Gasoline-like fuel effects on advanced combustion regimes

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2011 U.S. DOE Hydrogen and Vehicle Technologies Program Annual Merit Review and Peer Evaluation

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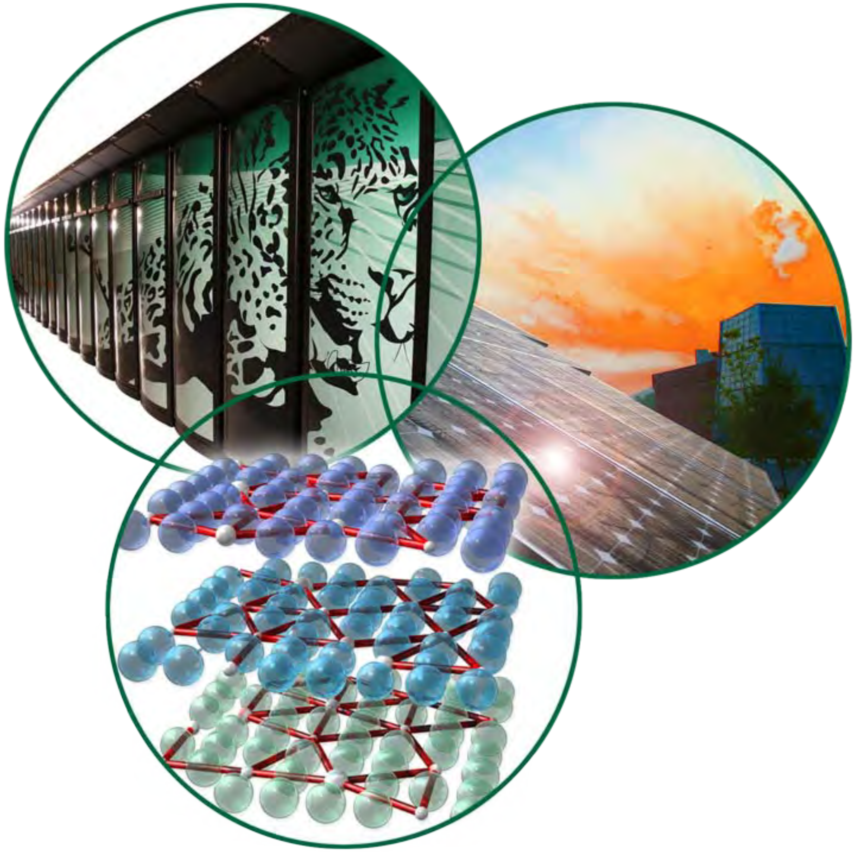

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Presentation Outline

- Project Overview
- Study 1: Fuel effects of reactivity controlled compression ignition (RCCI) combustion
  - Objectives and milestones
  - Approach
  - Technical accomplishments
- Study 2: Fuel effects of stoichiometric spark-assisted HCCI combustion
  - Objectives and milestones
  - Approach
  - Technical accomplishments
- Study 3: Fuel and fueling effects of particle emissions from a gasoline direct-injection engine
  - Objectives and milestones
  - Approach
  - Technical accomplishments
- Proposed future work
- Summary and conclusions

Project Overview

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

- **Our role**: Determine the effects of fuel properties and chemistries on combustion performance and emissions for advanced combustion regimes. Work toward real-world efficiency, emissions, and petroleum displacement.

Budget

- FY10: $1,470 k
- FY11: $200 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

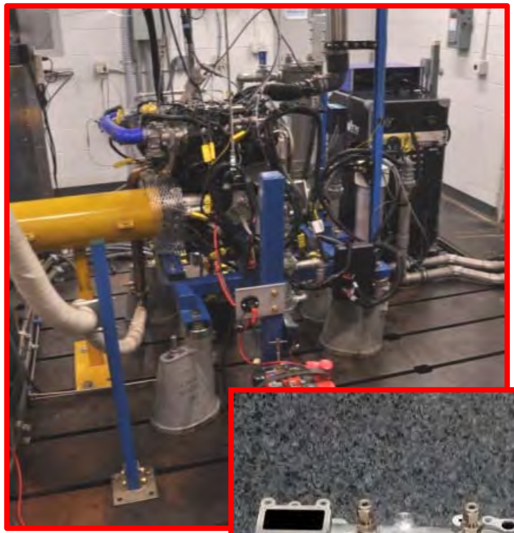
- Participation in Model Fuels Consortium, led by Reaction Design
- Members of the AEC/HCCI working group led by Sandia National Laboratory
- CRADA project with Delphi to increase efficiency of ethanol engines
- Related funds-in project with an OEM
- Collaboration with University of Wisconsin
- Collaboration with University of Michigan

Study 1: Fuel effects of Reactivity Controlled Compression Ignition (RCCI) combustion

Objective: Demonstrate efficiency in light-duty engines over a large section of the engine operating map using advanced combustion techniques.

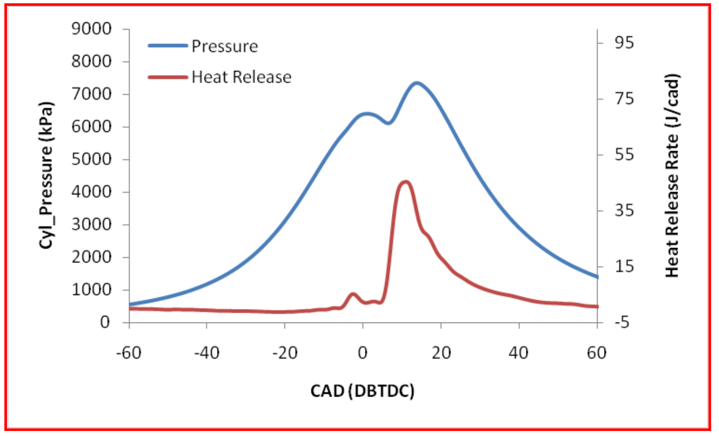
Approach: Partner with the University of Wisconsin (UW) to apply the RCCI combustion concept to a multi-cylinder engine.

