Use of Low Cetane Fuel to Enable Low Temperature Combustion

Stephen Ciatti, Christopher Kolodziej

Argonne National Laboratory

June 18, 2014

Project ID# ACE11

Overview

Timeline

- Started May 2008

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY13 $670k
  - FY14 $670k

Barriers

- From MYPP
  - Mechanism to control LTC Timing
  - LTC high load and high speed operation
  - LTC control during change of speed and load

Partners

- Argonne is project lead
- Partners are:
  - GM R&D
    - Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
  - University of Wisconsin-Madison
    - Graduate student performing gasoline-fueled engine simulations using KIVA
  - BP
    - Several different octane number gasoline-like fuels
  - Drivven
    - Controller algorithm upgrades

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Objectives of this Study (Relevance)

- Expand the operating range of a multi-cylinder gasoline LTC engine to lower loads on 87 AKI gasoline (previous results have shown successful operation from 4 – 20 bar BMEP)
- Used 0.4% EHN cetane enhancer to help decouple chemistry effects from mixing effects on the low load ignition limitations of 87 AKI gasoline; useful for simulation validation
- Reduce PM and NO_x emissions compared to conventional diesel combustion
- Better understand the effects of fuel/air mixture preparation, fuel reactivity, and intake conditions on low load ignition propensity and combustion stability
- Use 3D Computational Fluid Dynamics (CFD) to simulate the changes in fuel/air mixture conditions and combustion caused by the these variables (done at UW-ERC and at Argonne)
- Correlate ignition information with collaborators

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Milestones

Milestone	Target Date
Decoupled fuel mixing and chemistry effects on low load ignition and combustion stability using 87 AKI fuel + EHN cetane enhancer	Jun 2013 (Complete)
Baseline transient engine performance on diesel with three "engine in the loop" drive cycles for later comparison to gasoline transient performance	Sep-Dec 2013 (Complete)
Found minimum load of engine using 87 AKI gasoline and diesel fuel, using minimum fueling injection timing sweep at 1500 RPM	Jan 2014 (Complete)
Explored use of uncooled HP-EGR to attempt to reduce minimum stable load operation with 87 AKI gasoline at 1500 RPM	Feb 2014 (Complete)
Perform minimum fueling single injection timing sweeps at idle speed (850 RPM) with 87 AKI gasoline at 500 and 250 bar injection pressure	Mar 2014 (Complete)
Measure the effects of reduced injector nozzle inclusion angle on characteristics of minimum fueling single injection timing sweep (120° umbrella angle vs. stock 148° umbrella angle)	June 2014 (Ongoing)
CFD support for 120° inclusion angle 850 RPM	Sept 2014
CFD investigation of effects of uncooled HP-EGR on stable minimum fueling requirements	Sept 2014

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Approach

- Use a representative high volatility gasoline fuel similar to pump fuel, 87 AKI gasoline (donated by BP)
- 29 speed/load point map was used to identify challenging operating points in gasoline LTC (low load and speed in particular)
  - Incorporated new injection strategy, lower rail pressure and narrower inclusion angle injector nozzles as a result
  - Also utilized EHN cetane enhancer to create approx. 75 AKI gasoline with similar fluid properties – tool to decouple chemistry from fluid mechanics
- Focus on the operating range of 87 AKI gasoline at low speeds/load by better understanding its sensitivity to injection characteristics (timing, pressure, and nozzle angle) and charge air conditions (T, P, and O_2)
- Use production diesel hardware to identify and incorporate likely challenges of moving this combustion strategy into a multi-cylinder engine
- Use 3D CFD to help visualize the fuel and air mixture characteristics at start of combustion to determine the ignition conditions of local ϕ and T to guide injection strategy relative to operating conditions (Intake T, P, and O_2)

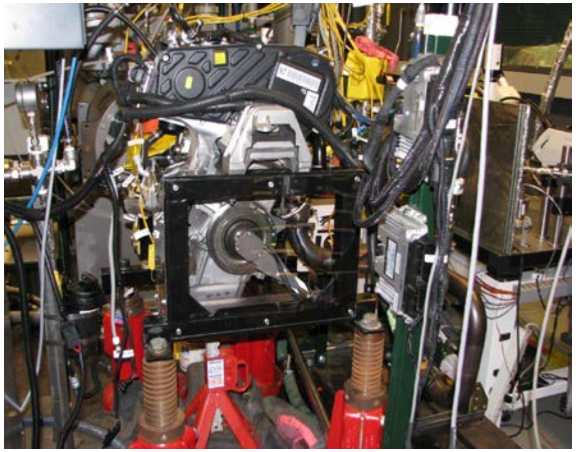
Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Engine Specifications and Tested Fuels Properties

Engine Specifications

Compression ratio	17.8:1
Bore (mm)	82
Stroke (mm)	90.4
Connecting rod length (mm)	145.4
Number of valves	4
EGR System	High Pressure EGR Mixing far upstream for homogeneity
Injector	7 holes, 0.141-mm diameter
Umbrella Angle	148° and 120°
Injection Rail Pressure	500 bar and 250 bar
Boosting	Variable Geometry Turbocharger (VGT)

G.M 1.9 L; 110 kW @ 4500 rpm - designed to run #2 diesel ; Bosch II generation common rail injection system



Experimental Setup

Properties of the Tested Fuel

Property	87 AKI gasoline	87 AKI + 0.4% EHN
AKI Rating	87	Est. 75
Specific gravity	.7018	.7018
Low heating value (MJ/kg)	44.0	44.0
Initial boiling point (°C)	93.2	93.2
T10 (°C)	119.8	119.8
T90 (°C)	234.2	234.2

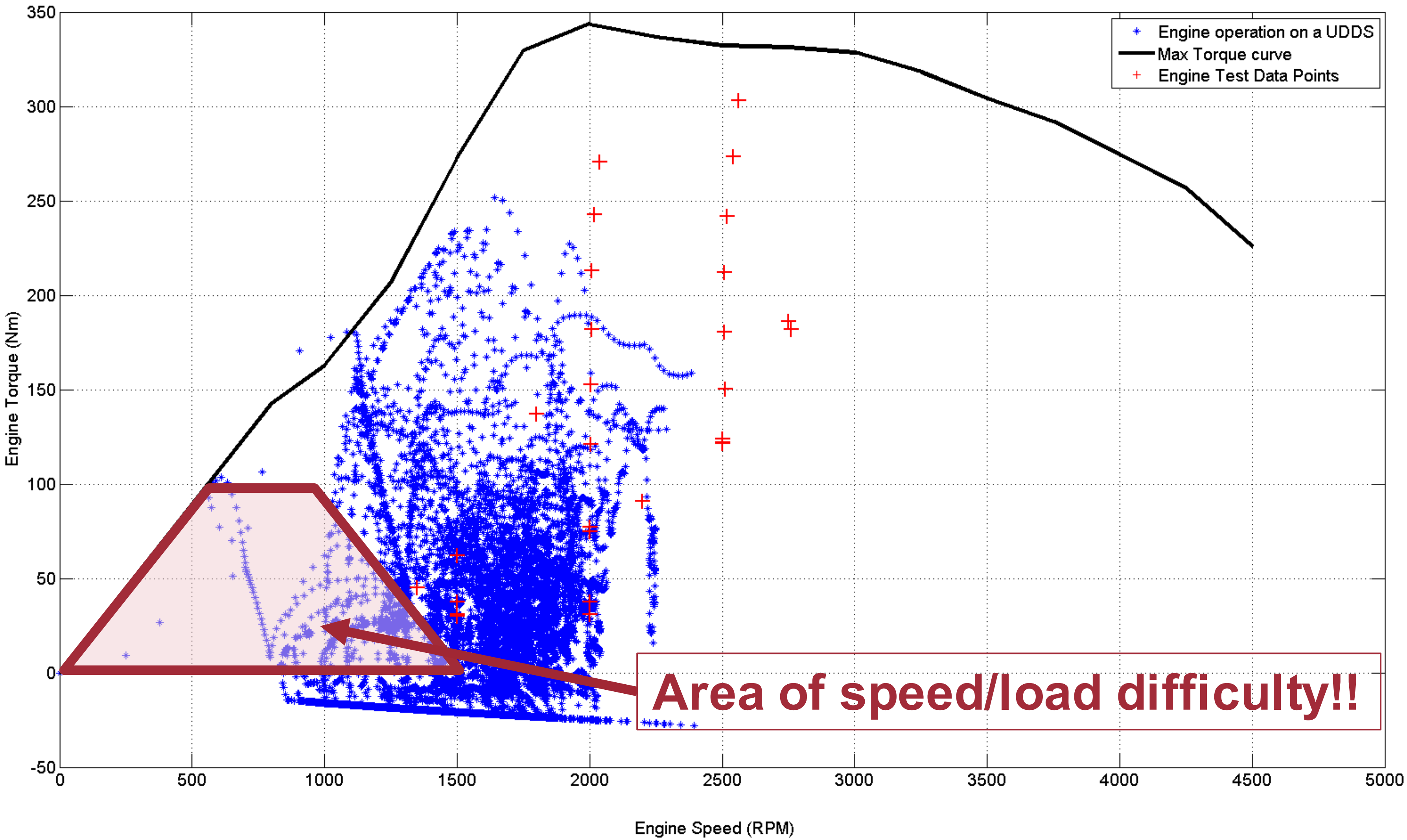
Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Technical Accomplishments - Stable Low Load/Speed Operation Investigations with 87 AKI Gasoline

- Autonomie simulations for vehicle drive cycle using 29 engine speed/load map points
- Aka, "How did we get here?" to identify challenges of low speed/load operation

