ACE011: Use of Low Cetane Fuel to Enable Low Temperature Combustion

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FY15 DOE VT Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
9:30 – 10:00 AM, Wednesday, June 10, 2015

Sponsor: US DOE OVT
Team Leader: Gurpreet Singh
Program Manager: Leo Breton

Project ID# ACE11

Overview

Timeline

- Started May 2008

Barriers

- From MYPP
  - Mechanism to control LTC Timing
    - Addressed in FY14-15
  - LTC high load and high speed operation
    - Covered in FY12-13
  - LTC control during change of speed and load
    - Will be addressed in FY16 and beyond

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY14 $670k
  - FY15 $550k

Partners

- GM R&D
  - Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- University of California – Berkeley
  - E10 auto-ignition characteristics
- University of Wisconsin-Madison
  - PM collaboration for different combustion strategies
  - Graduate student performing gasoline-fueled engine simulations using KIVA
- NREL
  - Advanced fuel property characterization

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

Objectives/Relevance: Multi-Cylinder GCI

Long-Term Objective

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

Current Specific Objectives:

1. Use in-cylinder imaging and simulation to see evidence of mixing influence upon auto-ignition
2. Evaluate effect of E10 upon low load performance compared to E0
3. Characterize PM from GCI to insure compliance with current/future regulations
4. Demonstrate efficiency potential of GCI in a multi-cylinder engine

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Milestones

Milestone	Target Date
Combustion imaging of gasoline operation for ignition timing and location for different fuels and additives	Jun 2014 (Complete)
Operate engine on a drive cycle using gasoline LTC to demonstrate at least 23% fuel economy improvement over an equivalent PFI SI gasoline engine	Sept 2014 (Complete)
Explore ITHR and φ distribution effects upon combustion stability to establish a lean limit of operation based upon combustion stability	Dec 2015 (Complete)
Validate simulation results upon boost effects on low load extension to idle by comparing imaging results	Mar 2015 (Complete)
Determine nozzle inclusion angle effects upon high load combustion noise and PM/NOx	Jun 2015 (Ongoing)
Determine load transient requirements for injection strategy	Sept 2015 (Ongoing)

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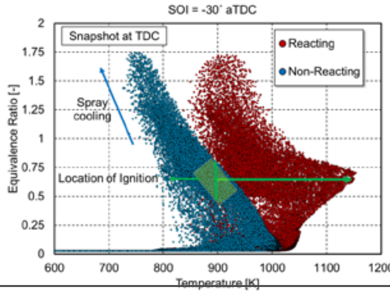
Approach/Strategy: Use endoscopic imaging, simulation & multi-cyl operation to understand ignition and operating boundaries

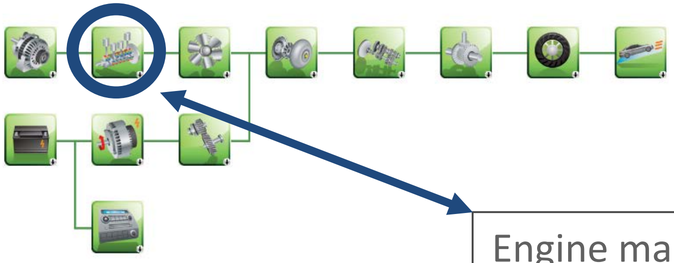
- Using experiments, CFD and Autonomie modeling, operate a GCI engine to understand factors involved in GCI auto-ignition
  - Low speeds/load - understanding sensitivity to injection characteristics (timing, pressure, and nozzle angle) and charge (T, P, and O_2)
  - Use validated modeling to assist in choosing optimum conditions

Endoscopic image of E10 “popcorn” GCI



Simulation of GCI auto-ignition conditions

- Use primarily production diesel hardware to identify and incorporate likely challenges of moving this combustion strategy into a multi-cylinder engine



Autonomie powertrain/vehicle modeling of US EPA combined cycle for GCI

Engine map input

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Technical Accomplishments & Progress (9 slides)

- Accomplishments for each of the four current specific objectives below are shown in the following 9 slides

- **Current Specific Objectives:**

1. **Use in-cylinder imaging and simulation to see evidence of mixing influence upon auto-ignition**
2. **Evaluate effect of E10 upon low load performance compared to E0**
3. **Characterize PM from GCI to insure compliance with current/future regulations**
4. **Demonstrate efficiency potential of GCI in a multi-cylinder engine**

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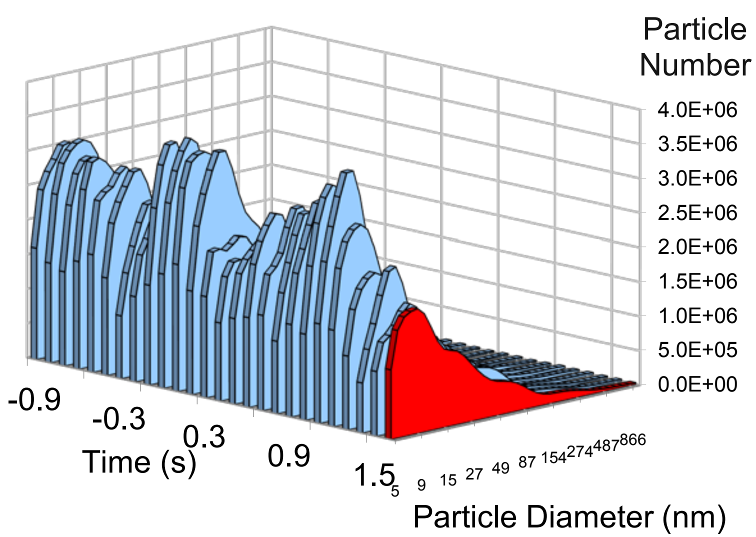
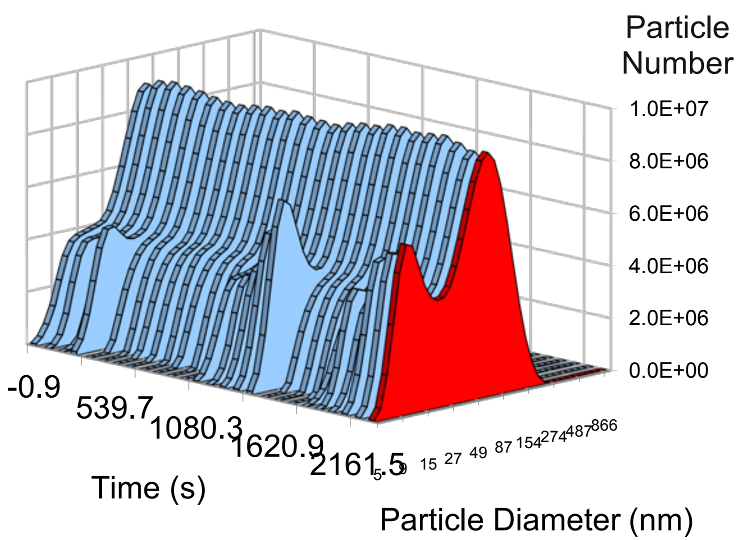
Technical Accomplishments
2000 RPM – 5 bar; significant soot differences between GCI and CDC ①





