Co-Optimization of
Fuels & Engines

Advanced Compression Ignition Combustion Engines: Gasoline-Range Fuels

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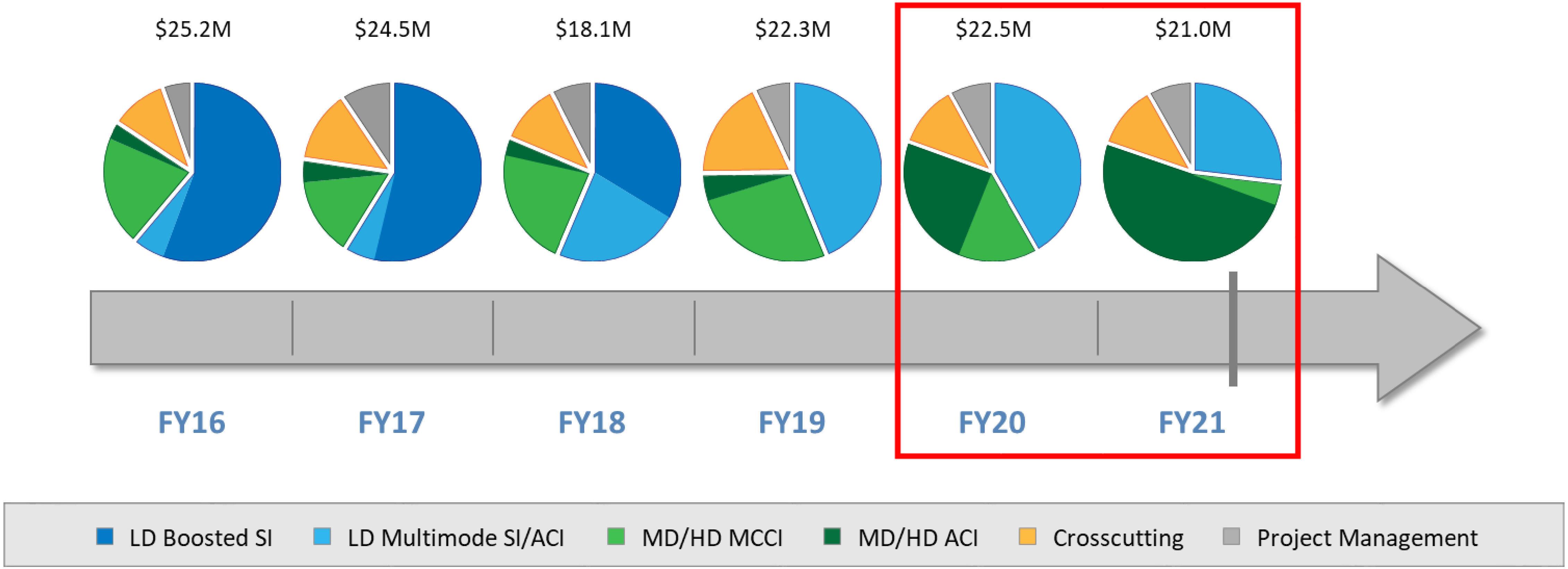
2020 DOE Vehicle Technologies Office
Annual Merit Review

better fuels | better vehicles | sooner

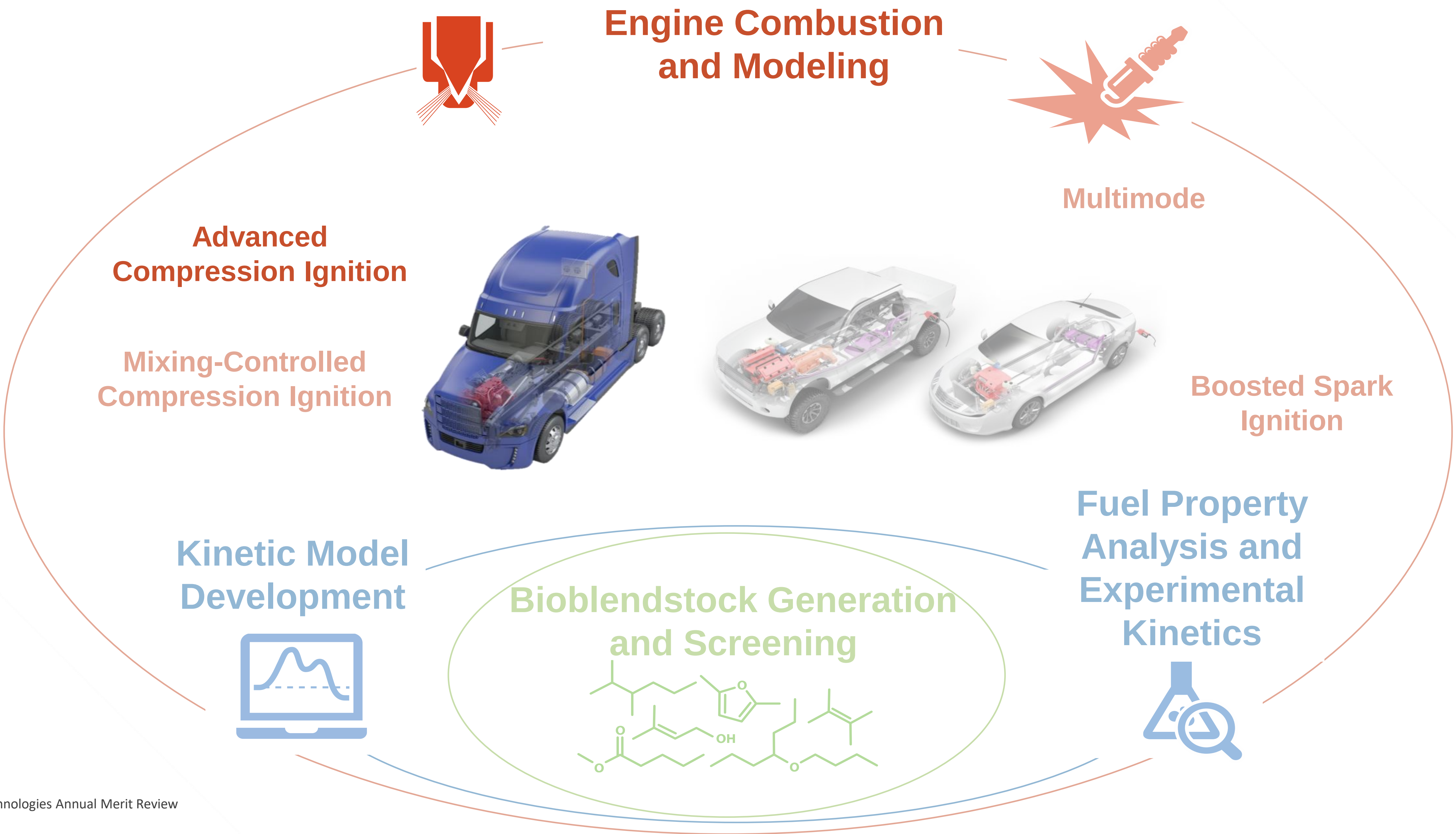
Overview



Barriers

- Determine factors limiting advanced compression ignition (ACI) engines and develop methods to extend limits
- Understanding impact of likely future fuels on ACI and whether ACI can be more fully enabled by fuel specifications different from gasoline

Co-Optima Program Integrated to Deliver Better Engines Sooner

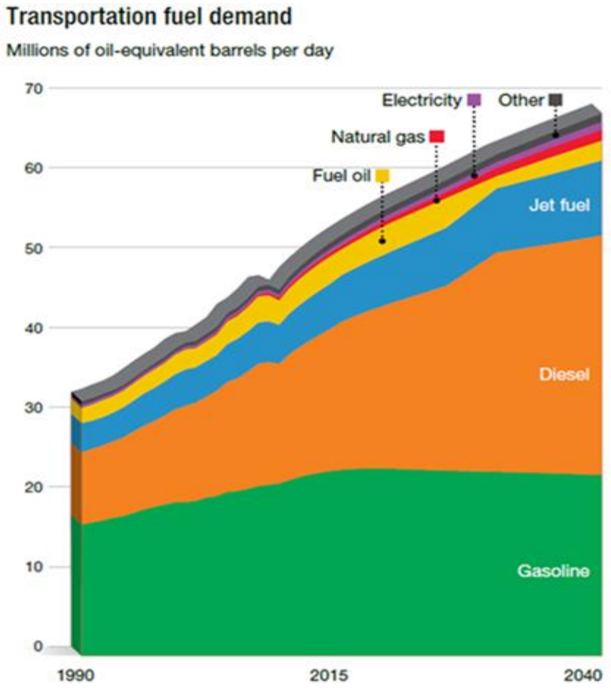


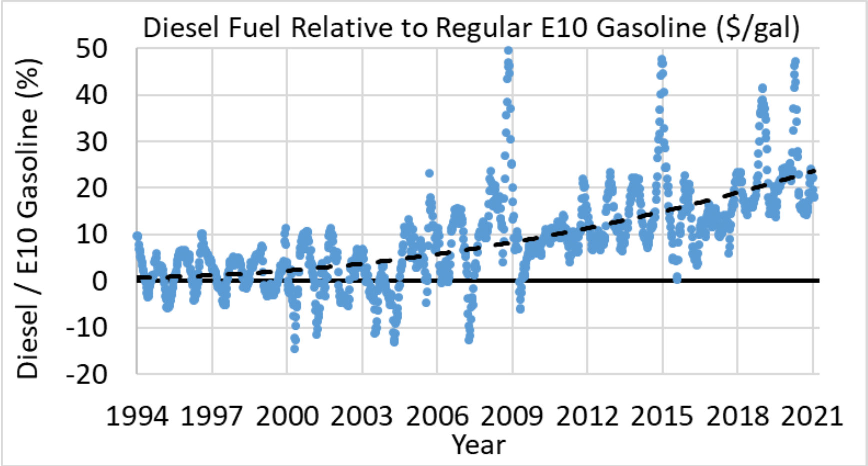
Relevance (Value Proposition and Potential)

ACI: Advanced Compression Ignition
CDC: Conventional Diesel Combustion
DEF: Diesel Exhaust Fluid
GHG: Green House Gas
TCO: Total Cost of Ownership

Relevance of Full-Time MD/HD ACI Engine and Fuels Research:

- Gasoline-like fuels with <u>similar or better efficiency</u> as conventional diesel combustion (CDC) in MD/HD engines
- <u>Significant reductions in PM/NOx emissions</u> (25-99.9%) relative to CDC
- <u>GHG reduction</u> with low carbon intensity liquid fuels for the MD/HD fleet
- Utilize <u>existing</u> liquid fuel (energy) distribution network
- <u>Reduced total cost of ownership</u> (TCO): fuel, DEF, etc.





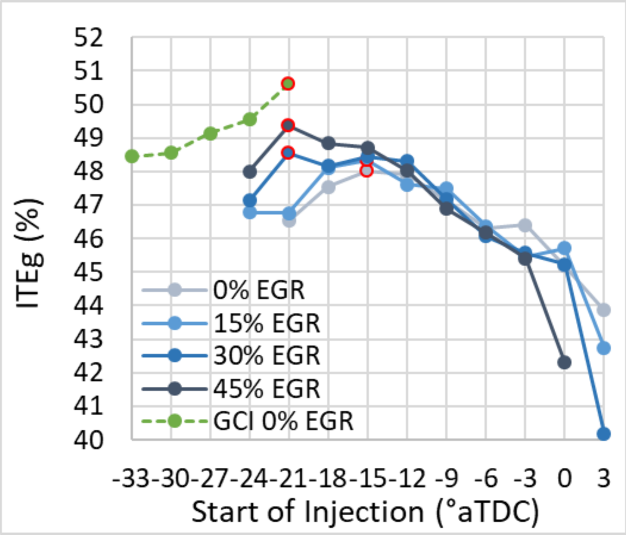
2018 Outlook for Energy: A View to 2040", ExxonMobil.
U.S. EIA weekly gasoline and diesel fuel updates, Jan. 25, 2021.

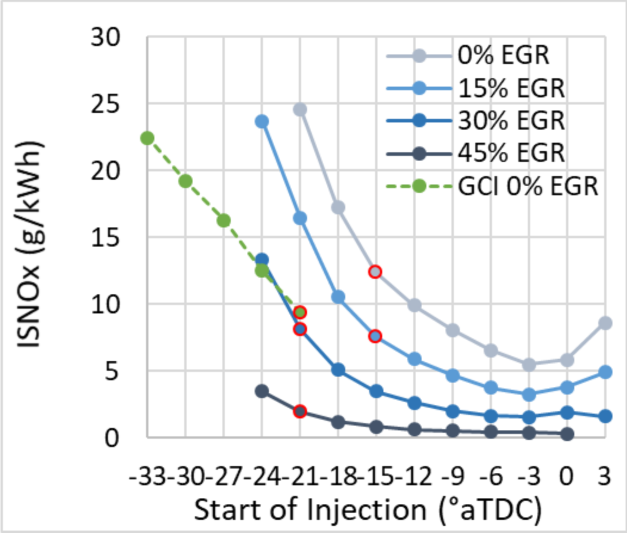
ACI Efficiency Relative to Conventional Diesel Combustion

GCI: Gasoline Compression Ignition
LTGC: Low-Temperature Gasoline Combustion

Heavy-Duty 14.6L* Engine at IMEPg = 5 bar

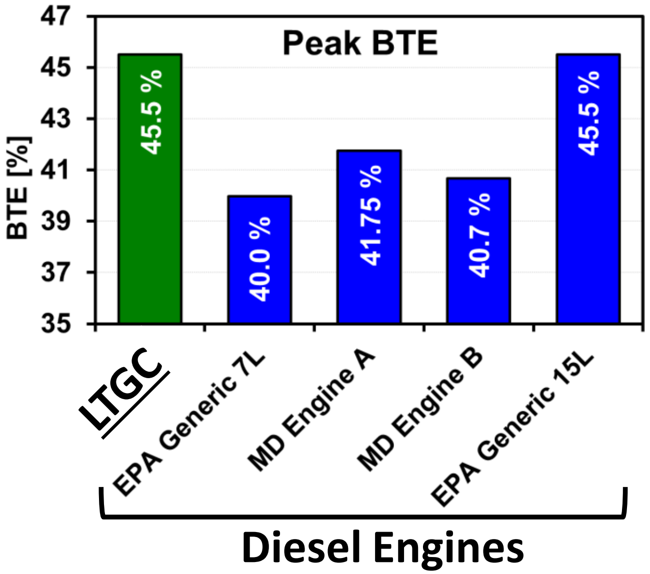
- **Injection-controlled Gasoline ACI yielded approximately a <u>4% relative increase in ITE</u> compared to conventional diesel combustion**
  - 75% reduction in soot emissions
  - At 0% EGR, GCI had 25% lower NOx emissions
  - Diesel required 30% EGR to match GCI NOx emissions