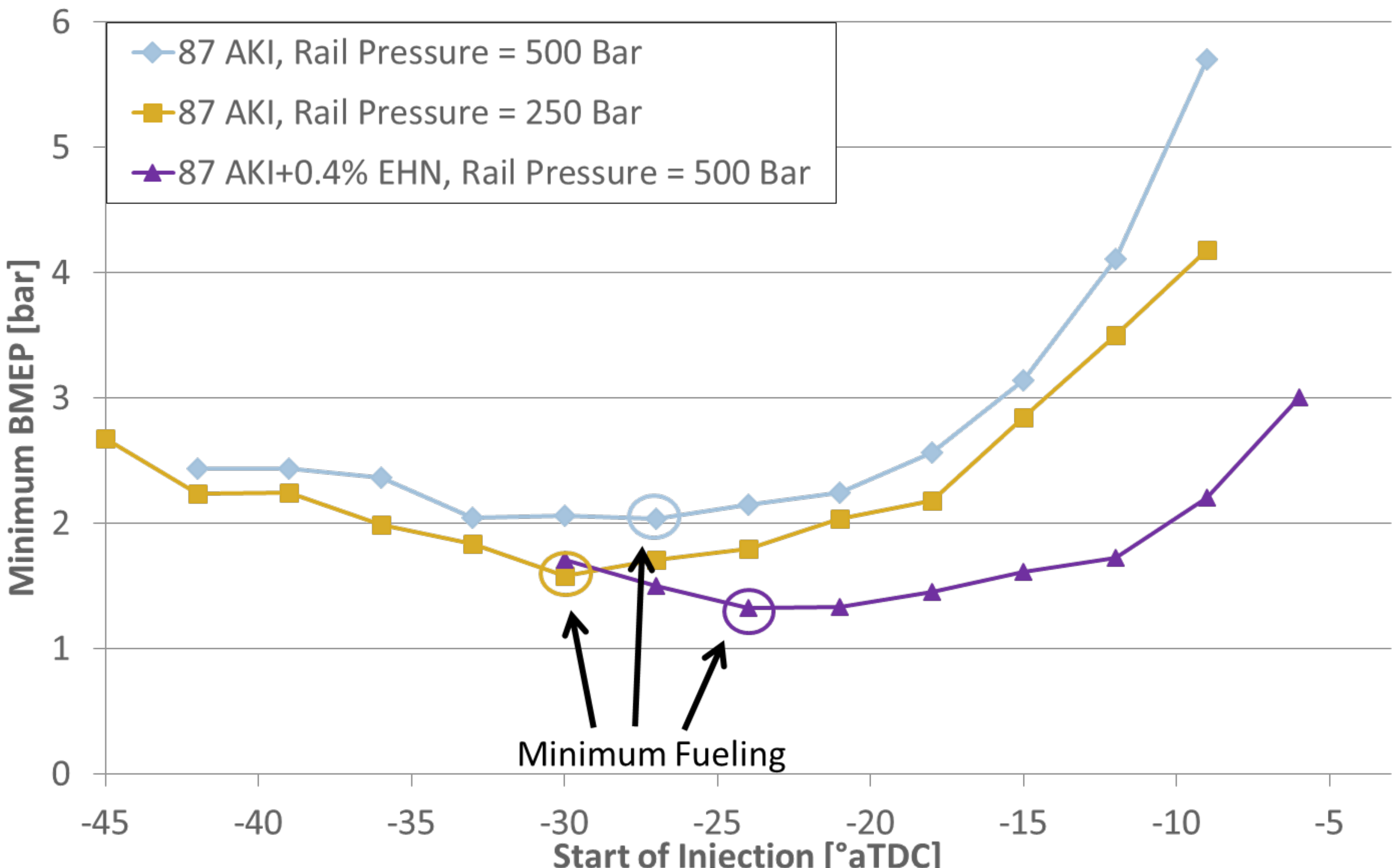
Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Engine Efficiency Map Generation on 87 AKI Gasoline with Triple Injection Strategy



Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

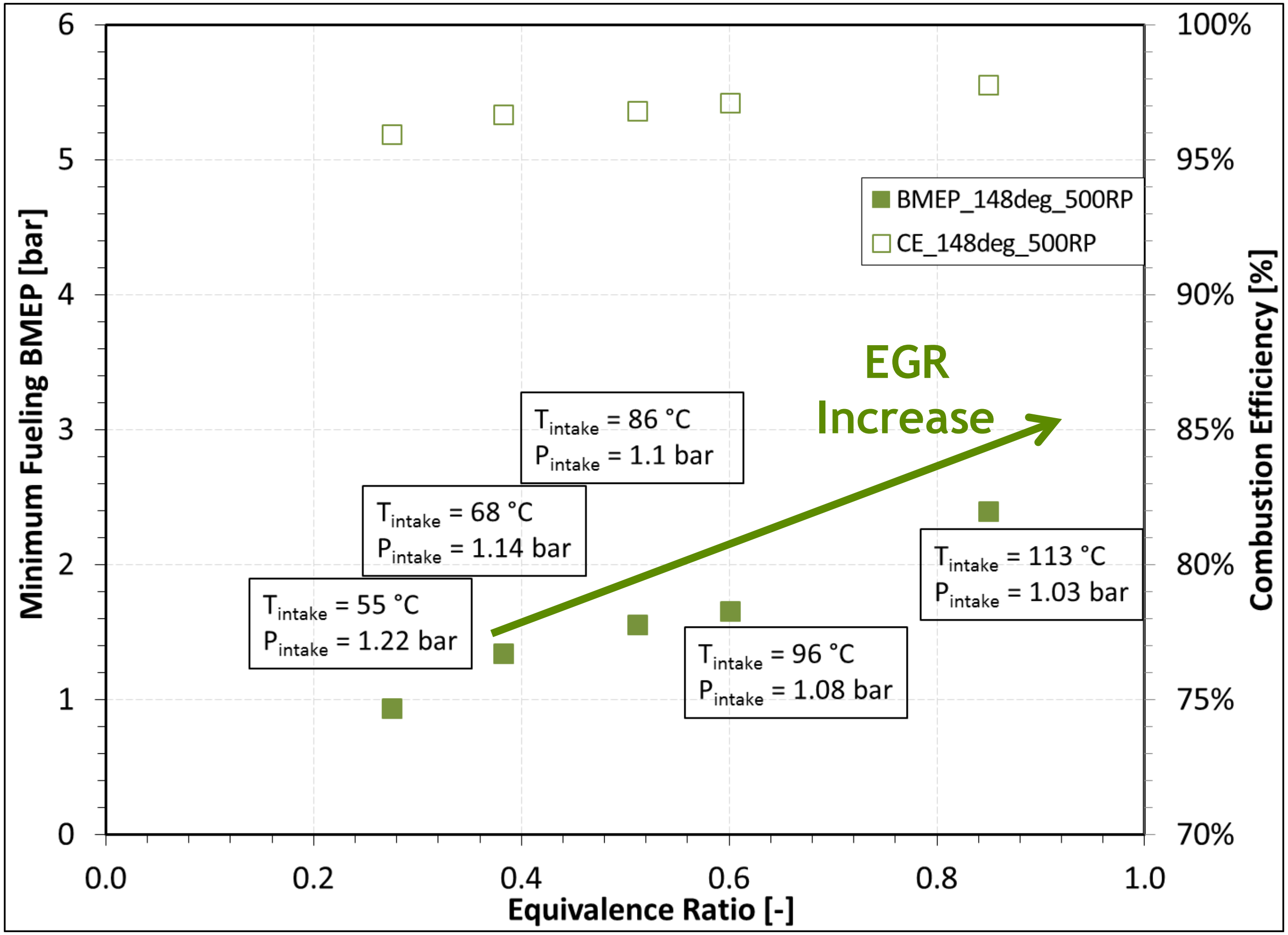
Brief experiment using EHN to study low load operation using a single injection



SAE Paper 2014-01-1302

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Effects of Uncooled HP-EGR



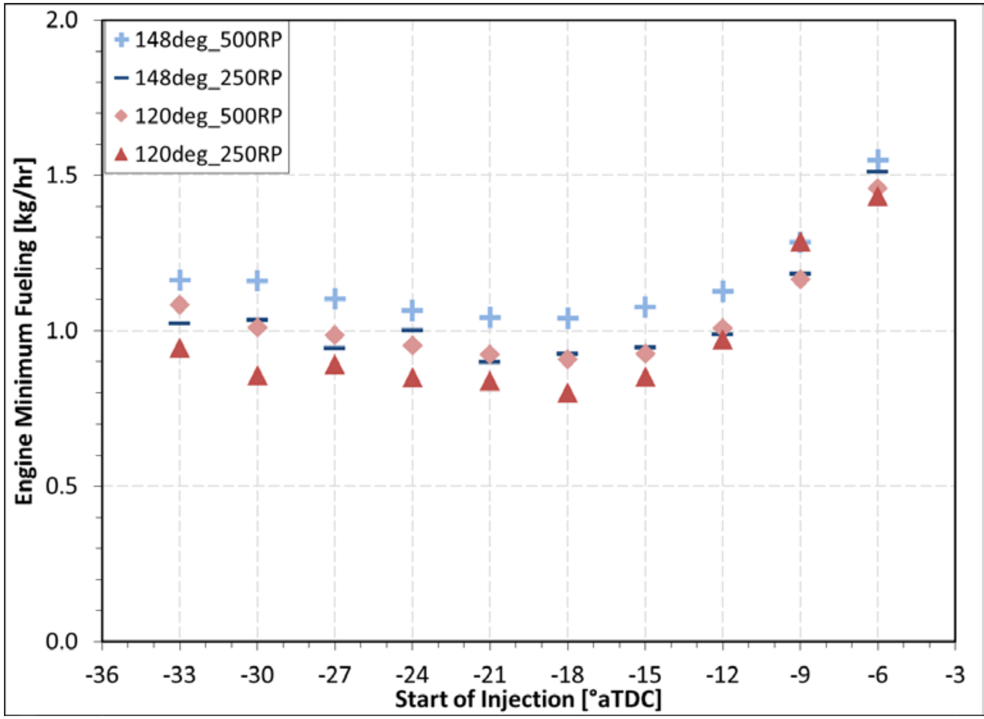
Uncooled EGR increased intake temperature significantly, but did not add reactivity. Simulations will help show whether the loss of reactivity was due to loss in boost or intake oxygen.