GCI FSN = 0.025

CDC FSN = 1.50

- Ensemble average movies from multiple combustion events
- Did not expect to see any GCI soot luminosity – only chemiluminescence!
  - FSN is so low and PN, PSD are so small - assumption was there would be no soot generated – imaging showed otherwise!
- Cambustion DMS500 samples @ 10 Hz - sequential distributions shown
- Much lower soot concentration, much shorter combustion duration = lower FSN

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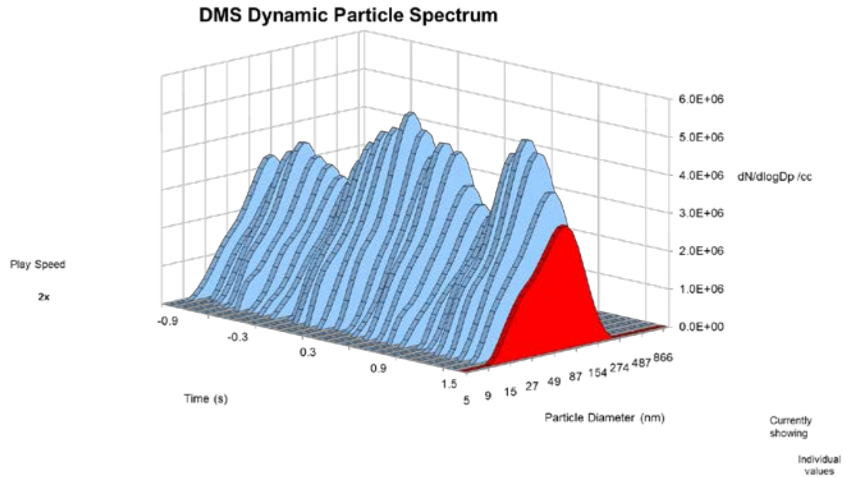
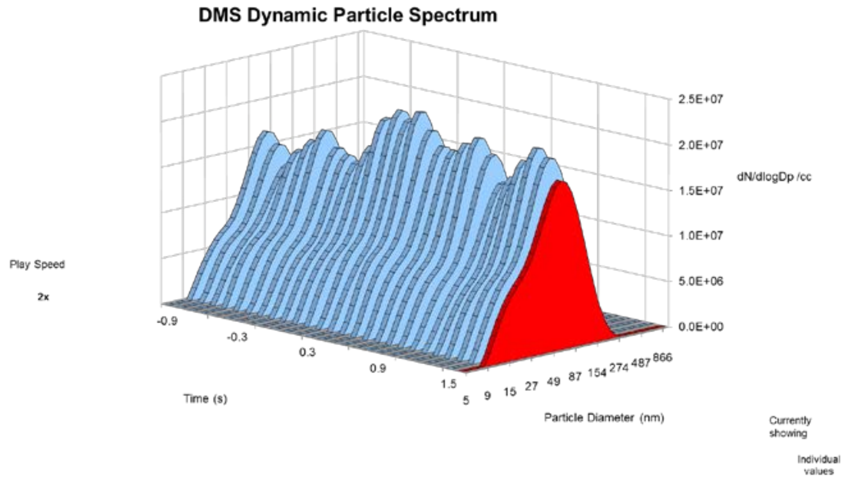
Swirl has influence over GCI soot luminosity, smoke and PN; less influence over PSD ①





Swirl Number 3.5
FSN = 0.063

Swirl Number 1.7
FSN = 0.165

- Ensemble average movies at 2000 RPM at 5 bar BMEP – swirl appears to have some ability to reduce smoke - This will be explored further in FY15 and beyond
- Particle size similar for high and low swirl, particle number levels are NOT
- Imaging shows GCI soot luminosity in time/space – not available from engine-out measurements

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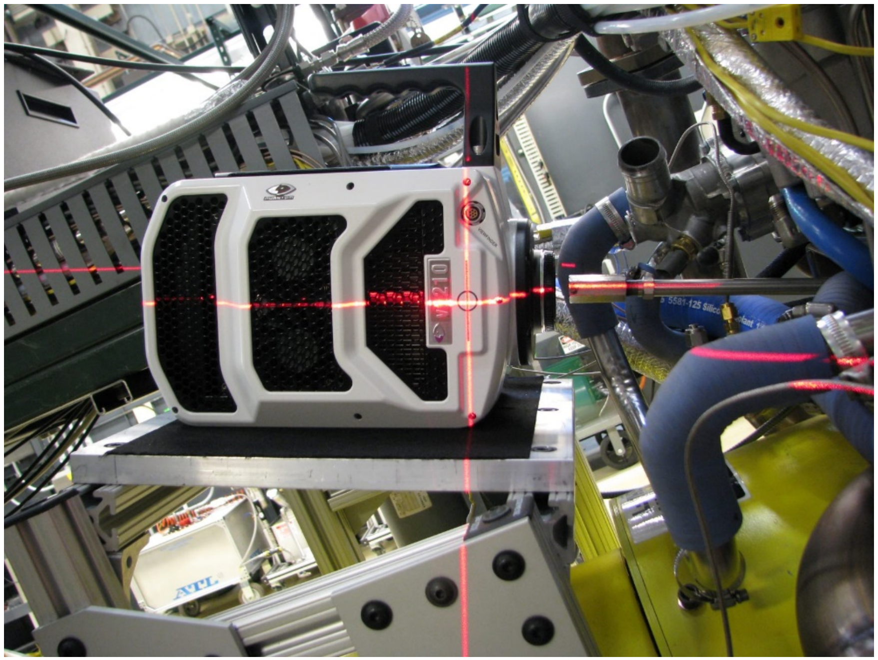
High speed imaging for 2 consecutive combustion events shows stochastic flow differences ①



- High speed imaging – one complete combustion event at 19,000 fps, 50 µs exposure time per frame
- 1500 RPM and 2 bar BMEP as a first cut at high-speed imaging (low vibration for the camera – additional conditions to follow) – link to simulation
- LES with detailed representation of different fuel kinetics are forthcoming

