to a 22 - 28% improvement in fuel economy with RCCI over UDDS compared to 2009 PFI baseline on same vehicle (10% increase over CDC)**
  - 2.7L PFI engine matches 0-60 time with best fuel economy from 2.4L engine (Backup slide)



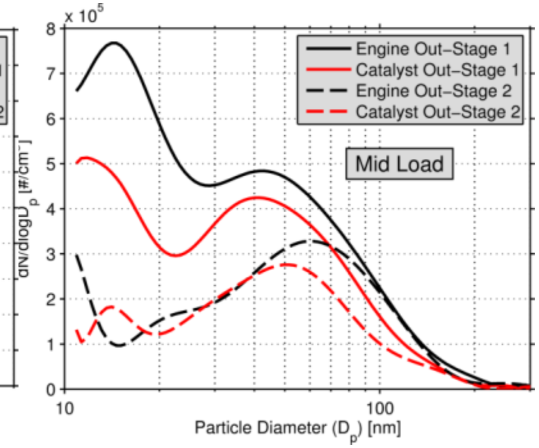


PNNL SPLAT collaboration key to understanding exact composition of LTC particles

DOC effective at reducing mass and number above catalyst light-off temperature (Pre- and post-DOC results)



1500 RPM, 2.6 bar BMEP

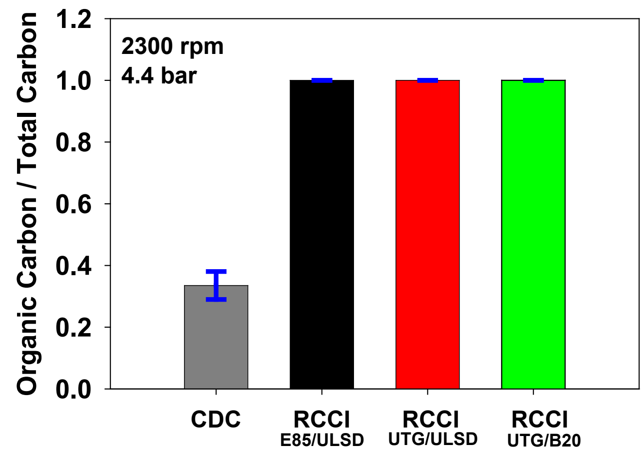


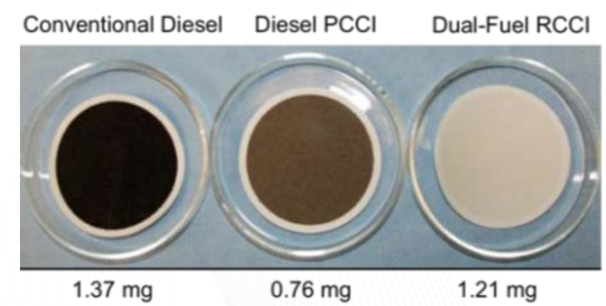
2000 RPM, 4.0 bar BMEP

Dempsey et al., 2014-01-1596

See Prikhodko et al., 2013-01-0515 for mode switching effects

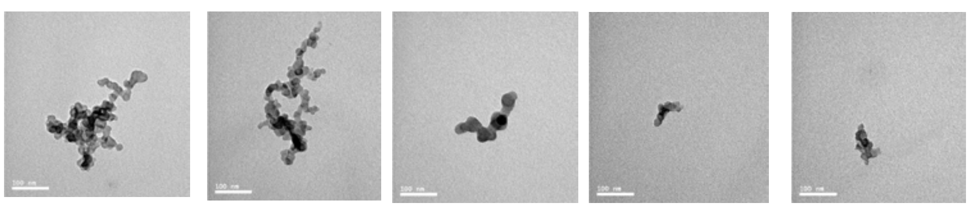
PM from RCCI combustion dominated by organic carbon





