

GASOLINE-LIKE FUEL EFFECTS ON ADVANCED COMBUSTION REGIMES

PROJECT ID: FT008

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June 19th, 2014

DOE Management Team

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PROJECT OVERVIEW

PROJECT OVERVIEW
RELEVANCE
MILESTONES
APPROACH
ACCOMPLISHMENTS
REVIEWER COMMENTS
COLLABORATIONS
FUTURE WORK
SUMMARY

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

- FY11: \$300k
- FY12: \$615k
- FY13: \$400k
- FY14: \$450k

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

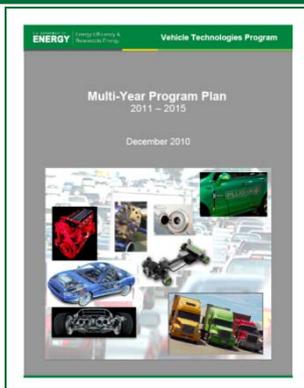
- *SAE Symposium*
- *ACEC Tech Team*
- *GM*
- *Chrysler*
- *Ford*
- *Chevron Energy Technology Co.*
- *MAHLE*
- *Delphi*
- *Others*

Other Collaborations

- *Sandia National Laboratories*
- *AEC/HCCI Working Group*
- *CLEERS Working Group*
- *University of Wisconsin*
- *Penn State University*

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

- PROJECT OVERVIEW
- RELEVANCE**
- MILESTONES
- APPROACH
- ACCOMPLISHMENTS
- REVIEWER COMMENTS
- COLLABORATIONS
- FUTURE WORK
- SUMMARY

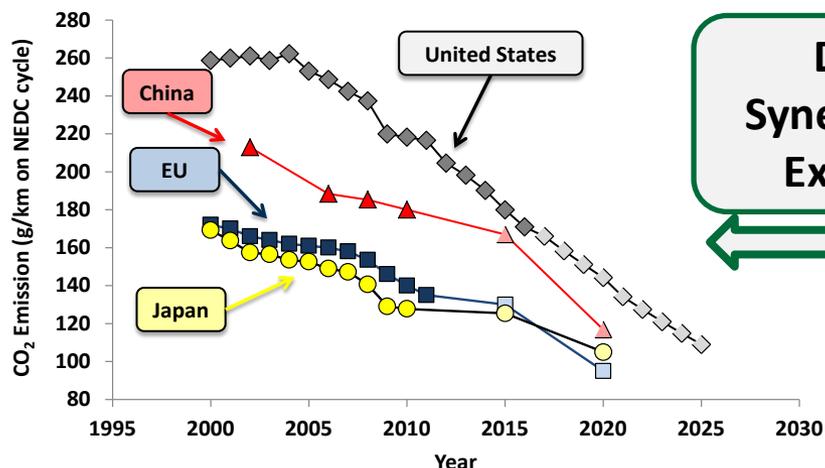


Goal of Fuels and Lubricant Technologies

(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...”

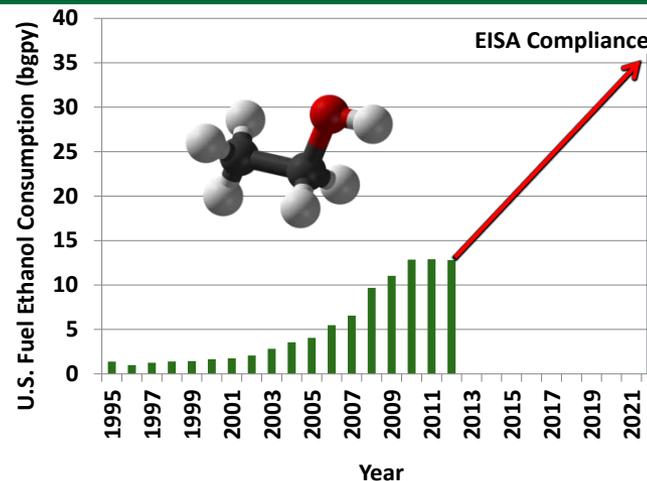
CAFE and GHG Emission Regulations



Do Synergies Exist?

Automakers employing new engine technology to produce more efficient engines

Renewable Fuels Standard



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

TWO MILESTONES TRACKED BY DOE

PROJECT OVERVIEW
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SUMMARY

2014 JOULE MILESTONE: MULTI-MODE RCCI LOAD EXPANSION

Demonstrate an increase in the RCCI operating range due to the use of renewable fuels allowing 75% coverage of non-idling portions of the city (UDDS) and highway (HWFET) light-duty federal drive cycles. **Status: Complete**

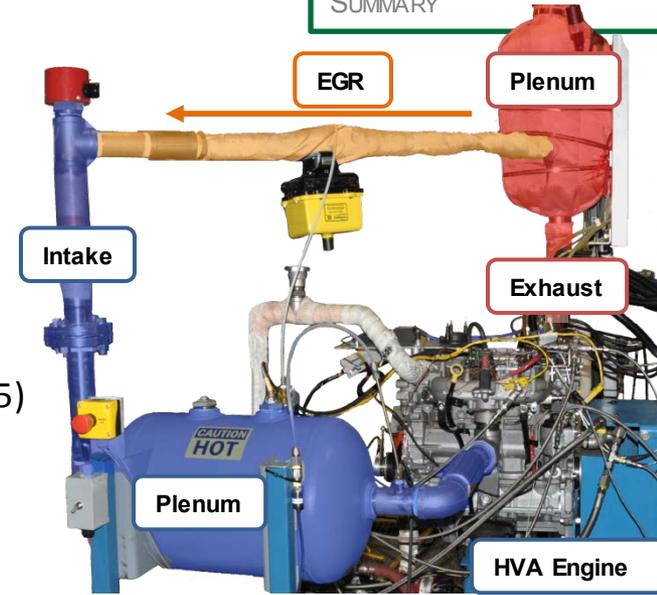
2014 TRACKED MILESTONE: MULTI-MODE VEHICLE ENERGY CONSUMPTION

Complete a vehicle system model showing fuel-based differences in energy consumption using experimental multi-mode engine maps that include SI, dilute SI, HCCI, and SA-HCCI combustion. **Status: On Track**

FLEXIBLE ENGINE PLATFORM ALLOWED DIRECT COMPARISONS OF FUEL EFFECTS FOR FOUR COMBUSTION STRATEGIES

PROJECT OVERVIEW
RELEVANCE
MILESTONES
APPROACH (1/4)
ACCOMPLISHMENTS
REVIEWER COMMENTS
COLLABORATIONS
FUTURE WORK
SUMMARY

- Single cylinder engine with hydraulic valve actuation (HVA)
 - Modified 2.0L GM Ecotec engine with side-mount direct injection
 - Laboratory air handling (thermal management, boost, external EGR)
 - Custom piston for high compression ratio (11.85:1, stock 9.2:1)
- Same fuels used for all combustion modes, represent possibilities for large scale use in U.S.
 - Regular grade gasoline (no oxygenates)
 - Iso-butanol fuel blend (24 vol% splash blend, oxygen-equivalent to E15)
 - Renewable super premium (RSP, 30 vol% ethanol splash blend)
- Mapped fuel consumption and emissions in operable speed-load range for each
 1. Conventional SI combustion - stoichiometric
 2. Dilute SI combustion (15% external cooled EGR) - stoichiometric
 3. Boosted HCCI with NVO strategy – fuel-lean
 4. Spark-assisted HCCI – stoichiometric
 - Inherent cycle-to-cycle instabilities
 - More details in technical backup slides

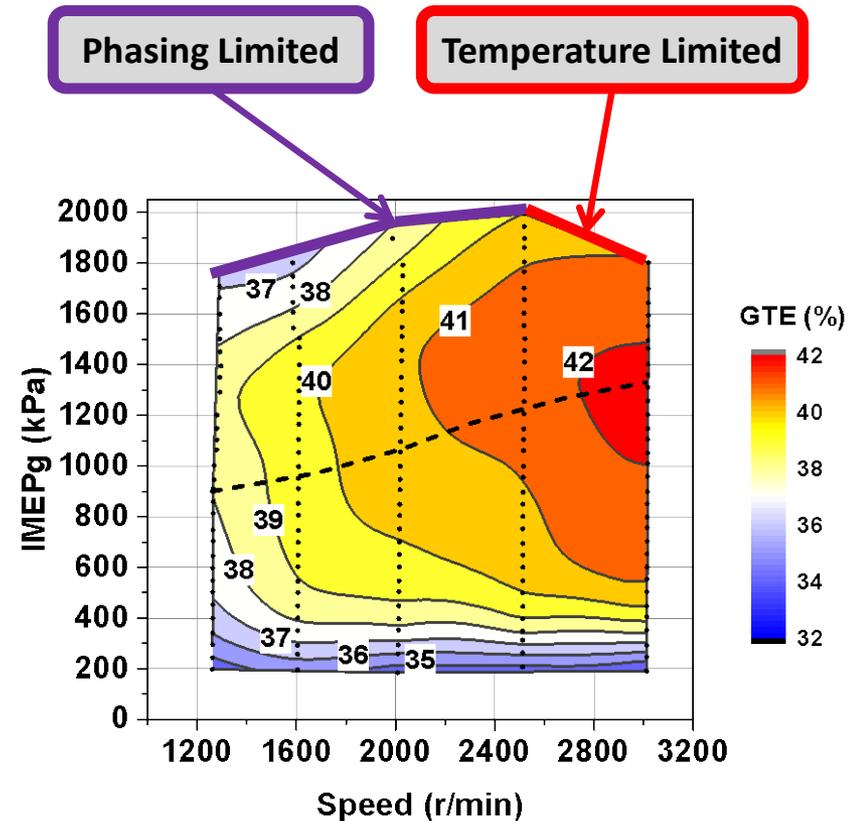


	Gasoline	IB24	RSP
RON	90.2	96.6	100.3
MON	83.9	86.8	88.8
HoV (kJ/kg)	352	443	529
HoV Gasoline Equivalent (kJ/kg)	352	470	599

COMMON STABILITY AND PEAK LOAD METRICS APPLIED TO ALL FUELS AND COMBUSTION MODES

APPROACH (2/4)

- Laboratory air-handling system used to increase intake and exhaust manifold pressure for higher load as-needed
 - 25% turbocharger efficiency used for conventional and dilute SI combustion
 - 10 kPa ΔP between intake and exhaust manifold for HCCI (except where noted)
- Limits for all combustion modes
 1. Peak cylinder pressure: 100 bar
 2. Exhaust gas temperature: 800°C
 3. Combustion phasing retard: CA50 of 25 CA aTDC_f
- Maximum efficiency phasing for conventional and dilute SI combustion
 - CA50 phasing of 8 CA aTDC_f in absence of knock
 - Retard phasing to mitigate knock as load increases until latest allowable phasing
 - Enrichment for further load increases not investigated
- HCCI noise limited to 95 dB
 - Narrow combustion phasing window (7-10 CA aTDC_f)
 - COV of IMEP \leq 2%
 - Dilution modulated to control noise



STUDIES HAVE BEEN PUBLISHED FOR FULL DETAILS ON THE APPROACH AND RESULTS

APPROACH (3/4)

