GASOLINE-LIKE FUEL EFFECTS ON ADVANCED COMBUSTION REGIMES

PROJECT ID: FT008

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Oak Ridge National Laboratory

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DOE Management Team
Steve Goguen, Kevin Stork, and Steve Przesmitzki

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

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

- 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

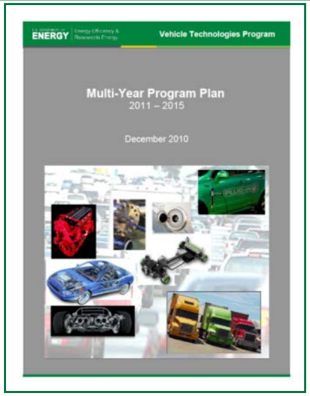
Industry

- ***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

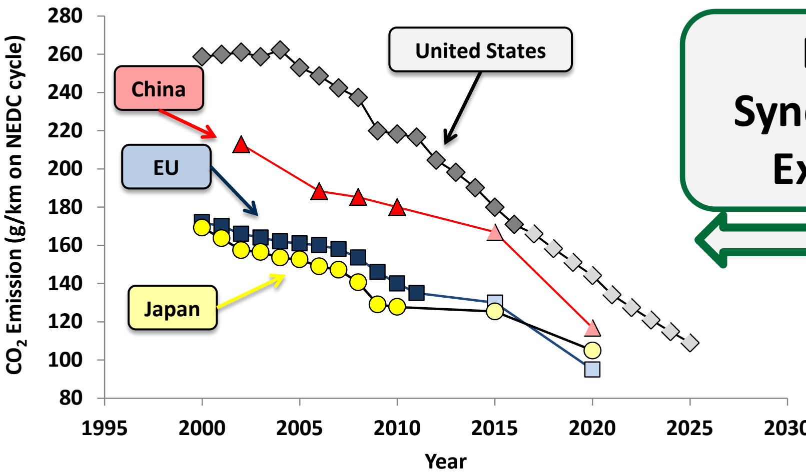


Goal of Fuels and Lubricant Technologies

(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…"

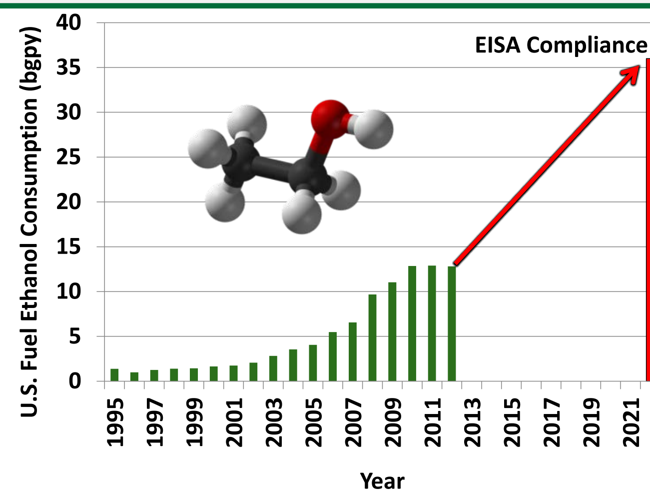
CAFE and GHG Emission Regulations



Automakers employing new engine technology to produce more efficient engines

Do Synergies Exist?

Renewable Fuels Standard



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

Two Milestones Tracked by DOE

2014 Joule Milestone: Multi-Mode RCCI Load Expansion

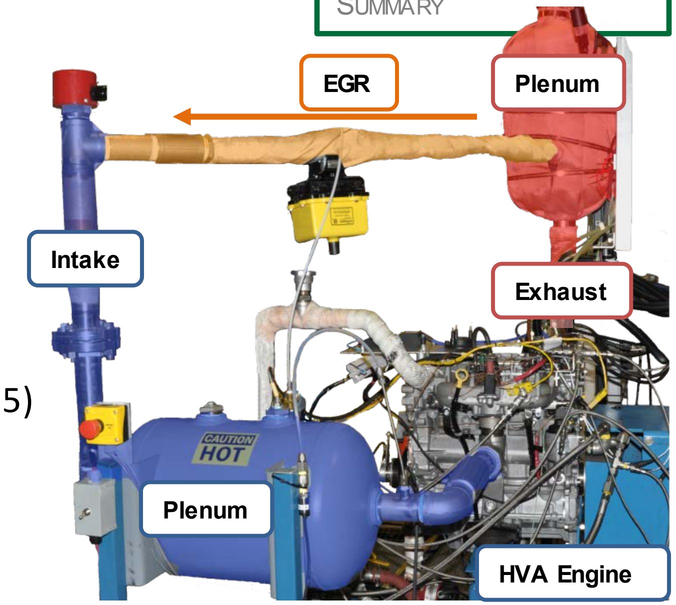
Demonstrate an increase in the RCCI operating range due to the use of renewable fuels allowing 75% coverage of non-idling portions of the city (UDDS) and highway (HWFET) light-duty federal drive cycles. ***Status: Complete***

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

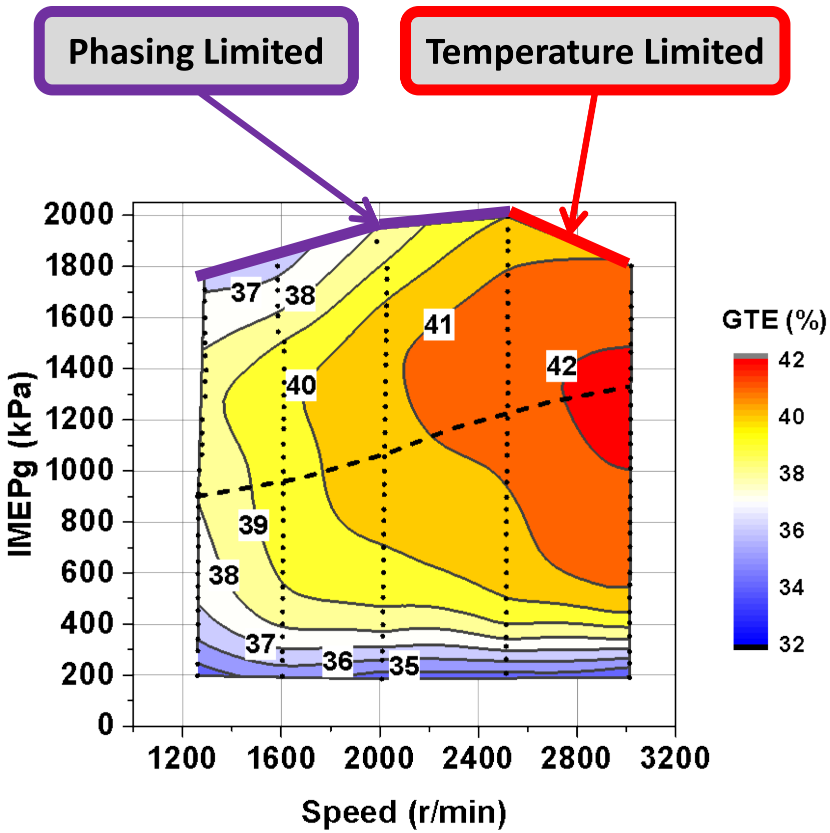
- Single cylinder engine with hydraulic valve actuation (HVA)
  - Modified 2.0L GM Ecotec engine with side-mount direct injection
  - Laboratory air handling (thermal management, boost, external EGR)
  - Custom piston for high compression ratio (11.85:1, stock 9.2:1)
- Same fuels used for all combustion 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

- 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 ≤ 2%
  - Dilution modulated to control noise



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

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

energy&fuels

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

Derek A. Splitter* and James P. Szybist

energy&fuels

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

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

SAE INTERNATIONAL

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

Derek Splitter and James Szybist
Oak Ridge National Lab.

