Gasoline-like Fuel Effects on Advanced Combustion Regimes

Project ID: FT008

<u>Jim Szybist</u>, Scott Curran, Scott Sluder,
Derek Splitter, Adam Dempsey,
and Robert Wagner

Oak Ridge National Laboratory

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<u>DOE Management Team</u>
Kevin Stork and Steve Goguen

ORNL is managed by UT-Battelle
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Project Overview

Barriers (MYPP 2011-2-15, Section 2.4, Challenges and Barriers C.)

Inadequate data and predictive tools for fuel property effects on combustion and engine efficiency optimization

Budget

	FY13	FY14	FY15
Multi-cylinder LTC	*$200*	*$200*	*$175*
High Octane	-	*$250*	*$250*
Dilute SI	*$200*	*$250*	*$250*
Total	***$400k***	***$700k***	***$675k***

Project Timeline

- ***Current fuels research program started at ORNL in 2004***
- ***Investigations have evolved and will continue to evolve with emerging research needs***

Partnerships and Collaborations with Industry, Other National Laboratories, and Universities

Industry

- ***Ford***
- ***ACEC Tech Team***
- ***GM***
- ***Chrysler***
- ***Chevron Energy Technology Co.***
- ***MAHLE***
- ***Delphi***
- ***Others***

Other Collaborations

- ***AEC/HCCI Working Group***
- ***CLEERS Working Group***
- ***University of Wisconsin***

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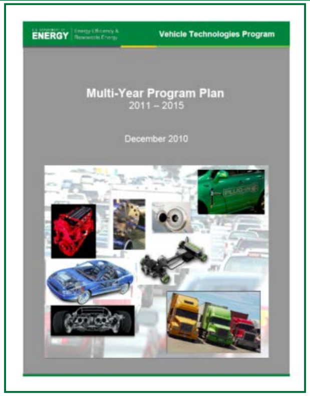
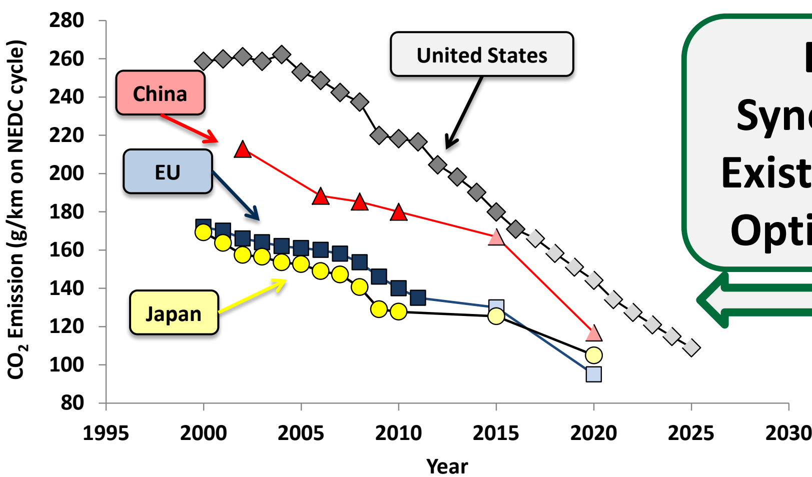
OBJECTIVE: IDENTIFY ALTERNATIVE FUELS THAT ENABLE IMPROVED EFFICIENCY AND PETROLEUM DISPLACEMENT



Goal of Fuels and Lubricant Technologies
(MYPP 2011-2015: Section 2.4.1)

"…identify fuel formulations optimized for use in light-duty advanced combustion engine regimes that provide high efficiencies and very low emissions which incorporate use of non-petroleum based blending components…"

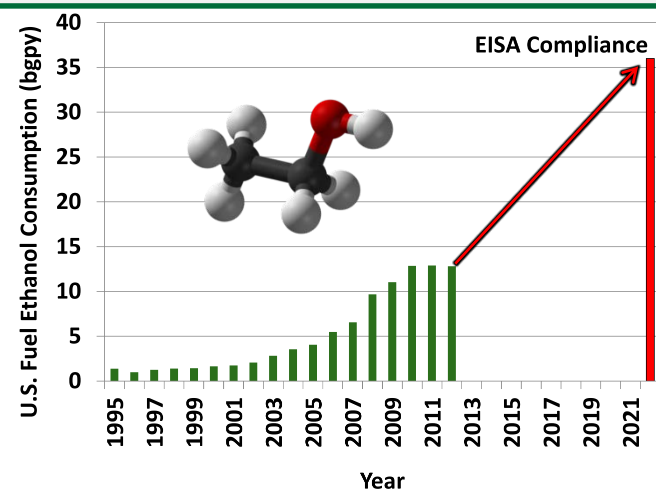
CAFE and GHG Emission Regulations



Automakers employing new engine technology to produce more efficient engines

Do Synergies Exist to Co-Optimize?

Renewable Fuels Standard



Uncertainty about the composition of future fuels (Tier 3 mentions possible high ethanol cert fuel)

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All Project Milestones Complete or On Track

2015 Joule Milestone: Multi-Mode RCCI Load Expansion

Demonstrate the synergies of fuel properties and advanced combustion to meet the ACEC 2020 Stretch goal of 36% BTE at 2000 rpm and 20% peak load.
Status: Complete

2015 Project Level Milestone: EGR Dilution Tolerance

Complete an experimental campaign investigating the EGR dilution limit for gasoline, an ethanol blend, and an iso-butanol blend. ***Status: Complete***

2015 Tracked Milestone: High Octane Vehicle Energy Consumption

Quantify and report potential fuel economy benefits for a light-duty vehicle using a high-octane E30 fuel relative to an 87 AKI E10 baseline fuel on the FTP, highway, and US06 certification cycles. ***Status: On Track***

Fuel Effects on Three Pathways Toward Efficient Gasoline Engines are Being Investigated

Approaches have differing levels of technology readiness as well as logistical and policy challenges to overcome before commercialization

Fuel Effects on Low Temperature Combustion

- RCCI: Reactivity Controlled Compression Ignition
- GCI: Gasoline Compression Ignition
- Advantage: Provide high engine efficiency with low NOx and soot emissions
- Disadvantage: High HC and CO emissions, combustion noise, and power density
- **Fuel Challenge:** **Fuel reactivity enabling desired heat release**

High EGR Dilution for SI Combustion

- High levels of EGR dilution with or without the presence of fuel reformate
- Advantage: Efficiency improvements through gamma, compression ratio, and reduced pumping
- Disadvantage: Combustion stability, transient operation, power density
- **Fuel Challenge:** **Fuel-specific differences in dilution tolerance, propensity to reform**

Knock Resistant Fuels for SI Combustion

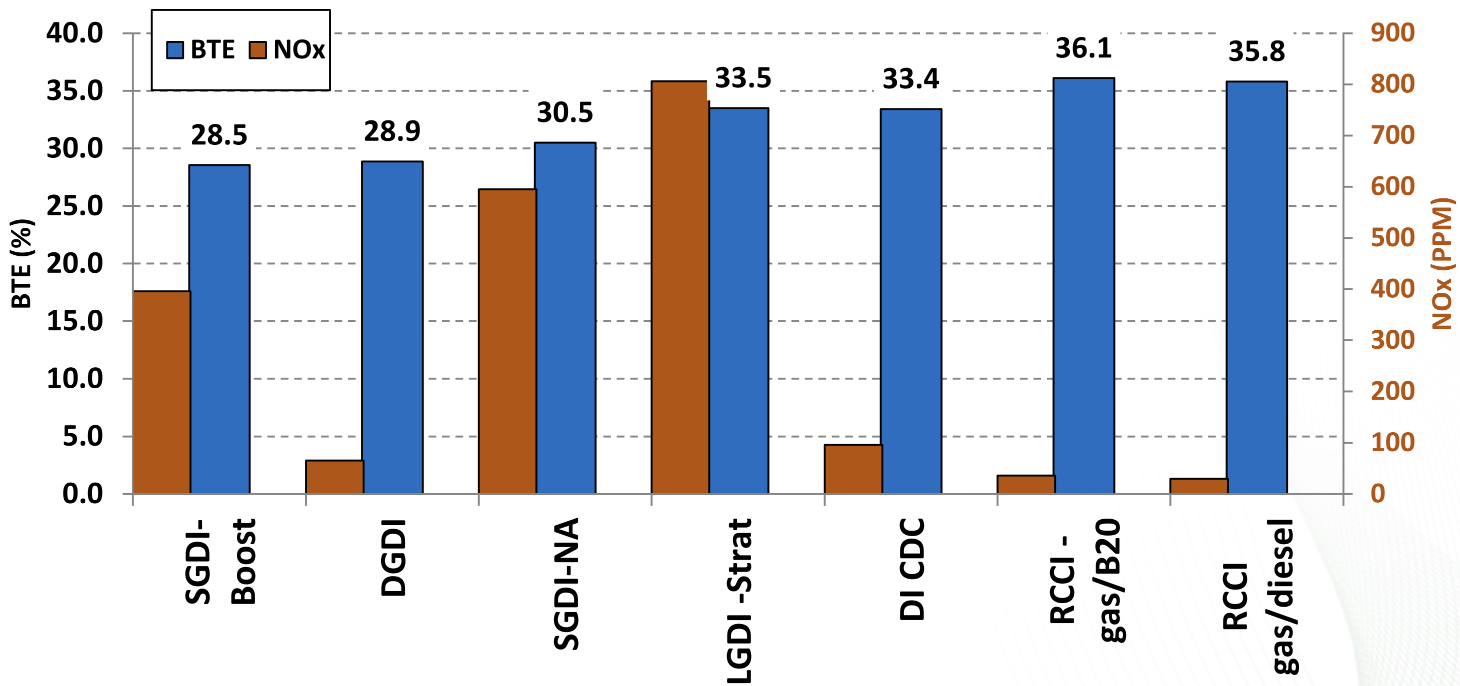
- Utilize high octane fuels to increase engine and/or vehicle efficiency
- Advantage: Enables higher compression ratio and/or downsized and downsped configurations
- Disadvantage: Supply and marketplace introduction challenges
- **Fuel Challenge:** **Understanding the relative benefit of fuels with differing composition**