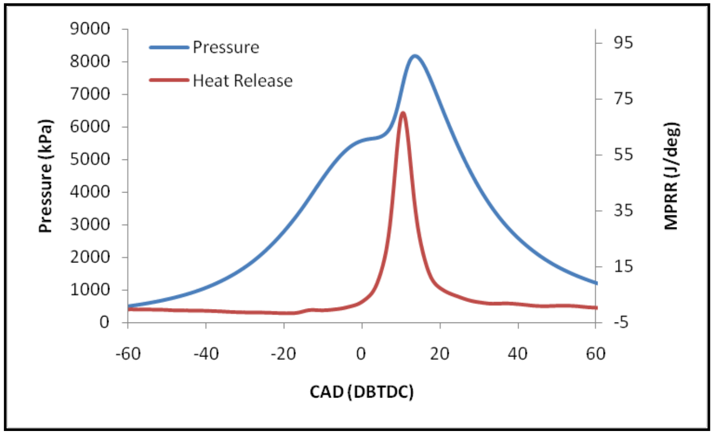
- UW has demonstrated 52% indicated thermal efficiency with RCCI in a light-duty single-cylinder engine
- ORNL's role is to adapt the combustion concept to a multi-cylinder engine and overcome all of the practical implementation barriers



Modified intake manifold

RCCI Results at 2000 rpm 6 bar BMEP





Current Status:

- System is fully operational and producing results
- Results show comparable efficiency to diesel combustion with very low NOx and smoke emissions
- System optimization is ongoing
  - Cylinder-to cylinder balancing
  - Air management and EGR distribution
- Complete details in ACE016

	Conventional Diesel	**RCCI** (81%gasoline)
BTE (%)	35.56	35.04
NOx (ppm)	216	19.9
HC (ppm)	136	3821
CO (ppm)	119	1673
FSN (-)	1.23	0.00
EGR Rate (%)	17.2	32.85
Boost (bar)	1.38	1.26

Study 2: Fuel effects of stoichiometric spark-assisted HCCI combustion

Specific Barrier: Advanced combustion strategies are being developed for higher efficiency operation. Simultaneously, fuel diversity is increasing due to EISA and other factors. This work aims to identify fuel-related problems and opportunities as they pertain to advanced combustion strategies.

Objectives:

1. Characterize stoichiometric SA-HCCI combustion with a baseline gasoline, including operable load range, emissions, combustion characteristics and thermal efficiency.

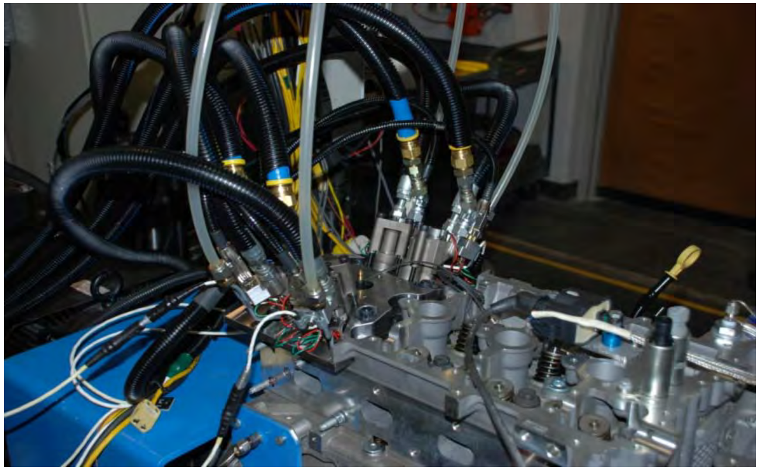
2. Complete Joule Milestone associated with SA-HCCI:

   Characterize the potential for gasoline-like bio-fuels to enable efficiency improvements of at least 5% (compared to conventional spark-ignited operation with gasoline) within the FTP drive-cycle load range using the ORNL spark-assisted HCCI operating methodology .

Status: Milestone completed using E85 ☑

Stoichiometric SA-HCCI approach: Single cylinder research engine with Sturman hydraulic valve actuation (HVA)

- Modified 2.0L GM Ecotec engine with direct injection
- Cylinders 1-3 are disabled, cylinder 4 modified for Sturman HVA system
- Engine management performed with Drivven engine controller
- Custom pistons to increase compression ratio



