Gasoline-like Fuel Effects on Advanced Combustion Regimes

Project ID: FT008

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DOE Management Team
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Project Overview

Barriers (MYPP 2011-2015, Section 2.4, Challenges and Barriers C.)

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

Budget

- FY10: $1,470k
- FY11: $300k
- FY12: $615k
- FY13: $400k

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

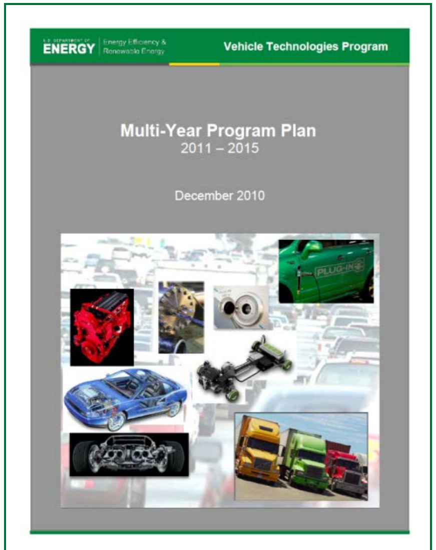
Industry

- *SAE Symposium*
- *ACEC Tech Team*
- *GM*
- *Chrysler*
- *Ford*
- *Related funds-in project with OEM*
- *MAHLE*
- *Major Energy Company*
- *Others*

Other Collaborations

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

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…"

Deployment

Applied

Fundamental

2013 SAE High Octane Fuels Symposium
Objective: Engage stakeholders to identify opportunities and barriers in deployment of a "renewable super premium" to enable higher efficiency in SI engines.

Multi-cylinder Mapping of Advanced Combustion Regimes
Objective: Exploit unique combustion properties of renewable fuels to expand the operable speed/load range for RCCI and PPC combustion compared to conventional diesel while maintaining high efficiency and low emissions.

Single-cylinder Mapping of Advanced Combustion Research
Objective: Exploit unique combustion properties of renewable fuels to expand the operable speed/load range for HCCI, SA-HCCI, and dilute SI combustion compared to conventional SI operation.

Characterization of Fuel-specific NVO Chemistry
Objective: Speciate products of NVO chemistry relevant to HCCI and SA-HCCI for renewable and conventional gasoline boiling range fuels.

Two High-Level DOE Milestones

2013 Joule Milestone: Multi-Mode RCCI Load Expansion

Demonstrate an increase in the RCCI operating range due to the use of renewable fuels allowing 60% coverage of non-idling portions of the city (UDDS) and highway (HWFET) light-duty federal drive cycles. ***Status: Complete***

2013 Tracked Milestone: Multi-Mode HCCI Engine Mapping

Generate engine maps for gasoline, an ethanol blend, and an iso-butanol blend for HCCI and SA-HCCI under applicable engine loads and idle to full load for conventional SI combustion. Engine maps will cover the speed range from 1000 to 3000 rpm. ***Status: On Track***

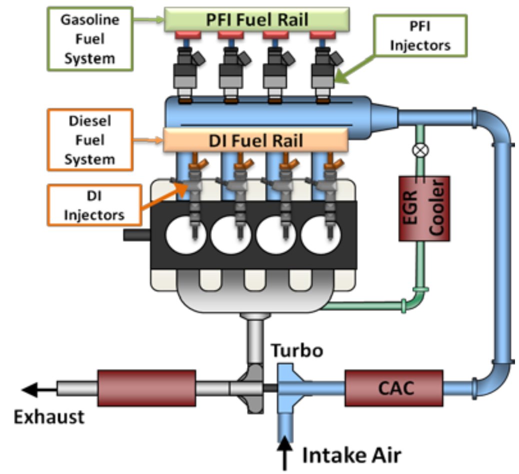
Additional Project-level Milestones

Characterize fuel-specific negative valve overlap (NVO) chemistry in low and no-oxygen environments relevant to HCCI and SA-HCCI combustion regimes. ***Status: Complete***

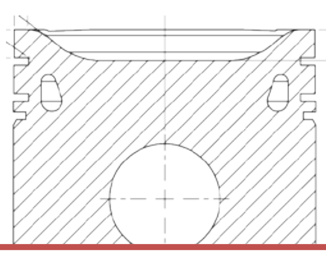
ORNL USES A MULTI-CYLINDER APPROACH TO RCCI WITH PRODUCTION AND PRODUCTION-VIABLE HARDWARE

Multi-cylinder Advanced Combustion

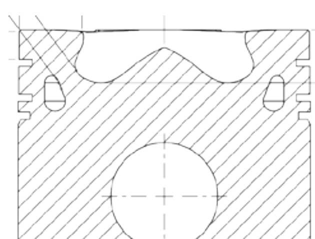
- 2007 GM 1.9-L 4-cylinder diesel engine
  - OEM (CR 17.5) and **modified RCCI** pistons (CR 15.1)
  - Dual-fuel system with PFI injectors
  - OEM diesel fuel system with DI injectors, OEM turbo, HP EGR loop
  - Microprocessor based control system
- Characterization of regulated and unregulated emissions
  - Modular catalysts
  - Particulate matter characterization
- Vehicle systems simulations using Autonomie (backup slide)



ORNL RCCI Multi-Cylinder 1.9L GM



Modified RCCI Piston



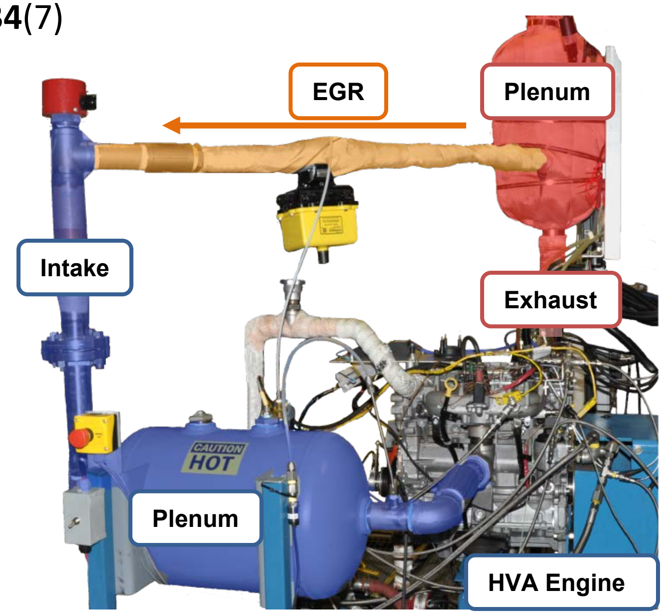
Stock GM 1.9 L piston

Base Multi-Cylinder 1.9L GM CIDI

Number of Cylinders	**4**
Bore, mm	**82.0**
Stroke, mm	**90.4**
Compression Ratio	**15.1**
Rated Power, kW	**110**
Rated Torque, Nm	**315**

