Co-Optimization of
Fuels & Engines

better fuels | better vehicles | sooner

US DOE Co-Optimization of Fuels and Engines (Co-Optima) Initiative: Recent progress on advanced compression-ignition

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Impact of Future Regulations on Engine Technology

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Co-Optima research is structured around two guiding hypotheses on engines and fuels

Central Engine Hypothesis

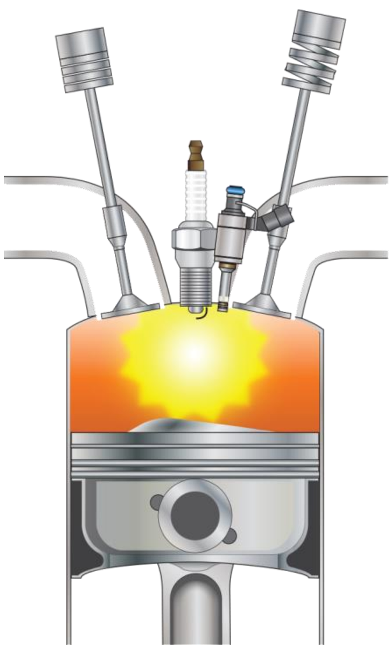
There are engine architectures and strategies that provide higher thermodynamic efficiencies than are available from modern internal combustion engines; new fuels are required to maximize efficiency and operability across a wide speed / load range

Central Fuel Hypothesis

If we identify target values for the critical fuel properties that maximize efficiency and emissions performance for a given engine architecture, then fuels that have properties with those values (regardless of chemical composition) will provide comparable performance

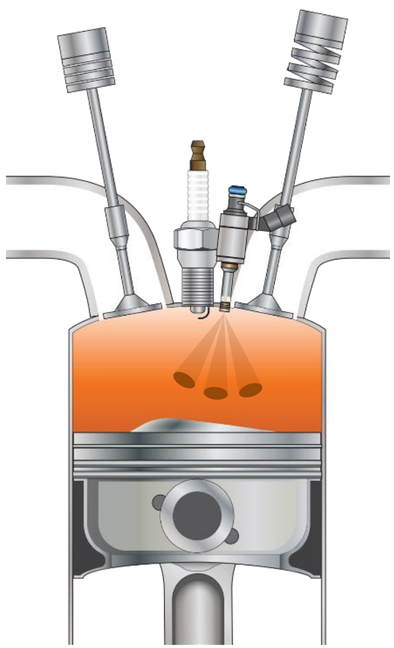
Co-Optima engine & fuel research proceeds along two parallel application/mode tracks

Light-Duty



Boosted SI

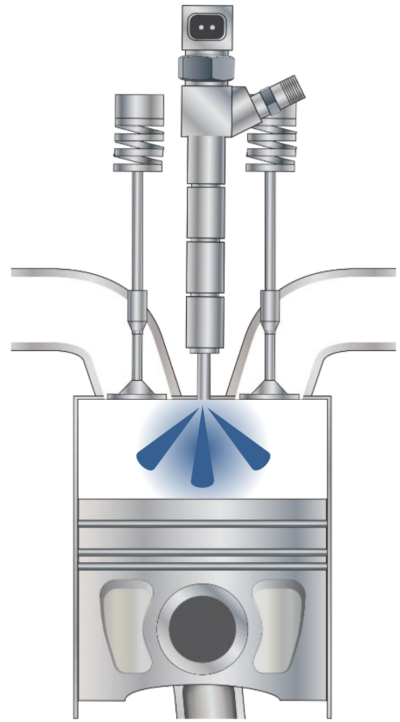
Near-term



Multi-mode SI / ACI

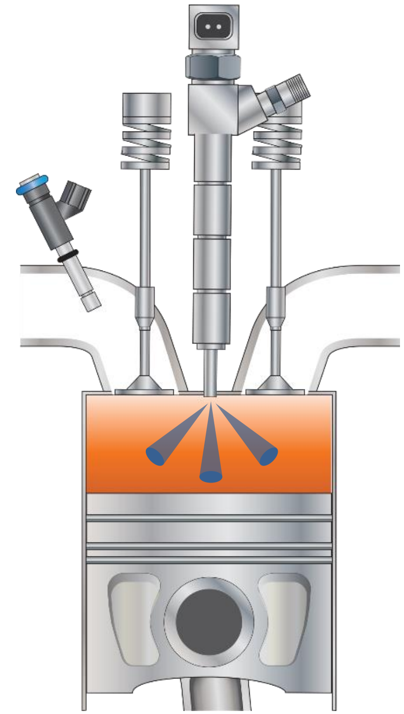
Mid-term

Medium and Heavy-Duty



Mixing Controlled

Near-term



Kinetically Controlled

Longer-term

Co-Optima's application/mode tracks use merit functions to guide fuel & engine research

- Merit functions quantify engine & fuel property effects to guide engine & fuel R&D for each combustion approach
  - Boosted SI, multimode ACI, mixing-controlled CI, etc.
- Boosted SI merit function quantifies engine & fuel effects as percentage-point decrease in fuel consumption
  - Actively updated – recently: adjusted many coefficients; removed LSPI term (too uncertain); added cold-start term

$$Merit\,[\Delta\%] = \frac{(RON_{mix} - 91)}{1.6} - K\frac{(S_{mix} - 8)}{1.6}$$

$$+\frac{0.085[ON/kJ/kg]\cdot((HoV_{mix}/(AFR_{mix}+1)) - (415[kJ/kg]/(14.0[-]+1)))}{1.6}$$

$$+\frac{((HoV_{mix}/(AFR_{mix}+1)) - (415[kJ/kg]/(14.0[-]+1)))}{15.2} + \frac{(S_{L\,mix} - 46[cm/s])}{5.4}$$

$$-H\left(PMI_{mix} - 1.6\right)\left[0.7 + 0.5(PMI_{mix} - 1.4)\right] + 0.008\,^{\circ}C^{-1}\left(T_{c,90,conv} - T_{c,90,mix}\right)$$

Overview: Co-Optima Engine & Fuel Tasks for Advanced Compression Ignition (ACI)

Co-Optima ACI projects use both gasoline-like & diesel-like fuels

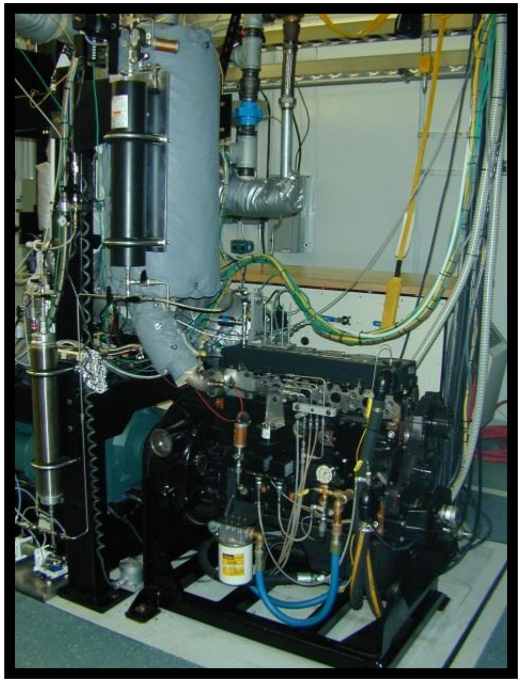
- **ACI approaches using "boosted-SI" gasoline-like fuels**
  - Low-Temperature Gasoline Combustion (LTGC): pre-vaporized, premixed
    Sandia National Laboratories, John Dec
  - Gasoline Compression Ignition (GCI): 2^{nd} injection near TDC, stratified
    Argonne National Laboratory, Steve Ciatti
- **ACI approaches using diesel-like or dual-fuel with gasoline-like fuel**
  - Development of Stratified ACI: Reactivity-Controlled CI (RCCI)
    Oak Ridge National Lab., Scott Curran (multi-cylinder LD metal engine)
  - Fundamental Processes of Stratified ACI: RCCI, "optical" fuels
    Sandia National Labs., Mark Musculus (single-cyl. HD optical engine)

    Collaborative Effort
  - Mixing-Controlled CI Combustion (MCCI): ducted fuel injection (diesel)
    Sandia National Laboratories, Chuck Mueller
- **ACI merit function development**
  - ANL/ NREL/ ORNL/ SNL – Andrew Ickes (lead, ANL)

LTGC (SNL, Dec): Determine optimal properties to allow both LTGC and boosted SI, evaluate fuel metrics

- **Motivation:** LTGC provides efficiencies at or above those of diesel engines
  - Substantial reduction in fuel consumption vs. SI $\Rightarrow$ use light-distillates efficiently for more effective use of crude oil supplies
  - Ultra-low NOx and PM minimize aftertreatment and cost
- **Project Objective:** Determine / develop optimal LTGC fuel
  - **FY17 Objectives:** Investigate the performance of "booted-SI" fuels for LTGC and the validity of the Central Fuel Hypothesis
    - $\Rightarrow$ Are RON & MON sufficient metrics for LTGC?
    - $\Rightarrow$ Also provide well-characterized data for kinetic model development
- **Approach:** Use Sandia single-cylinder LTGC engine
  - Well-controlled experiments for premixed fueling (also G-DI, PFS fueling, though not used here)
  - Work w/ Co-Optima Fuel Properties Team & Boosted-SI engine researchers to develop fuel test matrix