SAE INTERNATIONAL

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

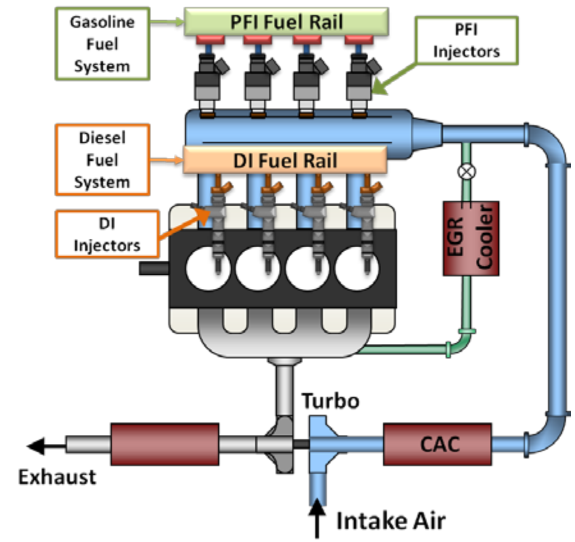
Vickey B. Kalaskar, Derek A. Splitter, and James P. Szybist
Oak Ridge National Lab.

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

Single- and Dual-Fuel Low Temperature Combustion (LTC) Experiments Conducted on Flexible Multi-Cylinder Platform

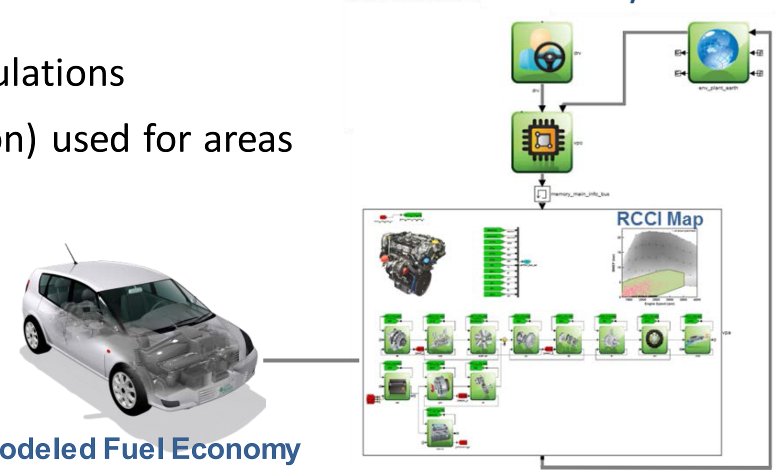
Approach (4/4)

- **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



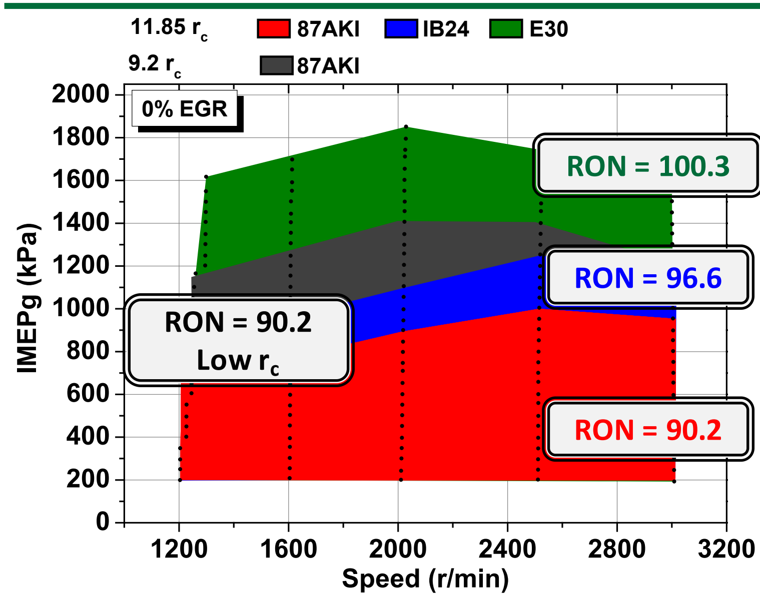
ORNL RCCI Multi-Cylinder 1.9L GM

AUTONOMIE Simulink/ Stateflow

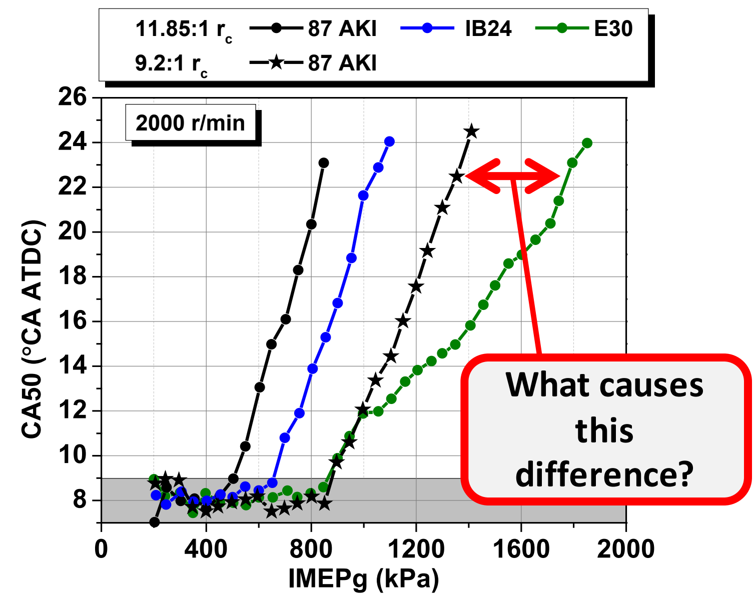


1 Autonomie, Developed by Argonne National Lab for U.S. DOE, http://www.autonomie.net/

E30 Enabled a Higher Increase in the Peak Engine Torque than Octane Number Alone Suggests for SI Combustion



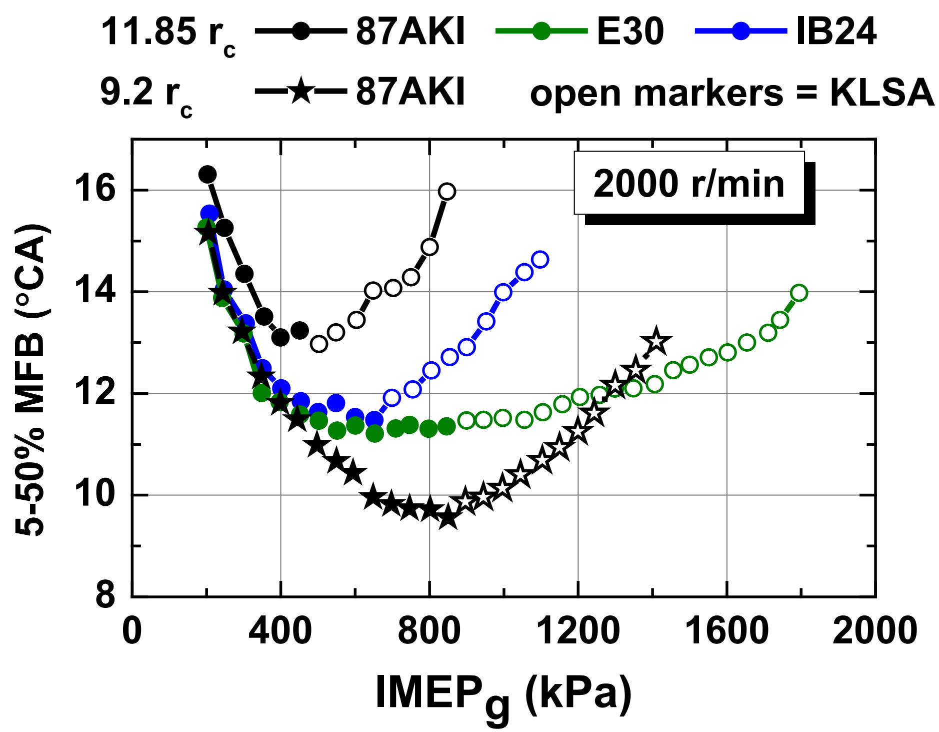
- Peak load dependent on fuel type
  - Trends with octane number
- Low octane fuels encounter knock at lighter loads, require combustion phasing retard to mitigate knock
  - Retarded phasing reduces efficiency and increases exhaust T
  - Operating limits for exhaust T and retarded phasing encountered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