<http://info.ornl.gov/sites/publications/Files/Pub44418.pdf>

energyfuels

ANALYSIS

Experimental Investigation of Spark-Ignited Combustion with High-Octane Biofuels and EGR. 1. Engine Load Range and Downsize Downsized Opportunity

Derek A. Splitter* and James P. Szybist[†]

Fuels, Engines, and Emissions Research Center, Oak Ridge National Laboratory, NTRC Building, 2560 Chalkhills Road, Knoxville, Tennessee 37932, United States

ABSTRACT: The present study experimentally investigates spark-ignited combustion with 87 AKI EGR gasoline in its neat form and in mid-level alcohol-gasoline blends with 24% vol/vol isobutanol-gasoline (IB24) and 30% vol/vol ethanol-gasoline (E30). A single-cylinder research engine was used with an 11.85:1 compression ratio, hydraulically actuated valves, laboratory intake air, and was capable of external exhaust gas recirculation (EGR). Experiments were conducted with all fuels in full-load conditions with $\lambda = 1$, using both 0% and 15% external cooled EGR. Higher octane number biofuel blends exhibited increased stoichiometric torque capability at the compression ratio, where the unique properties of ethanol enabled a doubling of the stoichiometric torque capability with E30 as compared to 87 AKI, up to 20 bar IMEP_{st} (indicated mean effective pressure area). At $\lambda = 1$, EGR provided thermodynamic advantages and was a key enabler for increasing engine efficiency for all fuel types. However, with 10% EGR, 10.5 bar IMEP was used for knock mitigation with gasoline or IB24. Torque densities with E30 with 15% EGR at $\lambda = 1$ operation were similar or better than a modern EURO IV calibration turbocharged engine. The results of the present study suggest that it could be possible to implement a 40% downsized + downsized configuration (1.3 L engine) into a representative midsize sedan. For example, for a midsize sedan at a 60 mph/city cruise, an estimated fuel consumption of 4.9 miles per gallon (MPG) (engine out 102 g CO₂/km) could be achieved with similar reserve power to a 2.0 L engine with FIAT 5.6L MPG, engine out 155 g CO₂/km. Data suggest that, with mid-level alcohol-gasoline blends, engine and vehicle optimization can offset the reduced fuel energy content of alcohol-gasoline blends and likely reduce vehicle fuel consumption and tailpipe CO₂ emissions.

INTRODUCTION

The Energy Independence and Security Act¹ of 2007 requires that, by year 2022, 16 billion gallons per year of bio-derived fuels be consumed in transportation. This requirement is a more than a 2-fold increase from the billion gallons consumed per year when the law was enacted. It sets the risk for complying with this mandate as specified by the Environmental Protection Agency (EPA) in the Renewable Fuel Standard II (RFS II)². When the total transportation fuel consumption is analyzed, it is apparent that this legislation increases the usage of biofuels. In 2012, the United States consumed 27.97 quadrillion BTU of energy for transportation and is projected to consume 29.24 quadrillion BTU in 2022. Assuming a gasoline equivalent energy of 42.8 MJ/kg and density of 740 kg/m³, the RFS standard will require an increase in percentage of transportation energy from biofuels to approximately 14% in 2022 from the approximately 2% in 2007. To date, the RFS II program has seen more than a doubling of fuel usage, with the annual recorded share of transportation energy from nonpetroleum sources totaling 4.3% in 2012. Although 2012 was the year with the largest biofuel energy share record,³ there is still an additional 2-fold increase in biofuel energy share required to comply with the RFS II mandate.

Consistent with RFS II legislation by the National Highway and Transportation Safety Administration passed in 2005 requires an effective 2-fold increase in corporate energy efficiency (CAFE) standards to achieve 54.5 US miles per gallon (MPG) as an effective 2-fold increase compared with present

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energyfuels

ANALYSIS

Experimental Investigation of Spark-Ignited Combustion with High-Octane Biofuels and EGR. 2. Fuel and EGR Effects on Knock-Limited Load and Speed

Derek A. Splitter* and James P. Szybist[†]

Fuels, Engines, and Emissions Research Center, Oak Ridge National Laboratory, NTRC Building, 2560 Chalkhills Road, Knoxville, Tennessee 37932, United States

ABSTRACT: The present study experimentally investigates spark-ignited combustion with 87 AKI EGR gasoline in its neat form and in mid-level alcohol-gasoline blends with 24% vol/vol isobutanol-gasoline (IB24) and 30% vol/vol ethanol-gasoline (E30). A single-cylinder research engine was used with an 11.85:1 compression ratio, hydraulically actuated valves, laboratory intake air, and was capable of external exhaust gas recirculation (EGR). Experiments were conducted with all fuels in full-load conditions with $\lambda = 1$, using both 0% and 15% external cooled EGR. Higher octane number biofuel blends exhibited increased stoichiometric torque capability at the compression ratio, where the unique properties of ethanol enabled a doubling of the stoichiometric torque capability with E30 as compared to that of 87 AKI, up to 20 bar IMEP (indicated mean effective pressure area) at $\lambda = 1$. This study demonstrates that for all fuels, EGR is a key enabler for increasing engine efficiency but is less useful for knock mitigation with 87 AKI gasoline or IB24. Under knocking conditions, 15% EGR is found to offer 1°C/A of CA50 timing advance with E30, whereas up to 5°C/A of CA50 advance is possible with knock-limited E30A1 gasoline. Compared to 87 AKI, both E30 and IB24 are found to have reduced catalytic flame temperature and shorter combustion durations, which reduce knock propensity beyond that indicated by the octane number. However, E30A1 EGR is found to exhibit the better knock mitigation property than other FFAE215% EGR or IB24 15% EGR, supporting the knock limited operating range and engine stoichiometric torque capability at high compression ratios. Furthermore, the fuel sensitivity (S) of E30 was attributed to reduced speed sensitivity of E30, expanding the low-speed stoichiometric torque capability at high compression ratios. The results illustrate that intermediate alcohol-gasoline blends exhibit knock mitigation and performance benefits that increase with the octane number, most particularly E30.

INTRODUCTION

The Energy Independence and Security Act¹ of 2007 requires that, by year 2022, 16 billion gallons per year of bio-derived fuels be consumed in transportation. This spike in bio-derived fuels is a more than a 2-fold increase from the billion gallons consumed per year when the law was enacted. It sets the risk for complying with this mandate as specified by the Environmental Protection Agency (EPA) in the Renewable Fuel Standard II (RFS II)². When the total transportation fuel consumption is analyzed, it is apparent that this legislation increases the usage of biofuels. In 2012, the United States consumed 27.97 quadrillion BTU of energy for transportation and is projected to consume 29.24 quadrillion BTU in 2022. Assuming a gasoline equivalent energy of 42.8 MJ/kg and density of 740 kg/m³, the RFS II standard will require an increase in percentage of transportation energy from biofuels to approximately 14% in 2022 from the approximately 2% in 2007. To date, the RFS II program has seen more than a doubling of fuel usage, with the annual recorded share of transportation energy from nonpetroleum sources totaling 4.3% in 2012. Although 2012 was the year with the largest biofuel energy share record,³ there is still an additional 2-fold increase in biofuel energy share required to comply with the RFS II mandate.

Consistent with RFS II legislation by the National Highway and Transportation Safety Administration passed in 2005 requires an effective 2-fold increase in corporate energy efficiency (CAFE) standards to achieve 54.5 US miles per gallon

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by 2025⁴ an effective 2-fold increase compared with present CAFE standards. Ideally, the RFS II CAFE mandate could be met sustainably through proper exploitation and implementation of high-efficiency petrol engines.

In the United States, the modernized operational spark engine (SE) engine has maintained over a 1996 market share in the light-duty (LD) vehicle sector (passenger cars and pickup trucks) since 1985, and over a 94% share since the EPA began record keeping in 1973. This LD sector engine dominance is due primarily to the fact that the SE engine has low production cost, low fuel cost, rugged operation, high power and torque density, low working vibration, and can employ known mature catalyst technologies to reduce regulated emissions (carbon monoxide (CO), hydrocarbon (HC), and carbon dioxide (CO₂)). The market sector dominance with the SE engine in combination of legislative CAFE and RFS II standards suggests that increases to SE engine efficiency with biofuels might offer a very plausible path toward sustainable CAFE and RFS II compliance.

Although the SE engine may have beneficial attributes, its efficiency is fundamentally limited by the density of air, and the compression ratio is limited by combustion knock. These two factors serve to lower thermodynamic efficiency (defined as the efficiency of converting heat energy to efficiency to do useful work) of

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SAE MOBILITY DATA CENTER

Intermediate Alcohol-Gasoline Blends, Fuels for Enabling Increased Engine Efficiency and Powertrain Possibilities

Derek Splitter and James Szybist
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ABSTRACT

The present study experimentally investigates spark-ignited combustion with 87 AKI EGR gasoline in its neat form and in mid-level alcohol-gasoline blends with 24% vol/vol isobutanol-gasoline (IB24) and 30% vol/vol ethanol-gasoline (E30). A single-cylinder research engine is used with a low and high compression ratio of 9.2:1 and 11.85:1 respectively. The engine is equipped with hydraulically actuated valves, laboratory intake air, and is capable of external exhaust gas recirculation (EGR). All fuels are operated to full-load conditions with $\lambda = 1$, using both 0% and 15% external cooled EGR. The results demonstrate that higher octane number bio-fuels better utilize higher compression ratios with high stoichiometric torque capability. Specifically, the unique properties of ethanol enabled a doubling of the stoichiometric torque capability with the 11.85:1 compression ratio using E30 as compared to 87 AKI, up to 20 bar IMEP_{st} at $\lambda = 1$ (with 15% EGR, 10.5 bar IMEP with 0% EGR). EGR was shown to provide thermodynamic advantages with all fuels. The results demonstrate that E30 may further the downsizing and downsweeping of engines by achieving increased low speed torque, even with high compression ratios. The results suggest that at mid-level alcohol-gasoline blends, engine and vehicle optimization can offset the reduced fuel energy content of alcohol-gasoline blends, and likely reduce vehicle fuel consumption and tailpipe CO₂ emissions.

CITATION: Splitter, D., and Szybist, J., "Intermediate Alcohol-Gasoline Blends, Fuels for Enabling Increased Engine Efficiency and Powertrain Possibilities," SAE Int. J. Fuels Lubr. 7(1):1214-1221, 2014.

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SAE INTERNATIONAL

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INTRODUCTION

The Energy Independence and Security Act of 2007 [1] requires that by year 2022, 16 billion gallons per year of bio-derived fuels be consumed in transportation. This up-to-date bio-derived fuels is more than a seven-fold increase from 4.7 billion gallons consumed per year when the law was enacted. The rules for complying with this mandate are specified by the U.S. Environmental Protection Agency in the Renewable Fuel Standard II (RFS II) [2]. When the transportation energy consumption is analyzed, it is apparent that this legislation increases the usage of bio-fuels. In the United States, consumed 27.97 quadrillion BTU of energy for transportation, and is projected to consume 29.24 quadrillion BTU in 2022 [3]. Assuming a gasoline equivalent energy of 42.8 MJ/kg and density of 740 kg/m³, the RFS standard will require an increase in the volumetric power of transportation energy from biofuels to approximately 2022 from the approximately 2% in 2007. To date, the RFS II program has seen more than a doubling of biofuel usage the annual recorded share of transportation energy from non-petroleum sources totaling 4.3% in 2012, although 2012 was the year with the largest biofuel energy share on record. There is still an additional 2-fold increase in biofuel energy share required to comply with the RFS II mandate.