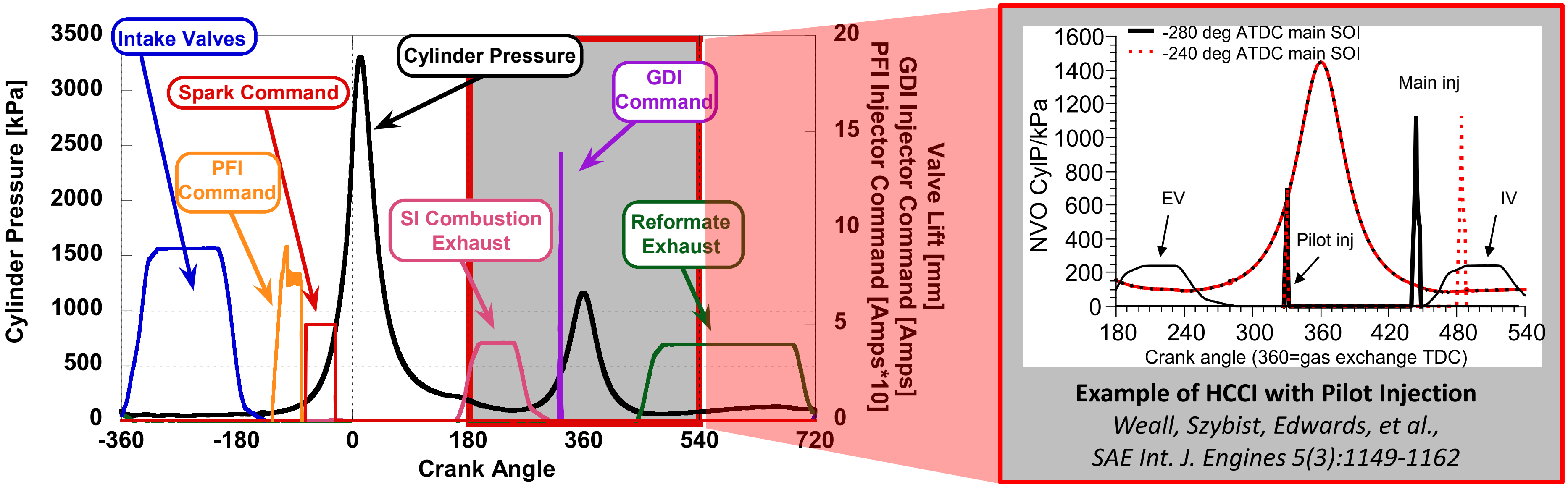
Flexible Single-Cylinder HVA Engine Platform Enables Direct Comparisons of Combustion Strategies

- Single cylinder engine with hydraulic valve actuation (HVA)
  - Modified 2.0L GM Ecotec engine
  - Wall-guided GDI fueling, aftermarket PFI fueling
  - Laboratory air handling (thermal management, boost, external EGR)
  - Multiple compression ratio pistons available (9.2, 10.5, **11.85**, 12.6, 13.5)
- HVA valvetrain enables fuels research with multiple combustion strategies
  - Impact of hydrocarbon blendstock on optimized FFV (high CR, boosted): SAE 2013-01-0188
  - Load expansion of lean-burn HCCI with boost and external EGR: SAE 2013-01-1665
  - Advanced combustion load expansion with SA-HCCI: JEGTP, 2012, **134**(7)
- FY13 approach: Fuel-specific combustion mode maps of performance and emissions
    - Regular grade gasoline (E0, 87 AKI)
    - 30 vol% ethanol splash blended with E0 (renewable super premium)
    - 24 vol% iso-butanol splash blended with E0
  - Combustion modes include conventional SI, high EGR dilution SI, stoichiometric SA-HCCI, and lean HCCI
  - Operating strategies include boost for load range expansion
  - Maps produced will be used for drive cycle simulations in FY14



Flexible HVA Engine Enables Unique Engine Cycle for Investigations of NVO Kinetics and Thermodynamics

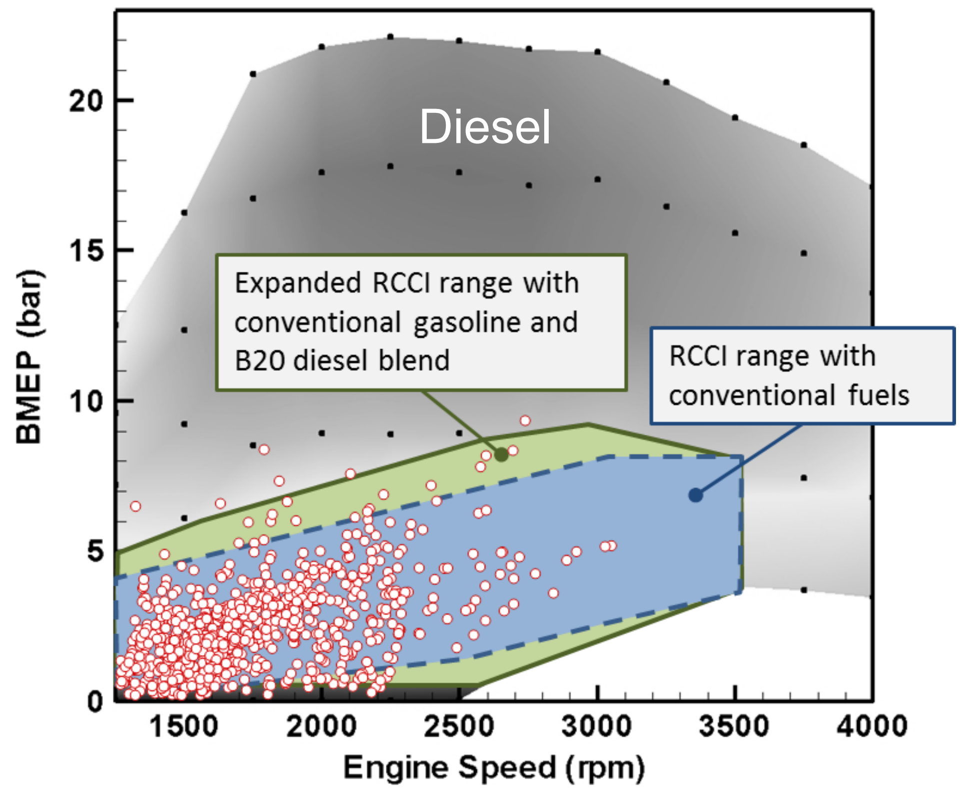
- Motivation: Fuel-specific autoignition behavior under NVO conditions for HCCI and SA-HCCI is often different than different than predicted by octane number
- 6-stroke engine allows NVO products to be quantified so that this chemistry can be better understood
  - SI combustion used to set-up NVO event relevant to HCCI and SA-HCCI
  - NVO conditions can be varied over a variety of valve timing conditions and SI operating conditions
- Exhaust streams for SI combustion and NVO products are separated using an exhaust divider
  - Analytical techniques used to speciate NVO products
  - Thermal and indicated data used to characterize thermodynamics
- Single-zone Chemkin modeling to assist in analyzing NVO chemistry



Example of HCCI with Pilot Injection
Weall, Szybist, Edwards, et al., SAE Int. J. Engines 5(3):1149-1162

Biodiesel Allows RCCI Load Expansion

- RCCI mapped (B20 + gasoline) with focus on efficiency while maintaining low emissions
  - Peak BTE within light-duty drive cycle range (42.5% BTE)
  - Better than peak BTE of 1.9L GM diesel
- Expanded RCCI operation needed for greater drive cycle coverage
  - Previous FY 12 milestone only focused on high load expansion
- Unique properties of renewable fuels act as an enabling technology
- Use of biodiesel enables improvement in both low and high load stability resulting in an expansion of RCCI drive cycle coverage
  - SAE 2013-01-2013, ASME ICEF2012-92192



