Gasoline-like Fuel Effects on Advanced Combustion Regimes

Project ID: FT008

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<u>DOE Management Team</u>
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Project overview

Broad Barrier: Inadequate data and predictive tools to assess fuel property effects on advanced combustion, emissions, and engine optimization

- **Relevance:** Determine the effects of fuel properties and chemistries on combustion performance and emissions for advanced combustion regimes. Work toward real-world **efficiency**, emissions, and direct **petroleum displacement with alternative fuels**.

Budget

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

Project Timeline

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

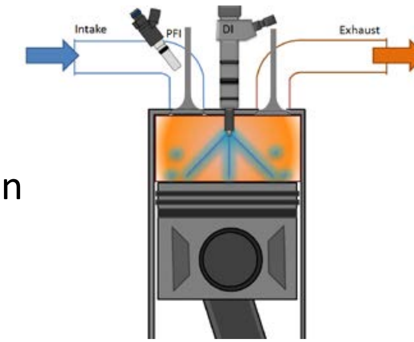
Industrial Partnerships and Collaboration

- Members of the AEC/HCCI working group led by Sandia National Laboratory
- Related funds-in project with an OEM
- University of Wisconsin – RCCI collaboration
- University of Michigan – Modeling and informal SA-HCCI

- SWRI – Advanced ignition system
- DRIVVEN – Engine controller
- Reaction Design – Model Fuels Consortium and data sharing
- Discussions and presentations to many more

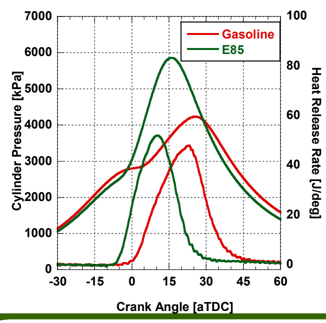
Investigations share common relevance to DOE goals: enable direct petroleum displacement, improved engine efficiency, and low emissions

Fuel-specific Load Range Expansion with Multi-Cylinder Reactivity Controlled Compression Ignition (RCCI)



- Dual-fuel combustion with gasoline-like and diesel-like fuels
- High level DOE milestone for biofuels to enable RCCI load range expansion
  - Diesel-like or higher brake thermal **efficiency**
  - Order of magnitude decrease in NO_X and soot relative to OEM calibration

Status: Milestone Complete

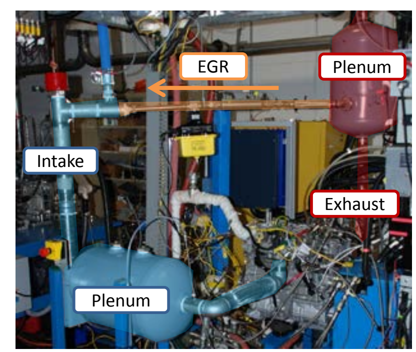


Impact of ASTM D5798 on Ethanol Optimization for High Efficiency

- Significant opportunity for ethanol optimization by taking advantage of higher octane number and latent heat of vaporization
- Milestone: Determine impacts of low octane ethanol blends on optimization potential. **Status: On Track**

Fuel Specific Characteristics of Advanced Combustion Regimes

- Fuel-specific **efficiency** advantage observed for ethanol and iso-butanol blends under both SI and SA-HCCI
- Milestone: Determine efficiency potential for ethanol and iso-butanol blends during HCCI and SA-HCCI. **Status: On Track**
- Milestone: Characterize NVO chemistry under stoichiometric and lean conditions. **Status: On Track**

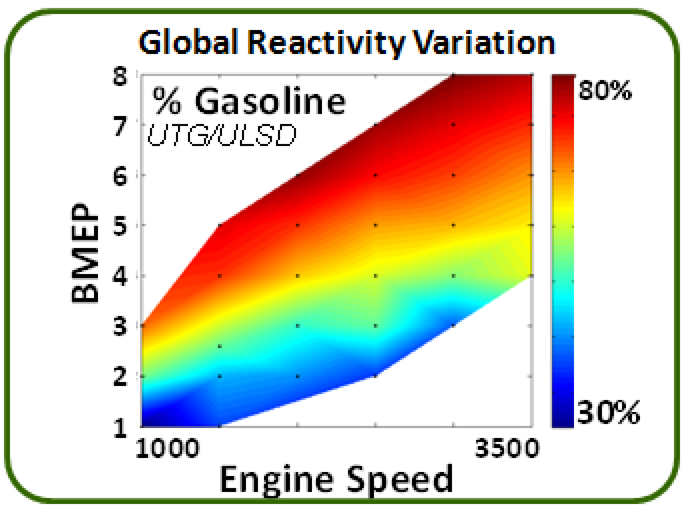


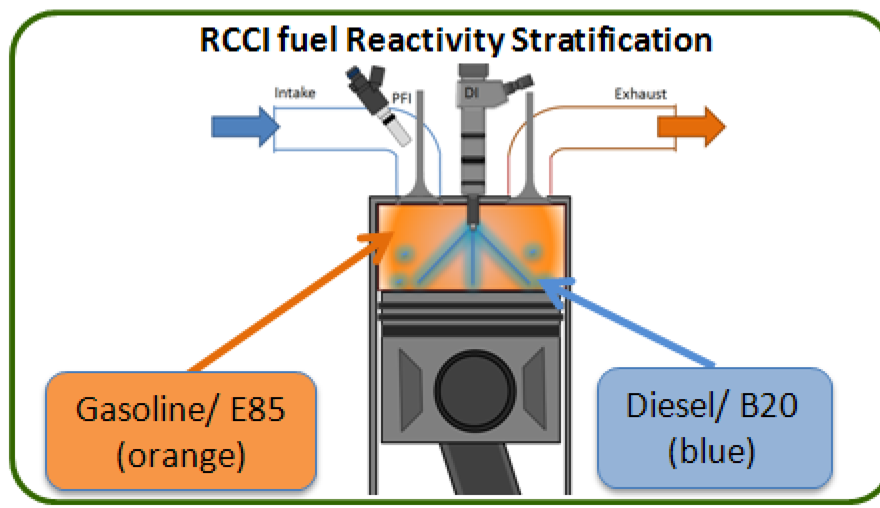
Study 1. RCCI load expansion opportunities with ethanol and biodiesel

- **Q2 Milestone – Biofuels Enabling RCCI Range Expansion**
  - Characterize the potential of biofuels to enable expansion of the operating range of reactivity controlled compression ignition (RCCI) combustion in a multi-cylinder engine with diesel-like or higher brake thermal efficiency and an order of magnitude decrease in engine-out NOx and soot emissions.

