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

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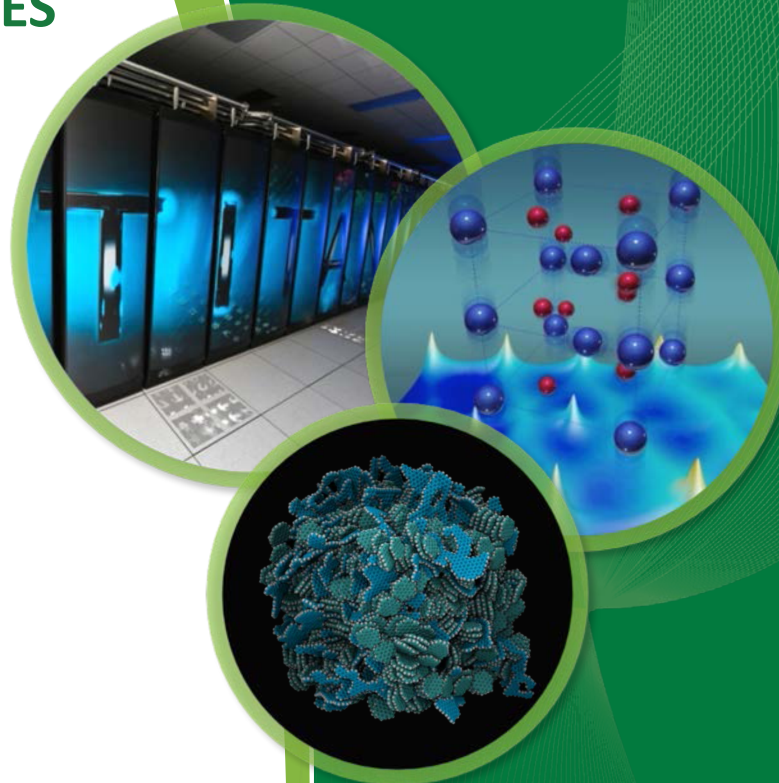

DOE Management Team
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Vehicle Technologies Office U.S. Department of Energy

2016 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

June, 2016

ACE016

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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*
- *Current project ends this FY, will inform new FY 17-19 project proposal*

Budget

FY 2014 – $500k

FY 2015 – $430k

FY 2016 – $400k

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

Barriers (MYPP 2.3 a,b,f)*

a) Lack of fundamental knowledge of advanced combustion regimes

b) Lack of effective emissions controls for LTC

f) Lack of emissions data on future engines

Partners / Interactions

Regular status reports to DOE

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

Industry: GM, MAHLE, Honeywell, and many others

Universities: U. Wisconsin, U. Minnesota, Clemson

DOE Labs: SNL, ANL, LANL

VTO: Vehicle systems (VSS) and Fuels (FLT)

ORNL: fuels, emissions, vehicle systems, others

Consortia: CLEERS, DERC

Relevance and Project Objectives

- Overall Objectives
  - **Develop and assess the potential of single- and dual-fuel advanced combustion concepts on multi-cylinder engines for improved efficiency and emissions**
  - **Address barriers to meeting VTO goals** of reducing petroleum energy use (engine system) including potential market penetration with efficient, cost-effective aftertreatments
  - **Minimize fuel penalties for aftertreatments** (Tier 3 goal)
  - **Characterize MCE LTC implementation losses** on thermodynamic basis including hardware effects
  - **Interact in industry/DOE tech teams** and CLEERS to respond to industry needs and support model development

Objectives March 2015–March 2016

1. **Stock piston RCCI development (a,f,c)**
2. **RCCI engine mapping (a,f,c)**
3. **Initial transient RCCI experiments (a,d,h)**
4. **RCCI-CDC transition PM (c,f)**
5. **Thermodynamic loss analysis (a,c)**
6. **Modeled RCCI drive cycle fuel economy (MG)**

Relevance to DOE VTO MYPP 2.3X

A. Lack of fundamental knowledge of advanced engine combustion regimes
B. Lack of cost-effective emission control.
C. Lack of modeling capability for combustion and emission control
D. Lack of effective engine controls.
F. Lack of actual emissions data on pre-commercial and future combustion engines.
H. Market perception

Milestones and Go/No-gos for FY 2015 and 2016

MILESTONES (1/1)

- **Complete** — FY 15, Q1: Demonstrate modeling capability of RCCI combustion
- **Complete** — FY 15, Q3: Develop experimental RCCI map suitable for drive cycle simulations
- **Complete** — FY 15, Q4 SMART: Demonstrate 30% increase in modeled fuel economy with RCCI over LD drive cycles [2]
- **On Track** — FY 16, Q3: Develop experimental multi-mode RCCI map suitable for drive cycle simulations with transient effects
- **On Track** — FY 16, Q4 SMART: - Demonstrate 25% increase in dyno fuel economy with RCCI over LD drive cycle on **transient experiments**.

Q4 SMART milestone in context of previous fuel economy potential milestones

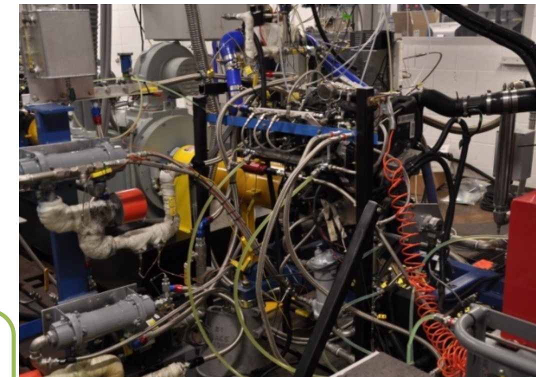
% Modeled Fuel Economy Increase With RCCI	FY 12	FY 13* RCCI Piston	FY 14* RCCI Piston	FY 15 Stock Piston	FY 16 SMART Milestone
Combined LD	NA	+33.5%	+41.4%	+ 44.7%	
UDDS (city)	NA	+33%	+42.6%	+51.8%	
HWFET (highway)	NA	+34%	+40.0%	+39.7%	

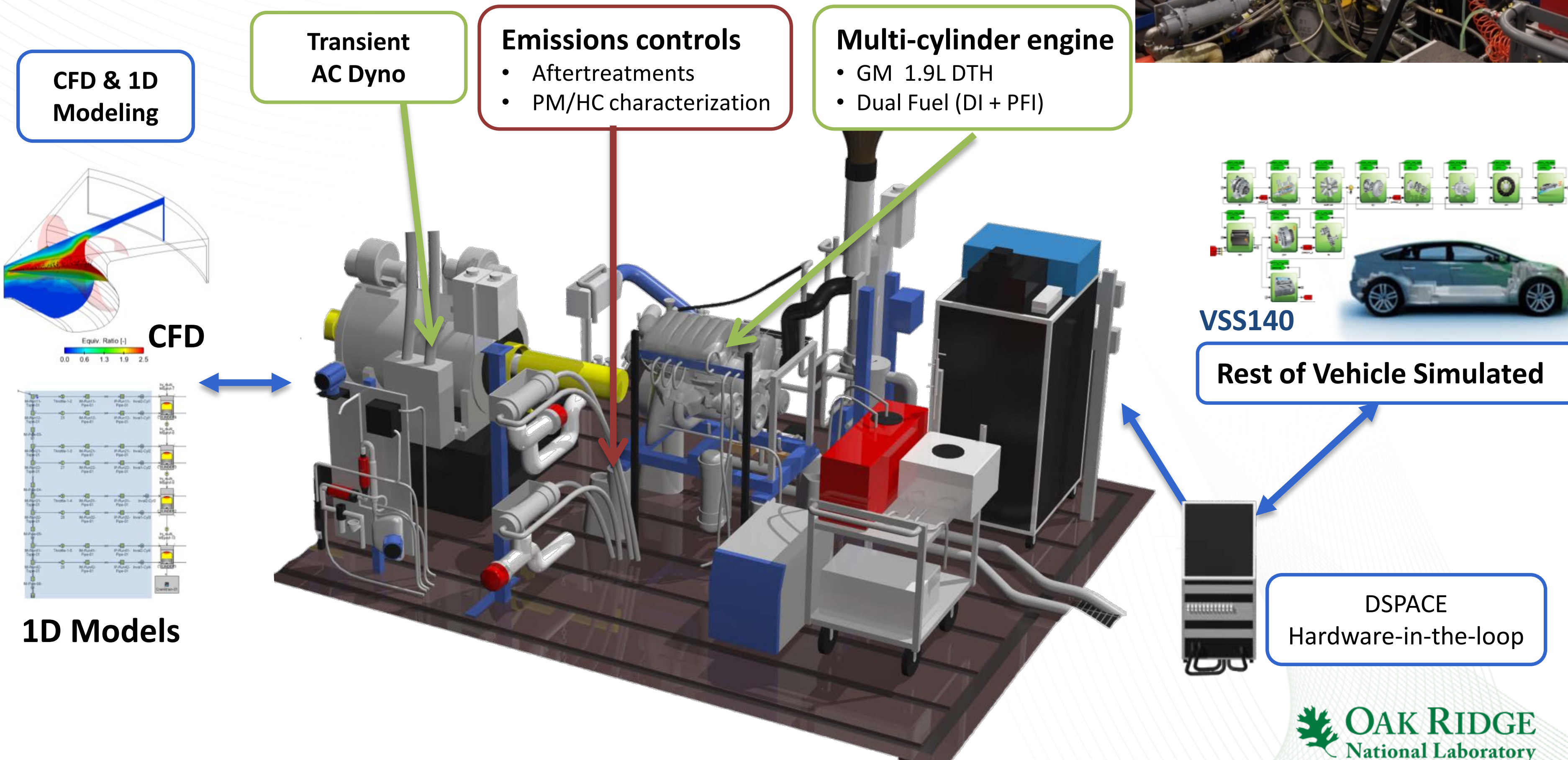
FY 13 – 15 modeled fuel economy results from vehicle systems simulations using MCE experimental engine data

[2] *In collaboration with VSS support task*

Approach: Multi-cylinder advanced combustion with production-viable hardware and aftertreatment integration

- GM 1.9 DTH multi-cylinder diesel engine with dual-fuel system
- Emissions characterization and aftertreatment integration needs
- CFD and 1-D modeling for guidance and insight
- Vehicle systems simulations using experimental data/ HIL experiments to address barriers for LTC





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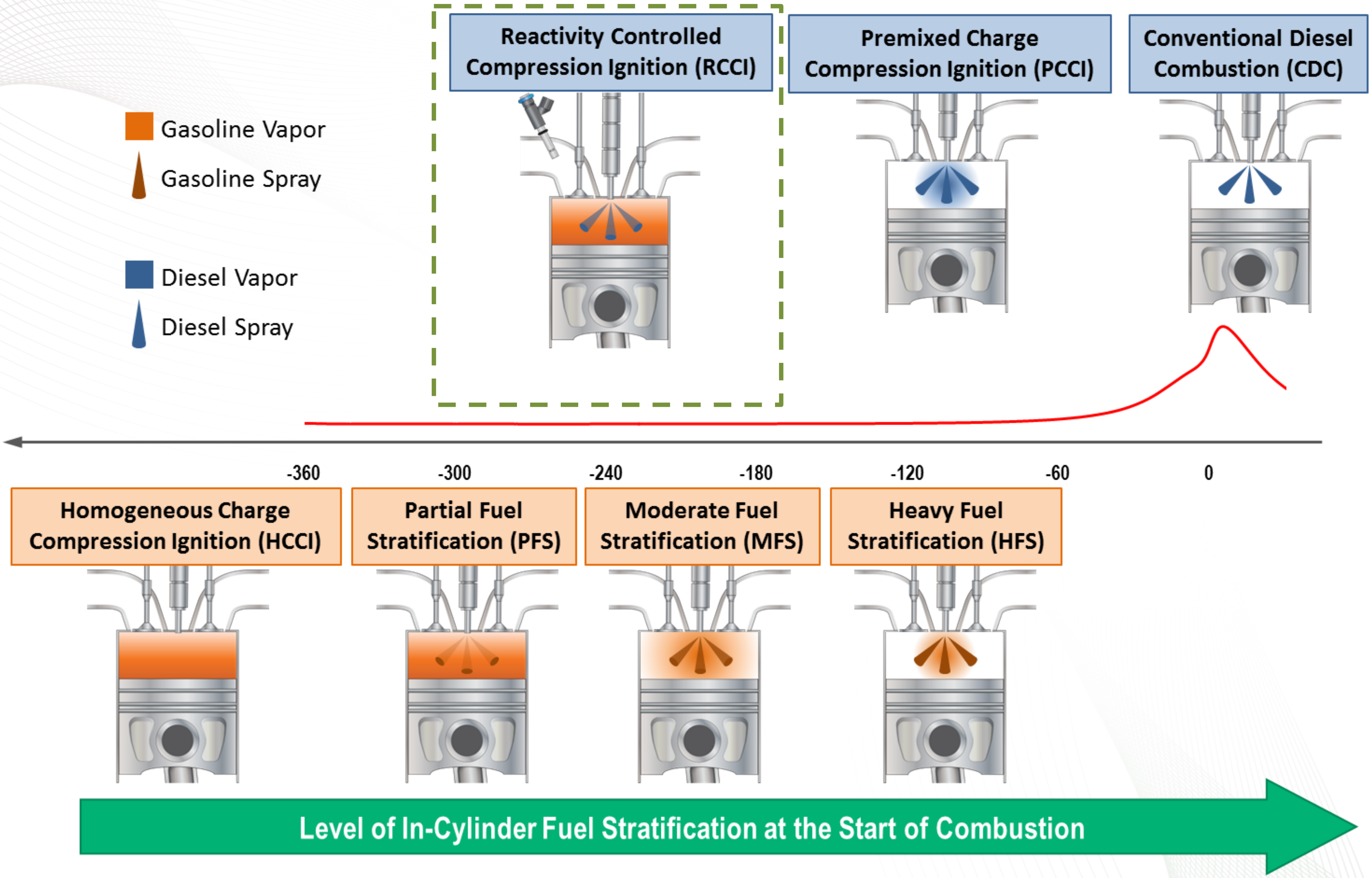
Different LTC approaches dominated by differences in fuel/air stratification

Approach (2/3)