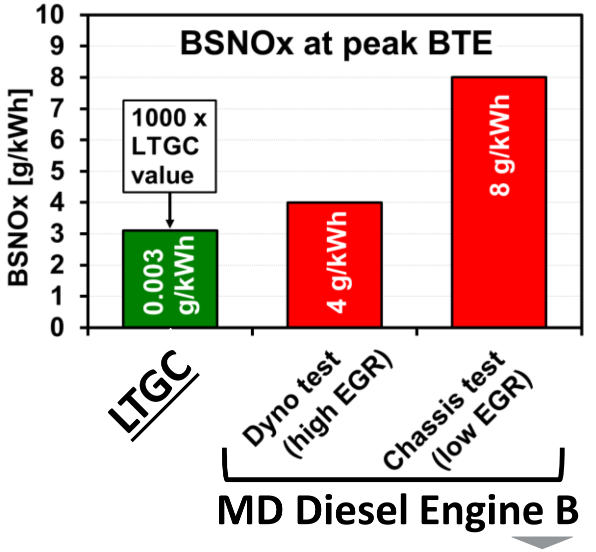




Medium-Duty 5.9L* LTGC & 6.7L* Diesel Engines at Peak BTE point, BMEP ~ 15 bar

- **Well-mixed Gasoline ACI (LTGC) yielded a <u>10.4% rel. increase in BTE</u> compared to average of the two market leading MD diesel engines**
  - Soot emissions not detectable with smoke meter
  - <u>NOx is more than 1000 times less than diesel</u> with high EGR





*** Engine displacements based on 6-cylinder configuration**

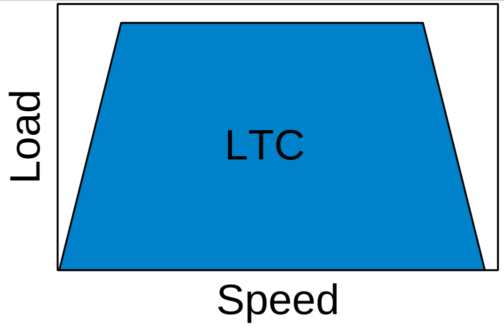
LD Full-Time ACI Research (Co-Optima 1.0)

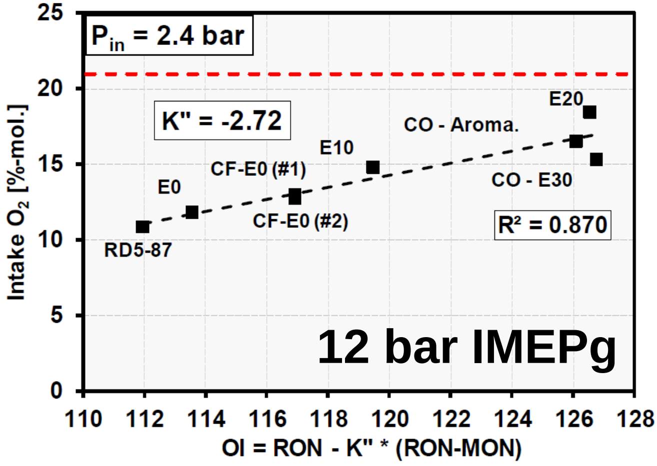
Co-Optima 1.0 ACI: Focus on kinetically-controlled low-temperature combustion (LTC) across the full operating map

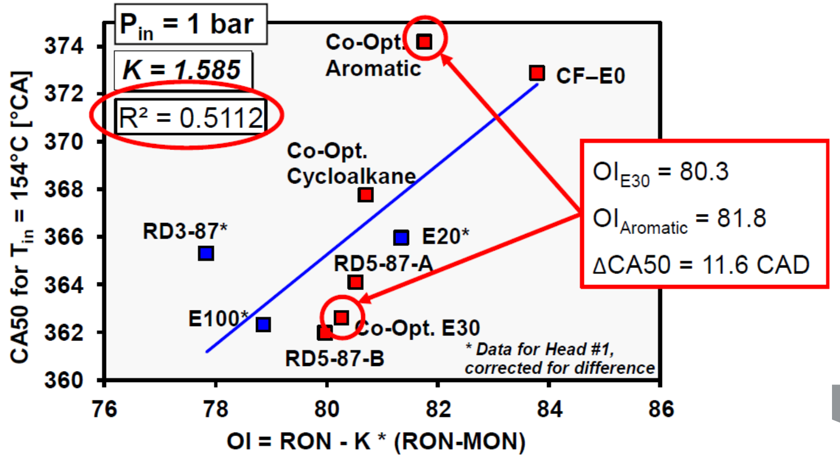
Question: Can high RON, high octane sensitivity (OS) gasolines (good for boosted SI engines) work with full-time LTC engines?

<u>High load</u>: <u>Yes</u>, higher OI reduces the EGR requirements, but can reduce stability, depending on fuel composition
(Discussed further on slide 15)

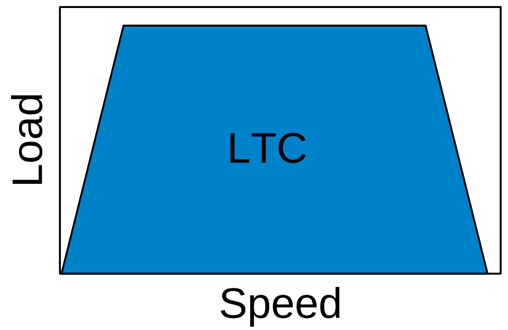
<u>Low load</u>: Can make LTC operation challenging if OI (at K≥1) and OS is too high ⇒ requires greater heating and reduces ϕ-sensitivity, depending on fuel composition







LD Full-Time ACI Research (Co-Optima 1.0)



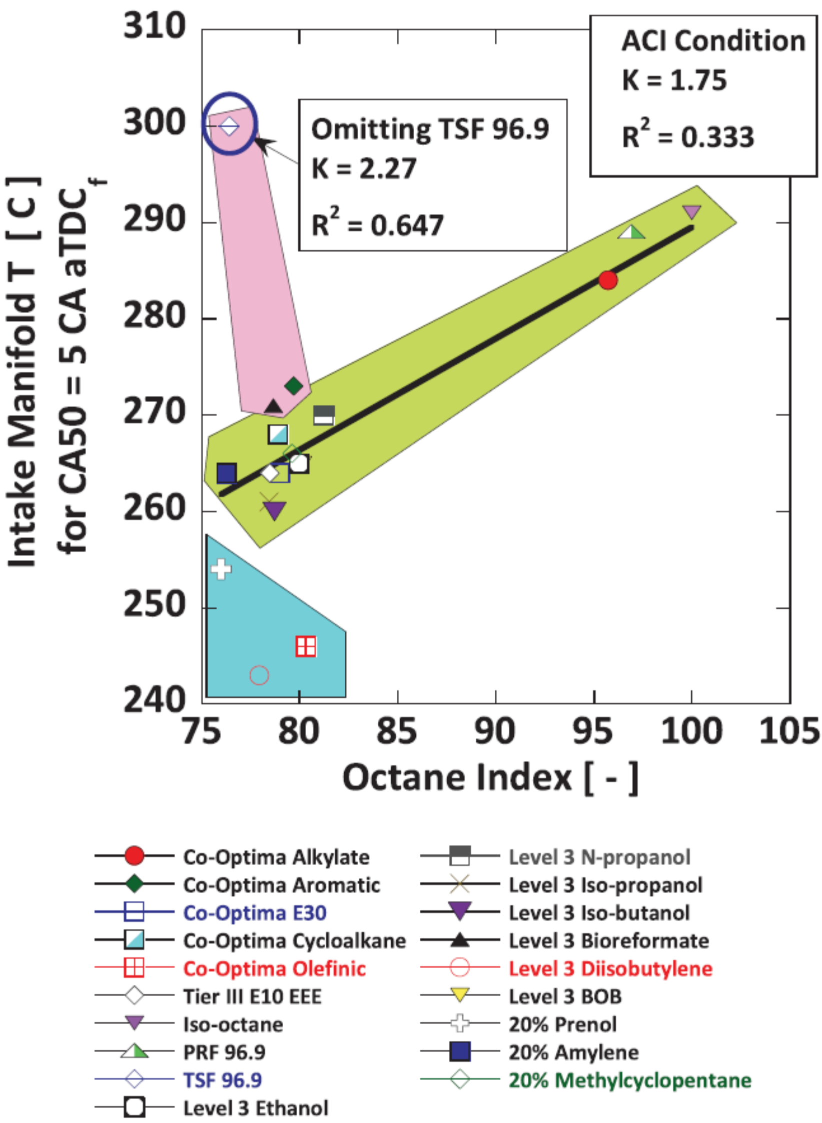
First attempt at an ACI Fuel Merit Function:

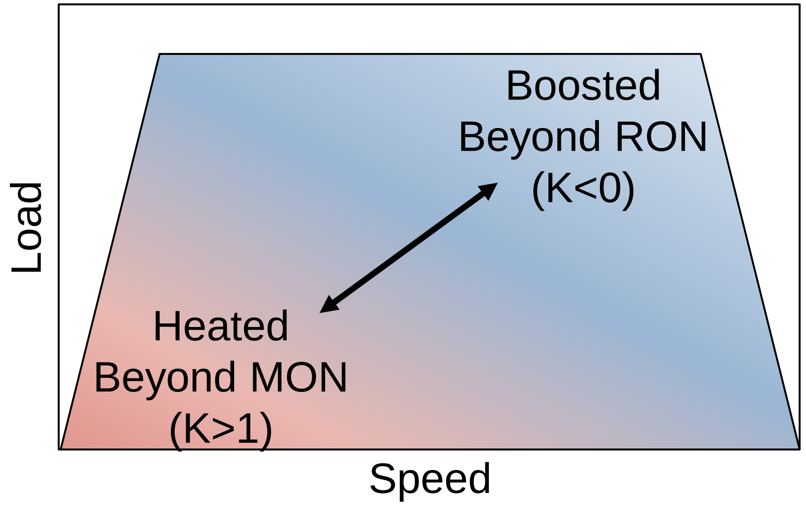
- **Focus on LTC across operating map**
- **RON was target fuel property**
- **Limited fuel-engine data sets for analysis early in Co-Optima**
- **Mixed results: negligible to moderate effect of RON on efficiency and load range**

Combustion Mode	Source	RON Range Tested	Representative ITE_{abs}/RON
GDCI	Delphi-Aramco	60-93	**0.17**
GCI	Aramco	≈40-68	**0.13**
GCI	Argonne Nat'l Laboratory	74.7-92.6	**0**
LTGC	Sandia Nat'l Laboratory	92-96	**0.08**

Reduced Relevance of RON/MON/OI for ACI Combustion

- **RON and MON are the only standard ASTM gasoline ratings relevant to autoignition, but are based on knock intensity**
- **Octane Index (OI) is based on RON, MON, and an engine-based "K"**
  - OI = RON – K (RON – MON)
- **Co-Optima researchers demonstrated RON, MON, and OI are not appropriate fuel properties for MON-like ACI combustion**
- **Fuel chemistry dependencies (<u>aromatic</u> and <u>olefin</u> content)**
- **At MON-like low load conditions, similar fuel property requirements between full-time ACI engines and multi-mode ACI/SI engines**

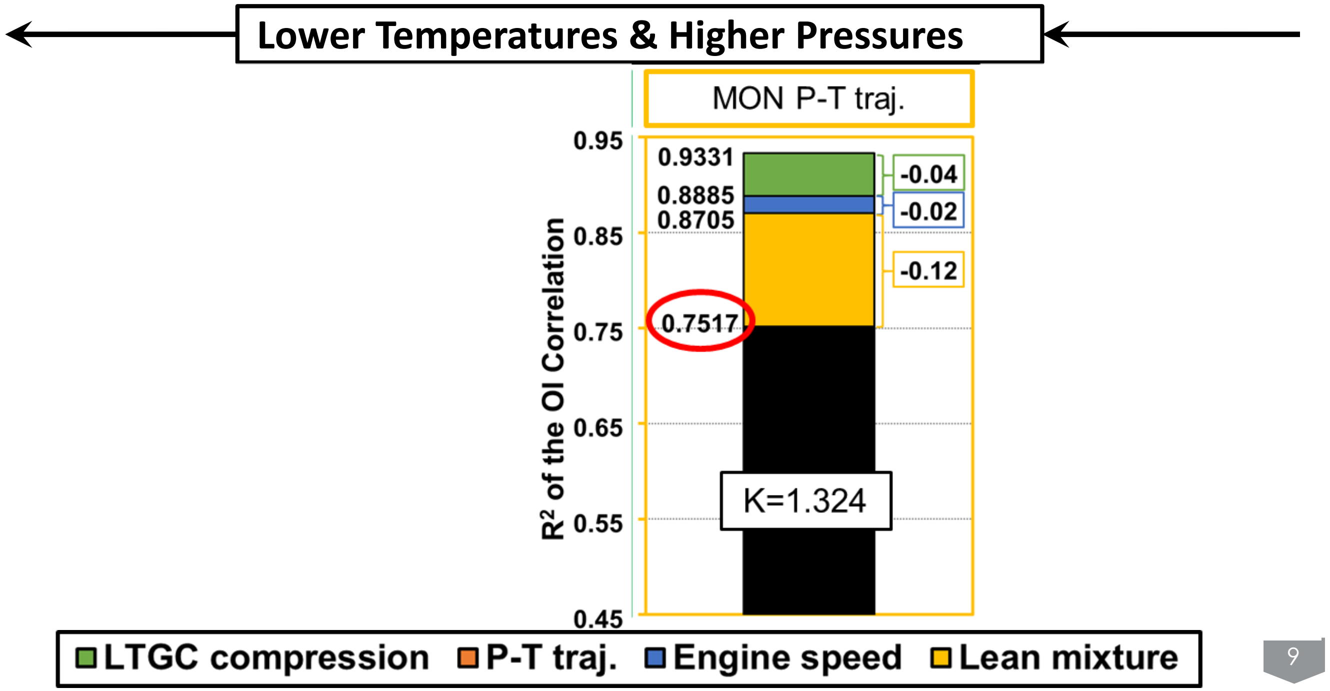




Szybist, S. and Splitter, D., AECS, 2020, <u>10.1016/j.jaecs.2020.100003</u>

Why do RON, MON, and OI not perform well for ACI combustion?

- **A detailed analysis of the factors affecting the OI under ACI conditions was performed ⇒ the OI does not perform well for any condition tested when operating at realistic ACI / LTGC conditions.**
- **Starting from the conditions of MON test (at which the OI performs very well), the effects of typical variations in operating conditions were analyzed for four P-T trajectories:**
  - OI still shows acceptable correlation for ACI piston-only compression vs. piston + flame for MON test (R^2 = 0.89 vs. 0.93).
  - The OI works better at MON conditions ⇒ the further the P-T trajectory from MON, the poorer the correlation.
  - Varying the engine speed is significant beyond RON but small beyond MON.
  - Varying ϕ has a very large effect beyond MON but marginal beyond RON.
    ⇒ Beyond MON: big differences in ϕ–sensitivity between fuels.
    ⇒ Beyond RON: all fuels are ϕ–sensitive.