TEM shows range of agglomerations and morphology

Partnering with PNNL to better understand composition through GC/MS



Near-zero smoke number for RCCI does not mean zero particulate matter

ACE023; George Muntean, PNNL: CLEERS Aftertreatment Modeling and Analysis

SPLAT Backup Slide

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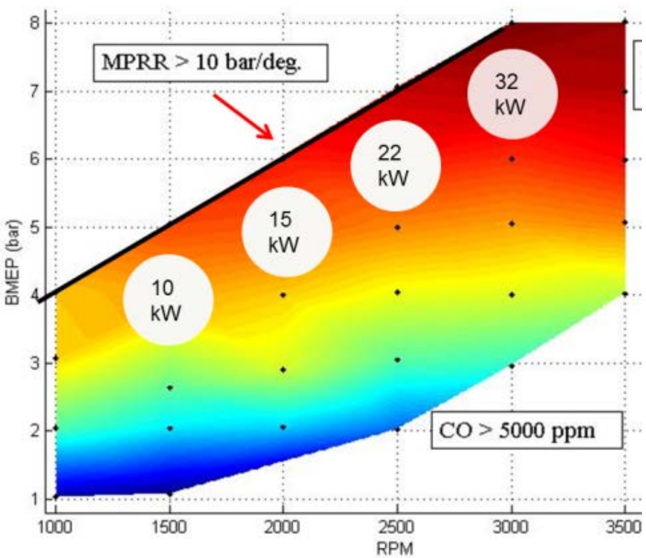
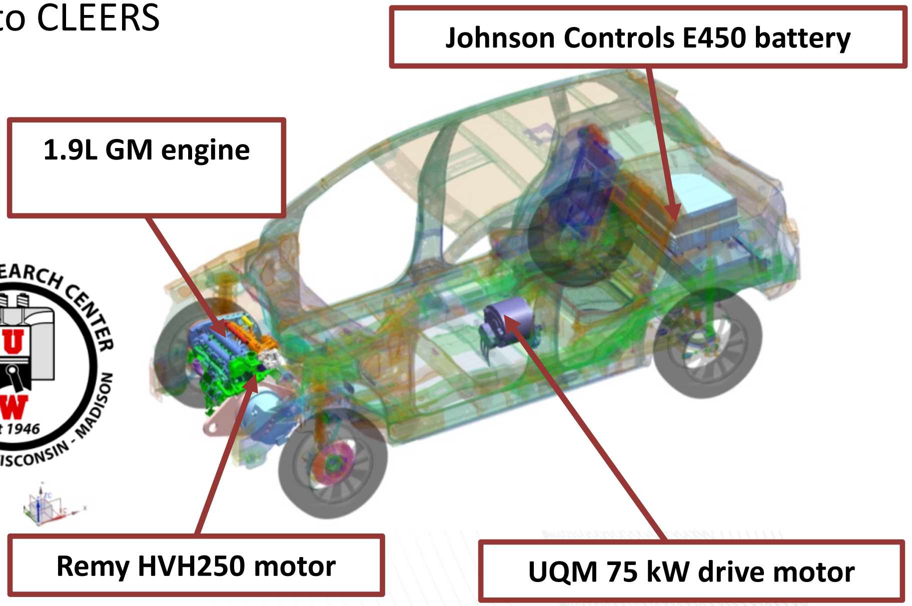
UW RCCI Hybrid being Evaluated at ORNL

- **Initial Results at Ford showed promising results**
  - **Emissions testing of UW RCCI Hybrid Vehicle at ORNL (May 12)**
    - Charge sustaining g mode with various power/efficiency levels
- **Further investigating multi-cylinder challenges**
  - Combustion stability / Controls for LTC on MCE\ load range limitations
- **Aftertreatment integration research including low-temp catalysts**
  - RCCI aftertreatment performance and feedback to CLEERS

Vehicle on the ORNL chassis dynamometer undergoing drive cycle evaluations



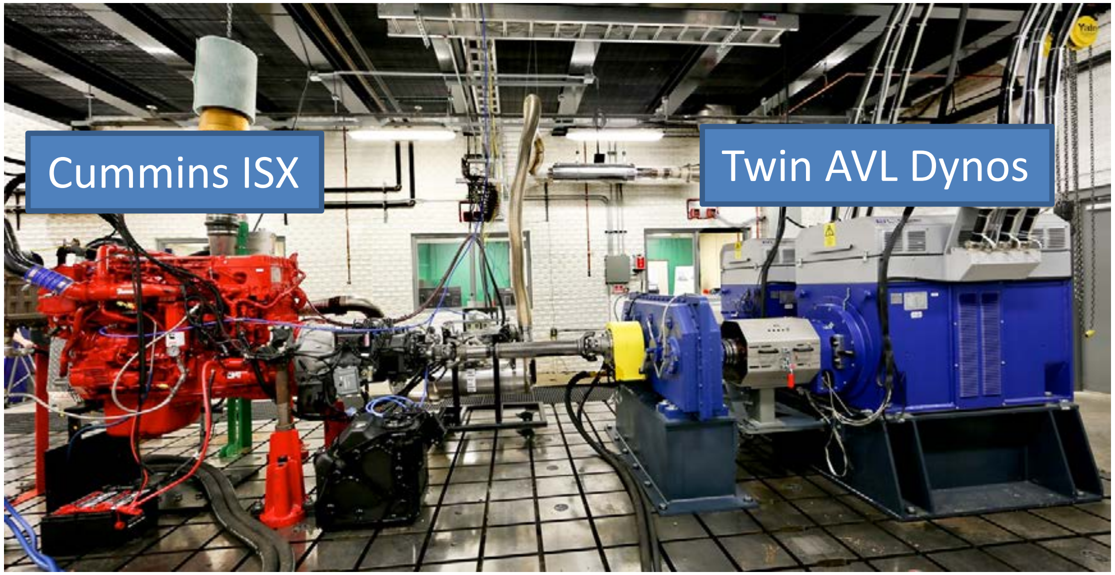
RCCI Power Levels for Series Mode



UW RCCI Hybrid

Heavy Duty RCCI with Cummins ISX

- **Collaboration with Cummins**
  - Material transfer for head allowing combustion analysis via in-cylinder pressure
  - Hooks into ECU for full control for RCCI
  - Focus on lower load operation and emissions controls (Q4 of 2014)
- **VSST collaboration**
  - Will allow for transient and controls research