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Industry Interest - Focus on Expansion of Lower Load Limit with 87 AKI Gasoline

Methodology

- Minimum fueling SOI sweeps
  - 3% CoV of IMEP limit for <u>each cylinder individually</u>
- Single injection per cycle
- 850 RPM engine speed
- 250 or 500 bar injection pressure
- 148° or 120° injector nozzle
- Lower load combustion noise target <85 dB
- Maximized boost (1.05 bar)
- 45 °C intake air temperature
  - No external intake heating
- No EGR

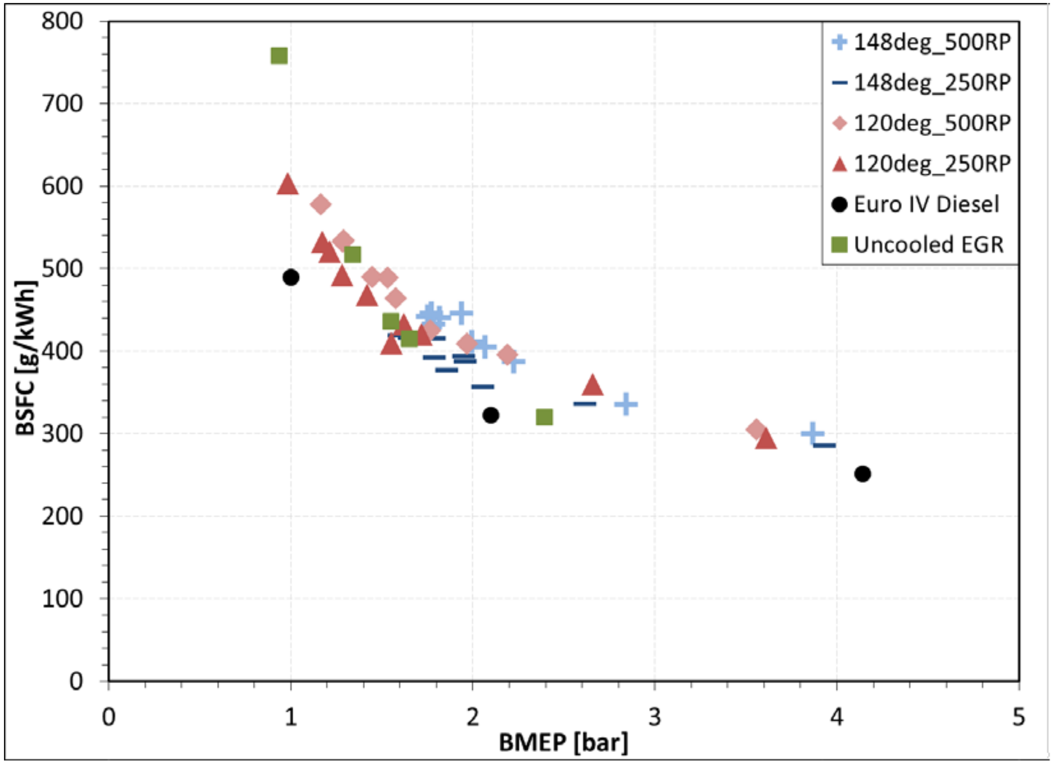


Draft paper ASME-ICEF2014-5632

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

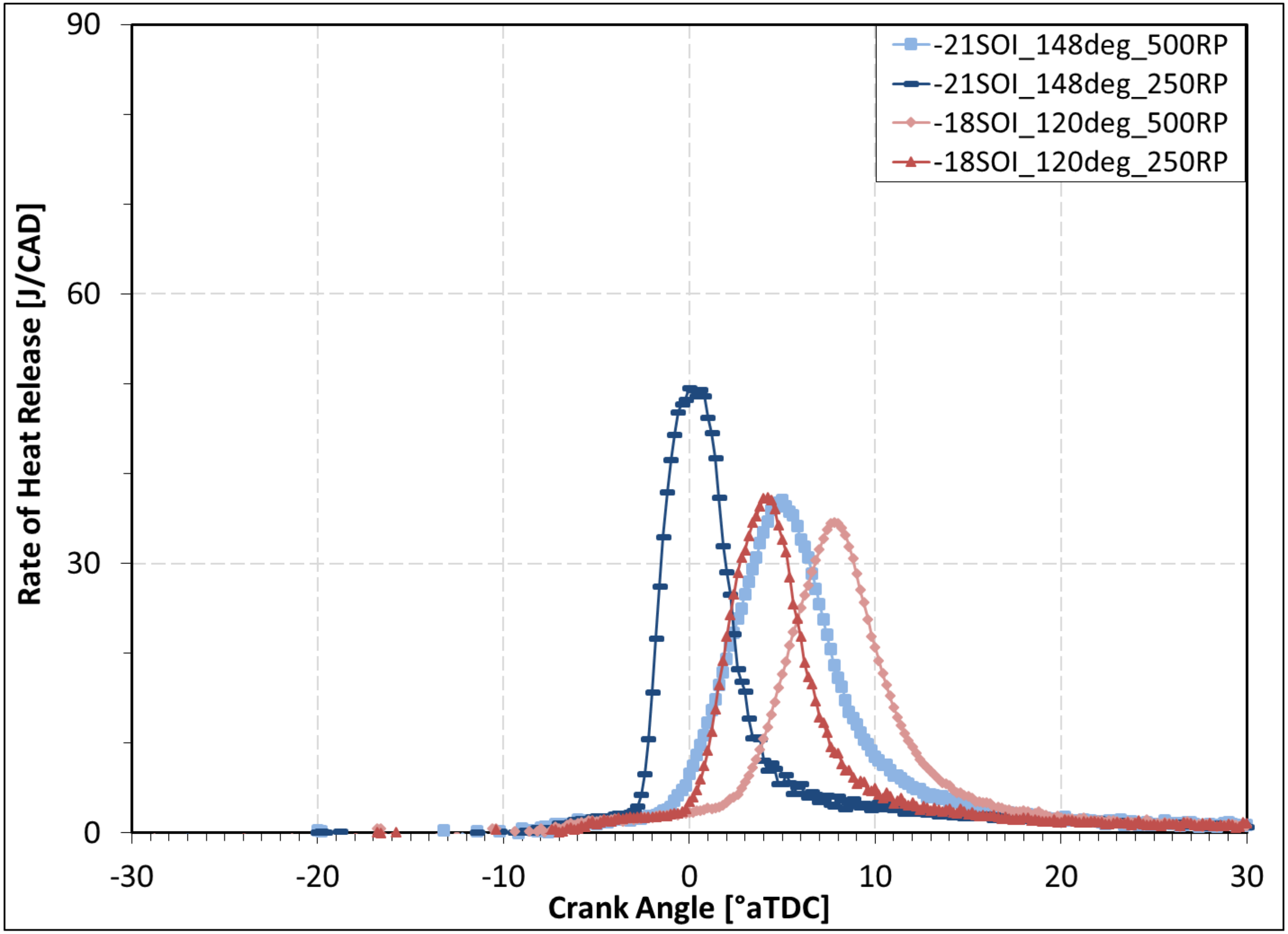
Brake-Specific Fuel Consumption for each Injection Combination Compared to Euro IV Diesel Operation

- 120° injector nozzle angle extended minimum load
- 250 bar RP allowed reduced minimum load for each nozzle as well as reduced BSFC
- Progress towards Euro IV diesel BSFC
- Note: Uncooled EGR points at 1500 RPM, all others at 850 RPM



Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

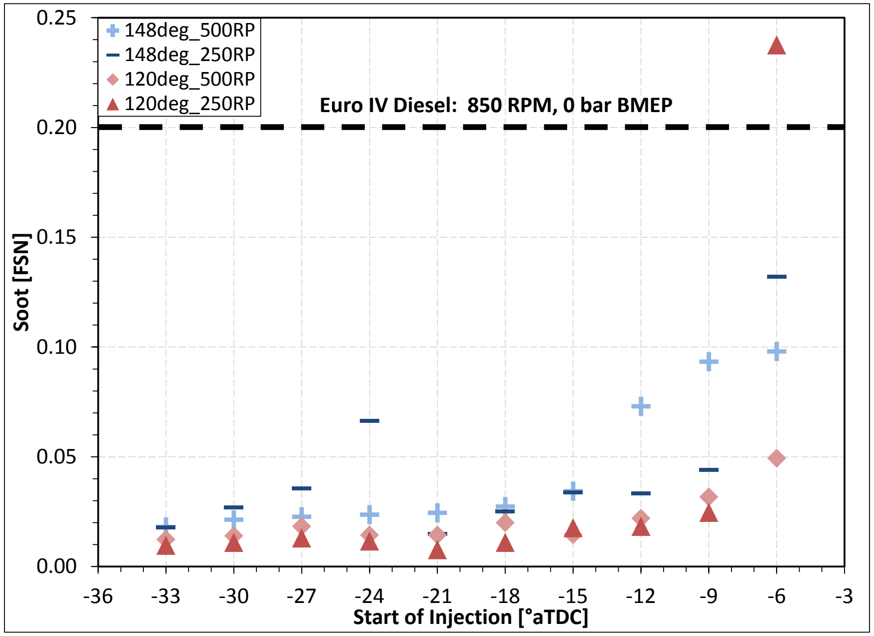
RoHR Comparison of Minimum Fueling Conditions

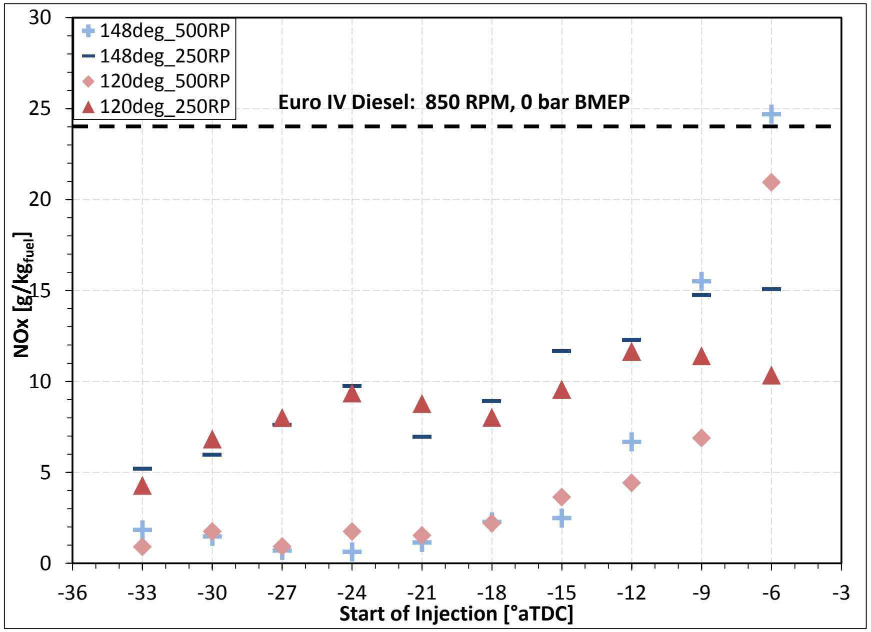


The 250 bar RP minimum fueling conditions had advanced combustion phasing than 500 bar, and 148° injector nozzle angle earlier than 120°.