TRANSITION SLIDE: FUEL EFFECTS ON LOW TEMPERATURE COMBUSTION

Biodiesel Enabled RCCI to Meet 2020 ACEC Stretch Efficiency Goal: 36% BTE at 2000 RPM, 20% Load

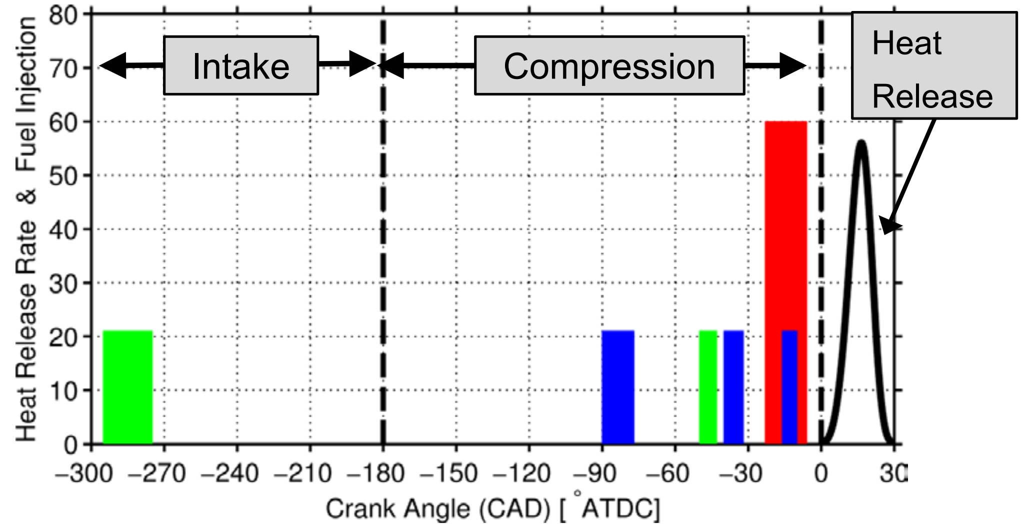
Joule Milestone: Demonstrate the synergies of fuel properties and advanced combustion to meet the ACEC 2020 Stretch goal of 36% BTE at 2000 rpm and 20% peak load.

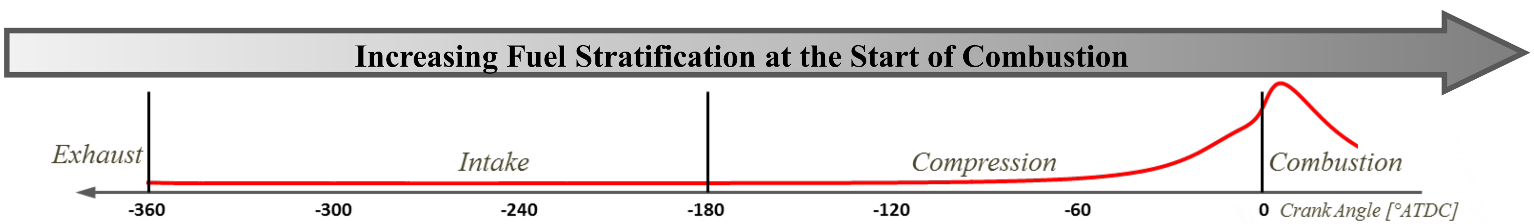
- Multi-cylinder engine experiments with a GM 1.9L ZDTH diesel platform with production-viable hardware modifications.
- Commercially-available B20 biodiesel blend had favorable combustion properties (decreased peak pressure rise rate) to enable higher efficiency RCCI operation.



There is a Spectrum of Single-Fuel GCI Advanced Combustion Strategies
Fuel/Air Stratification is Primary Difference

- Pursuing efficiency and emissions comparison of RCCI to GCI with multiple gasoline formulations on a common platform at 2000 rpm, 4 bar BMEP
- Considerable effort has been put into figuring out which GCI strategy is best-suited for the engine/hardware configuration

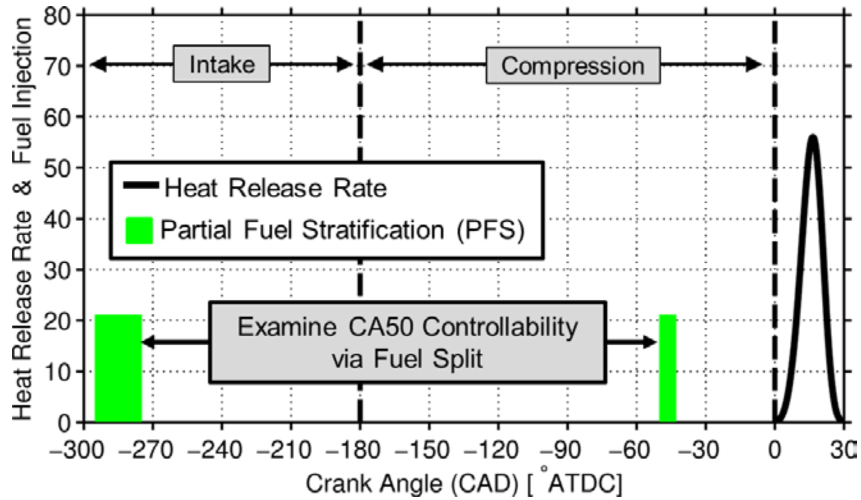


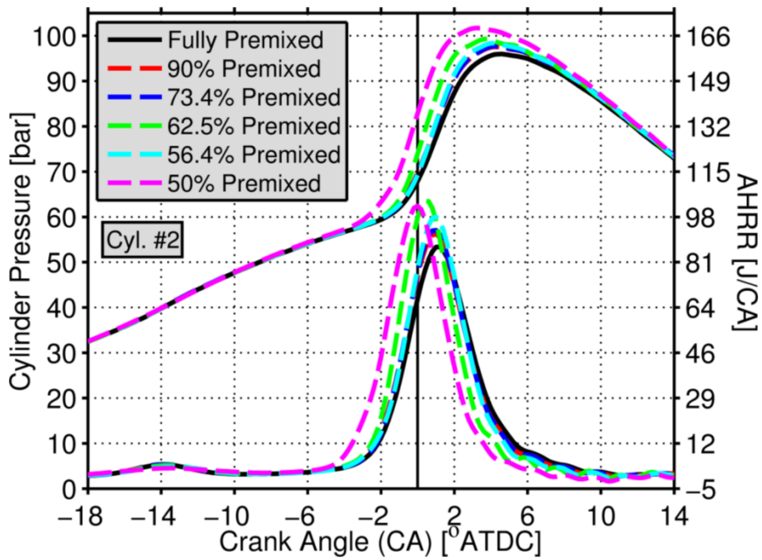


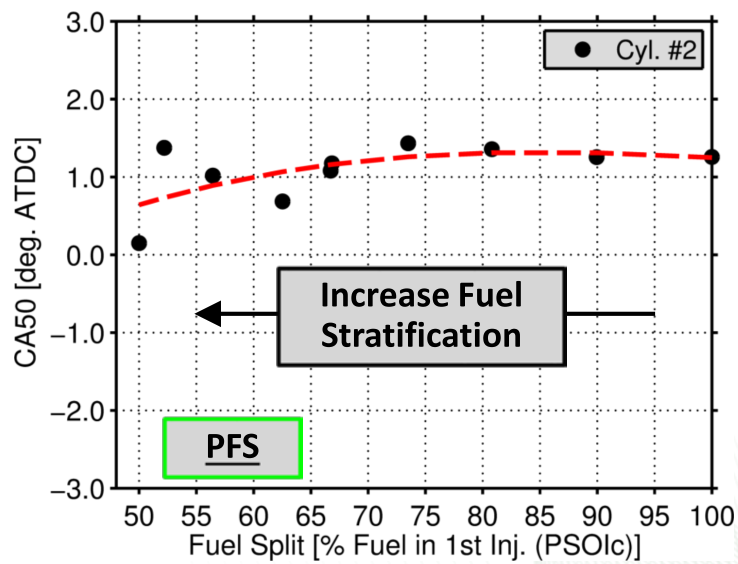
Partial Fuel Stratification (PFS)	Moderate Fuel Stratification (MFS)	Heavy Fuel Stratification (HFS)
		
- Majority Fuel Premixed (50 to 95%) - DI Mid-Way Through Compression	- Multiple DI during compression - Latest DI near TDC compression	- Single or multiple injections - All DI events near TDC

Combustion Phasing Controllability Challenges with PFS, the Majority Premixed GCI Strategy

- PFS Opportunity: Diesel-like BTE, very low engine-out NOx and soot emissions
- PFS Challenges:
  1. High HC and CO emissions
  2. Minimal ability to control combustion phasing with split of fuel in injection events