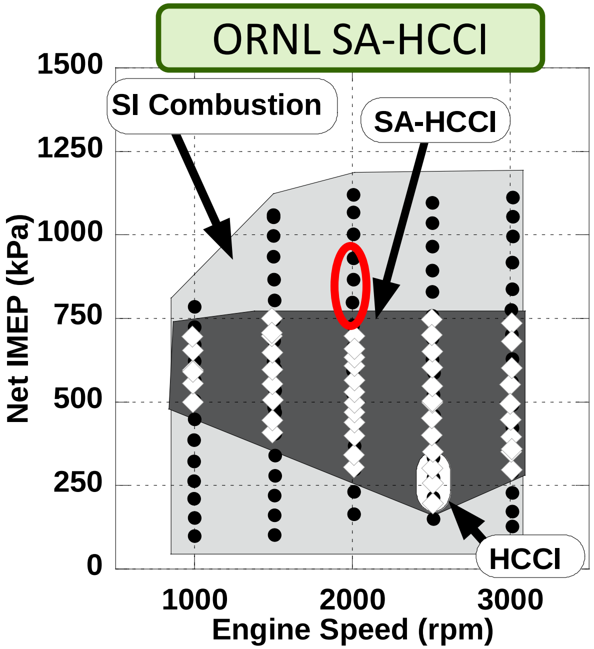
Bore	86 mm
Stroke	86 mm
Connecting Rod	145.5 mm
Fueling	Direct Injection
Compression Ratio	11.85
Valves per Cylinder	4

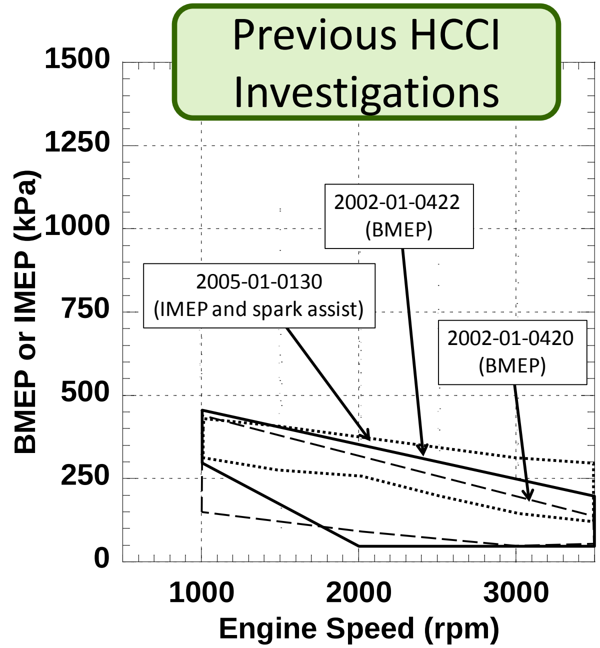
	SI Combustion	SA-HCCI
Fuel Rail Pressure (bar)	95	95
Fuel Injection Timing (CA)*	-280	-340
Equivalence Ratio	1.0	1.0
Intake Valve Opening (CA)*	-344	-313 to -234
Intake Valve Closing (CA)*	-180	-180 to -124
Intake Valve Lift (mm)	9	3 to 6
Exhaust Valve Opening (CA)*	180	170
Exhaust Valve Closing (CA)*	349	234 to 313
Exhaust Valve Lift (mm)	9	2 to 3.5
*0 CA refers to combustion TDC		

9.20 CR

11.85 CR

High load limit increased to 7.5 bar from 1000 to 3000 rpm with operating strategy



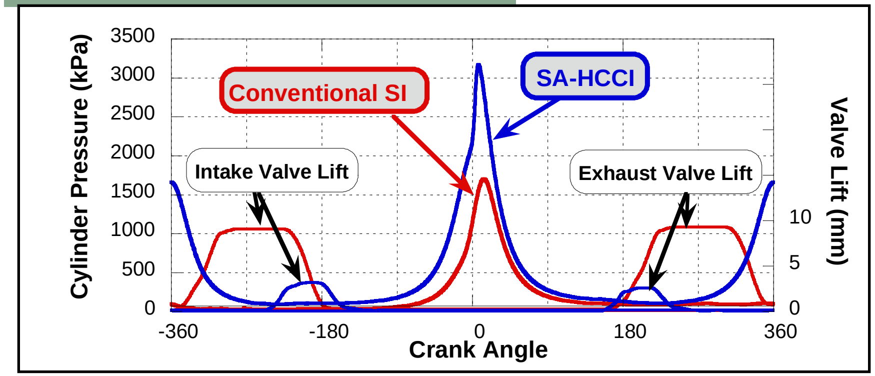


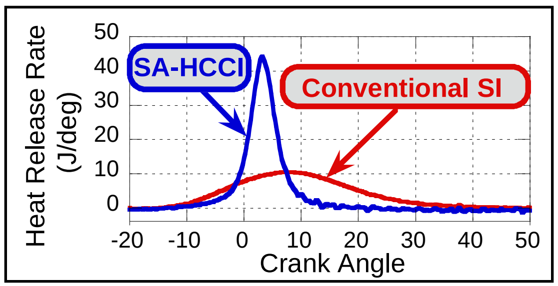
Attributes of the advanced combustion strategy

- Stoichiometric A/F ratio for compatibility with 3-way catalyst
- Spark assist
- Negative valve overlap for internal EGR
- Unthrottled operation
- Moderate pressure rise rate through control of spark, DI fuel injection timing and valve timing