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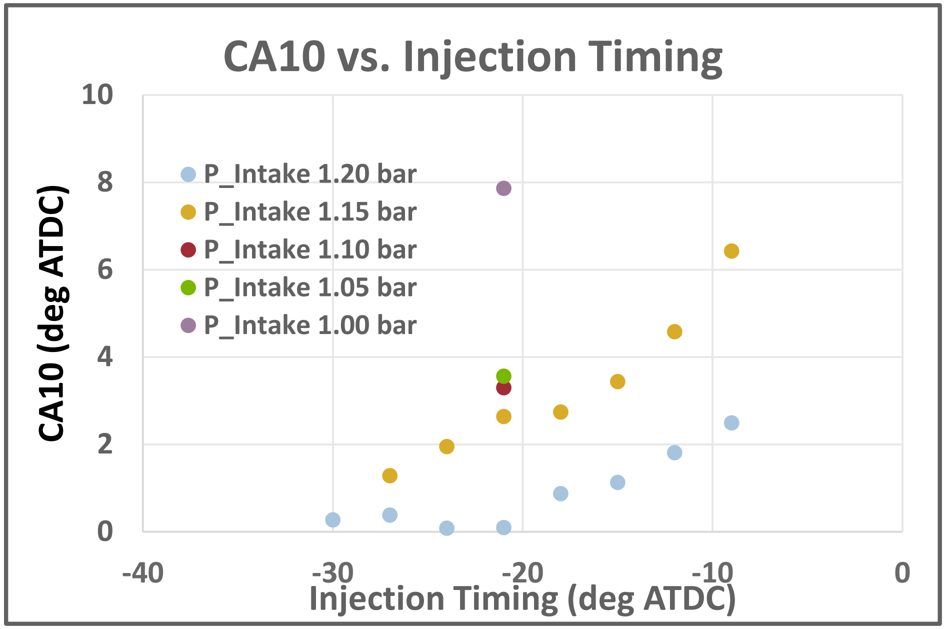
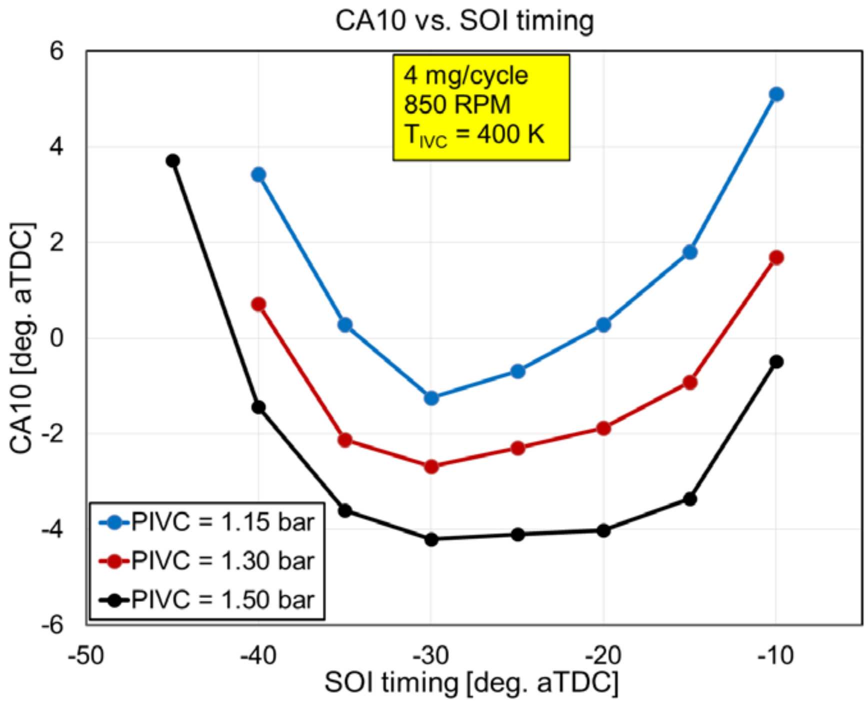
Experiments and simulation show significant influence of injection timing and boost upon reactivity ①





Experiment

Simulation

- Boost advances ignition and improves combustion efficiency allowing for wider range of SOI at higher boost
- Tradeoff between over-mixing/fuel in squish with early SOI, and reduced residence time with late SOI results in non-monotonic behavior of CA10 versus SOI
- Trend matches experimental data on the left

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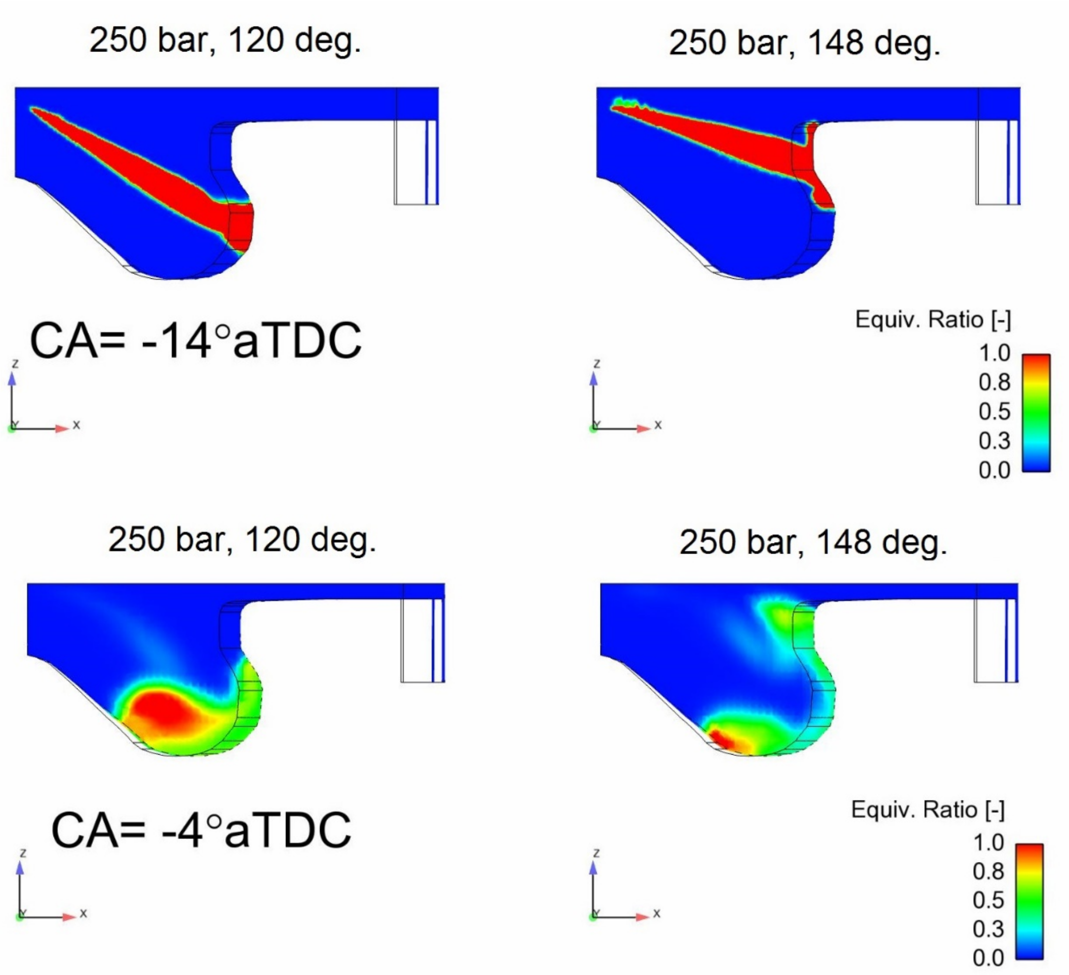
Simulations at 850 RPM, 250 bar RP show superior performance of 120 deg nozzle ①