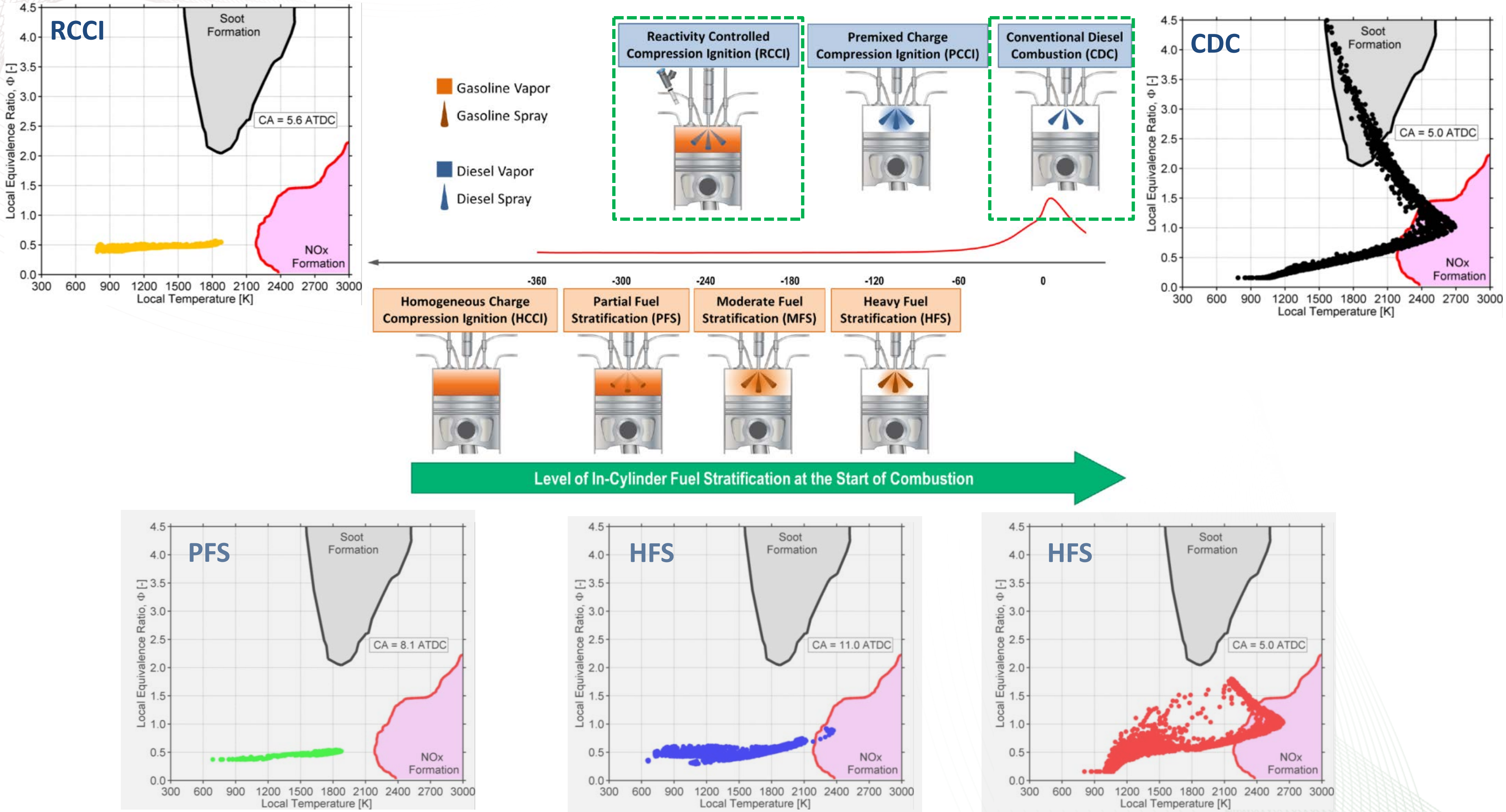


Dempsey et al., “A perspective on the range of gasoline compression ignition combustion strategies for high engine efficiency and low NOx and soot emissions: Effects of in-cylinder fuel stratification” IJER http://jer.sagepub.com/content/early/2016/01/14/1468087415621805.full.pdf+html

Different LTC approaches dominated by differences in fuel/air stratification

Approach (2/3)

- **GCI landscape explored in other activities at ORNL but included here for reference**
  - CFD using KIVA3V-Release 2 – RANS Simulations with a Lagrangian Drop/Eulerian Fluid Framework



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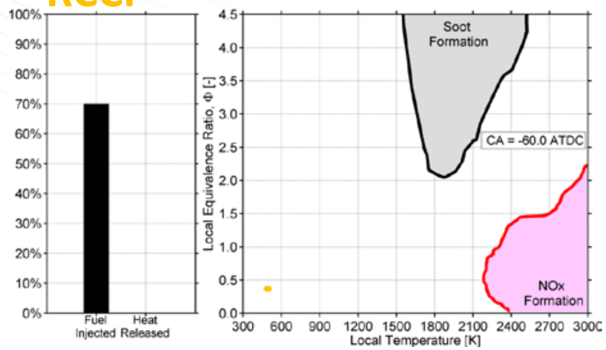
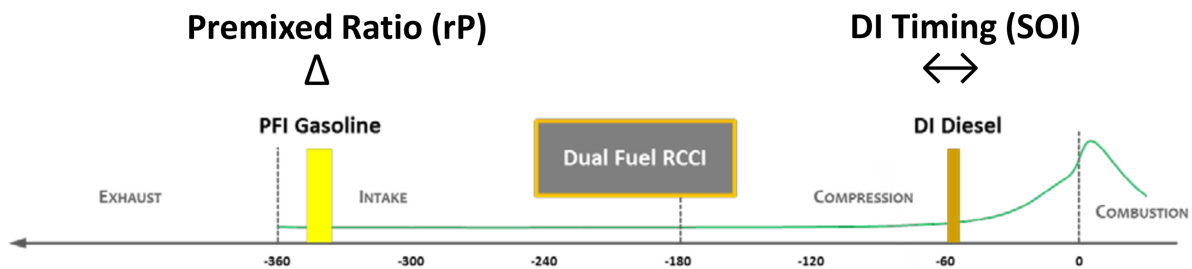
Reactivity Stratified Combustion Development

Approach (3/3)

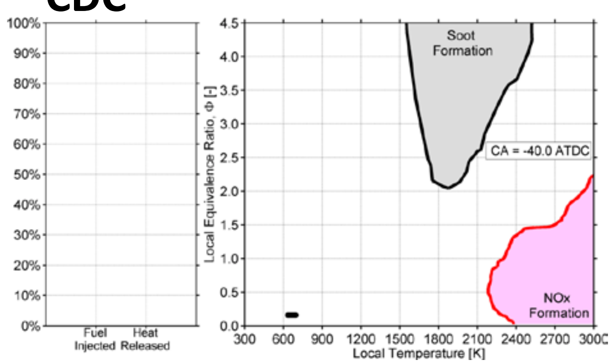
- **Current focus on dual-fuel RCCI as a way of adding additional control for tailoring reactivity in cylinder**
  - **Combustion timing control through ratio of the two fuels**
  - Wide operable load range achievable due to **different autoignition characteristics of two fuels**
    - **Current focus on high delta RCCI (i.e. gasoline/ diesel)**
  - Fuel stratification level ~ PFS or MFS with low NOx and soot
- **Challenges still exist with full speed/load range coverage, air handling requirements, combustion efficiency at low load, and combustion noise at high load**

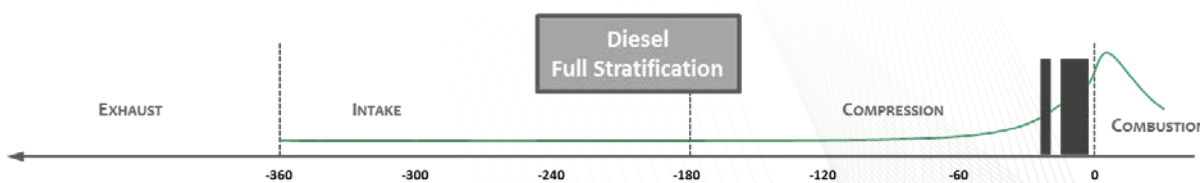
RCCI





CDC

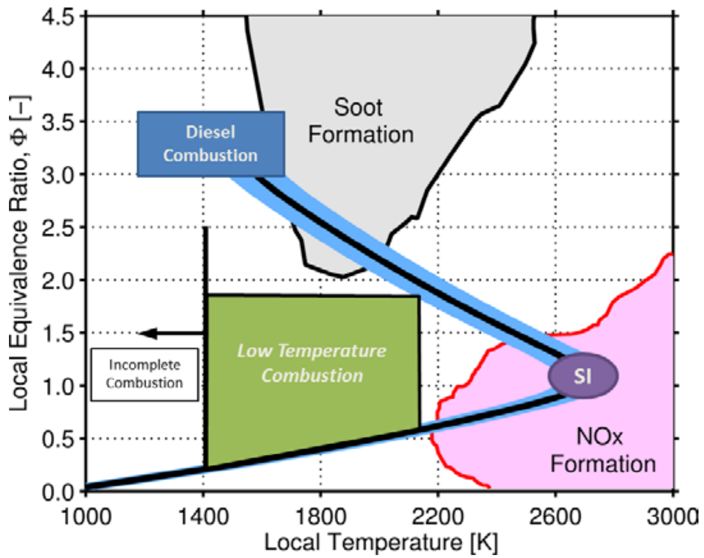




Technical Accomplishments Overview

Focus: Working within new constraints for RCCI combustion, effects on efficiency and emissions

- **Noise constrained stock piston RCCI** [Slides 10-13]
- **RCCI combustion map** [Slides 14]
- **CDC-RCCI multi-mode transitions** [Slide 15]
- **RCCI particulate matter (PM)** over transition from CDC to RCCI [Slides 16,17]
- **Thermodynamic analysis of BTE losses** using zero-order models and cycle simulations [Slides 18,19]
- **Modeled fuel economy using RCCI maps**[Slide 20]



ACE Sub Program Primary R&D Directions
(from 2015 VTO AMR Report Chapter 4*)

1. **Developing advanced combustion strategies** that **maximize energy efficiency** while **minimizing the formation of emissions** within the engine.
2. Developing **cost-effective aftertreatment technologies** that further reduce exhaust emissions at a **minimum energy penalty**.
3. **Reducing losses** and recovering waste energy.

Major goal of the ACE R&D subprogram :

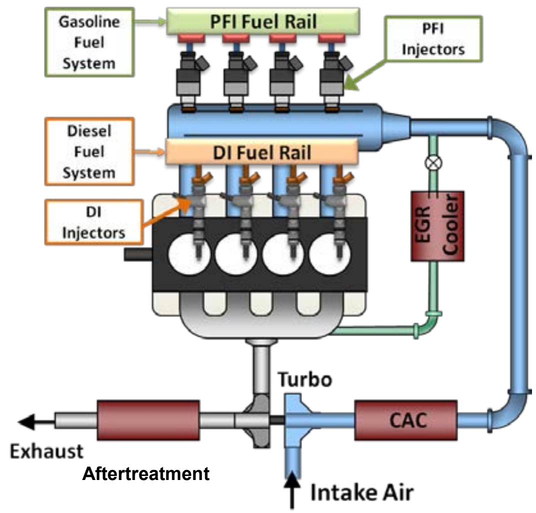
A. By 2015, …fuel economy improvements of 25% for gasoline vehicles and 40% for diesel vehicles

* http://energy.gov/sites/prod/files/2015/12/f27/04%20-%20Advanced%20Combustion%20Engines.pdf

New constraints on approach for LTC development and engine mapping using MCE platform

ACCOMPLISHMENTS (1/11)

- **1.9L GM diesel engine modified for both single- and dual-fuel LTC**
  - Stock-GM re-entrant piston used for FY 15/ 16 (premixed piston before)
  - Stock variable geometry turbocharger / high pressure loop EGR system
  - Stock DI common rail injectors: 7 holes, 140 µm holes, 148°included angle
  - PFI fuel injection system
  - Flush mount pressure transducers (PT) & fast int/exh PT (for CFD & 1D)
- **Jointly developed (ORNL/ANL) advanced combustion mapping guidelines**
  - Combustion noise high load limit (new)
  - Lower load limits of COV IMEP and exhaust temp + HC/CO
  - **US DRIVE ACEC Noise and Efficiency Guidelines followed**



ORNL Multi-Cylinder 1.9L LTC Engine

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

ORNL/ANL Mapping Guidelines

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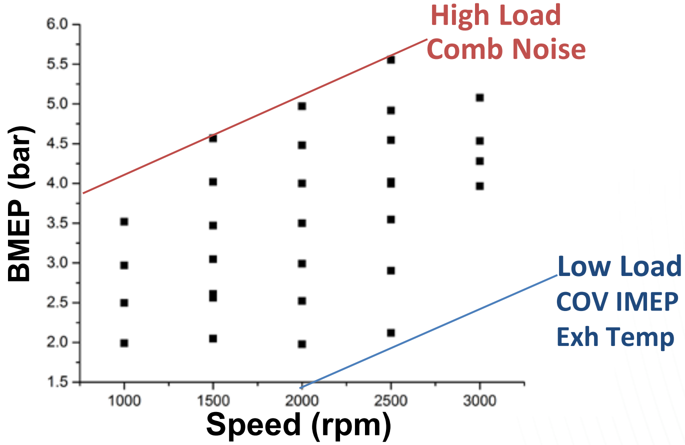
[ACE011]

Newly implemented advanced combustion guidelines co-developed by ORNL and ANL *[under continuing development]*