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Minimum Fueling 87 AKI Soot and NO_x Compared to Euro IV Diesel Idle Operation

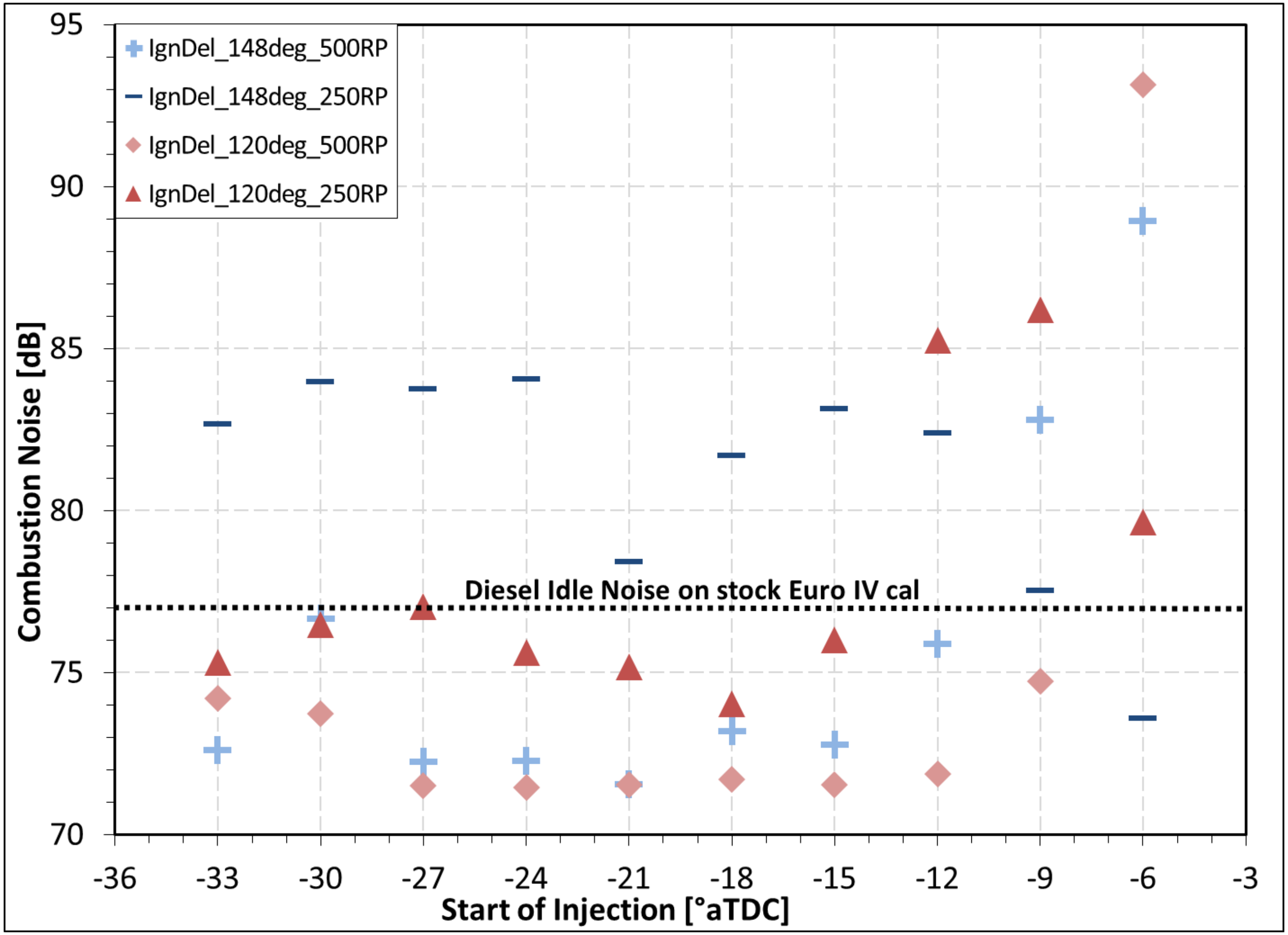




Soot and NO_x significantly reduced at low load compared to Euro IV diesel operation.

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Combustion Noise Results (AVL algorithm using pressure transducer)



Consistently low combustion noise, most points < 80 dB.

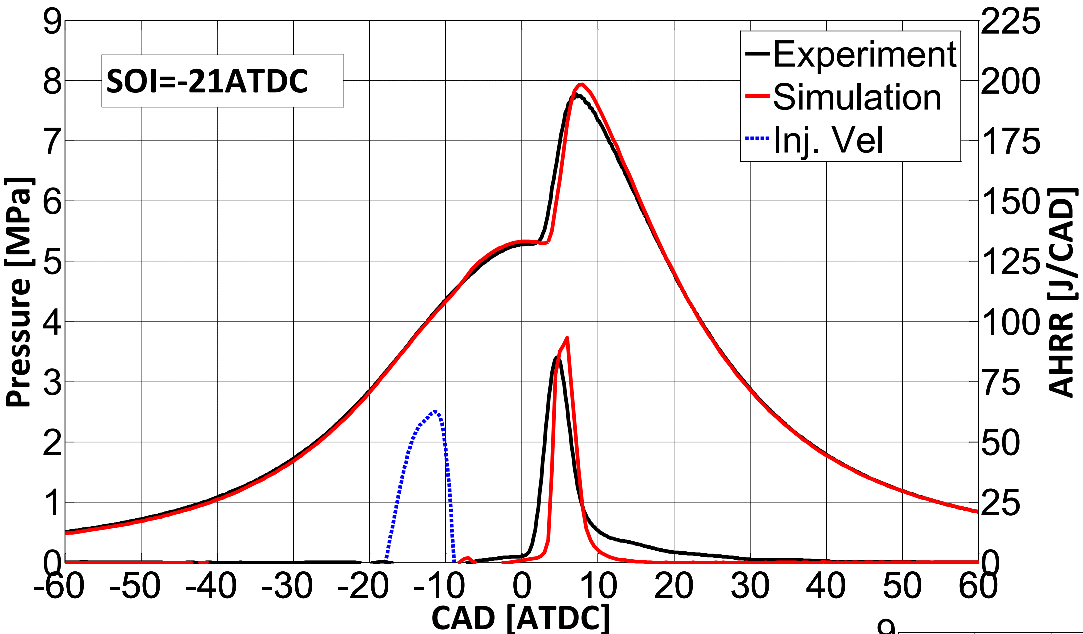
Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

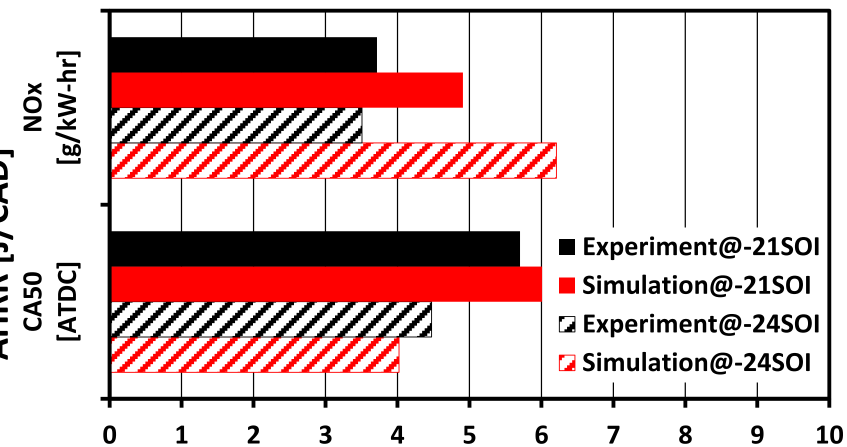
UW - ERC 3D KIVA Simulation support

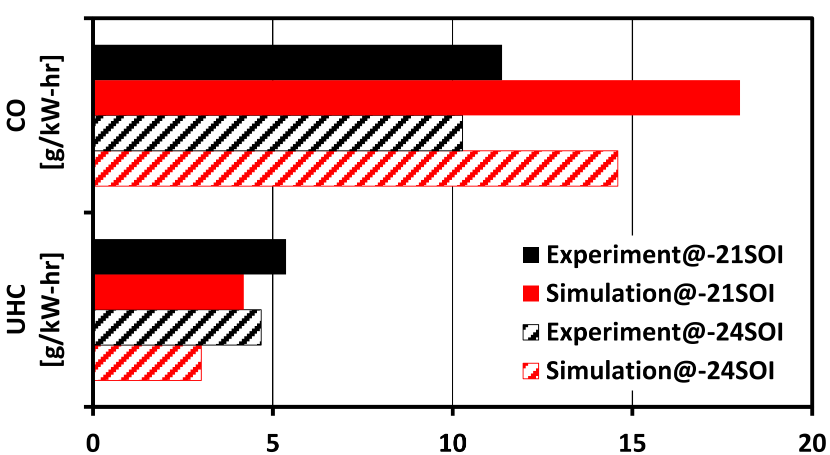
- 1500 RPM
- 2 bar BMEP
- 148°inclusion angle
- P_inj = 500 bar
- Investigate relationship between ϕ and T