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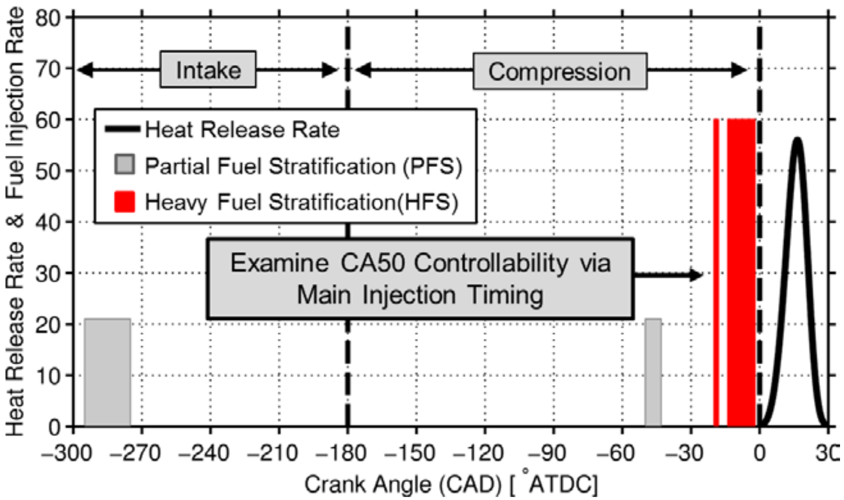
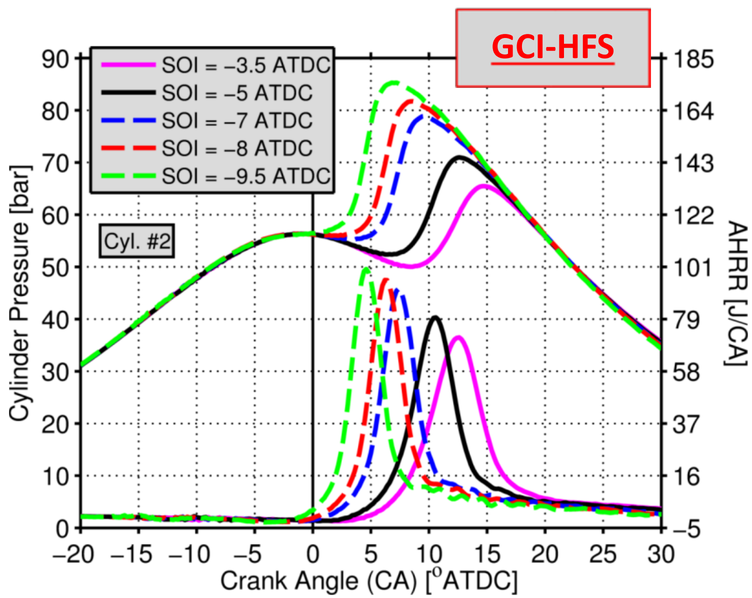
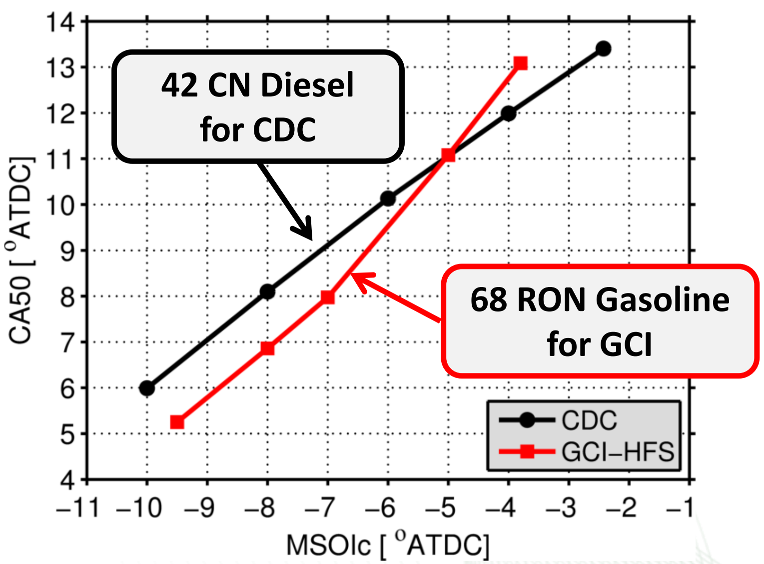
Highly Stratified GCI Allows Better Control of Combustion Phasing but Presents Other Issues

- HFS Opportunity: Diesel-like BTE, control authority over combustion phasing, low HC and CO
- HFS Challenge: Higher levels of EGR are required to achieve required targeted NOx and soot emissions





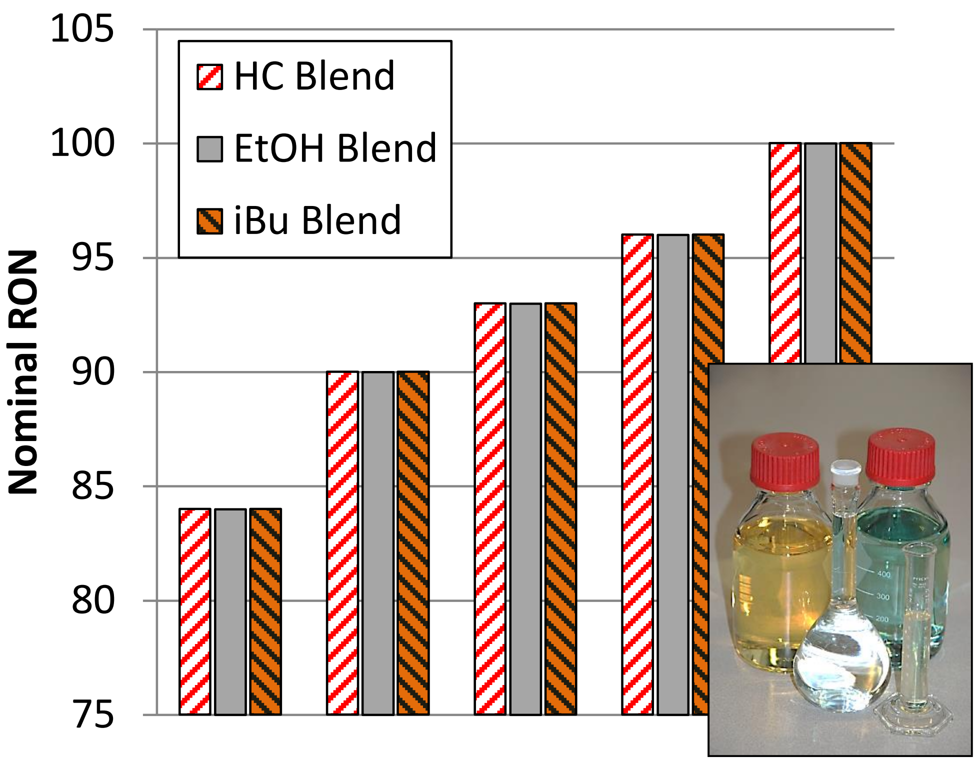


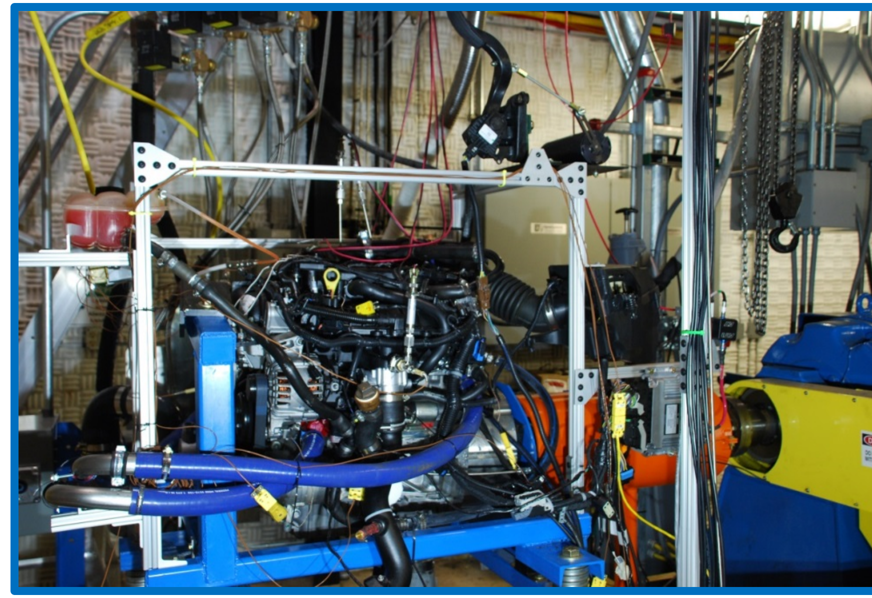
Transition Slide: High Octane Fuels

Potential of High Octane Fuels is Being Investigated at High CR

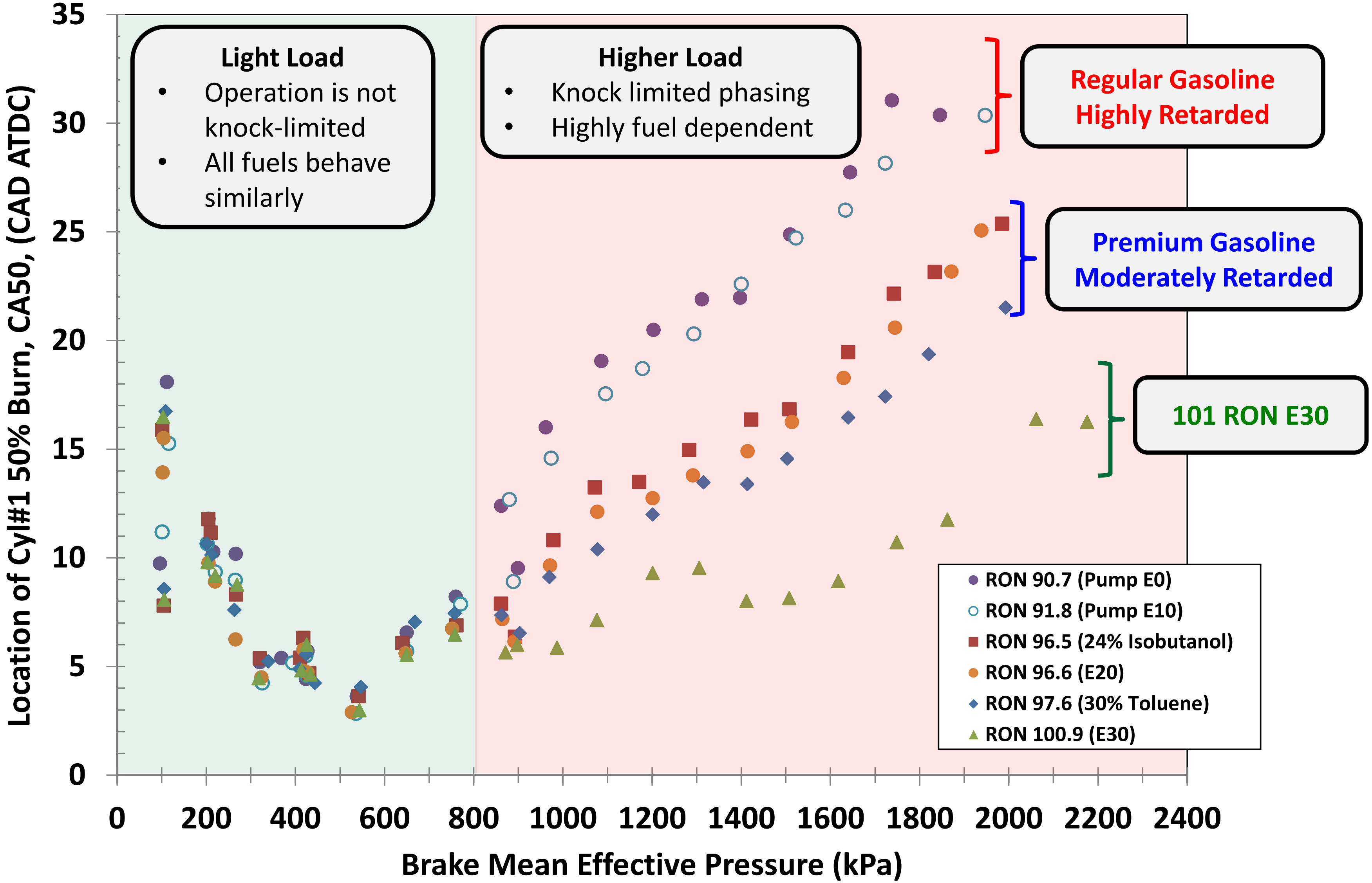
High Octane Fuels of Varying Composition Being Investigated