MCE LTC Mapping



RCCI engine operating points at every 500 RPM and every 0.5 bar BMEP

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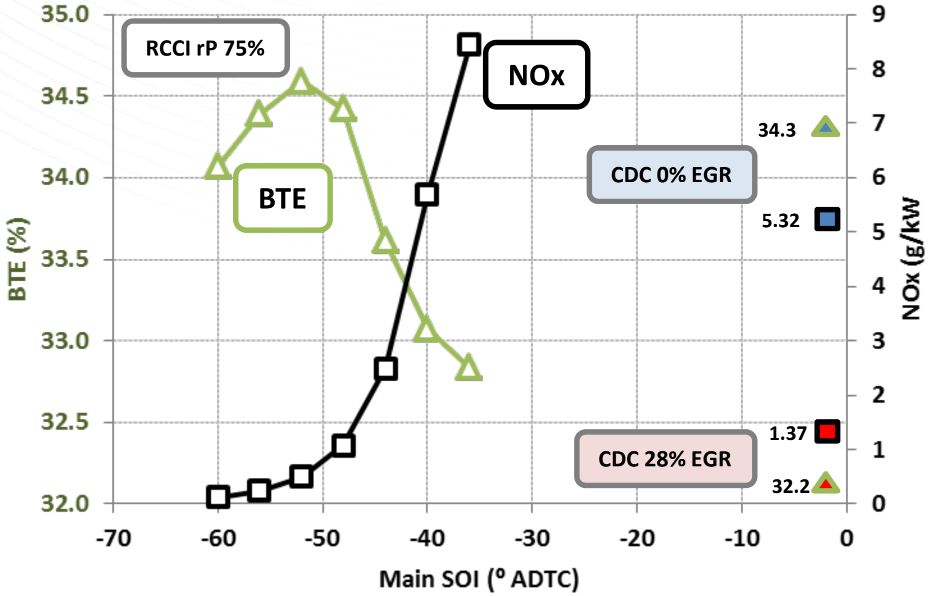
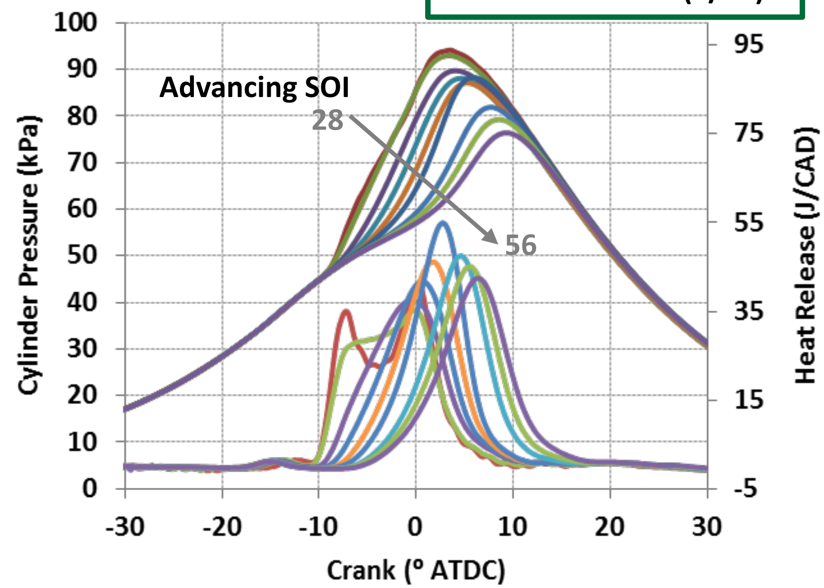
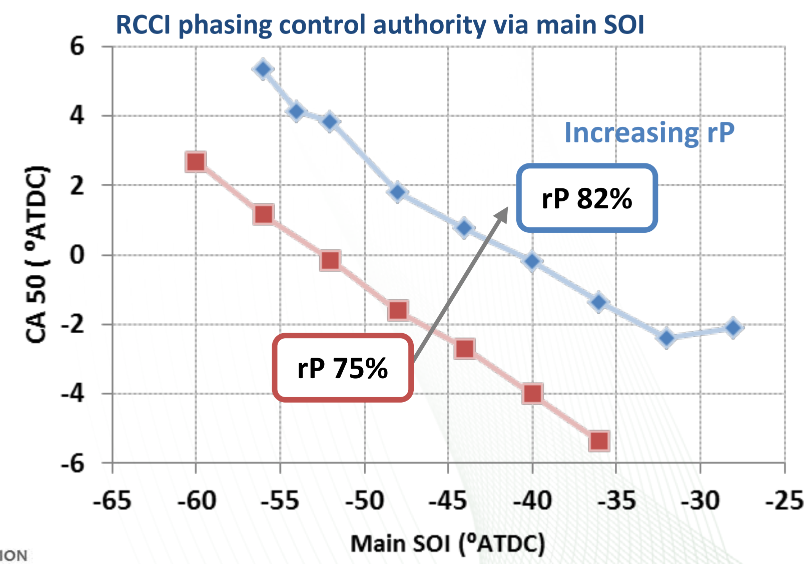
Dual-fuel RCCI provides two main controls over combustion process: DI SOI provides strong control authority over phasing

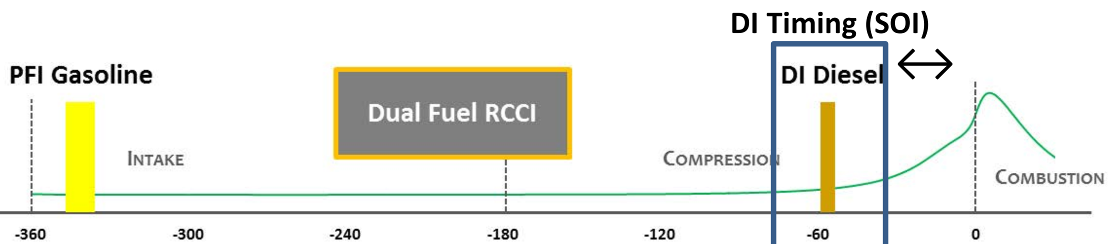
ACCOMPLISHMENTS (2/11)

- **2000rpm, 4.0bar RCCI SOI Sweep**
- **82% and 75% premixed ratio (rP)**
  - Combustion noise Limit = 89 dB
  - Target NOx = 0.3g/kw-hr or lower
  - High BTE point does not equal low NOx point
- **Control ~0.32º phasing / SOIº**









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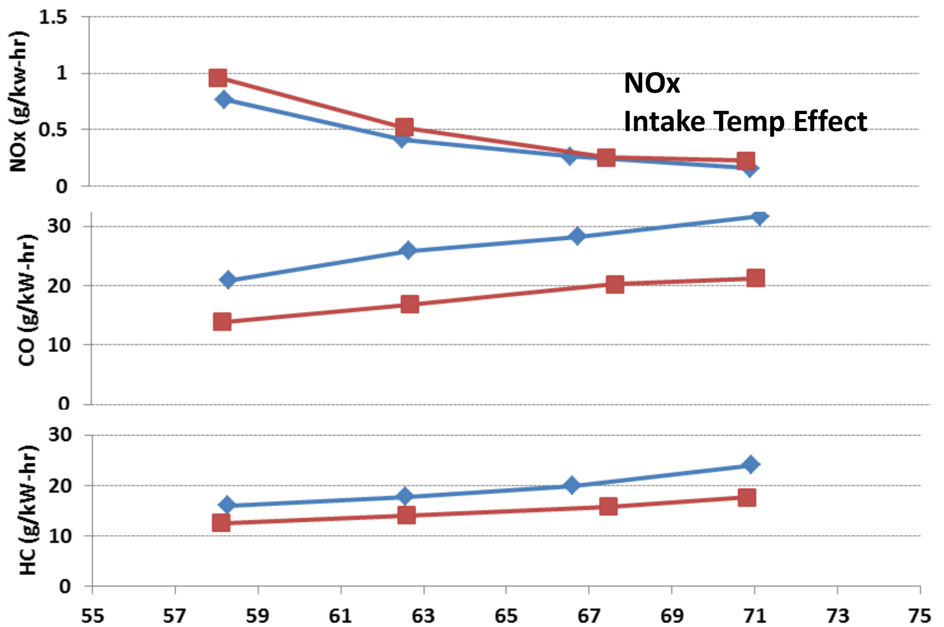
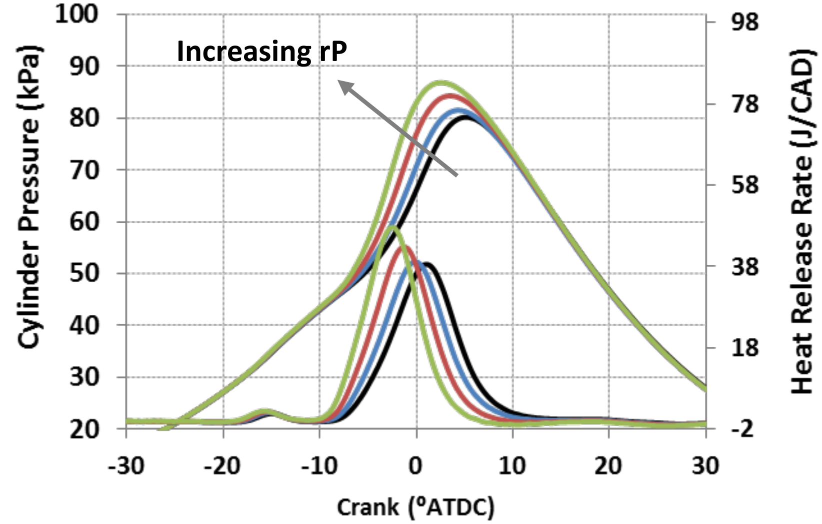
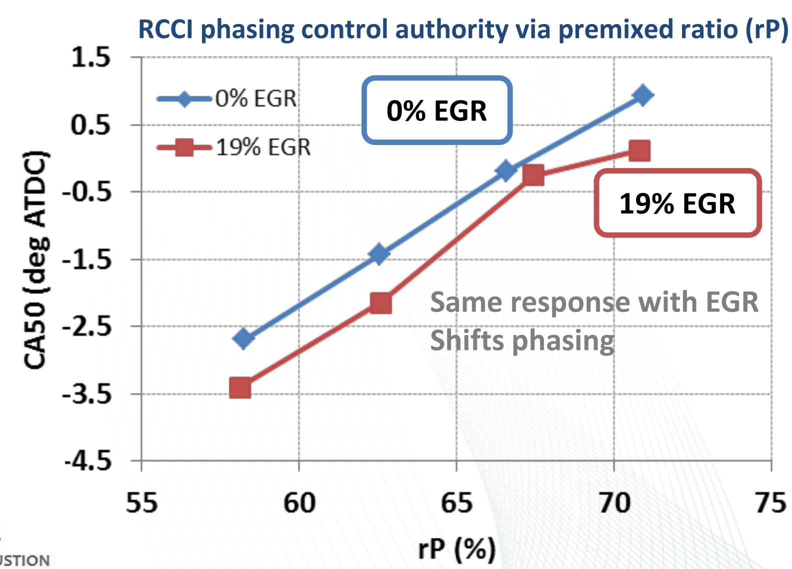
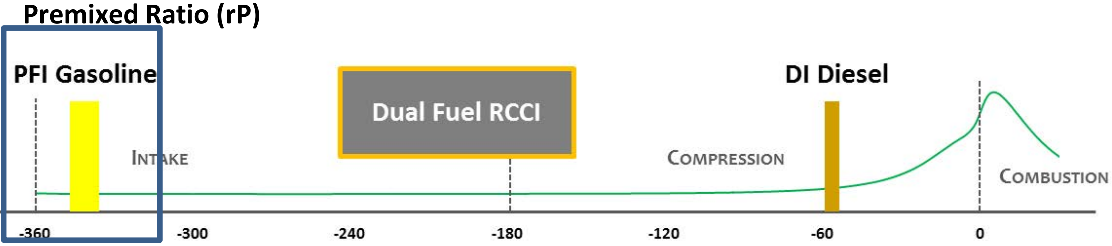
Dual-fuel RCCI provides two main controls over combustion process: Ratio of two fuels also provides timing control

- **2000 rpm, 3.0bar BMEP rP sweep,**
- Fixed Main SOI = -48° ATDC
- 2 EGR levels – intake temp climbed
  - 0% EGR, Global Phi = 0.29
  - 19% EGR, Global Phi = 0.38
- **Control ~0.29° phasing / %rP**









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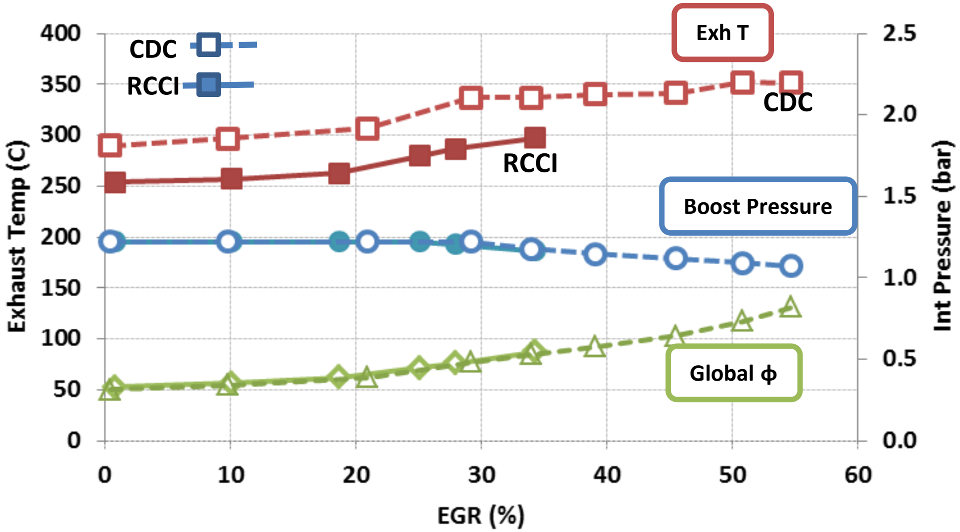
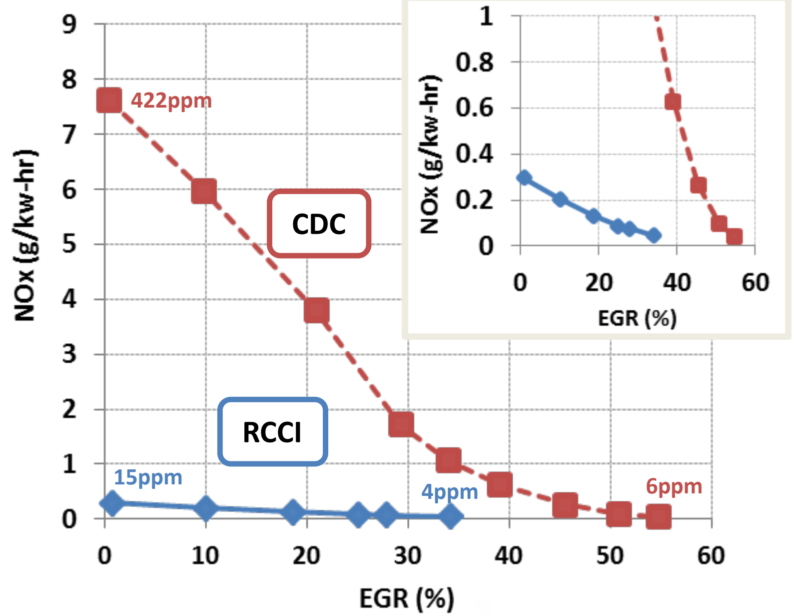
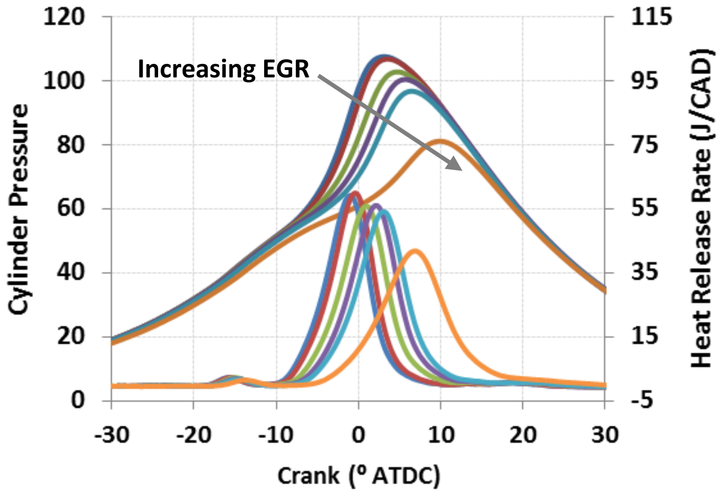
Limitations of stock air handling system