Gasoline-Like Fuel Effects on High-Load, Boosted HCCI Combustion Employing Negative Valve Overlap Strategy

Vickey B. Kalaskar, Derek A. Splitter, and James P. Szybist
Oak Ridge National Lab.

ABSTRACT

In recent years a number of studies have demonstrated that boosted operation combined with external EGR is a path forward for expanding the high load limit of homogeneous charge compression ignition (HCCI) combustion with the negative valve overlap (NVO) charge strategy. However, the effects of fuel composition with this strategy have not been fully explored. In this study boosted HCCI combustion is investigated in a single-cylinder research engine equipped with direct injection (DI) loading, cooled external exhaust gas recirculation (EGR), laboratory pressurized intake air, and a fully variable hydraulic valve actuation (HVA) valve train. Three fuels with significant compositional differences are investigated: regular grade gasoline (RGN + 90.2), 30% ethanol-gasoline blend (E30, RON + 100.3), and 24% iso-butanol-gasoline blend (IB24, RON + 98.4). Results include engine loads from 350 to 800 kPa IMEP_{st} for all fuels at three engine speeds 1600, 2000, and 2500 rpm. All operating conditions achieved thermal efficiency (gross indicated efficiency) between 36 and 47%, low NO_x emissions (0.1 g/kWh), and high combustion efficiency (96.5%). Detailed sweeps of intake manifold pressure (atmospheric to 200 mBar), EGR (0 - 25% EGR), and injection timing are conducted to identify fuel-specific effects. The major finding of this study is that while significant fuel compositional differences exist, in boosted HCCI operation only minor changes in operational conditions are required to achieve comparable operation for all fuels. In boosted HCCI operation all fuels were able to achieve matched load-speed operation, whereas in conventional SI operation the fuel-specific knock differences resulted in significant differences in the operable load-speed space. Although all fuels were operable in boosted HCCI, the respective air handling requirements are also discussed, including an analysis of the demanded turbocharger efficiency.

CITATION: Kalaskar, V., Splitter, D., and Szybist, J., "Gasoline-Like Fuel Effects on High-Load, Boosted HCCI Combustion Employing Negative Valve Overlap Strategy," SAE Int. J. Fuels Lubr. 7(1):1214-1221, 2014.

INTRODUCTION

Despite the fact that HCCI has not realized its potential on production engines in the more than 30 decades since it was originally reported [1, 2, 3], it remains a promising mode of combustion to simultaneously achieve high efficiency and low NO_x emissions. While there has been a substantial amount of research and development on HCCI combustion, there remains a significant number of implementation barriers.

Some of the barriers associated with HCCI have been overcome, or substantially reduced. Specifically, sensors for feedback control, engine controllers, valve trains, and DI fueling systems have all developed at a rapid rate, providing a greater means to control HCCI combustion [4]. However, additional substantial barriers still remain, that limit the current production viability of HCCI. Specifically, under naturally aspirated conditions, HCCI combustion is limited to a relatively light operating load of approximately 400 kPa net indicated mean effective pressure (IMEP_{st}). While this has always been

a limitation of naturally aspirated HCCI combustion, it is becoming even more critical given the trends of engine downsizing and hybridization for fuel economy improvements [5]. Downsized engines utilize turbo-machinery for higher specific power, allowing the engine to operate at higher loads with higher efficiency than a larger displacement naturally aspirated engine. Hybrid electric technologies aim to minimize the use of the engine at the lightest load conditions where efficiency is lowest. In both cases the engine duty cycle is shifted to higher specific power conditions, thereby reducing the relevance of naturally aspirated HCCI combustion.

Using a boosted air handling system has been shown as a way to provide additional thrust has been identified as a path for higher load HCCI combustion [6, 7, 8, 9, 10]. The present study builds on the cited works by employing DI fueling, the engine facility used at ORNL, has been previously reported in [11] where engine loads in excess of 800 kPa IMEP_{st} were demonstrated, while also characterizing the NVO engine control authority and sensitivity. The results specifically found

¹ Defined as the indicated mean effective pressure for the entire 4-stroke process. [4, 12, 13].

<http://info.ornl.gov/sites/publications/Files/Pub44420.pdf>

<http://info.ornl.gov/sites/publications/Files/Pub47043.pdf>

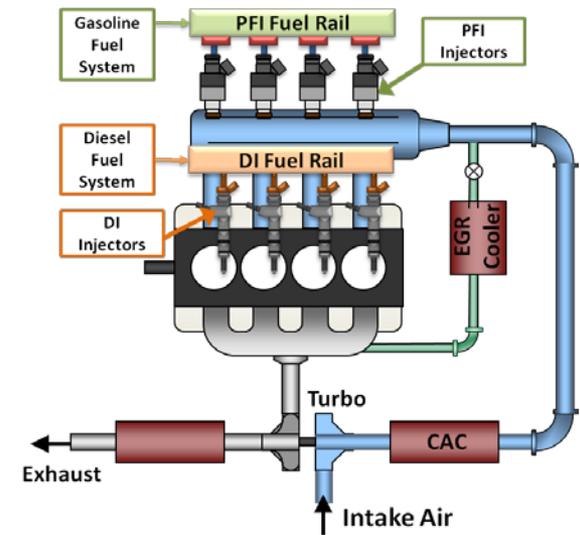
OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

SINGLE- AND DUAL-FUEL LOW TEMPERATURE COMBUSTION (LTC) EXPERIMENTS CONDUCTED ON FLEXIBLE MULTI-CYLINDER PLATFORM

APPROACH (4/4)

- **2007 GM 1.9-L multi-cylinder diesel engine**
 - OEM (CR 17.5) and **modified RCCI** pistons (CR 15.1)
 - 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
 - Multi-mode (RCCI to conventional diesel combustion) used for areas of the drive cycle outside the RCCI operating range
 - Comparison between 2009 PFI, diesel and multi-mode diesel/RCCI

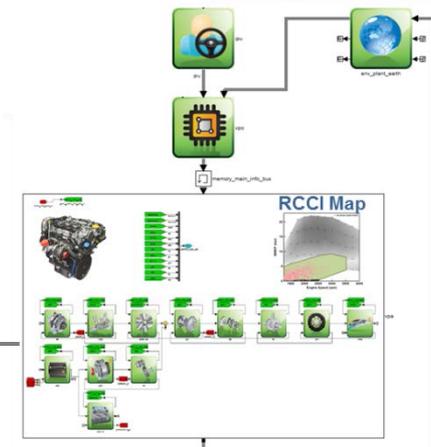


ORNL RCCI Multi-Cylinder 1.9L GM

AUTONOMIE Simulink/ Stateflow



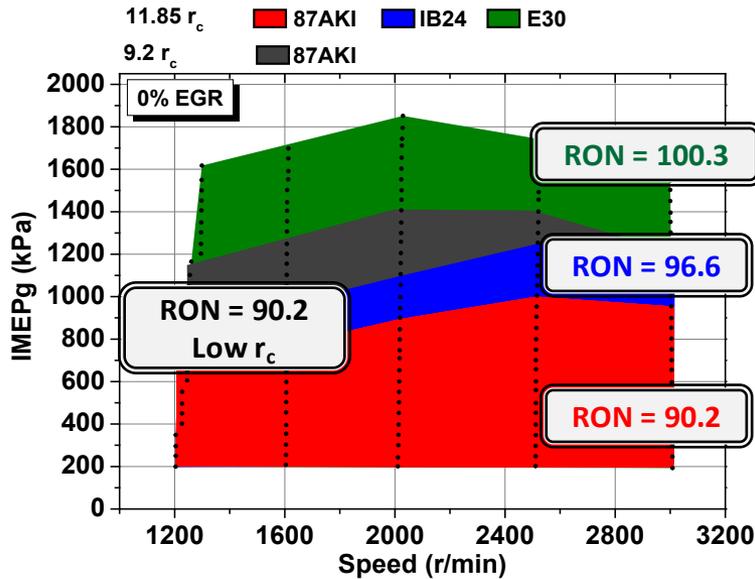
Modeled Fuel Economy



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

E30 ENABLED A HIGHER INCREASE IN THE PEAK ENGINE TORQUE THAN OCTANE NUMBER ALONE SUGGESTS FOR SI COMBUSTION

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 SUMMARY



- Peak load dependent on fuel type
 - Trends with octane number
- Low octane fuels encounter knock at lighter loads, require combustion phasing retard to mitigate knock
 - Retarded phasing reduces efficiency and increases exhaust T
 - Operating limits for exhaust T and retarded phasing encountered at lighter loads

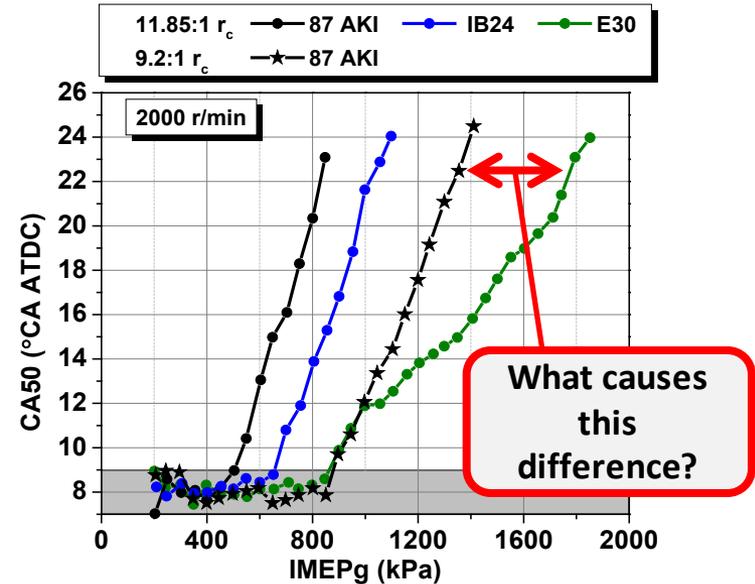
- E30 is more effective at mitigating knock than octane number alone suggests

- Knock is initially encountered where expected based on RON
- Phasing retard is more effective at knock mitigation for E30
- Knock mitigation allows higher engine load

- Reason for this behavior isn't fully understood

- Octane sensitivity, heat of vaporization, **flame speed**, pressure sensitivity, ethanol-specific kinetics