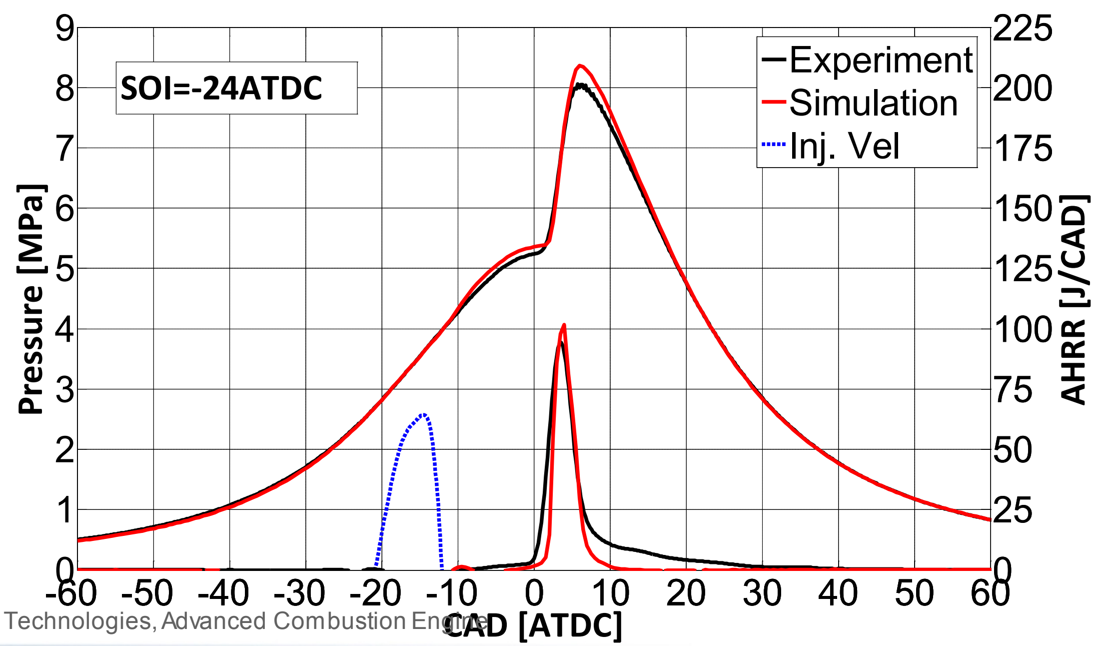
Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Validation of Experimental Data Points



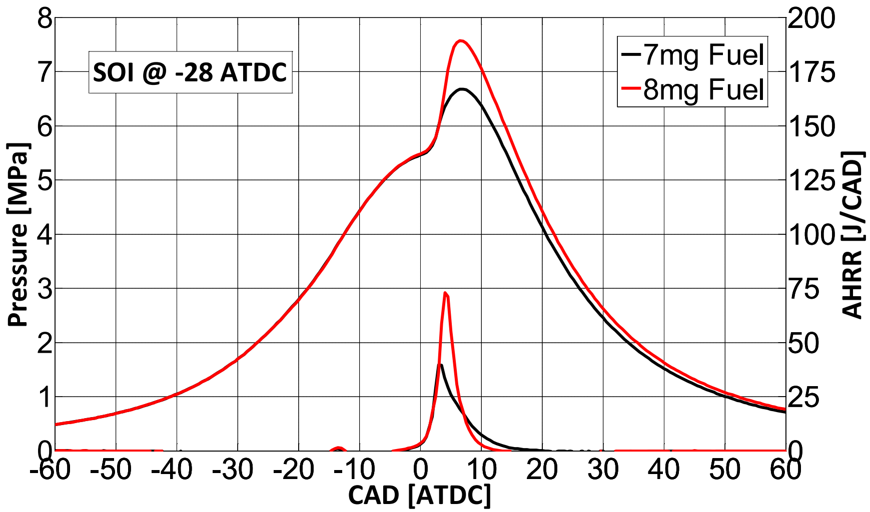


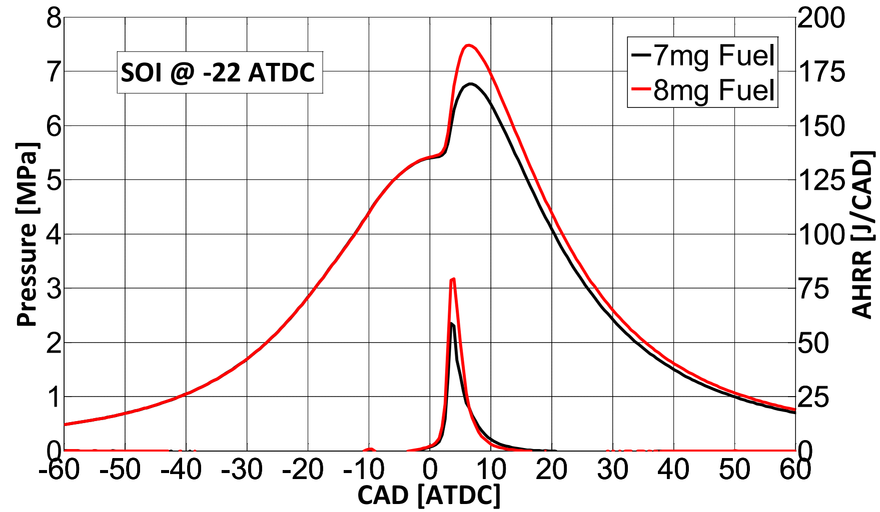


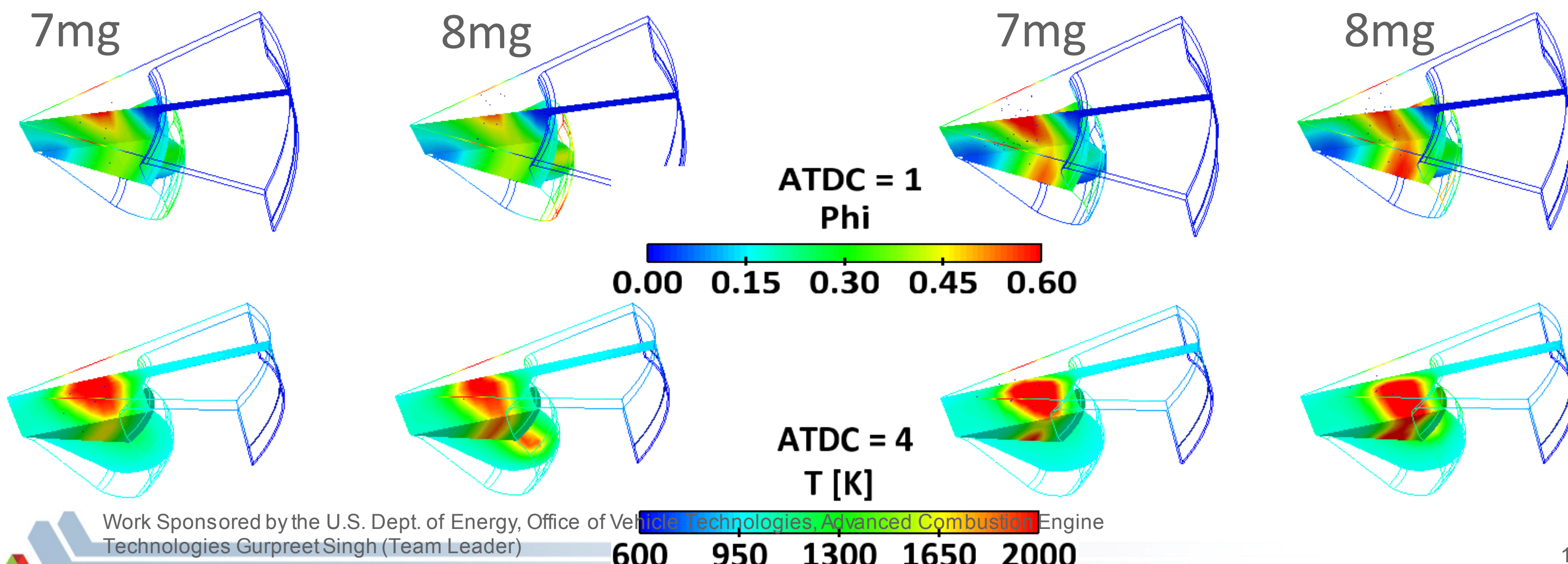


Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Same CA50 with Different Fuel Amount