Dual-Fuel low temperature combustion (LTC) provides control of combustion processes through in-cylinder mixing

- Global fuel reactivity changes with gasoline/diesel ratio
- Reactivity stratification
- Increased control of combustion allows for higher load than many alternate LTC strategies





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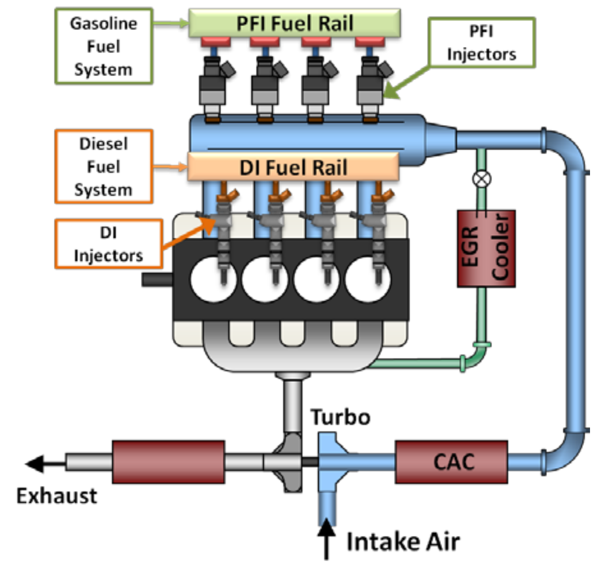
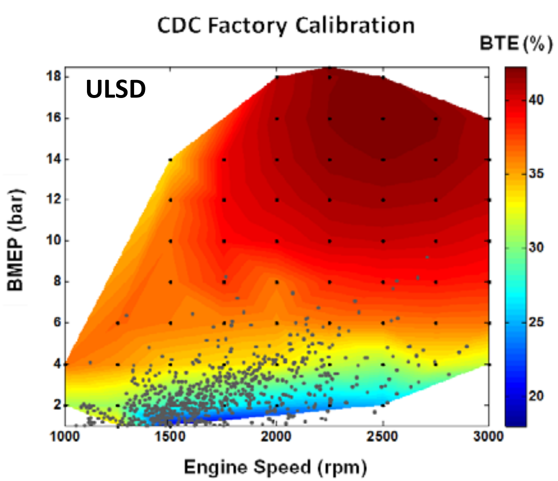
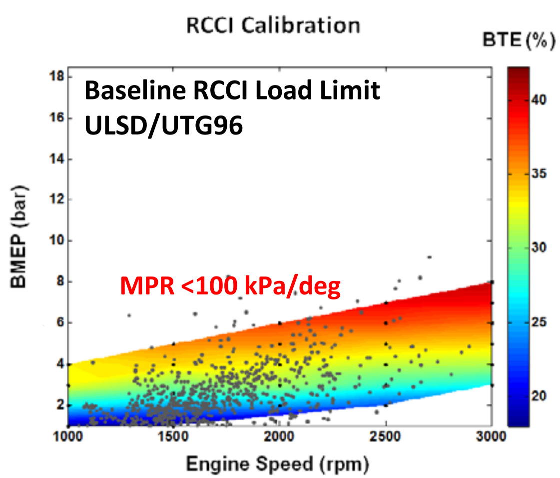
ORNL's approach to multi-cylinder RCCI

- **RCCI engine based on 2007 GM 1.9-L multi-cylinder diesel engine**
  - Dual-fuel system with PFI injectors
  - OEM diesel fuel system with DI injectors
  - OEM variable geometry turbocharger
  - Custom EGR cooler
- **RCCI pistons designed by UW-M (CR = 15.1)**
  - Based on heavy-duty RCCI piston
  - Reduce heat transfer losses & minimize squish region
- **DRIVVEN control system with DCAT**
  - Full control of DI & PFI fuel systems
  - Cylinder-to-cylinder balancing



ORNL Multi-Cylinder RCCI Engine



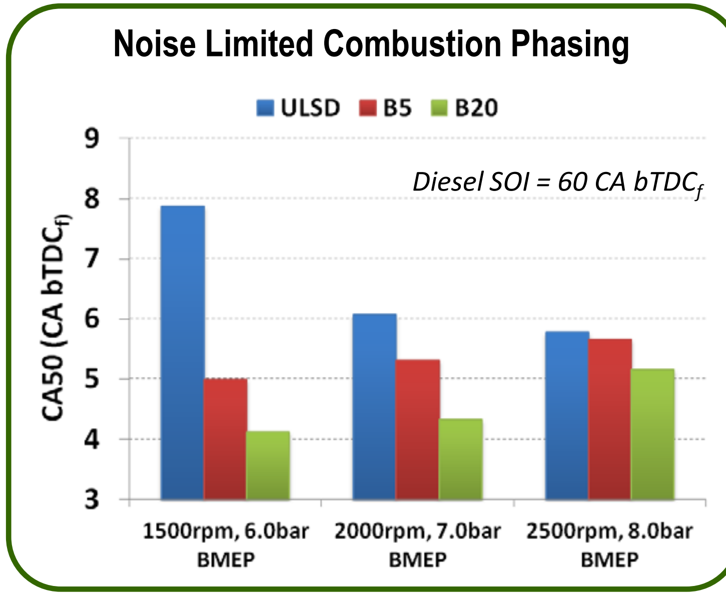


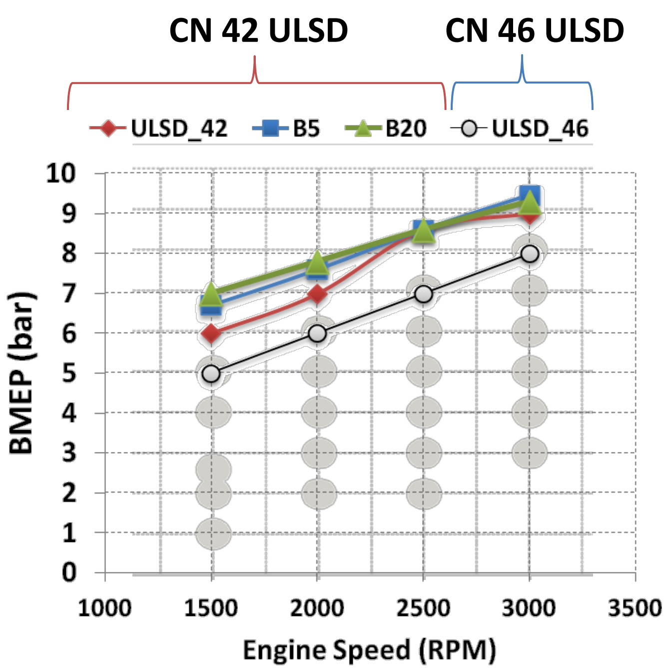
Base Multi-Cylinder 1.9L GM CIDI

Number of Cylinders	4
Bore, mm	82.0
Stroke, mm	90.4
Compression Ratio	17.1
Rated Power, kW	110
Rated Torque, Nm	315