- Ford 1.6L Ecoboost
  - Modern downsized boosted SI engine with DI fueling, used in Fusion, Escape (backup slide)
- Study includes multiple paths to highly knock-resistant fuels

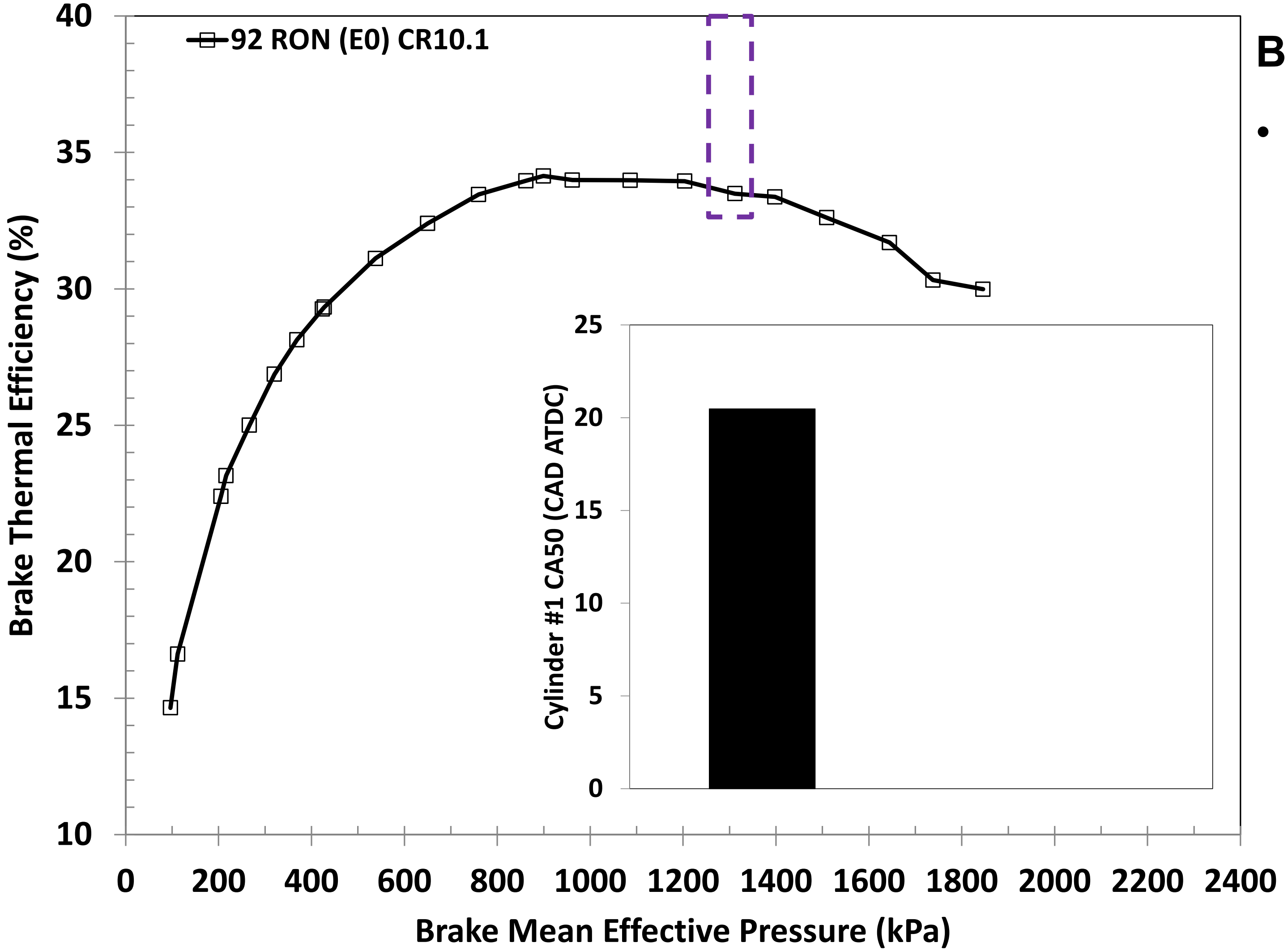




Engine Responds to Knock Sensors, Retards Combustion Phasing as Load Increases for Knock-Prone Fuels



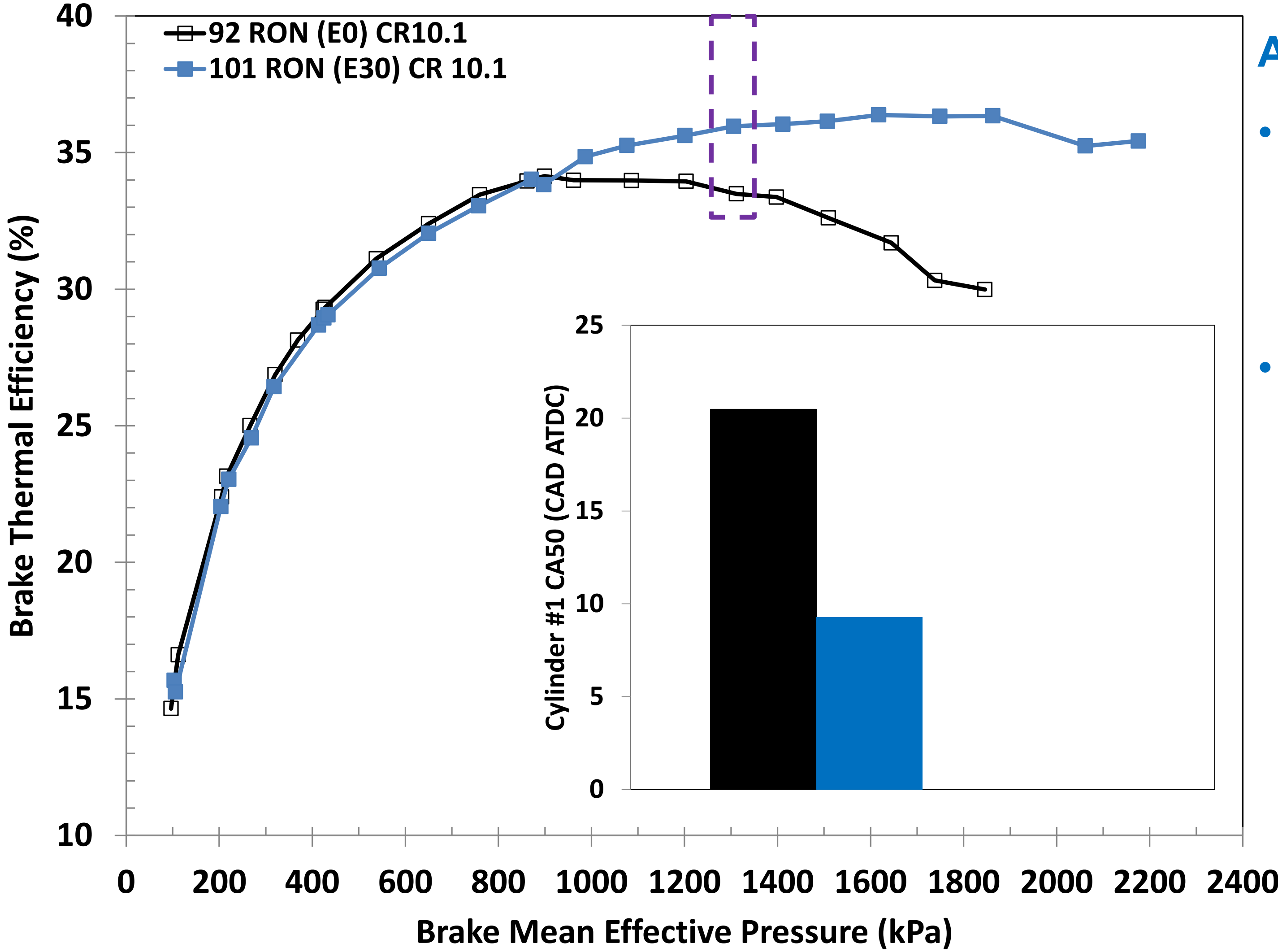
Fuel and Compression Ratio Need to be Matched to Provide the Best Efficiency at the Required Power Density



Baseline:

- **Efficiency declines above 1100 kPa.**

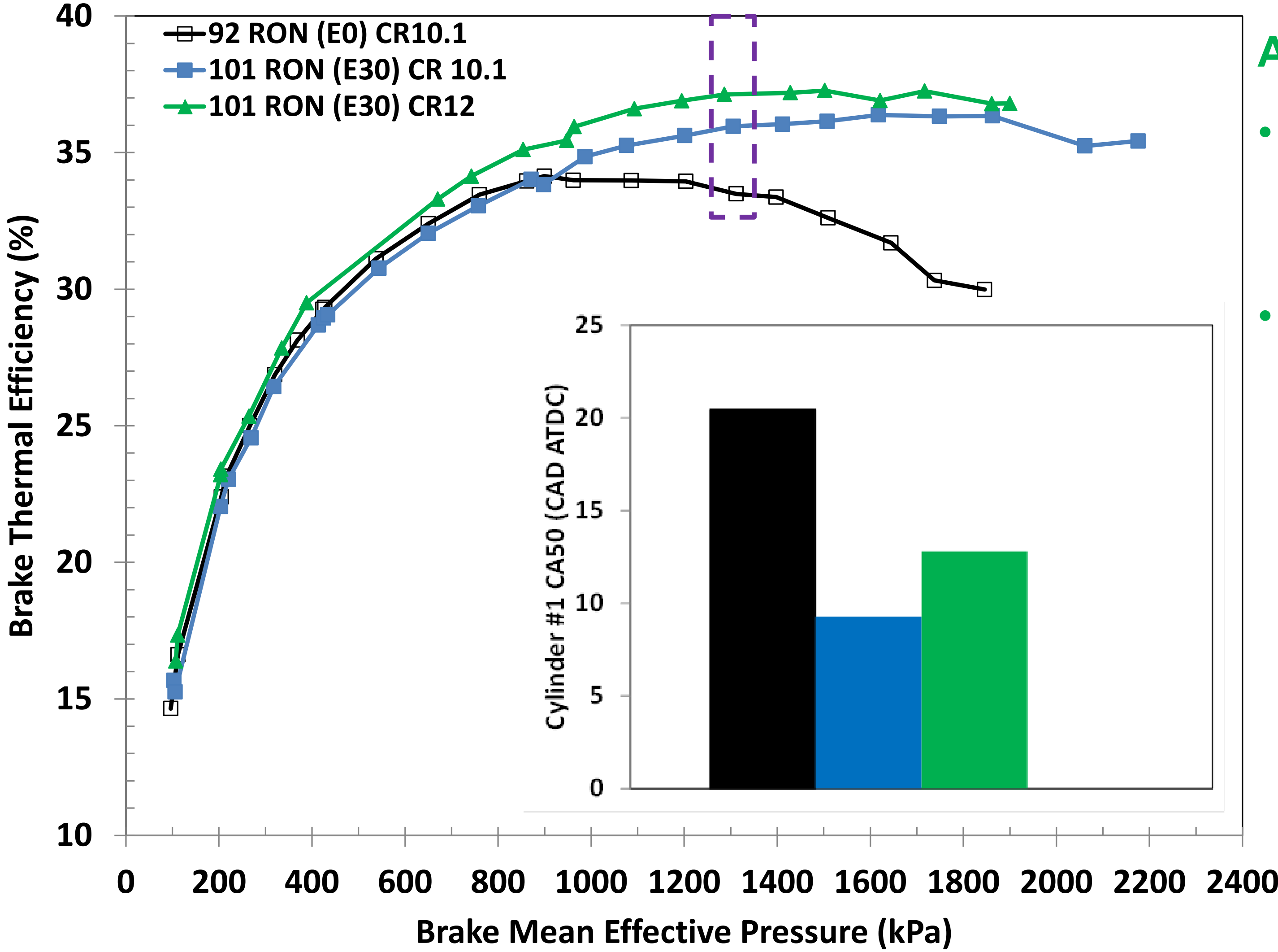
Fuel and Compression Ratio Need to be Matched to Provide the Best Efficiency at the Required Power Density



At CR10.1:

- Better efficiency at high BMEP levels
- Higher max BMEP

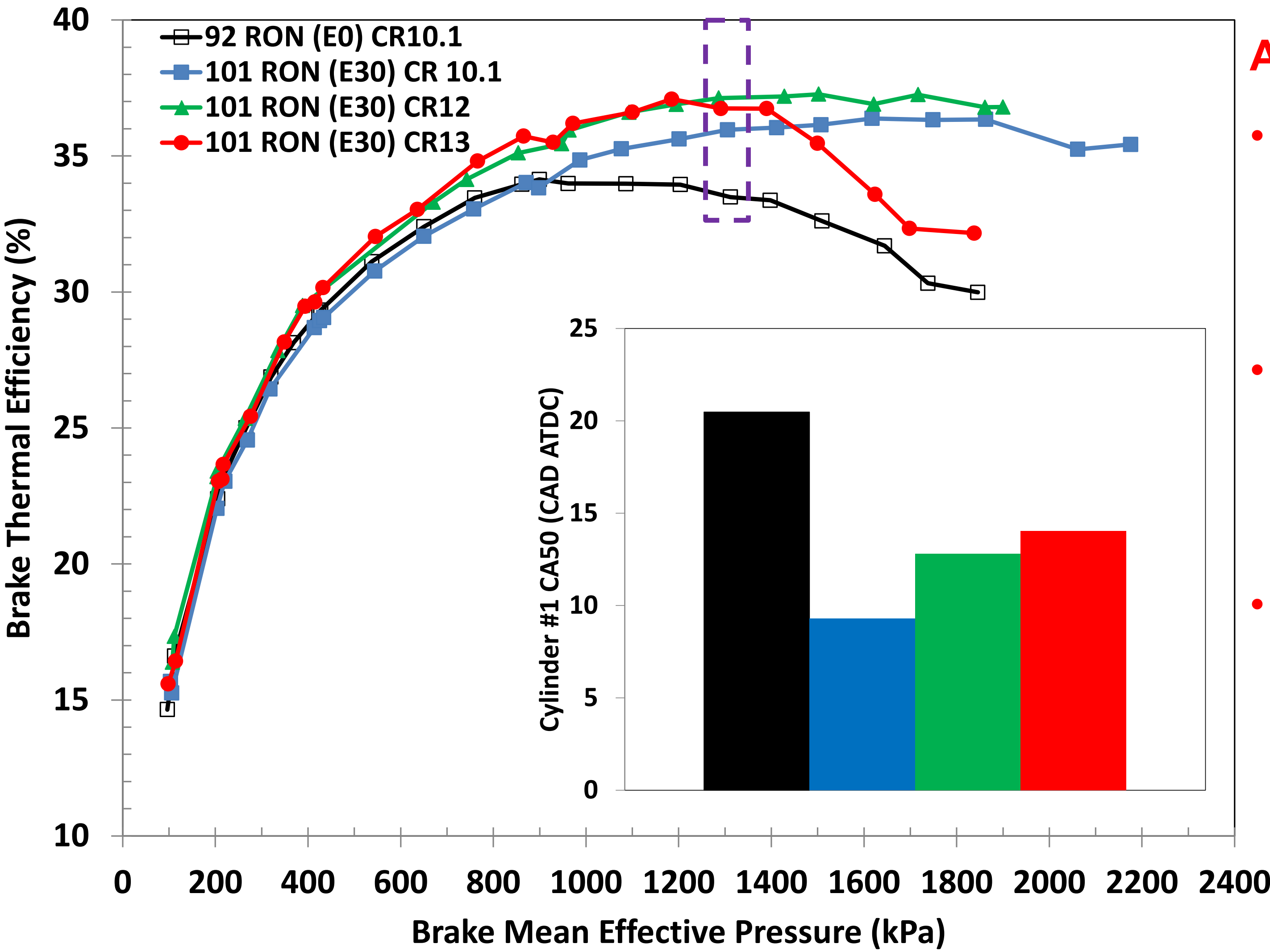
Fuel and Compression Ratio Need to be Matched to Provide the Best Efficiency at the Required Power Density



At CR12:

- **Better efficiency at all BMEP levels**
- **Comparable max BMEP to baseline**

Fuel and Compression Ratio Need to be Matched to Provide the Best Efficiency at the Required Power Density



At CR13:

- **Better efficiency at low BMEP levels**
- **Sharper decline in efficiency at moderate BMEP levels**
- **Comparable max torque to baseline**

Impact of Fuel and Compression Ratio on Fuel Economy is being Evaluated in Vehicle System Simulations using Autonomie (Backup Slide)

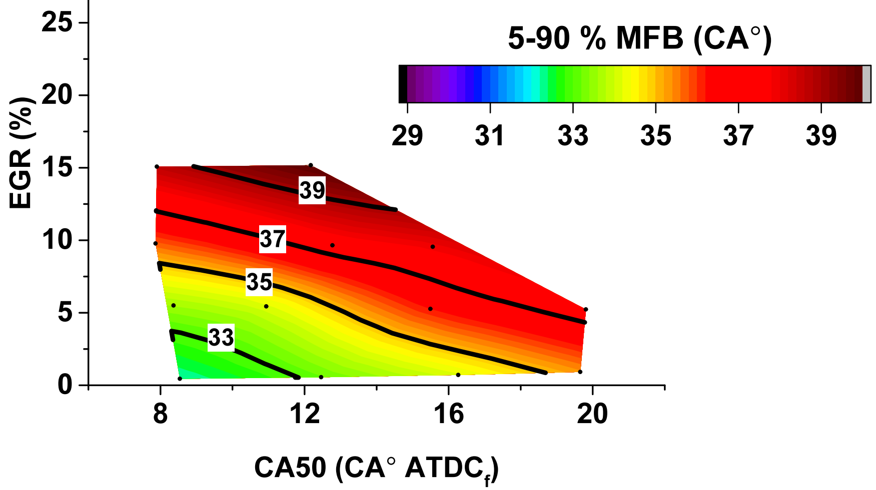
Transition Slide: Fuel Effects on Highly Dilute SI Combustion

Investigated EGR Dilution Tolerance of Fuel Blends with Four Pure Components: iso-octane, n-heptane, Toluene, and Ethanol

- Dilution tolerance experiments utilized stability limit (<5% COV) to map the phasing/EGR space
  - 2000 RPM and constant fueling, nominally 3.5 bar IMEPg (light load, dilution tolerance is poor)
  - 6 fuel blends varying in composition but with a matched 95 RON
  - Experiments conducted in a modern single-cylinder GM LNF engine (backup slide)
- Calculated flame speed agreed with data, correlated well with dilution tolerance in the engine