LTGC Research Engine



LTGC (SNL, Dec): at ϕ = 0.4, identical RON & S fuels have diverging CA50; alternative "O_2" OI works well

Accomplishments – Fuel Reactivity

- Designed fuel test matrix with five fuels with RON ≈ 98, four with S ≈ 10.5, one with S ≈ 1

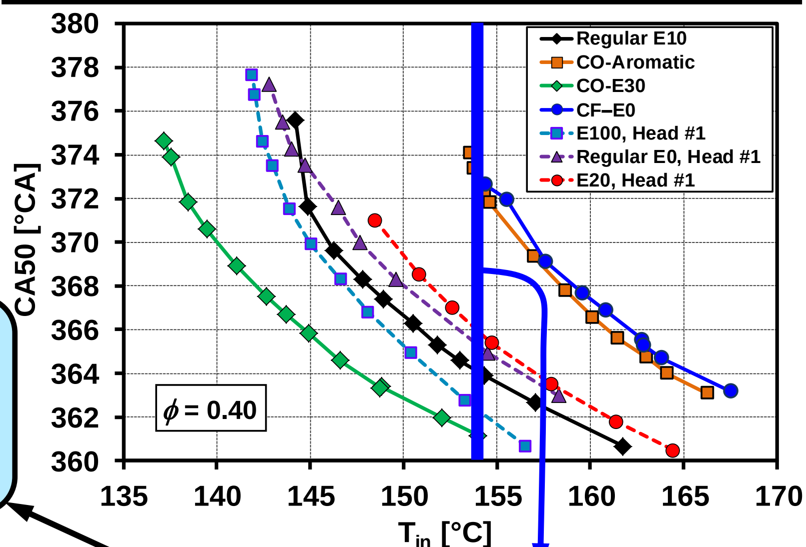
Co-Optima Core Fuels	Alkylate	E30	Aromatic	Olefin	Cyclo-alkane
RON	98.0	97.4	98.1	98.2	98.0
MON	96.6	86.6	87.8	88.0	87.1
S	1.4	10.8	10.3	10.2	10.9
Aromatics	0.7	13.8	39.8	13.4	33.2
n+i-Paraffin	98.1	40.5	46.2	56.4	40.6
Cycloalkane	0.0	7.0	8.0	2.9	24.2
Olefins	0.1	6.0	4.5	26.5	1.6
Ethanol	0.0	30.4	0.0	0.0	0.0

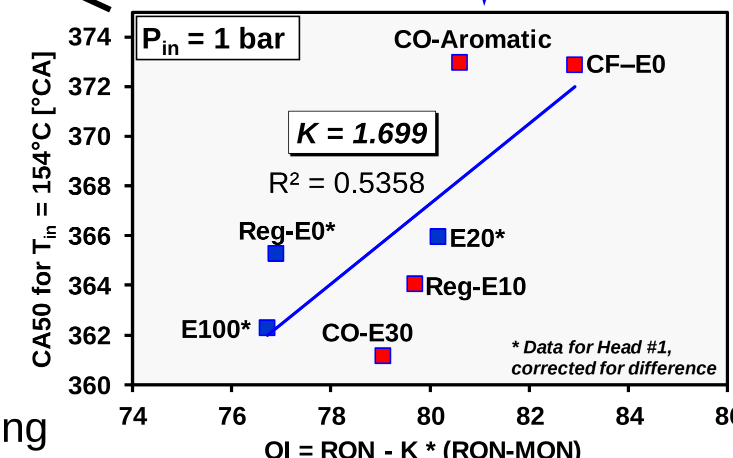
LTGC (SNL, Dec): at ϕ = 0.4, identical RON & S fuels have diverging CA50; alternative "O_2" OI works well

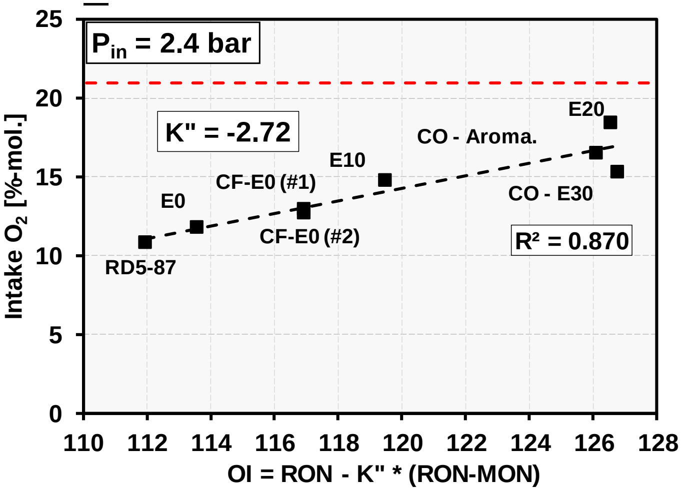
Accomplishments – Fuel Reactivity

- Designed fuel test matrix with five fuels with RON ≈ 98, four with S ≈ 10.5, one with S ≈ 1
- P_{in} = 1.0 bar: Surprisingly, reactivity varies among matched RON&S fuels: E30>>Aromatic
  - For LTGC at P_{in} = 1 bar with these fuels, Octane Index (OI) gives poor correlation (R^2 =0.536)
  - RON and MON appear insufficient for specifying fuel reactivity for lean LTGC (ϕ = 0.4) at this cond.
  - Perhaps this is because E30 is less ϕ-sensitive, or differences in HOV ⇒ Further studies are planned
- P_{in} = 2.4 bar: Try OI'' based on intake O_2, since T_{in} = 60°C for all
  - OI'' correlates fuels fairly well at P_{in}=2.4 bar, R^2 =0.870
  - Further understanding of this intake-O_2 based OI'' is needed

Required T_{in} for P_{in} = 1.0 bar, Indicates Reactivity







LTGC (SNL, Dec): Reactivity of E30 (high RON & S) is similar to E0, correlates with ITHR & ϕ-sensitivity

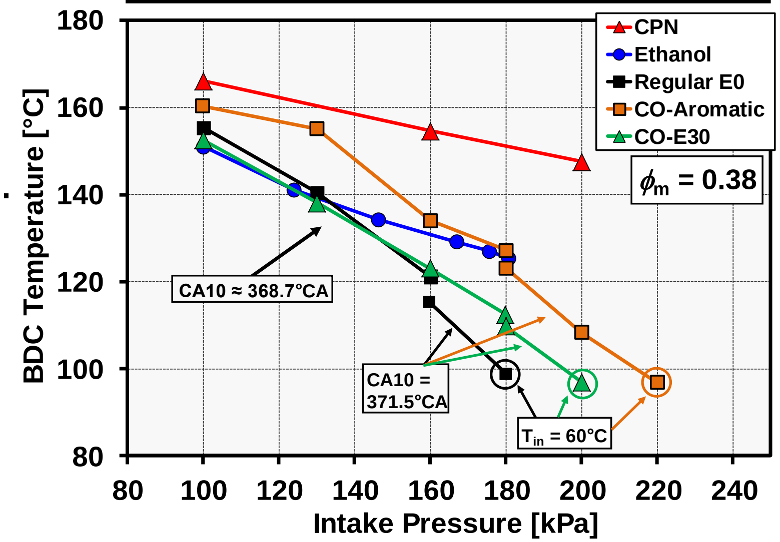
Reactivity Changes w/ Boost

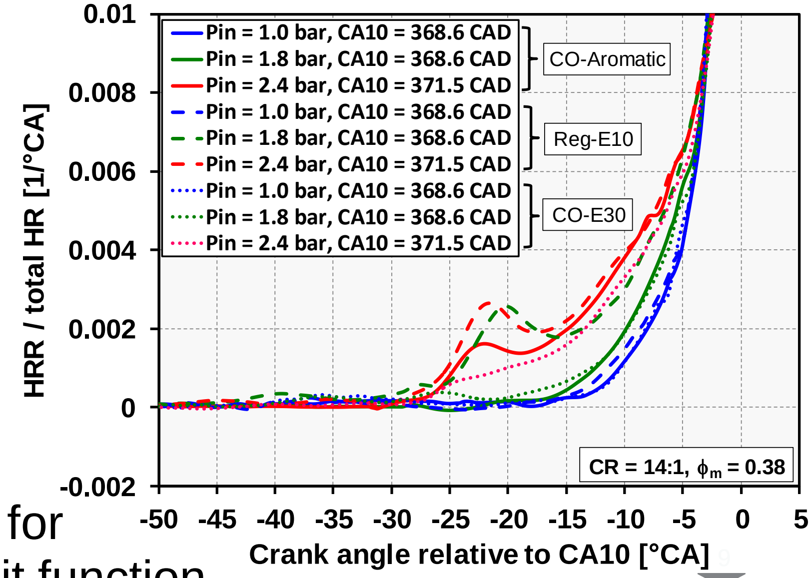
- Increased fuel autoignition reactivity with boost is a key challenge for both LTGC and SI
  - LTGC: High EGR required for CA50 control limits O_2.
  - SI: Increased knock propensity limits CR
- **Despite higher RON & S, E30 has similar reactivity to Reg-E0 for P_{in} = 1.0 – 1.6 bar ⇒ Somewhat less reactive for higher P_{in}**
- Higher RON & S aromatic fuel is much less reactive than Reg-E0, esp. at P_{in} ≥ 1.8 bar
  - At P_{in} = 1.8 bar, aromatic & E30 have lower ITHR than Reg-E10 ⇒ may affect reactivity trends
  - Also agrees with lower ϕ-sensitivity (for PFS)