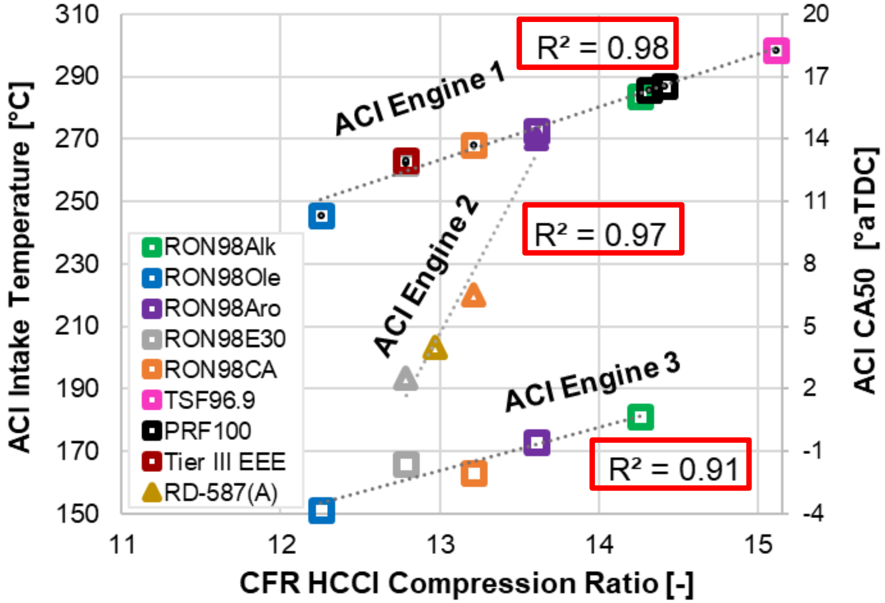


- **OI is not an adequate metric for ACI autoignition.**

Co-Optima CFR HCCI Fuel Ratings for Low Load MON-like ACI

Swept parameters of the Lund-Chevron HCCI Number Method

- CA50 range: TDC to 6 °aTDC, **3 °aTDC most stable**
- Lambda range: 2 to 5, **λ = 3 most stable**
- Intake pressure: 1.0 to 1.3 bar, **1.0 bar best correlation**
- Intake temperature: 30 to 200 °C, **150-200 °C higher octane**
- Engine speed: 600 vs. 900 RPM?
  - 900 RPM: Closer to modern engine speeds
  - 600 RPM: More time allows higher octane range, less fuel req.



High temperature HCCI test better predictor than MON or OI

Engine 1	2020	2020	2019
R^2	600 RPM	900 RPM	900 RPM
100 C	0.35	-	0.69
150 C	0.87	0.97	0.91
200 C	0.94	0.98	0.97

Engine 2	2020	2020	2019
R^2	600 RPM	900 RPM	900 RPM
100 C	0.42	-	0.89
150 C	0.64	0.89	0.93
200 C	0.85	0.97	0.81

Engine 3	2020	2020	2019
R^2	600 RPM	900 RPM	900 RPM
100 C	0.65	-	0.82
150 C	0.9	0.93	0.9
200 C	0.87	0.91	0.85

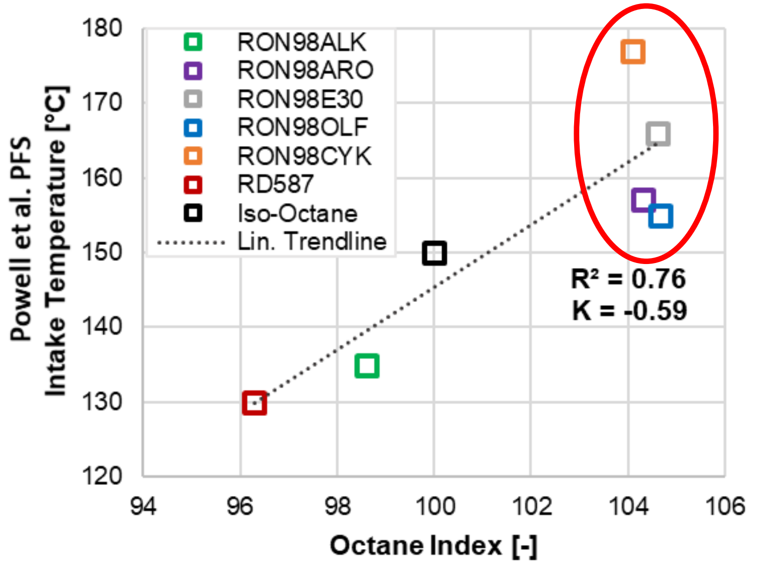
Co-Optima CFR HCCI Fuel Ratings for Boosted "Beyond-RON" ACI

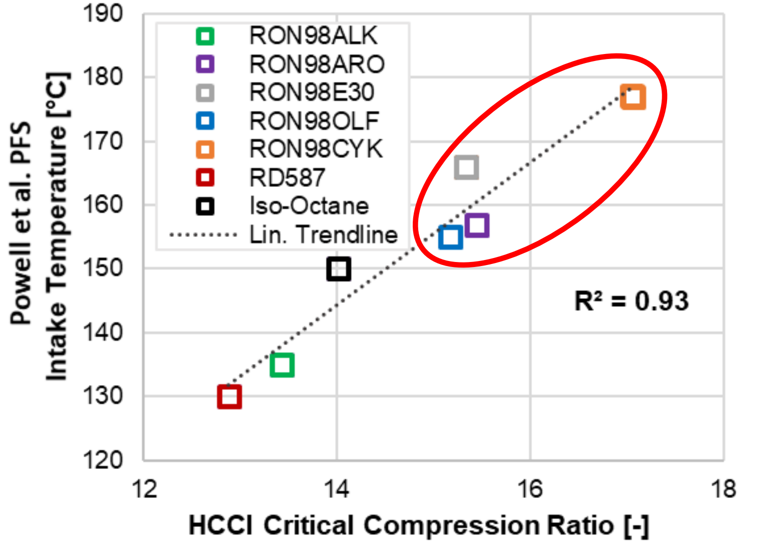
PFS: Partial Fuel Stratification

CFR Supercharged HCCI Test

- CA50 range: TDC to 6 °aTDC, **3 °aTDC most stable**
- Lambda range: 2 to 5, **λ = 3 most stable**
- Intake pressure: 1.0 to 1.5 bar, **1.5 bar highest with carburetor**
- Intake temperature: 30 to 200 °C, **55 °C compression ratio limited**
- Engine speed: 600 vs. 900 RPM?
  - 900 RPM: Closer to modern engine speeds
  - 600 RPM: More time allows higher octane range, less fuel req.

Updating the RON/MON test methods to HCCI combustion significantly improved ACI reactivity ratings



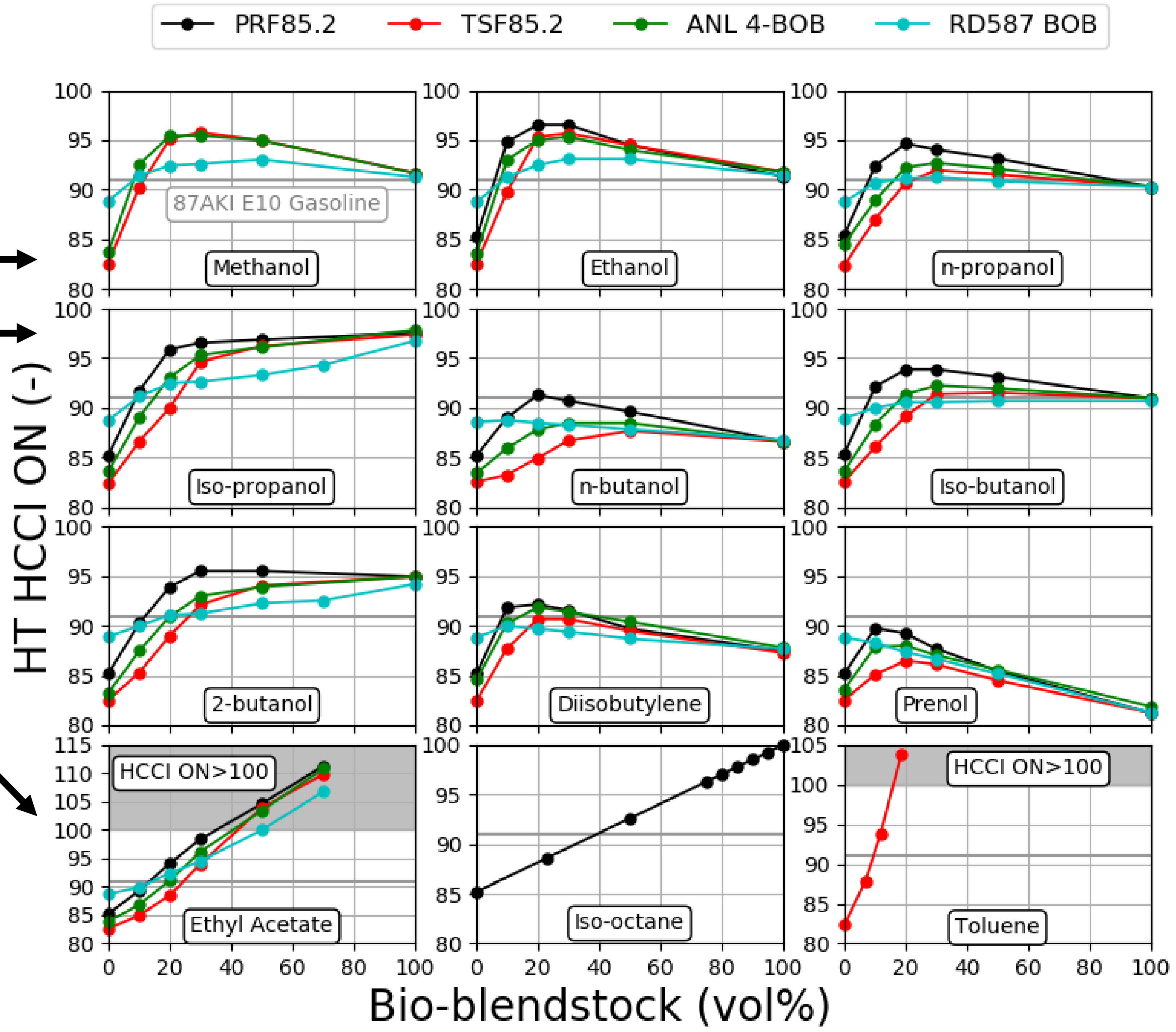


CA50 = 3°aTDC, λ=3, IMP = 1.5 bar, MAT = 55°C, 600 RPM

Powell et al., doi: 10.3390/en14030607

High Temperature (HT) HCCI Non-Linear Biofuel Blending Characteristics

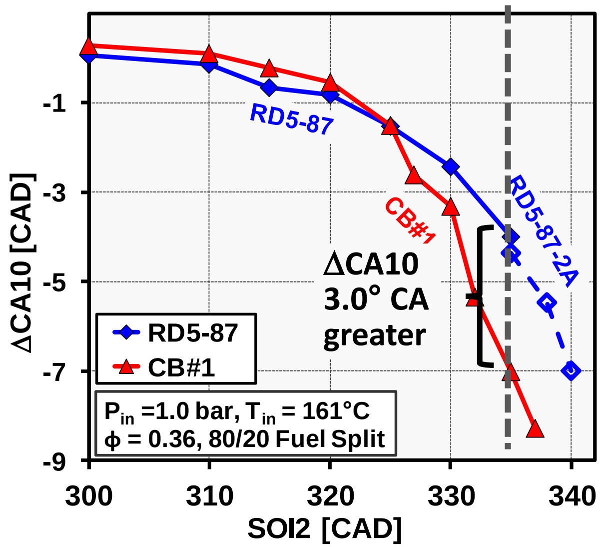
- **Under high temperature <u>lean compression ignition</u>, biofuel blending can show:**
  - "Hyper-boosting" blending
  - Synergistic blending
  - Linear blending



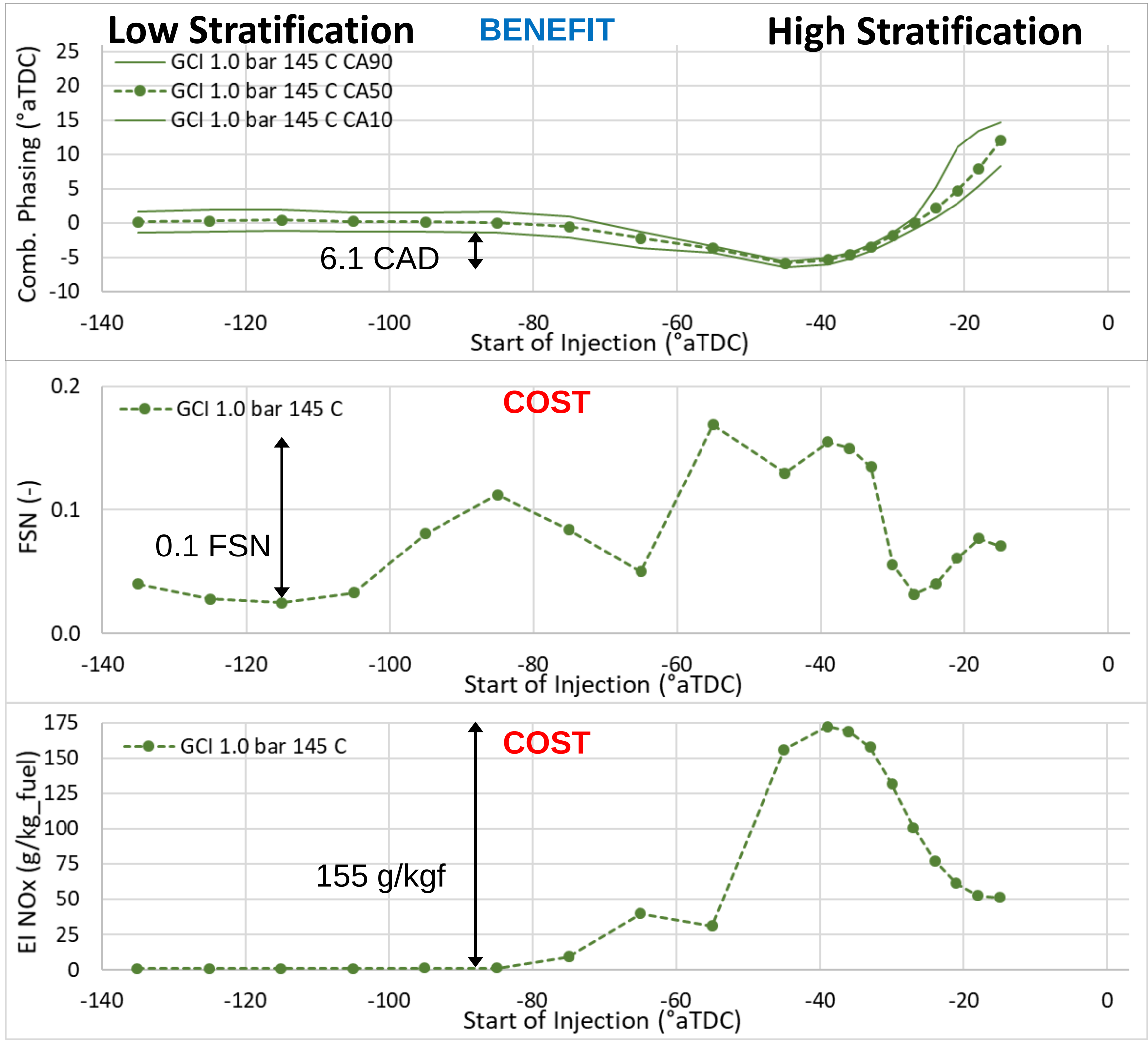
Fuel Properties Relevant for Improved Low-Load ACI Combustion