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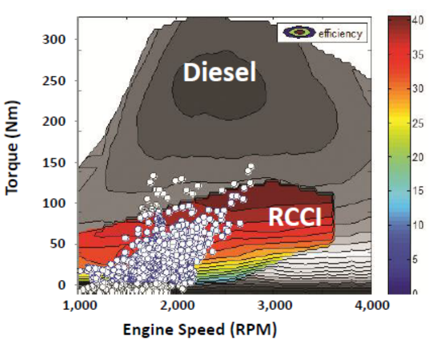
Increased RCCI Drive Cycle Coverage

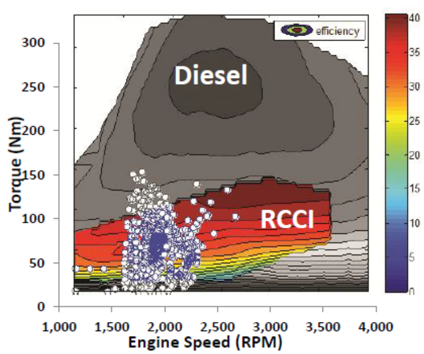
- To evaluate improvement in drive-cycle coverage, mapping data used to perform vehicle system simulations in Autonomie
  - Allows for determination of increases in coverage in terms of miles of drive cycle
- Experimental engine maps used in Autonomie drive cycle simulations
  - RCCI/diesel multi-mode strategy used for areas outside RCCI coverage
  - Details on modeling & multi-mode operation (backup slide)

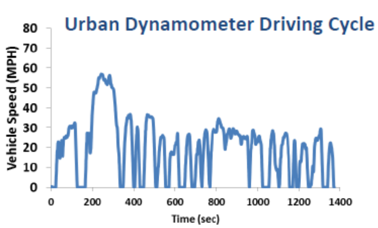
RCCI drive cycle coverage as compared to diesel baseline

UDDS

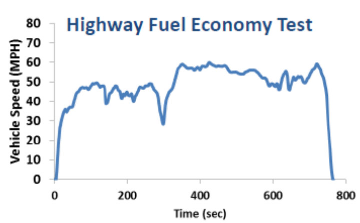


HWFET



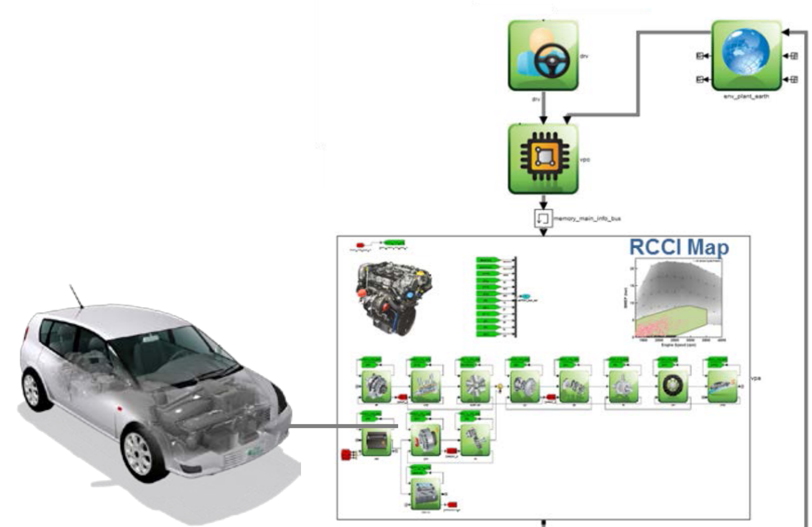


Commonly called the "LA4" or "the city test" and represents city driving conditions



Represents highway driving conditions under 60 mph

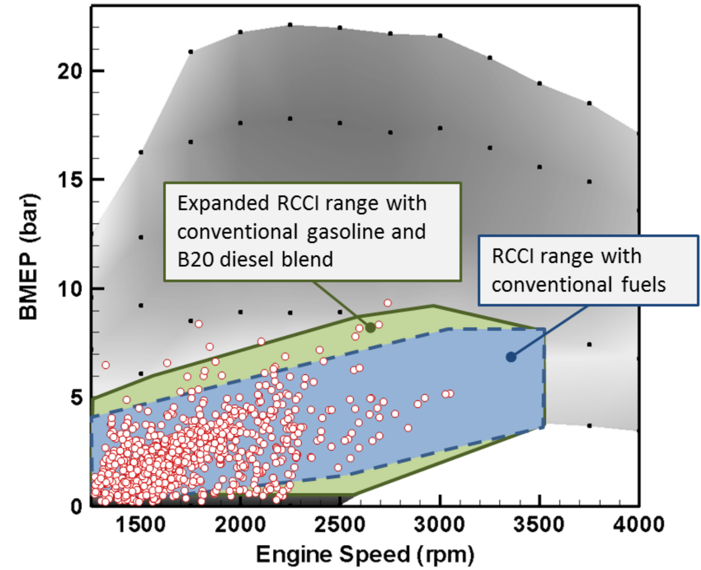
AUTONOMIE Simulink/ Stateflow



Modeled Fuel Economy

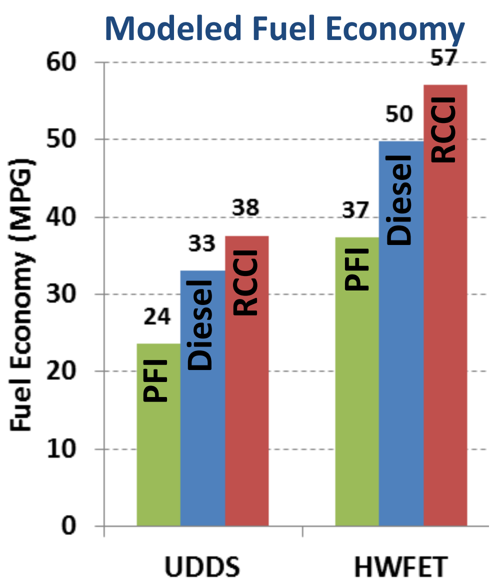
Increased RCCI Coverage Improves Fuel Economy

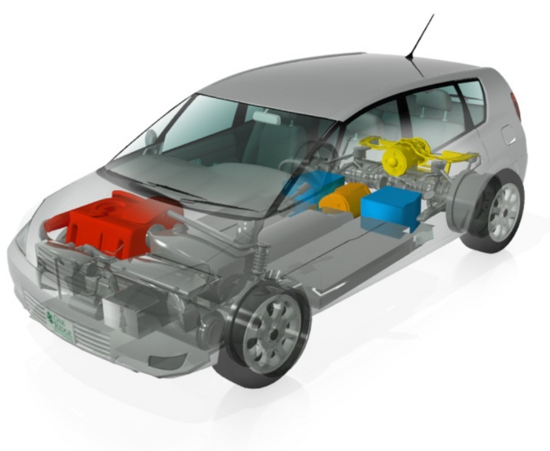
- Modeling results show greater than 70% drive cycle coverage with RCCI over UDDS (city) and HWFET (highway) with B20 and gasoline
  - Multi-mode operation used for points outside RCCI coverage
  - Results compared to base diesel engine and 4.0L PFI gasoline engine



Modeled Drive Cycle Performance

Cycle	RCCI Mode % Distance	Total B20 Fuel	% B20 during RCCI
UDDS (city)	72%	56%	41%
HWFET (highway)	88%	44%	37%