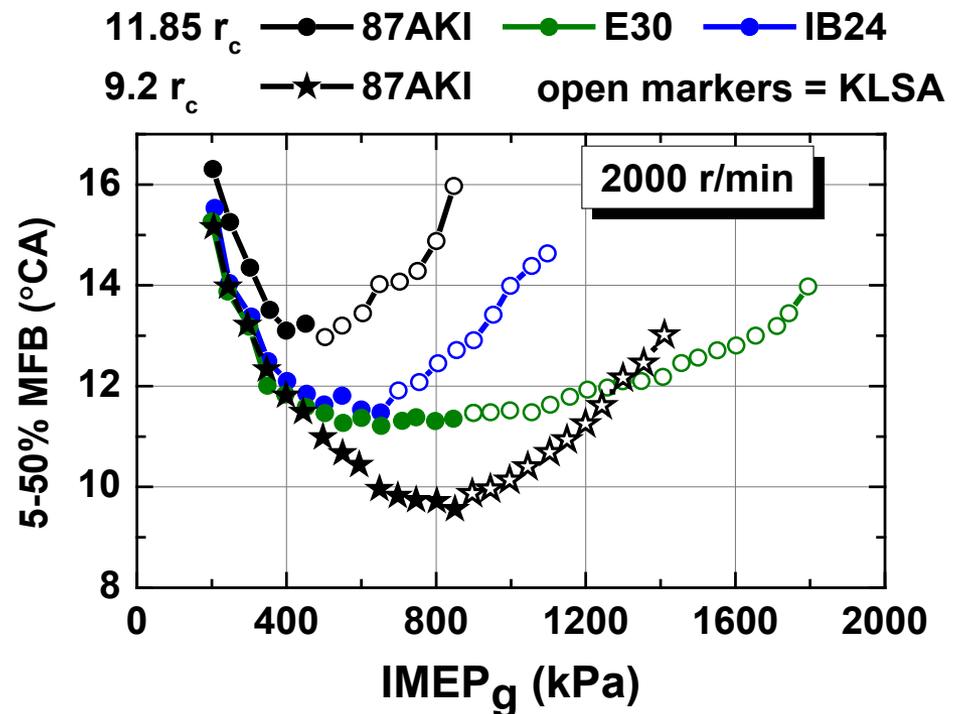
- System efficiency benefits from high torque at low speed



ALCOHOL FUELS HAVE SHORTER COMBUSTION DURATION AT RETARDED PHASING, CONTRIBUTES TO KNOCK MITIGATION

ACCOMPLISHMENTS (2/9)

- Short combustion duration increases efficiency mitigates knock
 - Increases the time available for expansion and decreases the time that unburned gases are exposed to high temperature for knock
- Combustion duration is dependent on load and phasing for all fuels
 - Flame speed initially decreases at advanced phasing
 - Flame speed increases with phasing retard to mitigate knock
- E30 combustion duration is less sensitive to late combustion phasing
 - Publication decouples phasing and load
- Flame speed is very dependent on combustion chamber design
 - OEM 9.2:1 r_c piston has a substantially higher flame speed than the 11.85:1 r_c piston



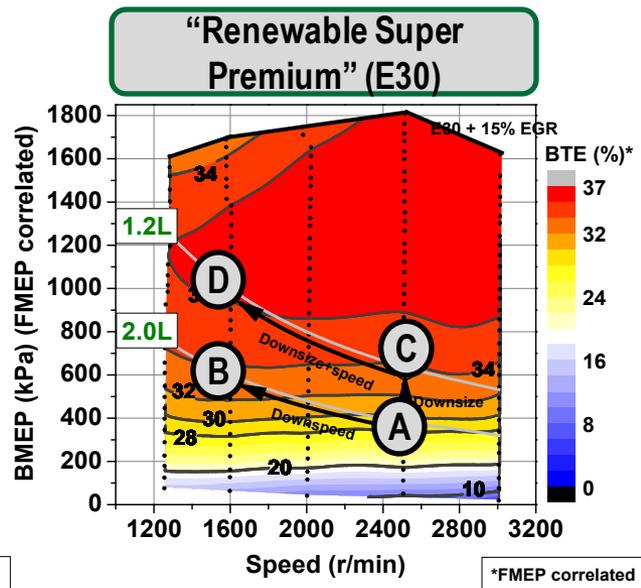
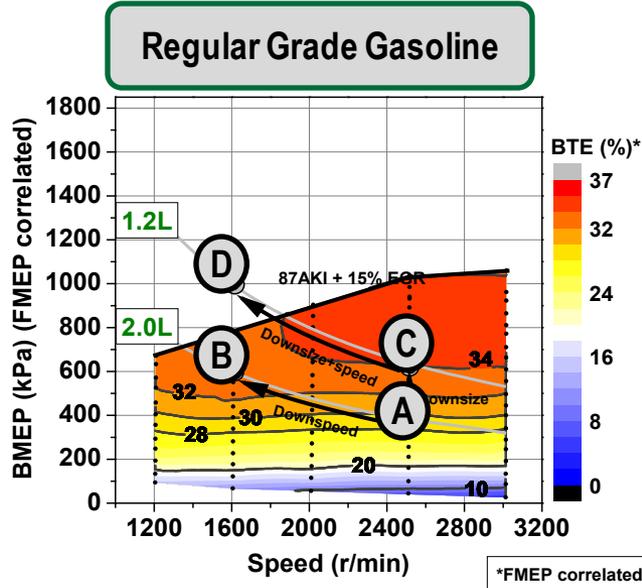
HIGHER PEAK TORQUE FOR E30 CAN ENABLE FUEL ECONOMY BENEFITS (EFFICIENCY OUTPACES ENERGY DENSITY PENALTY)

ACCOMPLISHMENTS (3/9)

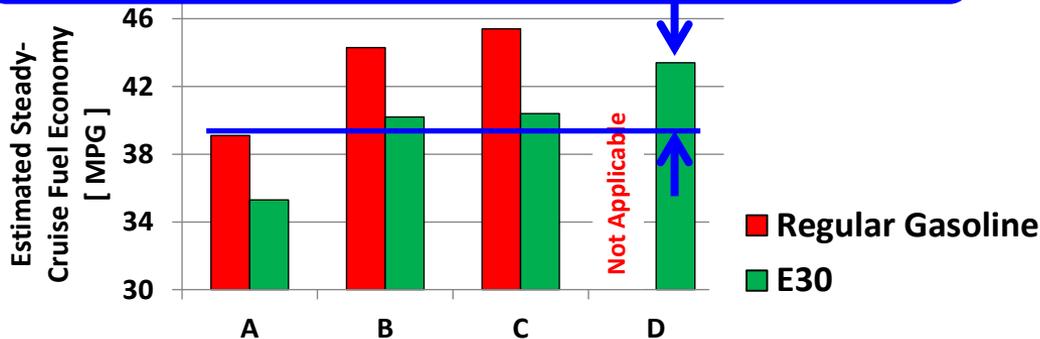
Note: This analysis is simplistic and is meant to illustrate trends of downsizing and downspeaking. These results are not quantitatively representative for all driving cycles.

Steady cruise at 65 mph
(16 kW brake power)

- (A)** Standard Configuration
- (B)** Aggressive Downspeaking
- (C)** Aggressive Downsizing
- (D)** Aggressive Downsizing and Downspeaking



Benefits can Enable Higher Fuel Economy for High Octane Blends Despite Energy Density Penalty

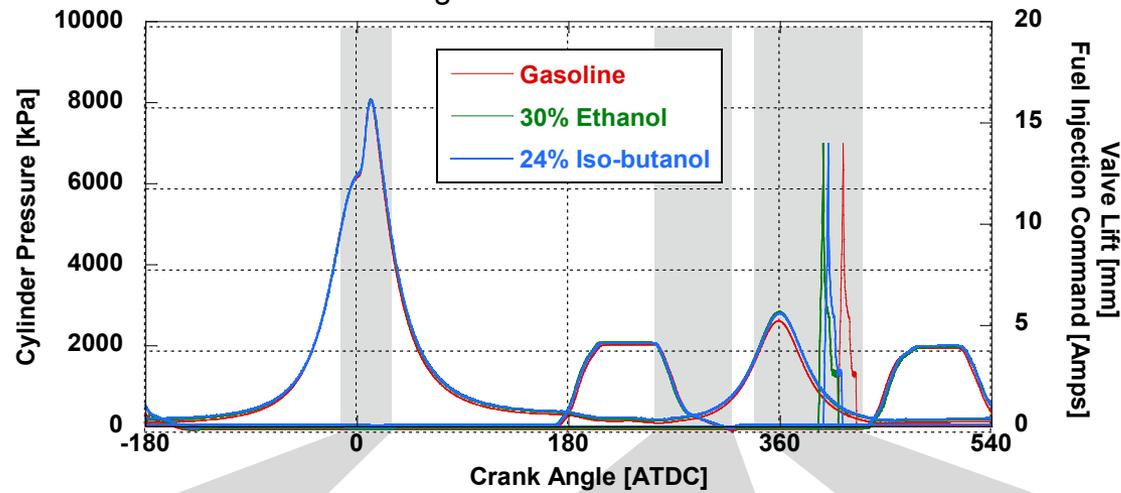


- Downsizing and downspeaking options are more limited for regular grade gasoline
- RSP can enable much more aggressive downsizing and downspeaking

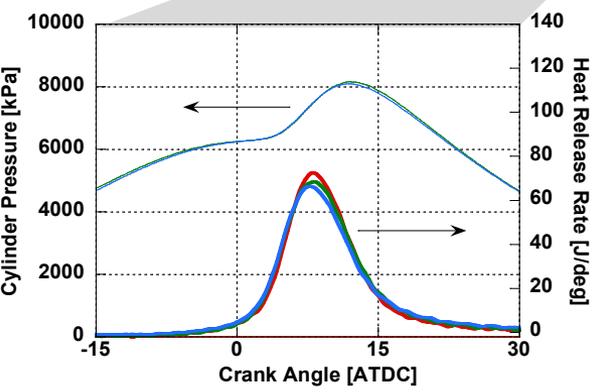
HCCI STRATEGY ALLOWED COMPARABLE PERFORMANCE AND EFFICIENCY FOR ALL FUELS WITH ONLY MINOR CHANGES IN CONTROLS

ACCOMPLISHMENTS (4/9)

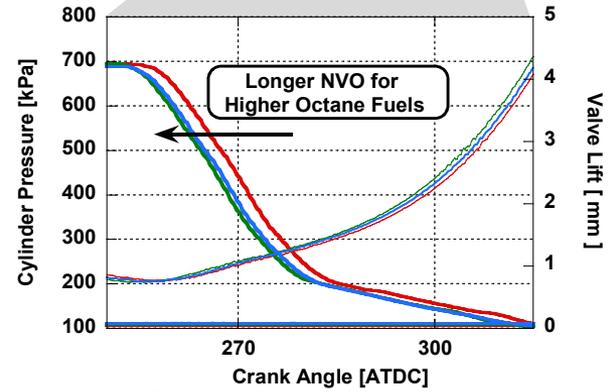
2000 RPM, 7.0 bar IMEP_{gross}, 230 kPaa MAP, 20% EGR