- **Lower HCCI ON/MON benefits:**
  - Reduces intake/residual heating requirements
  - Reduces HC/CO emissions
  - Increases low load/cold-start combustion stability
- **Phi-sensitivity combined w/ appropriate stratification:**
  - Allows moderate stratification to extend the low-load limit
  - Extends high-load limit by improving stability
  - Increased efficiency at moderate-to-high loads ⇒ less CA50 retard required to control knock
  - Less stratification required to gain benefits means less NOx & PM

Metric-1: ΔCA10 with SOI2



RD587 Gasoline
1200 RPM, ≈3.3 bar IMEPg
Φ = 0.3, 0% EGR
P_{in}, T_{in} = 1.0 bar, 145 °C
RP = 500 bar



Characteristics of High Load ACI Operation Approaches

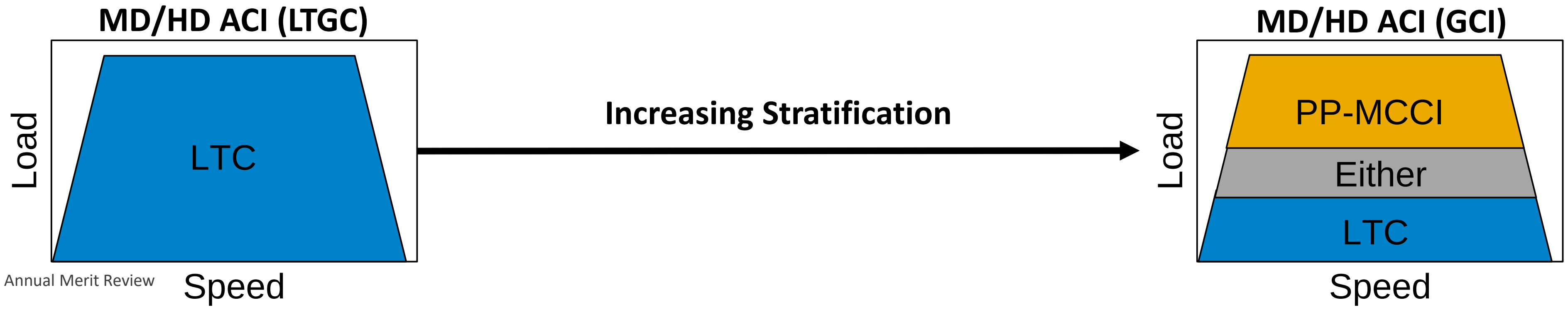
CDC: Conventional Diesel Comb.
LTC: Low Temperature Combustion
PP-MCCI: Partially-Premixed Mixing Controlled Compression Ignition

Low Stratification LTGC:

- **Near-zero engine-out PM/NOx emissions**
- **Injection-based combustion-phasing control similar to that at lower loads ⇒ Less control than GCI**
- **Peak load limited by:**
  - knock/stability limit for low-to-moderate boost or high speeds
  - O_2 availability due to high EGR for higher boost

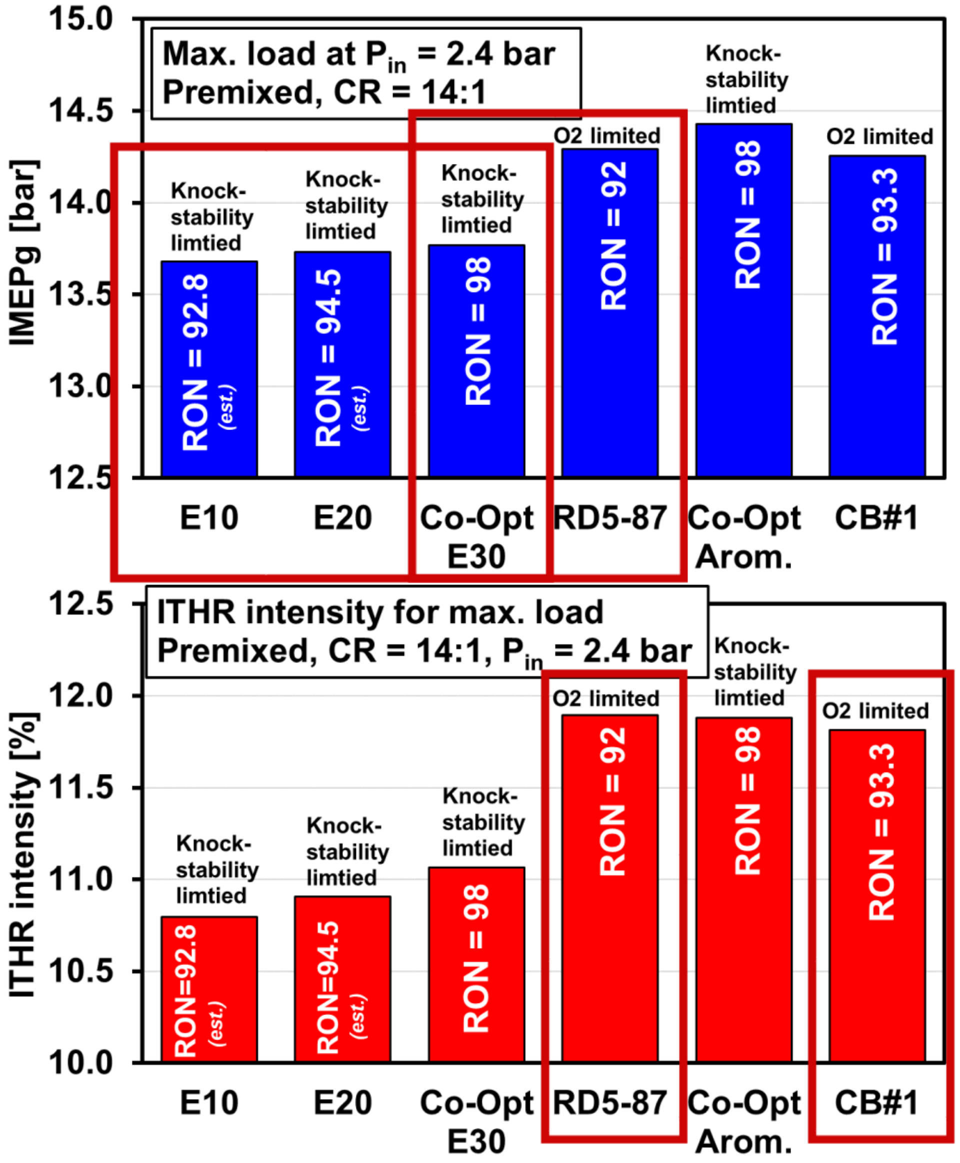
High Stratification GCI:

- **Lower PM/NOx than conventional diesel combustion (CDC), but aftertreatment still required**
- **Increased injection-based combustion phasing control**
- **Peak load limited by soot and NOx emissions (similar to CDC)**
  - Low sooting fuels extend maximum load
  - Low reactivity fuels (under boosted conditions) can maximize partially-premixed fueling, reducing soot and NOx



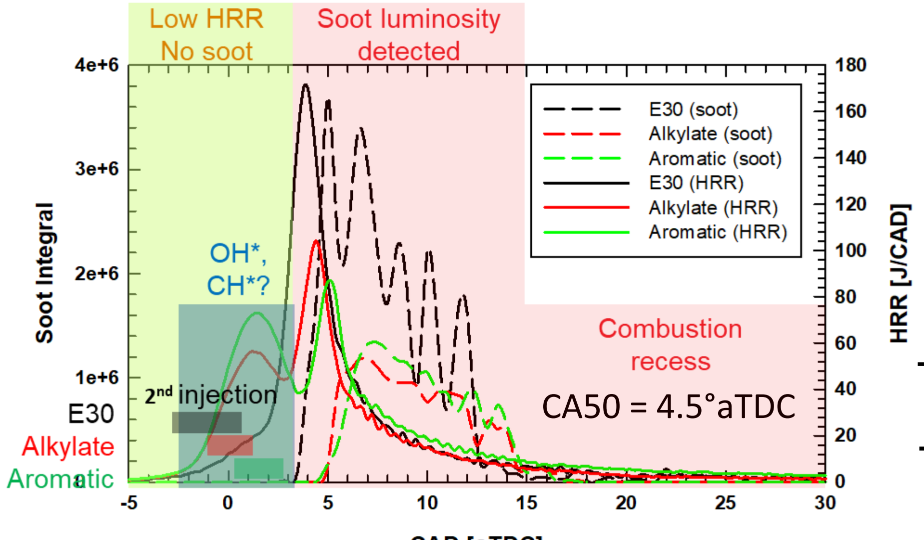
Extending Maximum Load of Low Stratification ACI Engines

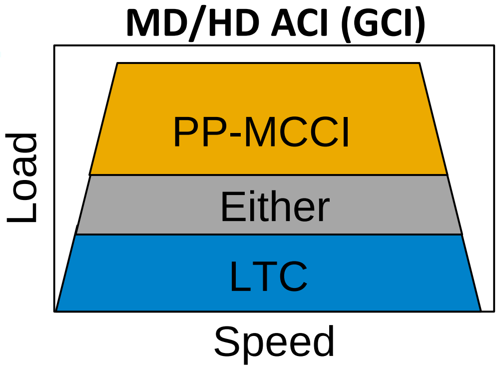
- **Max. load of well-mixed ACI (LTGC) is limited by two factors:**
  - **Knock-stability limit** ⇒ stable condition at which more fueling leads to knock & more retarded CA50 leads to instability & misfire
  - **O2 limit** ⇒ stable condition at which all the in-cylinder O2 is utilized (high EGR), so more fueling will not increase the load
- **Reduced reactivity does not necessarily extend the max. load ⇒ the fuel must provide good combustion stability**
  - Max. load is barely increased by increasing the ethanol content
  - Co-Opt E30 shows lower max. load than regular gasoline (RD5-87) in spite of its reduced reactivity
- **Fuels with higher intermediate-temperature heat release (ITHR) allow higher max. loads ⇒ ITHR allows more retarded CA50 with good stability, extending the load limit**
  - For conditions at which the load is knock-stability limited, there is a very strong correlation between ITHR intensity and max. load
  - For RD5-87 & CB#1, high ITHR allows load increase to the O2 limit



Reduced Sooting Propensity:

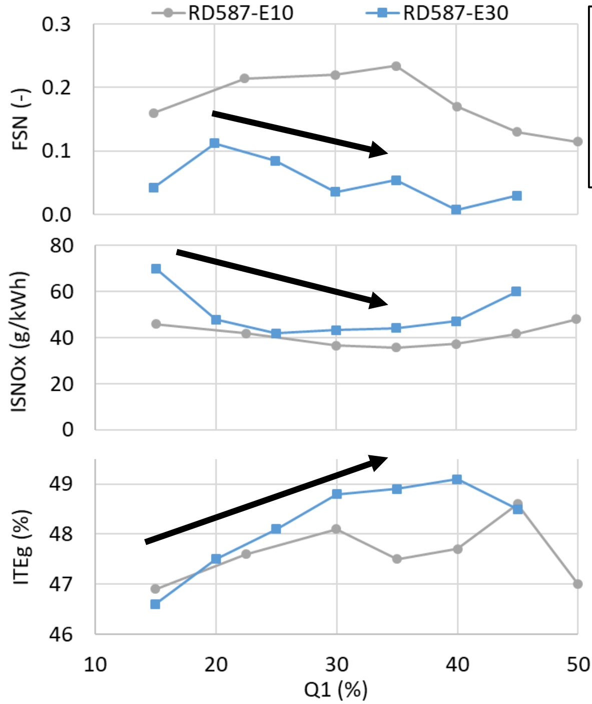
- E30 gasoline increased peak in-cylinder soot luminosity, but provided lowest engine-out soot emissions
- Oxygenated gasoline components can increase in-cylinder soot oxidation and reduce engine-out emissions





Utilization of Partially-Premixed Fraction:

- Increased PP fraction generally reduces soot/NOx and increases efficiency
- Further quantification of fuel property and chemical composition effects required



1200 RPM, ≈10 bar IMEPg
Φ = 0.43, 0% EGR
P_{in}, T_{in} = 1.5 bar, 60 °C
RP = 1000 bar
Late Pilot, Double Injection

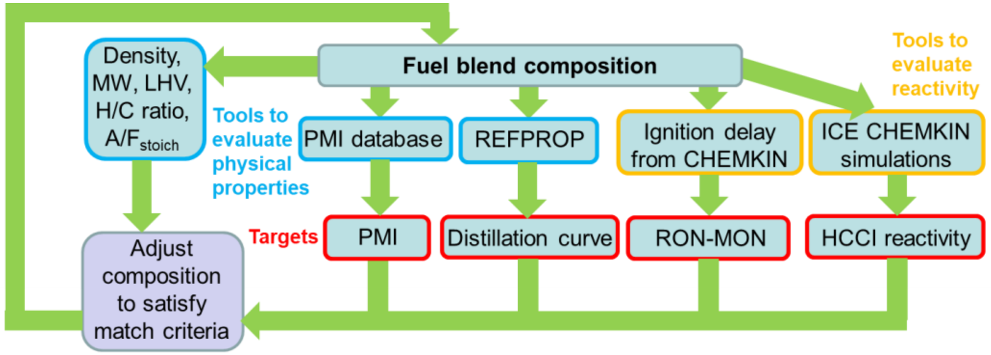
- **Developed a holistic methodology to design custom fuel blends suitable for both ACI / LTGC and modern spark-ignition (SI) engines.**
  - Custom fuel blends must accomplish several requirements.
  - Numerical models based on chemical kinetic simulations with a detailed mechanism are used to estimate the properties of a fuel blend ⇒ CHEMKIN simulations + LLNL Co-Opt mech. with Sandia LTGC engine geometry used to evaluate the fuel requirements.
  - Multi-component fuel blends are designed by adjusting the composition to accomplish the fuel requirements.