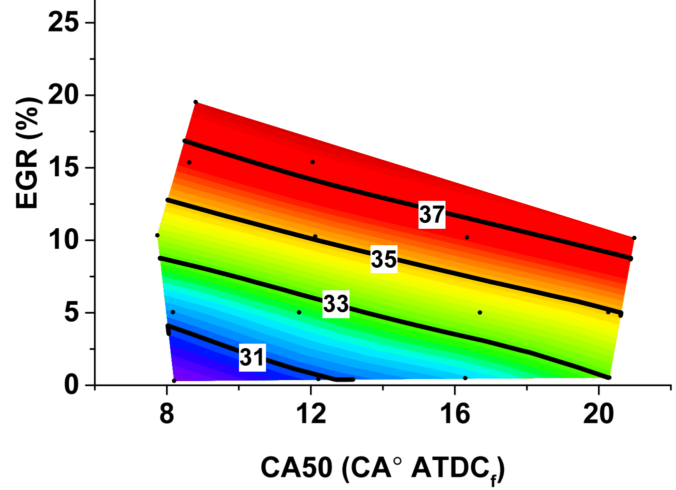
95% iso-octane, 5% n-heptane

- **Slowest predicted flame speed**
- **Slowest measured 5-90% combustion duration**
- **EGR rate limited to 15%**



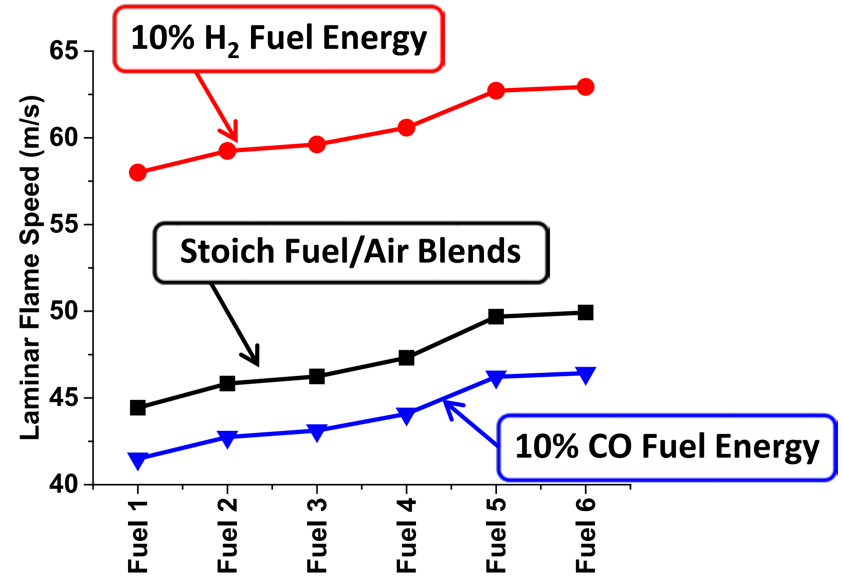
30% Toluene, 30% EtOH, 20% iso-Octane, and 20% n-heptane

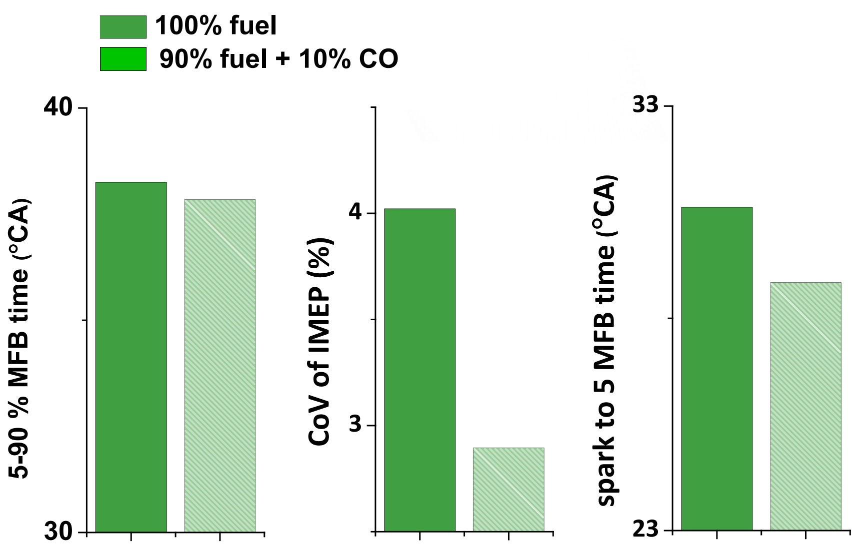
- **Fastest predicted flame speed**
- **Faster 5-90% combustion duration**
- **Tolerant of 20% EGR at early phasing**



Addition of Simulated Reformate Illuminated that Dilution Tolerance Relied on the Early Flame Kernel Growth

- Reformate study complementary to ACE015
- High flame speed of H_2 enhances stability
- CO has low flame as individual component
  - Predicted to decrease mixture combustion duration
- Experimental results show similar combustion duration but enhanced stability
  - CO was found to decrease the early flame kernel growth (spark to 5% MFB duration)
- Early flame kernel growth was indicative of combustion stability with all fuels
- Developing better understanding of role that CO can play in enhancing stability
  - Supporting Chemkin modeling
  - Possible explanations include role of water, changes in Lewis Number, ignition energy and water/gas shift





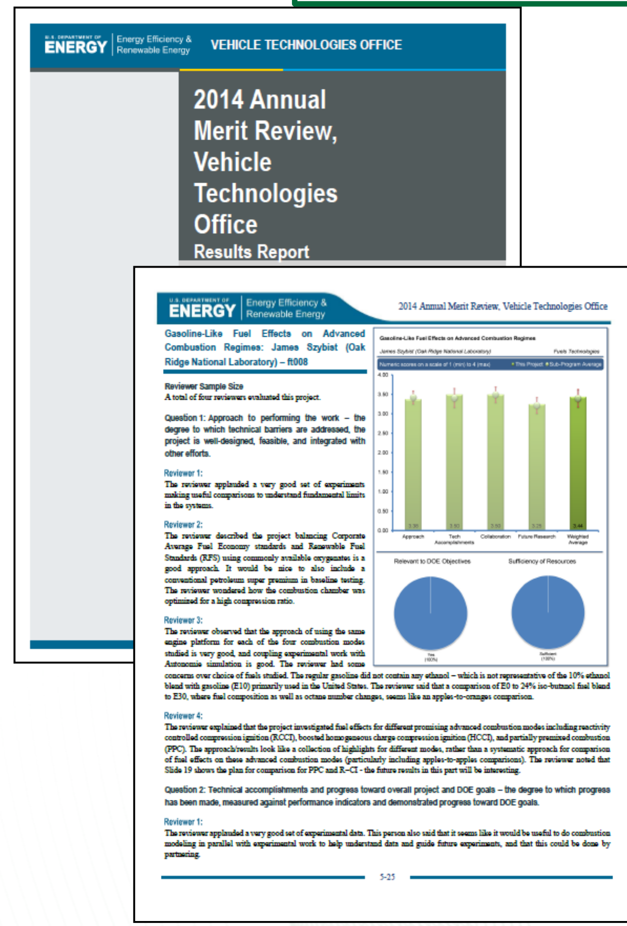
REVIEWER COMMENTS FROM FY 2014 – FT008

Reviewer Comments were Overall Very Positive (paraphrasing)

- *A very good set of experiments was done, making useful comparisons to the fundamental limits in the systems*
- *Renewable super premium for downspeeding and downsizing is encouraging and warrants further investigation*
- *This project directly supports DOE objectives of petroleum displacement and utilizing renewable fuels in advanced combustion*
- *Having joint publications is good evidence of the strong collaboration in this project*

Areas for Improvement (paraphrasing)

- *The studies could benefit from additional modeling.* FY15 and FY16 work includes kinetic modeling to support dilute combustion, vehicle system modeling to support the high octane work, and GT-Power and CFD modeling to support air handling considerations for GCI and RCCI.
- *Concern that RCCI fuel economy results may not be representative because the transients aren't adequately represented.* An engine and dyno controller upgrade is in progress that will allow transient and hardware-in-the-loop investigations. It will be online in FY16.
- *Concerns over fuel choices for SI high octane studies, especially that E0 isn't representative.* The fuel matrix for the continuing multi-cylinder high octane work includes more fuels and was developed in collaboration with the Ford to ensure that we have the right fuels moving forward, including E10 as the baseline.



http://energy.gov/eere/vehicles/downloads/2014-annual-merit-review-results-report-fuels-lubricants-technologies

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Collaborations Leverage Fuels Research at ORNL

- Industry Partners
  - Ford supporting high octane work by supplying an instrument engine and an open-access ECU, consulting on results
  - Related FOA and industry funds-in project with CRC
  - ACEC – Direct input from and data sharing with the USDRIVE Fuels Working Group
  - ACEC – Support for ACEC-DOE goals and combustion noise discussions
  - Chevron Energy Technologies– Supplying fuels for LTC project, upcoming joint publications
  - GM - GM 1.9 Hardware
  - MAHLE – Premixed compression ignition piston design
  - Chrysler – Engine data for vehicle systems modeling comparisons
  - Delphi – Injector hardware and GDCI discussions
  - Borg Warner, Honewell, and Eaton independetly providing support on air-handling for LTC
- National Lab Partners
  - SNL collaboration on NVO chemistry (co-authored 2014 SAE paper with Dick Steeper, upcoming 2015 SAE paper with Isaac Ekoto)
  - Collaborating with NREL and ANL on related high octane ethanol fuel project (BETO-funded)
- University Partners
  - University of Minnesota – Kinetic modeling on NVO chemistry with Will Northrop
  - The University of Wisconsin-Madison – RCCI modeling
  - Clemson University – Visiting student working on air-handling modeling for LTC
- Working Group Partners
  - DOE AEC/HCCI working group meeting twice a year
  - CLEERS (Cross-Cut Lean Exhaust Emissions Reduction Simulations)

Discussion of engine research with industry visitors at ORNL.