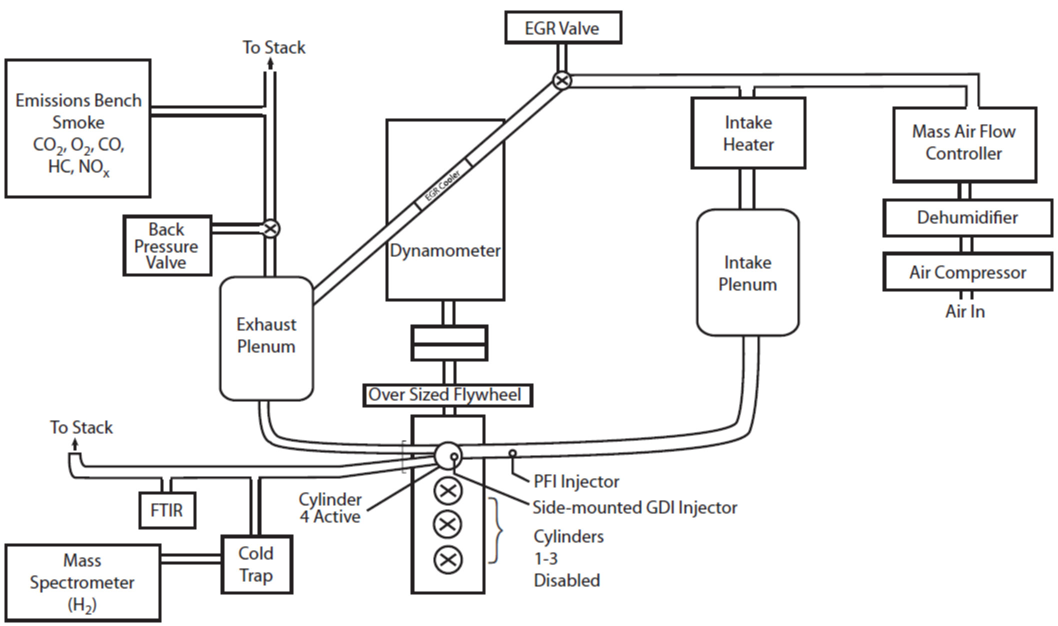




14% improvement over UDDS coverage allowed with biodiesel as compared to RCCI with gasoline and diesel fuel

Experimental 6-stroke Investigation Completed Spanning Wide Range of Fuels and NVO Conditions

- Fuels: Iso-octane, methanol, ethanol, iso-butanol, and hydrous ethanol
- 5 different NVO durations at 2000 rpm: 120, 140, 160, 180, and 210 CA
- 3 different start-of-NVO conditions
  - High temperature, no O_2 available: setup by stoichiometric SI combustion without EGR
  - Reduced temperature, no O_2 available: setup by stoichiometric SI combustion with 20% EGR
  - Reduced temperature with 5% O_2 available: setup by lean SI combustion at λ=1.2
- Chemical speciation with FTIR and mass spectrometer



Divided Exhaust System on ORNL HVA Engine

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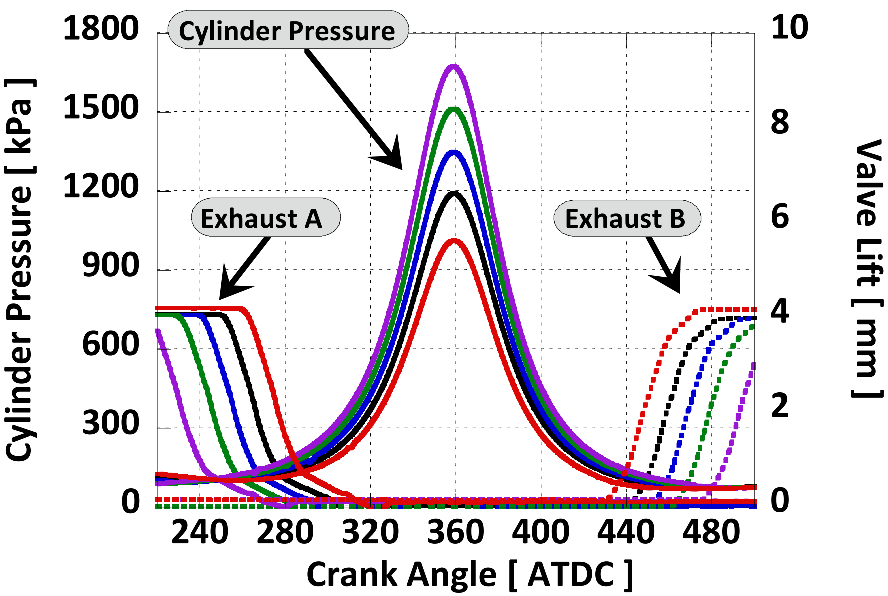
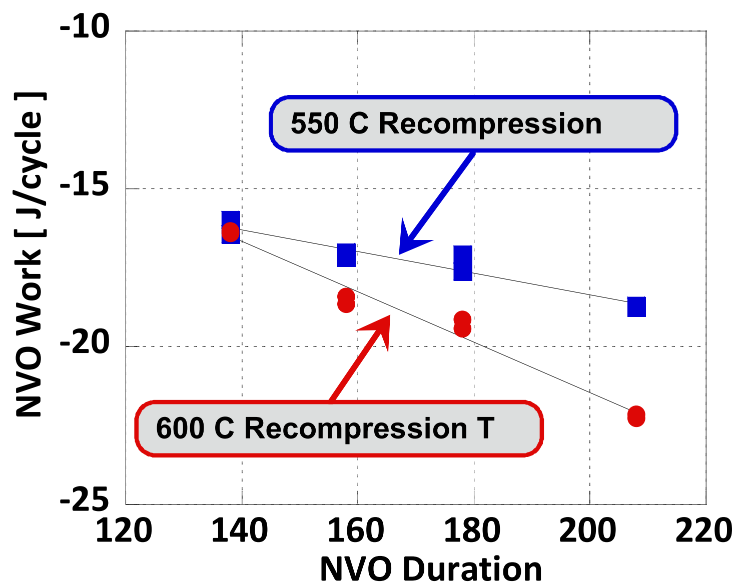
Significant Changes in NVO Work for Fuels

Heat Losses Result in Work Input during Motored NVO

- Work increases with longer NVO and higher temperature at the start of recompression