ORNL Vehicle Systems Integration Lab (VSI) [Hyperlink]

ORNL VSI Powertrain Test Cell

- **2010 ISX with full aftertreatmnent**
- **Uniquely capable of analyzing light-duty to full heavy-duty Class 8 powertrains**
- **Configurations available to evaluate and characterize engines, electric machines, transmissions, and integrated powertrains**

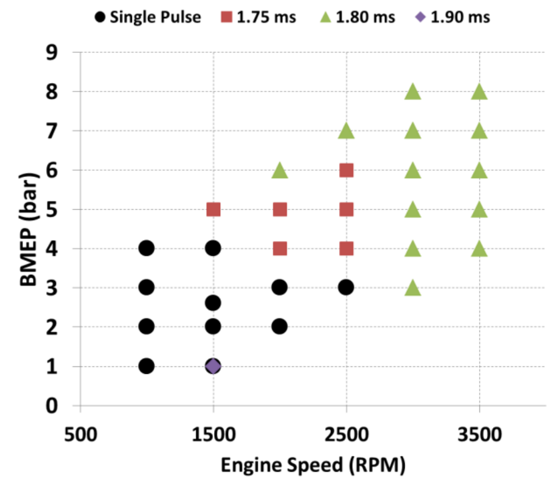
Test cell specifications:

- **Twin AVL 500 kW AC transient dynamometers each capable of absorbing 3,000 N·m of continuous torque and 3,500 rpm/sec**

ISX Aftreatment-train

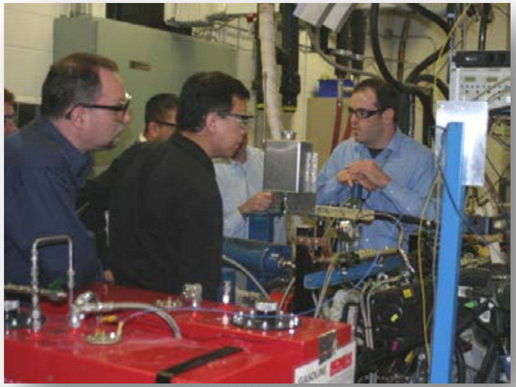
RCCI Data Being Shared with Community via CLEERS and Direct Contact

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



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

- **Data being shared for VSST and FLT Projects**
  - VSST support task aiding in FY 15 vehicle systems simulations
- **Detailed RCCI combustion and emissions data shared**
  - Data being shared with Converge for model validation
  - Data provided to industry
- **Many technical papers and presentation**
  - Requests for additional data from papers



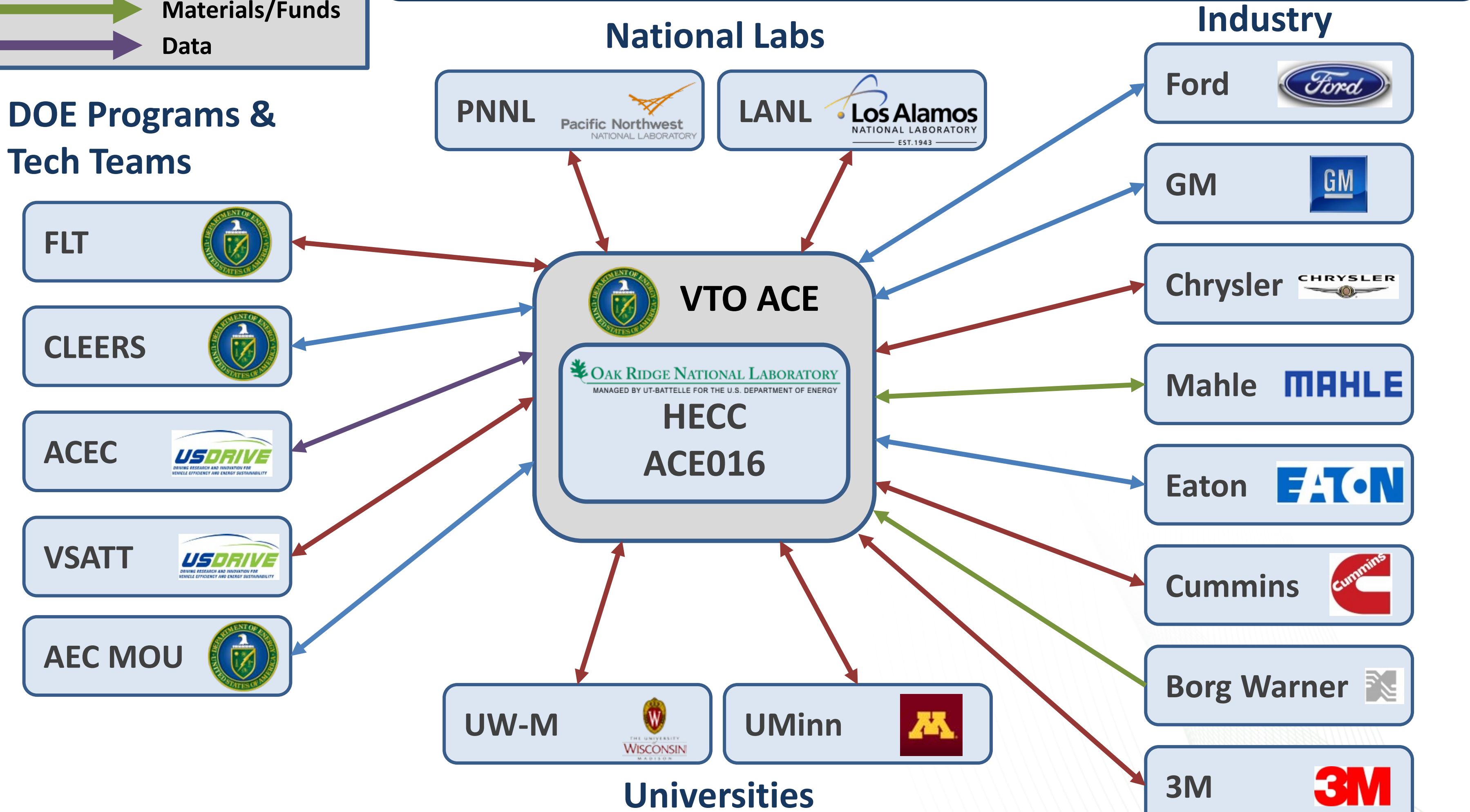
Discussion of ACE research with industry visitors at ORNL.