Future Work:

- Evaluate E30 ϕ-sensitivity & high load behavior
- Evaluate the other three fuels in test matrix ⇒ High-Olefin, High-Cycloalkane, & Alkylate
- Investigate Co-Optima fuels with good potential for full-time LTGC-ACI engines ⇒ Support ACI merit function

ΔT_{BDC} indicates changes in reactivity





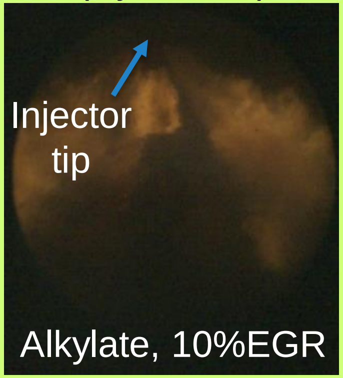
GCI (ANL, Ciatti): Minimize pollutant emissions, noise, fuel consumption for three 98 RON "boosted-SI" fuels

- **Objective**:
  - Demonstrate **Gasoline Compression Ignition (GCI)** combustion with high RON, high S **Boosted-SI** fuels in a 1.9L GM engine
  - Investigate parameters that affect engine performance and emission; and identify condition with desirable outputs (i.e. **pollutant emissions, noise, efficiency**)
- **Approach**: double injection strategy to control combustion phasing (**CA50 ~ 5 aTDC**) while maintaining combustion stability (**COV_{IMEP}<3%)** and noise (**<90 dB),** low FSN (**<0.1**). Parametric study of:
  - **Exhaust Gas Recirculation**
  - **Global lambda**

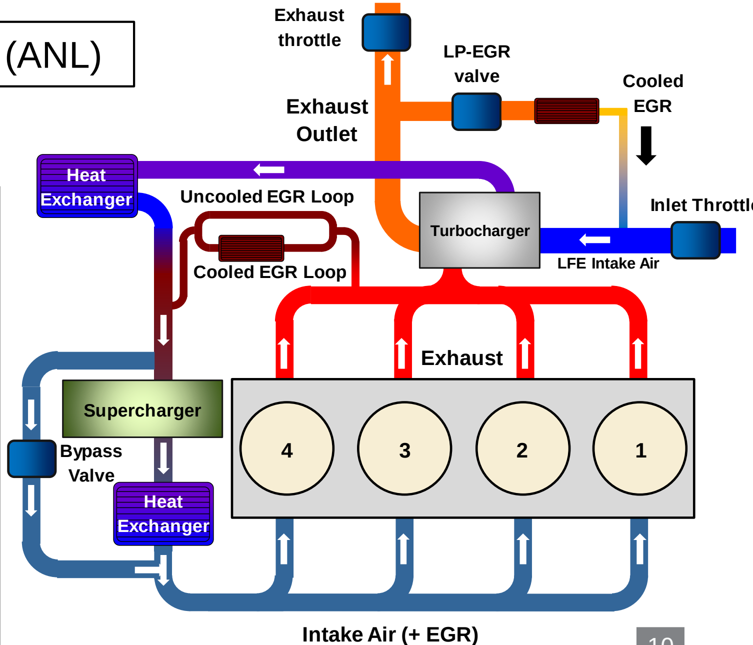
  Impact on:
  - CA10, CA50, HRR
  - Emission (NOx/HC/CO)

Parameter	Value
Engine 1.9L GM 4-cylinder (17.8:1 CR)	
Engine Speed [rpm]	1000
Engine Load [bar BMEP]	3-6
Fuel – 98 RON: Aromatic, Alkylate, E30	
Injection Pressure [bar]	600
Start of Injection [°aTDC]	-50/varied
Fuel Split (~ % by duration)	55/45
EGR [%]	20 (0-30)
Boost Pressure [bar(a)]	1.4 (1.0-1.7)
Intake Air Temp [°C]	55 (35-85)
Global λ (= 1/Φ)	1.8 (1.6, 2.0)

Endoscope Imaging (Cylinder 4)

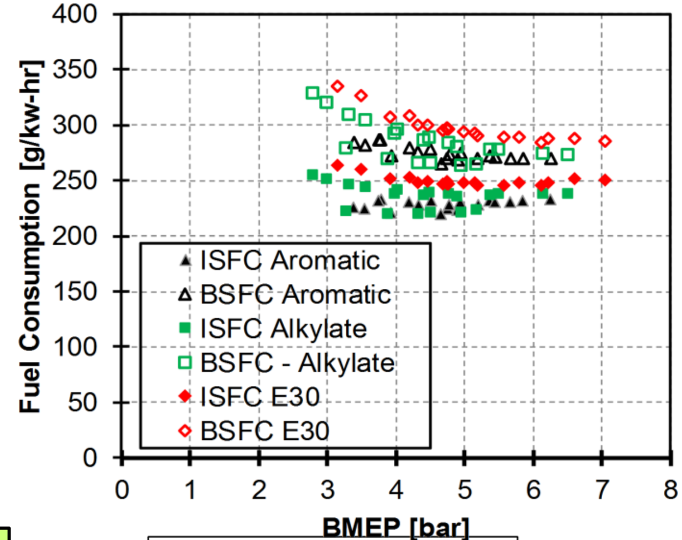


GM1.9L Engine (ANL)



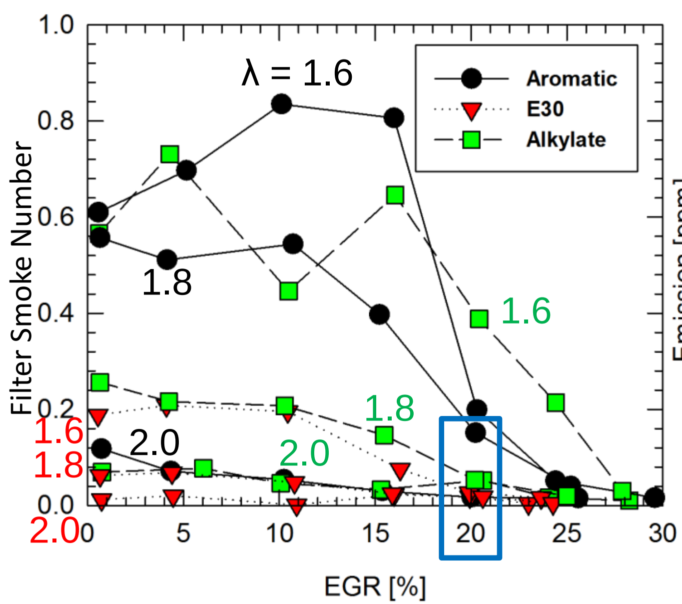
GCI (ANL, Ciatti): Co-Optima core fuels with CA50, noise, & COV const., ↑EGR ⇒ ↓FSN & NOx, ↑CO & HC

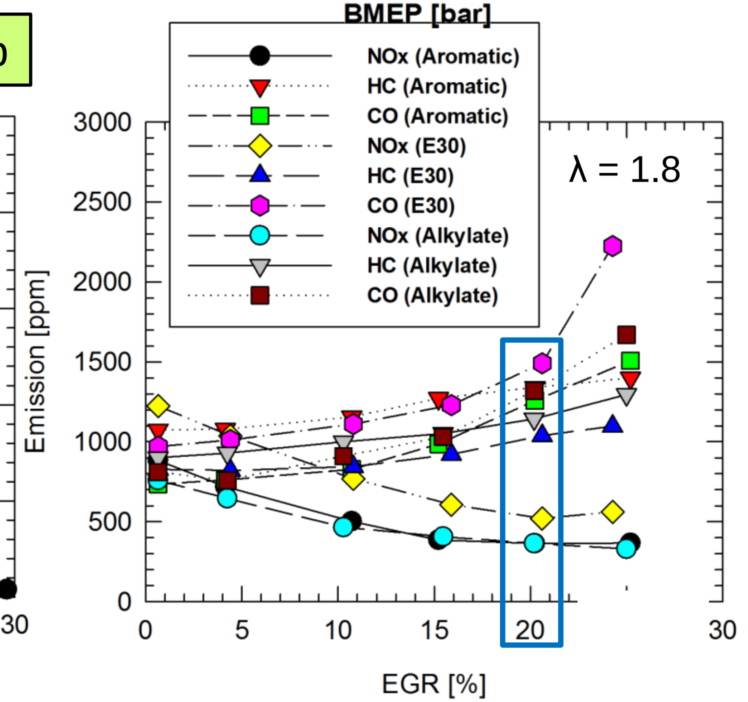
- For Co-Optima core fuels, as EGR is increased to 20%:
  - FSN decreases ~70%, with FSN Aromatic > Alkylate > E30
  - NOx emissions are halved, while CO and HC emissions increase 20-50%
  - Exhaust emissions control still required
- BSFC/ISFC are larger than expected due to turbocharger issues
- λ=1.8, EGR=20% point selected for endoscope imaging