Comparable Pressure and Heat Release for All Fuels

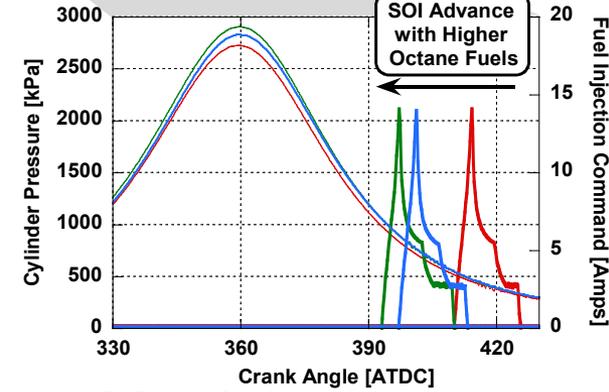


NVO Duration for "Coarse" Phasing Control



3 CA advance in exhaust valve closing angle for E30

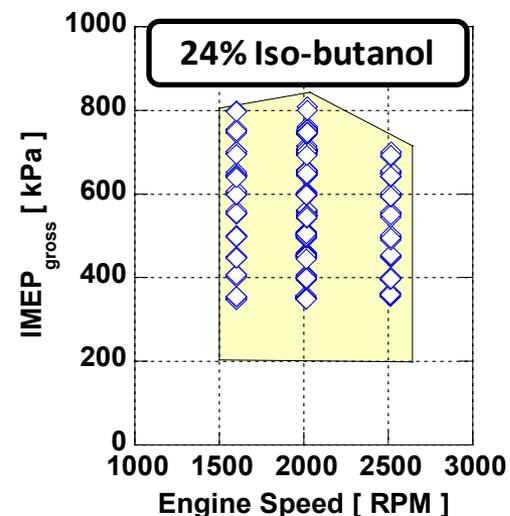
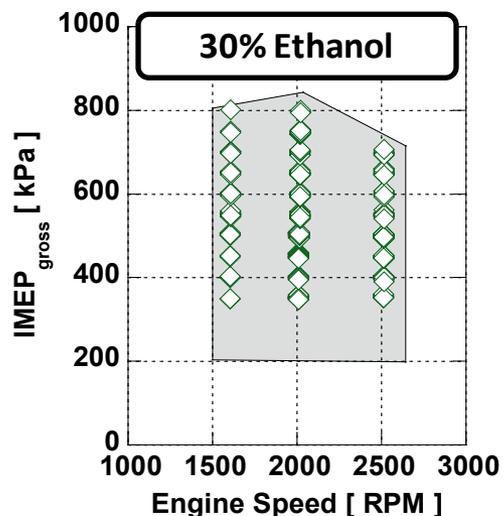
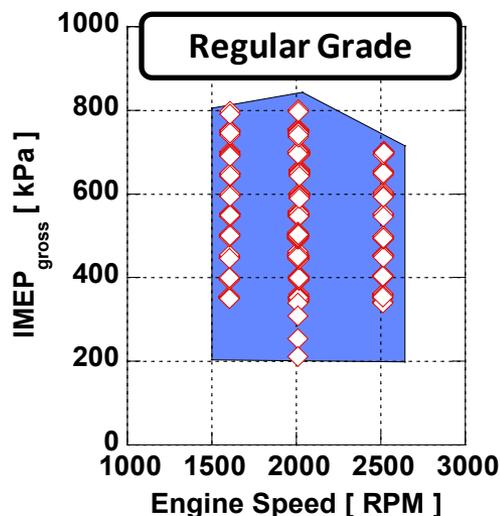
Fuel Injection Timing for "Fine" Phasing Control



12 CA advance in injection timing for E30

NO FUEL-SPECIFIC DIFFERENCES IN HCCI OPERABLE PEAK LOAD WHEN MINOR CHANGES TO ENGINE OPERATING PARAMETERS ARE APPLIED

ACCOMPLISHMENTS (5/9)

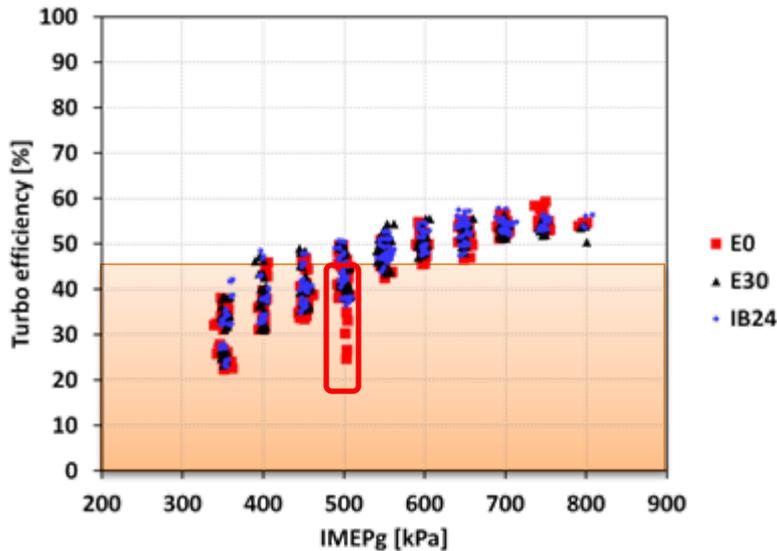


- Engine limitations encountered prior to fuel-specific differences
 - 100 bar peak cylinder pressure limit for all fuels
 - Comparable efficiency and emission for all fuels as well (including NO_x < 0.1 g/kWh)
- Low load limit of HCCI was not included in this investigation (requires pilot injection)
 - Previously investigated at ORNL (*SAE Int. J. Engines* 5(3):1149-1162, 2012)
- Significant gross thermal efficiency improvements relative to SI combustion
 - Transference to brake work is dependent on turbocharger efficiency

PUMPING WORK CAN CONSUME GROSS EFFICIENCY BENEFIT OF BOOSTED HCCI WITH REASONABLE TURBOCHARGER EFFICIENCY ASSUMPTIONS

ACCOMPLISHMENTS (6/9)

- At 10 kPa ΔP, turbocharger efficiency requirement becomes unrealistic
 - Too little enthalpy in exhaust to meet air handling requirements
 - Increasing backpressure for realistic turbo efficiency increases pumping work

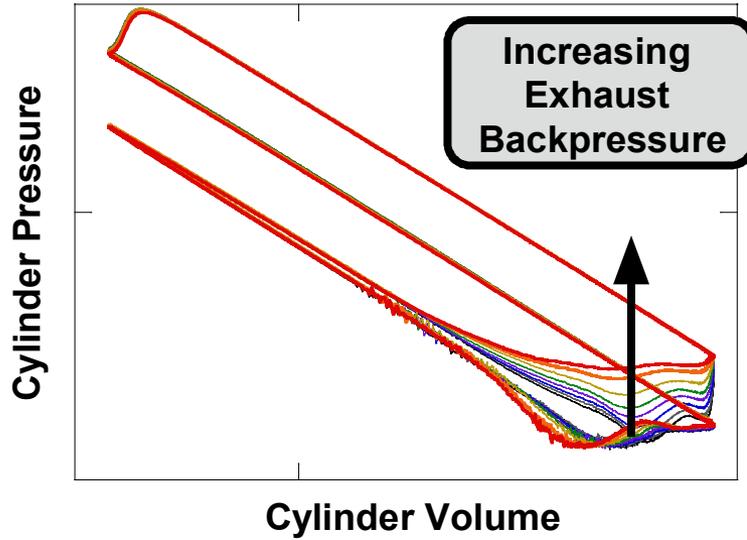


$$\eta_{combined} = \frac{\left(\frac{\gamma_{comp}}{\gamma_{comp} - 1}\right) \left(\frac{T_{comp,in}}{T_{turb,in}}\right) \left[\left(\frac{P_{comp,in}}{P_{comp,out}}\right)^{\left(\frac{\gamma_{comp}-1}{\gamma_{comp}}\right)} - 1 \right]}{\left(1 + \frac{1}{AFR}\right) \left[1 - \frac{P_{turb,out}}{P_{turb,in}} \left(\frac{\gamma_{turb}-1}{\gamma_{turb}}\right) \right]}$$

**Exhaust
Backpressure**

PUMPING WORK CAN CONSUME GROSS EFFICIENCY BENEFIT OF BOOSTED HCCI WITH REASONABLE TURBOCHARGER EFFICIENCY ASSUMPTIONS

- At 10 kPa ΔP, turbocharger efficiency requirement becomes unrealistic
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$$\eta_{combined} = \frac{\left(\frac{\gamma_{comp}}{\gamma_{comp} - 1}\right) \left(\frac{T_{comp,in}}{T_{turb,in}}\right) \frac{\left[\left(\frac{P_{comp,in}}{P_{comp,out}}\right)^{\left(\frac{\gamma_{comp}-1}{\gamma_{comp}}\right)} - 1\right]}{\left(1 + \frac{1}{AFR}\right) \left[1 - \frac{P_{turb,out}}{P_{turb,in}} \left(\frac{\gamma_{turb}-1}{\gamma_{turb}}\right)\right]}$$

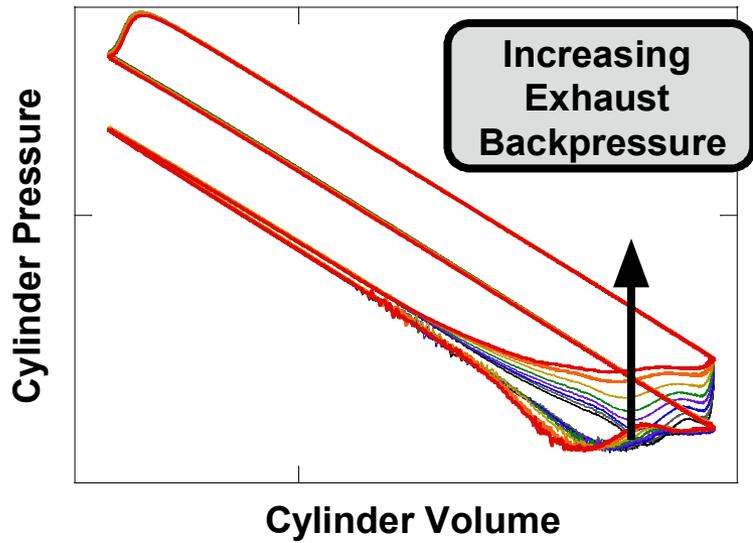
Exhaust Backpressure

Pumping work is increased by a factor of 3 to reduce turbocharger efficiency requirement down from 45% to 25% (-30 to -90 kPa PMEP)