- 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



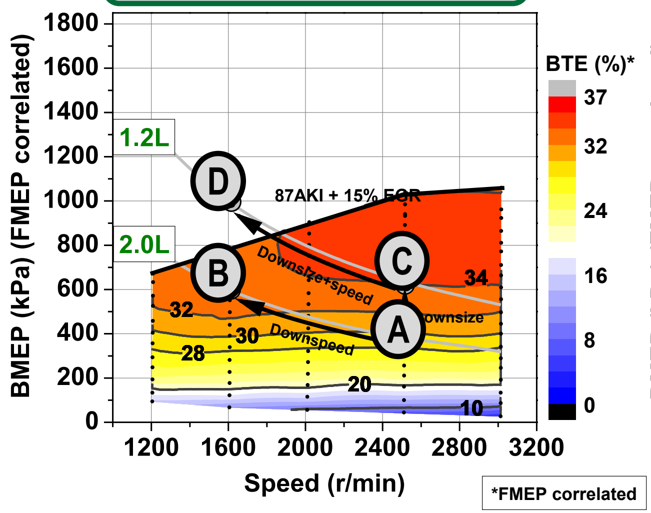
Higher Peak Torque for E30 can Enable Fuel Economy Benefits (Efficiency Outpaces Energy Density Penalty)

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

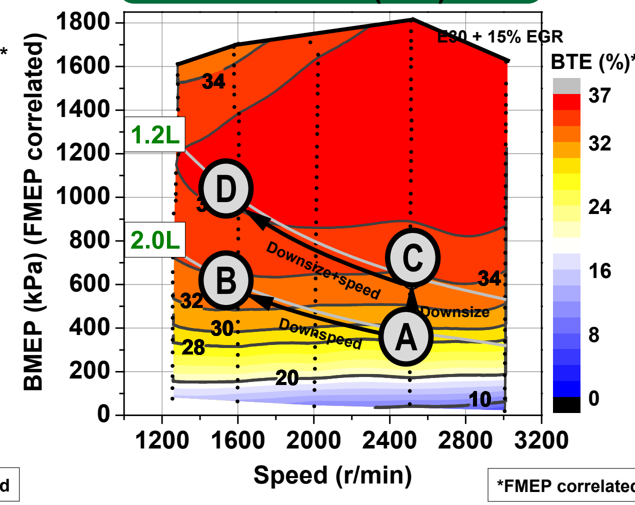
Steady cruise at 65 mph
(16 kW brake power)

- A Standard Configuration
- B Aggressive Downspeeding
- C Aggressive Downsizing
- D Aggressive Downsizing and Downspeeding

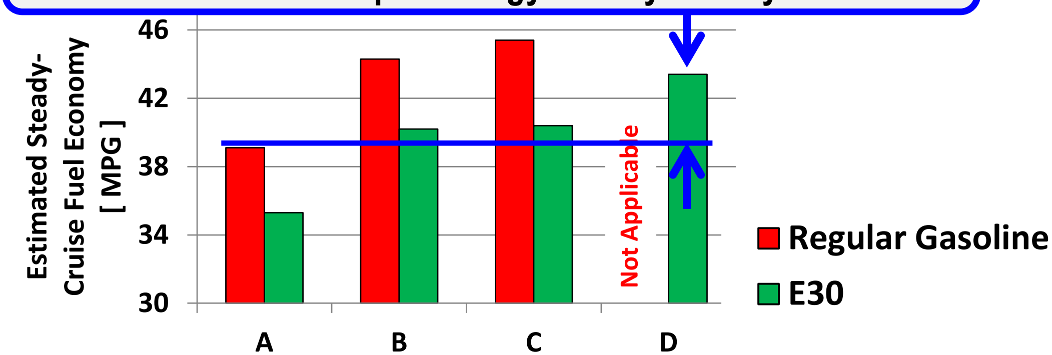
Regular Grade Gasoline



"Renewable Super Premium" (E30)



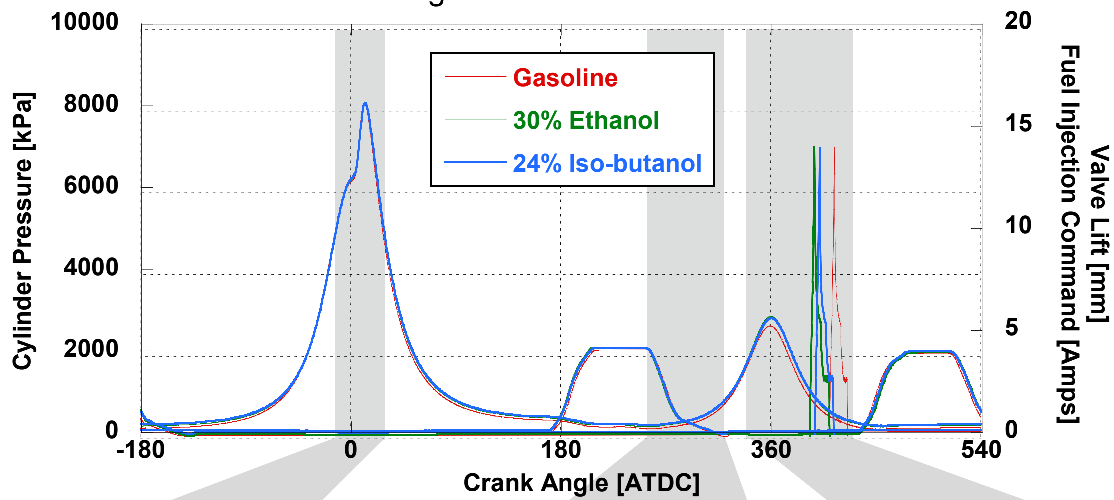
Benefits can Enable Higher Fuel Economy for High Octane Blends Despite Energy Density Penalty



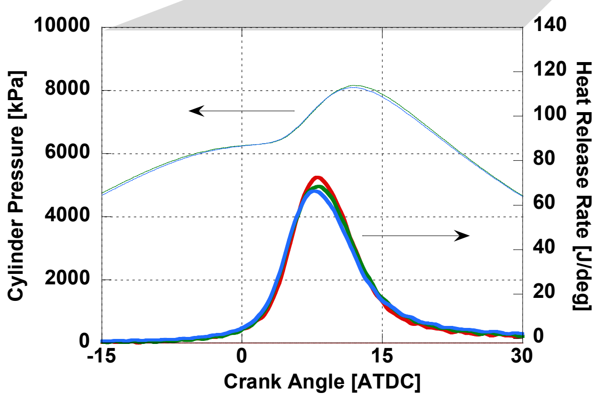
- Downsizing and downspeeding options are more limited for regular grade gasoline
- RSP can enable much more aggressive downsizing and downspeeding

HCCI Strategy Allowed Comparable Performance and Efficiency for All Fuels with Only Minor Changes in Controls

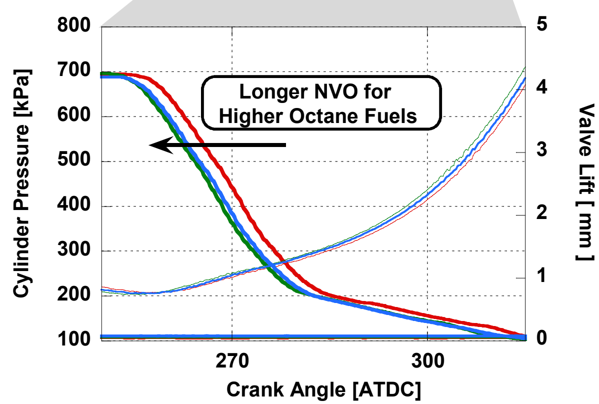
2000 RPM, 7.0 bar $IMEP_{gross}$, 230 kPaa MAP, 20% EGR