Accomplishments (4/11)

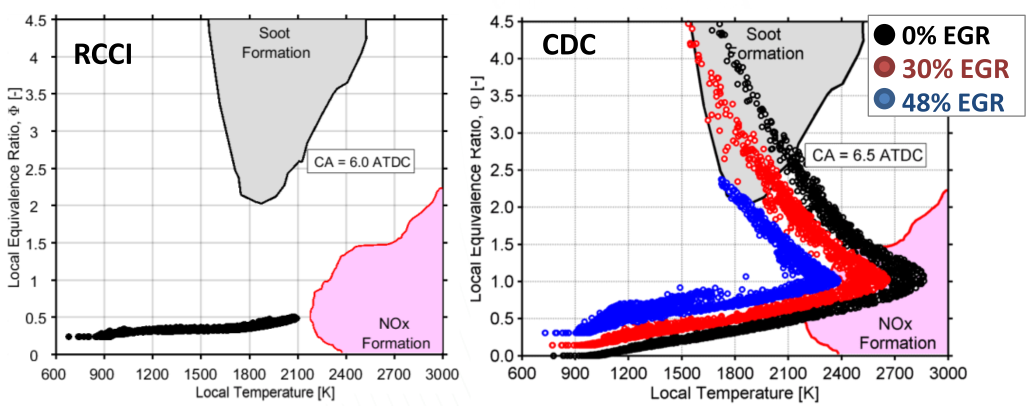
- **2000 rpm, 4.0bar EGR sweep for RCCI and CDC**
  - Try to maintain boost pressure of 1.22 bar abs







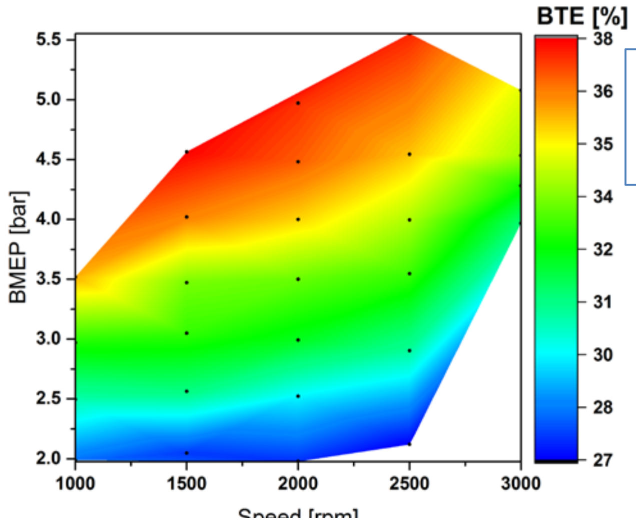
Phi-T plots illustrate NOx avoidance with RCCI without high EGR



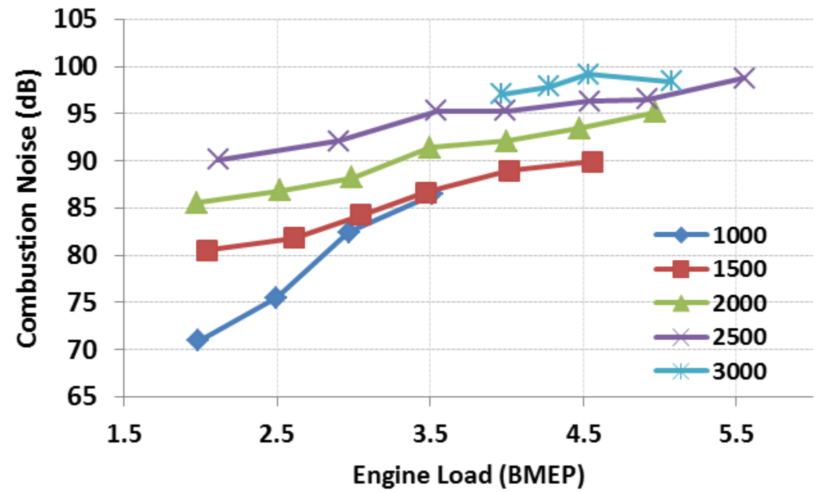
RCCI mapping with combustion noise constraints using production viable hardware

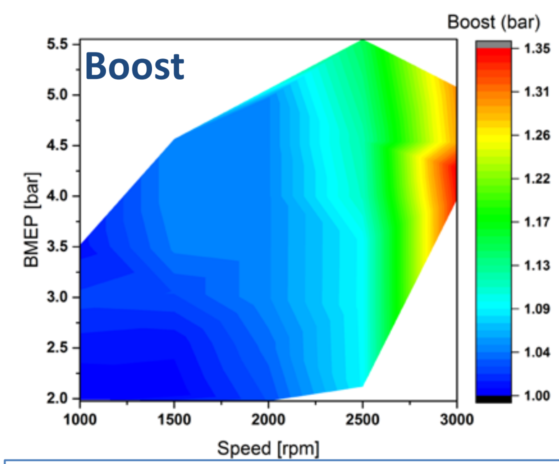
Accomplishments (5/11)

- Full maps used in vehicle systems simulations for estimating fuel economy
- Mapping results shared on CLEERS Database [ACE022]

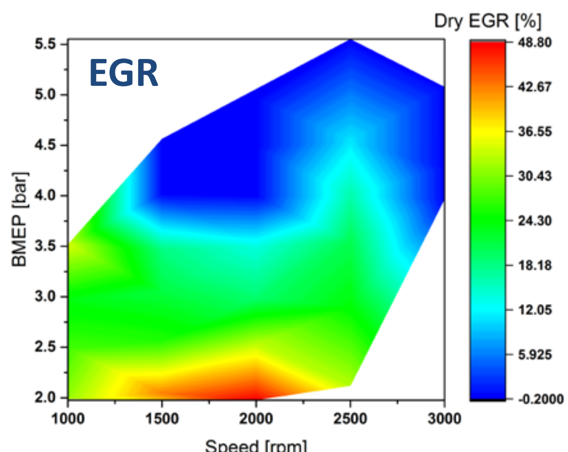


Fy 15 Map up to 7% improvement over CDC

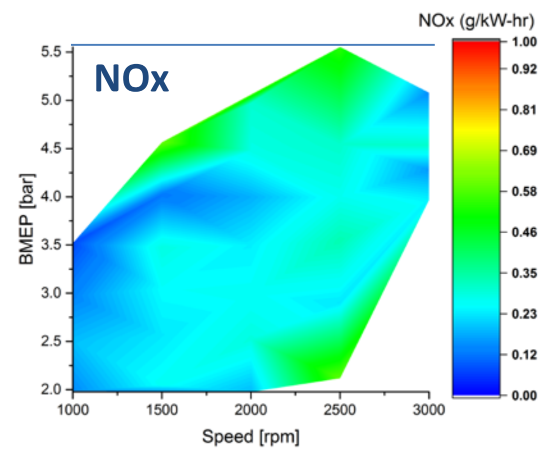




Low boost used to minimize pumping losses



Higher EGR % compared to previous maps



Much of map near or < 0.25 g/kw-hr NOx

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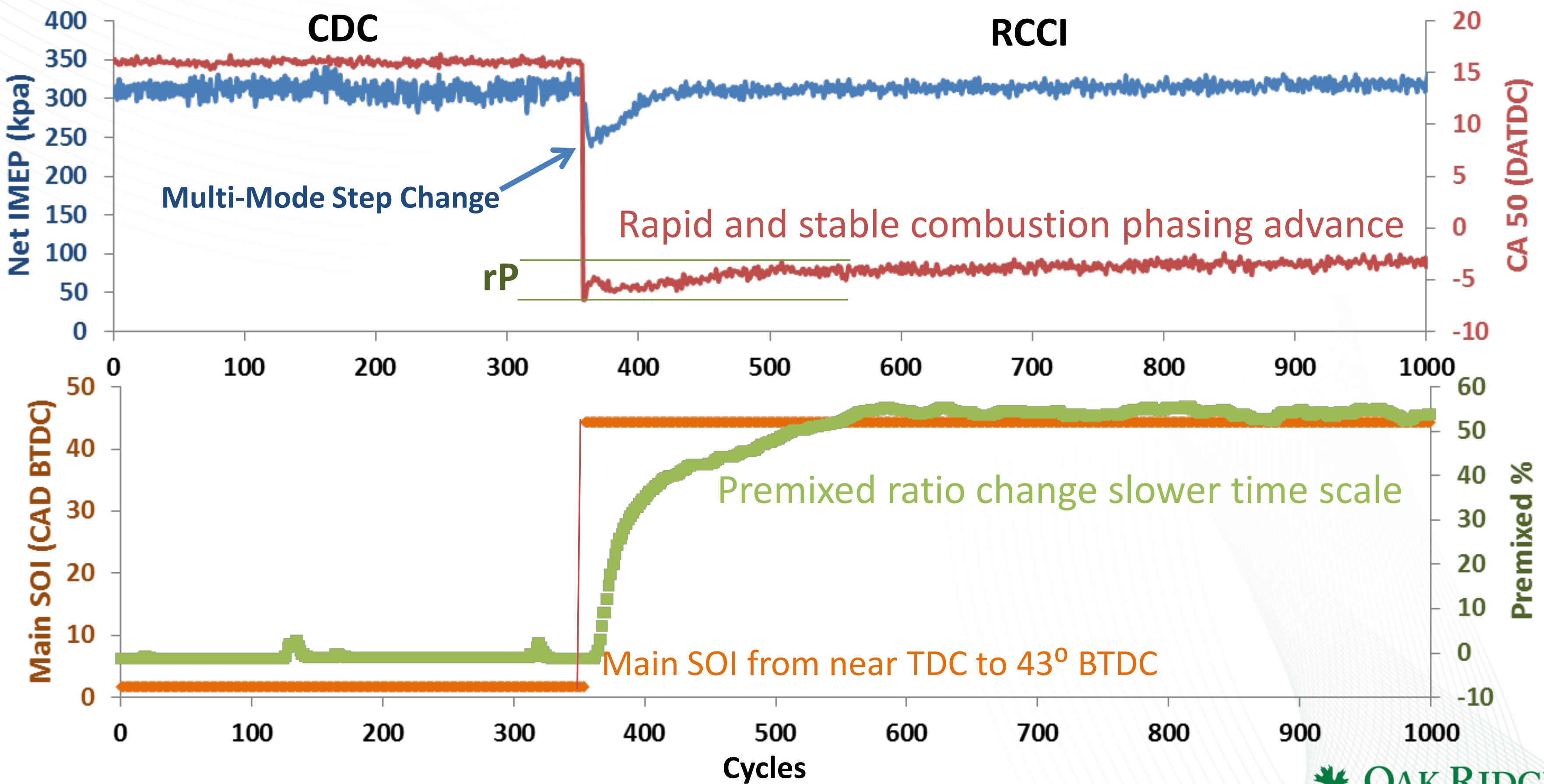
Stock pistons allows for more realistic multi-mode transitions compared to previous results

- **Mode switching experiments for CDC to RCCI and RCCI to CDC enabled w/ stock pistons**
  - Provides additional data for multi-mode model development for FY 16 Q4 milestone
- **Development for transient HIL experiments currently underway (backup slide)**

CDC – RCCI Mode Switch at 2000 RPM, 2.0bar BMEP (good example of transition point)



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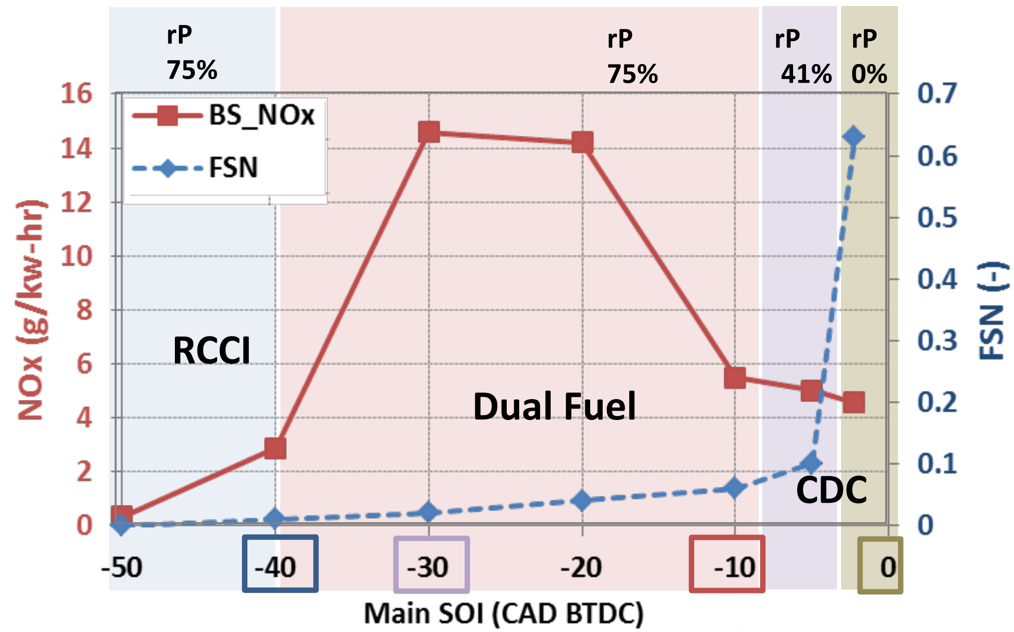
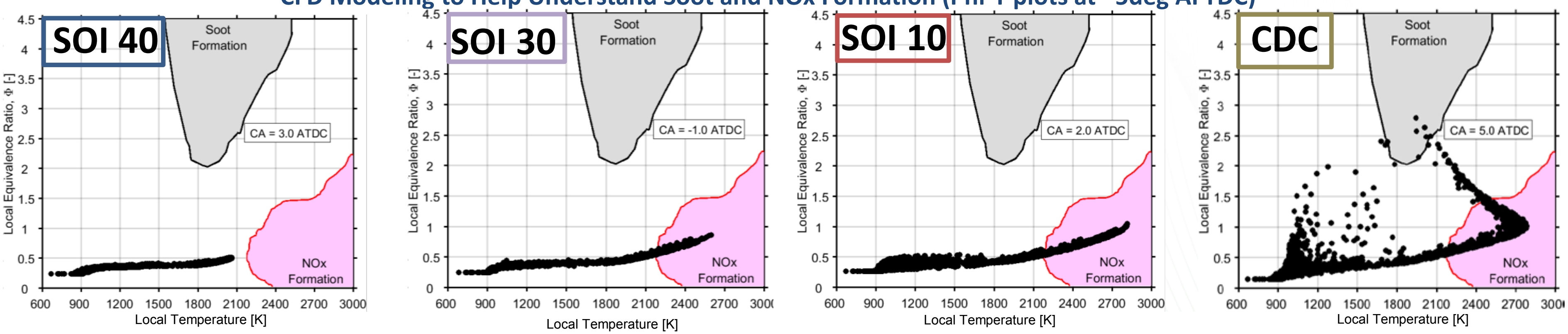
Particulate size distribution and CFD results help to further understand nature and formation of RCCI PM not captured in FSN