PUMPING WORK CAN CONSUME GROSS EFFICIENCY BENEFIT OF BOOSTED HCCI WITH REASONABLE TURBOCHARGER EFFICIENCY ASSUMPTIONS

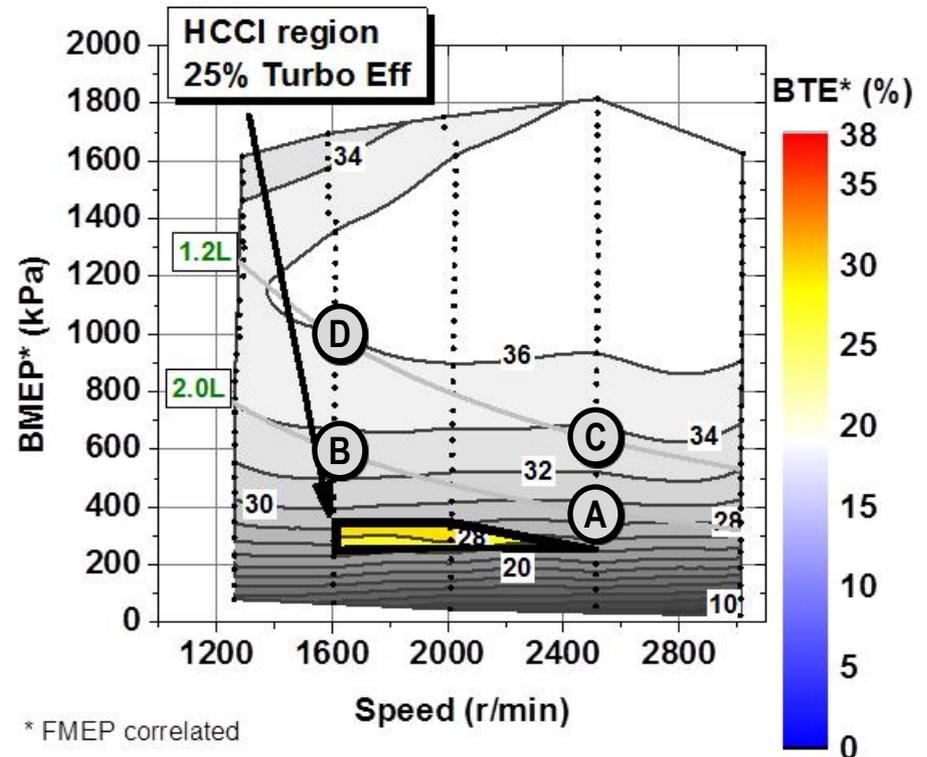
ACCOMPLISHMENTS (6/9)

- At 10 kPa ΔP , turbocharger efficiency requirement becomes unrealistic
 - Too little enthalpy in exhaust to meet air handling requirements
 - Increasing backpressure for realistic turbo efficiency increases pumping work



Pumping work is increased by a factor of 3 to reduce turbocharger efficiency requirement down from 45% to 25% (-30 to -90 kPa PMEP)

Impact of HCCI on real world efficiency will be more dependent on turbocharger efficiency than fuel type



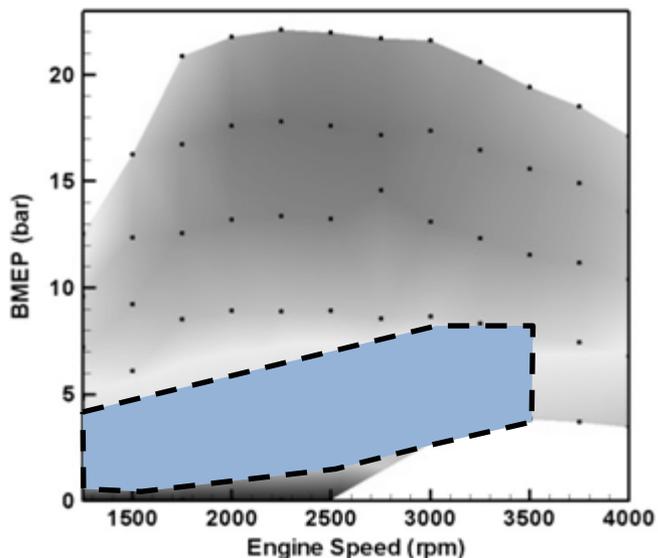
* FMEP correlated

HIGH-LEVEL MILESTONE MET TO EXCEED 75% DRIVE CYCLE COVERAGE OVER CITY AND HIGHWAY CYCLES WITH RCCI COMBUSTION

ACCOMPLISHMENTS (7/9)

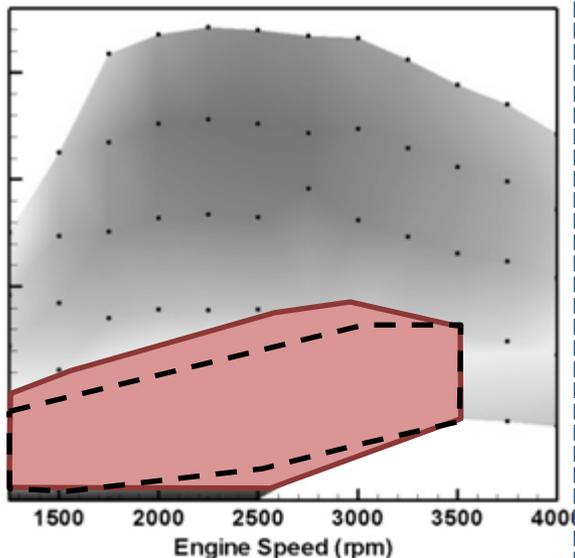
- Conventional diesel combustion modes used for speed/load demands outside of RCCI range
 - B20 RCCI expands high and low load of RCCI improving drive-cycle coverage
 - E30 RCCI map shifted RCCI range up, reducing coverage compared to B20 map

Diesel / Gasoline



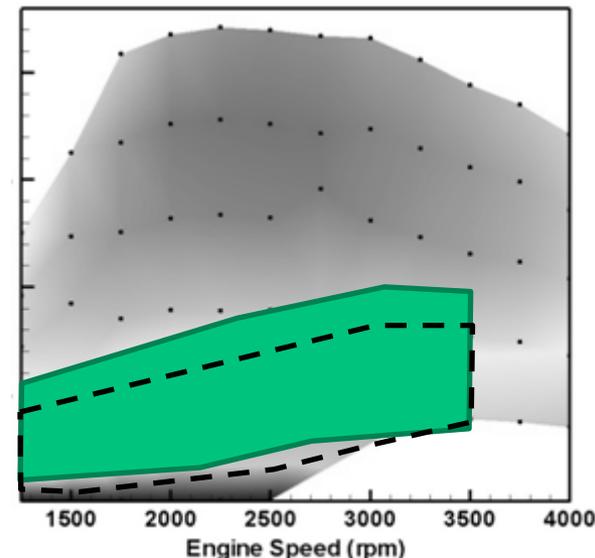
RCCI operational space with conventional fuels

20% Biodiesel Blend / Gasoline



Expanded low and high load due to higher PFI to DI ratio

Diesel / 30% Ethanol Blend



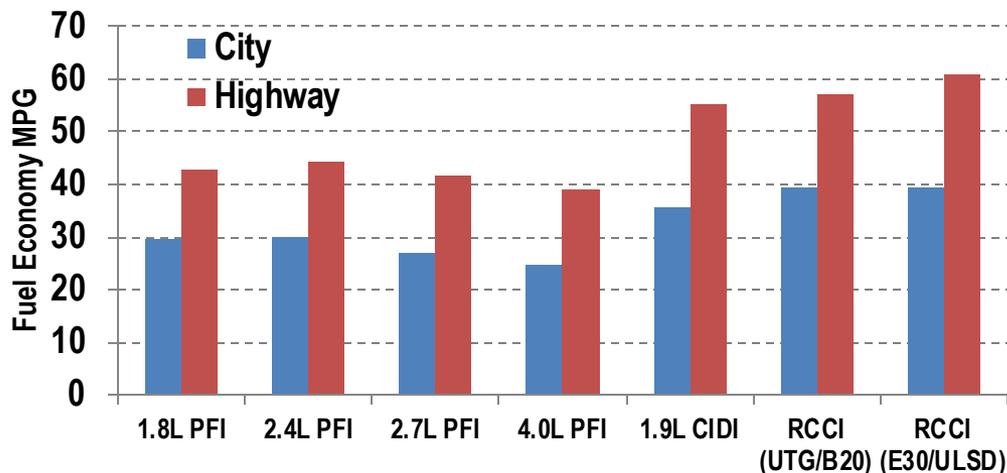
Expanded high load due to higher octane and charge cooling, reduced low load due to stability issues

EXPANDED RANGE ENABLED BY BIOFUEL BLENDS ENABLED IMPROVED FUEL ECONOMY RELATIVE TO GASOLINE OR DIESEL BASELINES

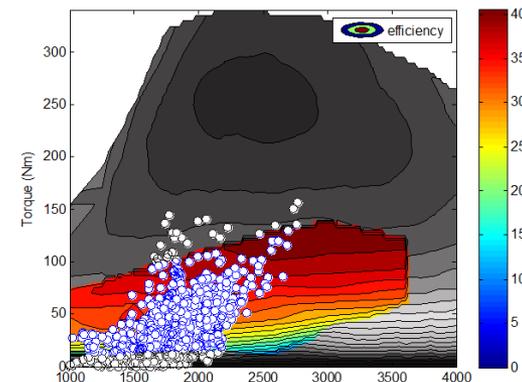
ACCOMPLISHMENTS (8/9)

- Modeling results show greater than 75% drive cycle coverage with RCCI over UDDS (city) and HWFET (highway) with B20 and gasoline
 - Optimized shifting schedule allowed for better total coverage
 - Sacrifice a little on HWFET fuel economy but improves UDDS

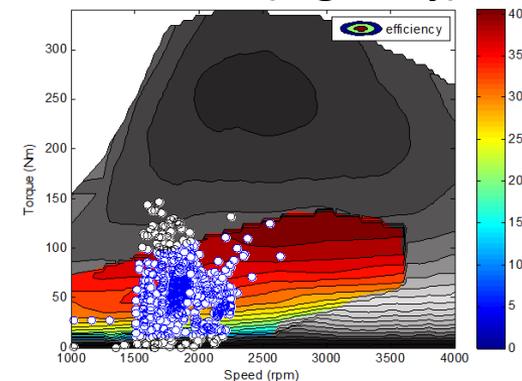
RCCI	Fuel Economy	RCCI distance	cycle distance	Cycle Coverage
UNIT	MPG	MILE	MILE	%
UDDS	39.50	5.87	7.45	79
HWFET	53.55	9.49	10.25	93



UDDS (city)



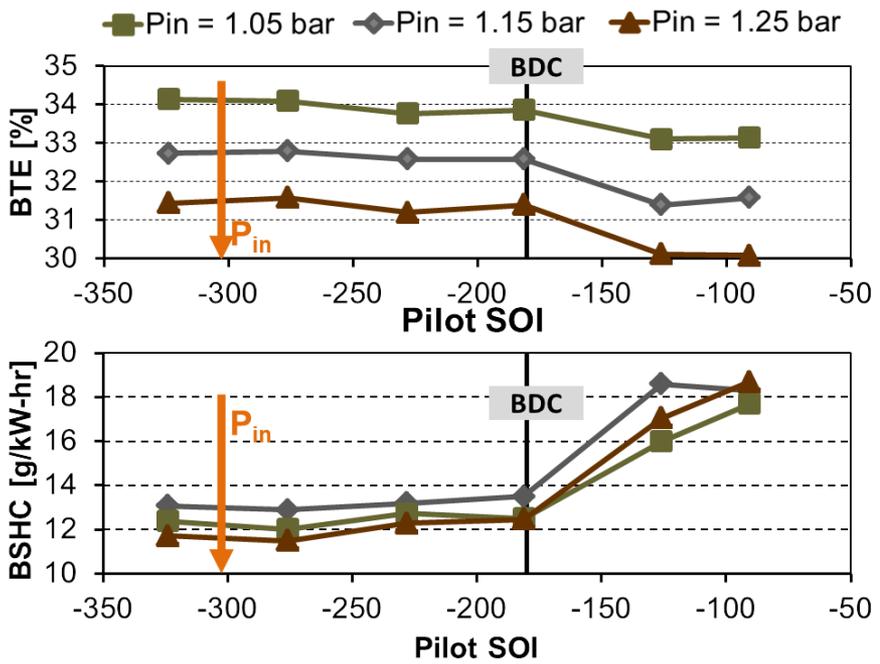
HWFET (highway)



- 41% improvement in combined city/hwy MPG compared to PFI baseline
- 6% improvement in combined compared to conventional diesel combustion (CDC)

Exploratory “PPC” Studies on Single Fuel have been Conducted for Apples-to-Apples Comparison to RCCI

- Initial results show BTE higher than diesel but lower than RCCI
 - While achieving very low NOx and soot emissions
- Huge parameter space – combustion strategy development remains
 - Initial pilot sweep results with main SOI around 30 CAD BTDC (varies stratification)
 - Results for boost sweep show strong effect from pumping work
- Plans to conduct larger fuels matrix (fuels supplied by Chevron Energy Technology Co.)