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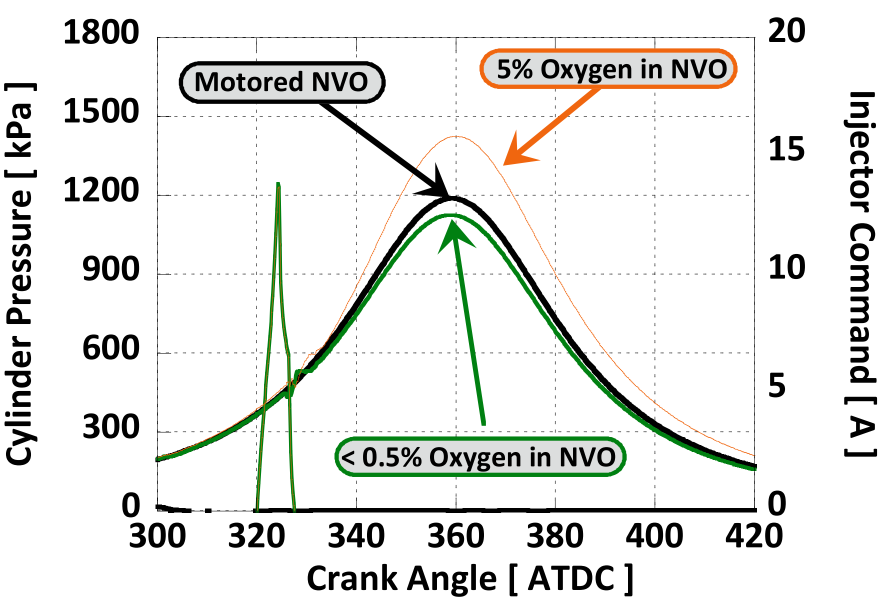
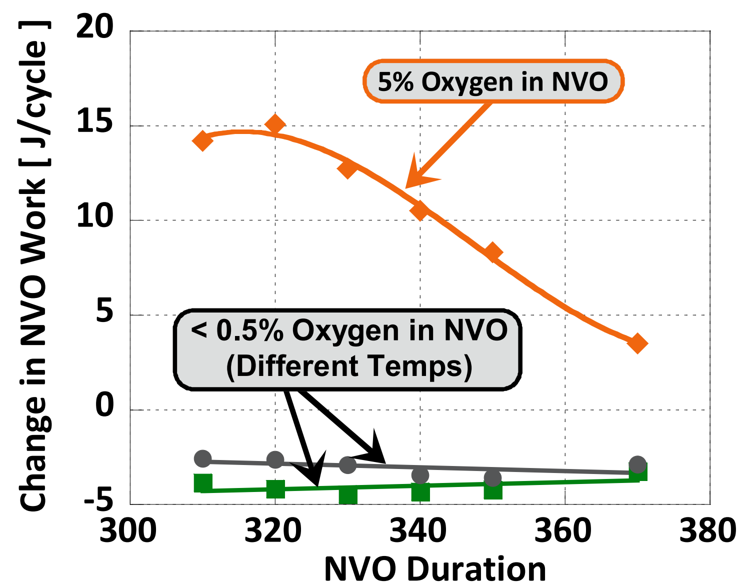
Work Input with Fuel Present is Dependent on Injection Timing, Oxygen Concentration

- Presence of oxygen allows combustion reactions to dominate, provides positive work out





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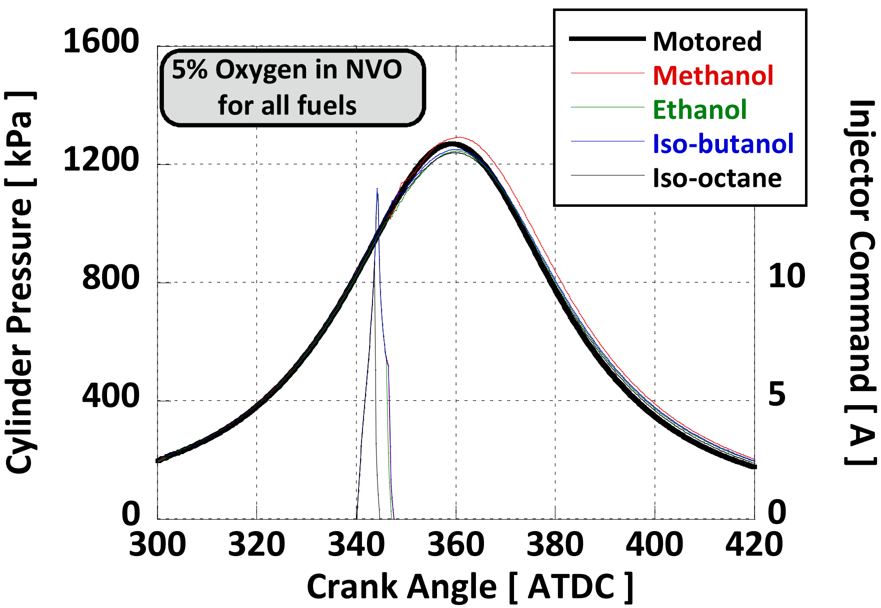
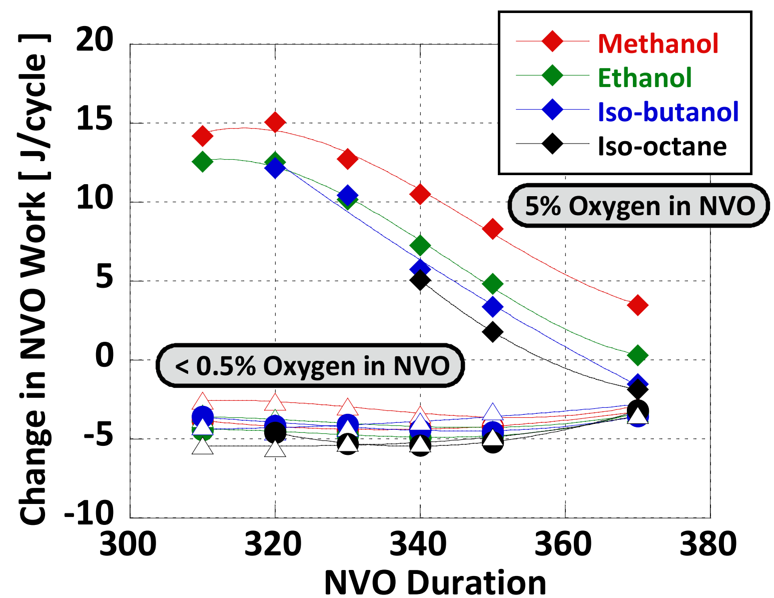
Work Output is Dependent on Fuel Type

- Iso-octane requires largest work input despite lowest latent heat of vaporization

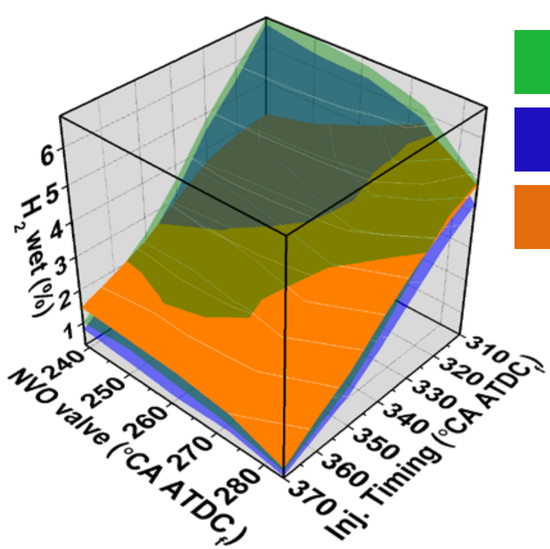




Experiments Reveal that Fuels Can Undergo a Significant Amount of Reforming, Implications for HCCI Kinetics

- CO and H_2 both increase with earlier fuel injection timing
  - Implies that reforming reaction timescales are relatively slow
- Additional factors affecting the temperature/pressure history and chemistry are minor by comparison
  - NVO duration, start of recompression temperature, presence of oxygen
- Significant fuel-specific dependencies on H_2 and CO production
- Reforming reactions can significantly alter kinetics of parent fuel