Comparable Pressure and Heat Release for All Fuels

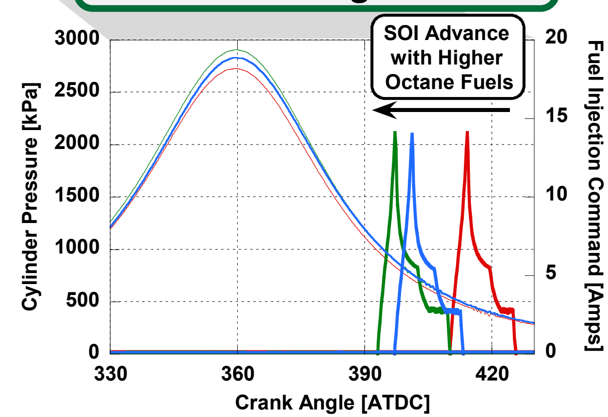


NVO Duration for "Coarse" Phasing Control



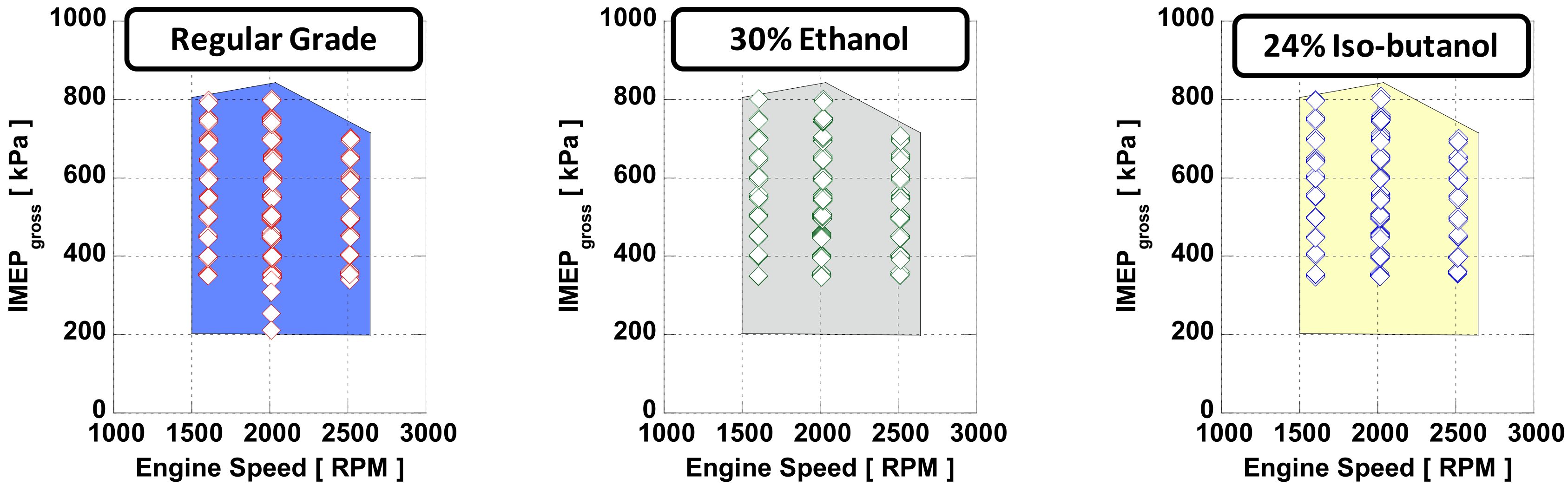
3 CA advance in exhaust valve closing angle for E30

Fuel Injection Timing for "Fine" Phasing Control



12 CA advance in injection timing for E30

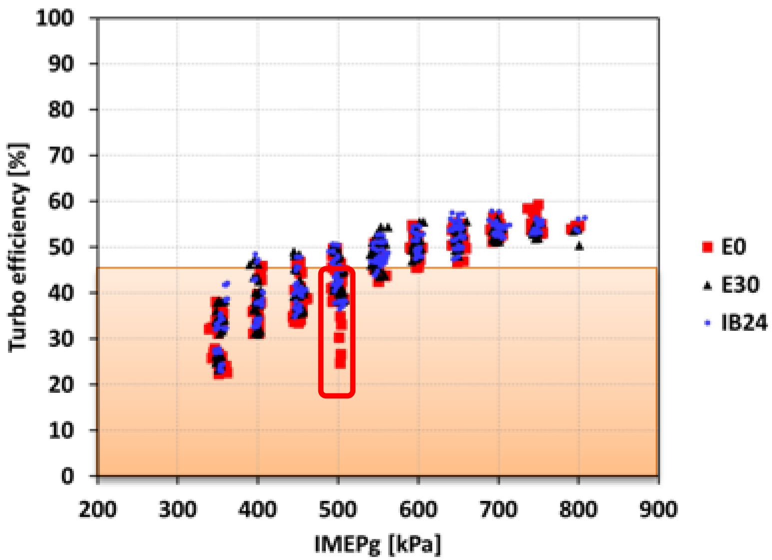
No Fuel-Specific Differences in HCCI Operable Peak Load when Minor Changes to Engine Operating Parameters are Applied



- 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 NOx < 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

- 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

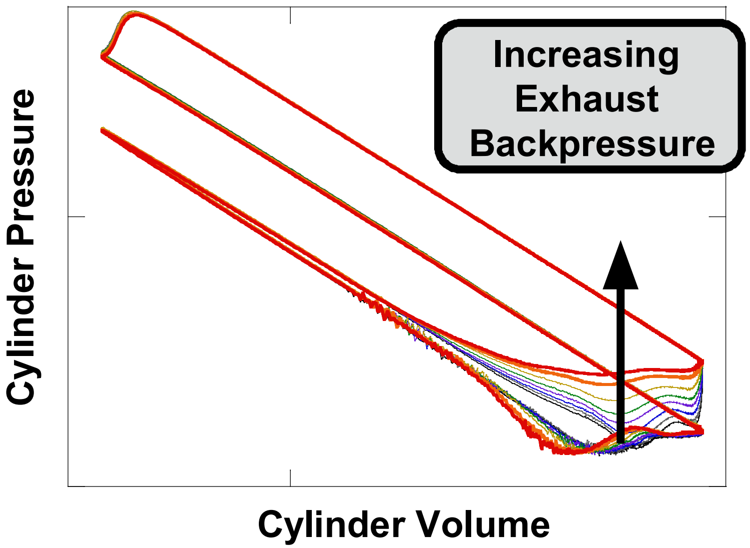


$$\eta_{combined} = \frac{\left(\frac{\gamma_{comp}}{\gamma_{comp}-1}\right)}{\left(\frac{\gamma_{turb}}{\gamma_{turb}-1}\right)} \left(\frac{T_{comp,in}}{T_{turb,in}}\right) \frac{\left[\left(\frac{P_{comp,in}}{P_{comp,out}}\right)^{\left(\frac{\gamma_{comp}-1}{\gamma_{comp}}\right)} - 1\right]}{\left(1+\frac{1}{AFR}\right)\left[1-\left(\frac{P_{turb,out}}{P_{t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

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
  - Too little enthalpy in exhaust to meet air handling requirements
  - Increasing backpressure for realistic turbo efficiency increases pumping work