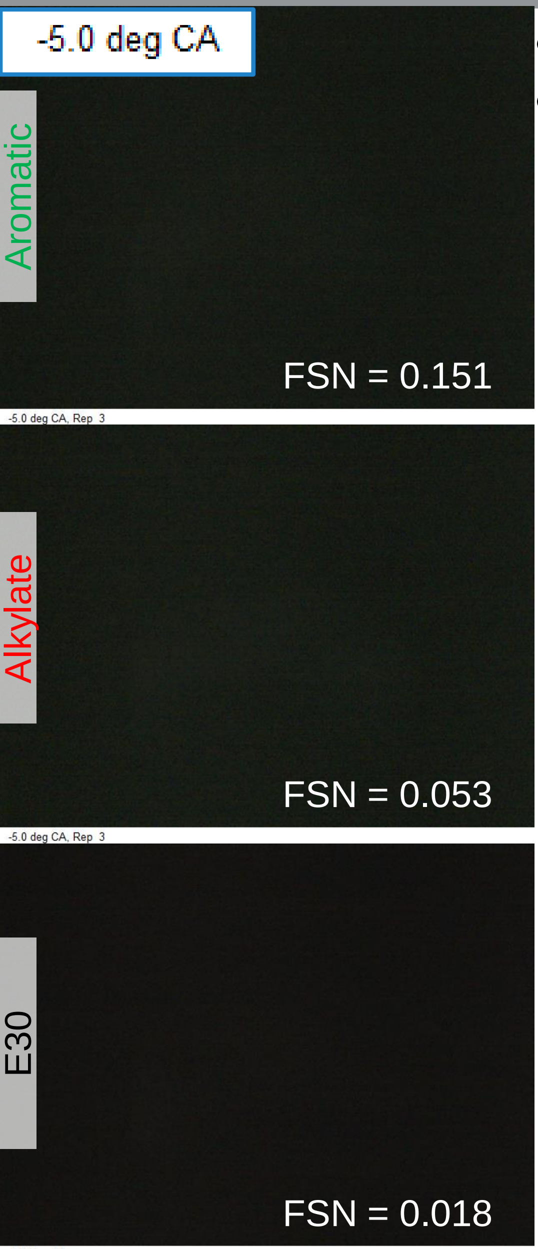
Co-Optima Core Fuels	Alkylate	Aromatic	E30
RON	98	98	98
MON	97	87	88
S	1	11	11
Aromatics	0	36	8
Saturates	100	65	57
Olefins	0	4	5
Ethanol	0	0	30

Global Lambda and EGR Sweep

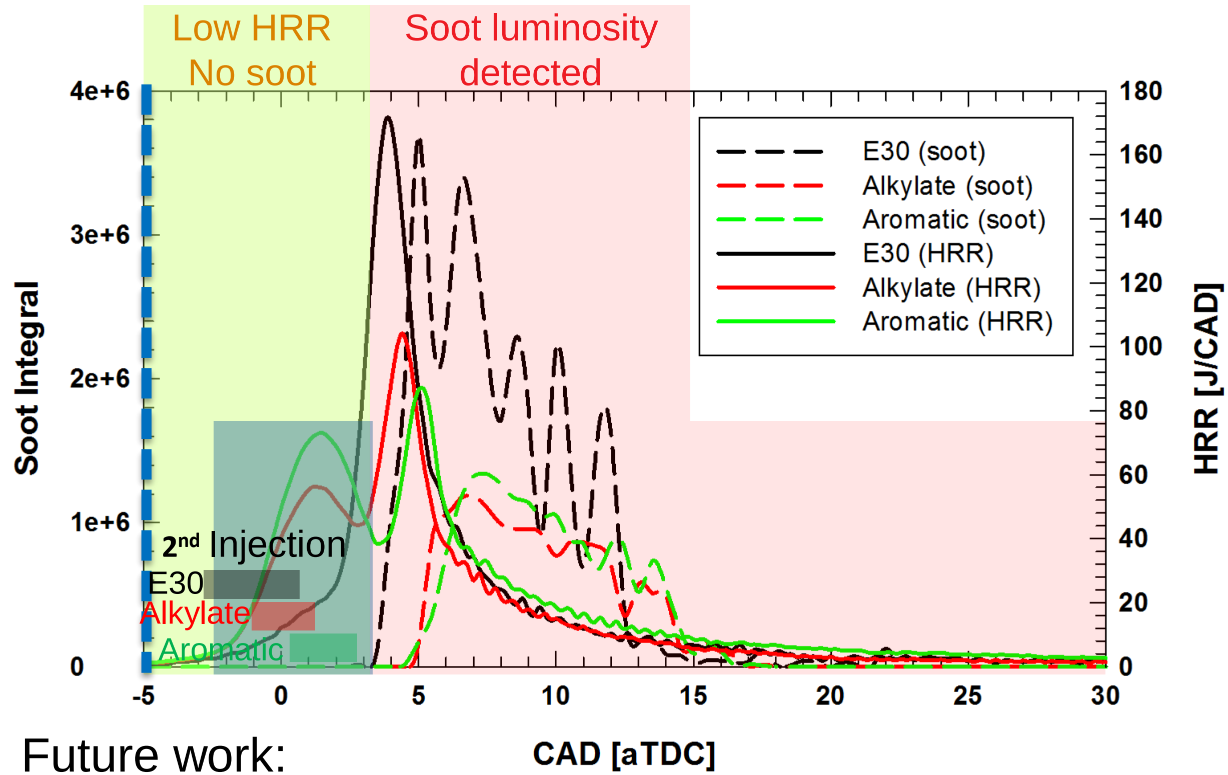




GCI (ANL, Ciatti): at 20% EGR & λ=1.8, E30 has fastest burn, highest in-cyl. soot, low late-cycle soot (& FSN)



- Soot luminosity appears near second HRR peak, akin to conv. diesel
- E30: highest peak soot KL integral, but lowest late-cycle (& lowest FSN)



- <u>Future work:</u>
  - Improve engine efficiency and BSFC with turbocharger operation and injection strategy (higher BMEP points)
  - Endoscope imaging for OH* chemiluminescence in low HRR region where soot is absent
  - PM measurement for GCI soot characteristics

Stratified ACI (ORNL, Curran & SNL, Musculus): RCCI in LD multi-cylinder metal and HD single-cylinder optical engine

Motivation for Using RCCI in ACI Engines

On-the-fly in-cylinder mixing of two fuels =
Control of combustion phasing & HRR

- Global octane number adjusted by fuel ratio
- Reactivity stratification by injection timing

RCCI Challenges

Peak pressure rise rate (PPRR) limits high load

- E30 extends limit ⇒ not well understood

Incomplete combustion at lowest loads

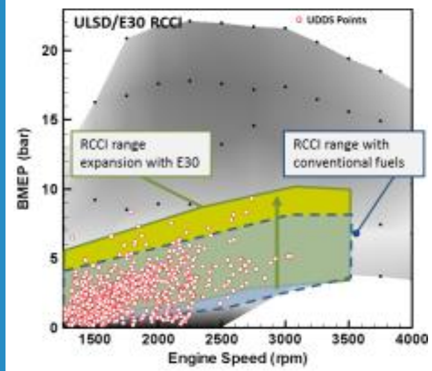
- Reasons are unclear

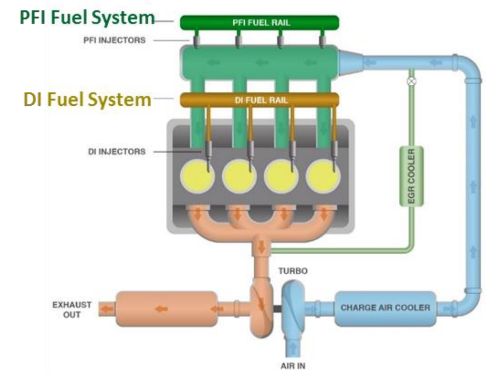
Approach for RCCI Work

- Use ORNL multi-cylinder metal engine to identify key fuel-property & operating-condition combinations where an improved understanding is required
- Use SNL single-cylinder optical engine to image in-cylinder mixing, ignition, and combustion processes at these conditions

ORNL Metal Engine

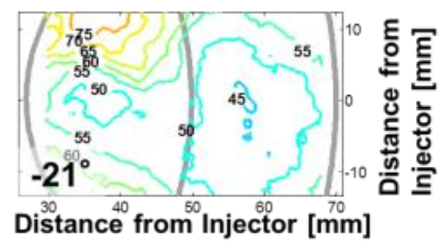
- Multi-cylinder light-duty diesel engine (PFI + DI)
- Transient capable + emissions characterization