ACE projects leverage resources and expertise across industry, universities and DOE programs to meet these objectives

COLLABORATIONS

Key: Type of Partnership
- Information
- Collaboration
- Materials/Funds
- Data

HECC Project Main Objective: 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



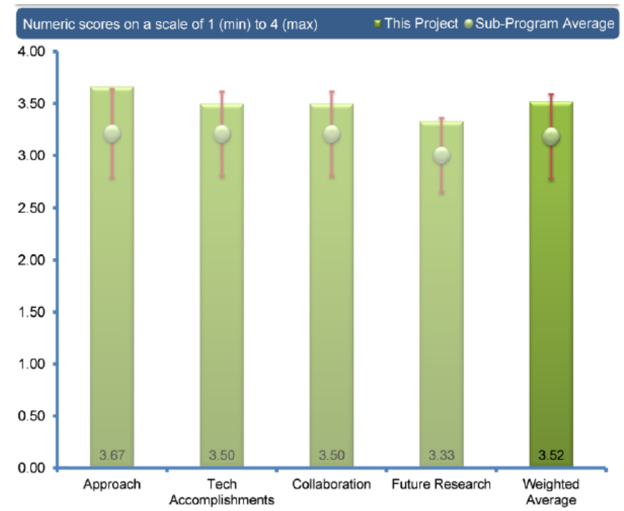
More details in backup slide

Reviewer Comments from FY 2013 – ACE016 - HECC

REVIEWER COMMENTS

Positive Comments

- Reviewer comments were generally positive.
- The reviewers indicated the project very relevant and does support overall DOE objectives, namely that improving engine efficiency is key and that "the combination of engine testing and zero-dim vehicle analysis was very fruitful for this project".
- The reviewers indicated the project provides "a critical step in providing efficiency and emissions data so that the barriers to advanced combustion modes could be better understood and therefore better addressed ".



Addressing significant Questions/ Recommendations from 2013 Reviewers

- **Reviewers noted that it was not fair to compare fuel economy for an 8-bar BMEP engine with an 18-bar BMEP engine because vehicle performance would be so different.** The project is focused on the DOE baseline of 1.9L PFI gasoline baseline but also compared results to a diesel baseline with the same engine. This is an important thing to note and discussions have started about compared to high BMEP SI engines as well.
- **The PI should attempt to estimate the cumulative TP emissions to see how close the project was to a Tier 2-Bin 2 or partial-zero-emissions-vehicle (PZEV) TP emissions standard.** This has been done, slide 14 of the 2013 ACE 016 presentation showed the % difference from baseline. We have been reluctant to share the absolute numbers with the community until we have transient data to validate the emissions. The collaboration with UW's RCCI project will allow the first on-vehicle validation of the ORNL RCCI series hybrid modeling results.