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

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

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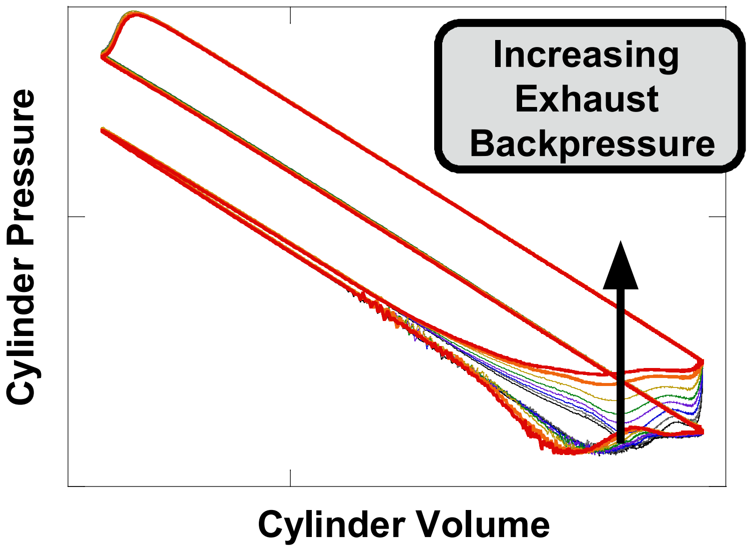
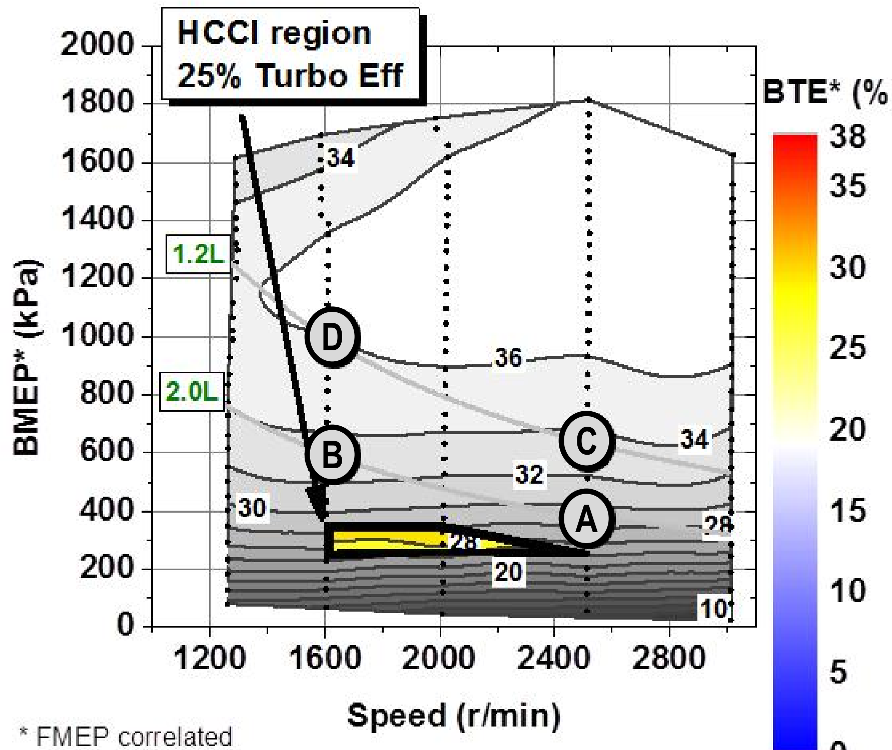


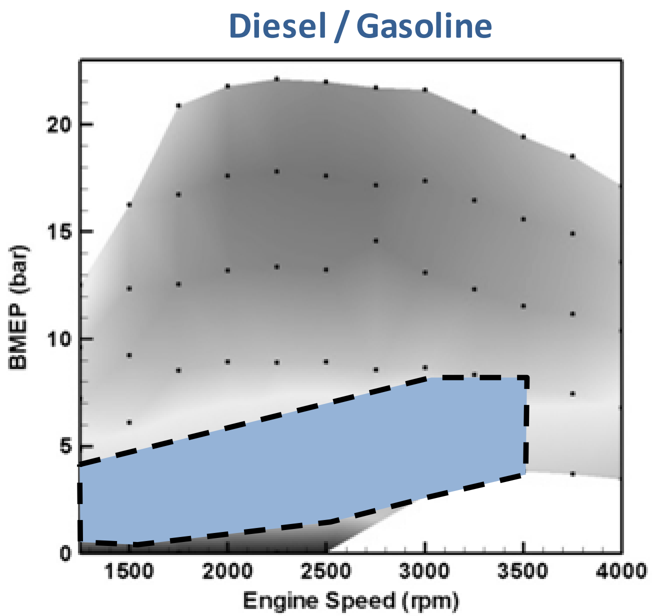
Pumping work is increased by a factor of 3 to reduce turbocharger efficiency requirement down from 45% to 25% (-30 to -90 kPa PMEP)

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

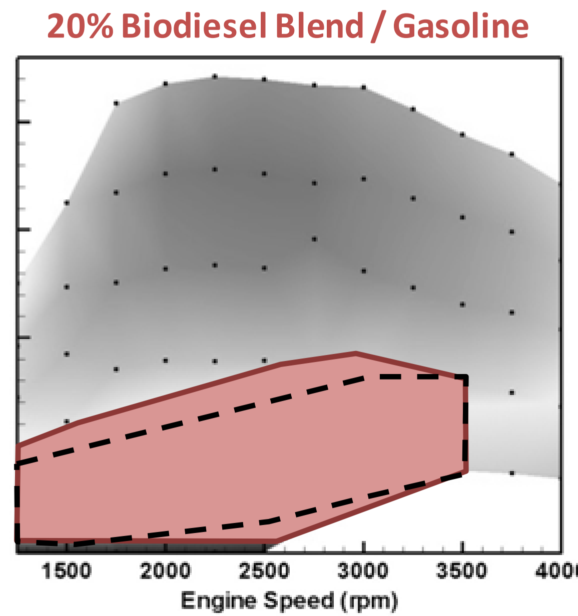


High-level Milestone Met to Exceed 75% Drive Cycle Coverage over City and Highway Cycles with RCCI Combustion

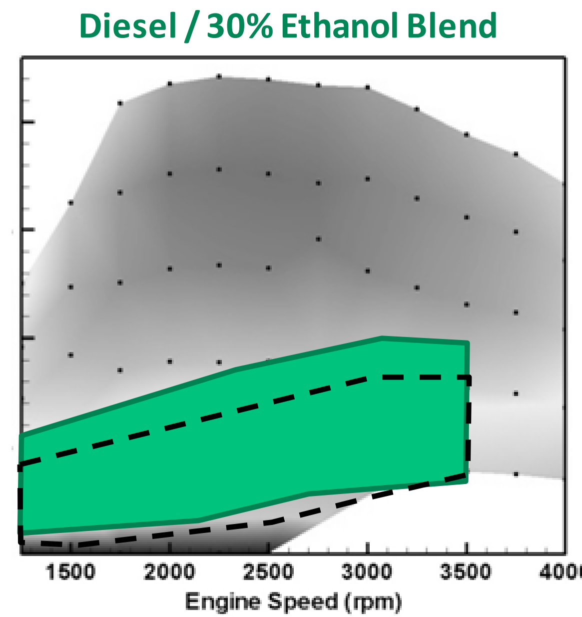
- Conventional diesel combustion modes used for speed/load demands outside of RCCI range
  - B20 RCCI expands high and low load of RCCI improving drive-cycle coverage
  - E30 RCCI map shifted RCCI range up, reducing coverage compared to B20 map