- Current bowl shape provides CW vortex for 148 deg injection angle
- Shallower than 120 deg inclusion angles create CCW vortex similar to 148 deg
- Bowl re-design necessary to optimize for different injector inclusion angle

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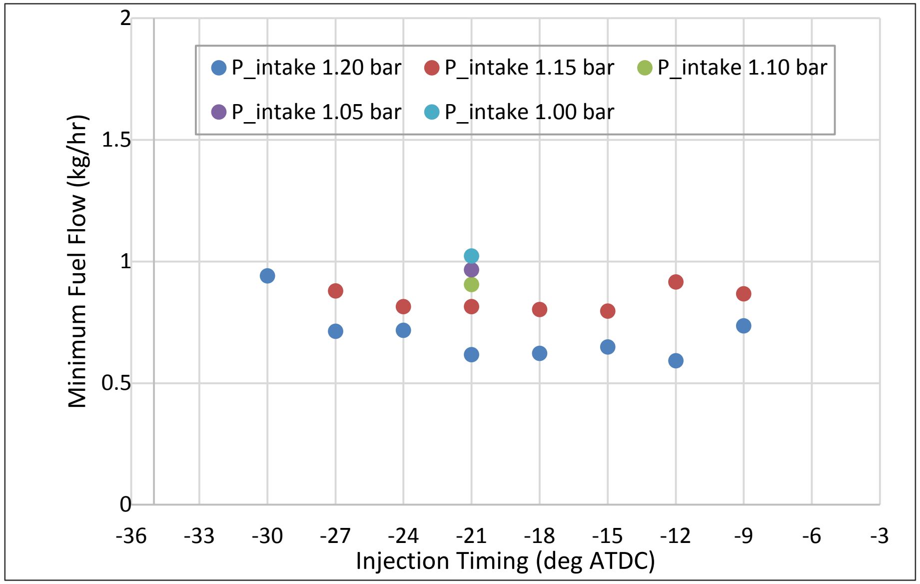
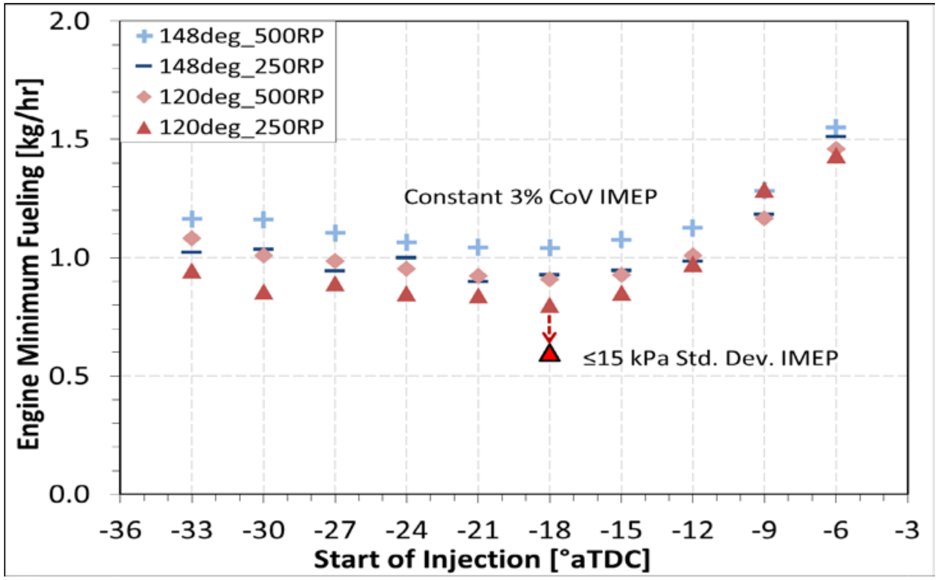
E10 and E0 exhibit similar minimum fueling traits P_intake, P_inj and Nozzle angle have influence ②

E10 (87 AKI)



E0 (87 AKI)



- E10 (LEV III/CARB) data shows that minimum load is reduced with increased boost.
- Identical boost (1.05 bar), minimum fuel rate E10 & E0 almost identical
- E10 (AKI = 87, RON = 90.7, Sensitivity = 7)
- E0 (AKI = 87, RON = 93, sensitivity = 12)
- E0 mimics E10 ignition behavior despite higher RON and sensitivity
- UCB observes EtOH inhibits HCCI ignition similarly