Comments cited above were paraphrased as appropriate from 2012 Annual Merit Review document, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/2012_amr_04.pdf

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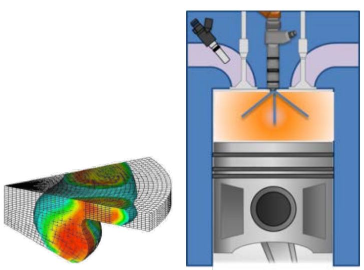
Remaining Challenges and Barriers

FUTURE WORK

- **Previous vehicle system simulations performed using two different pistons**
  - FY 14 mapping will take place with stock piston with gasoline/diesel fuels
- **Validation of Vehicle System Simulation Data**
  - Goes back to MYPP barriers, working with UW-Madison RCCI hybrid team
- **Installation of instrumented head for HD RCCI project**
  - Cummins has been very supportive with Materials Transfer and ECU hooks

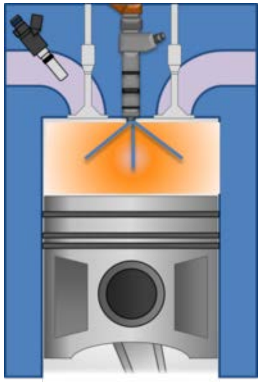


Combustion
Metric: Indicated efficiency

Engine System
Metric: Brake efficiency

Full Vehicle
Metric: Fuel Economy

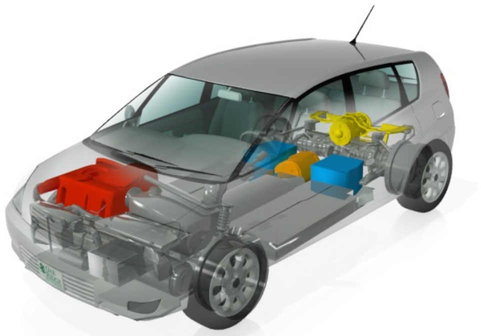
Future Work



FY 14

- **U. Wisc RCCI Hybrid Evaluation May 12 (backup –slide)**
- **Q3 and Q4 DOE Milestones – RCCI/ Multi-mode with Stock Piston**
- **RCCI aftertreatment integration studies** (couple to mapping)
- **HD RCCI in collaboration with Cummins and VSST projects**
- **Couple MCE experiments to high fidelity CFD modeling for insights into efficiency/emissions**

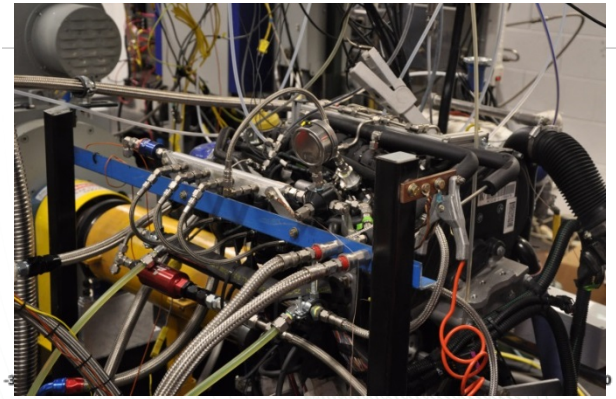
FY 15



- **Further investigating multi-cylinder challenges focused on transients**
  - Enabling technologies including advanced air-handling/ pistons/ sensors
  - Combustion stability / Controls for LTC on MCE
- **Transient Hardware-in-the-Loop for Advanced Combustion Research**
  - Will provide additional capabilities to address aftreatrement and drive cycle challenges
- **Expand collaboration with VSST projects**
- **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 to advanced combustion research**
  - Multi-cylinder advanced combustion experiments
  - Aftertreatment integration
  - Vehicle systems level modeling
- **Current research focused on investigated fuel economy potential of LTC**
  - RCCI combustion research and development leading to engine mapping
  - 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 for advanced combustion/ multi-mode
  - Low temperature catalysts