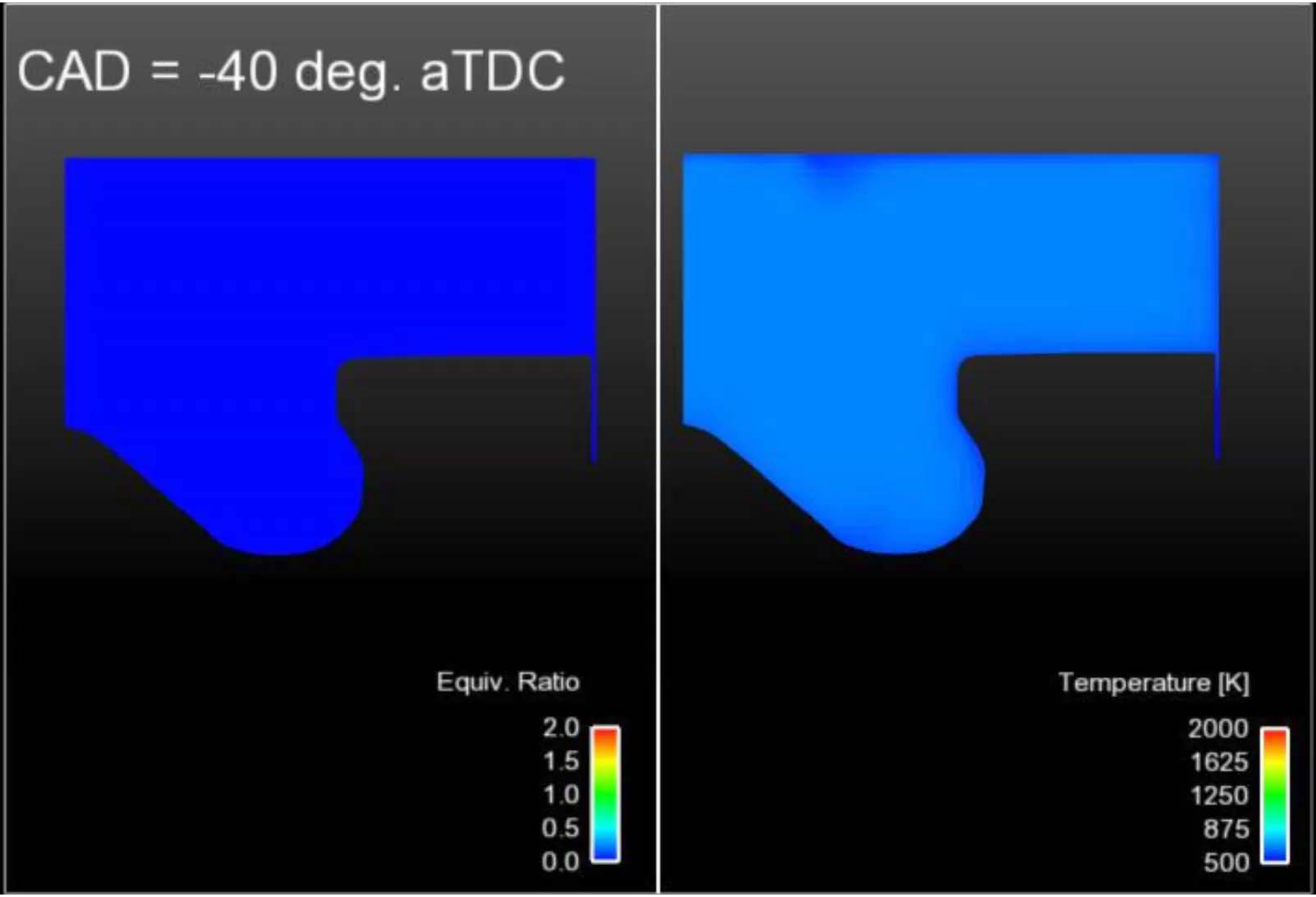
Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Argonne CONVERGE 3D CFD Simulations

- 1500 RPM
- 2 bar BMEP
- 148°inclusion angle
- P_inj = 250 bar

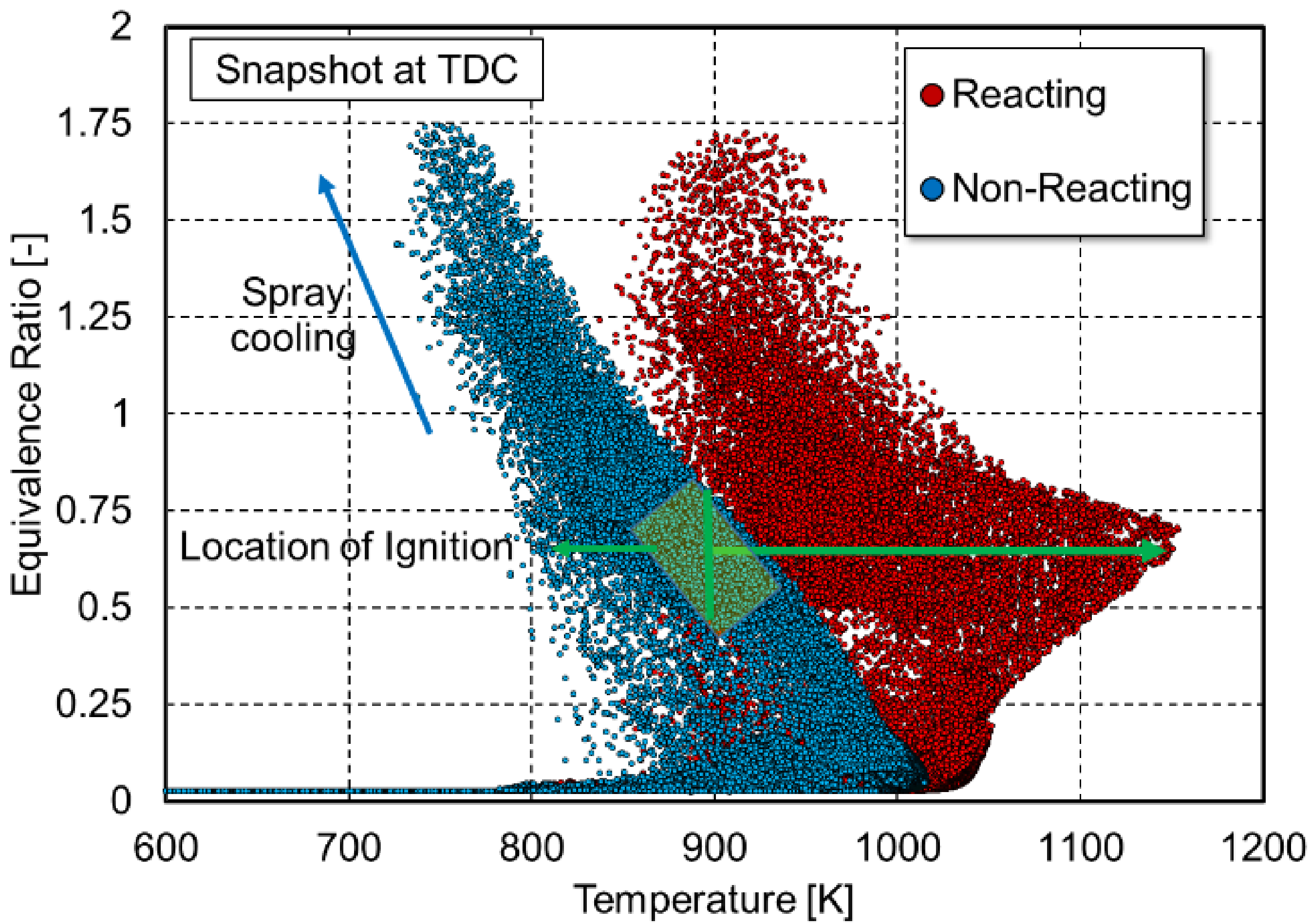
Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Argonne Simulations of 1500 RPM 2 bar BMEP, 250 bar RP, 148° Nozzle Inclusion Angle, and -24 °aTDC



Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Constant Fueling SOI Sweep with Simulation



Local equivalence ratio of ignition close to 0.7 with a maximum of 1.75 at start of combustion

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Responses to FY13 Reviewer Comments

- Reviewer Comment
  - Are there realistic constraints on combustion NVH?
  - CFD results not well integrated into guiding the work
  - Link to John Dec's work?
  - Link to RCM work?
  - Strategy for idle and low load?

- Response
  - This year the target range is 80-90 dB, with a high limit of 95 dB for exploration purposes.
  - Additional CFD support was obtained from Argonne (Sibendu Som); the simulation work has been critical
  - John's work in ITHR has been used to provide insight into the low load/speed operation as a basis of boost dependence. As we move into E10 work, his results will be even more relevant
  - RCM work shows that ϕ=2.0 provides shortest ignition delay (highest reactivity) but all in gas phase. Simulation shows that for two-phase, ϕ and T are interlinked, creating a different situation
  - This year's work explicitly addresses this question. EHN, lower rail pressure and narrower nozzle inclusion angle. In addition, LP-EGR with DPF and a clutched supercharger will be added to assist in low speed/load operation to explore possibilities.

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Collaborators to this work

- General Motors
  - Engine hardware, technical guidance, and engineering support
- University of Wisconsin
  - KIVA 3D simulation support, especially with cetane enhancers like EHN
- British Petroleum
  - Fuels provider
- Drivven
  - Engine controller and algorithm support/modification
- Argonne
  - CFD support and future high fidelity support
  - APS gasoline flow through diesel injector measurements (for CFD)
  - RCM – Reaction mechanism and reduced mechanism support (for CFD)
- Univ. of California – Berkeley
  - E10 HCCI ignition information
- Eaton Corp
  - Supercharger provider

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Remaining barriers and challenges

- Continuing to expand the engine operating map
  - Low load at idle speed
  - Injection strategy approaches (lower injection pressure – GDI or similar?)
- Reducing NO_x and PM emissions to achieve LTC behavior across entire map
  - LP-EGR will be incorporated into engine to provide reduced O_2 concentration and provide additional premixing at higher loads
- Reliable and repeatable ignition and combustion phasing
  - At low speeds and loads, challenge is to provide enough ignition propensity
  - At high speeds and loads, challenge is to reduce ignition propensity for more premixing
  - Utilize endoscopic imaging to better validate CFD simulation, acquire deeper insight into mixing conditions and local temperature
- Strategy to allow for future transient engine operation
  - Consistent injection strategy (number of injections, nozzle configuration, rail pressure)
  - EGR approach; Low Pressure vs. High Pressure

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Project Future Work

- Utilize simulation and experiments to re-characterize a vehicle speed/load map using the 120 deg nozzles
  - Identify what regions of opportunity have changed/stayed the same
  - Will we lose capability at mid-to-high loads?
  - Additional Autonomie vehicle simulation will be done with new map
- Install LP-EGR loop with DPF to facilitate more boost at low speeds/loads while maintaining elevated T (GM Recommendation)
- Comparison of experimental and simulations of constant fueling SOI sweep
- Simulations of uncooled EGR effects
- Collaborate with UC-Berkeley HCCI project to study E10 (87 AKI) and compare to current E0 fuel
  - CFD support will be important here as well
- Continue to track and account for combustion noise
  - Target <90 dB for high load, <85 dB for low load
- Begin to characterize particulate emissions
  - New Dekati dilution system, use SMPS and TEM sampling
- Opportunity to utilize high-efficiency supercharger and explore possibility to use a lower pressure diesel injection system to enable reduction of load and ease of starting