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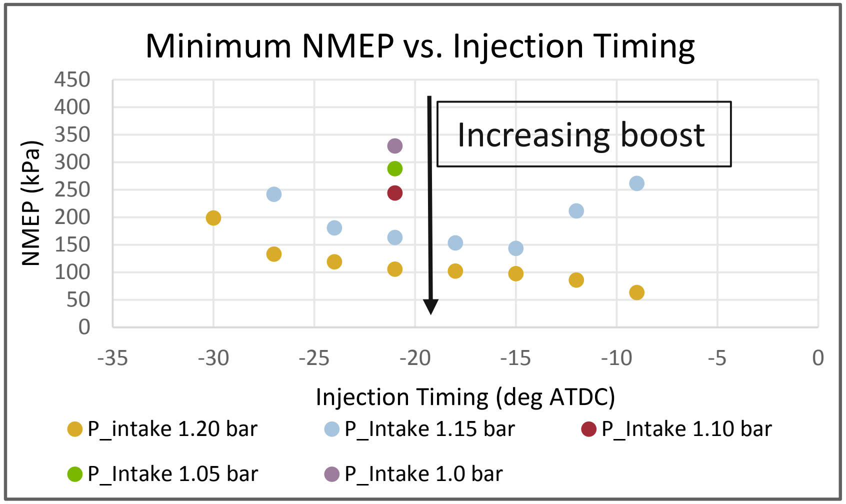
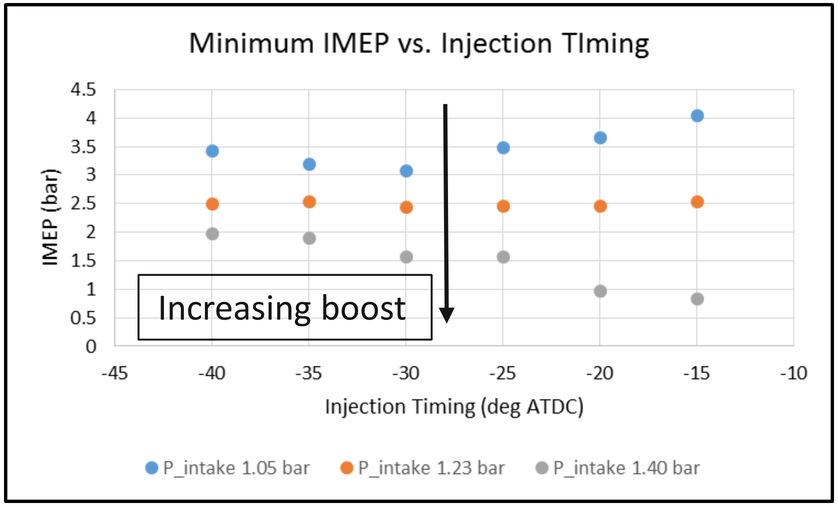
Argonne/UCB ignition studies display significant E10 auto-ignition sensitivity to boost levels ②



Argonne GCI Engine



UCB HCCI Engine

- Both Argonne and UCB show significant reactivity increase for E10 when boost is increased.
- SOI range expands when boost is increased
- Likely important for OEM’s when deciding on air handling systems
- Dual stage turbocharging or super/turbo combo
- Argonne S/C has electro-magnetic clutch and bypass (Eaton prototype)

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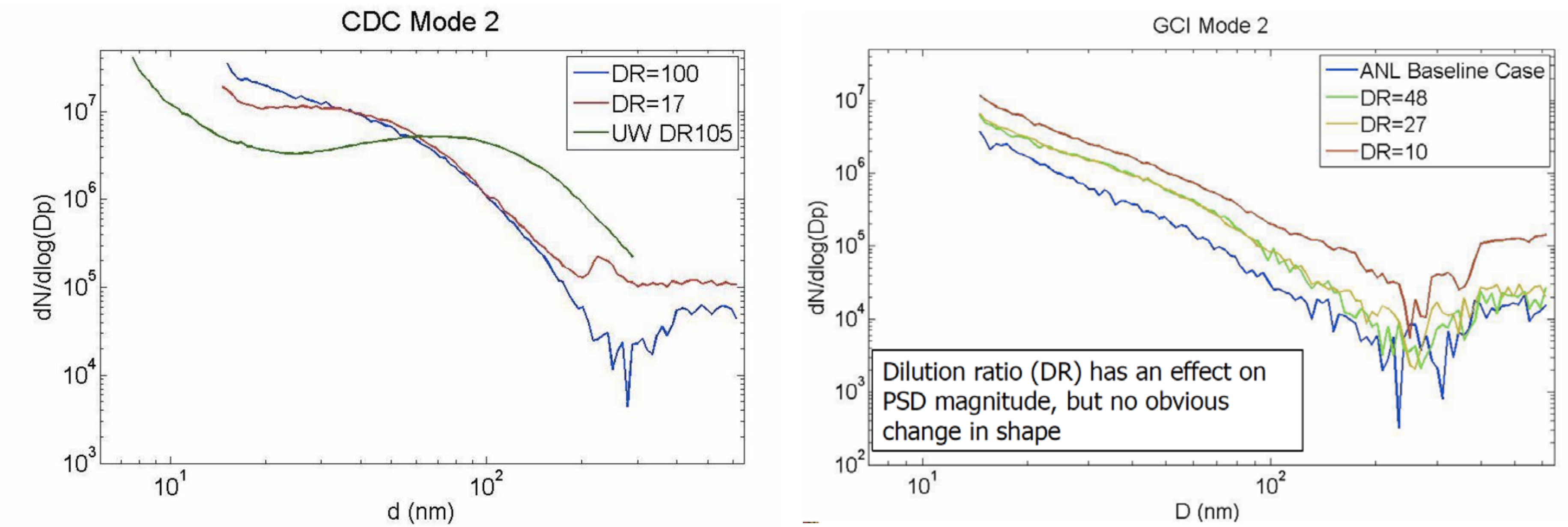
Argonne/UW collaboration shows PM differences between multi/single cylinder engine and between combustion regimes ③



- Difficult to match identical engine conditions
  - Boosting differences, charge flow dynamics
- PN and PSD are dependent upon sampling conditions
  - Ongoing work to better match dilution, sampling locations, temperatures and flows
  - Important for PM understanding and future regulations compliance
- Both Argonne and UW show very low GCI PN for sizes above 100 nm