SA-HCCI is a true mixed-mode combustion strategy

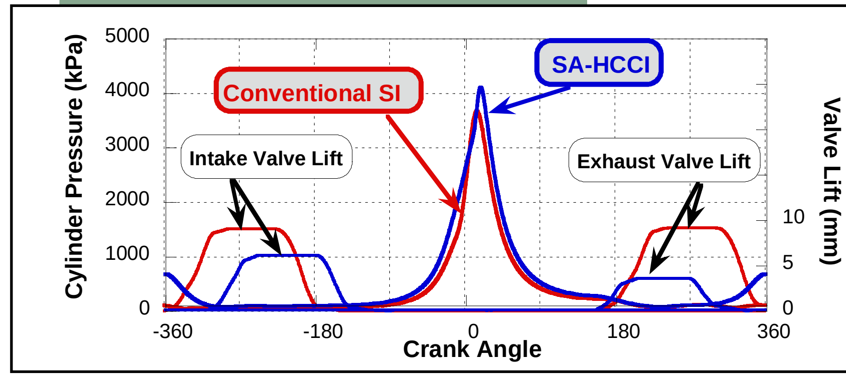
2500 rpm, 2 bar IMEP

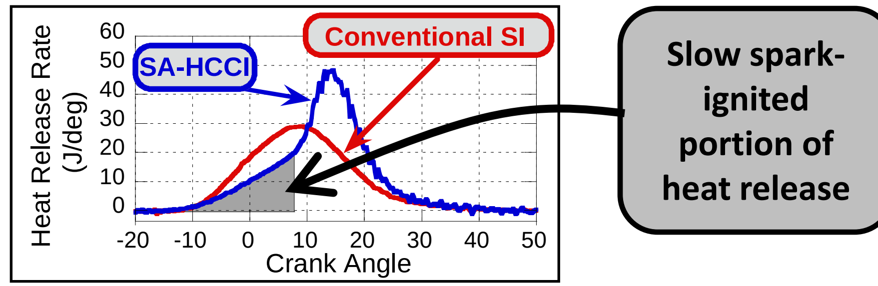




Combustion dominated by volumetric heat release at light loads

2500 rpm, 6.5 bar IMEP



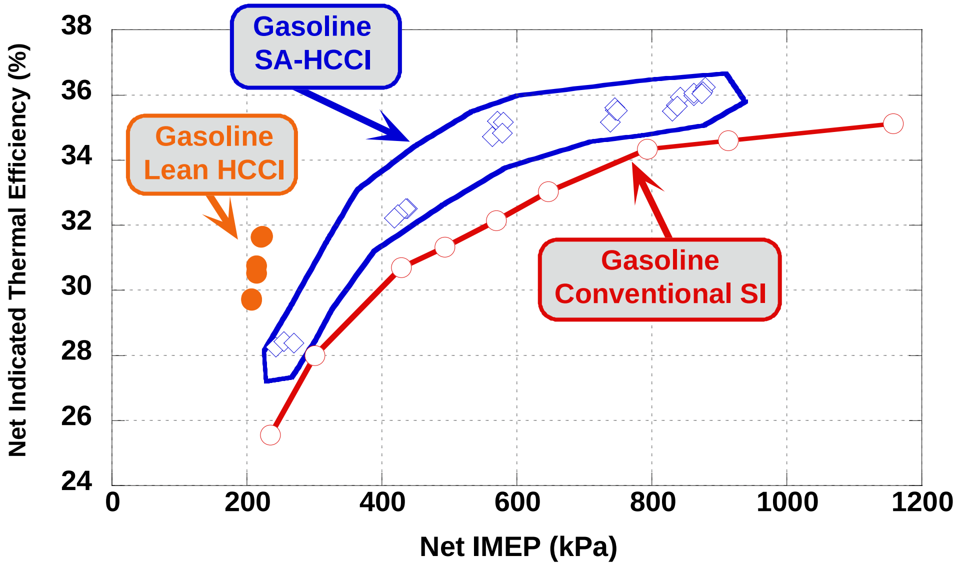


An initial spark-ignited heat release is followed by volumetric heat at higher loads

Pressure rise rates are moderate at all engine loads (<7 bar/CA)

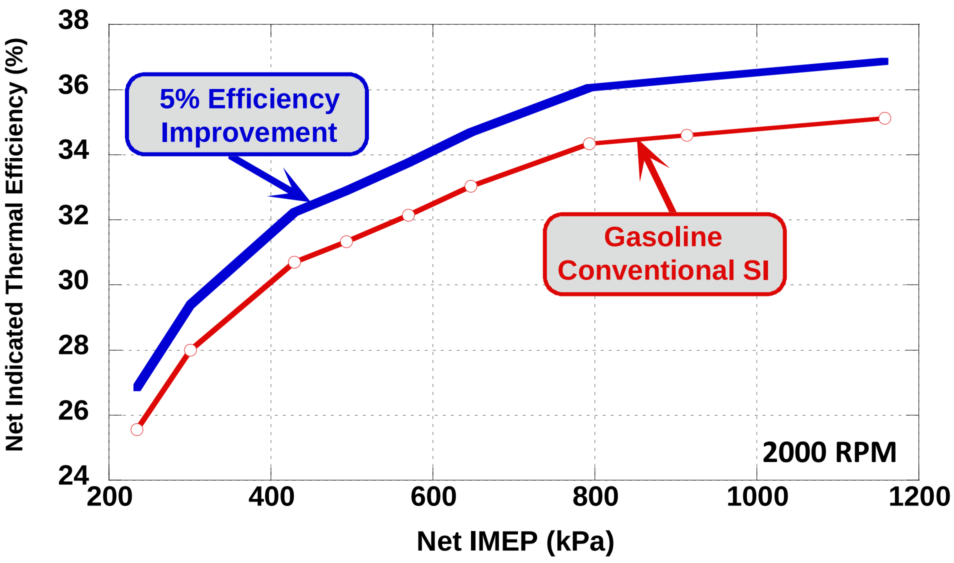
- Achieved through control of DI fuel injection timing, spark timing, and timing of valve events

Stoichiometric SA-HCCI combustion improves fuel efficiency up to 9% compared to SI combustion