RCCI operational space with conventional fuels



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



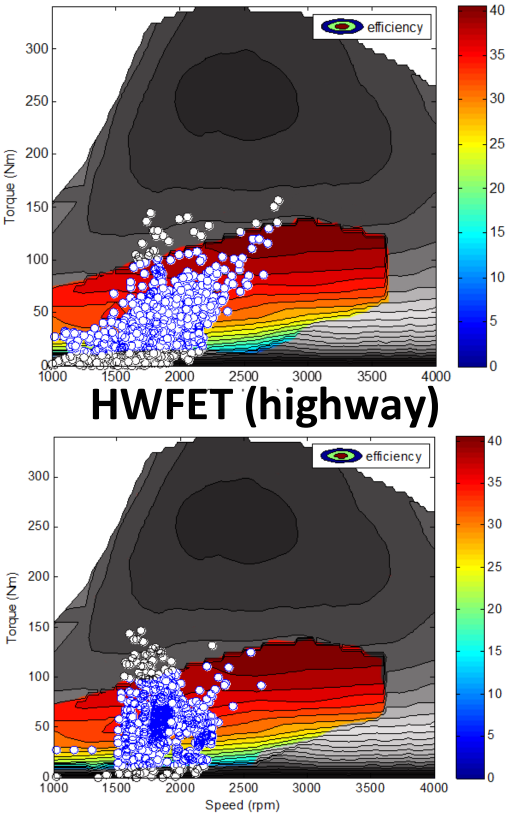
Expanded high load due to higher octane and charge cooling, reduced low load due to stability issues

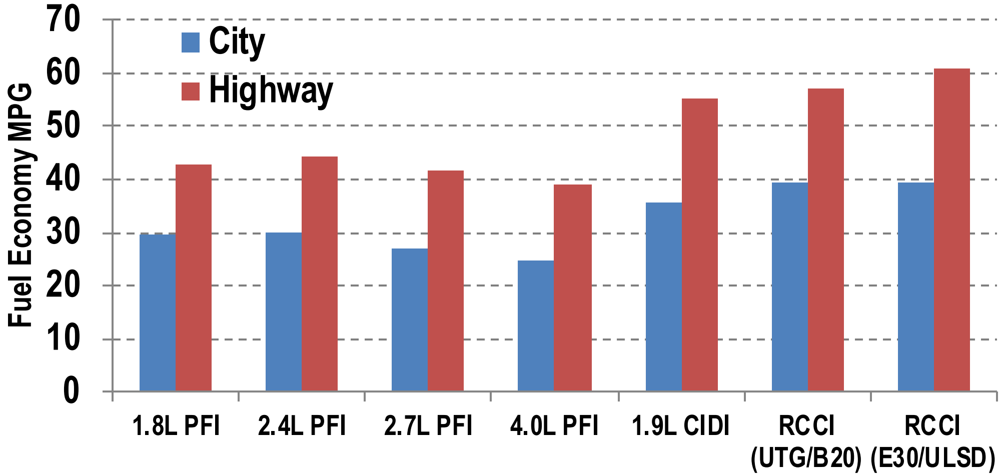
Expanded Range Enabled by Biofuel Blends Enabled Improved Fuel Economy Relative to Gasoline or Diesel Baselines

- **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)

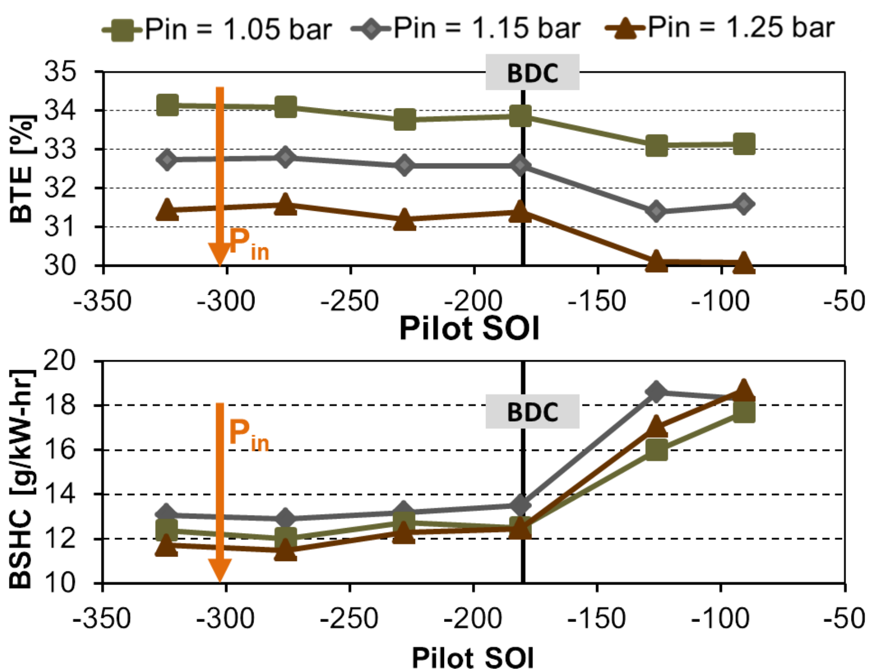




- **41% improvement in combined city/hwy MPG compared to PFI baseline**
- **6% improvement in combined compared to conventional diesel combustion (CDC)**

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.)



2000 rpm, 4.0 bar BMEP

	CDC	RCCI	PPC
Fuels	ULSD	B20 96RON	70 RON
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

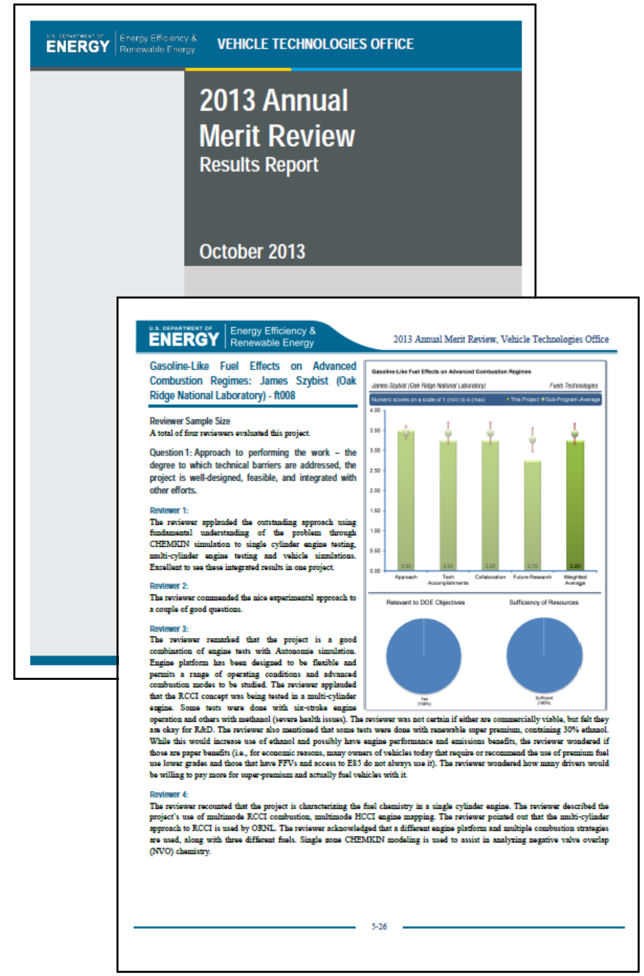
REVIEWER COMMENTS FROM FY 2013 – FT008

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.



U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

2013 Annual Merit Review
Results Report
October 2013

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy — 2013 Annual Merit Review, Vehicle Technologies Office

Gasoline-Like Fuel Effects on Advanced Combustion Regimes: James Szybist (Oak Ridge National Laboratory) - ft008

Reviewer Sample Size
A total of four reviewers evaluated this project.

Question 1: Approach to performing the work – the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts.

Reviewer 1:
The reviewer applauded the outstanding approach using fundamental understanding of the problem through CHEMKIN simulation to single cylinder engine testing, multi-cylinder engine testing and vehicle simulations. Excellent to see these integrated results in one project.

Reviewer 2:
The reviewer commended the nice experimental approach to a couple of good questions.