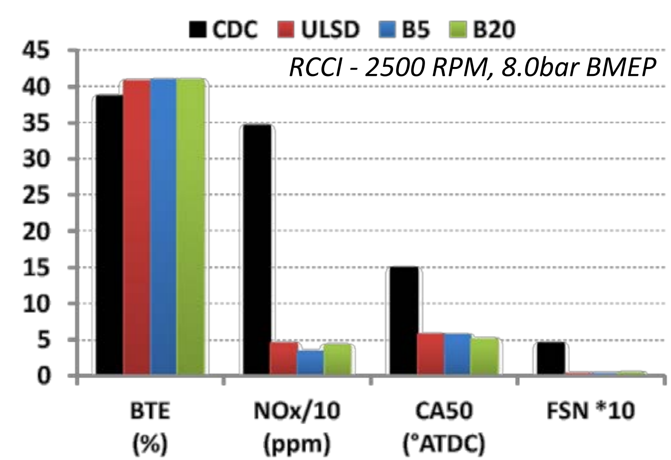
Biodiesel enables load expansion by reducing the pressure rise rate

- **Reduced pressure rise rate allows more advanced phasing**
  - Better stability, HC and CO emissions with advanced phasing
  - Due to fuel-specific differences in NTC heat release
  - Allows higher ratio of gasoline for higher load
- **Reduced noise is not purely a cetane number (CN) effect**
  - Biodiesel (SME) CN = 47.5
  - Two #2 diesel fuels with CN = 42.5 and 46.5

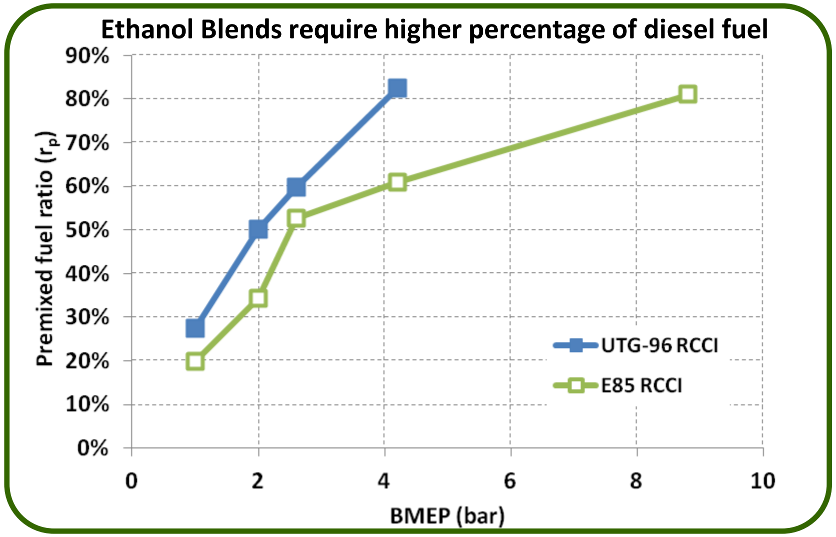


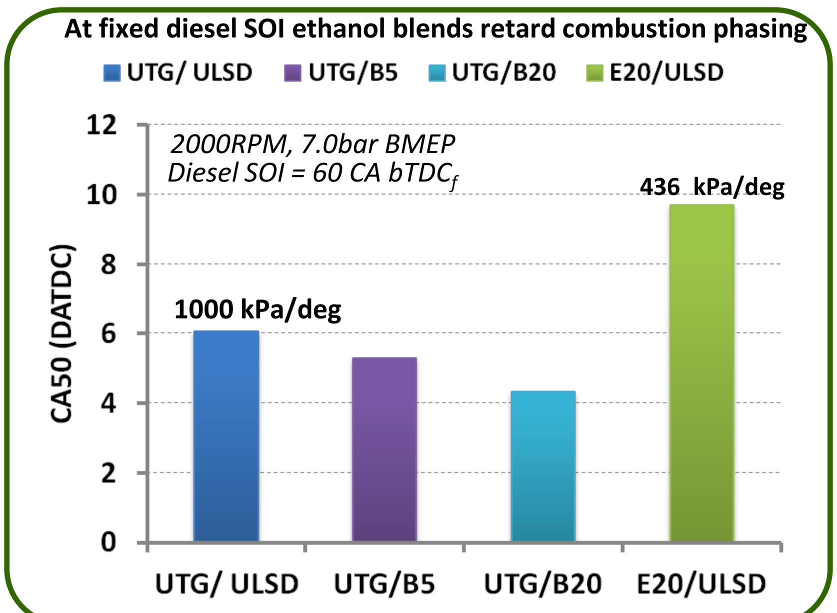


Biodiesel blends allow combustion phasing to be maintained despite increasing amount of gasoline while observing MPRR limit of 1000 kPa/deg