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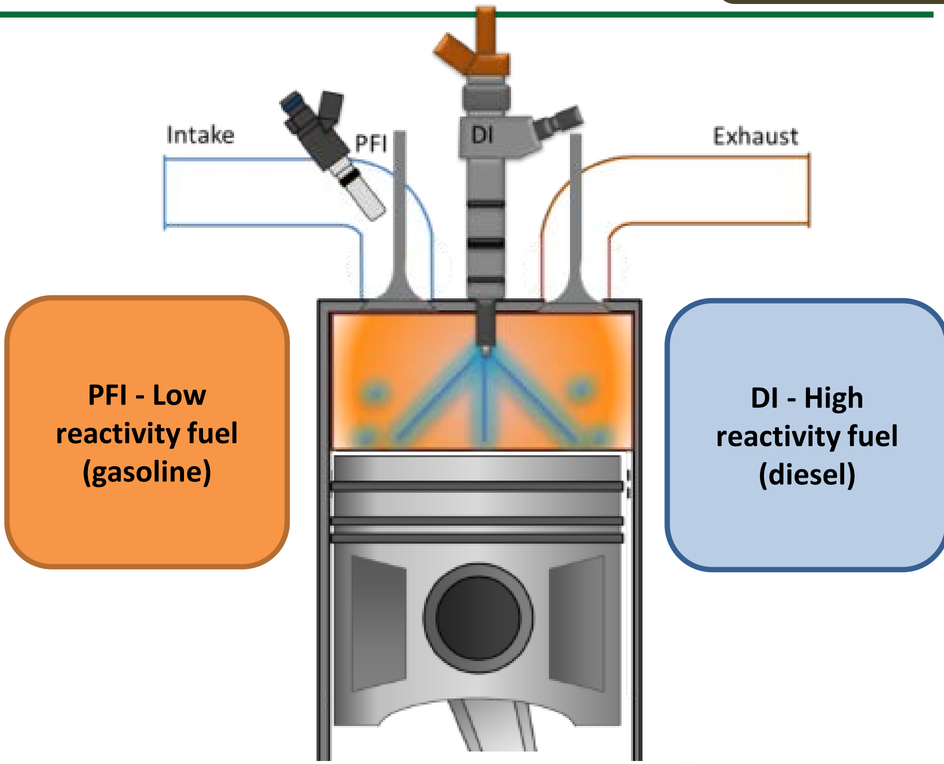
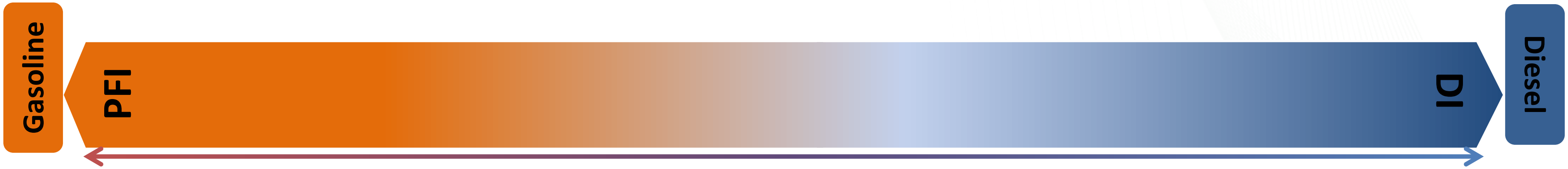
Technical Back-Up Slides

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

Back-Up 1

- **Reactivity controlled compression ignition (RCCI) allows precise reaction and heat-release control**
  - A low-reactivity fuel is introduced early and premixed with air.
  - A high-reactivity fuel is injected into the premixed charge before ignition.
- **RCCI increases engine operating range for premixed combustion**
  - Global fuel reactivity (phasing)
  - Fuel reactivity gradients (pressure rise)
  - Equivalence ratio and 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

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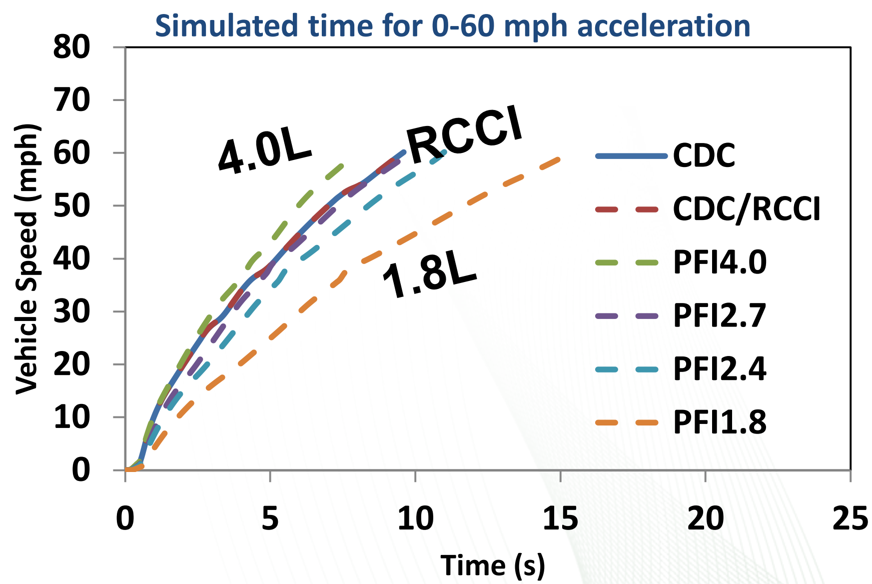
Matching Engine Based on 0-60 Performance

Back-Up 2

- **Current range of engine maps allows matching based on performance to have best comparison against "representative" 2009 PFI baseline**
  - Previous study compared to 4.0L PFI only *(submitted to IJER)*
  - 0-60 mph acceleration simulations performed with standard performance transmission (non fuel economy optimized transmission) for each vehicle on same mid-size sedan
- **2.7 L PFI engine best match for performance (2.4 L best fuel economy)**
  - 1.8 L PFI underpowered for vehicle size

0-60MPH acceleration (default shifting strategy)

T/D	Distance(M)	Time(S)	Fuel economy
CDC	153.9	9.50	6.55
CDC/RCCI	154.1	9.50	6.58
PFI4.0	124.4	7.90	3.30
PFI2.7	155.0	9.80	3.79
PFI2.4	169.0	10.90	4.76
PFI1.8	234.7	15.20	6.16