Reviewer 3:
The reviewer remarked that the project is a good combination of engine tests with Autonomie simulation. Engine platform has been designed to be flexible and permits a range of operating conditions and advanced combustion modes to be studied. The reviewer applauded that the RCCI concept was being tested in a multi-cylinder engine. Some tests were done with six-stroke engine operation and others with methanol (severe health issues). The reviewer was not certain if either are commercially viable, but felt they are okay for R&D. The reviewer also mentioned that some tests were done with renewable super premium, containing 30% ethanol. While this would increase use of ethanol and possibly have engine performance and emissions benefits, the reviewer wondered if those are paper benefits (i.e., for economic reasons, many owners of vehicles today that require or recommend the use of premium fuel use lower grades and those that have FFVs and access to E85 do not always use it). The reviewer wondered how many drivers would be willing to pay more for super-premium and actually fuel vehicles with it.

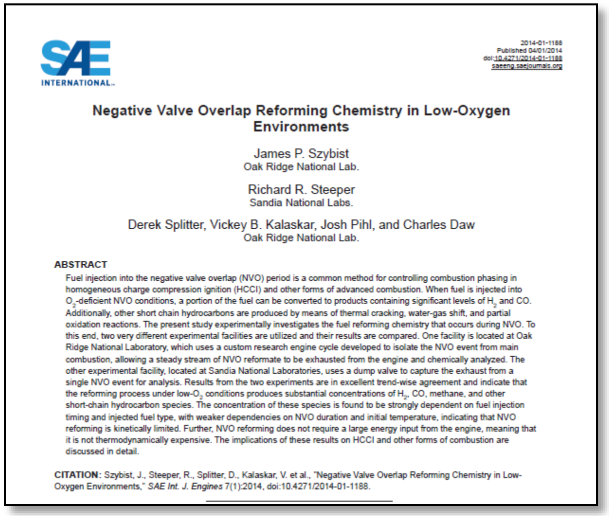
Reviewer 4:
The reviewer recounted that the project is characterizing the fuel chemistry in a single cylinder engine. The reviewer described the project's use of multimode RCCI combustion, multimode HCCI engine mapping. The reviewer pointed out that the multi-cylinder approach to RCCI is used by ORNL. The reviewer acknowledged that a different engine platform and multiple combustion strategies are used, along with three different fuels. Single zone CHEMKIN modeling is used to assist in analyzing negative valve overlap (NVO) chemistry.

5-26

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

COLLABORATIONS LEVERAGE FUELS RESEARCH AT ORNL

- 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



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Negative Valve Overlap Reforming Chemistry in Low-Oxygen Environments

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ABSTRACT

Fuel injection into the negative valve overlap (NVO) period is a common method for controlling combustion phasing in homogeneous charge compression ignition (HCCI) and other forms of advanced combustion. When fuel is injected into O_2-deficient NVO conditions, a portion of the fuel can be converted to products containing significant levels of H_2 and CO. Additionally, other short chain hydrocarbons are produced by means of thermal cracking, water-gas shift, and partial oxidation reactions. The present study experimentally investigates the fuel reforming chemistry that occurs during NVO. To this end, two very different experimental facilities are utilized and their results are compared. One facility is located at Oak Ridge National Laboratory, which uses a custom research engine cycle developed to isolate the NVO event from main combustion, allowing a steady stream of NVO reformate to be exhausted from the engine and chemically analyzed. The other experimental facility, located at Sandia National Laboratories, uses a dump valve to capture the exhaust from a single NVO event for analysis. Results from the two experiments are in excellent trend-wise agreement and indicate that the reforming process under low-O_2 conditions produces substantial concentrations of H_2, CO, methane, and other short-chain hydrocarbon species. The concentration of these species is found to be strongly dependent on fuel injection timing and injected fuel type, with weaker dependencies on NVO duration and initial temperature, indicating that NVO reforming is kinetically limited. Further, NVO reforming does not require a large energy input from the engine, meaning that it is not thermodynamically expensive. The implications of these results on HCCI and other forms of combustion are discussed in detail.

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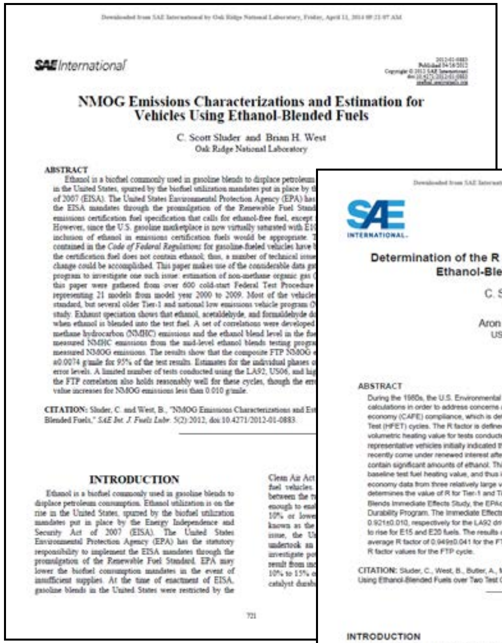
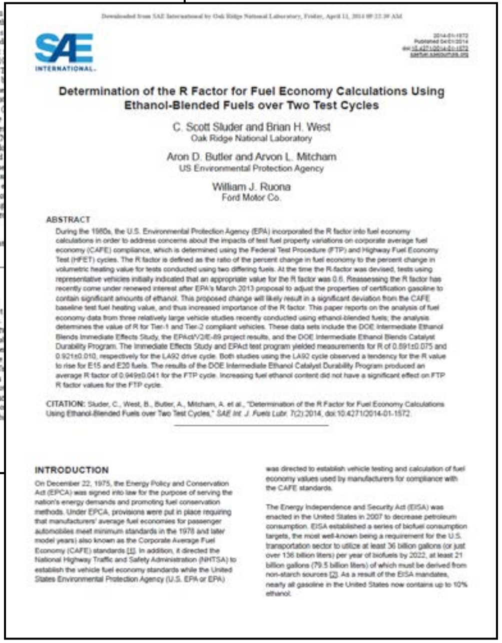
Discussion of engine research with industry visitors at ORNL.

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

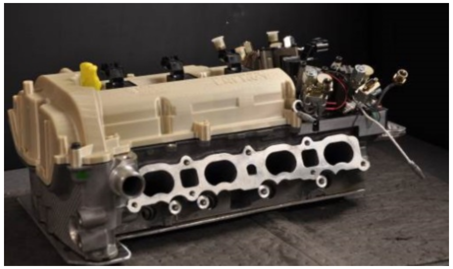




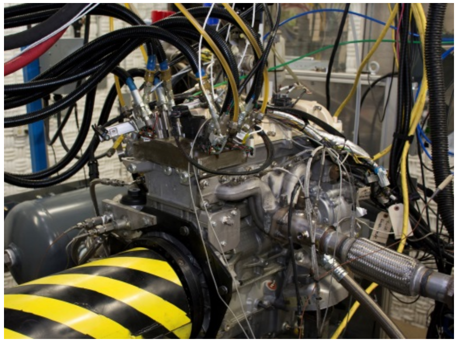
On SI Engine Platform, Moving Focus of Project to Fuel Effects on Highly Dilute SI Combustion with Reformate