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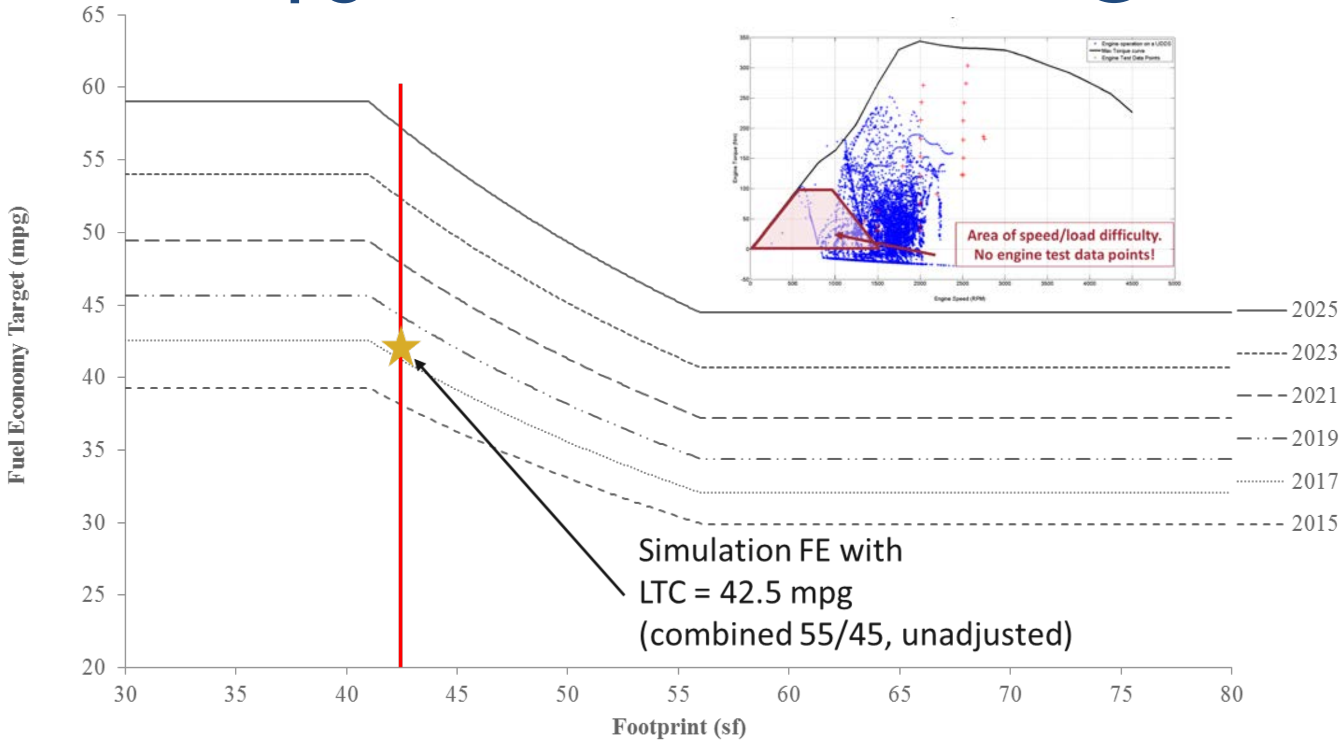
Autonomie shows GCI Engine provides significant FE improvement - 42.5 mpg for mid-size vehicle ④

Cadillac BLS wagon

http://www.carinf.com/en/9220414062.html



Fuel Economy

Fuel Economy [MPG]	PFI	SIDI	LTC	LTC with new map
UDDS	29.2	32.2	37.5	37.8
HWFET	39.0	41.9	47.6	50.7
Combined [55/45]	32.9	35.9	41.4	42.7
Improvement over PFI		9%	26%	29.6%
Improvement over SIDI			15%	19%

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Responses to FY14 Reviewer Comments

- **Reviewer Comment**
  - E0 is not representative of pump gasoline in the US – E10 to be used?
  - Link to John Dec's work?
  - Does this project have effective collaborations?
  - Metrics for combustion performance?

- **Response**
  - We have moved to Haltermann LEV III/CARB E10 this year
  - We are performing E10 work and UCB is providing insight into how our work links to John Dec's, particularly boost.
  - We have continued collaborations with General Motors and internal Argonne work, while forming new ones with UCB and UW -ERC
  - We are now using USCAR metrics for comparing different LTC approaches for BSFC, stability, emissions and combustion noise.

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Collaborations

Engine maps, piston crowns and other hardware, cylinder head modifications, technical support

E10 auto-ignition characteristics for boost, temperature, injection timing

PM collaboration for different combustion strategies

Graduate student performing gasoline-fueled engine simulations using KIVA

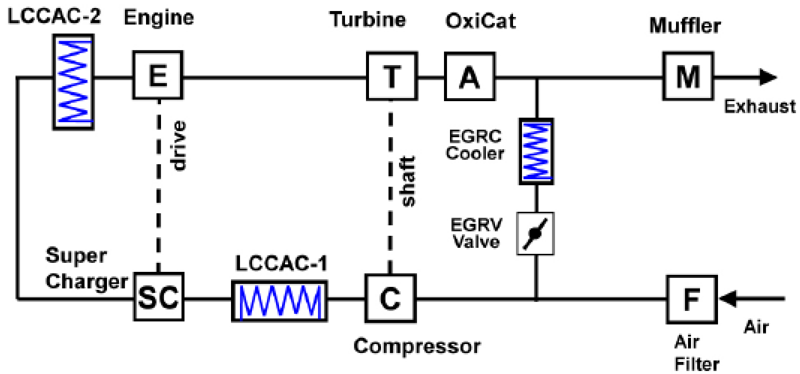
(Q4 FY 15 fuel characterization)

- In addition, this project is involved in the AEC Working Group
  - Cummins, CAT, DDC, Mack, John Deere, GE, International, Ford, GM, Chrysler, ExxonMobil, ConocoPhillips, Shell Chevron, BP, ANL, SNL, LLNL, ORNL, NREL

Remaining barriers and challenges

- Reliable and repeatable ignition and combustion phasing
  - Characterize fuel dependence (EtOH) and strategies to mitigate it
  - At high speeds and loads, challenge is to reduce ignition propensity for more premixing
    - Slight amounts of swirl may assist in this area

- Develop operating strategy that allows smooth transient behavior
  - Characterize injection/boost/EGR interactions
  - LP EGR is likely useful



LP EGR system for GDCI, courtesy of Delphi
SAE 2014-01-1300

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Project Future Work

- Continue to characterize E10 at a variety of speeds loads
  - Further determine E10 ignition effects and sensitivity to boost
- Install LP-EGR loop with DPF
  - Provide more boost at low speeds/loads with EGR
  - GM Recommendation
- Develop strategy for transient operation with injection, boost and EGR
- Continue to track and account for USCAR guidelines combustion noise
  - Target <90 dB for high load, <85 dB for low load
- Continue to characterize GCI particulate emissions
  - Cambustion DMS500, Dekati dilution system, SMPS, AVL Smokemeter
  - Further investigate swirl to reduce PM at medium/high loads

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Summary

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

1. In-cylinder imaging and simulation developed improved understanding of the physical processes of GCI auto-ignition
   - Soot radiation seen even though ultra-low soot was produced engine-out
2. E10 and E0 were studied for low load/idle operation
   - Performance was almost identical even with significant RON and sensitivity differences
3. PM comparison between GCI and CDC (with UW) and PM characterization of GCI showed potential of swirl to reduce PN.
4. 29% FE improvement shown by Autonomie in EPA combined cycle
   - Cadillac BLS using GCI compared to standard PFI engine

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Technical Back up slides

Engine Specifications and Tested Fuels Properties
E10 was used for idle and low load exploration

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) And/or Eaton Supecharger

Properties of the Tested Fuel

Property	87 AKI gasoline	E10 gasoline
AKI Rating	87	87.2
RON	93	90.7
MON	81	83.7
Sensitivity	12	7
Specific gravity	.7018	.7342
Lower heating value (MJ/kg)	44.0	42.0
Initial boiling point (°C)	93.2	103.5
T10 (°C)	119.8	132.3
T90 (°C)	234.2	320.7