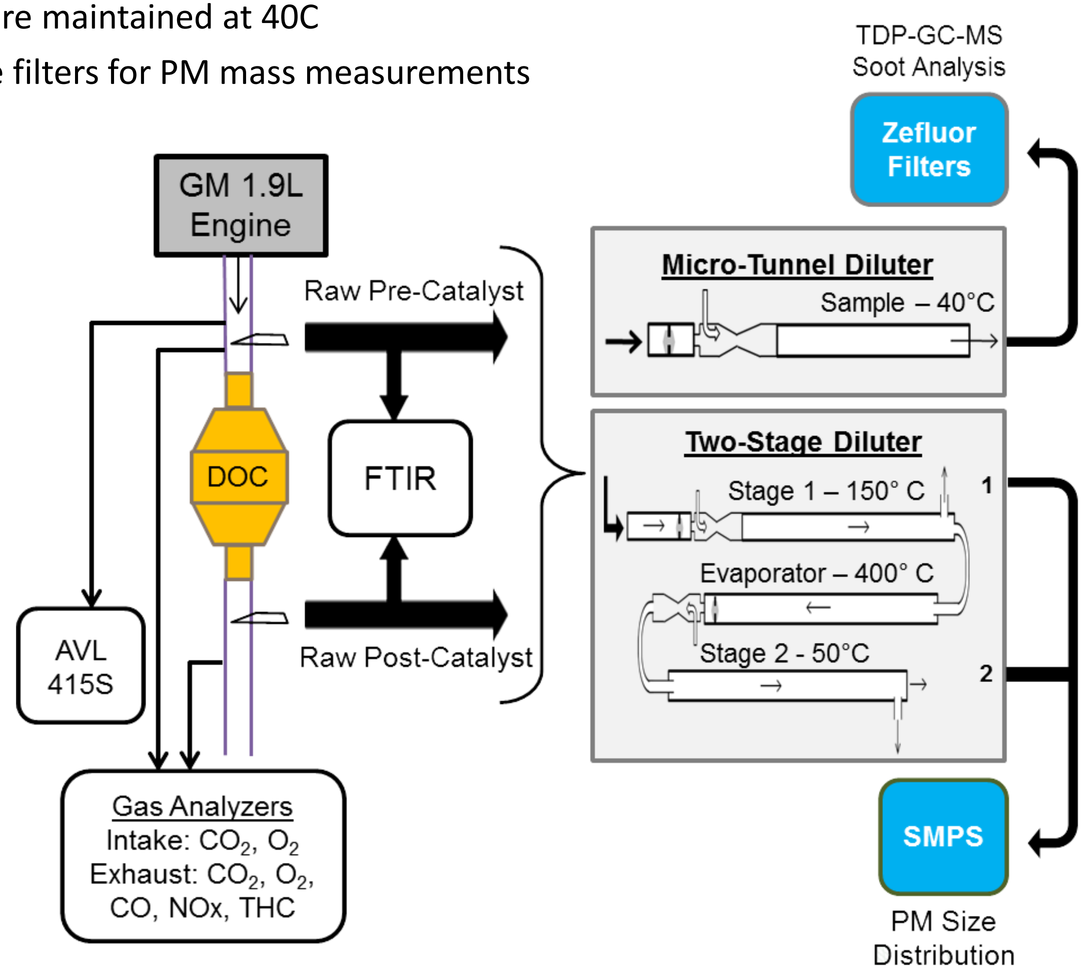
Driven by Feedback on 4.0L as baseline here and ACEC

Experimental Setup: Particulate Sampling System

Back-Up 3

- ***Micro-Tunnel Diluter***
  - Dilution Ratio of ~12 and sample temperature maintained at 40C
  - Supplies exhaust sample to PTFE membrane filters for PM mass measurements

- ***Two-Stage Dilution System***
- Based on European PMP System
- Supplies exhaust sample to the SMPS
- *Stage 1*
  - Dilution Ratio of ~12
  - Sample Temperature 150C
- *Evaporator*
  - Sample heated to 400C
- *Stage 2*
  - Total Dilution Ratio of ~80
  - Sample Temperature 50C
- 3 to 6 SMPS scans at each condition
- See the paper for detailed discussion on particle loss characterization of the system using sodium chloride and tetracontane (C_{40}).