- Advantages over conventional SI
  - Efficiency improvement of 3-9% over operable load range
- Advantages over lean-burn HCCI
  - Larger operating load range
  - Compatibility with conventional 3-way catalyst for NOx aftertreatment (stoichiometric A/F)
- Disadvantages over lean-burn HCCI
  - Smaller efficiency improvement over conventional SI combustion

Joule Milestone: 5% efficiency improvement with bio-fuel using ORNL SA-HCCI combustion strategy



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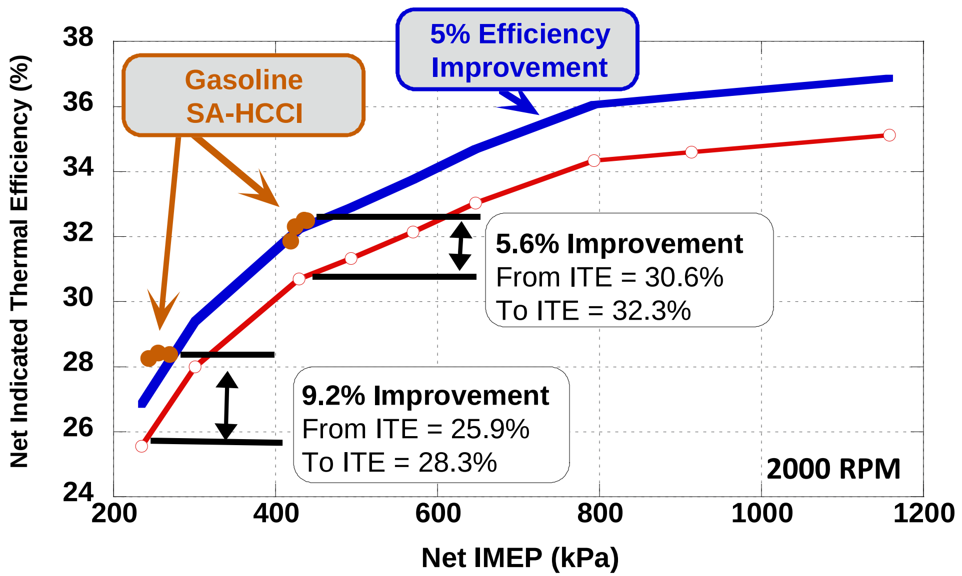
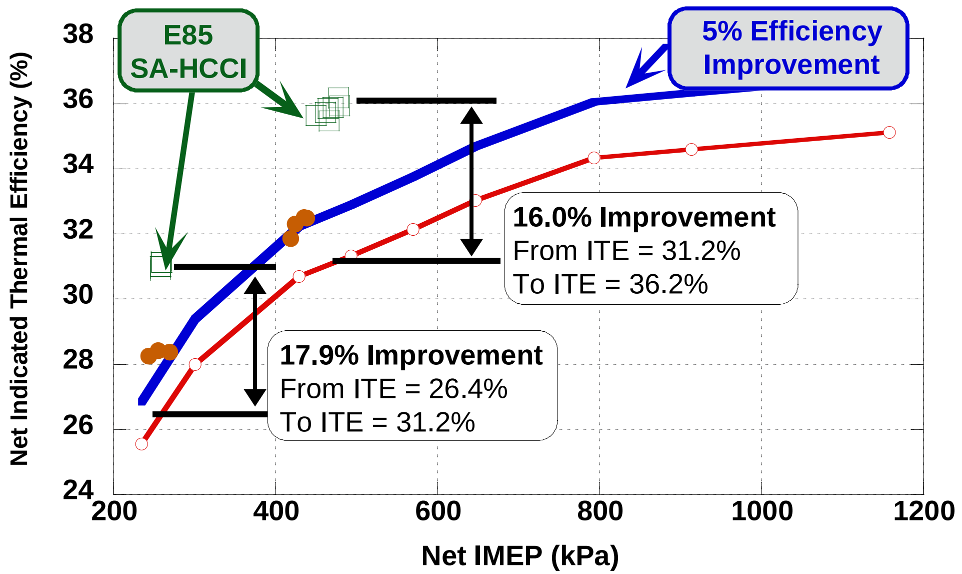


Efficiency target in milestone can be achieved with conventional gasoline

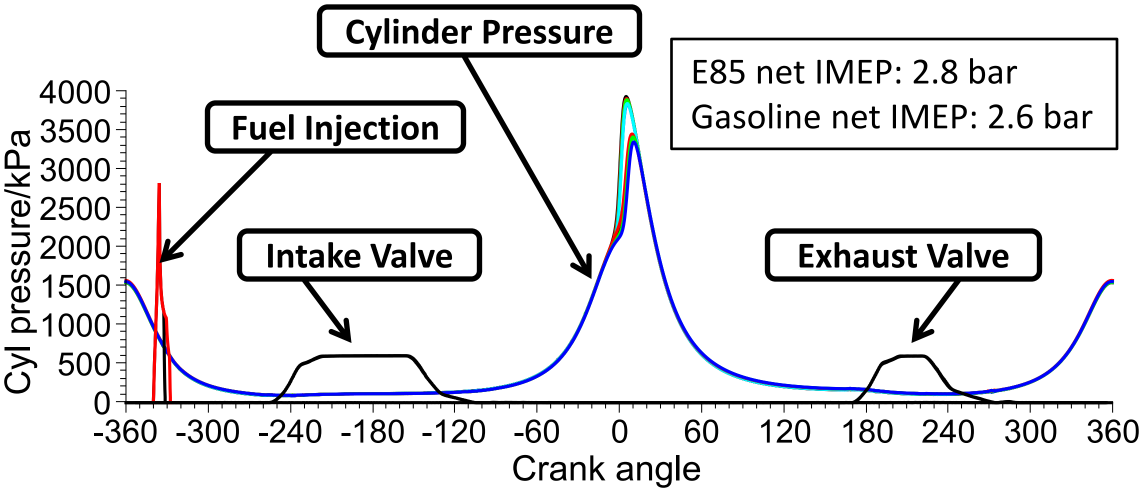
Joule Milestone: 5% efficiency improvement with bio-fuel using ORNL SA-HCCI combustion strategy