- Transition from CDC to RCCI across SOI sweep for 2000 RPM, 4.0BAR BMEP
  - RCCI point 75% UTG-96/ULSD (rP) @ SOI = 50^{o} BTDC (note SOI 5 needed to drop to 41% rP) (Cyl P and AHRR in backup)



CFD Modeling to Help Understand Soot and NOx Formation (Phi-T plots at ~5deg AFTDC)



KIVA3V-Release 2 – RANS Simulations with a Lagrangian Drop/Eulerian Fluid Framework

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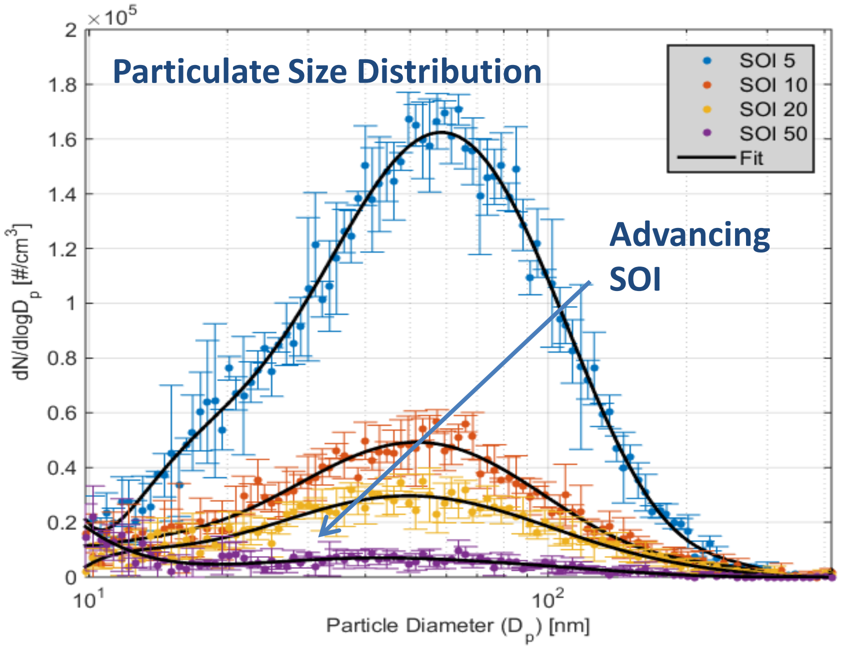

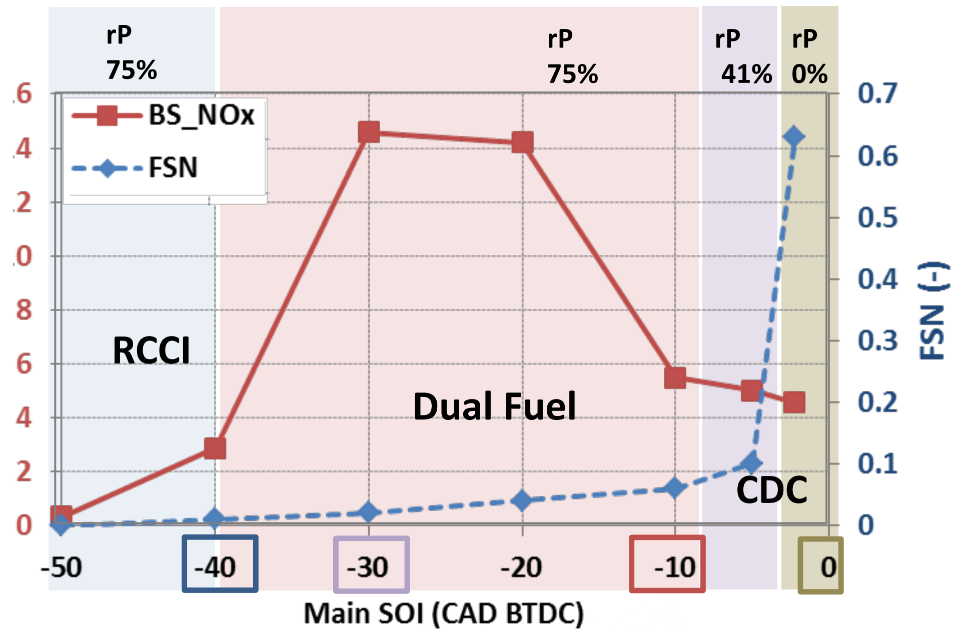

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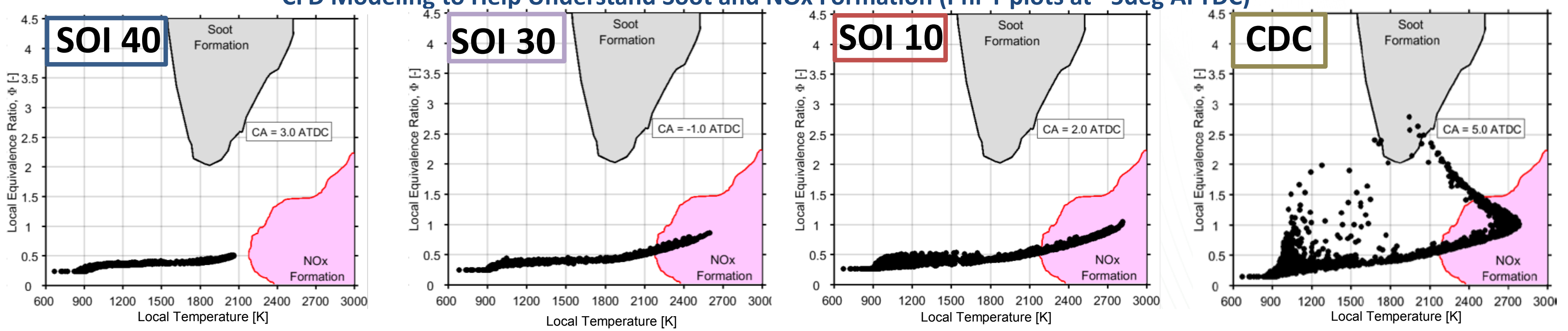

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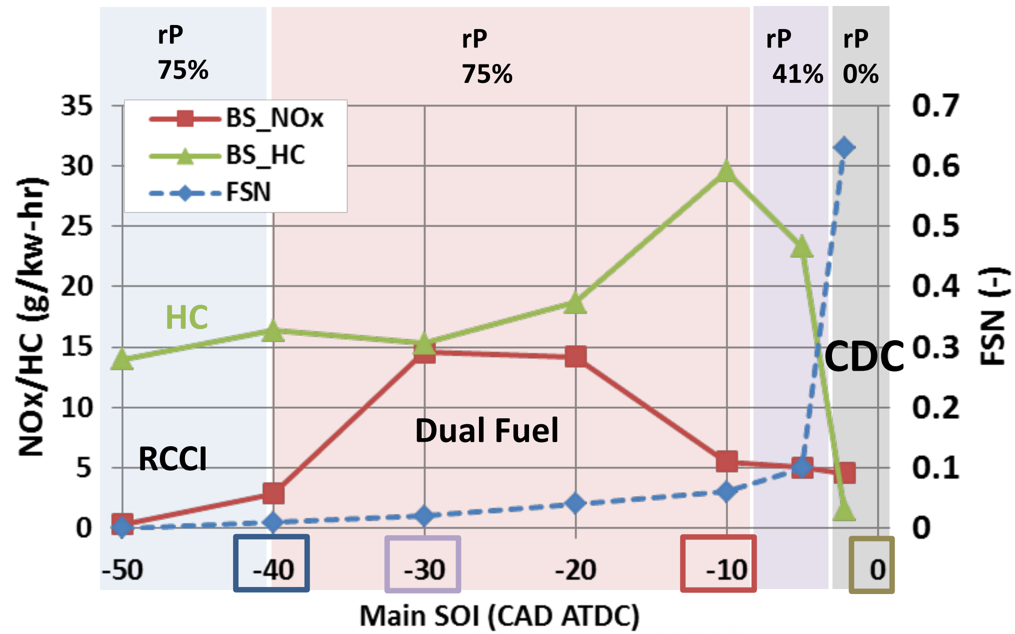

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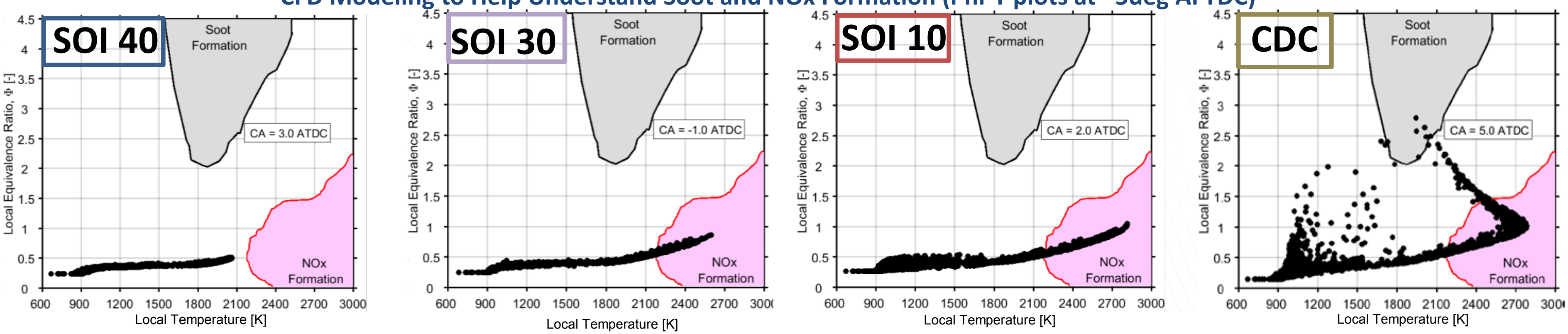

KIVA3V-Release 2 – RANS Simulations with a Lagrangian Drop/Eulerian Fluid Framework

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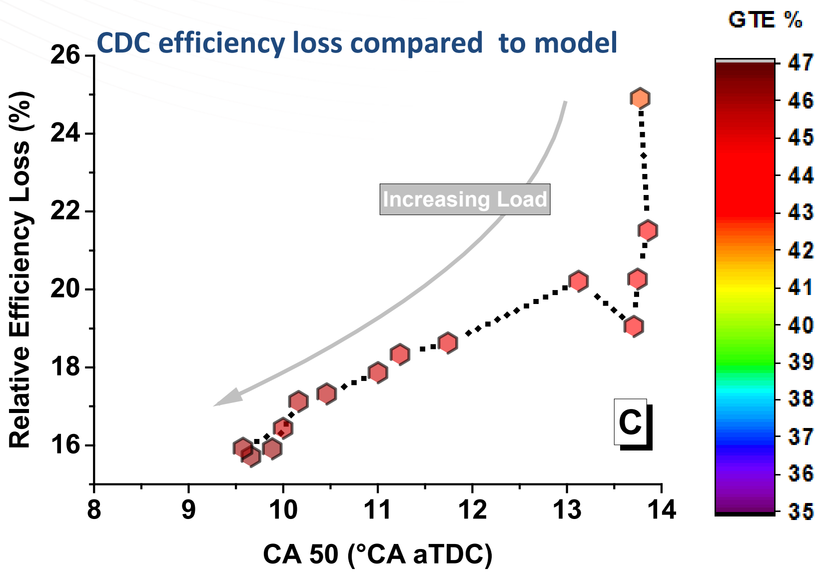
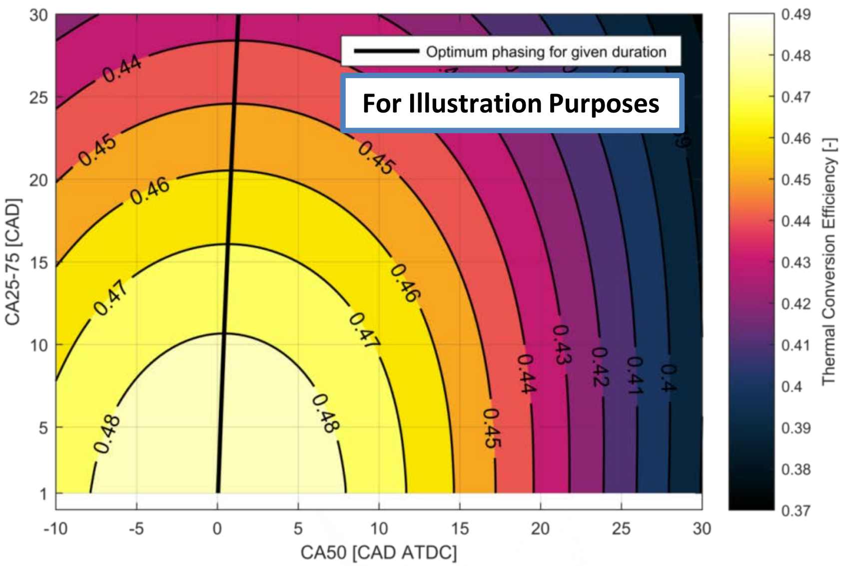
Comparing fundamental thermodynamic underpinnings of combustion strategies to gain insights into loss mechanisms

- Comparative analysis between measured and modelled efficiency illustrate fundamental sources of efficiency reductions or opportunities inherent to various combustion regimes
  - Examine the measured efficiency in context of what is thermodynamically possible with the working fluid and boundary conditions prescribed by a strategy
  - Accounting for real combustion, molar expansion, heat transfer, DI injection effects



Incomplete combustion losses and **heat transfer losses both go down as load increases**

More realistic approach to determine max eff.
Constant gamma, zero combustion duration, no molar expansion effects captured (vs. Otto Cycle)