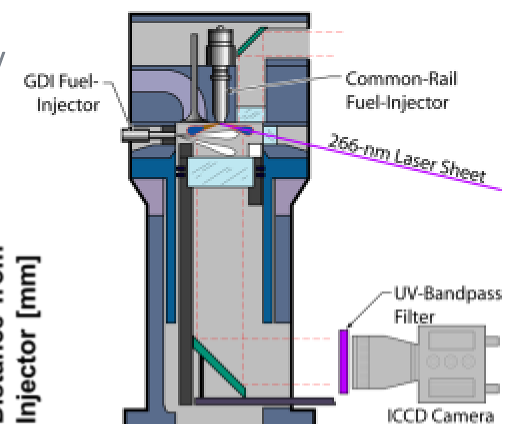




SNL Optical Engine

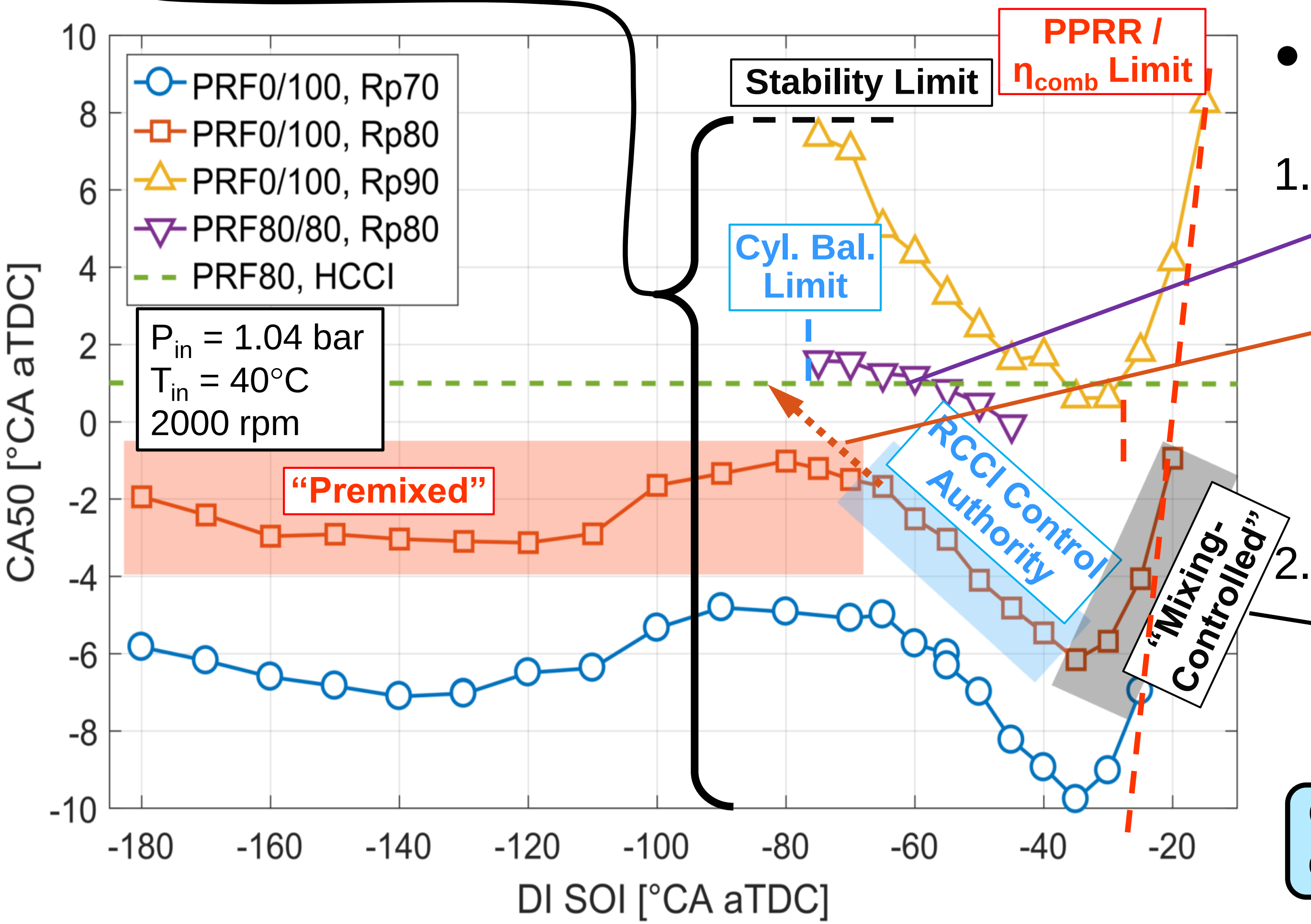
- Single-cylinder heavy-duty diesel engine (GDI + DI)
- Image combustion & in-cylinder mixing (PRF)





Stratified ACI (ORNL, Curran): Constant PRF limits of RCCI CA50 control authority approach premixed & mixing-control

- Use PRFs (iso-octane & n-heptane): similar physical properties, different reactivity
  - DI SOI from -70 to -35 °CA aTDC have characteristic RCCI CA50 control authority
  - Control authority is limited by constant PRF in each sweep
    - > Varying PRF by changing premixed ratio (Rp) would yield much greater CA 50 control



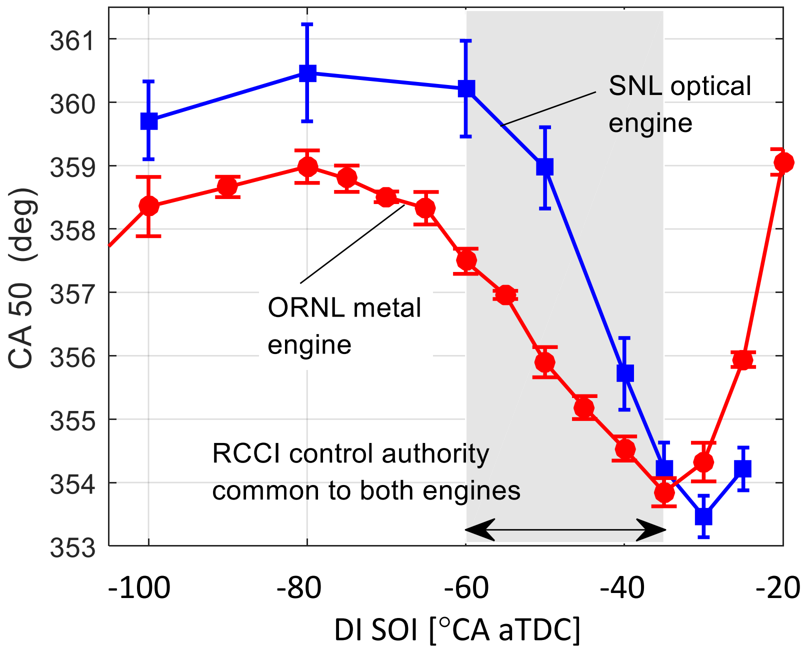
- Two limits of control authority range:

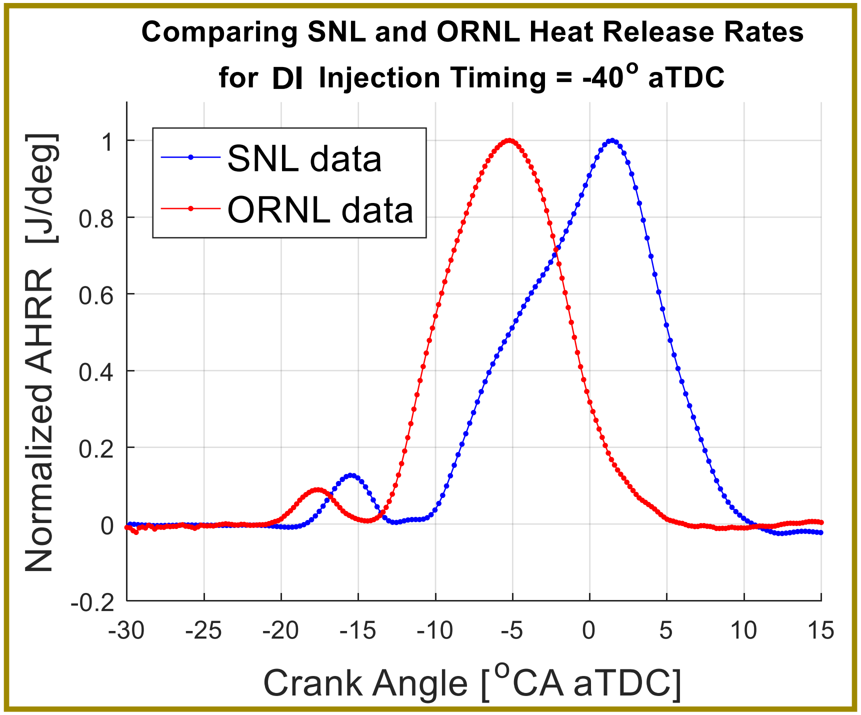
1. "Premixed"
   - Premixed + DI PRF80 reaches premixed "HCCI"
   - Premixed PRF100 + DI PRF0 does not reach premixed "HCCI" CA50
     - > Wall wetting?
     - > Incomplete mixing?
2. "Mixing-Controlled"
   - Late DI SOI: control authority trend reverses
     - > Fuel-rich mixing-controlled combustion?