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On SI Engine Platform, Moving Focus of Project to Fuel Effects on Highly Dilute SI Combustion with Reformate

Fuel Effects Gasoline LTC Combustion

- Apples-to-apples comparison of RCCI vs. range of GCI strategies using different gasoline-range fuels
- Move towards transient dyno operation and hardware in the loop in 2017-2018
- Expand CFD and GT-Power modeling starting in FY2016

High Octane Fuels for SI Combustion

- Experimental matrix of fuels and compression ratios to provide engine efficiency maps is planned into FY2017
- In FY16, expand vehicle system modeling effort to provide fuel economy for various powertrain configurations
- FY18, downselect fuel candidates based on interactions with other stakeholders (industry, Optima), upgrade engine hardware to maintain state-of-the-art and address hardware limitations

Fuel Effects on Dilute Combustion

- In FY16, expand kinetic modeling efforts to better understand fuel-specific dilution tolerances, targeting an understanding of how CO stabilized dilute combustion
- Get input on utility of dilute combustion stabilized by reformate (leveraging ACE015)
- FY17-18, pursue fuel effects dilute combustion by developing a better understanding of the early combustion processes (spark to 5% MFB)

Summary

Relevance

Identify and promote pathways for alternative fuels that can displace significant quantities of petroleum to support higher engine efficiency

Experimental Approach

- Three paths toward efficient gasoline engines with different technology readiness are being pursued

Accomplishments

- DOE Joule Milestone: Fuels enable 36% BTE for RCCI at 2000 rpm, 20% load (2020 ACEC stretch goal)
- Spectrum of GCI strategies have been categorized according to fuel/air stratification level
  - Focus on fuel related benefits and challenges GCI strategy (emissions, controllability)
- Demonstrated fuel-dependency of combustion phasing and efficiency for three compression ratios
  - Of the six fuels investigated, the highest octane provided the best efficiency, advanced phasing
  - Two engine maps have been completed to support engine modeling (87 AKI E10 and 101 RON E30)
- Completed campaign to measure fuel-specific effect on EGR dilution tolerance for SI combustion
  - Dilution tolerance correlated with flame speed for air/fuel mixtures
  - Unexpected result for simulated reformate: CO stabilized combustion, being pursued further

Collaborations

Collaboration efforts with industry, other national laboratories, and academia have produced joint publications, shared materials, and shared ideas to ensure that efforts are relevant

Future Work

- Fuel effects on GCI to compare to RCCI, expand transient capabilities, modeling efforts
- Focus on understanding early portion of combustion for dilute combustion, including kinetics
- Continue to generate engine efficiency maps for high octane work, vehicle system modeling

Contacts:

Jim Szybist
szybistjp@ornl.gov

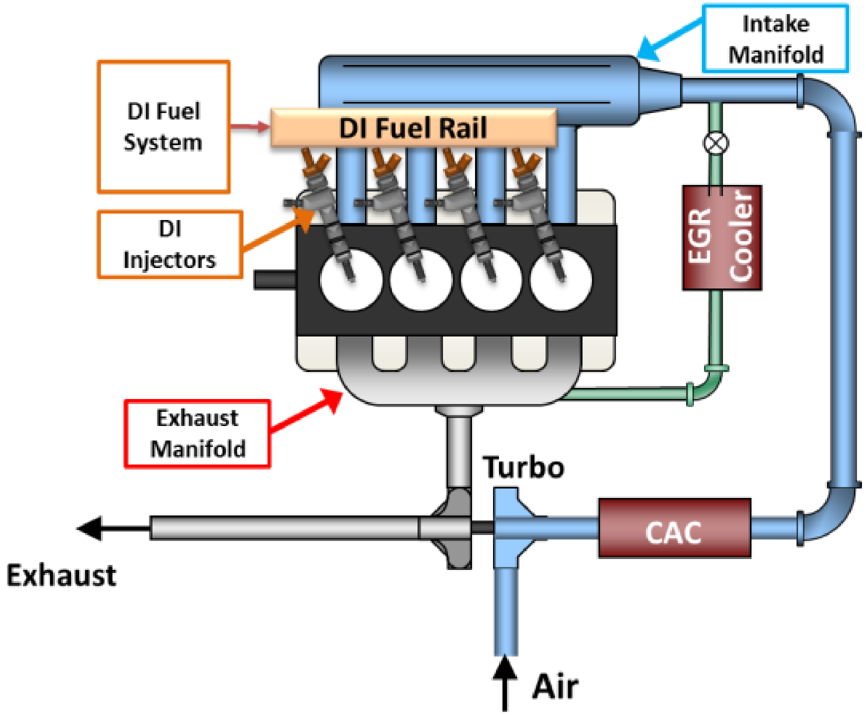
Scott Curran
curransj@ornl.gov

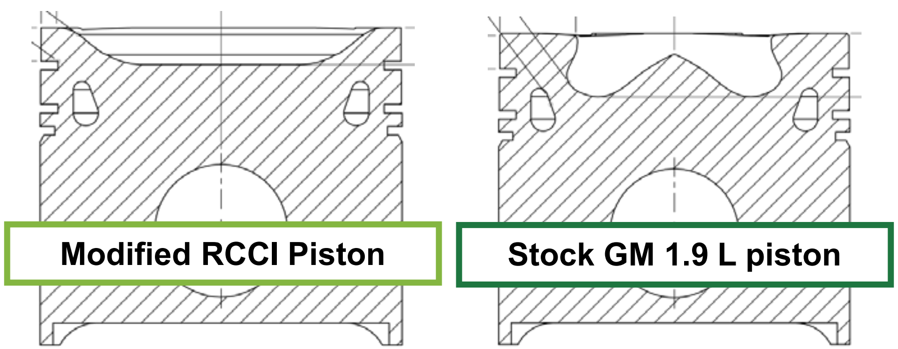
Scott Sluder
sluders@ornl.gov

Technical Back-Up Slides

Majority Premixed LTC GCI with Non-Ideal Diesel Injector

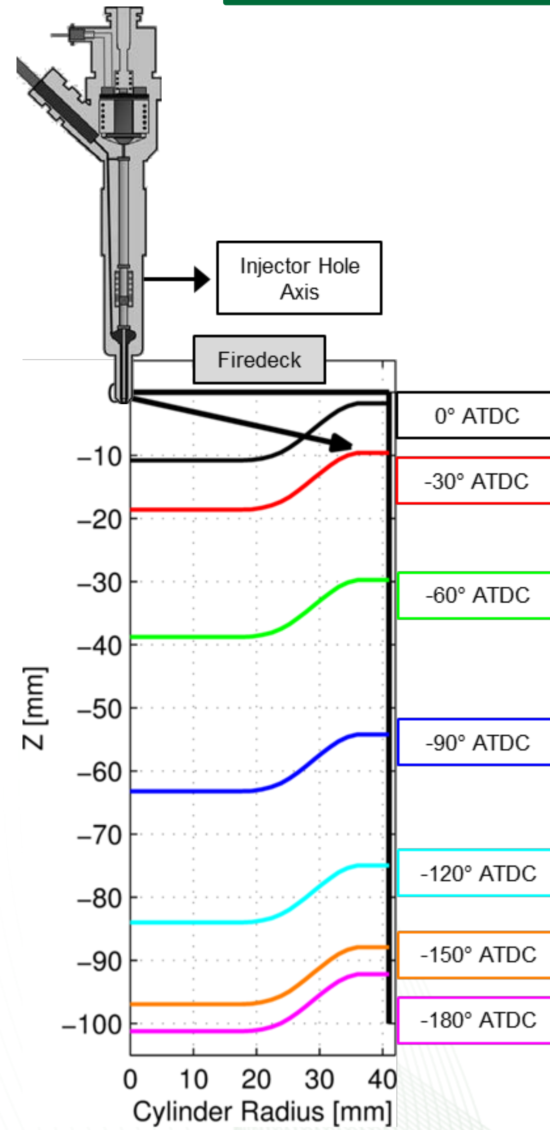
Backup 1





Modified RCCI Piston

Stock GM 1.9 L piston



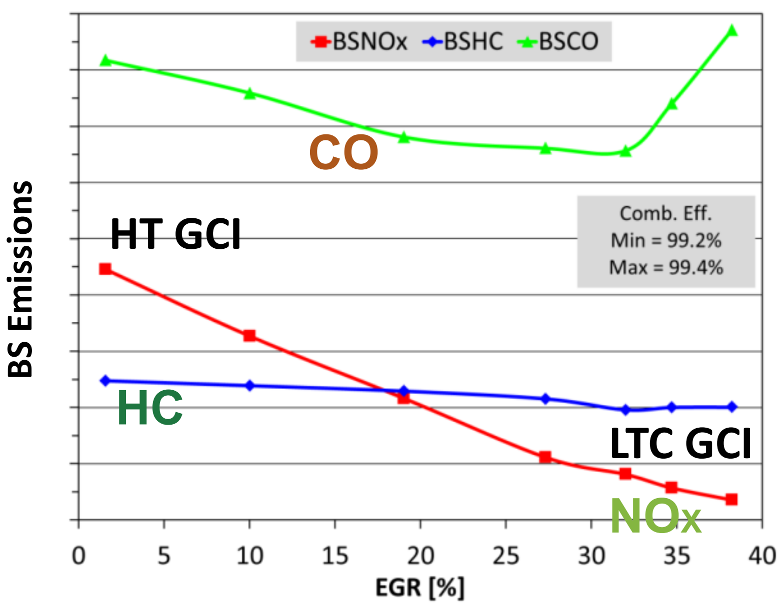
Premixed piston not ideal for mixing limited GCI – however air handling issues are expected to persist

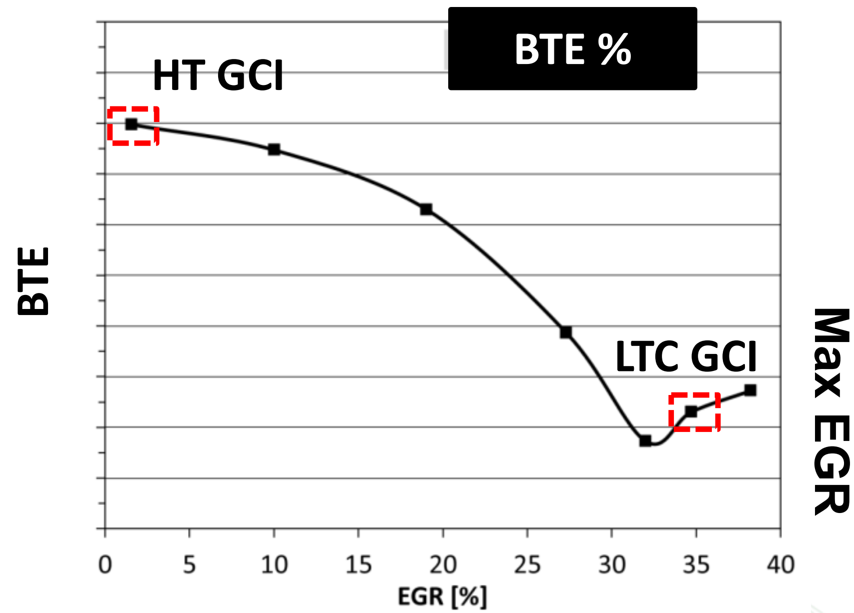
Backup 2

- High dilution necessary for low NOx with GCI approach
- High dilution approach limited by turbo-machinery, leads to reduced efficiency
- Majority premixed GCI (PPC) achieves similar emissions results at LT GCI but with higher efficiency