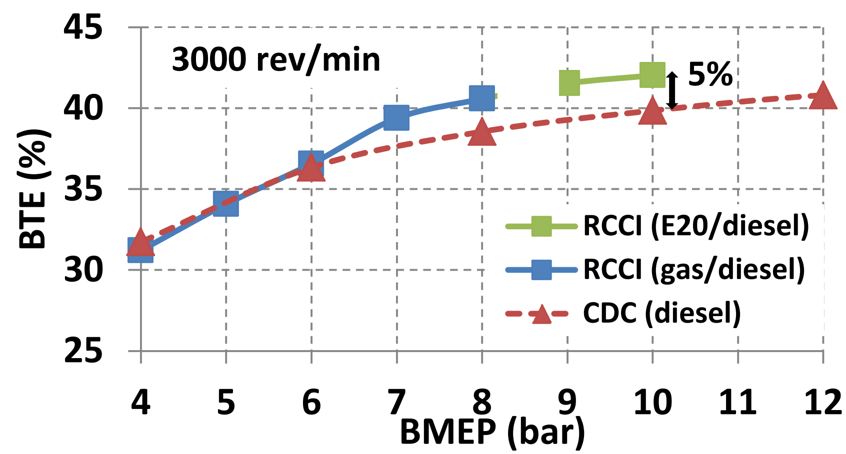


Ethanol blends also enable RCCI load expansion



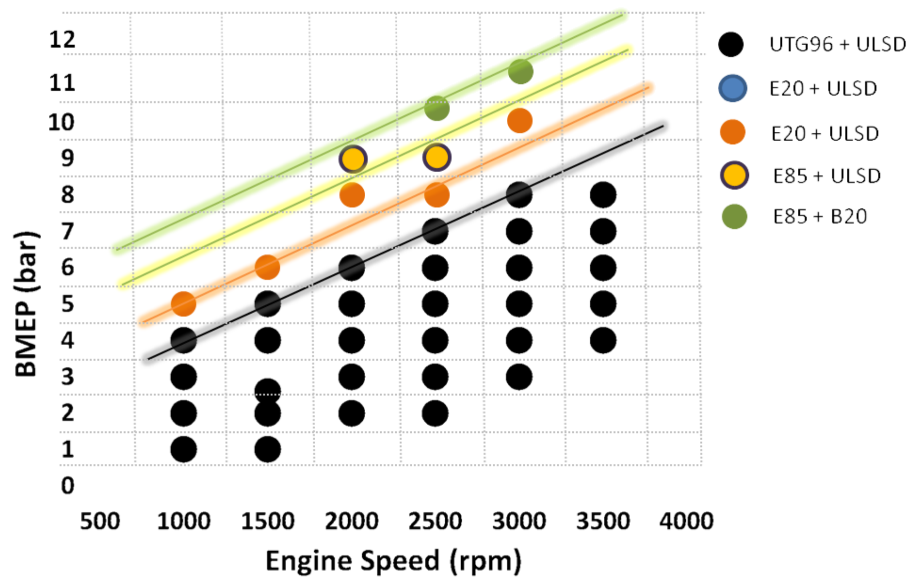


- **DI to PFI fueling ratio changes**
  - Lower reactivity of E85 requires higher fraction of diesel / biodiesel
  - Both a chemical octane effect and a charge cooling effect with E85
- **More combustion stability at late combustion phasing**
- **Cyclic instabilities observed at high load limit for E85**
  - High pressure rise followed by near misfire
  - Minor stochastic perturbations may cause large operational changes due to homogeneity of fuel



High-level DOE milestone completed

- **Q2 milestone complete: biofuels enabling RCCI load range expansion**
  – Biodiesel reduces pressure rise rate, allows combustion phasing to be advanced for more stability and lower unburned emissions
  – Ethanol blends enable stable combustion at more retarded combustion phasing
  – Order of magnitude reduction in NO_X and soot emissions
  – Brake efficiency advantage over diesel combustion at high loads



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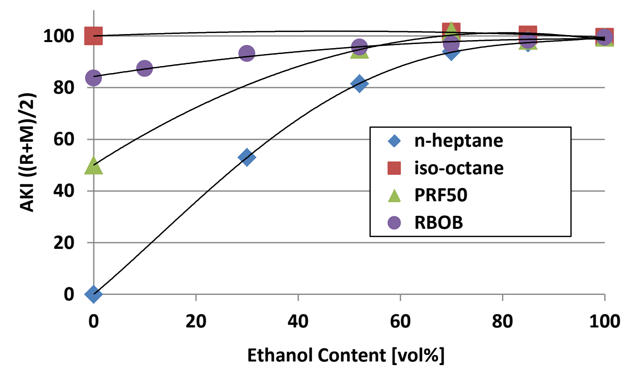
Study 2. Impact of hydrocarbon blendstock on engine optimization for engine for high ethanol fuels

Background: 2011 ASTM standard replaces previous specifications for E85

Designation: D5798 – 11

Standard Specification for
Ethanol Fuel Blends for Flexible-Fuel Automotive Spark-Ignition Engines[1]

- **Potential for lower octane number fuel**
  - Lower ethanol content (as low as 51 vol%)
  - Low octane number refinery hydrocarbon streams
  - No minimum octane number requirement



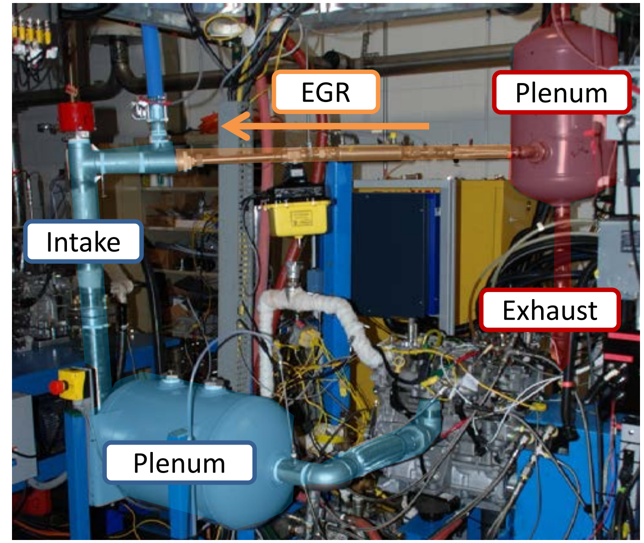
Results from ORNL blending study showing anti-knock index (AKI) of ethanol blends with different hydrocarbons.

- **Earlier ORNL blending study revealed sufficiently high octane number sufficient for current FFV's**
- **Numerous DOE-funded projects have shown potential for E85-optimized engines**
  - High latent heat of vaporization and octane number are the basis for optimization
  - Engine technologies: direct injection fueling, high compression ratio, boosted air handling for engine downsizing
  - Impact of current fuel standard on potential for optimization is unclear

Objective: Experimentally determine impact of lower ethanol content and low octane hydrocarbon streams on ethanol-optimized engine

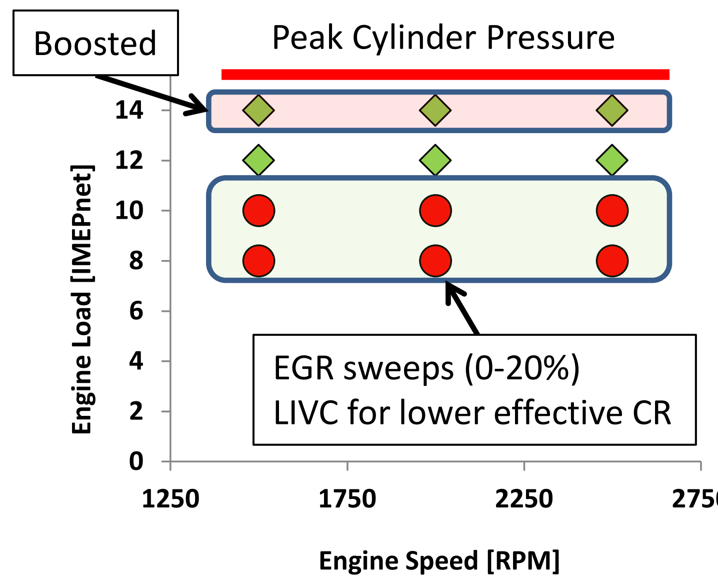
Experimental approach: determine optimization potential for high ethanol content fuels with low octane number hydrocarbons

- **Single cylinder engine with hydraulic valve actuation (HVA)**
  - Modified 2.0L GM Ecotec engine
  - High compression ratio (12.6), direct injection fueling, boost
  - Knock-prone operating conditions (low speed, high load)
- **Optimal combustion phasing maintained except under knock-limited cases (MFB50 = 8-9 CA aTDC$_f$)**
  - Knock mitigation ability of EGR and lower effective compression ratio investigated at 8 and 10 bar IMEP$_{net}$
- **Fuel matrix designed to provide a range in octane number**