	CDC	RCCI	PPC
	ULSD	B20 96RON	70 RON
Fuels			
BTE (%)	33.4	35.8	34.7
NOx (ppm)	96	26	10
HC (ppm)	161	2164	2615
CO (ppm)	322	1733	2100
FSN (-)	1.02	0.01	0.01

2000 rpm, 4.0 bar BMEP

REVIEWER COMMENTS FROM FY 2013 – FT008

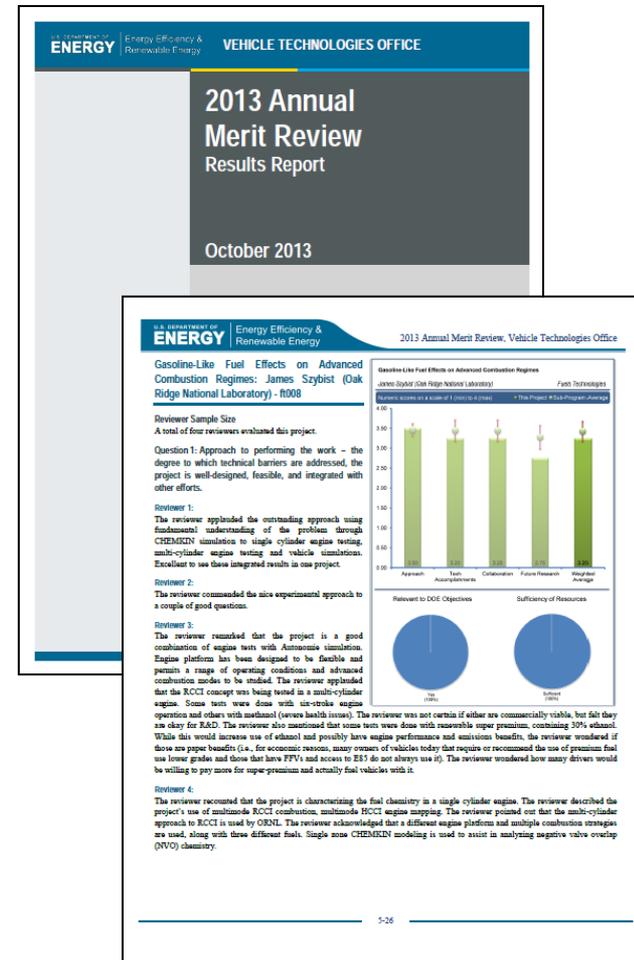
PROJECT OVERVIEW
RELEVANCE
MILESTONES
APPROACH
ACCOMPLISHMENTS
REVIEW COMMENTS
COLLABORATIONS
FUTURE WORK
SUMMARY

Reviewer Comments were Overall Very Positive (paraphrasing)

- Outstanding approach using fundamental modeling, to single- and multi-cylinder engine testing, to vehicle simulations. Excellent to see these integrated in one project.
- All high-level milestones had either been completed or were on-track for completion
- This project is in alignment with the DOE goal of reduced petroleum consumption through higher efficiency and direct displacement with renewable fuels
- Strong collaborations with industry, National Laboratories, and universities

Areas for Improvement (paraphrasing)

- It would be nice to see the effect that the reformate species have on the subsequent combustion event. This is an excellent suggestion. This is the direction that the research is headed (see Future Work slides).
- Performing a cold-start FTP emissions test should be the top priority for the RCCI project. This is currently outside the scope of this project, and will likely be outside the scope for several years. We are currently focused on more fundamental fuel/engine/combustion interactions. The initial steps for transient operation are being pursued.
- Unsure whether RSP will be a good deal to consumer. This project aims to highlight the technical possibilities of RSP. We are aware that in doing so, we need to identify economic and deployment concerns.



http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2013/2013_amr_05.pdf

COLLABORATIONS LEVERAGE FUELS RESEARCH AT ORNL

PROJECT OVERVIEW
RELEVANCE
MILESTONES
APPROACH
ACCOMPLISHMENTS
REVIEWER COMMENTS
COLLABORATIONS (1/2)
FUTURE WORK
SUMMARY

• National Lab Partners

- Sandia National Laboratories study on NVO chemistry (co-authored 2014 SAE paper with results from both organizations)

• Industry Partners

- Chevron Energy Technologies— Supplying fuels for LTC project, upcoming joint publications
- ACEC – Support for ACEC-DOE goals and combustion noise discussions
- 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
- Others - Borg Warner

• University Partners

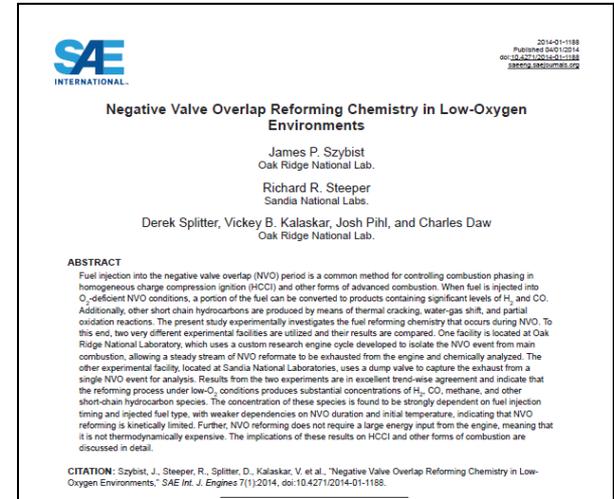
- Penn State University – Student researcher at ORNL for 8 months
- The University of Wisconsin-Madison – RCCI modeling

• Working Group Partners

- DOE AEC/HCCI working group meeting twice a year
- CLEERS (Cross-Cut Lean Exhaust Emissions Reduction Simulations)

• Other internal collaboration

- ORNL/ DOE Activities - ACE, Vehicle Systems, Stretch Efficiency and others
- ORNL bioenergy researchers, materials groups and others

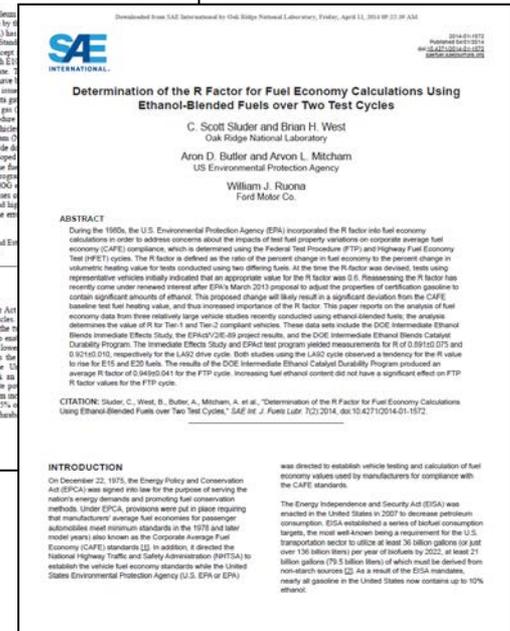
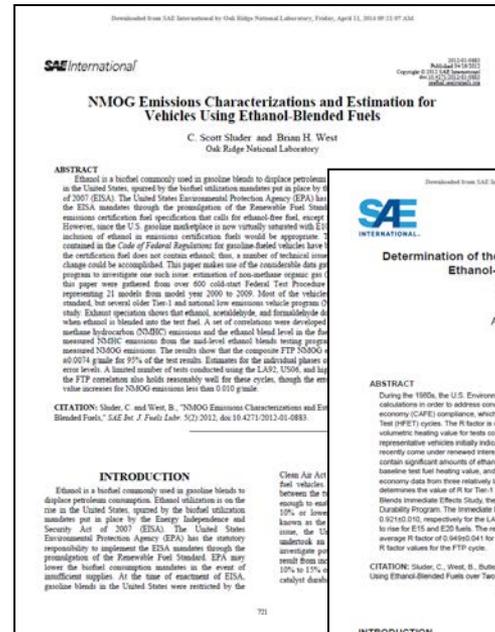


Discussion of engine research with industry visitors at ORNL.

THIS PROJECT CONTRIBUTES TO THE BROADER IMPACT OF ORNL'S FUELS PROGRAM

COLLABORATIONS (2/2)

- This project generated a significant portion of the data that is the basis for the High Octane Fuels Symposium (2014 was 2nd annual event)
 - Bring together industry stakeholders, regulators, and scientists to discuss future of renewable super premium
 - Topic is gaining significant momentum due to ORNL scientific work related to this project and organizing efforts
- Wrapped up \$46M DOE Intermediate Blends Studies with important publications
 - ORNL's NMOG correlation adopted directly in EPA Tier 3 and California LEV III Standards
 - Expected to be used routinely in new car certification tests
 - Significant reduction in test burden for OEMs
 - ORNL's analysis of the R-factor was cited by multiple stakeholders in the comments to the Tier 3 docket



ON SI ENGINE PLATFORM, MOVING FOCUS OF PROJECT TO FUEL EFFECTS ON HIGHLY DILUTE SI COMBUSTION WITH REFORMATE

PROJECT OVERVIEW
RELEVANCE
MILESTONES
APPROACH
ACCOMPLISHMENTS
REVIEWER COMMENTS
COLLABORATIONS
FUTURE WORK (1/2)
SUMMARY

EGR DILUTION FOR SI COMBUSTION BENEFITED EFFICIENCY FOR ALL FUEL TYPES

- 6-stroke experiments presented at 2013 AMR illustrated a pathway toward in-cylinder reforming
 - H_2 , CO, and methane are all high octane number components → enables higher compression ratio
 - High flame speed of H_2 promotes stable combustion in dilute environments
- Fuel effects may be more closely associated with elemental composition than reactivity
 - Higher H/C fuels may generate more H_2
- Investigations to be performed on highly flexible and customized multi-cylinder engine platform
- Leverages activities in ACE program (see ACE015)