Gain insight from optical diagnostics

Fundamental Stratified ACI (SNL, Musculus): Good matching of combustion phasing & control authority in optical & metal engines

The mid-point of combustion heat release (CA50) depends on the injection timing of high-reactivity (PRF 0) fuel from the common rail (CR) DI injector

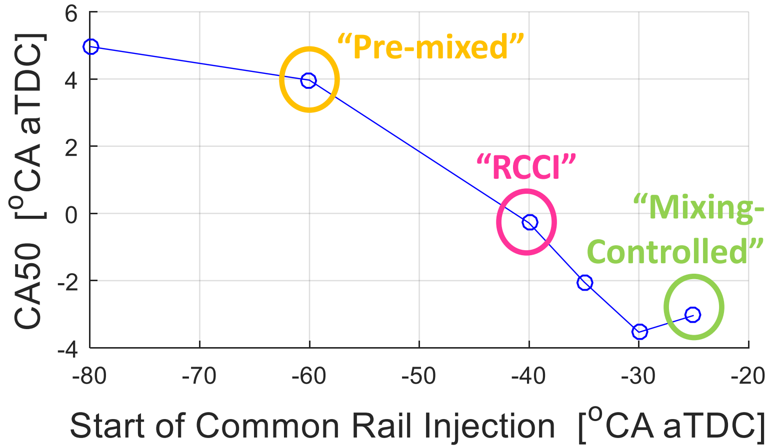


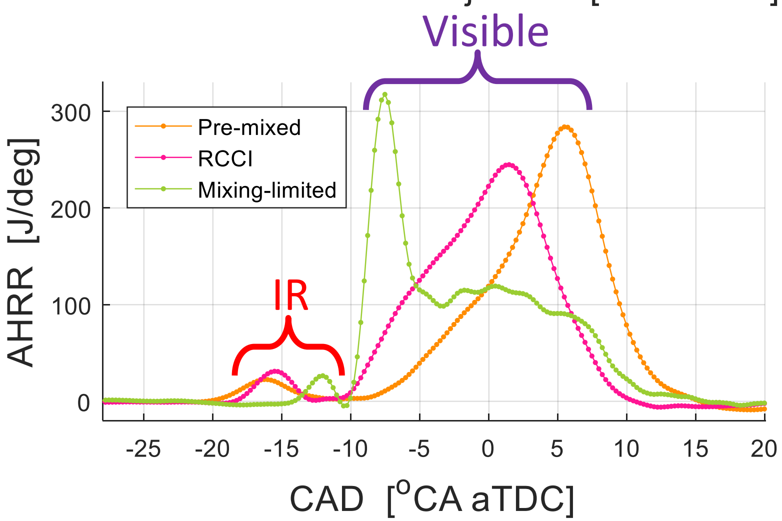


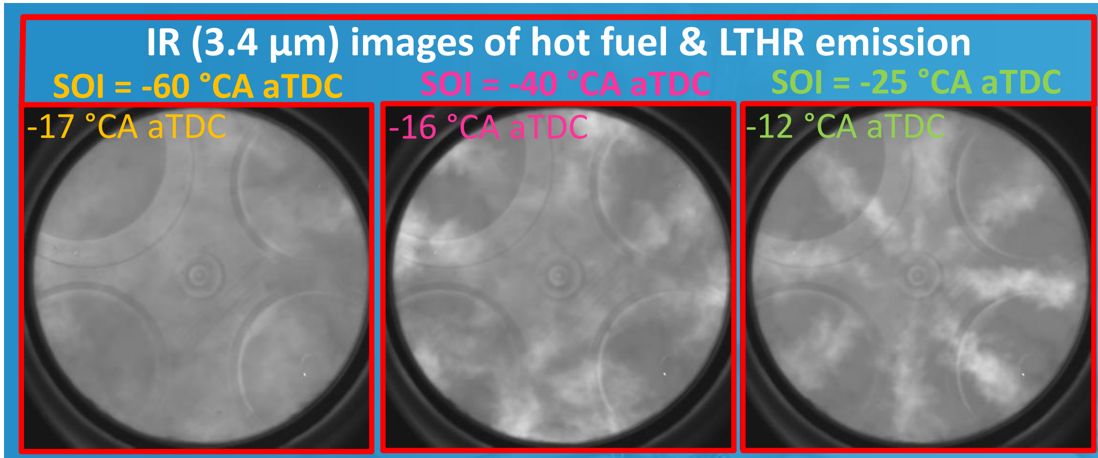
For a DI injection in the "RCCI regime," the heat release phasing is shifted, but the curves have the same characteristic shapes

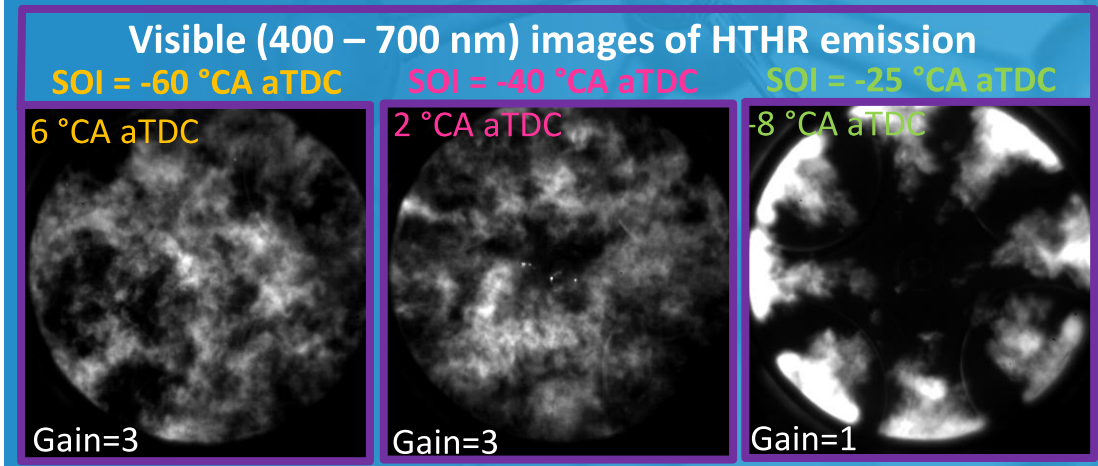
- Matching SNL HD optical engine with ORNL LD metal engine: **1. charge-gas ρ & T @ mid-control-authority DI injection, 2. premixed iso-octane (80%), 3. global Φ (0.35)**
- Even with different engine displacement (heavy-duty vs light-duty), compression ratios, and piston geometry, the **combustion characteristics are similar**, with three CA50 regimes (pre-mixed, RCCI, & mixing-controlled) and similar heat release shapes

Fundamental Stratified ACI (SNL, Musculus): Structure in IR & visible images (=incomplete mixing?), bright @ late DI (=rich?)









- **Structure in IR imaging of 1st-stage and visible imaging of 2nd-stage ignition at all conditions – incomplete mixing?**
- **Brightening jet structure in visible imaging indicates transition to richer mixtures**

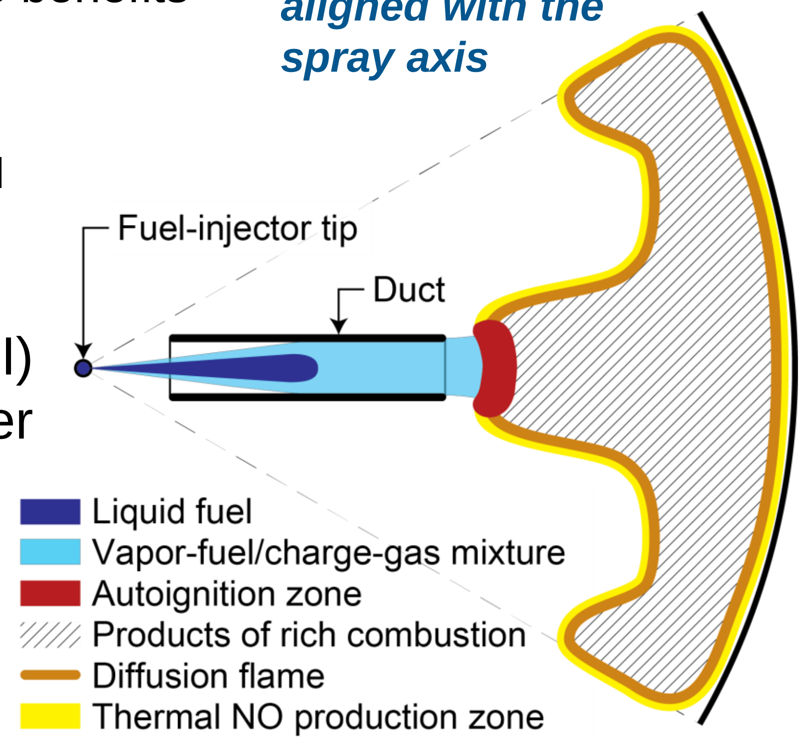
Next steps

- Follow up with laser-sheet mixing diagnostics to quantify mixing effects for these PRFs
- Image combustion phenomena for ORNL fuels with different physical properties

MCCI (SNL, Mueller): Maintain high efficiency, control, & fuel flexibility of diesel; use ducted injection for soot