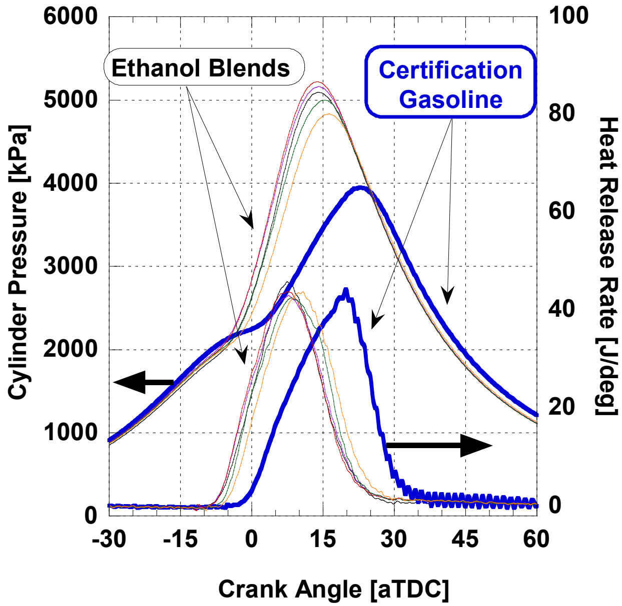


	AKI (R+M)/2	0 vol % Ethanol	51 vol % Ethanol	67 vol % Ethanol
UTG-96	**92**	X	X	
Straight Run Gasoline	**64**		X	X
N-heptane	**0**		X‡	X
E85 (pre-blended)	**97**			

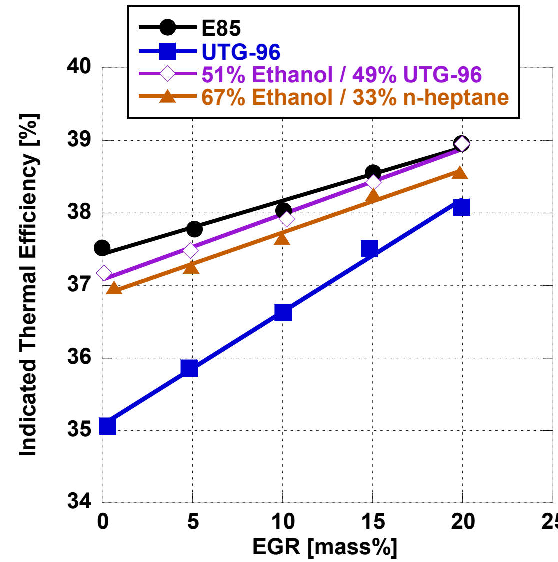
‡Data not available for presentation

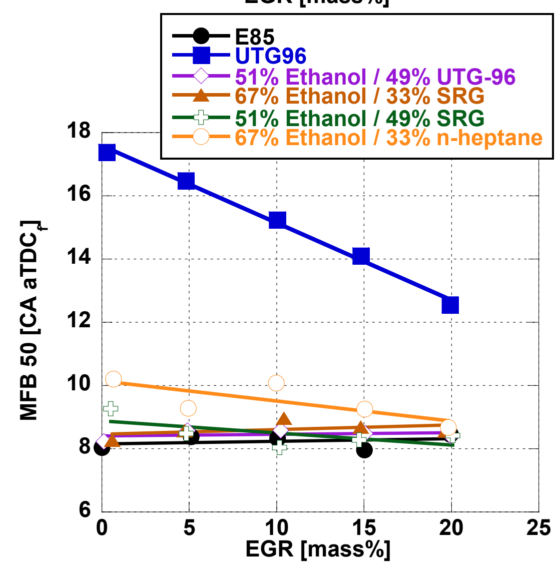


All ethanol fuel blends are knock resistant relative to premium grade gasoline



1500 rpm, 8 bar $IMEP_{net}$



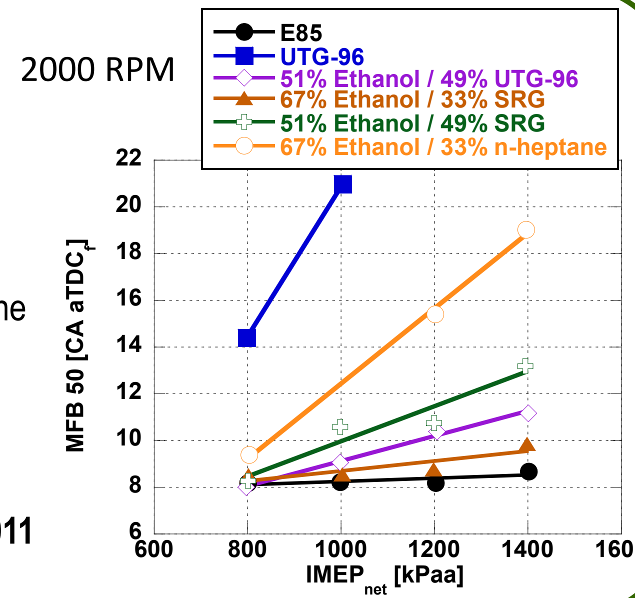


*Note: SRG fuels not included because LHV not yet available.

- **Superior resistance to knock for all ethanol blends despite low-octane hydrocarbon blending streams**
  - Illustrates impact of charge cooling in addition to chemical octane number
- **EGR increases efficiency for all fuels**
  - Reduced pumping and thermodynamic benefits (gamma)
  - Additional combustion phasing benefit for UTG-96
- **Retarded combustion phasing required for UTG-96**
  - Unable to operate at 12 or 14 bar $IMEP_{net}$

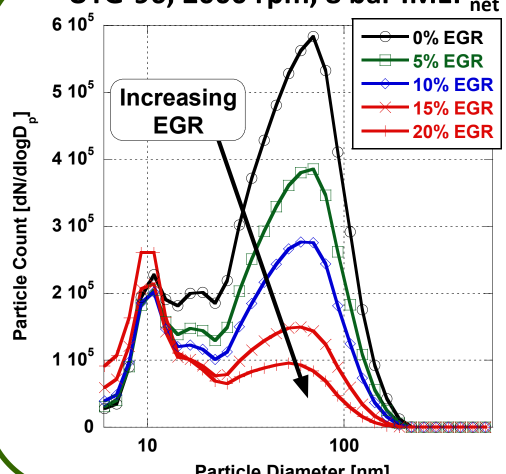
Additional findings and preliminary conclusions