Fuel requirements

- High-load operation allowed
- Low intake heat required
- High RON
- High octane sensitivity
- High ϕ-sensitivity

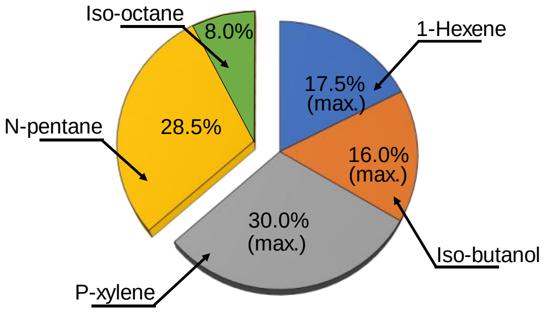
Numerical models based on CHEMKIN simulations

- LLNL detailed chemistry
- ICE reactor for HCCI reactivity
- Ignition delay calculations for RON and MON
- Evaluation of ϕ-sensitivity at engine-like cond.



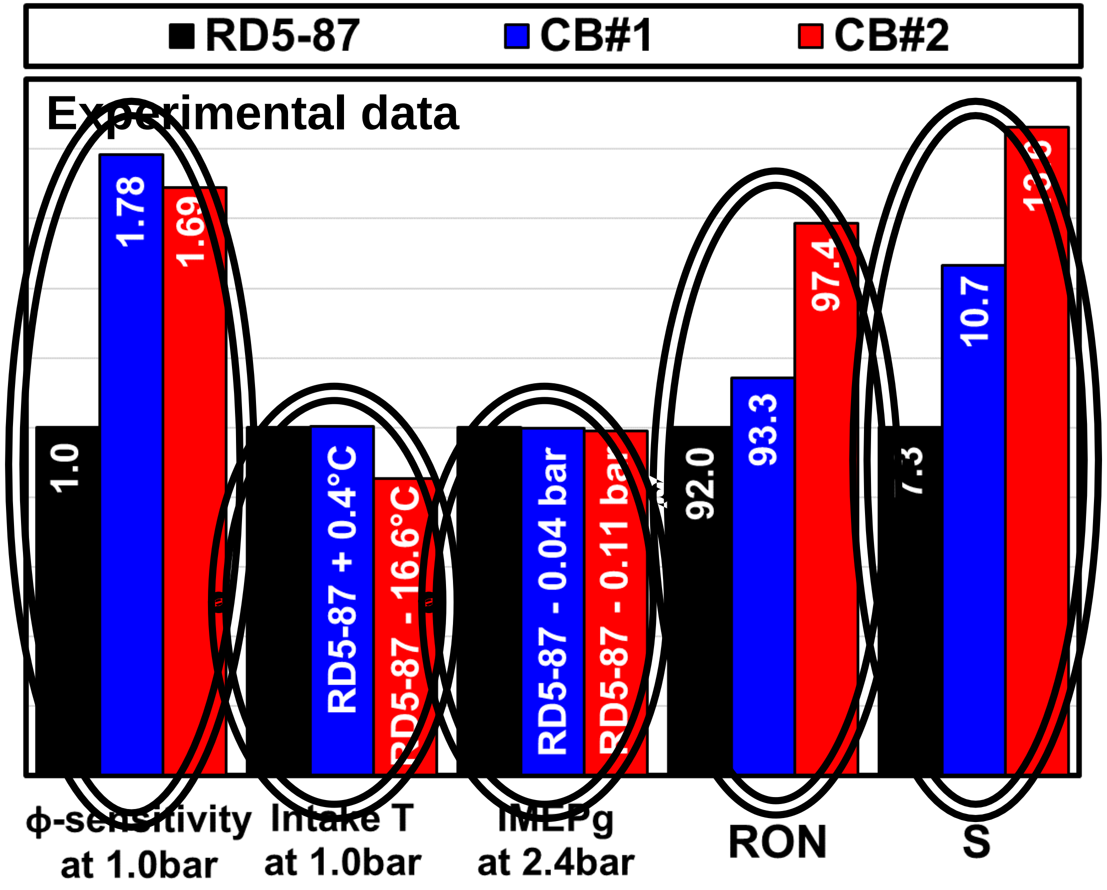
Blend formulation

E.g., CB#1



Previous Results Using this Approach: CB#1 and CB#2

- **Methodology used to design gasoline-like fuels with moderate (CB#1) and high (CB#2) HPF content.**
  - CB#1 ⇒ 12.4% isobutanol.
  - CB#2 ⇒ 40.0% furans.
- **Both CB#1 and CB#2 are significantly more ϕ–sensitive than reg. gasoline (RD5-87) at naturally aspirated cond.**
- **CB#1 is as easy to autoignite as RD5-87 at P_{in} = 1.0 bar. CB#2 makes autoignition easier that RD5-87 ⇒ CB#2 requires less intake heat.**
- **All fuels allow high load operation at boosted ACI cond.**
- **CB#1 and CB#2 improve the RON of RD5-87 by 1.3 and 5.4 units, respectively.**
- **CB#1 and CB#2 improve the octane sensitivity of RD5-87 by 3.4 and 6.3 units, respectively.**
- **CB#1 and CB#2 have been demonstrated to be better fuels than RD5-87 for ACI and modern SI engines.**



CB#1 tested at CR=14:1 / CB#2 tested at CR=16:1
ϕ-sensitivity, intake temperature at 1.0bar and IMEPg at 2.4bar were normalized to properly compare data at different CR.

Relevant Ongoing ACI Work

SNL

- **<u>FY21 Objective:</u> MD/HD ACI Task B: Developed a high HPF-content (40%) gasoline-range fuel and demonstrated that this fuel provided enhanced combustion-phasing control in a MD ACI engine with ultra-low NOx and PM, and the same high-load capability as regular gasoline**
- **A paper reporting the results of this study is in preparation:**
  D. Lopez Pintor and J. E. Dec, "Experimental evaluation of a gasoline-like fuel blend with high renewable content to simultaneously increase ϕ-sensitivity, RON and octane sensitivity," *Fuel Communications*, to be submitted
- **Determine if models based upon mixing-limited vaporization apply for injection at gasoline-ACI conditions for various fuels**

ANL

- **Characterize Supercharged HCCI biofuel blending characteristics and compare to RON, MON, and High Temp. HCCI blending**
- **At low load, evaluate fuel stratification effects on combustion phasing vs. emissions for Top Ten gasoline bioblendstocks**
- **Numerically and experimentally investigate fuel effects on the trade-offs between GCI efficiency and PM/PN emissions, including impingement effects**
- **Study the effects of RON 90 and RON 98 gasolines with different bioblendstocks on high load GCI**

NREL

- **Characterize phi-sensitivities of 2-pentanol, 3-pentanol and methyl pentanoate using a lean premixed charge with controlled stratification, and measure the impacts of fuel distillation T90 / PMI on soot emissions in a MD single cylinder engine**
- **Continue to build, optimize, and validate ACI engine ignition model based on Co-Optima kinetic model**

Future Work (Remaining Barriers)

SNL

- **Develop and demonstrate that a fuel with near-100% renewable content that works well with ACI (LTGC) over the load/speed map and in modern SI engines**
- **For this fuel $\Rightarrow$ demonstrate exhaust temperatures sufficiently high for an oxidation catalyst**
- **For LTGC using this new fuel for MD/HD applications, demonstrate the ability to meet future emissions standards with simpler aftertreatment than required by diesel engines**
- **Determine how distillation shape (high-boiling point temperature range) affects liquid concentration in transient developing sprays**

ANL

- **Use CFR HCCI fuel ratings to predict fuel performance in modern MD/HD ACI engines across the load range**
- **Impact of HPF blend-stocks (RON 90-98) on GCI high-load efficiency/emissions captured by CFD simulations and experiments**
- **Explore opportunities for engine/fuel optimization with low carbon liquid fuels in HD applications**
- **Evaluate fuel property impacts on efficiency, emissions, and combustion phasing control of high load high stratification GCI (ranging from early to late pilot) using engine experiments and simulations**

NREL

- **Demonstrate an oxygenated ACI blendstock with high phi-sensitivity mitigates the NO_X/PM tradeoff at extreme EGR rates required for relatively high-load, high-compression ratio ACI**
- **Develop ability to model ACI combustion for large numbers of biobased compounds on a large-scale screening process that would exceed the logistical limitations of engine testing**
- **Enhance the understanding of how fuel properties translate to ACI ignition behavior and guide the development of relevant fuel standards, particularly for oxygenates/biobased fuels**

Collaborators

- **Inside Co-Optima:**
  - LLNL (Pitz and Wagnon) – detailed chemical-kinetic mechanism and mechanism evaluation, and mechanism extension to selected oxygenates
  - SNL (Sjöberg and Kim) – evaluation of CB#1 for spark-ignition (SI) and boosted-SI combustion
  - SNL (Monroe, Davis, and George) – Prenol blending characteristics
  - PNNL (Dagle) – High iso-olefin blend testing
  - **And many others in the Co-Optima team…**
- **Outside Co-Optima:**
  - **Bosch** (NREL) – technical assistance with OEM injector performance and GDI injector for retrofit
  - **Caterpillar** (ANL) – Engine hardware and technical support
  - **CFR Engines Inc.** (ANL) – Technical support
  - **Convergent Science, Inc.** (ANL, SNL) – 3D CFD technical support, model advancement
  - **Delphi** (SNL) – ECN injectors
  - **Ford** (NREL) – technical assistance with combustion system and operating conditions
  - **Hyundai KEFICO** (SNL) – GDI Injectors
  - **Marathon Petroleum** (ANL) – Octane testing guidance, fuels potential
  - **Navistar** (ANL) – Engine hardware and technical support
  - **Prof. Bengt Johansson**, Chalmers University (ANL) – CFR HCCI ratings, gasoline HD PPC
  - **University of Connecticut** (ANL) – Mechanism reduction
  - **And many, many others…**

Co-Optima Publications and Presentations

1. D. Lopez Pintor, J. Dec, and G. Gentz, "Φ-Sensitivity for LTGC Engines: Understanding the Fundamentals and Tailoring Fuel Blends to Maximize This Property," *SAE Technical Paper 2019-01-0961*, Apr. 2019, doi: https://doi.org/10.4271/2019-01-0961

2. D. Lopez Pintor, G. Gentz, and J. E. Dec, "Experimental evaluation of a custom gasoline-like blend designed to simultaneously improve ϕ-sensitivity, RON and octane sensitivity," *SAE Int. J. Adv. & Curr. Prac. in Mobility*, vol. 2, no. 4, pp. 2196–2216, 2020, doi: https://doi.org/10.4271/2020-01-1136

3. D. Lopez Pintor and J. E. Dec, " Understanding the performance of OI in LTGC engines from beyond MON to beyond RON," *SAE WCX 2021, April 13-15 2021, virtual conference, paper no 21PFL-0439*

4. D. Lopez Pintor and J. E. Dec, "Can ϕ–sensitivity, RON and S of a fuel be increased simultaneously? A combined computational and experimental approach to a high-HPF-content fuel blend for ACI engines," *ACS Spring 2021, April 5-30 2021, virtual conference, paper no* 3554031

5. D. Lopez Pintor and J. E. Dec, "Experimental evaluation of a gasoline-like fuel blend with high renewable content to simultaneously increase ϕ-sensitivity, RON and octane sensitivity," *Fuel Communications*, to be submitted

6. K. Kalvakala, et al., "Effect of fuel composition and octane sensitivity on PAH and soot emissions of gasoline-butanol blend surrogates", 12th US National Combustion Meeting, College Station, USA, 2021.

7. K. Kalvakala, et al., "Effect of blending methanol, ethanol, and n-butanol with gasoline on PAHs and soot emissions", 9th International Conference on Fuel Science: From Production to Propulsion, Aachen, Germany, 2021.

Co-Optima Publications and Presentations (Cont.)

8. Waqas, M.U., et al., “Detection of Low Temperature Heat Release (LTHR) in the Standard Cooperative Fuel Research (CFR) Engine in both SI and HCCI Combustion Modes,” Fuel 256:115745, 2019, https://doi.org/10.1016/j.fuel.2019.115745

9. Waqas, M., et al., "Characterization of Low Temperature Reactions in the Standard Cooperative Fuel Research (CFR) Engine," SAE Int. J. Engines 12(5):597-610, 2019, https://doi.org/10.4271/03-12-05-0038 .

10. Pulpeiro-Gonzalez, J., et al. “Improvements to a CFR Engine Three Pressure Analysis GT-Power Model for HCCI and SI Conditions”, SAE Technical Paper 2019-32-0608, 2019.

11. Waqas, M., et al., “An experimental and numerical investigation to characterize the low-temperature heat release in stoichiometric and lean combustion”, PROCI 38(4):5673-5683, https://doi.org/10.1016/j.proci.2020.07.146 .

12. K. Kalvakala, et al., “Numerical analysis of fuel effects on advanced compression ignition using a cooperative fuel research engine computational fluid dynamics model”, Journal of Energy Resources Technology, Vol. 143(10), pp. 102304, 2021.

13. Waqas, M., et al., "Effect of Intake Temperature and Engine Speed on the Auto-Ignition Reactivity of the Fuels for HCCI Fuel Rating," SAE Technical Paper 2021-01-0510, 2021, https://doi.org/10.4271/2021-01-0510 .

14. Gainey, B., Hoth, A., Waqas, M., Lawler, B. et al., "High Temperature HCCI Critical Compression Ratio of the C1-C4 Alcohol Fuels," SAE Technical Paper 2021-01-0511, 2021, https://doi.org/10.4271/2021-01-0511 .

15. Karathanassis et al. "Comparative Investigation of Gasoline-like Surrogate Fuels using 3D Computed Tomography" ICLASS 2021

16. Hwang et al. "Spatio-temporal identification of plume dynamics by 3D computed tomography using engine combustion network spray G injector and various fuels," Fuel 280:118359, 2020

Summary

- Gasoline ACI fuels/engines allow for simultaneous reductions in PM, NOx, and lifecycle GHG emissions
- Gasoline ACI increases efficiency compared to diesel, and for LTGC, NOx & PM are up to 1000 times lower
- Full-time kinetically controlled ACI engines can require less EGR dilution at full load when using high RON, high OS fuels
- RON, MON, and OI are poor metrics for ACI reactivity, especially at low load, under lean combustion
- Lean HCCI fuel ratings on the well-distributed CFR octane engine correlate very well with low load ACI engine performance
- Oxygenated fuel components reduce engine-out soot emissions in highly stratified ACI engines, especially at medium-high load where MCCI combustion is employed
- A new ACI fuel design methodology based on chemical kinetic simulations has been demonstrated to give improved performance for LTGC-ACI and to have a higher RON and Octane-Sensitivity for better performance in boosted SI engines.