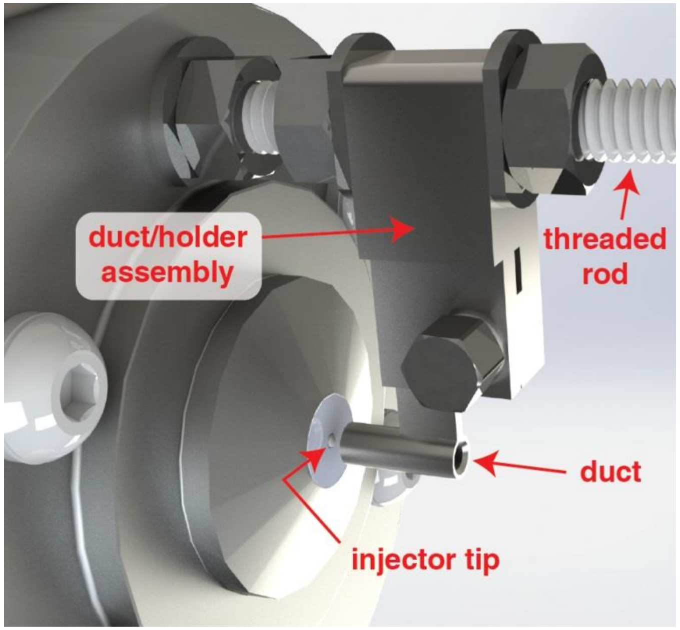
- Mixing-controlled CI combustion is desirable for many reasons
  - > Inherently high efficiencies, low HC & CO emissions
  - > Ignition timing easily controlled by injection timing
  - > Inherently fuel-flexible (cetane # is key fuel parameter)
  - – Soot is a barrier to fully achieving the above benefits
    - > Soot is a potent toxin
    - > 2nd only to CO_2 as a climate-forcing species
    - > Limits amount of EGR possible for NO_x control
    - > Aftertreatment is expensive, has efficiency penalties (backpressure, regeneration)
- **<u>Approach</u>:** Use Ducted Fuel Injection (DFI) to make richest autoigniting mixtures leaner
  - – **Effective at lowering soot** (next slide)
  - – Geometrically & conceptually simple
  - – Tolerant to dilution for NO_x control
  - – Synergistic with Co-Optima oxygenated fuels, but does not require oxygenation
  - – <u>Might</u> increase comb. efficiency by limiting over-mixing at spray periphery

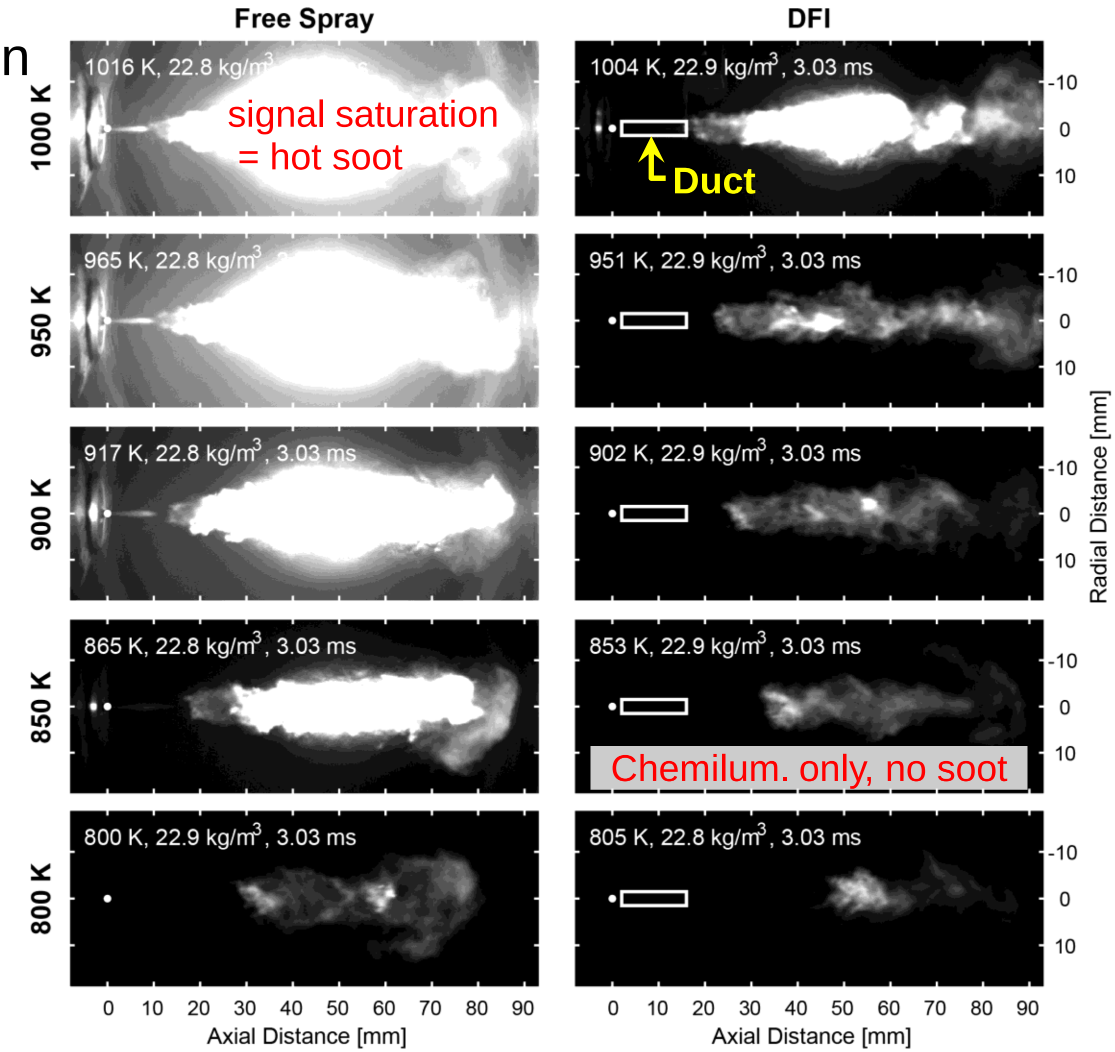
DFI Concept: Inject fuel down a small tube/duct aligned with the spray axis



MCCI (SNL, Mueller): Initial DFI data show considerable soot reduction even with non-oxygenated fuel, no EGR

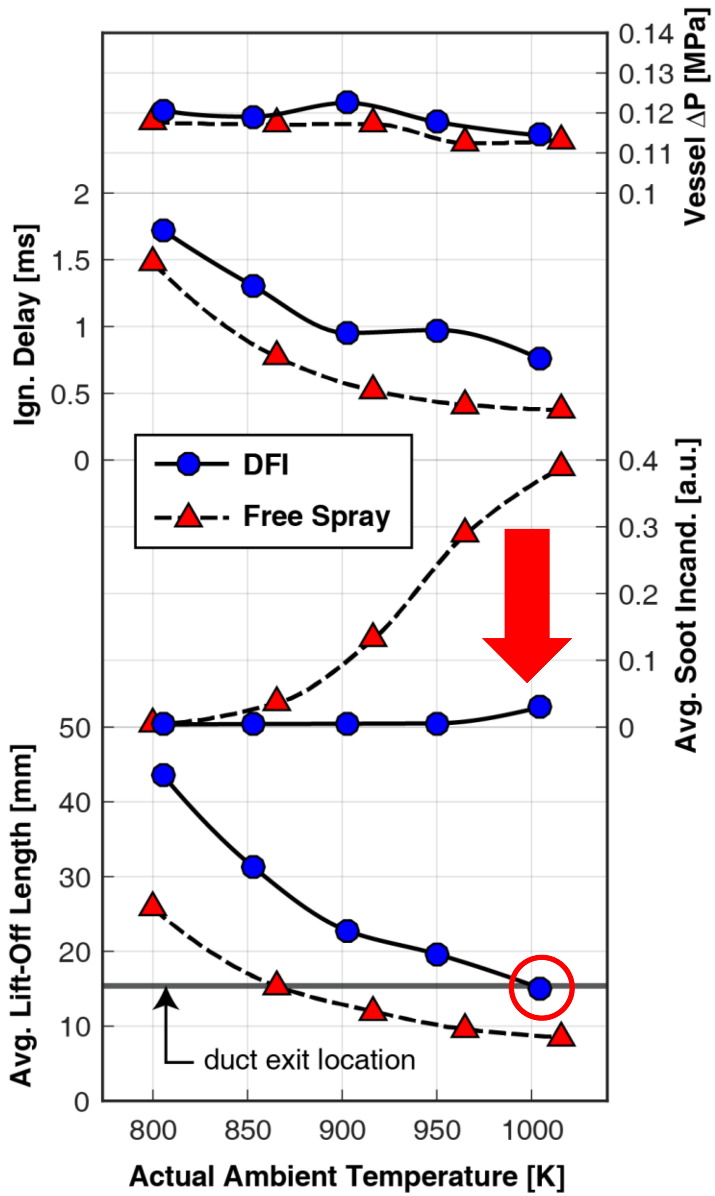
- Ducted Fuel Injection (DFI) in Sandia constant-volume combustion vessel
  - 90 µm orifice diameter
  - 1500 bar injection pressure
  - 21 mol% oxygen (no EGR)
  - n-dodecane fuel (not oxygenated)



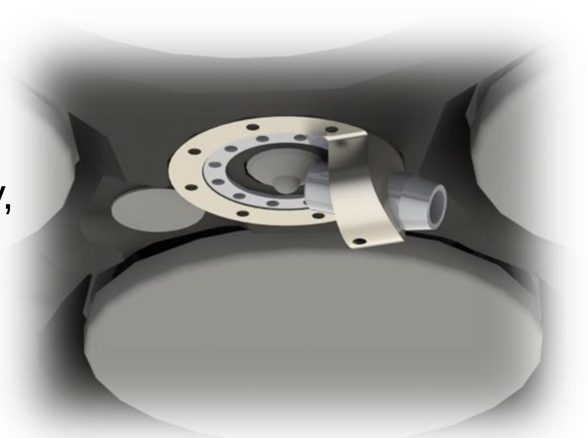


DFI is effective at lowering or preventing soot incandescence over a range of temperatures

MCCI (SNL, Mueller): DFI reduces in-cylinder soot by factor of ~10, longer lift-off, higher pressure rise