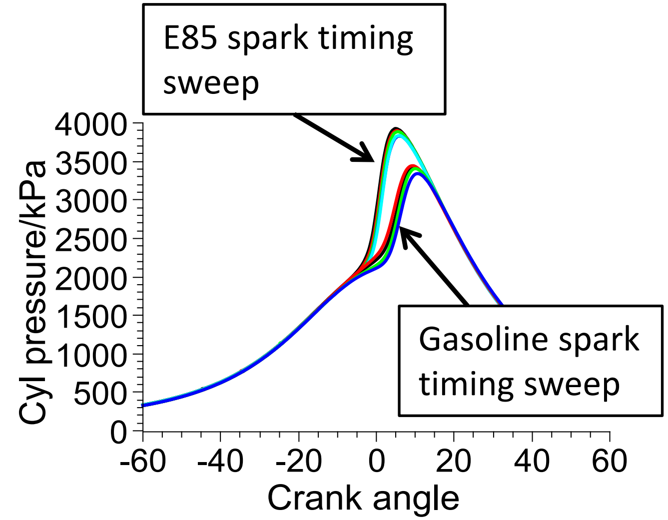
Joule milestone accomplished using E85 with efficiency improvements more than triple the target.



- Substantial efficiency improvement over gasoline under SA-HCCI conditions
- E85 exhibits additional unique behavior
  - E85 differences are subject of ongoing analysis
  - Efficiency increase possibly explained by molar expansion ratio effect (see ACE015)

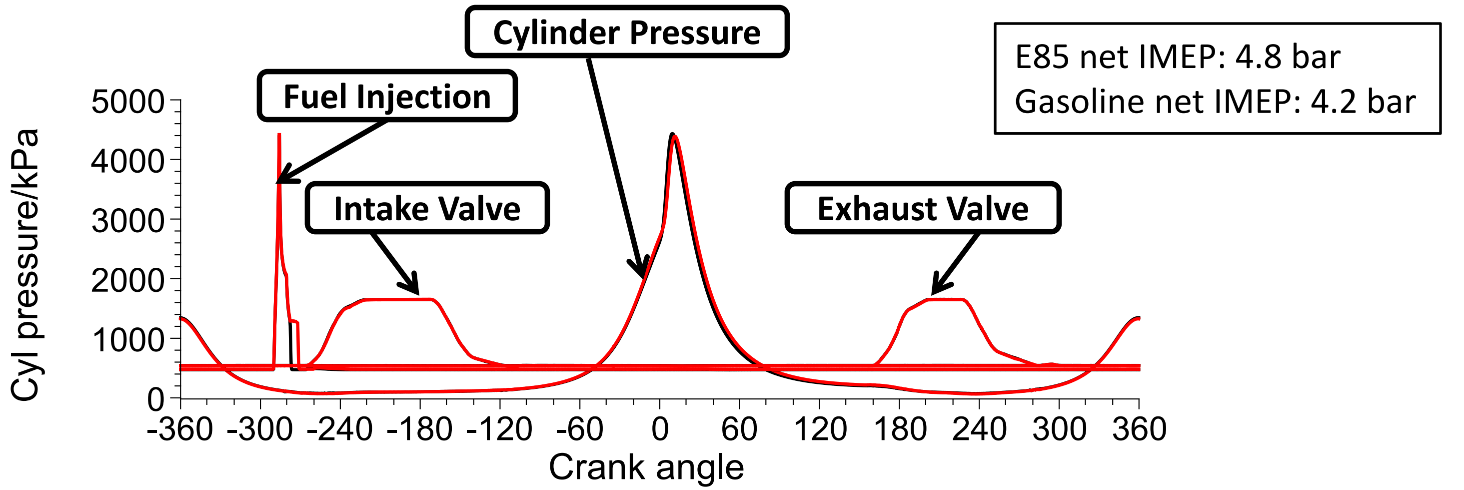
E85 autoignites more readily than gasoline under constant operating conditions at light engine loads





- Combustion phasing for E85 is more advanced than for gasoline under the same valve events and start of injection timing at light load conditions
  - E85 has a much higher octane number than gasoline
- Enhanced ignitibility observations could be due to two different phenomena and is the subject of planned future research
  - Engine operating in high T, low P ignition regime (i.e.“beyond MON”) regime where neither RON nor MON adequately represent the propensity for autoignition
  - Fuel injected into NVO undergoes reforming, altering ignition chemistry

E85 and gasoline behave similarly at higher engine loads



- E85 and gasoline exhibit similar combustion stability, pressure rise, and combustion phasing
- Fuel SOI timing is later at higher load condition
  - Fuel injected into lower temperature and pressure section of negative valve overlap
  - Lower probability of reactions occurring during NVO

Study 3: Enabling high efficiency ethanol engines

CRADA project with Delphi Automotive systems

- Specific Barrier: EISA legislation requires increased use of renewable fuels, but reduced fuel economy is a market barrier for E85

☑ Objective 1 accomplished in in FY10: Demonstrated a reduction in the fuel economy gap between E85 and gasoline by taking advantage of unique E85 fuel properties.