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Summary

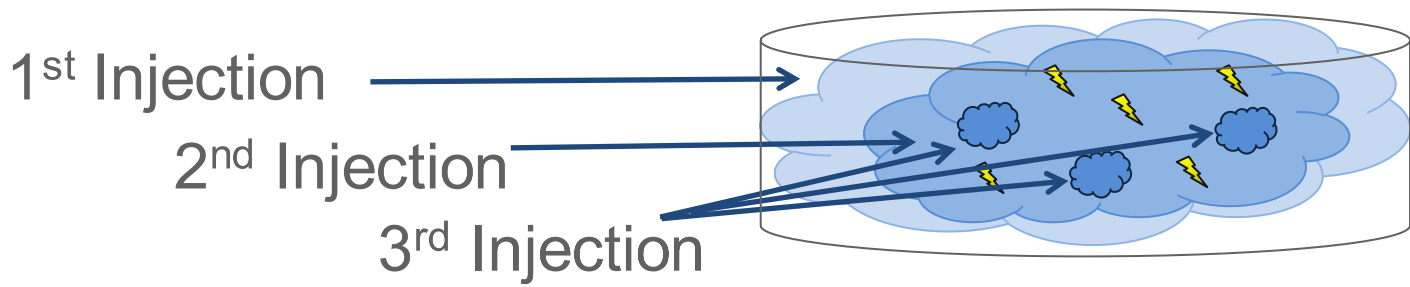
- Wide range of loads explored using pump style gasoline (87 AKI)
  - 1.0 bar to 19.5 bar BMEP
- Providing engine speed/load map identified challenges at very low speeds and loads
  - Still achieved a 26% improvement in fuel economy compared to PFI SI engine for the same vehicle
- Minimum fueling injection timing sweeps performed at 850 RPM, Rail Pressures (500, 250 bar), Inclusion angle (148°, 120°), and uncooled HP-EGR
- Discovered that the lower rail pressure and narrow inclusion angle facilitated reduced load; 1 bar BMEP
- CFD simulations (with RCM and APS support) identified target areas for study and will guide future explorations

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

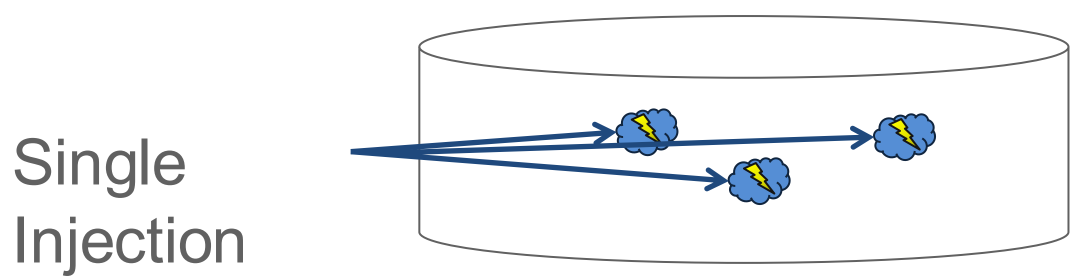
Technical Back up slides

Primary need to investigate combustion stability at lower loads

- Multiple injections allow control of fuel stratification to control combustion phasing and the rate of heat release



- At low loads and low total injection quantities, critical local richness required for stable auto-ignition becomes easily over-mixed
- To better understand local fuel richness necessary for stable auto-ignition and find conditions to extend the lower load limit with 87 AKI gasoline, single injection timing sweeps will be examined

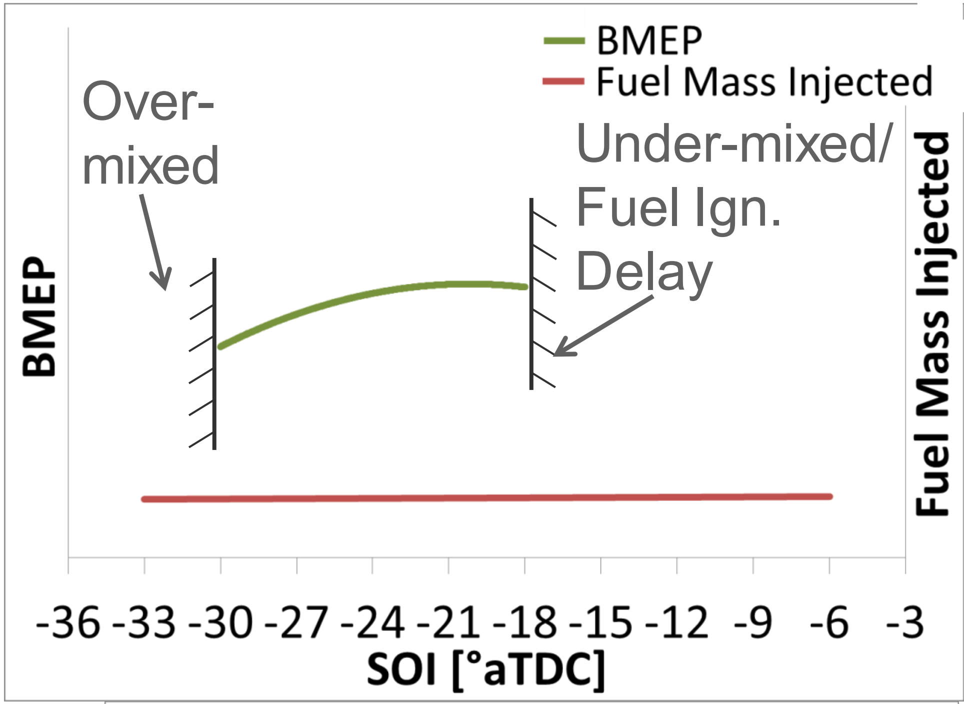


Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Problems of Constant Fueling SOI Sweeps with Gasoline

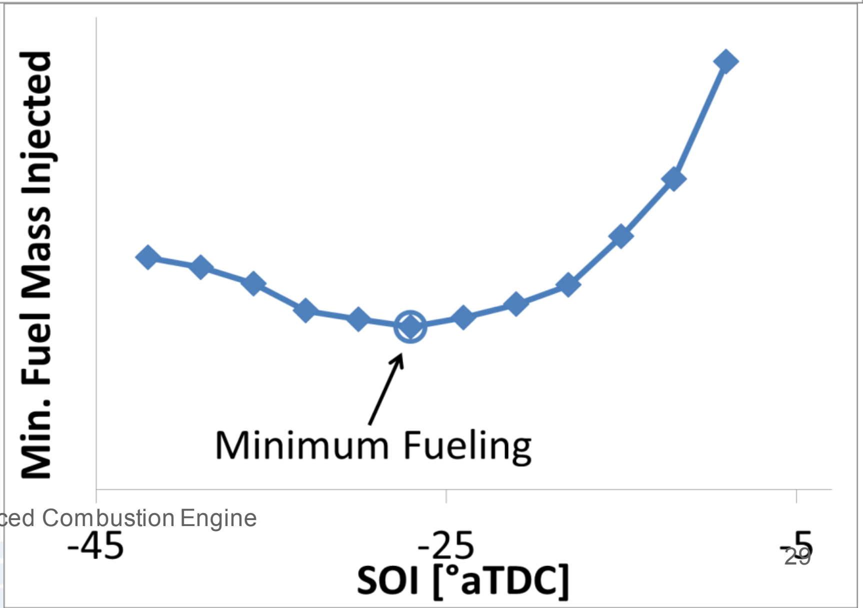
Narrow Window of Operation

- At early SOIs, no combustion due to fuel over-mixing
- At late SOIs, no combustion due to long ignition delay of fuel
- Range typically only 10-15 CAD



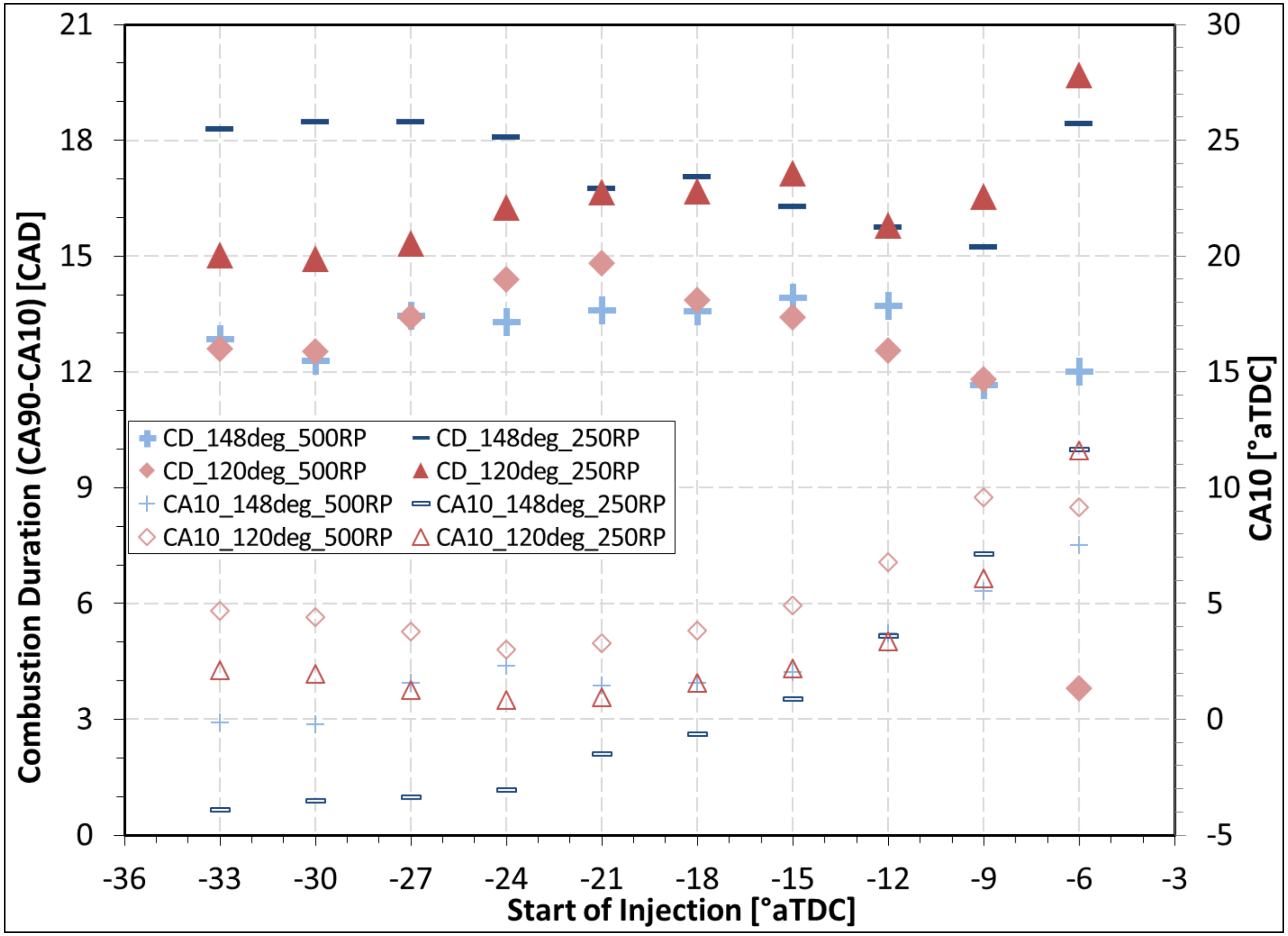
Solution: "Minimum Fueling SOI Sweep"