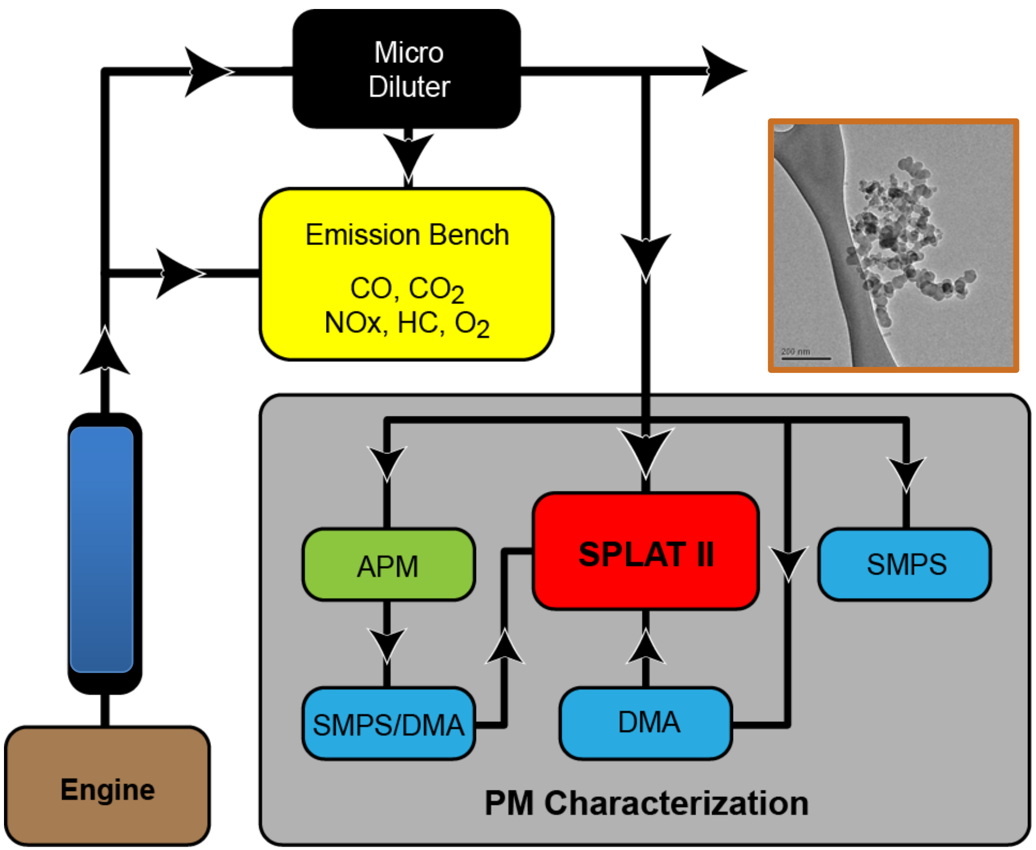


SPLAT - Experimental Setup

Back-Up 4

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Real-time, *in-situ,* highly detailed particulate matter (PM) characterization:



- **SMPS:**
  - ✓ size distributions, d_m
- **SPLAT II:**
  - ✓ single particle size, d_{va}
  - ✓ single particle composition, *MS*
- **DMA/SPLAT:**
  - ✓ effective density, ρ_{eff}
  - ✓ fractal dimension, D_{fa}
  - ✓ primary spherule diameter, d_p
- **APM/DMA/SPLAT:**
  - ✓ particle mass, m_p
  - ✓ fractal dimensions, D_{fm}, D_{pr}
  - ✓ primary spherule diameter, d_p
  - ✓ number of spherules, N_p
  - ✓ void fraction, Φ
  - ✓ shape (χ_t, χ_v)

For more background see
Zelenyuk, Leoper, Narayanaswamy et al. DEER 2012

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Collaborations and Industry Feedback

Back-Up 5

- **University Partners**
  - The University of Wisconsin-Madison – RCCI modeling and RCCI Hybrid
  - The University of Minnesota – RCCI PM Collaboration
- **Industry Partners**
  - ACEC/ USDRIVE – Goal Setting, Noise and Drive Cycle Estimates
  - GM - GM 1.9 – Hardware and LTC noise discussion
  - Cummins – Hardware and ECU support of HD RCCI project
  - Chrysler – Engine Data for Q4 milestone
  - Converge – Providing RCCI data – receiving licenses for CFD collaboration
  - 3M – Collaboration on heat transfer experiments for aftertreatments
  - MAHLE – Premixed Compression Ignition Piston Design
  - National Instruments – Hardware for RCCI Hybrid Vehicle
  - FORD– Sharing RCCI data and RCCI discussions
  - MECA – Catalysts supply and industry feedback
  - Borg Warner – Hardware and discussion of advanced air handling
  - Energy Company– Fuel effects collaboration for LTC
  - SAE – Chair of Dual Fuel Supersession -> interacting with other RCCI researchers
- **VTO Activities**
  - VSST – ACE support task (VSST 140)
  - FLT – Advanced fuels for advanced combustion engines
- **DOE AEC/ HCCI working Group**
  - Research is shared with DOE's AEC/HCCI working group meeting twice a year
- **Other DOE Labs**
  - LANL – Provide MCE LTC engine for evaluation of mixed-potential sensors
  - PNNL – SPLAT RCCI PM campaign
  - SNL – Discussions on LTC

Model Development and Refinement

Hardware for LTC

Feedback and Data Sharing

Goal Setting

Leveraging and Outreach

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