Accomplishment: Reduced fuel economy gap by 20% (SAE 2010-01-0619) while maintaining gasoline compatibility and OEM efficiency

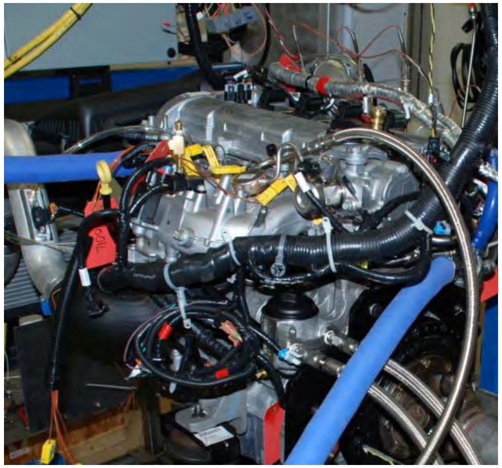
- Objective 2: Characterize particle emissions on an engine intended for high efficiency operation with ethanol fuels (study leveraged with health impacts – ACE045)

☑ Objective 2 accomplished during FY11

Motivation for Objective 2: Particle number emission regulations under consideration for SI engines, and engines optimized for E85 have several unconventional features

- Direct fuel injection
  - Fuel/air mixing
  - Fuel impingement on piston
- High compression ratio
  - Impingement due to smaller clearances
- Flexible cam-based valvetrains with 2-step cam lift and wide authority cam phasing
  - Charge motion impacts on fuel/air mixing

Approach for ethanol-optimized particle study



4-cylinder GDI engine, high CR (11.85) and flexible cam-based valvetrain
- PFI fueling capability added

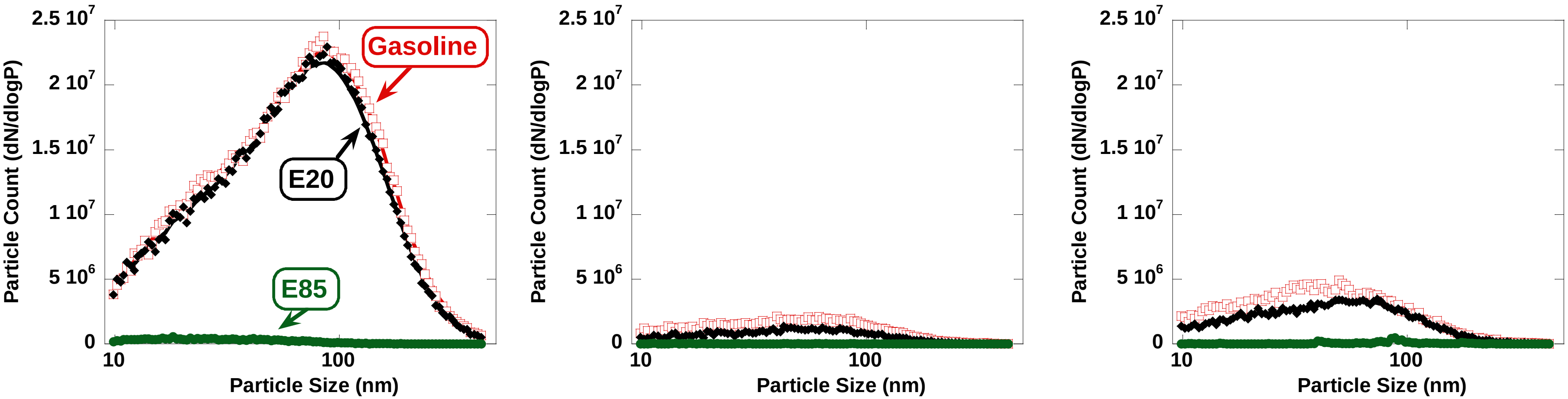
2-stage dilution with evaporator tube

SMPS for particle sizing (9 to 500nm)

- Single operating point, stoichiometric combustion
  - 1500 rpm, 8 bar BMEP
- 3 fueling and 3 breathing techniques
  - SOI Sweeps for single and multi-pulse GDI
- 3 fuels: Gasoline, E20 and E85

Fuel injection timing and fuel type significantly impact particle emission

E85 produces fewer particles than gasoline



Early fuel injection timing (320 deg $bTDC_f$)
- Highest particle emissions
- Likely fuel spray impingement on piston

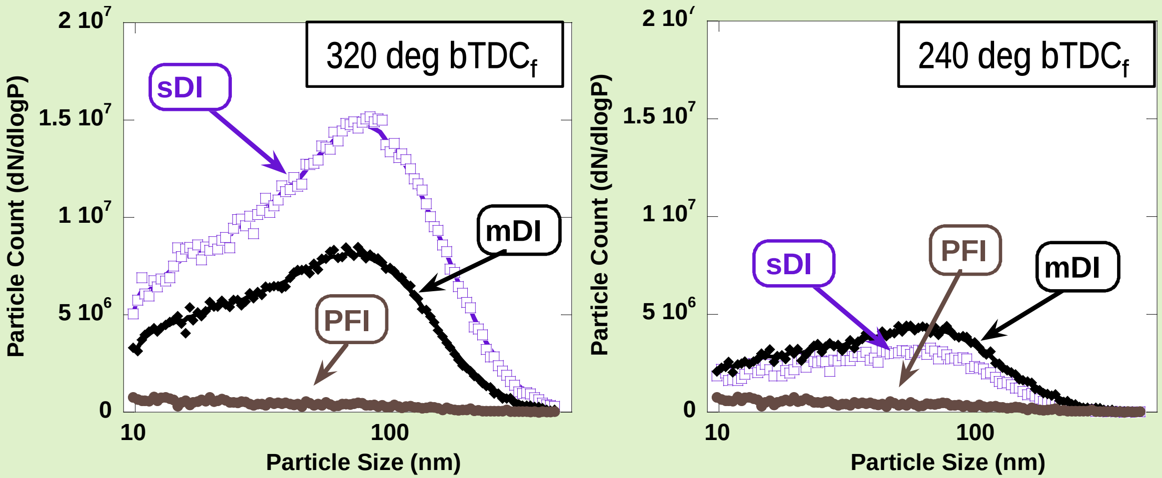
Near-optimal injection timing (280 deg $bTDC_f$)
- Lowest particle emissions
- Good fuel-air mixing