Hydrogen



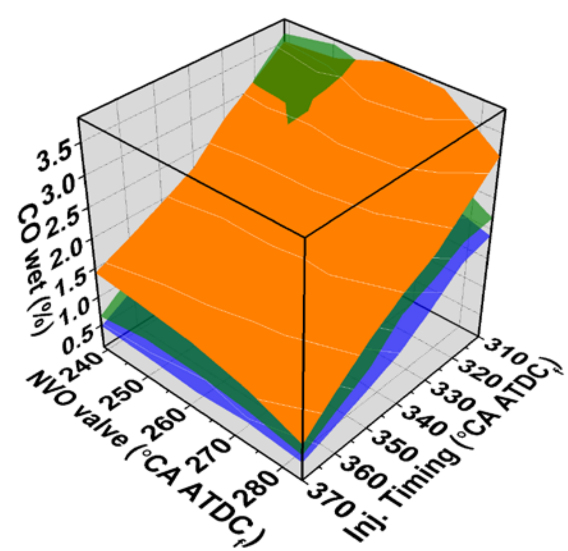
High T, No O_2 Present

Reduced T, No O_2 Present

5% O_2 Present

Response surfaces for methanol

Carbon Monoxide



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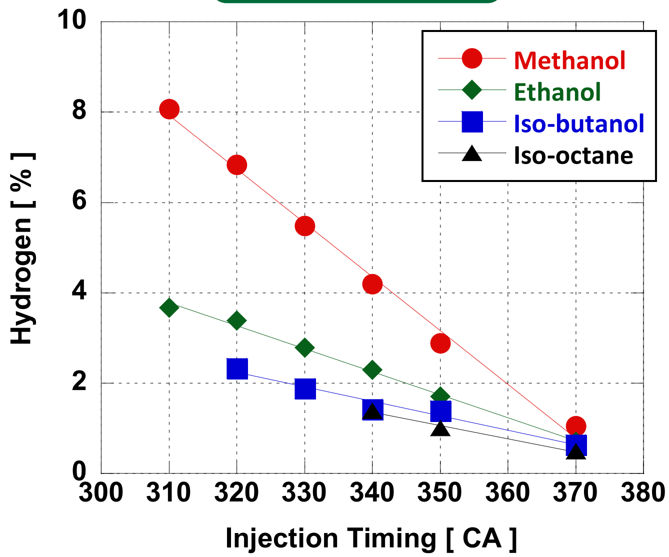
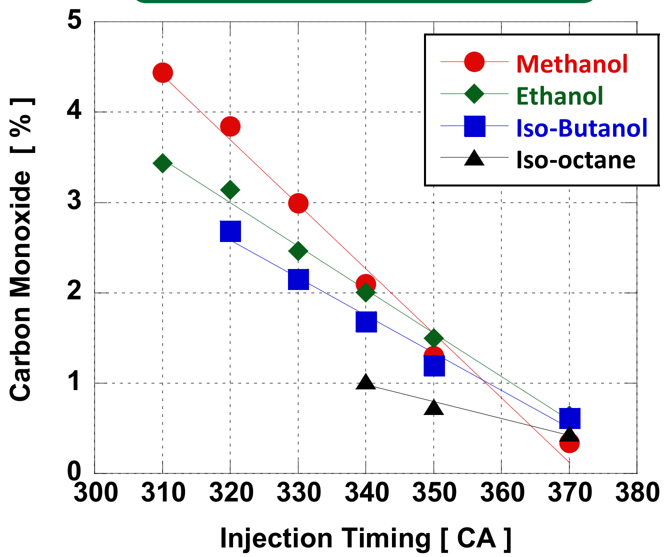


Carbon Monoxide

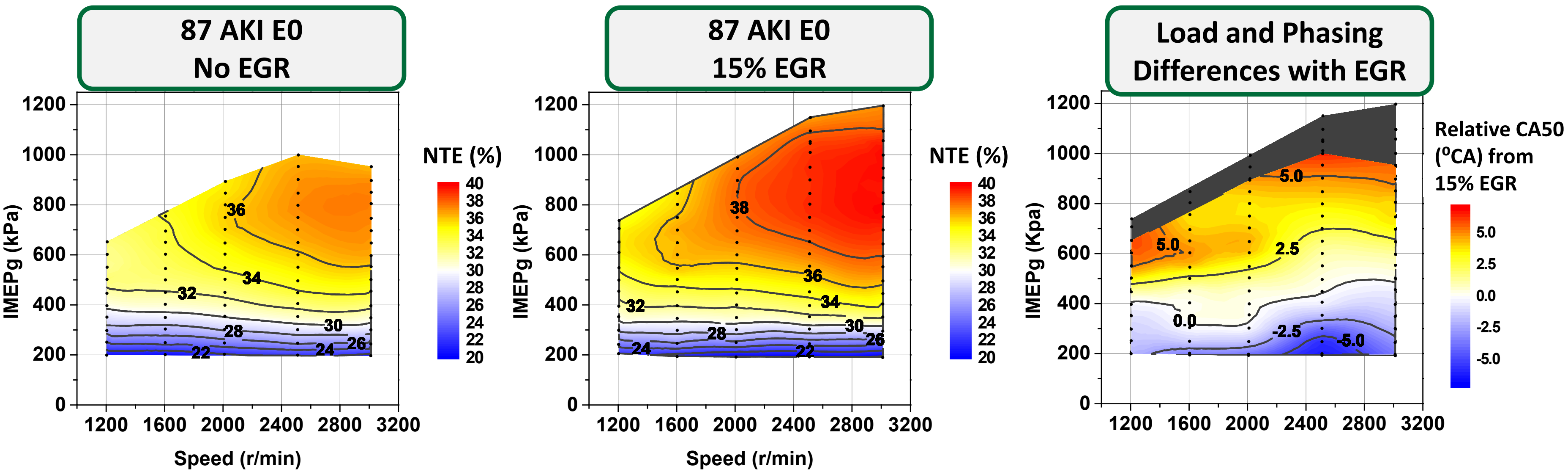


Direct Fuel and Combustion Mode Comparison for SI Engine Platform has Begun, On Track for 2013 Milestone

Combustion Modes
Conventional SI (stoichiometric)
Dilute SI (stoichiometric, 15% EGR)
Boosted lean-burn HCCI
Stoichiometric SA-HCCI

Fuels Investigated
Pump gasoline (E0, 87 AKI)
"Renewable Super Premium" E30 splash blend w/pump gasoline
24 vol% iso-butanol splash blended with pump gasoline

- Combustion modes mapped on single-cylinder HVA engine up to 3000 rpm
- Load limit will be fuel-specific for each combustion mode based
- Data is being collected in a manner conducive to drive cycle simulations



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Collaborations Leverage Fuels Research at ORNL

- National Lab Partners
  - Sandia National Laboratory – NVO chemistry
- Industry Partners
  - ACEC – Support for ACEC-DOE goals and combustion noise discussions
  - Energy Company– Fuel effects collaboration for LTC
  - GM - GM 1.9 Hardware
  - MAHLE – Premixed compression ignition piston design
  - Chrysler – Engine data for vehicle systems modeling comparisons
  - Drivven – Same/ next -cycle controls
  - Related funds-in project with OEM
  - Others - Infineum, Borg Warner
- University Partners
  - 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.