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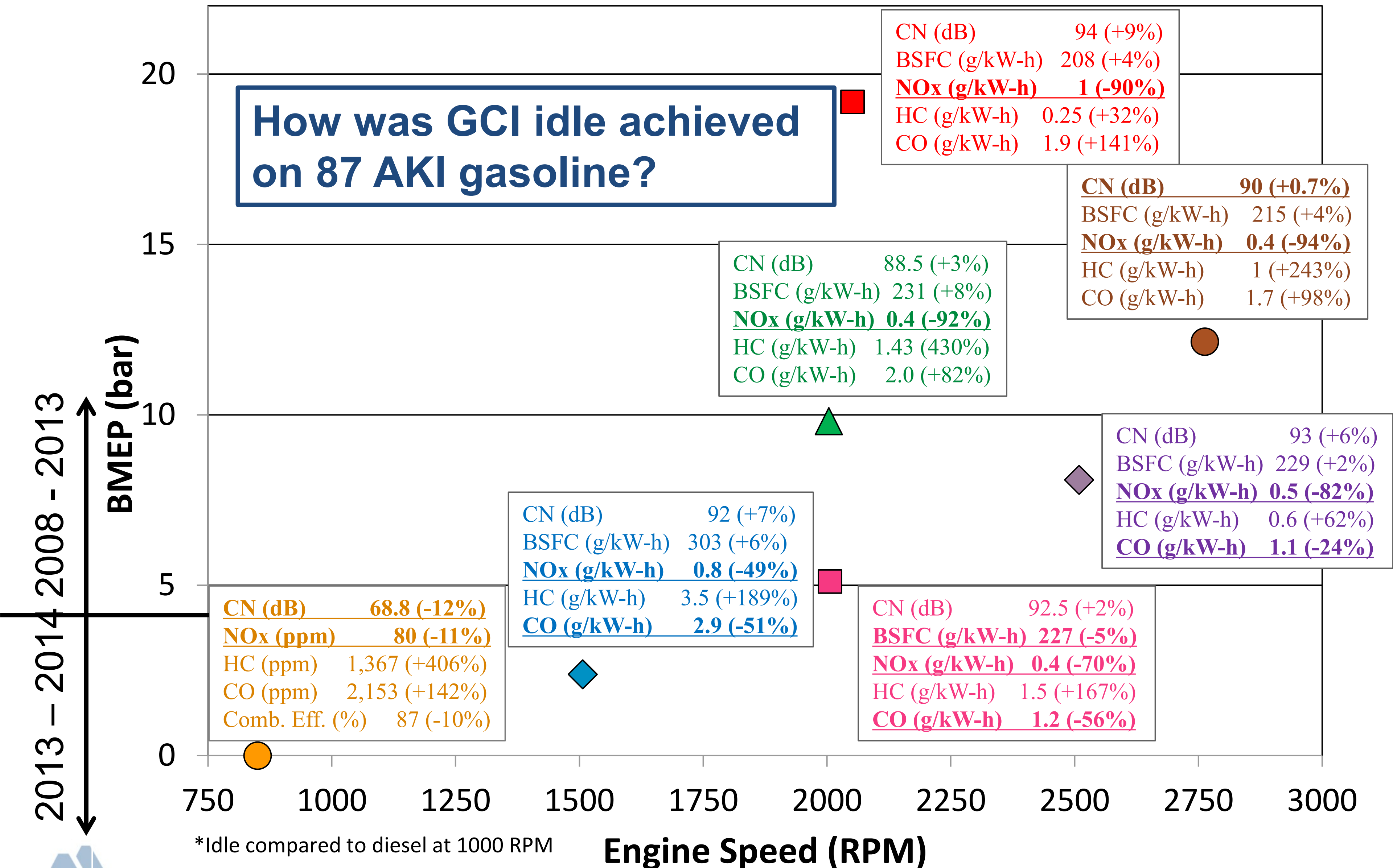
Progress of GCI Load Range Using 87 AKI Gasoline



*Idle compared to diesel at 1000 RPM

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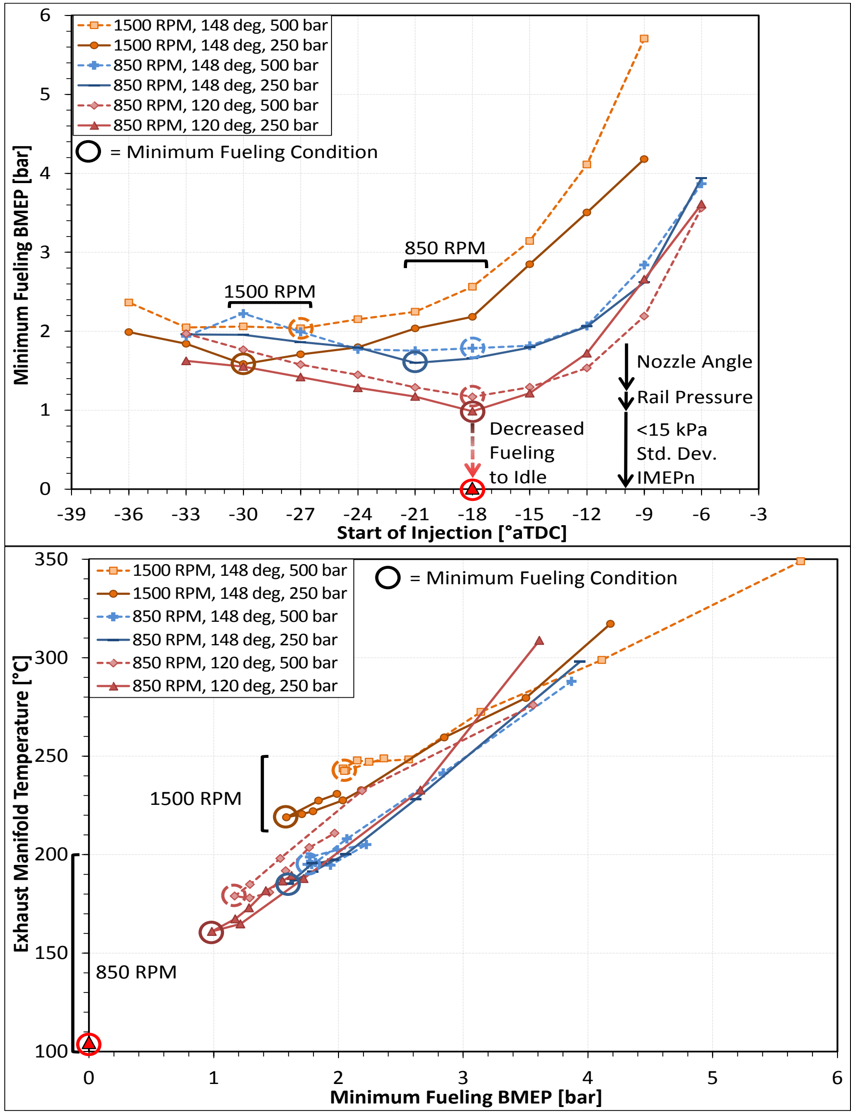
Expansion of Lower Load Limit with 87 AKI Gasoline