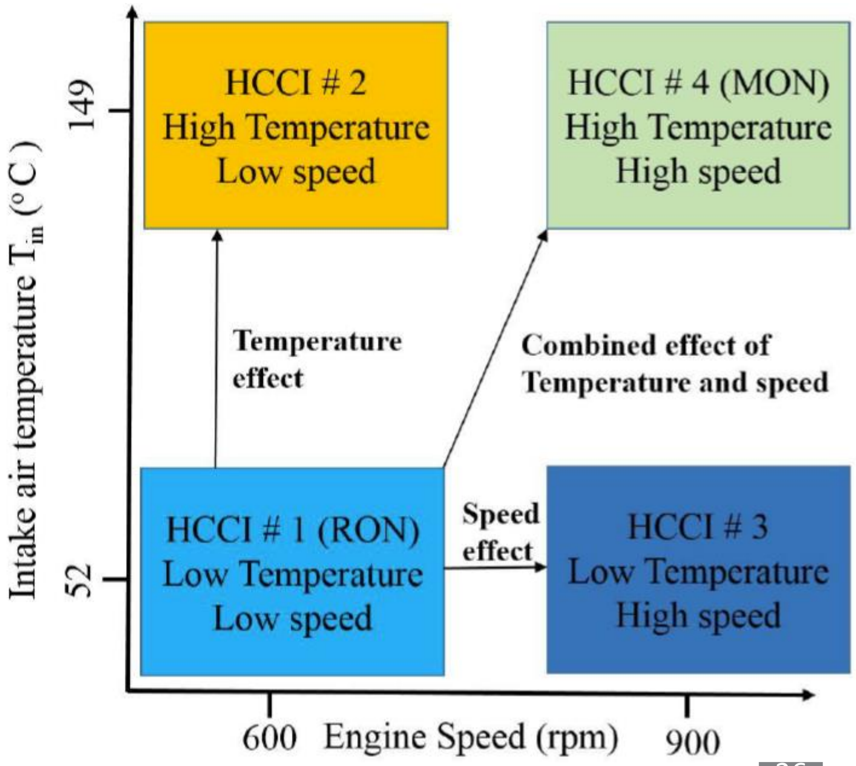
Technical Back-Up Slides

(Include this “divider” slide if you are including back-up technical slides **[maximum of five]**. These back-up technical slides will be available for your presentation and will be included in the USB drive and Web PDF files released to the public.)

CFR Engine for HCCI Fuel Ratings for Low Load MON-like ACI

- **CFR HCCI combustion demonstrated: Najt and Foster, SAE 830264**
- **CFR motored autoignition studies: Leppard, SAE 892081; Boehman group (2007-)**
- **CFR HCCI fuel ratings: Lund-Chevron HCCI Number, SAE 2014-01-2667**
  - Similar speeds/intake temperatures to IFP's SI "Four-Octane-Number Method", SAE 780080
- **Test methodology:**
  - Adjust compression ratio (CR) to achieve desired combustion phasing (CA50 = 3 °aTDC)
- **Minor Engine Modifications Required:**
  - Lean (λ = 3) excess air ratio control
  - Combustion phasing detection
- **Why based off CFR octane engine?**
  - >2,000 units in operation worldwide (>700 in N. America)
  - Variable CR (4-18:1) allows wide range of fuel ratings

Need to identify the most relevant CFR test conditions for modern ACI (HCCI) engines

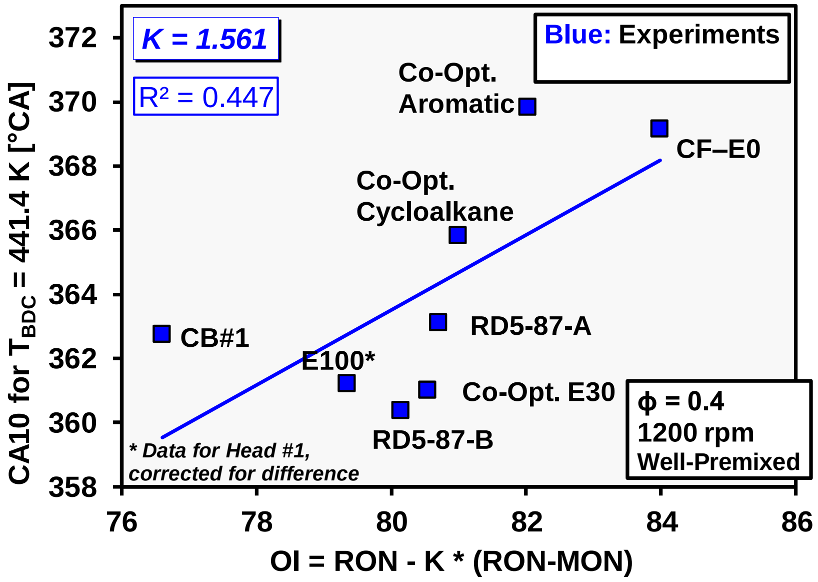


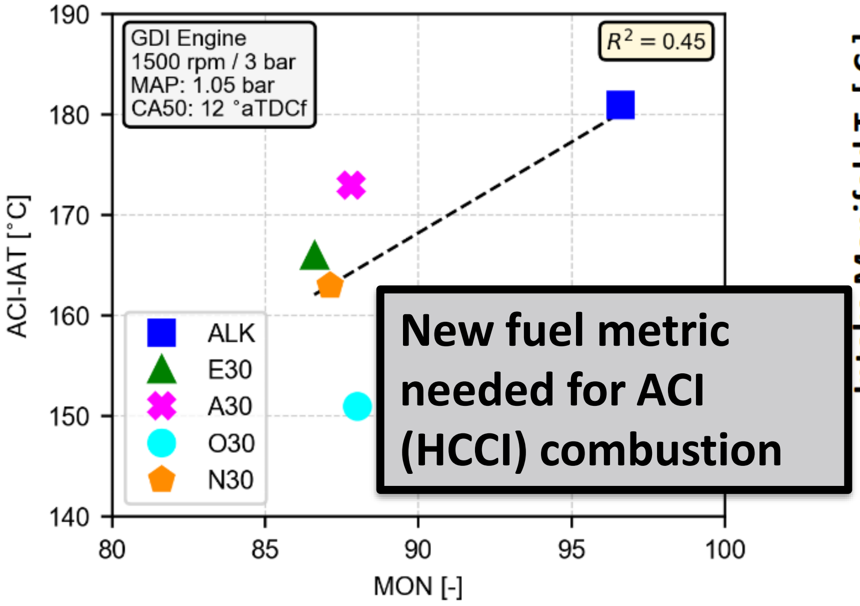
Waqas, PhD thesis, KAUST (2018)

Poor Correlation of Octane Ratings with HCCI Reactivity

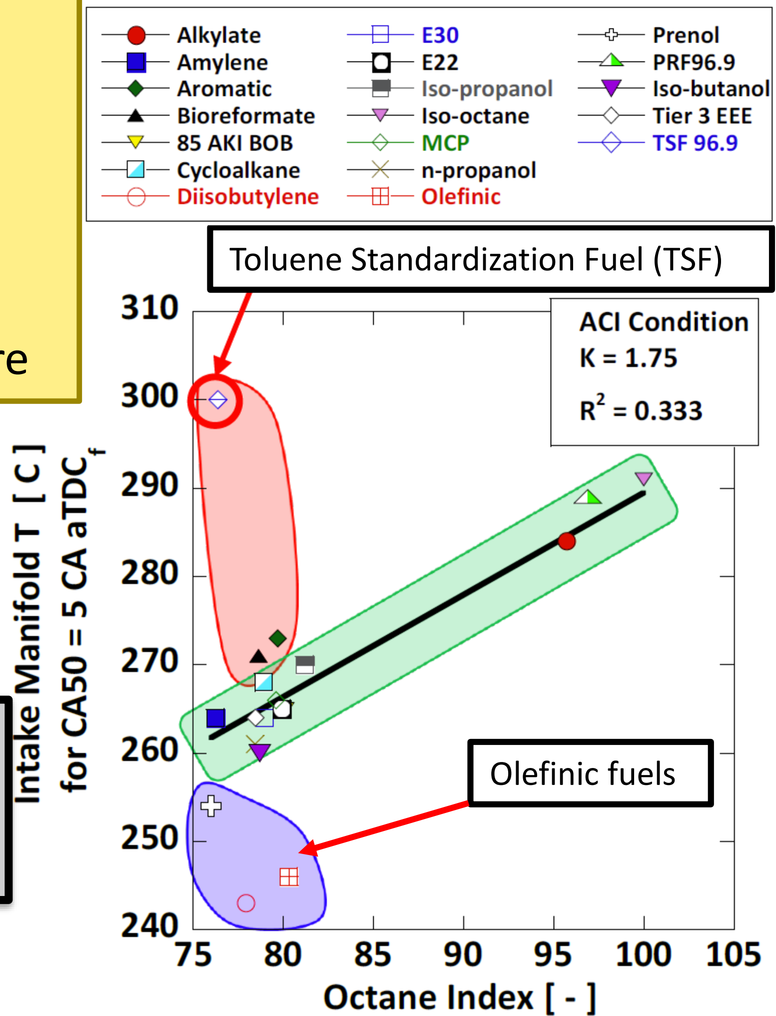
- **Modern Co-Optima engines at low load HCCI with MON-like P-T cylinder conditions**
- **Fuels with varied RON, MON, and chemical composition**

Dec, SNL	Rockstroh, ANL	Szybist, ORNL
1200 RPM	1500 RPM	2000 RPM
P_{in} = 1.0 bar (abs)	P_{in} = 1.05 bar (abs)	P_{in} = 1.0 bar (abs)
T_{in} = 154 °C	T_{in} = 150-180 °C	T_{in} = 154 °C
λ = 2.5	λ = 3.3	λ = 3.3
CR = 14:1	CR = 15.3:1	CR = 13.7:1
MD Diesel Architecture	LD GDI Architecture	LD GDI Architecture



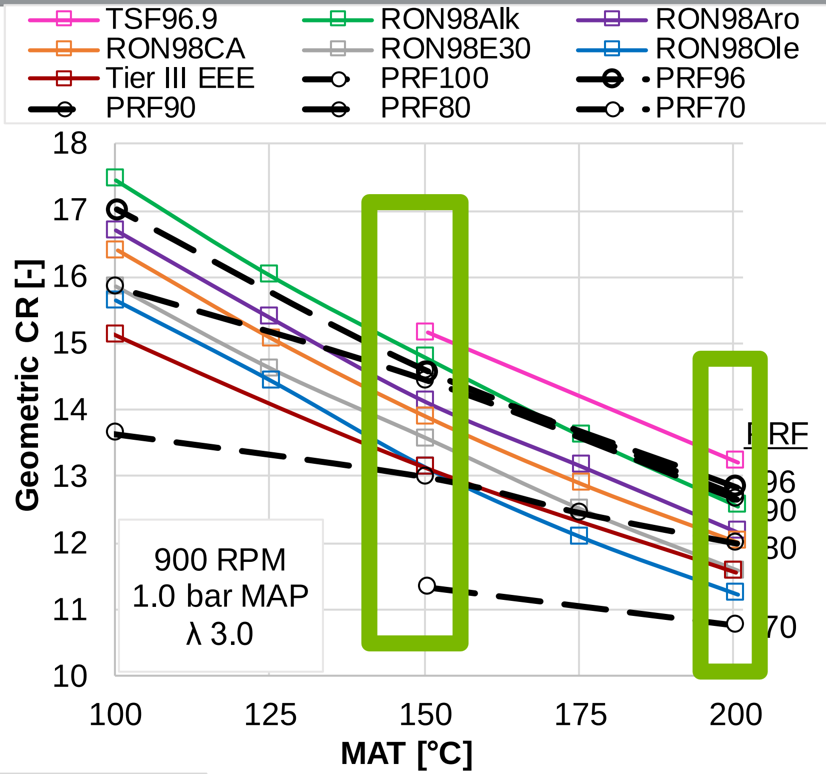


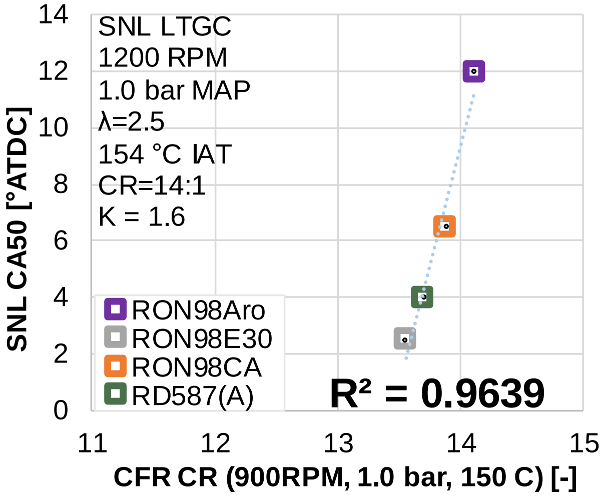
New fuel metric needed for ACI (HCCI) combustion

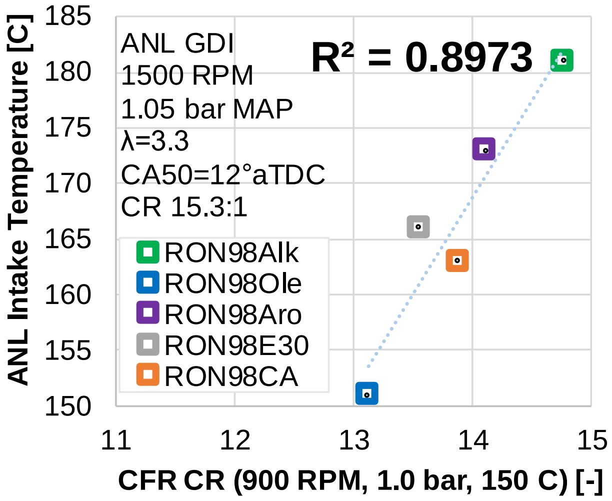


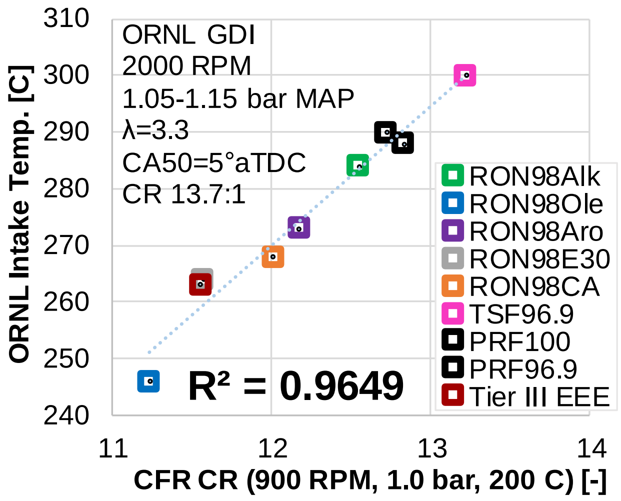
Co-Optima CFR HCCI Fuel Ratings for Low Load ACI

- Sweep parameters of the Lund-Chevron HCCI Number Method
- CA50 range: TDC to 6 °aTDC, **3 °aTDC most stable**
- Lambda range: 2 to 5, **λ = 3 most stable**
- Intake pressure: 1.0 to 1.3 bar, **1.0 bar best correlation**
- Intake temperature: 30 to 200 °C, **150-200 °C higher octane**
- Engine speed: 600 vs. 900 RPM?
  - 900 RPM: Closer to modern engine speeds
  - 600 RPM: More time allows higher octane range, less fuel req.