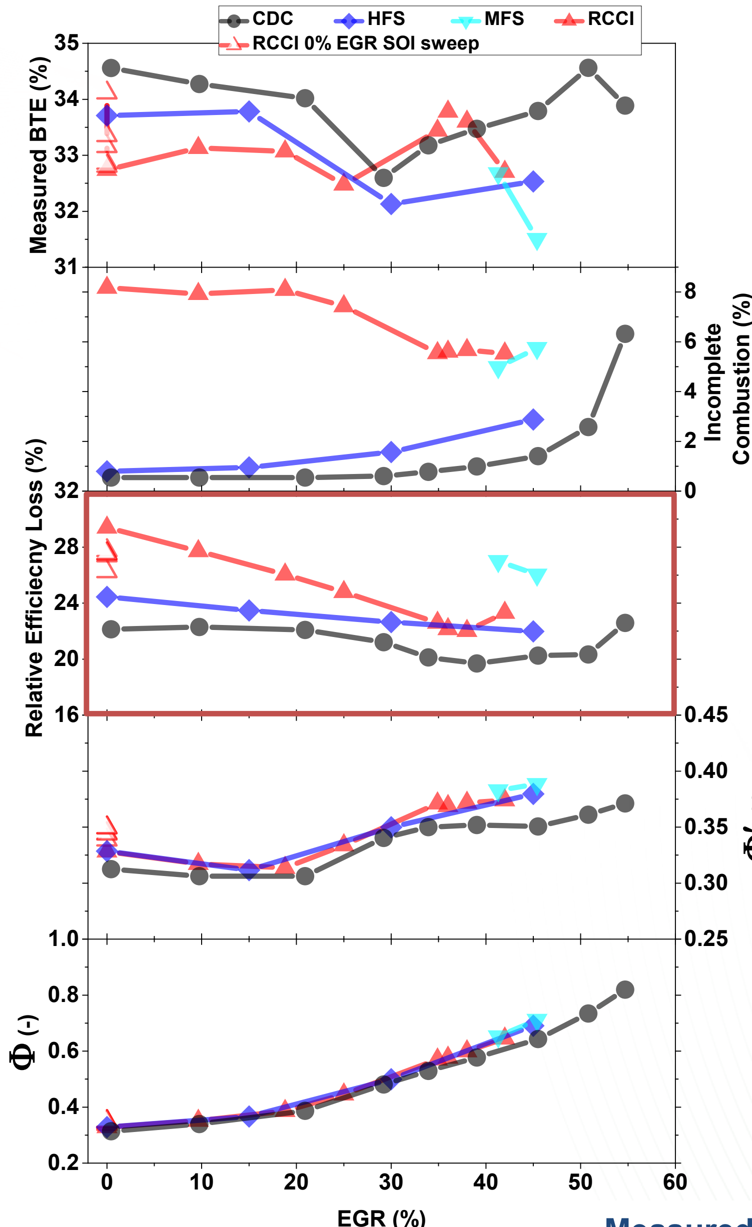


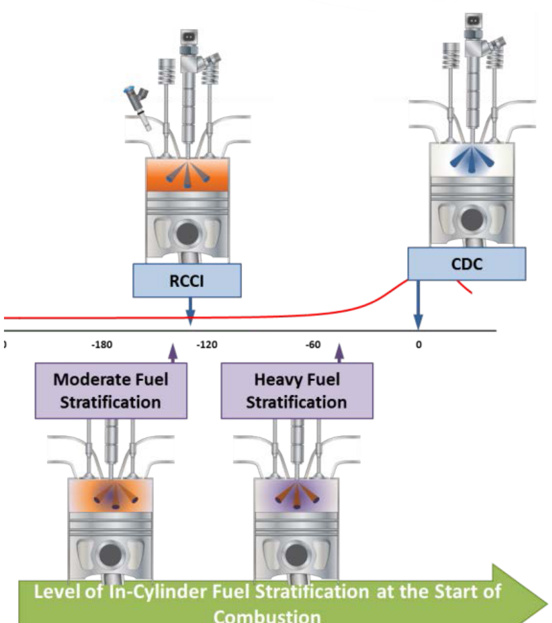
Contour plot of thermal efficiency as a function of combustion duration and phasing for a stoichiometric mixture of iso-octane and air

- **9.2 compression ratio 0% EGR**

Thermodynamic losses for dual-fuel LTC, single-fuel LTC, CDC 2000rpm, 4.0bar EGR Sweep (air handling is key)

- **EGR Sweep trying to maintain constant intake pressure**
- Along with cycle simulations (backup), this approach being used to investigate path forward on air handling systems
- Results to be presented at Thiesel and AEC
  - Back up slide with additional findings





Boost increase makes PMEP kick up, can't move boost and EGR, makes Φ' constant

Highly premixed strategies increase incomplete combustion (ring pack crevice and overly lean regions)

Losses in HX and inc. comb. matter in LTC, CDC is flat as model predicted
(HX losses are not changing, spray/bowl interaction driven?)

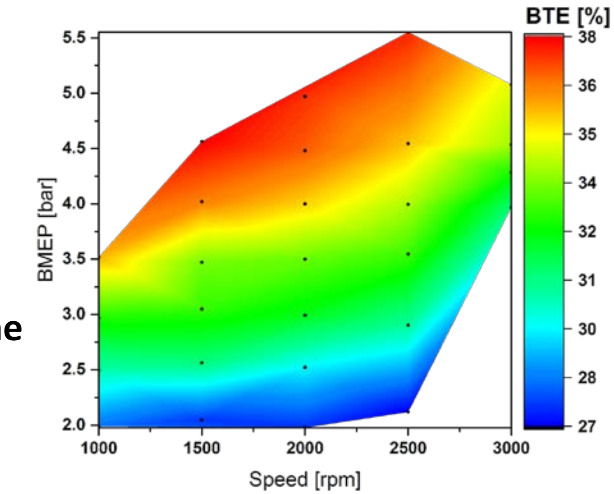
Maintaining charge mass (constant Φ') with the addition of EGR, makes model predicted GTE flat

Charge dilution (constant Φ) with the addition of EGR, makes model predicted GTE flat

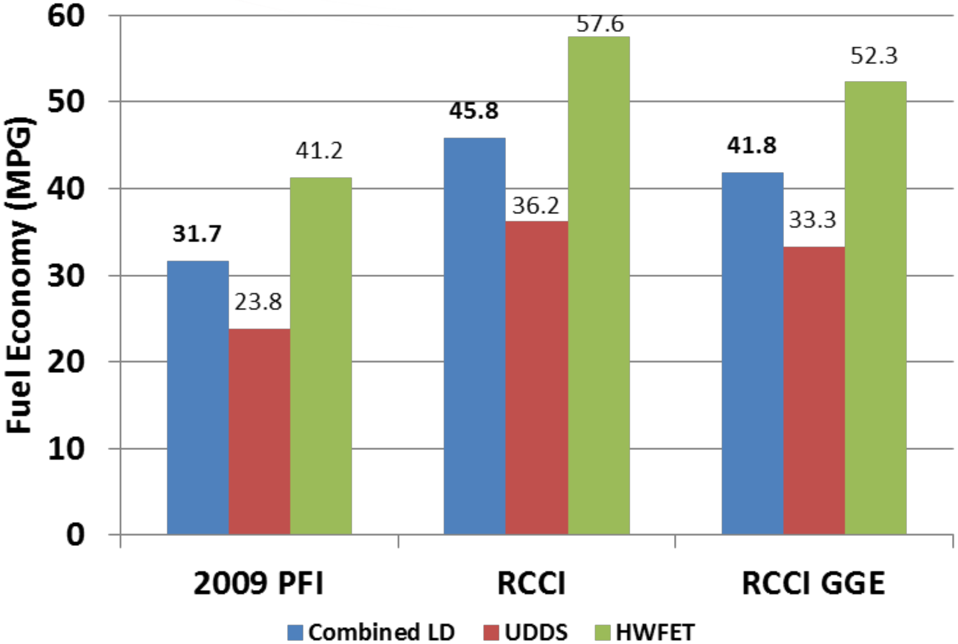
BTE from RCCI engine mapping translated to drive cycle fuel economy using vehicle systems simulations (30% improvement)

ACCOMPLISHMENTS (11/11)

- **RCCI fuel economy improvements despite lack of complete drive cycle coverage (Further development possible)**
  - **UDDS = 44.9% drive cycle coverage by distance**
  - **HWFET = 47.6% drive cycle coverage by distance**
  - **Estimated amount of gasoline/ diesel carried on board**
- **Modeling results showed >30% improvement** in combined gasoline energy equivalent fuel economy with RCCI compared to **2009 PFI baseline**
  - New to FY 16, comparison to 1.6L turbo-GDI
- **Supported by VSS support task**



Modeled Fuel Economy over US Light Duty Drive Cycles



Modeled Fuel Economy Improvements with RCCI Compared to 2.7L 2009 PFI (matched 0-60 time)

% Modeled Fuel Economy Improvement With RCCI	RCCI MPG	RCCI MPGGE
Combined Cycle*	**+ 44.7%**	**+32.2%**
UDDS (city)	+51.8%	+ 39.8%
HWFET (highway)	+39.7%	+ 26.8%

*Combined cycle = 55% UDDS, 45% HWFET)

Results compared to 1.6L turbo-GDI show RCCI provides > 26% fuel economy improvement (>12% on GGE basis)

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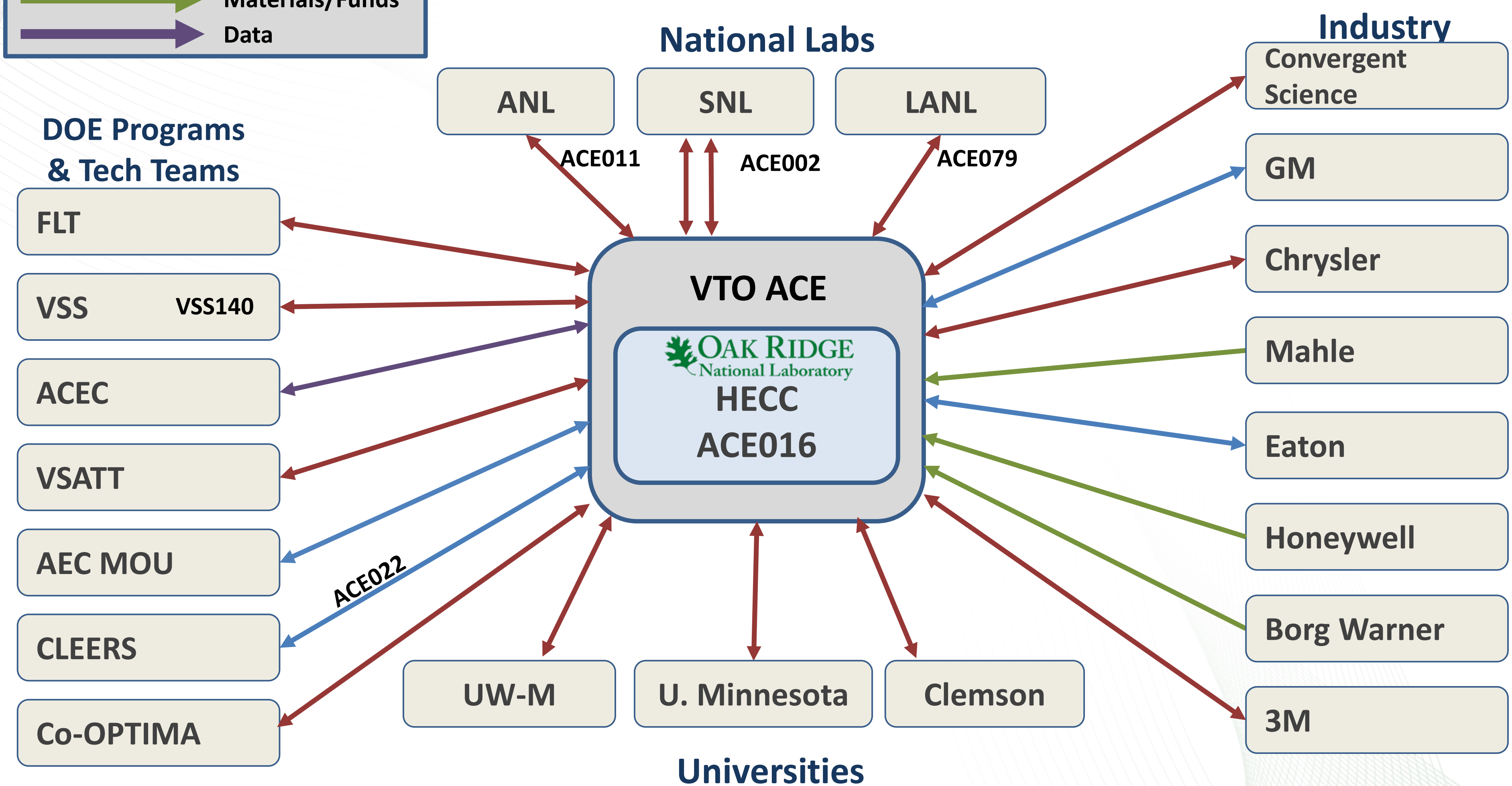
ACE projects leverage resources and expertise across industry, universities and DOE programs to meet these objectives

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

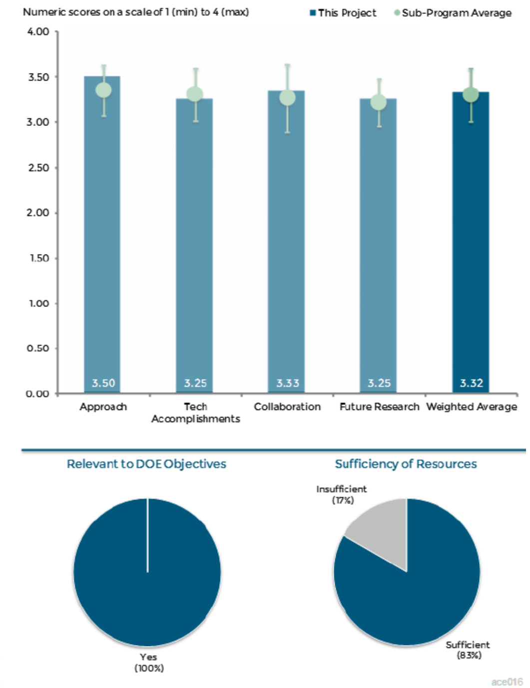


More details in backup slide

Reviewer Comments from FY 2015 – ACE016 - HECC

REVIEWER COMMENTS

Addressing significant Questions/ Recommendations



–**Reviewer noted that work towards evaluating transient control capabilities of RCCI should be accelerated**
- Agreed and effort has been accelerated

–**Reviewer noted that no data is given of soot and suggested that it would valuable to understand the soot-NOx tradeoff and what optimization has been done**
- A slide dedicated to the soot/NOx tradeoff going from CDC to RCCI has been added including particulate size distributions