Methodology

- Minimum fueling SOI sweeps
  - 3% CoV of IMEP limit for <u>each cylinder individually</u>
- Single injection per cycle
- 850 RPM engine speed (previous studies also done at 1500 RPM)
- 250 or 500 bar injection pressure
- 148° and 120° injector nozzle
- Combustion noise target <90 dB
- Maximized boost (1.05 bar)
- 45 °C intake air temperature
  - No external intake heating
- No EGR



Based on SAE 2015-01-0832

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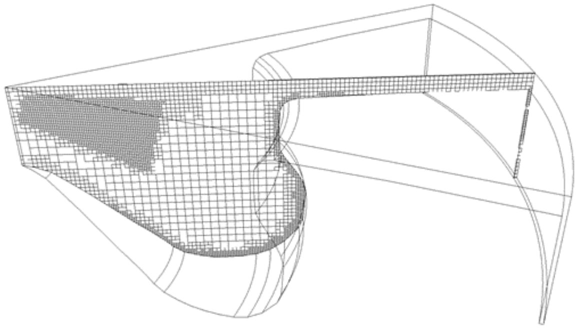
Simulation setup in CONVERGE

Engine specs

Cylinders	4
Geometric CR	17.8
Effective CR	17.5
Bore (mm)	82
Stroke (mm)	90.4
Connecting Rod Length (mm)	145.4
IVC (° bTDC)	132
EVO (° aTDC)	116
Number of injector nozzle holes	7
Nozzle hole diameter (μm)	141
Injector umbrella angle (deg.)	148
Injection pressure (bar)	250

Minimum cell size	0.175 mm
Multi-zone resolution	ΔT = 5 K, $\Delta\varphi$= 0.05
Turbulence Model	RANS, RNG k-ε



5.47 hours on 64 cores

Peak cell count = 420K cells

Simulation

RPM	1500
T_{liner} (K)	380
T_{head} (K)	400
T_{piston} (K)	400
Simulation start (°aTDC)	-132
Simulation end (°aTDC)	60
Kinetic Mechanism	Liu et al. (48 sp. 152 rxn.)

Fuel Surrogate composition for simulations

Isooctane (% by mass)	87
n-heptane (% by mass)	13

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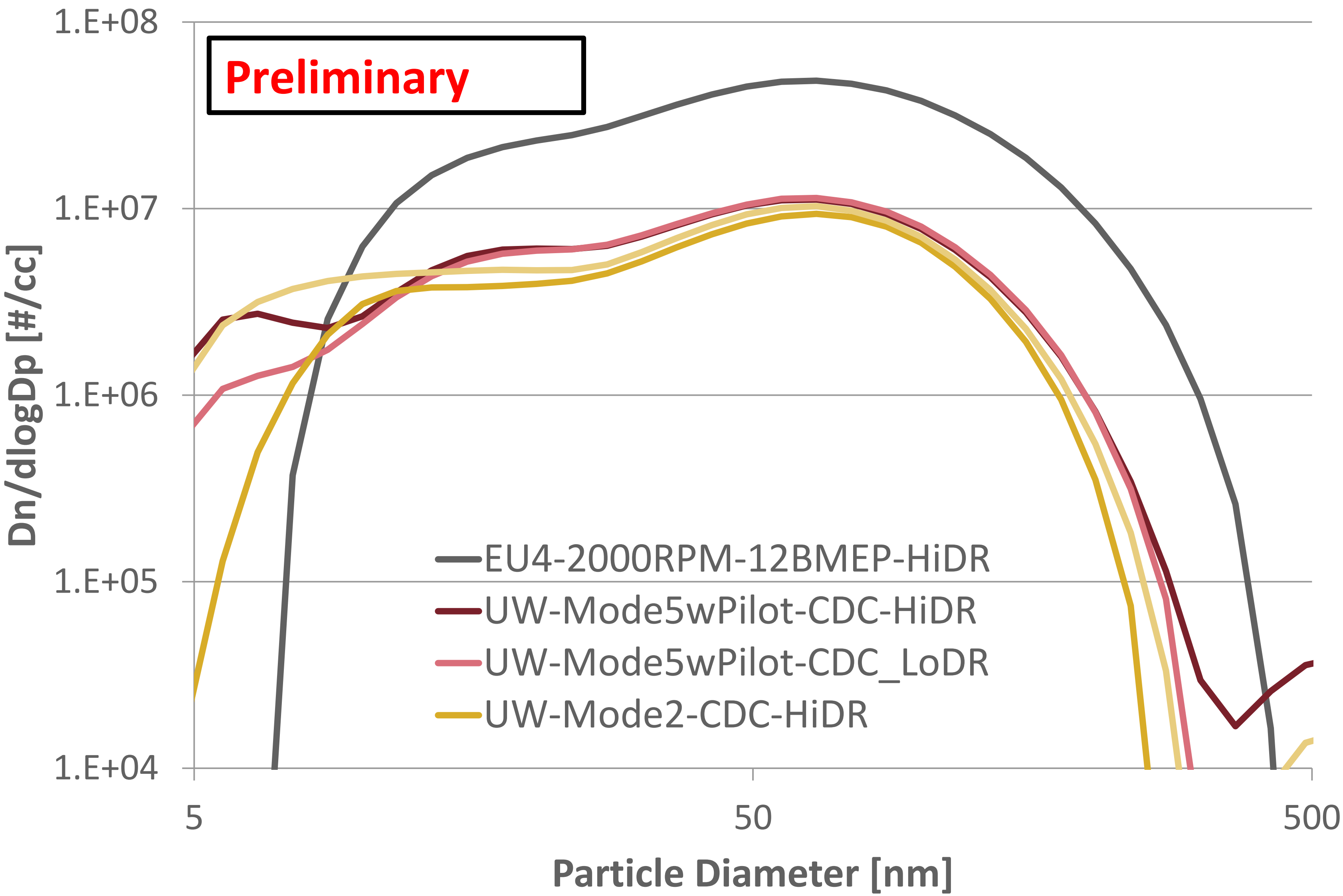
Preliminary data from Cambustion DMS-500 fast response particle analyzer



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