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



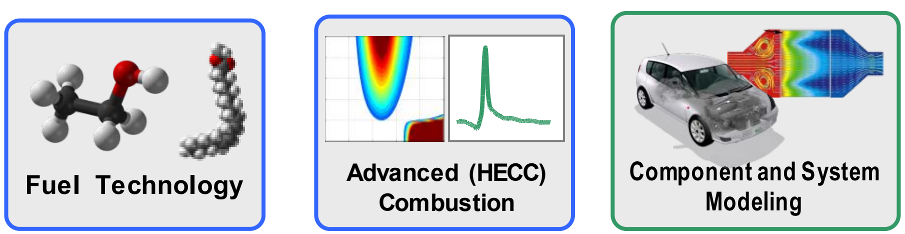
Engine Installed at ORNL

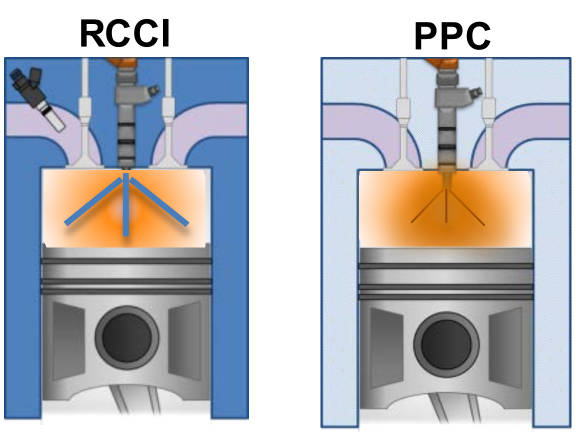
Investigations Focusing on Octane Number Effects on Fuel Economy are Continuing to be Pursued at ORNL through a Different Fuel Effects Project Led by Scott Sluder

Future Work for Multi-Cylinder LTC will Continue to Expand the Operable Load Range

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

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

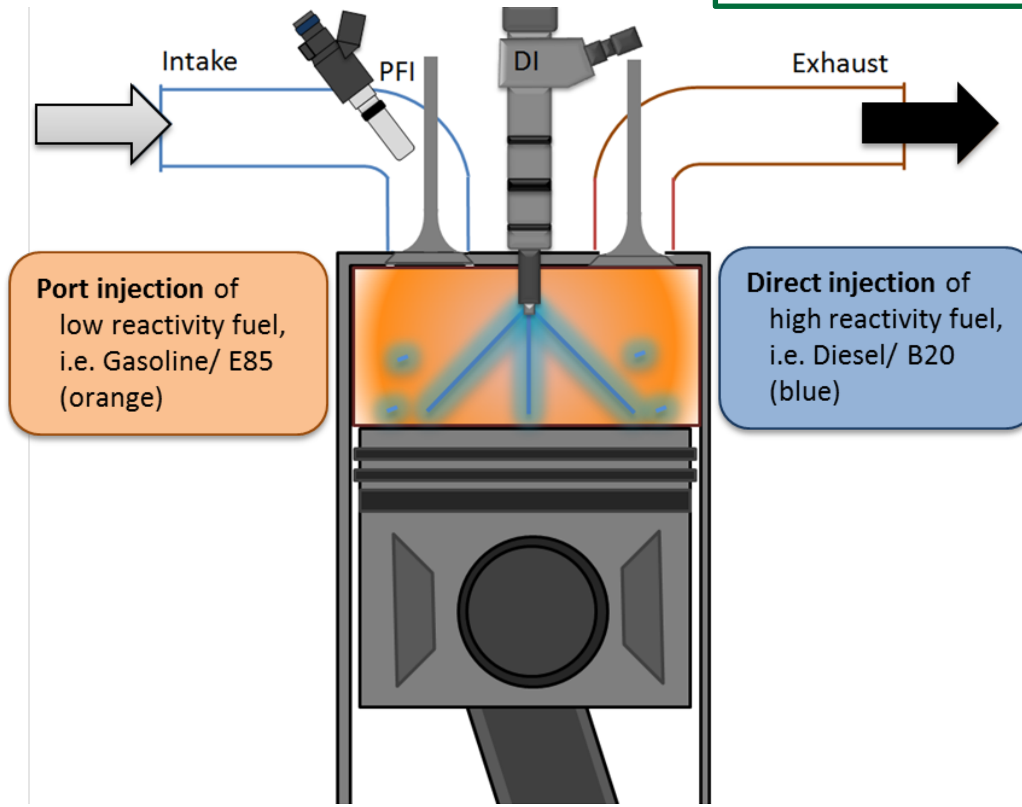
Backup 1

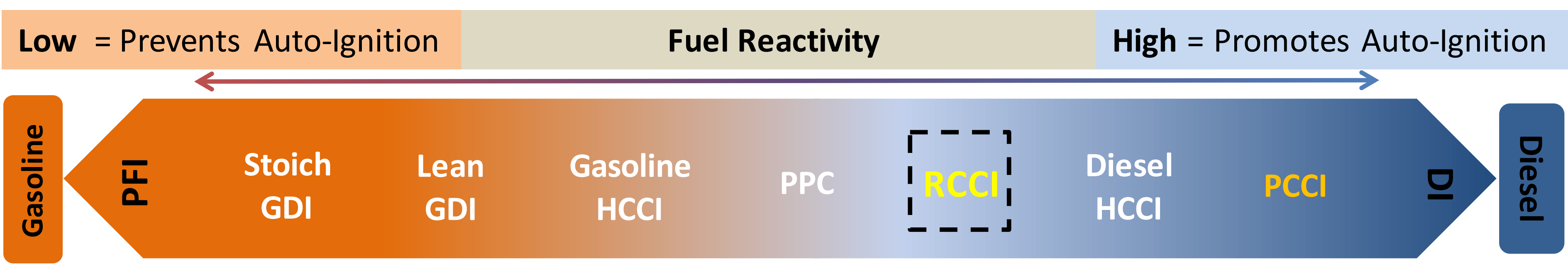
RCCI allows increased engine operating range for premixed combustion through:

- 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



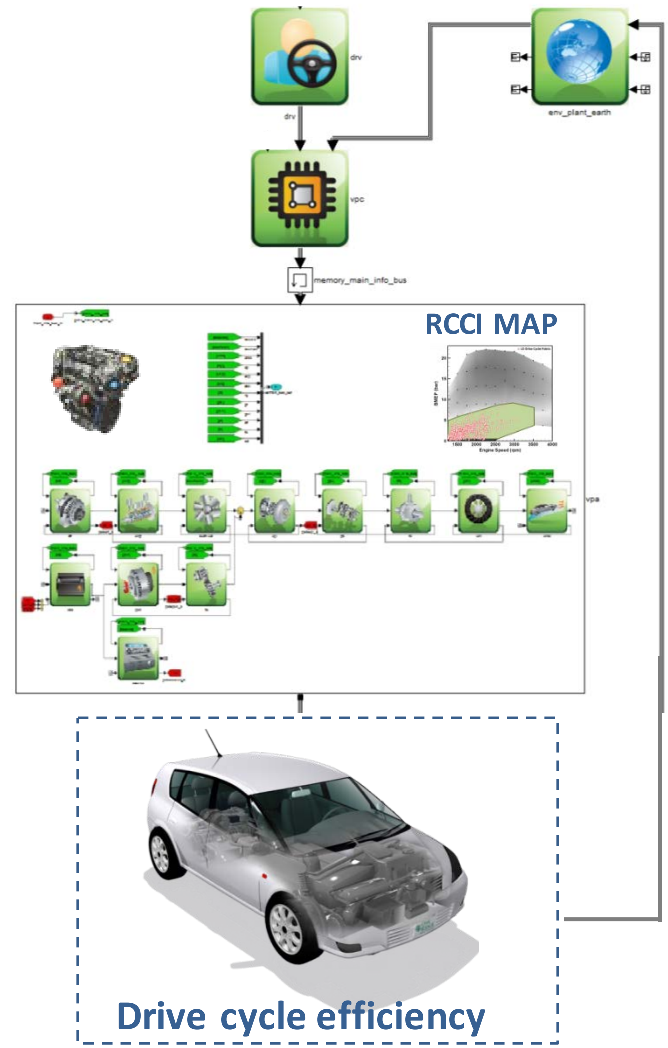


VEHICLE SYSTEM MODELING USING EXPERIMENTAL/ INDUSTRY ENGINE MAPS ON SAME VEHICLE IN AUTONOMIE 1

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

AUTONOMIE Simulink/ Stateflow



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

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 λ=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