–**Reviewer noted that the FY 15 AMR results showing UW RCCI hybrid vehicle collaboration were interesting, but not realistic for what vehicles will operate like**
- The importance of that collaboration was in gaining access to a vehicle that had a RCCI enabled engine – series hybrid easiest implementation

Positive Comments

- **Reviewers noted “The approach has been outstanding throughout the years toward integrating research level activities in high efficient combustion strategies to multi-cylinder engine and then eventually into a LD Vehicle”**
- **A reviewer noted that it was “commendable that the ACEC noise and efficiency recommendations are being followed.”**
- **Reviewers noted that” the technical accomplishments have been outstanding especially in assessing the possibility of using RCCI in powerplant”**

Comments cited above were paraphrased as appropriate from 2015 Annual Merit Review document http://energy.gov/sites/prod/files/2015/12/f27/04%20-%20Advanced%20Combustion%20Engines.pdf ,

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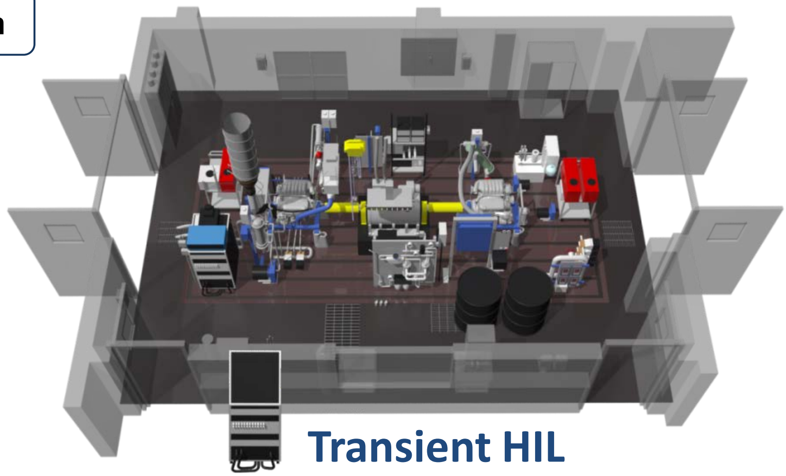
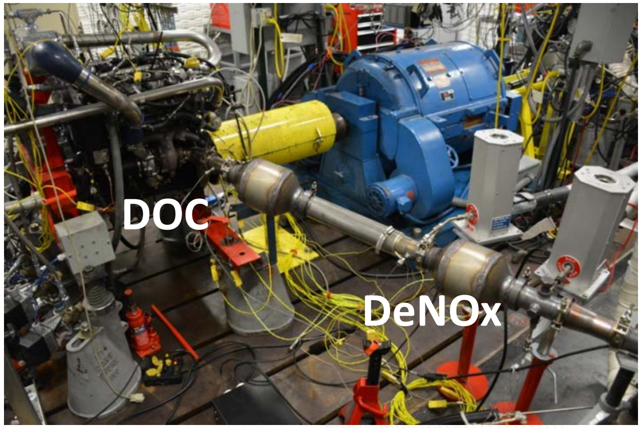
Remaining Challenges and Barriers

CHALLENGES/ BARRIERS

Remaining challenges and barriers being addressed in three year plan

- **Transients:** transient LTC operation and multi-mode transients (w/ aftertreatment effects)
- **LTC development:** understanding and tailoring reactivity stratification in cylinder
- **Air-handling:** matching air handling to LTC and multi-mode strategies (1D + CFD + MCE)
- **Aftertreatments :** after-treatment synergies for allowing high engine systems efficiency
  - Lean NOx aftertreatment studies currently underway
  - Higher efficiency with lifting NOx constraint?
  - Air handling matching to help further drive down NOx
- **Dual-fuel:** challenges of dual diesel/gasoline fuel systems and aftertreatments needed for multi-mode operation (being addressed in future work)





First coupled NOx aftertreatment studies underway

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Future Work - FY 16 and FY 17 - 19

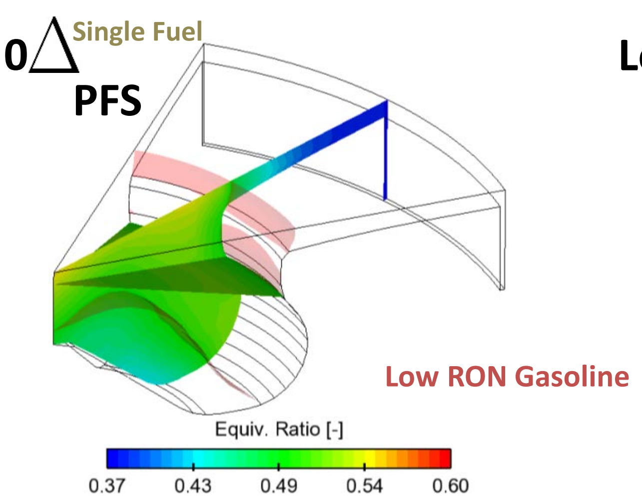
FY 16 Remainder -High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines

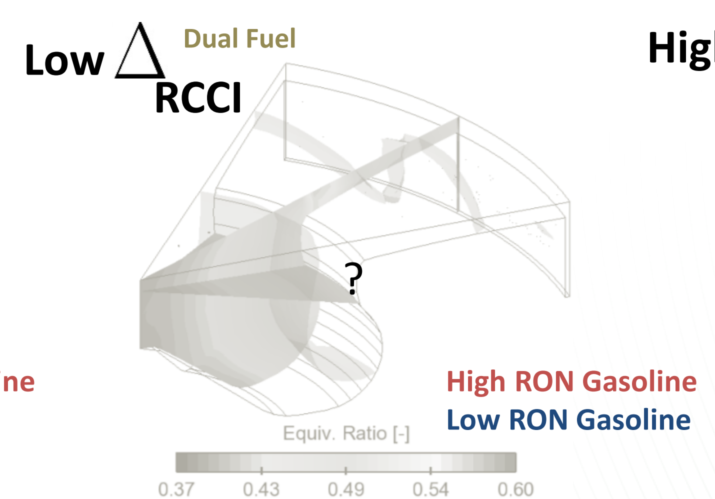
- Transient HIL experiments for FY 16 Q2/ Q3
- Q3 and Q4 DOE Milestones – RCCI/ multi-mode with stock pistons
- Collaboration with SNL on injector studies for combustion noise reduction **(ACE002 – Busch)**
  - Important with new focus on noise constraints and finding solutions that are decoupled from dilution

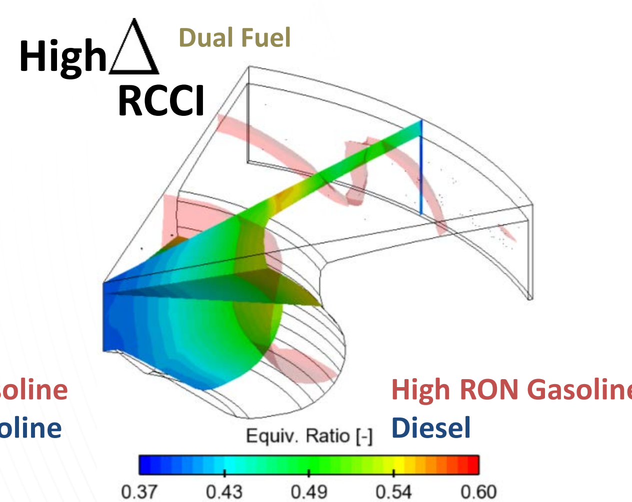
FY 17 – 19, Reactivity Stratified Combustion Development for FY 17 Lab Call 1E

Long term Objective. Develop and assess the potential of reactivity stratified combustion concepts on MCEs

- Dual-fuel/ single-fuel LTC approaches where reactivity stratification is achieved through equivalence ratio and temperature stratification
- Experiments and high-fidelity simulation of high-delta reactivity (e.g., gasoline and diesel) and low-delta reactivity (e.g., low octane and high octane gasoline) combustion







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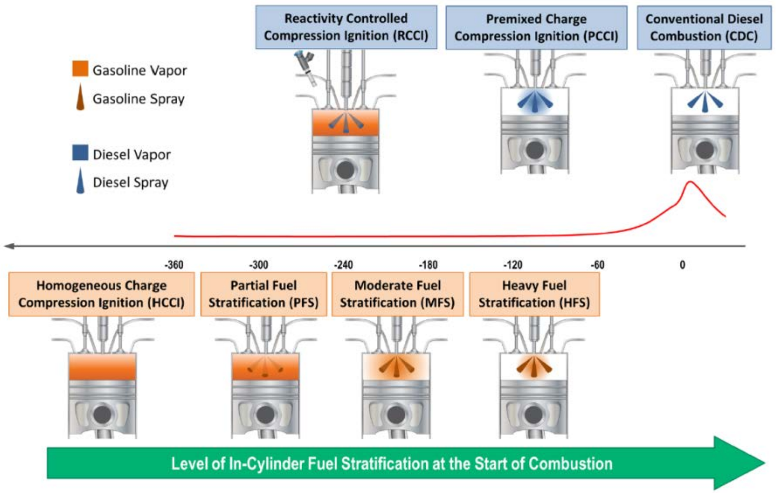
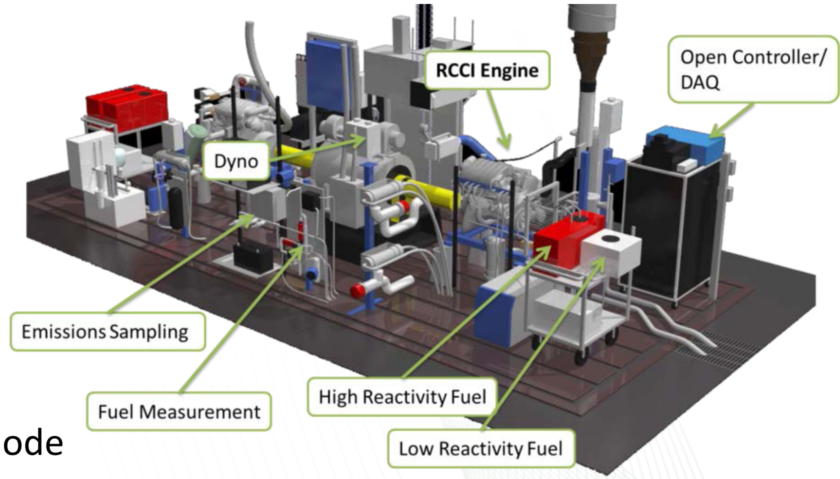
Summary

- **Relevance**
  - Results focused on implementation challenges with LTC related to VTO ACE goals to show engine system and fuel economy benefits leading to petroleum reductions
- **Approach/Strategy**
  - Multi-cylinder engine research with coupled aftertreatment integration using vehicle systems simulations, CFD and thermodynamic modeling
- **Technical Accomplishments**
  - RCCI Mapping
  - RCCI fuel economy modeling
  - Aftertreatment needs
  - PM study
  - Thermodynamic loss mechanisms
- **Collaboration and Coordination**
  - Industry and Tech Teams
  - University and National lab partners
- **Proposed future work**
  - Transient operation for advanced combustion/ multi-mode
  - FY 17 – 19 planning





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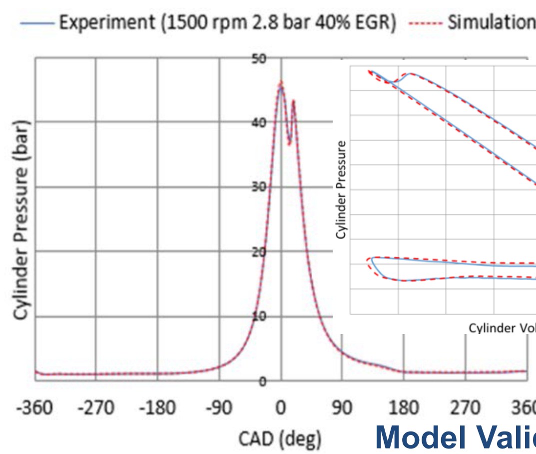
Backup Slides

Contact
Scott Curran
curransj@ornl.gov, 865-946-1522

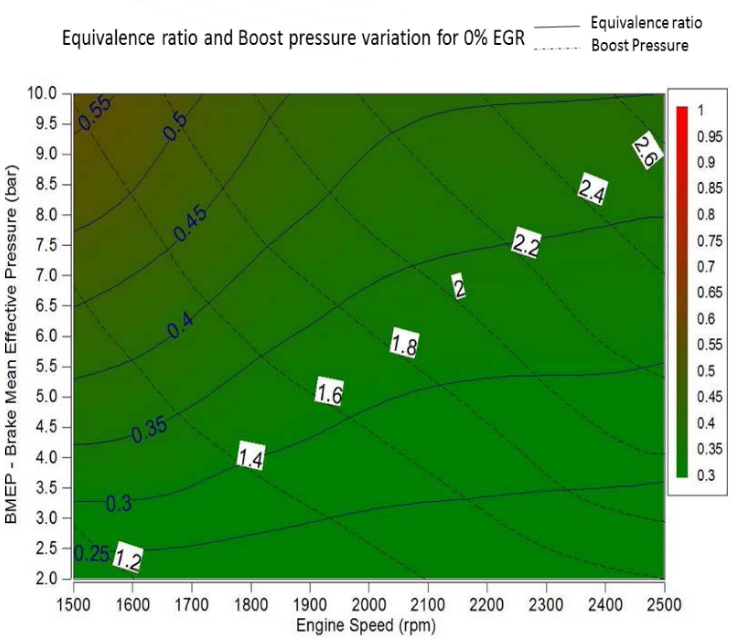
1-D cycle simulation of advanced combustion strategies focusing on air handling system efficiency (Clemson collaboration)