2000 rpm, 4.0 bar BMEP

	CDC	RCCI	GCI HT	GCI LT High EGR	GCI LT Maj Pre
BTE (%)	33.4	35.8	34.0	31.4	34.7
NOx (ppm)	96	26	460	30	10
HC (ppm)	161	2164	1359	1700	2615
CO (ppm)	322	1733	1397	3000	2100
FSN (-)	1.02	0.01	0.05	0.12	0.01

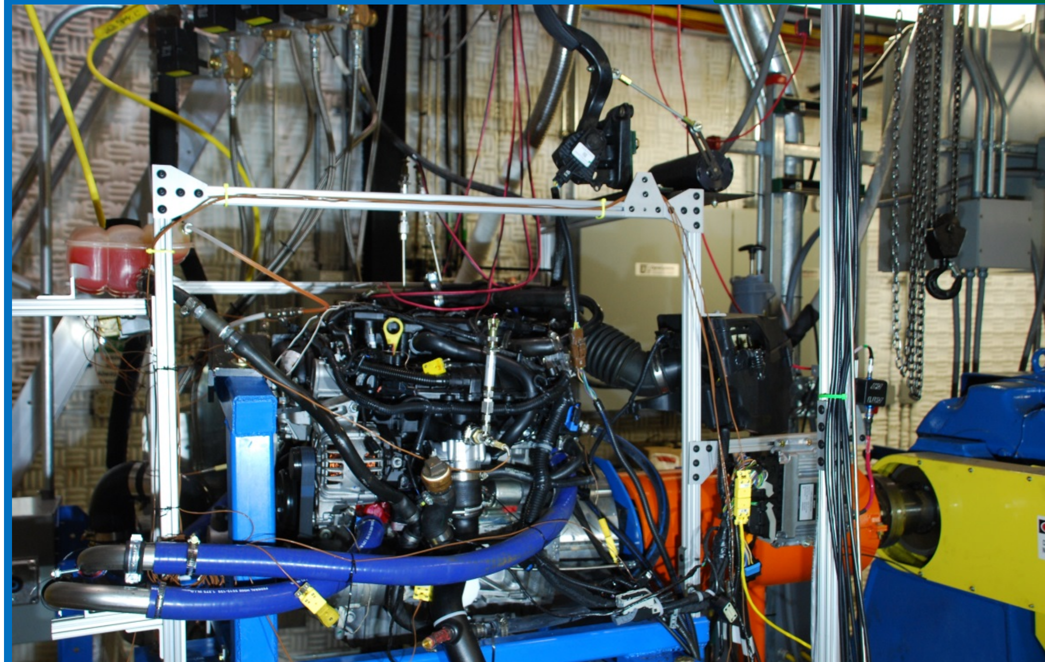




High Octane Studies at ORNL use a Modern GTDI Engine

Backup 3

- Ford Ecoboost 1.6L 4-cyl
  - Turbocharged
  - Center mount direct-injection
  - Dual variable cam timing
  - CR 10.1 (OEM)
- Engine Control
  - Active Ford technical support
  - ECU with dyno calibration; access to change parameters
- High-compression pistons
  - Nominally 12:1, 13:1
  - Blanks to produce additional configurations
  - High CR pistons do not limit cam phasing for this engine design

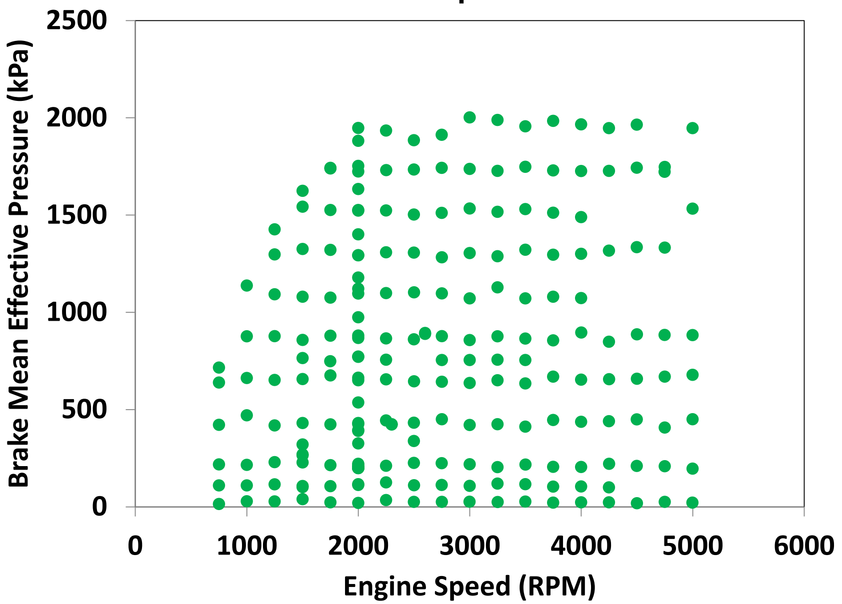


Engine Mapping Will Be Coupled with Vehicle Modelling to Estimate Fuel Economy Benefits

Backup 4

- E10 baseline map and E30 map at CR13 currently completed, others planned
- Vehicle modelling using Autonomie:
  - Model industry-relevant vehicle platforms, including mid-size sedan and small SUV
  - Include heating value changes to evaluate fuel formulations on common basis
  - Evaluate potential vehicle-system level benefits enabled by high-octane fuels
  - Evaluate directional changes in regulated emissions

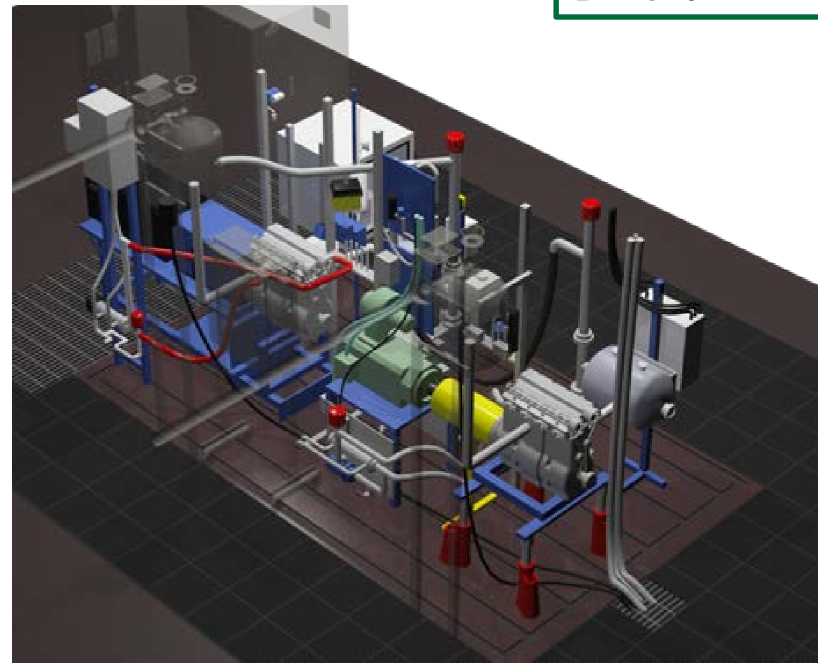
Baseline engine map using 87 AKI E10 with OEM pistons

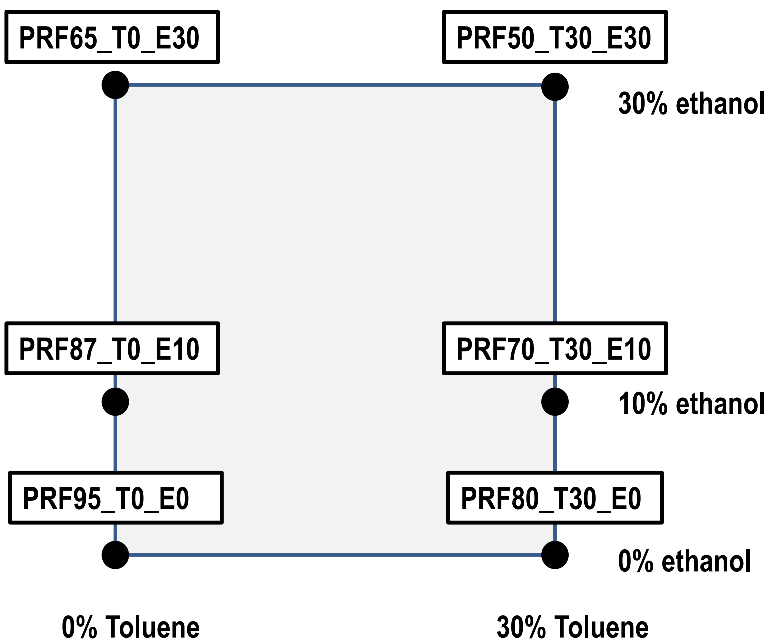


Dilution Tolerance Experiments Conducted on a Single Cylinder Research Engine for Precise Controlled of Operating Conditions

Backup 5

- 2007 GM LNF 2.0L Ecotec
  - Single cylinder
  - Stock 9.2 CR
  - Production cam and cam phasing
  - Side-mount DI fuel injection
- Laboratory air, EGR, fueling





- All fuels blended to 95 RON
- H/C ratio varied from 2.4 to 1.8
- O/C ratio varied 0 to 0.03
- H_2 and CO fumigated into intake at 10% of total fuel energy

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