Opportunities for Engine Optimization



- **Lower knock resistance for ethanol blends with low octane number hydrocarbons**
  - More opportunity to optimize with high grade hydrocarbon blendstocks
  - Largest performance degradation of ethanol blend seen with 33 vol% n-heptane, but still significantly better performance than premium grade gasoline
  - Energy companies unlikely to use hydrocarbon blending stream with lower octane number than straight run gasoline
- **Preliminary conclusion: Significant opportunity to optimize for ethanol fuels within even with lower ethanol content and lower octane hydrocarbons in 2011 version of ASTM D5798**

UTG-96, 2000 rpm, 8 bar IMEP$_{net}$

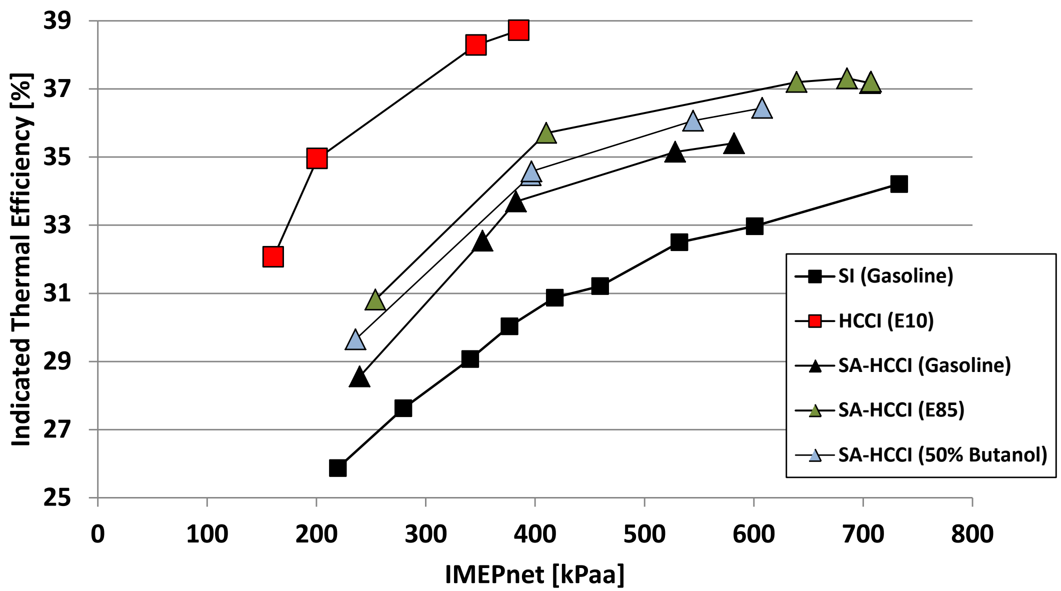


Particle Emissions

- **Particle number size distributions monitored with EEPS**
- **All ethanol blends reduced particle emissions by approximately one order of magnitude relative to gasoline**
  - Optimizing for high ethanol content fuels leads to better efficiency, more power, and low particle emissions, consistent with particle emissions study presented at FY11 merit review
- **Observed particle emissions decrease substantially with increasing EGR for all fuels**
  - Follow-on work to be performed by Storey and other ORNL colleagues as part of an existing project within the Advanced Combustion Engines program

Study 3. Fuel effects on advanced combustion operating regimes on gasoline engine platforms

- **Background: Advanced combustion strategies offer the potential for improved efficiency while maintaining low tailpipe-out emissions on gasoline engine platforms. Alternative fuel composition may offer the potential for increased efficiency and expanded load operation.**

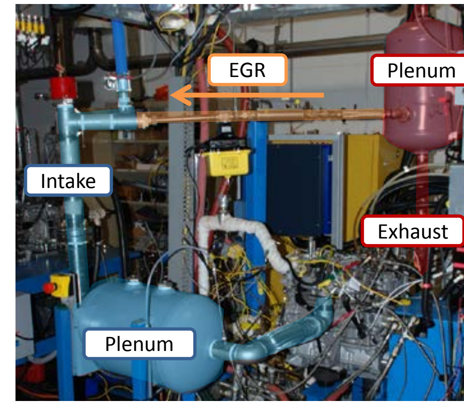


- **Objective: Characterize fuel-specific attributes of gasoline-like fuels on advanced combustion operating regimes that enable increased efficiency.**

Two advanced combustion studies are planned for remainder of FY12

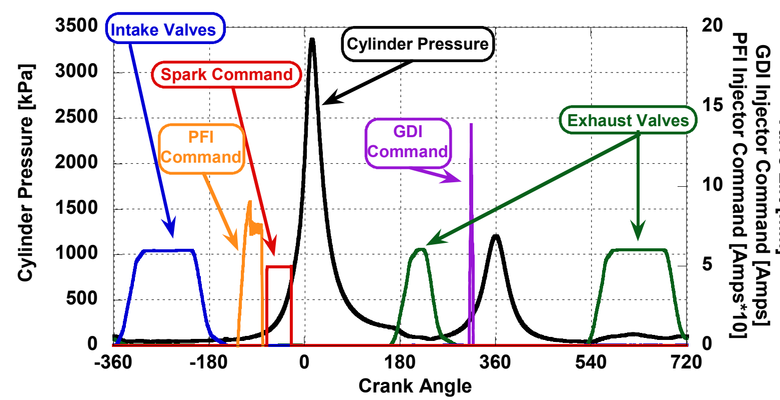
Fuel-Specific Characteristics in Advanced Combustion Regimes for Increased Efficiency

- **Previous work has shown limitations of naturally-aspirated advanced combustion strategies**
  - HCCI limited to ~4 bar $IMEP_{net}$
  - Stoichiometric spark-assisted HCCI is limited to ~7.5 bar $IMEP_{net}$
- **FY12 experiments aimed at expanding operating range and taking advantage of fuel-specific characteristics**
  - New air handling system allows for boosted operation and external EGR
  - Installing new extended-spark ignition system for improved stability

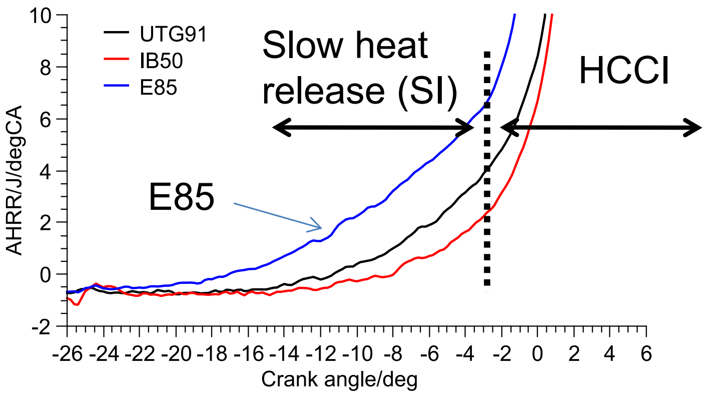


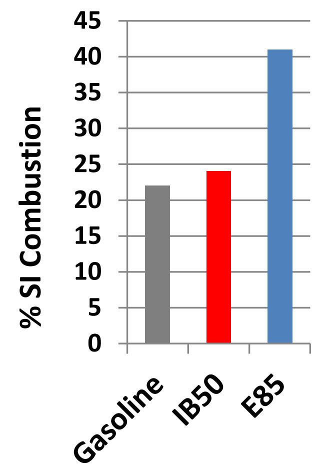
Fuel-Specific Differences of NVO Chemistry using ORNL 6-Stoke Engine Cycle