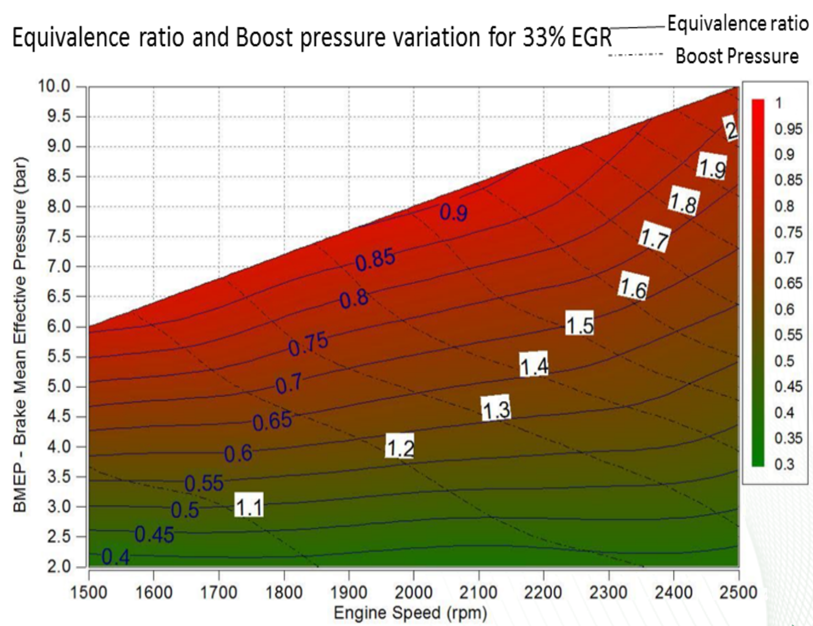
Back-Up 2

- **Validated model used to evaluate effects of options such as hybrid high-pressure low pressure EGR and advanced boosting systems**
- In case of LTC, the lower exhaust temperatures current air handling systems is not be able to provide both high EGR and high boost to operate at the overall lean conditions.
  - The low exhaust temperatures of LTC affect the turbocharger efficiency increasing the pumping losses thereby lowering BTE
- **Model to be used in the evaluation of different air handling options for LTC**



Model Validation with CDC



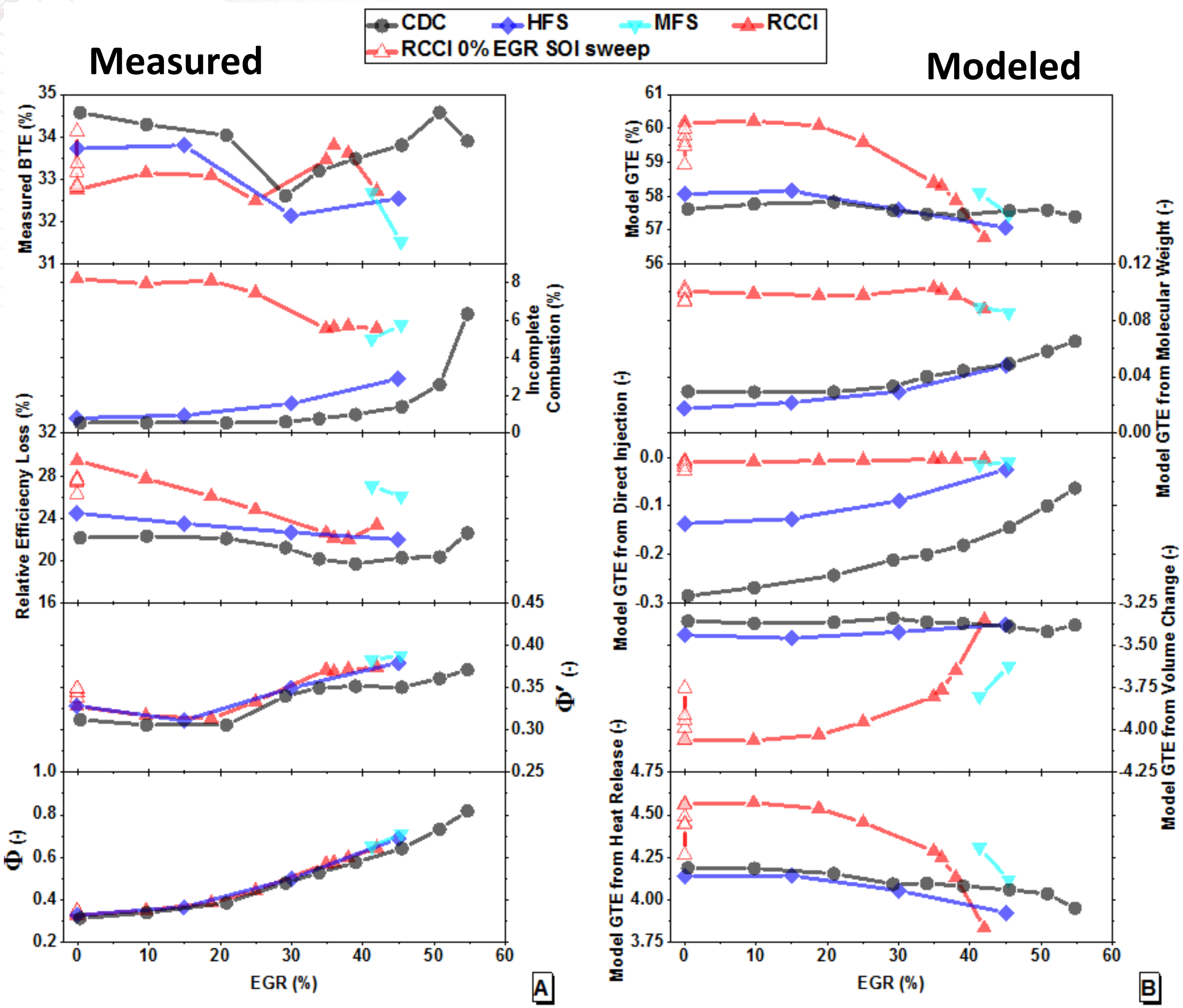


Globally stoichiometric condition is reached quickly with greater than 30% EGR.

Thermodynamic Losses for RCCI Compared Against CDC and Heavily Stratified GCI (with ~70 RON gasoline)

Back-Up 2

- (A) **Measured** trends in RCCI, GCI (MFS and HFS) and CDC as a function of EGR rate.
- (B) Model predicted trends in efficiency contributions for conditions in (A).



By independently calculating the change in pressure from each term, the impact of each on work extraction and efficiency can be determined

Equation 1.

$$\frac{\mathbf{dp}}{\mathbf{d\theta}} = \left(\frac{\mathrm{dp}}{\mathrm{d\theta}}\right)_Q + \left(\frac{\mathrm{dp}}{\mathrm{d\theta}}\right)_V + \left(\frac{\mathrm{dp}}{\mathrm{d\theta}}\right)_m + \left(\frac{\mathrm{dp}}{\mathrm{d\theta}}\right)_M$$

Equation 1.

$$\left(\frac{\mathbf{dp}}{\mathbf{d\theta}}\right)_{\boldsymbol{Q}} = \left(\frac{\gamma - 1}{V}\right)\dot{Q}$$

Equation 1.

$$\left(\frac{\mathbf{dp}}{\mathbf{d\theta}}\right)_{\boldsymbol{V}} = -\frac{\gamma p}{V}\frac{\mathrm{d}V}{\mathrm{d}\theta}$$

Equation 1.

$$\left(\frac{\mathbf{dp}}{\mathbf{d\theta}}\right)_{\boldsymbol{m}} = \left[\frac{\gamma p}{m} - \left(\frac{\gamma - 1}{V}\right)\left(h^s - h_f^s\right)\right]\frac{\mathrm{d}m}{\mathrm{d}\theta}$$

Equation 1.

$$\left(\frac{\boldsymbol{dp}}{\boldsymbol{d\theta}}\right)_{\boldsymbol{M}} = -\frac{p}{M}\frac{\mathrm{d}M}{\mathrm{d}\theta}$$

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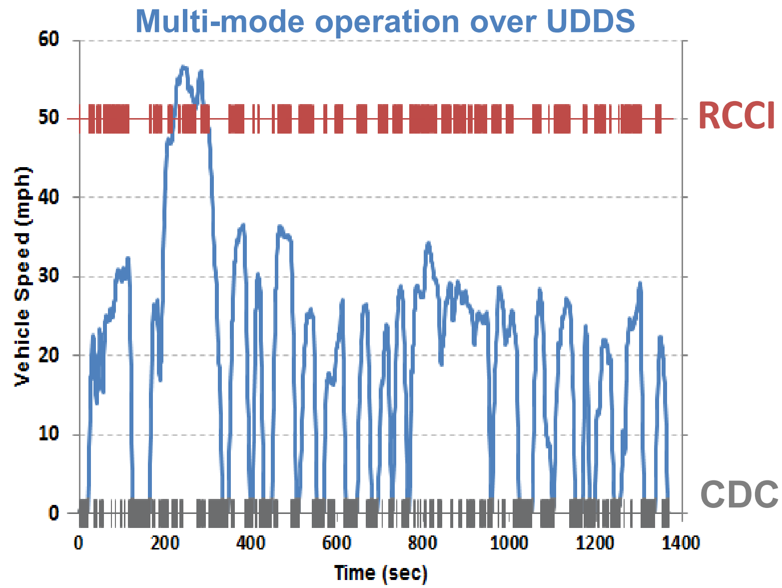
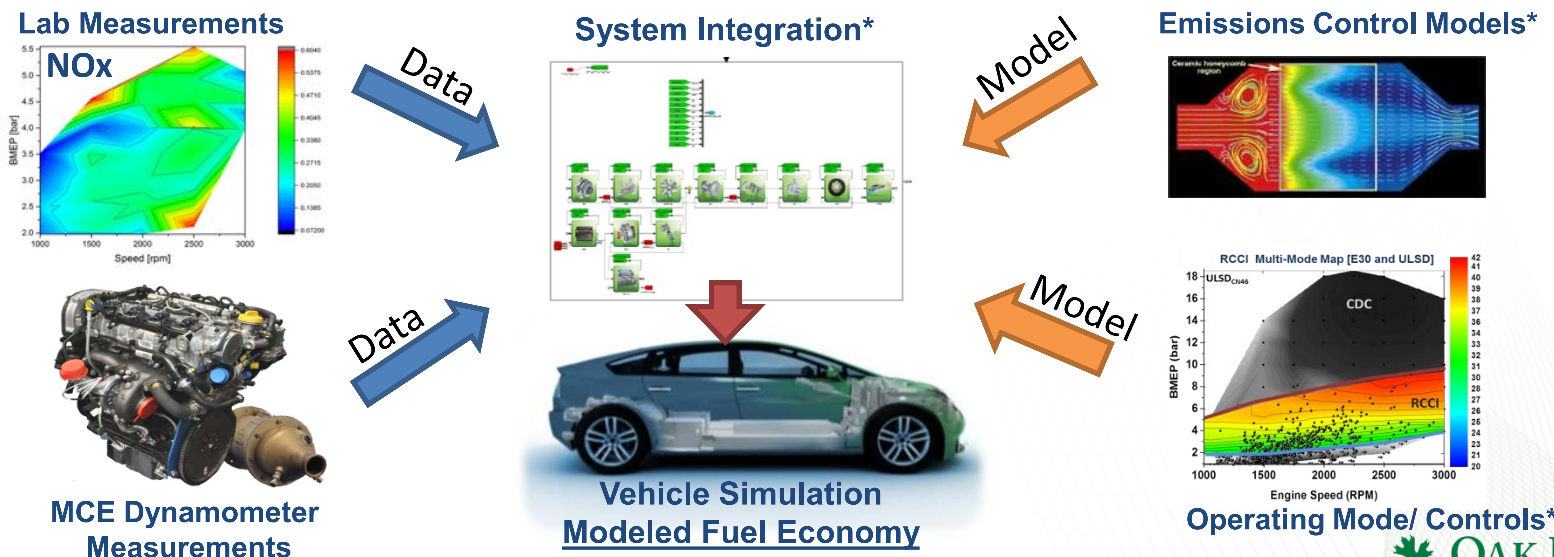
Vehicle systems simulation used to model fuel economy using MCE LTC experimental data

Back-Up 3

Drive cycle benefits and challenges for LTC in light-duty vehicles are not well understood

- **Base vehicle**
  - Mid-size passenger sedan, 1580kg, Auto. transmission
- **Engine maps based on steady state experimental data**
  - FY 15 1.9L, RCCI Map – ORNL experimental map from Q3 milestone
  - 1.9L , Diesel Map (CDC) experimental ORNL map
  - 2.7L 2009 PFI Engine map–OEM supplied production maps
  - 1.6 L turbo GDI Map – ORNL experimental map
- **Multi-mode RCCI/Diesel strategy used**
  - RCCI map covers most of light-duty drive cycles
  - Must switch to CDC mode outside of RCCI envelope (+ cold start)





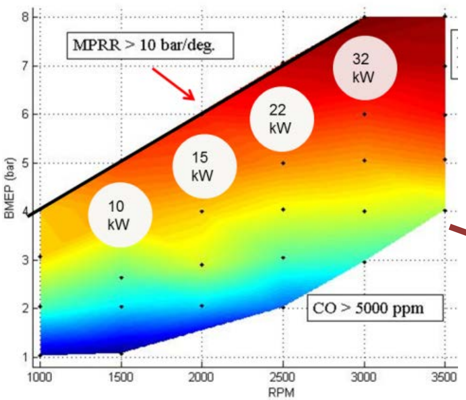
* *In collaboration with VSS support task*

UW RCCI Evaluated at ORNL (2 joint papers)

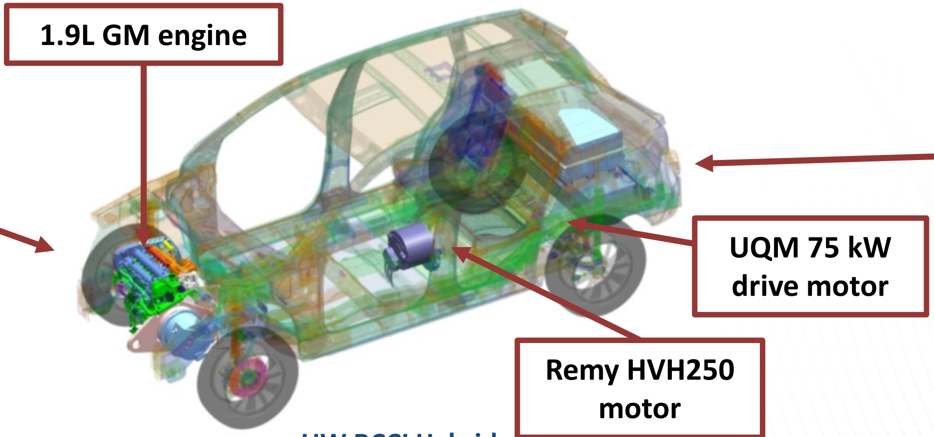
Back-Up 4

- **Series hybrid RCCI vehicle**
  - Charge sustaining mode with various power/efficiency levels
  - Collaboration with National Instruments on Controller
  - Initial chassis dynamometer testing performed at FORD
  - Leverages UW DOE AVTC vehicle from EcoCAR
- **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

UW RCCI Hybrid in ORNL Chassis Laboratory



RCCI Power Levels for Series Mode



UW RCCI Hybrid

NI Powertrain Controller

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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
  - Clemson University – Cycle Simulations for Advanced Combustion Air-handling
- **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
  - Convergent Science – 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
  - MECA – Catalysts supply and industry feedback
  - Borg Warner – Hardware and discussion of advanced air handling
  - 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
  - SNL – Discussions on LTC, Injector Noise