ORNL Technical Work Helped Set Stage for Symposium on High Octane Fuels for Improved SI Engine Efficiency

- Synergies exist between RFS and CAFE through ethanol due to chemical octane number and high latent heat
  - Well-established efficiency benefit to high ethanol fuel blends (ORNL and others)
  - Anti-knock properties of ethanol allow high compression ratio and aggressive downsizing
  - Efficiency advantage can overcome energy density penalty at ~E20 in optimized engine
- Symposium brought together stakeholders and technical experts
  - Speakers from regulatory agencies, OEMs, energy companies, convenience stores, academia (88 participants)
- Primary conclusion is that switching to a new fuel on a national scale is non-trivial
  - EPA regulatory authority not straight-forward: reliant on GHG emissions, numerous hurdles
  - OEMs conflicted: concerns over misfueling, fuel availability, and fuel pricing
  - Oil industry opposed to new fuel: lifecycle GHG emissions unclear, RFS should be revised or repealed because of lack of cellulosic ethanol, premium grade gasoline already available
- Retailers do not have deep pockets for potential > $10 billion cost of equipment upgrades
- Despite significant obstacles, introduction of new "renewable super premium" offers a real opportunity for increasing efficiency of vehicles on a national scale

Complete symposium overview available at: http://info.ornl.gov/sites/publications/Files/Pub41330.pdf

Continue to Investigate Alternate Fuels as Enabling Technology for Higher Efficiency on CI Engine Platforms

- Unique properties of renewable fuels can offer increased performance and/ or load expansion for advanced combustion
  - Enables potential for improved fuel economy taking into account engine systems efficiency

Pathway 1: Dual Fuel Approach

- Previous work in this area includes ethanol and biodiesel blends
- Continuing work with dual fuel approach will continue with looking at optimum blends to maximize drive cycle coverage and efficiency to improve fuel economy

Pathway 2: Single Fuel Approach

- Use of a cetane improver to modulate reactivity of gasoline range fuels
- Gasoline compression ignition type techniques (GCI/ PPC)

Moving Toward a Different Fuel-Based Strategy for Higher Efficiency on SI Engine Platforms

- Knock mitigation enables higher efficiency operation on SI engines
  - Enables higher compression ratio for higher thermodynamic efficiency and more aggressive downsizing for system efficiency

Pathway 1: Fuels with High Octane Number and High Latent Heat of Vaporization

- Previous work in this area includes ethanol optimization investigations
- Continuing work along pathway 1 will continue under a different project to quantify efficiency gains with higher octane number – from both renewable and HC sources

Pathway 2: Modulate Anti-knock Characteristics to be Less Reliant on Fuels Properties

- 6-stroke experiments are relevant to NVO chemistry, but they also illustrate a path of in-cylinder reforming that has combustion benefits, similar to the SWRI D-EGR concept
  - 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
    - Dilute combustion is thermodynamically favorable due to reduced heat transfer and higher ratio of specific heat (γ)
- Continuing experiments will focus on in-cylinder reforming chemistry in multi-cylinder engine platform (additional details in backup slide)

Summary

Relevance

Identify and promote pathways for alternative fuels to support higher efficiency and petroleum displacement from fundamental research through deployment

Experimental Approach

- Experimental approach to multi-cylinder RCCI uses of production viable hardware and applies a mapping approach to quantify efficiency and emissions benefits through drive cycle simulation
- Flexible HVA valve train allows efficiency comparisons of different combustion operating modes on a common SI engine platform, as well as unique engine cycles to investigate NVO chemistry

Accomplishments

- Demonstrated the potential of RCCI for improving fuel economy over light duty drive cycles
- Showed added load expansion benefit of RCCI with unique properties of renewable fuels
- Completed unique experimental campaign investigating fuel-specific NVO chemistry in low-oxygen environments → fuel properties can be altered significantly during NVO period
- On track to complete direct comparison of SI, dilute SI, HCCI, and SA-HCCI combustion for 3 fuels

Collaborations

Numerous collaborations with industry, other national laboratories, and academia to ensure that efforts are relevant to research needs of the broader engines and fuels community

Future Work

- Quantify efficiency and emissions for advanced combustion CI strategies using single-fuel in gasoline boiling range (additized gasoline RCCI and GCI/PPC combustion)
- Investigate in-cylinder reforming strategies as a way for engines to mitigate knock on SI platforms in a way that decreases dependence on fuel properties

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Technical Back-Up Slides

Dual Fuel RCCI Concept

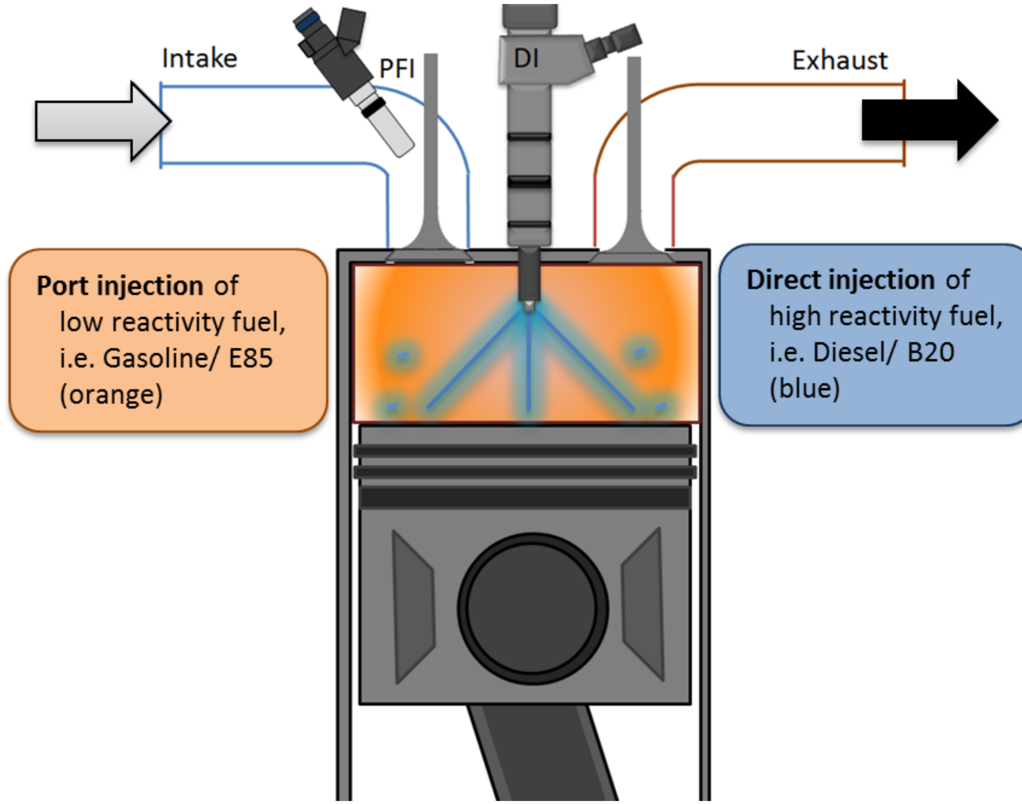
Backup 1

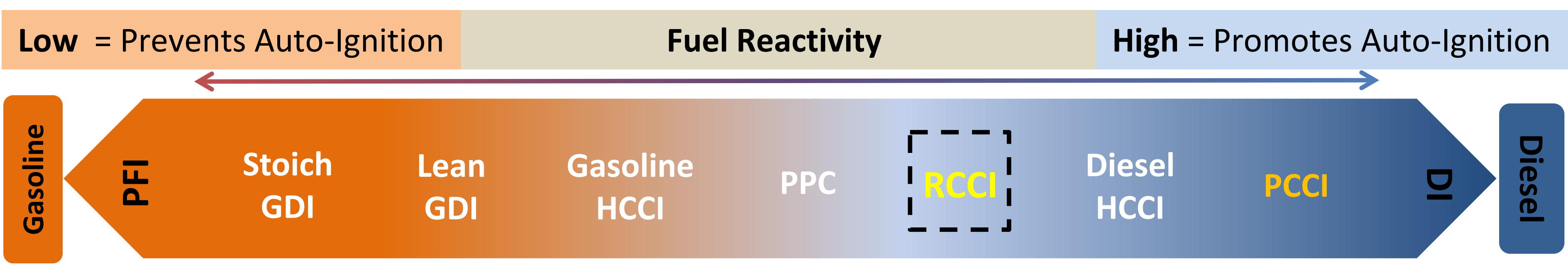
RCCI allows increased engine operating range for premixed combustion through:

- 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





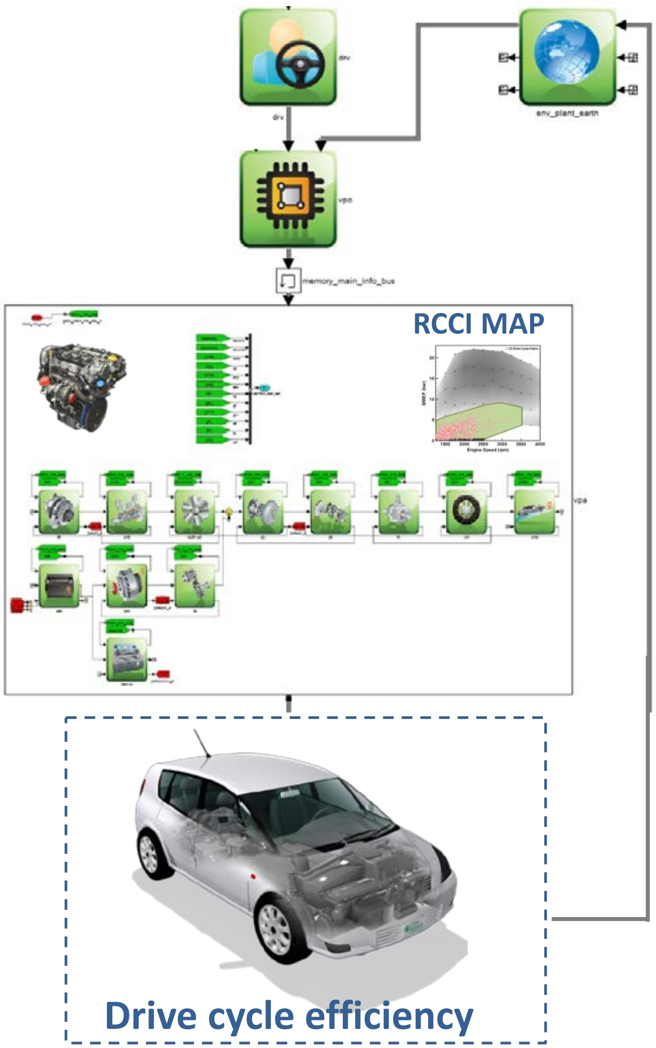
VEHICLE SYSTEM MODELING USING EXPERIMENTAL/ INDUSTRY ENGINE MAPS ON SAME VEHICLE IN AUTONOMIE 1

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

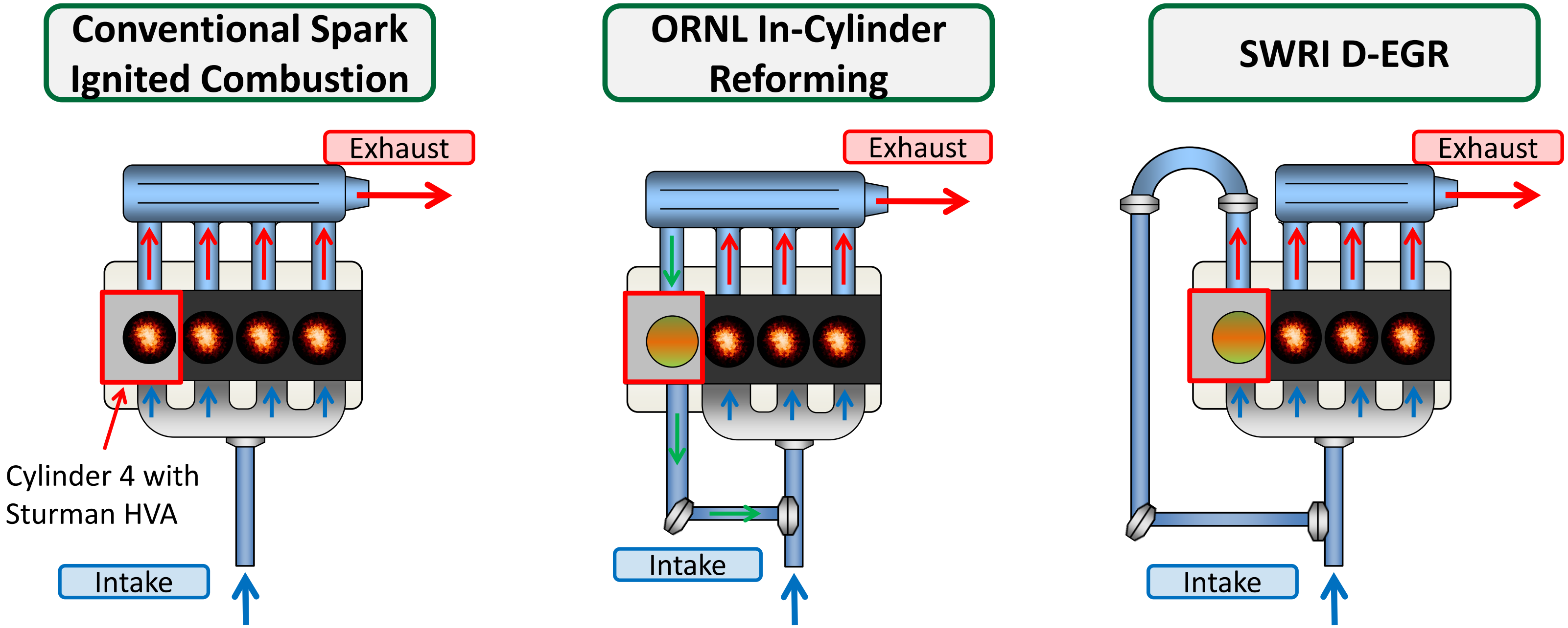
1 Autonomie, Developed by Argonne National Lab for U.S. DOE, http://www.autonomie.net/

AUTONOMIE Simulink/ Stateflow



Continuing Work will Focus on In-cylinder Reforming on a Multi-Cylinder Engine

- Application of in-cylinder fuel-rich chemistry relies on multi-cylinder engine strategy where cylinders operate differently
  - Move Sturman HVA system from single-cylinder engine to cylinder 4 on a multi-cylinder engine to maintain experimental flexibility
  - Maintain 2.0L GM Ecotec engine platform, use existing engine installation at ORNL



- 2-year process to evaluate these combustion concepts on multi-cylinder platform
- Continue to apply unique ORNL analytical capabilities and thermodynamic analyses