Late fuel injection timing (240 deg $bTDC_f$)
- Rising particle emissions
- Insufficient time and charge motion for fuel-air mixing

- Gasoline and E20 produce comparable levels of particles at this condition
  - ➢ Particle emissions will continue to be problematic for low-level ethanol blends
- E85 results in significantly lower particle emissions across all operating strategies
  - – Higher particle emissions under throttled and late intake valve closing conditions

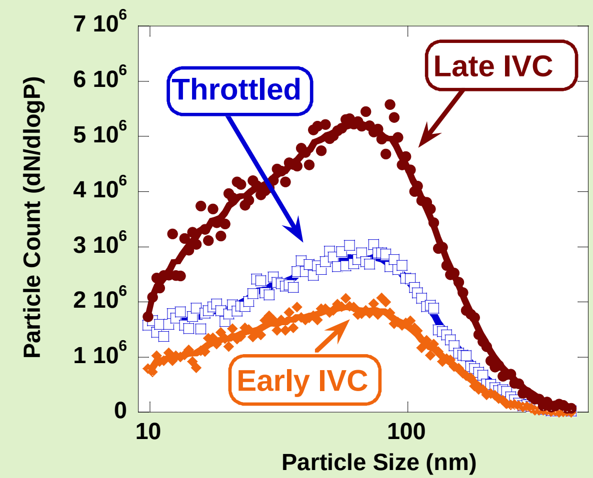
Fueling and breathing strategies also affect particle emissions

Fueling : Gasoline



Throttled operation at two different injection timings

Breathing: Gasoline



mDI at 280 deg bTDC$_f$

- Port fuel injection produces the lowest particle count under all conditions
  - Likely due to homogeneity of fuel and air mixture
- Multi-pulse reduces particles at advanced SOI timing but increases at retarded timings
  - Reduced fuel impingement on piston, but reduced homogeneity of fuel and air
- Early IVC produces the lowest particle emissions while late IVC produces the highest
  - Differences related to charge motion, may or may not be engine specific

Collaborations

- Members of AEC/HCCI working group
  - ORNL delivers two presentations at each bi-annual meeting, receives valuable feedback from industry, National Labs, and academia
- Informal collaboration with the University of Michigan
  - UM is working on a combustion mode similar to SA-HCCI (their chosen acronym is SACI)
  - Collaborations have included data sharing and exchanges of ideas
- Formal collaboration with University of Michigan
  - Modeling of SA-HCCI
- Collaboration with the University of Wisconsin on dual-fuel combustion mode
  - Guidance on RCCI combustion mode, exchange of data and ideas
  - Graduate student from UW coming to do research at ORNL on multi-cylinder platform
- Concluded EtOH related CRADA with Delphi
  - Ongoing collaboration with Delphi with an advanced combustion CRADA (ACE053)
- Fuels-related funds-in project with OEM

Proposed Future Work

- Dual-fuel RCCI combustion
  - Continue collaboration with University of Wisconsin
  - Expand range of engine speed/load operating conditions
  - Operate RCCI combustion using E85 rather than petroleum-derived gasoline
- Stoichiometric spark-assisted HCCI
  - Extend range of fuels to include low and intermediate level ethanol blends as well as n-butanol and iso-butanol
  - Determine why E85 ignitibility is enhanced at low loads using in-cylinder sampling techniques
  - Translate efficiency benefits to real world fuel economy benefits through a combination of experiments and drive-cycle simulation
- Ethanol optimization and SI-engine particle characterization
  - CRADA project with Delphi has come to a natural and successful end
  - GDI particle characterization effort with fuels focus will continue at a level of effort to be determined
  - Currently seeking opportunities with industrial partners in this area

Summary

Relevance

- Studies aimed at increasing engine efficiency with low emissions by taking advantage of fuel properties with engine operating strategy and configuration.

Technical Accomplishments

- Joule milestone completed using E85 in the ORNL SA-HCCI combustion regime
  - Efficiency improvement of 5% was targeted with bio-fuel in advanced combustion regime
  - Achieved efficiency improvements more than triple the milestone target
- Advanced combustion load expansion: SA-HCCI combustion regime provides efficiency benefits from 2 to 9 bar IMEP while maintaining compatibility with NOx aftertreatment
- E85 nearly eliminates particle emissions during GDI fueling strategies, little difference exists between gasoline and E20
  - Particles also effected by fueling strategy, engine breathing, and fuel injection timing

Future Work

- Continue to develop RCCI for higher efficiency operation, including with E85
- Investigate reason E85 exhibits enhanced ignitibility during SA-HCCI with in-cylinder sampling
- Translate SA-HCCI efficiency benefits to real-world fuel economy improvement with modeling