High temperature HCCI test better predictor than MON or OI

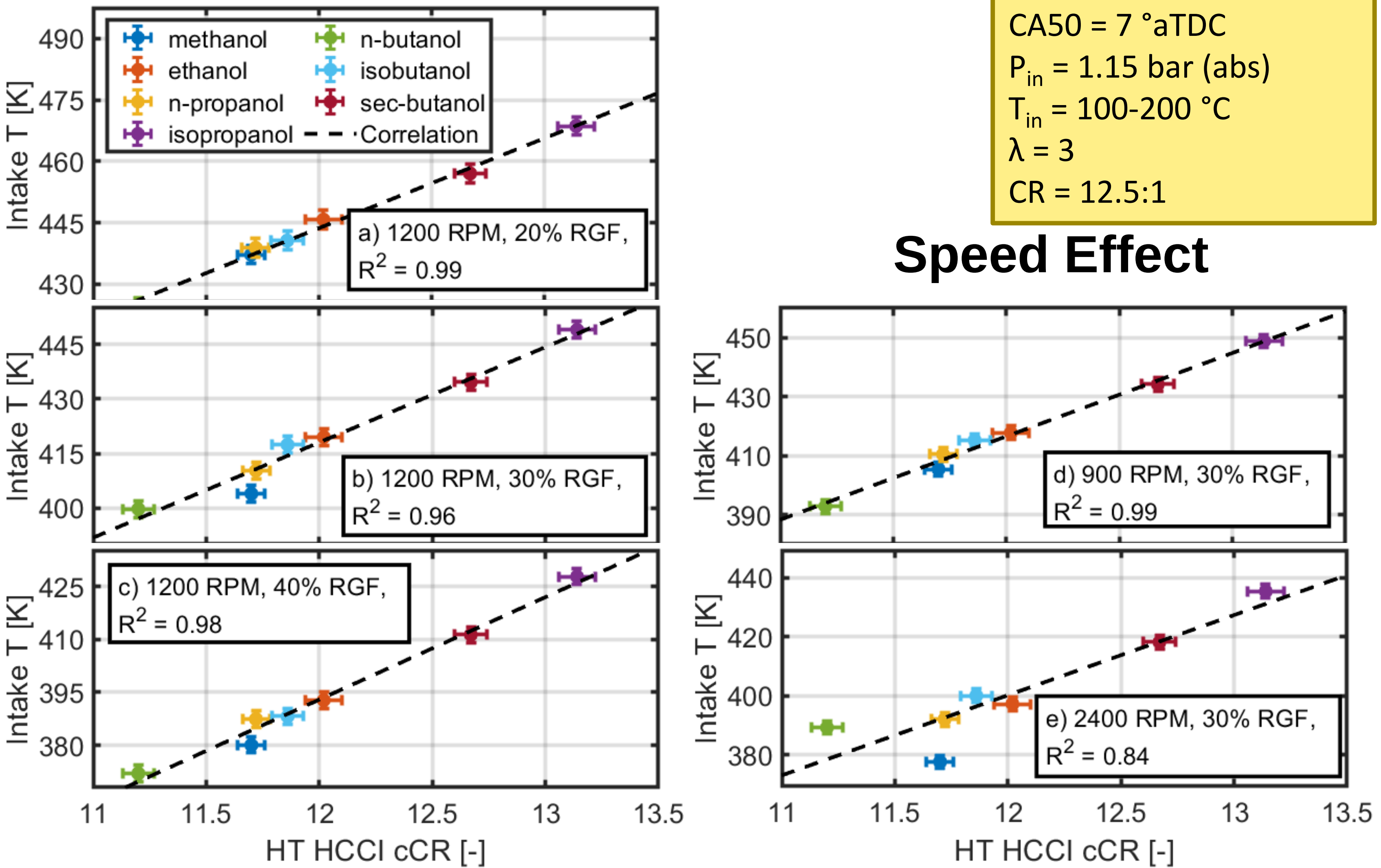
Clemson LD GDI HCCI Engine Data

- C1-C4 neat alcohols
- Effect of practical high residual fraction HCCI modes
- Reduced correlation at 2400 RPM

Use of high residual strategies did not reduce applicability of CFR HCCI test at low speeds

Exhaust Rebreathe Effect

Speed Effect



Clemson Engine

20-40% Residuals

900-2400 RPM

CA50 = 7 °aTDC

P_{in} = 1.15 bar (abs)

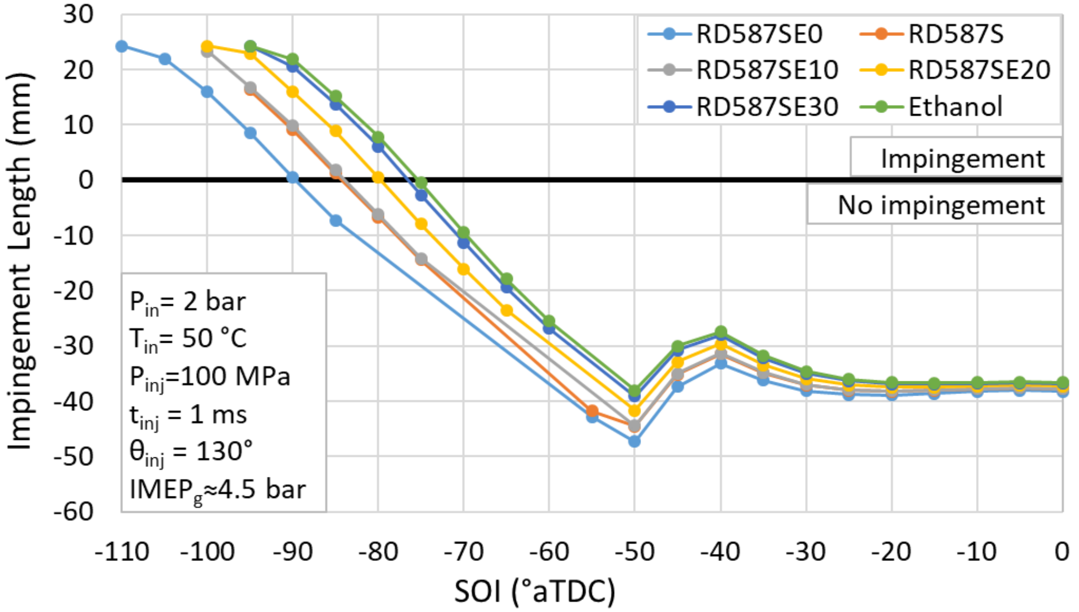
T_{in} = 100-200 °C

λ = 3

CR = 12.5:1

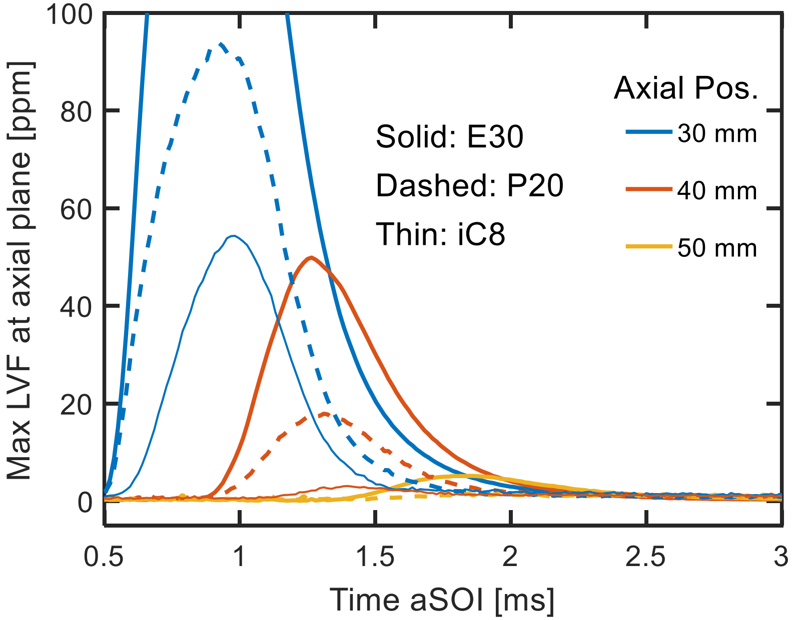
Spray Impingement On-Going Work

- 1D spray simulations (DICOM) suggest non-linear effect of ethanol concentration on likelihood of fuel impingement
- Start of injection (SOI) of impingement retards significantly for E0 to E30, but little difference between E30 and E100



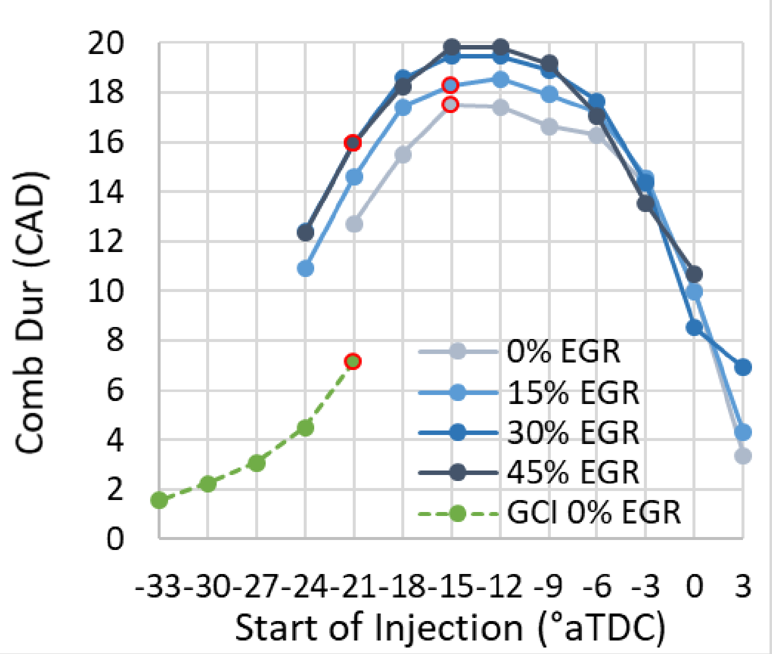
- Spray visualizations from a multi-hole GDI injector agree that E30 has higher liquid volume fraction (LVF) farther from the injector and longer than for E0 gasoline surrogates

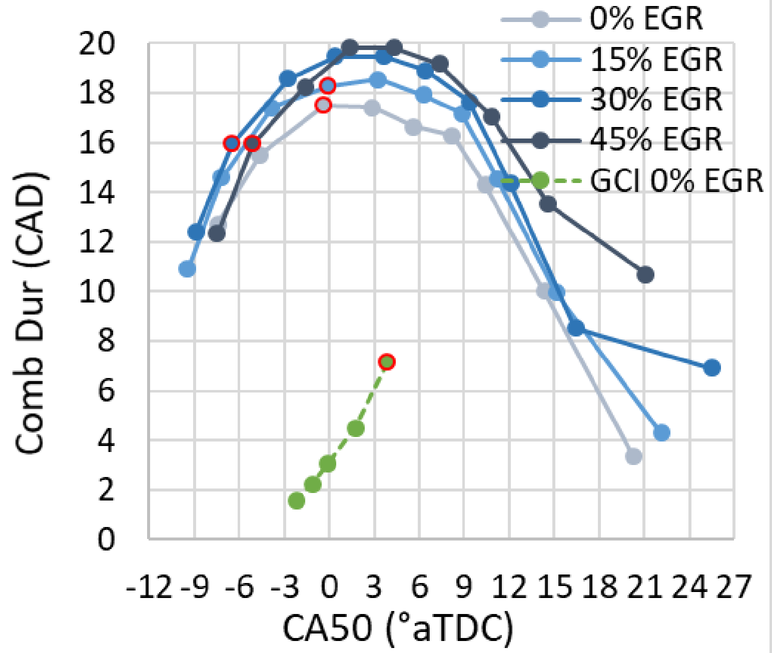
- As a result, many Co-Optima ACI engine experimentalists modified injection strategies based on fuel properties and engine operating conditions to avoid fuel impingement
  - Narrower nozzle inclusion angle (120-130°)
  - Multiple short-pulsed injections



COMBUSTION CHARACTERISTICS

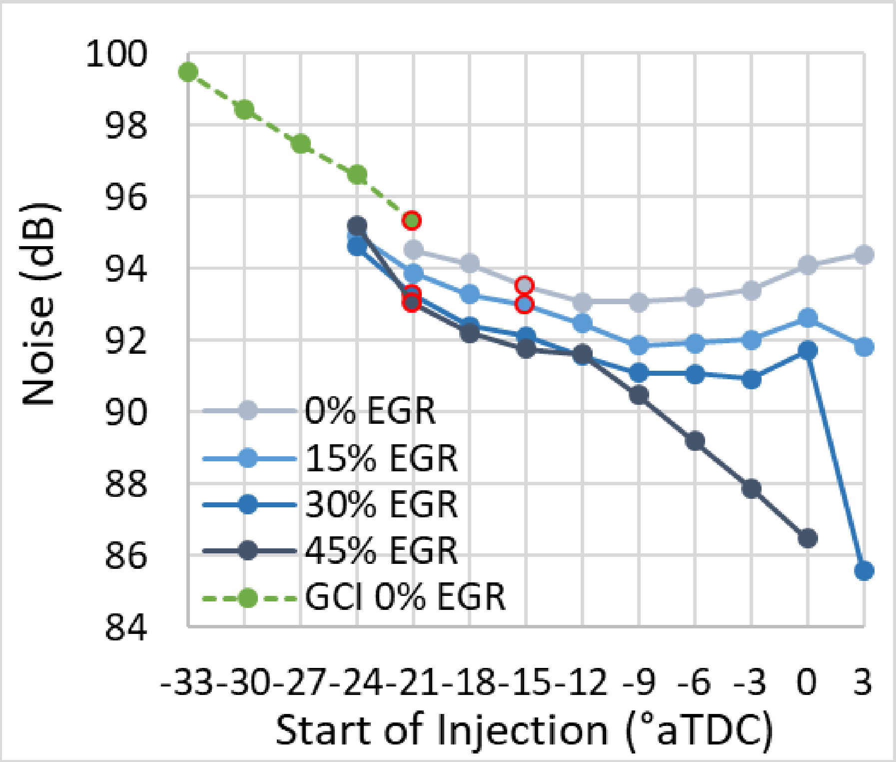
- 87 AKI E10 gasoline (RD587) had a significantly longer ignition delay than diesel, even in the diesel baseline test with 45% EGR
- Longer ignition delay allowed for more fuel and air premixing
- More premixing allowed for significantly shorter combustion durations, increasing constant volume combustion, but also increasing the combustion noise level
- Note: Gasoline tests were performed at **500 bar** injection pressure, while diesel tests at **1250 bar**