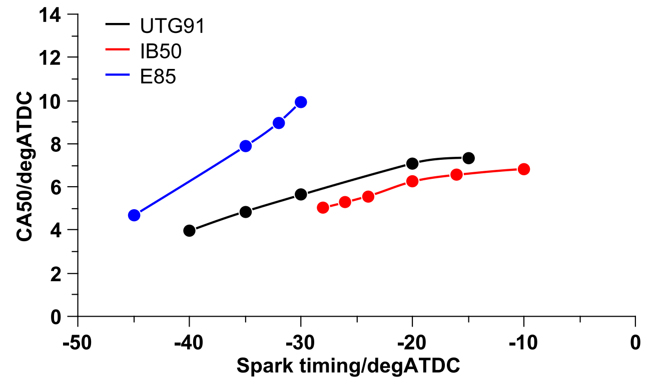
- **Fuel injection timing into NVO is a dominant control parameter for HCCI and SA-HCCI**
  - Thought to be dominated by heat release for lean operation
  - Continues to be effective for SA-HCCI despite lack of oxygen in residual
  - Likely due to fuel reforming
- **NVO chemistry can be investigated directly using the unique ORNL 6-stroke engine cycle**

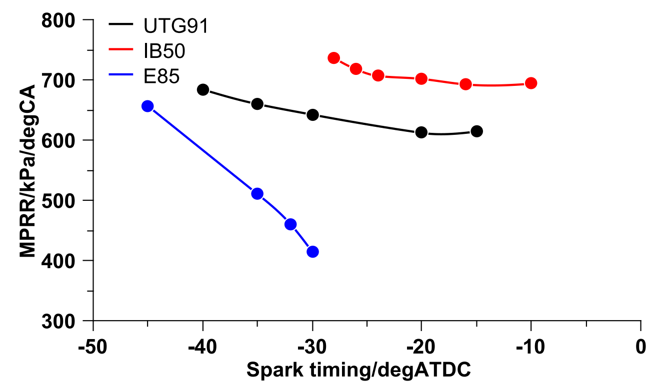


SA-HCCI with E85 has highest efficiency and maximum load limit
Shows potential for additional load range expansion





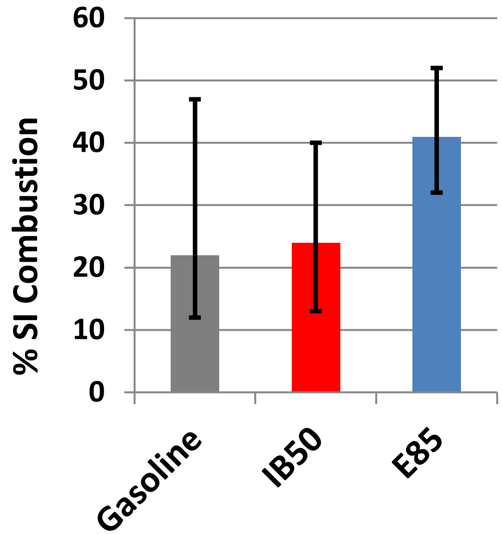


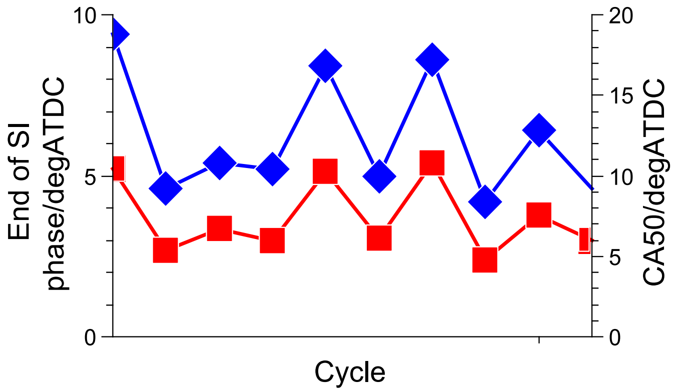


- **E85 shows highest resistance to auto ignition**
  - Largest fraction of fuel is consumed during the SI phase of combustion
- **As a result of larger SI combustion contribution, spark timing is a more influential control over combustion phasing and pressure rise (i.e. noise)**

Cyclic variability in SI portion of combustion is a barrier to realize potential of E85

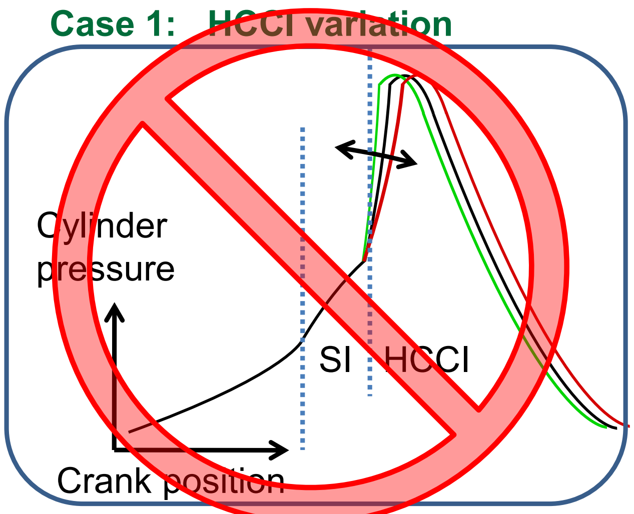
- **CA50 can change by more than 5 CA on a cycle-to-cycle basis**
  - Result is individual cycles with very high cylinder pressure rise despite stable combustion as quantified by COV of $IMEP_{net}$



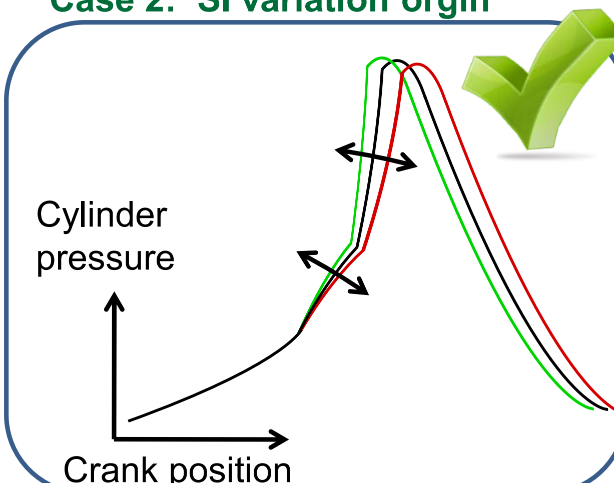


- **Observations reveal cyclic variability is caused by SI portion of combustion**
  - Variability is amplified in volumetric portion of combustion
- **No evidence of variability originating in volumetric portion of cycle**