Modified Cylinder Head



Engine Installed at ORNL



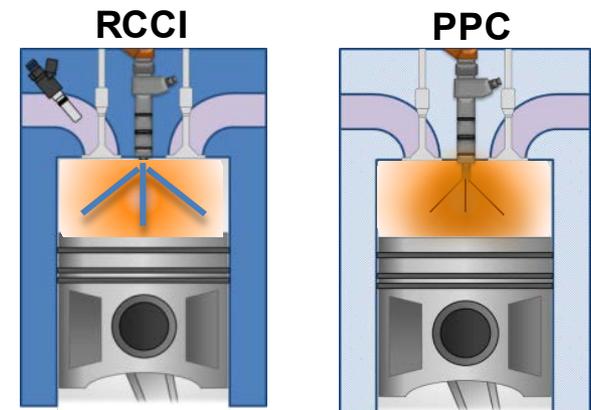
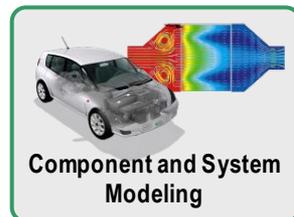
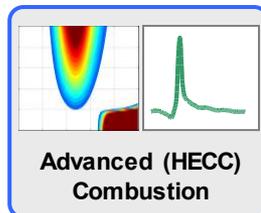
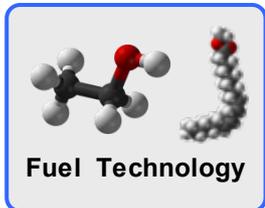
INVESTIGATIONS FOCUSING ON OCTANE NUMBER EFFECTS ON FUEL ECONOMY ARE CONTINUING TO BE PURSUED AT ORNL THROUGH A DIFFERENT FUEL EFFECTS PROJECT LED BY SCOTT SLUDER

FUTURE WORK FOR MULTI-CYLINDER LTC WILL CONTINUE TO EXPAND THE OPERABLE LOAD RANGE

FUTURE WORK (2/2)

OTHER POTENTIAL ADVANCED COMBUSTION APPROACHES WILL CONTINUE TO BE EVALUATED ON MULTI-CYLINDER ENGINES WITH A FOCUS ON FUEL AND LUBRICANT EFFECTS

- Combination of ethanol blend for low reactivity fuel and biodiesel blend for high reactivity fuel to approach 100% drive cycle coverage with RCCI
 - Use of biodiesel enabled PCCI for remainder of low load coverage
 - Transient RCCI operation drive cycle coverage evaluation with renewable fuels
- Evaluate PPC as compared to RCCI on the same engine, with the same hardware over a variety of gasoline-range fuels that seem well suited for gasoline compression ignition concepts
- Identify other alternative fuels that may have high enabling potential for single and dual-fuel advanced combustion



SUMMARY

PROJECT OVERVIEW
RELEVANCE
MILESTONES
APPROACH
ACCOMPLISHMENTS
REVIEWER COMMENTS
COLLABORATIONS
FUTURE WORK
SUMMARY

RELEVANCE

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

EXPERIMENTAL APPROACH

- Flexible HVA valve train allows efficiency and emissions comparisons of different combustion operating modes on a common SI engine platform with different fuels
- Experimental approach to multi-cylinder RCCI uses production viable hardware and applies a mapping approach to quantify efficiency and emissions benefits through drive cycle simulation

ACCOMPLISHMENTS

- Compared 4 combustion modes (SI, dilute SI, HCCI and SA-HCCI) for 3 fuels (gasoline, IB24, and E30)
 - E30 can approach or exceed fuel economy of gasoline with proper engine/transmission configuration
 - HCCI combustion will be more constrained by air handling hardware than fuel composition
- Demonstrated >75% drive cycle coverage with RCCI to meet DOE milestone
 - Drive cycle modeling projects significant fuel economy improvement
- Single-fuel “PPC” strategy being developed for direct comparison with RCCI

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

- Investigate fuel effects on in-cylinder reforming and highly dilute SI combustion on highly flexible multi-cylinder engine platform with HVA valvetrain on one cylinder
- Continue to expand operable load range of multi-cylinder RCCI for drive cycle coverage, provide comparisons to PPC combustion with same engine hardware

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Technical Back-Up Slides



DUAL FUEL RCCI CONCEPT

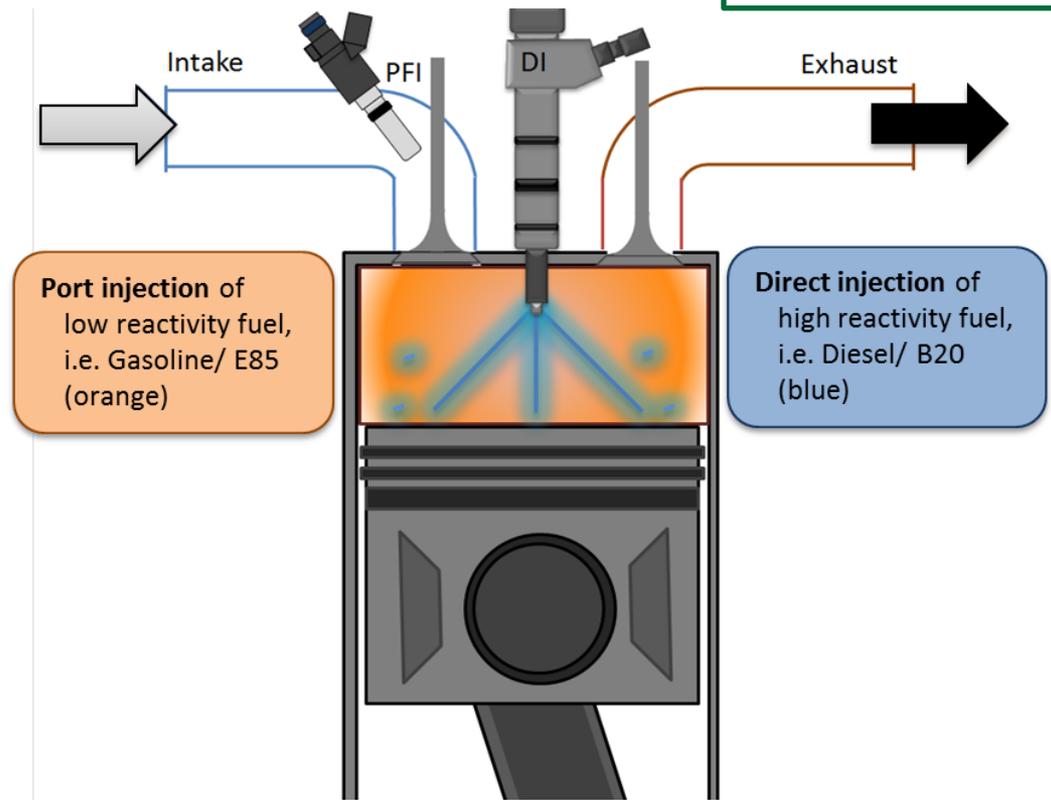
BACKUP 1

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 a both benefits and challenges to implementation of LTC

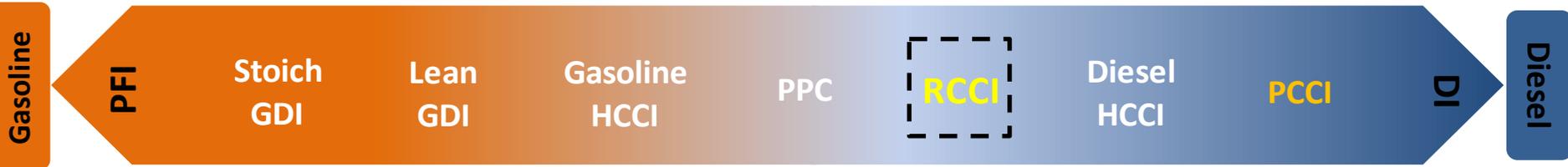
- Diesel-like efficiency or better
- Low NOx and soot
- Controls and emissions challenges



Low = Prevents Auto-Ignition

Fuel Reactivity

High = Promotes Auto-Ignition



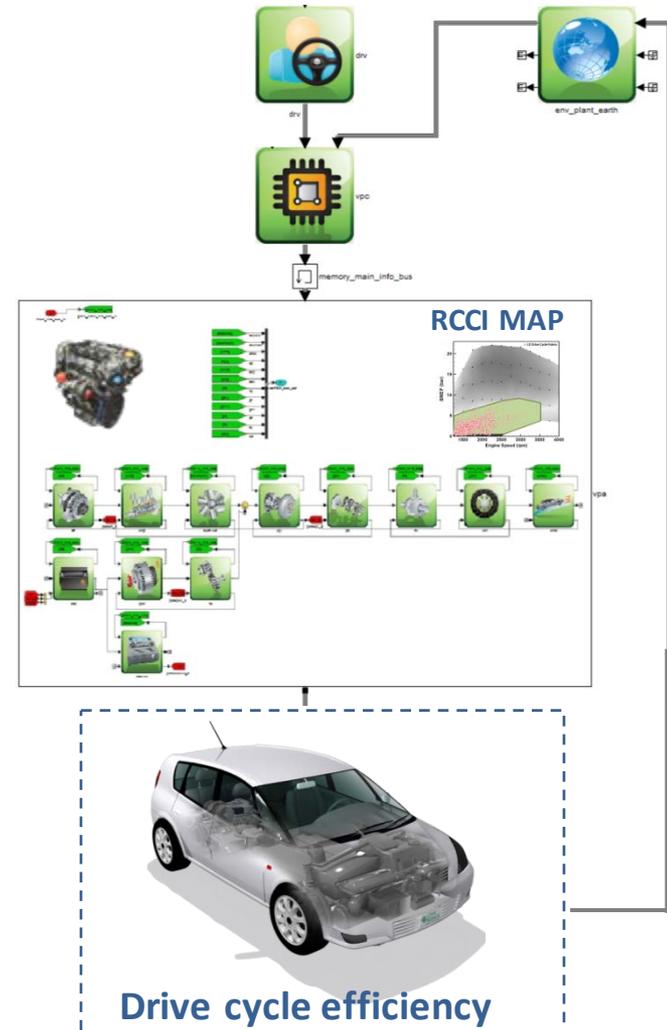
VEHICLE SYSTEM MODELING USING EXPERIMENTAL/ INDUSTRY ENGINE MAPS ON SAME VEHICLE IN AUTONOMIE 1

BACKUP 2

- 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 – ORNL Experimental map
 - 4.0L 2009 PFI Map – Automotive OEM
 - 1.9L Diesel Map (for comparison) Experimental ORNL map
- Multi-mode RCCI/Diesel strategy used
 - 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

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

AUTONOMIE Simulink/ Stateflow



SA-HCCI REDUCES COMBUSTION STABILITY AND INCREASES COMPLEXITY WHILE OFFERING LITTLE OR NO EFFICIENCY BENEFIT

BACKUP 3

- Lean operation of HCCI offers BTE gain vs. SI, dilute SI, or SA-HCCI
- Dilute SI and SA-HCCI produce comparable efficiency
 - SA-HCCI at $\lambda=1$ has higher EGR
 - SA-HCCI has lower pumping work
 - Hot EGR γ reduces GTE benefit vs. cooled EGR

At 2000 rpm, 500 kPa IMEPg, SA-HCCI has the lowest stability for CA50 and IMEPg