- Fueling reduced until CoV of IMEP increases to approx. 3% at each SOI
- Expanded range of SOI test conditions
- Finds optimum injection timing of maximum ignition propensity



Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

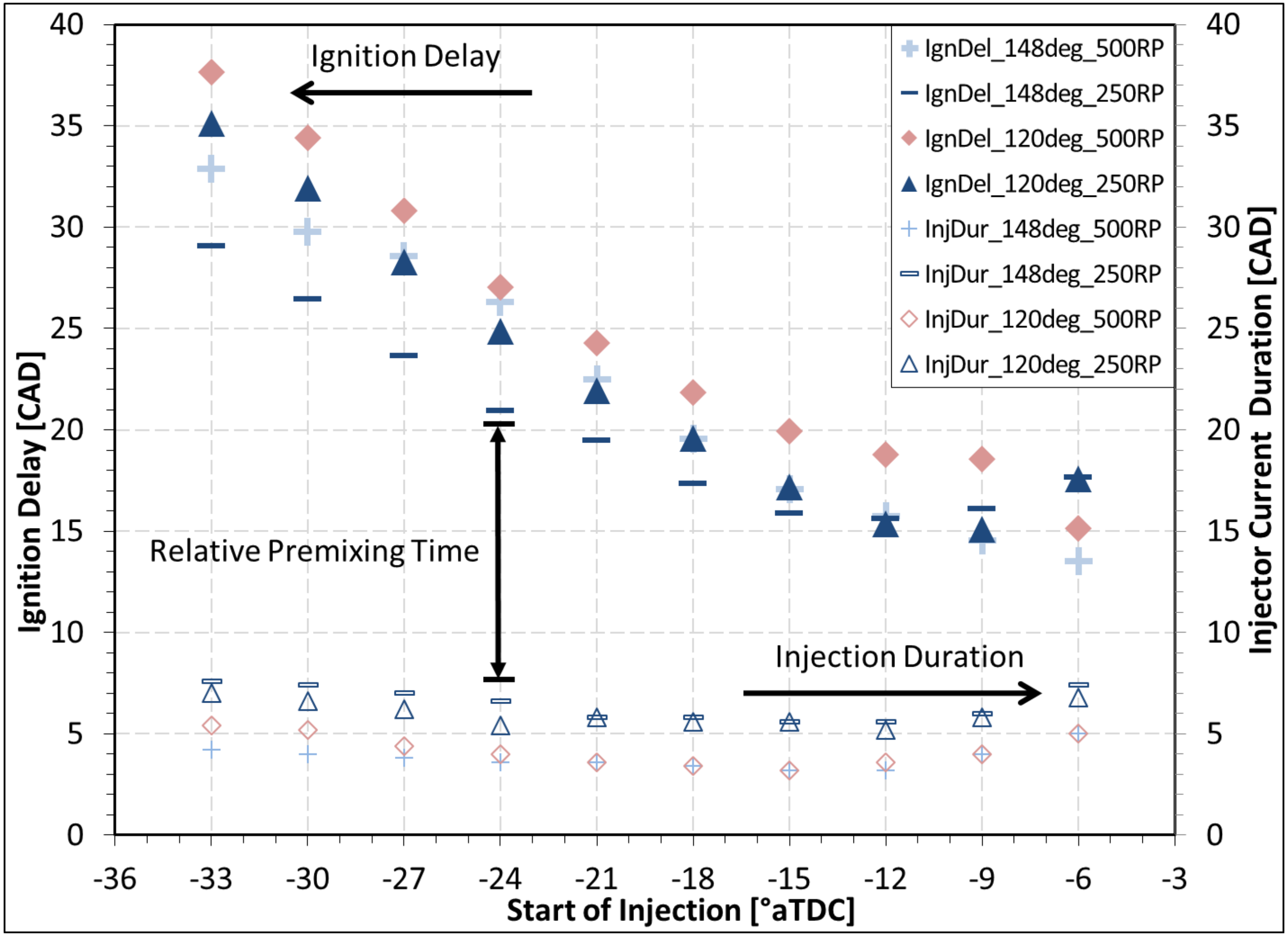
Effects of Injection Conditions on Combustion Duration and Start of Combustion



Advanced of -15 °aTDC, similar combustion duration and start of combustion. This could be beneficial in low load control.

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

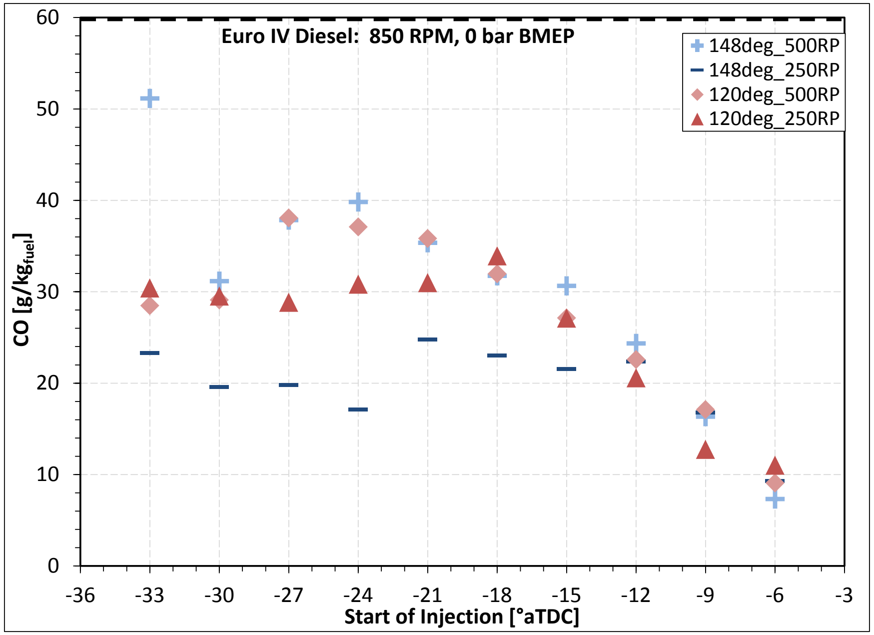
Injection Conditions on Ignition Delay and Premixing Time

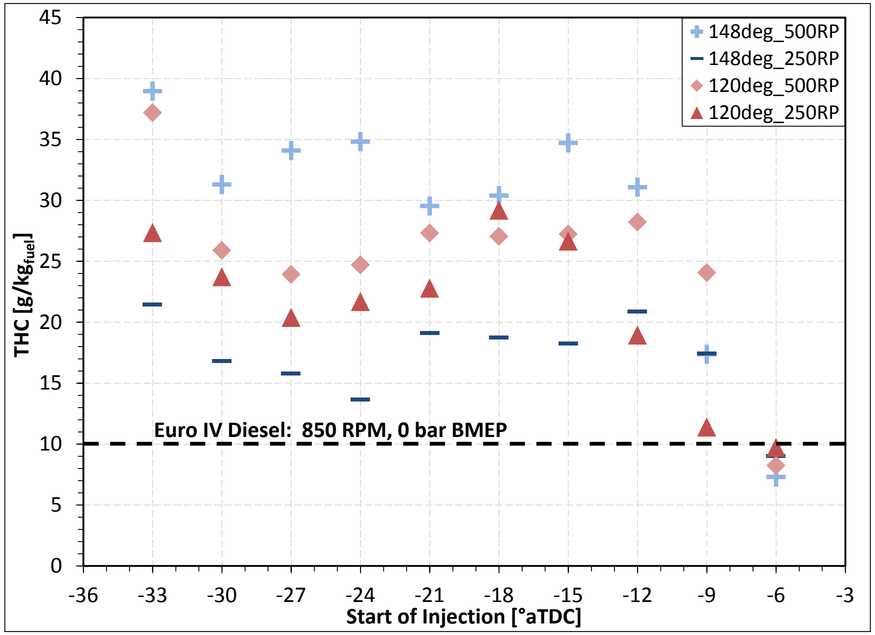


In general, 250 bar RP had shorter ignition delays and relative premixing times for each injector nozzle angle.

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)

Minimum Fueling 87 AKI CO and THC Compared to Euro IV Diesel Idle Operation





Significant reduction in CO at low load compared to Euro IV diesel operation, but higher THC.

Work Sponsored by the U.S. Dept. of Energy, Office of Vehicle Technologies, Advanced Combustion Engine Technologies Gurpreet Singh (Team Leader)