Case 1: HCCI variation



Case 2: SI variation orgin



Cyclic variability reductions to enable further load expansion for E85 are planned with extended-spark ignition system

ORNL Hardware for DCO Ignition System

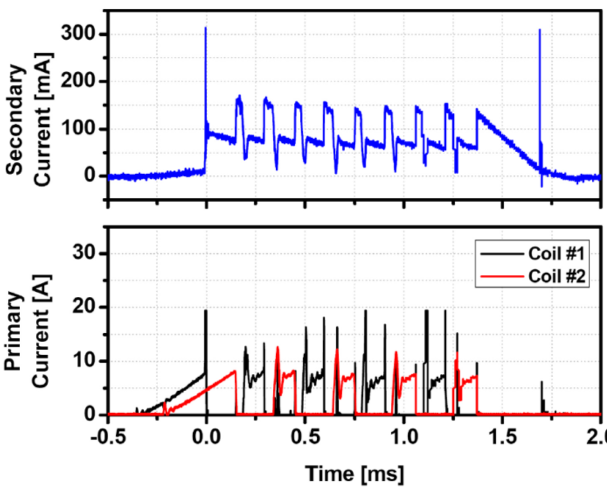
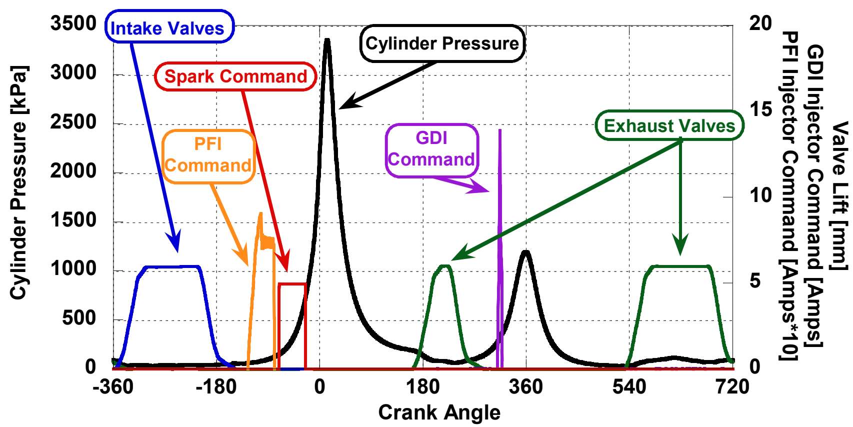
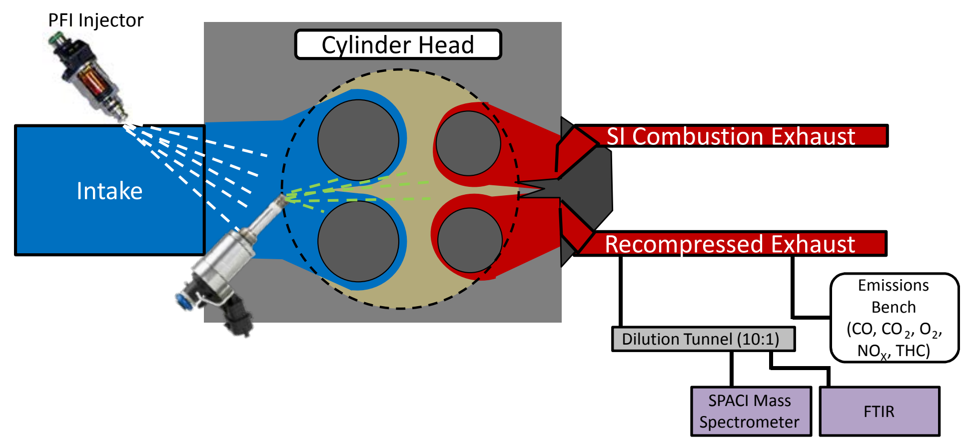


*Image from Alger et al., 2011-01-0661

- **Southwest Research Institute developed Dual Coil Offset (DCO) ignition system to extend EGR limit for dilute combustion**
  - Recipient of 2011 R&D 100 award
- **Extended spark increases likelihood of reliable ignition**
- **Ignition control strategy can be readily incorporated into control system on ORNL single-cylinder engine with HVA**

Characterization of fuel-specific chemistry with fuel injection into NVO with ORNL's 6-stroke engine cycle





- **Single-cylinder HVA engine is uniquely capable because there are no mechanical linkages between the crankshaft and the valve train**
  - Controls developed to operate engine in a 6-stroke mode
- **Fuel injection into NVO is a high sensitivity control for HCCI (fuel-lean) and SA-HCCI (stoichiometric)**
  - Exothermic oxidation reactions, endothermic reforming reactions, and other cracking reactions are all likely under different scenarios
- **6-stroke engine cycle is capable of simulating NVO conditions**
  - NVO exhaust separated from combustion exhaust with mechanical device
  - Exhaust composition analyzed using FTIR, mass spectrometer (H_2), and standard emission bench
  - Combustion analysis and exhaust temperature

Summary: Numerous ongoing activities investigating effects of gasoline-like fuels on high efficiency operating regimes

Completed high-level DOE milestone by expanding RCCI load regime with biofuels

- E85 and B20 enabled extension of the RCCI high load limit from 6.5 to 10 bar BMEP at 2600 RPM
- Order of magnitude decrease in NOx and soot emissions while thermal efficiency was higher than the OEM calibration

Impact of new ASTM fuel standard on potential for ethanol optimized vehicles

- Potential for lower octane number in fuel for flex fuel vehicles (as low as 51% ethanol, low octane hydrocarbon blending streams)
- All ethanol blends tested show significant opportunity for optimization compared to premium grade gasoline without ethanol
- Data shows consistent GDI particle emissions reduction with increases in EGR (finding being pursued by other ORNL researchers as part of an ACE project)

Fuel-specific characteristics of advanced combustion regimes

- Previous research shows efficiency and load expansions benefits of ethanol and iso-butanol fuels in both SI and SA-HCCI combustion
- On-track to continue SA-HCCI load expansion with E85 in FY12 with new air handling capabilities and advanced ignition system
- On-track to investigate NVO chemistry for SA-HCCI and HCCI using the ORNL 6-stroke engine cycle