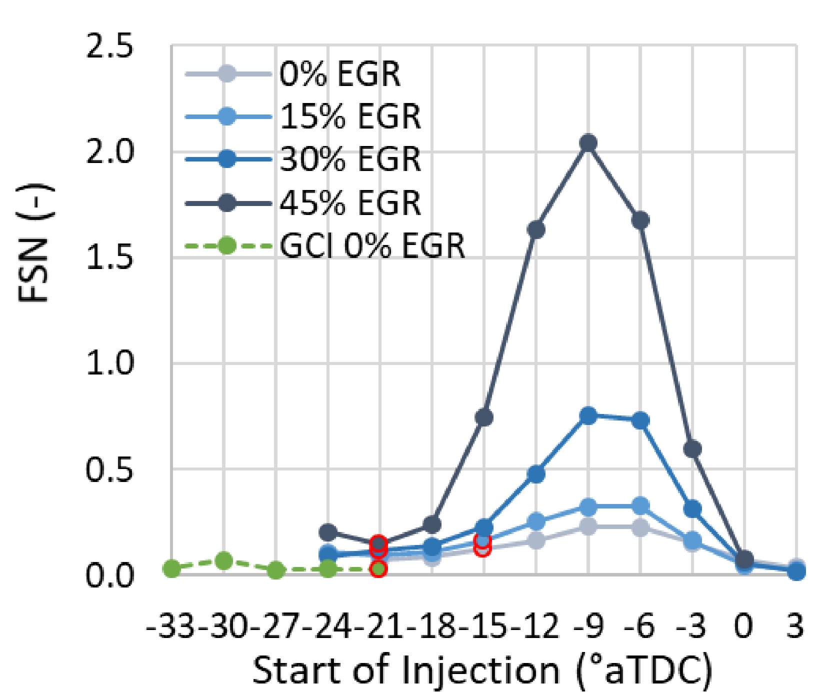
COMBUSTION CHARACTERISTICS

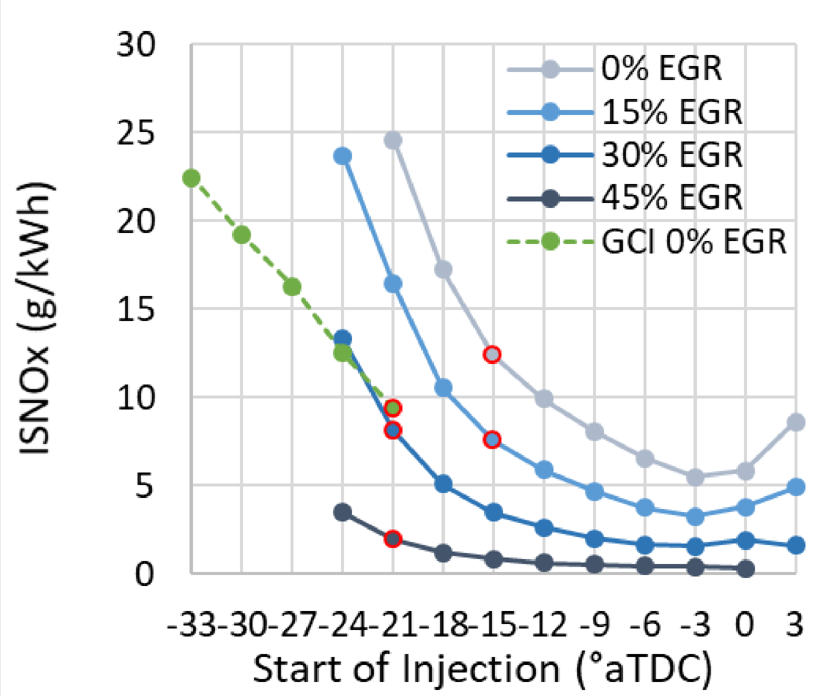
- Diesel baseline SOI sweeps were limited to 95 dB combustion noise level
- The combustion noise limit was increased to 100 dB with gasoline to capture a wider injection timing range
- For the same SOI, combustion noise was higher with gasoline than diesel fuel
- However, combustion noise could have been significantly reduced by a double-injection strategy
- At this time, a simple “apples-to-apples” comparison was desired using single injections with both fuels



EMISSIONS

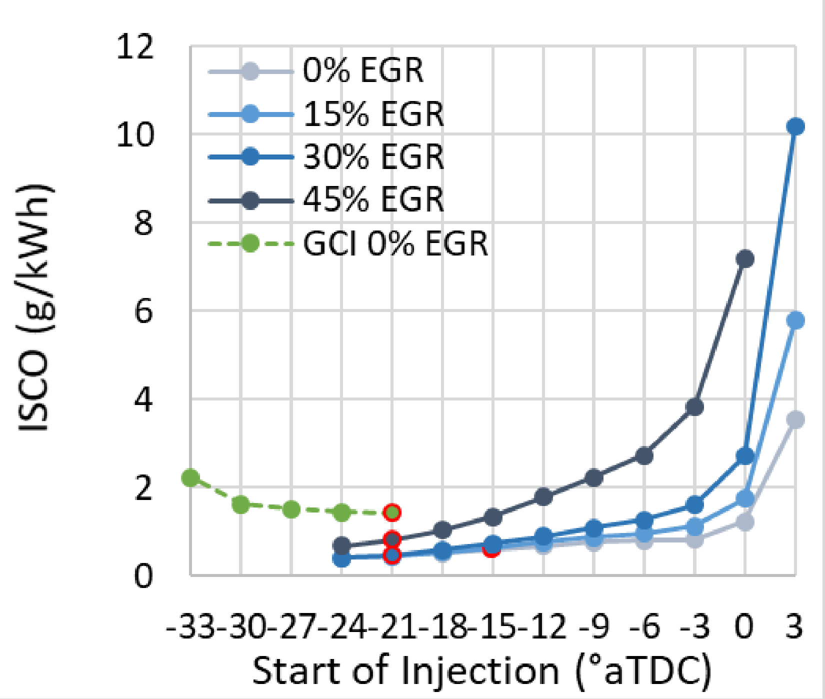
- At the SOIs of highest ITE (red circles), diesel had approximately 0.1 FSN, while GCI had 0.025 FSN
  - Gasoline showed a 75% reduction in FSN
  - Reduced FSN likely due to longer ignition delay and premixing time
- Comparing the SOIs of highest ITE for diesel and gasoline (with 0% EGR), GCI showed a 25% reduction in NOx emissions
  - Diesel with 30% EGR achieved similar NOx emissions as the GCI SOI sweep without EGR
  - Future GCI testing with EGR will likely further reduce NOx emissions

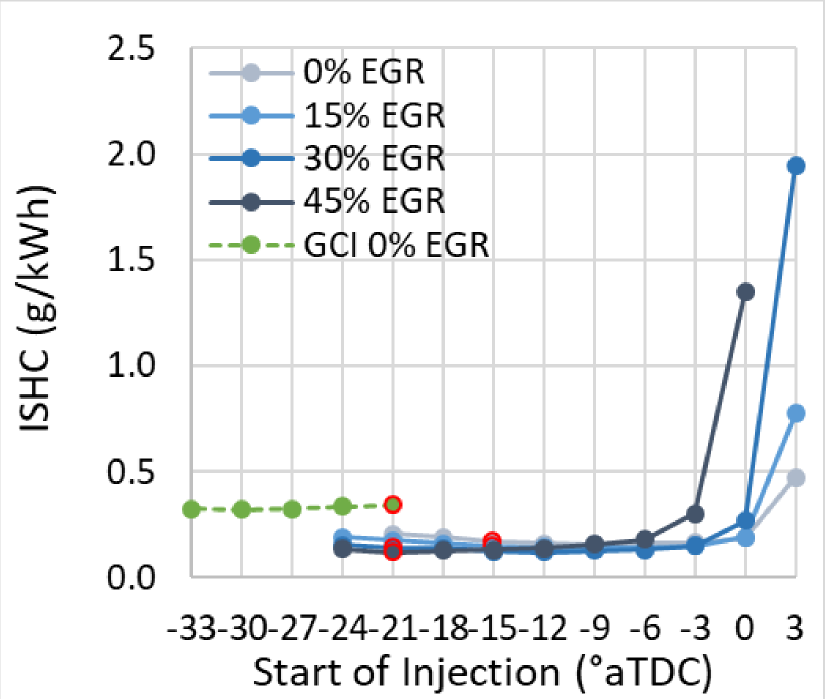




EMISSIONS

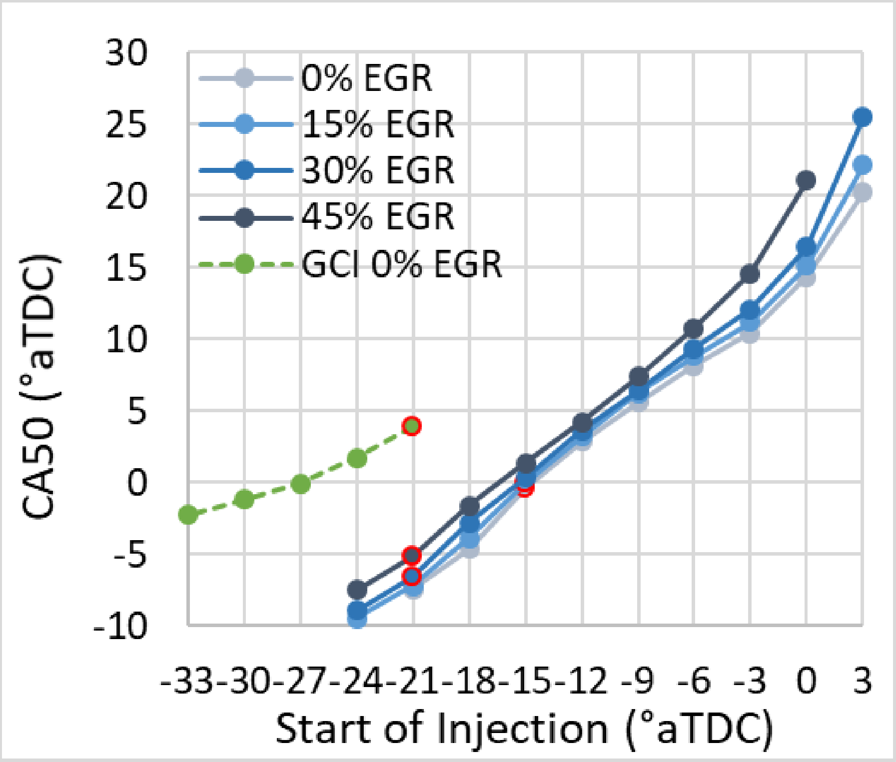
- CO and THC emissions were slightly higher for GCI than the 0% EGR diesel SOI sweep
- However, the increase was minor (equivalent to the CO increase with 45% EGR) and overall CO and THC emissions should be managed by an oxidation catalyst





COMBUSTION PHASING CONTROL

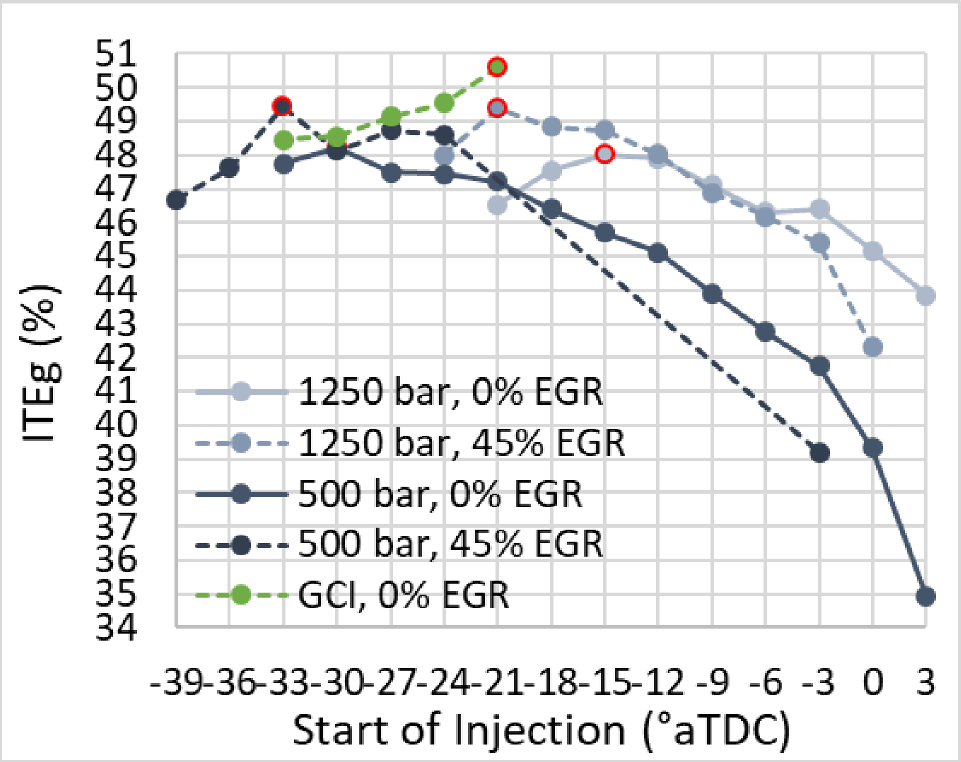
- With diesel fuel, combustion phasing (CA50) changed linearly with injection timing, which makes combustion phasing control with injection timing quite easy to achieve
- With gasoline, CA50 could still easily be controlled by injection timing
- However, the SOI vs. CA50 plot shows changes in slope at the earlier SOIs
- Future gasoline testing will include the late part of the SOI sweep until the misfiring limit to evaluate SOI vs. CA50 linearity



EFFECTS OF RAIL PRESSURE

Can diesel perform as well as gasoline at the same rail pressure with increased EGR and mixing time (injection advance)?

- At 500 bar, high ITE can be observed at earlier SOI than 1250 bar RP
  - Even earlier than GCI
- GCI still showed 1 percentage point ITE higher than diesel LTC



SOOT-NOX TRADE-OFF COMPARISON

- Comparing 0% EGR tests, highest ITE (red) SOIs moved towards origin with increased diesel RP and again with gasoline
- With 45% EGR, NOx is significantly reduced for diesel
- Similar improvements to NOx emissions expected for GCI with use of small amounts of EGR