- Effects of DFI on combustion observables
  - Lift-off lengths increase with DFI
    - > Flame anchors to duct exit at 1000 K
    - > Longer ignition delay could increase noise
  - Soot incandescence decreases by 10×
    - > Similar for quantitative in-cylinder soot
  - Total pressure rise (ΔP) in vessel is slightly, but consistently larger with DFI
    - > Higher combustion efficiency?
    - > Reduce over-mixing at spray periphery?
- <u>Future Work</u>:
  - Optical engine tests
    - > emissions, efficiency, & fuel effects
    - > Vertical-sheet LII
  - Develop merit function



ACI Merit Function (NREL/ORNL/SNL + ANL-Ickes): Quantify fuel properties enabling high-efficiency ACI

- ACI merit function: quantify enabling engine conditions & fuel properties
  - Boosted SI merit function quantifies efficiency effects to guide fuel and engine co-optimization
  - ACI approaches already have high efficiency; quantify enabling fuel & engine effects to guide co-optimization
- Will synthesize results from multiple Co-Optima ACI approaches
  - > Highlight key enabling fuel properties for each combustion approach
  - > Relate fuel properties to engine features that affect operating range and efficiency
- Design engine and fuel experiments to inform merit function(s) across the suite of ACI combustion concepts

LTGC | RCCI | GCI

LLFC | SI-based

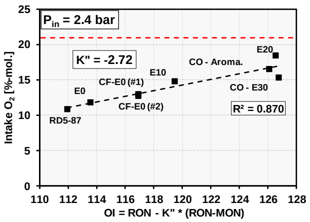
(Industry solutions incorporated based on published literature and industry support/guidance)

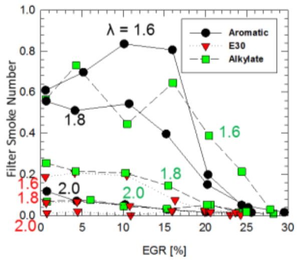
Identify enabling fuel properties and engine features and quantify their effects for each ACI approach

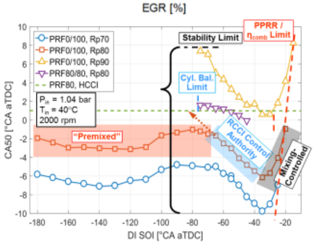
Specific focus on properties/ranges that preclude each ACI approach

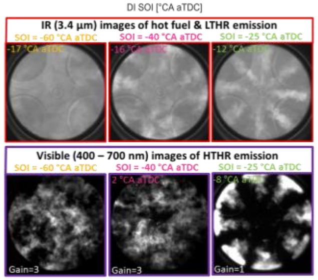
Property guidance and merit function to direct ACI engine & fuel co-optimization

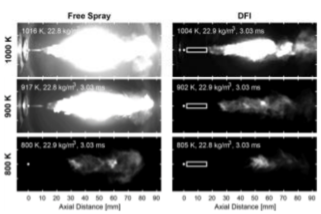
Summary: Co-Optima Engine & Fuel Tasks for Advanced Compression Ignition (ACI)











ACI approaches using "boosted-SI" gasoline-like fuels

LTGC
- •SNL
- •Dec

Identical RON & S fuels: diverging CA50, "O2" OI works well

E30 reactivity similar to E0, correlates w/ ITHR & ϕ-sensitivity

GCI
- •ANL
- •Ciatti

W/ CA50, noise, COV const., ↑EGR ⇒ ↓FSN&NOx, ↑CO&HC

20% EGR & λ=1.8: E30=highest in-cyl. soot, low late-cyc. soot

ACI approaches using diesel-like fuel or dual fuels

RCCI
- •ORNL
- •Curran

Const. PRF control authority limits = premixed, mixing-control

Wall-wetting/incomplete-mixing may narrow premixed limit

RCCI
- •SNL
- •Musculus

Matched optical/metal engine comb. phasing & control auth.

Image struct. (=incomplete mixing?), bright @ late DI (=rich?)

MCCI
- •SNL
- •Mueller

DFI reduces in-cyl. soot 10X w/ non-oxygenated fuel, no EGR

Longer lift-off & ignition delay (noise?), higher ΔP (efficiency?)

ACI merit function development

ACI MF
- •ANL lead
- •Ickes

Identify/quantify fuel properties enabling high-efficiency ACI

Merit function to guide ACI engine & fuel co-optimization

Acknowledgement

- The work on LTGC, Fundamentals of Stratified ACI (RCCI), and MCCI was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA.

  Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Publications and Presentations – 1

ANL, Ciatti – GCI (Gasoline Compression Ignition)

- Ciatti, S. and Cung, K., "Performance of High RON Fuels in a Multi-Cylinder Engine at GCI Operating Conditions," DOE Advanced Engine Combustion Working Group Meeting, January 2017.
- Ciatti, S. and Cung, K., "Performance of High RON Fuels in a Multi-Cylinder Engine at GCI Operating Conditions,“ Oral only presentation at the SAE World Congress, April 2017.

SNL, Dec – LTGC (Low-Temperature Gasoline Combustion)

- Dec, J.E., Dernotte, J., and Ji, C., "Fuel Effects on LTGC Combustion – Initial Results for a Co-Optima Fuel," GM/Sandia Working Group Meeting, August 2016.
- Dec, J.E., Ji, C., and Gentz, G., "Additional Evaluation of Co-Optima Fuels," GM/Sandia Working Group Meeting, April 2017.

ORNL, Curran – RCCI Metal Engine

- Dempsey, A.B, Curran, S.J., and Wagner, R.M., "A perspective on the range of gasoline compression ignition combustion strategies for high engine efficiency and low NOx and soot emissions: Effects of in-cylinder fuel stratification", 2016, *International Journal of Engine Research, DOI: 10.1177/1468087415621805.*
- Wissink, M et al., " Performance and emissions of RCCI with iso-octane and n-heptane on a light-duty multi-cylinder engine," DOE Advanced Engine Combustion Working Group Meeting, January 2017.
- Wissink, M et al., " Performance and emissions of RCCI with iso-octane and n-heptane on a light-duty multi-cylinder engine," Oral only presentation at the SAE World Congress, April 2017.
- Wissink, M., et al., "Extending RCCI Load Limits," presented at Co-Optima Stakeholders Meeting, March, 2017.
- Wagner, M., "Pushing the efficiency of internal combustion engines and UAV", 2017 UAV Israel, Jan 2017.
- Wagner, M., "Reactivity Stratified Combustion and Future Fuel", KAUST Combustion Conference, March 2017.
- Wagner, M., "Directions in High Efficiency Engine Research and Future Fuel Opportunities," Centennial Seminar Series, Missouri University of Science and Technology, August 2016.
- Curran, S., Wagner, R., "Reactivity Stratified Combustion Development for Light-Duty Multi-Cylinder Engines" IEA Technology Collaboration Programmes (TCP) for Clean and Efficient Combustion, 38th Task Leaders Meeting, Ruka, Finland, June 2016.

SNL, Musculus – RCCI Optical Engine

- Eagle, W.E. and Musculus, M.P.B., "Optical imaging to understand fuel reactivity effects on RCCI combustion," DOE Advanced Engine Combustion Working Group Meeting, August 2016.

Publications and Presentations – 2

SNL, Mueller – Mixing-Controlled CI Combustion and Fuels Research

- **Publications**

1. Mueller, C.J., Nilsen, C.W., Ruth, D.J., Gehmlich, R.K., Pickett, L.M., and Skeen, S.A., "Ducted Fuel Injection: A New Approach for Lowering Soot Emissions from Direct-Injection Engines," *Applied Energy*, submitted March 21, 2017.
2. Cheng, A.S. and Mueller, C.J., "Conceptual Investigation of the Origins of Hydrocarbon Emissions from Mixing-Controlled, Compression-Ignition Combustion," *SAE Int. J. Engines* **10**(3), 2017, doi:10.4271/2017-01-0724.
3. Das, D.D., McEnally, C.S., Kwan, T.A., Zimmerman, J.B., Cannella, W.J., Mueller, C.J., and Pfefferle, L.D., "Sooting Tendencies of Diesel Fuels, Jet Fuels, and Their Surrogates in Diffusion Flames," *Fuel* **197**:445-458, 2017, doi:10.1016/j.fuel.2017.01.099.
4. Das, D.D., Cannella, W.J., McEnally, C.S., Mueller, C.J., and Pfefferle, L.D., "Two-Dimensional Soot Volume Fraction Measurements in Flames Doped with Large Hydrocarbons," *Proc. Combust. Inst.* **36**(1):871–879, 2017, doi:10.1016/j.proci.2016.06.047.
5. Mueller, C.J., "Improved Mixing-Controlled Combustion Technologies and Fuels for High-Efficiency Compression Ignition Engines," *Proc. of DOE Advanced Engine Combustion and Fuels Program Review*, DOE Office of Vehicle Technologies Annual Report, 2016.
6. Dumitrescu, C.E., Cheng, A.S., Kurtz, E., and Mueller, C.J., "A Comparison of Methyl Decanoate and Tripropylene Glycol Monomethyl Ether for Soot-Free Combustion in an Optical Direct-Injection Diesel Engine." ICEF2016-9366, 2016 ASME Internal Combustion Engine Fall Technical Conference, Greenville, SC, Oct. 9-12, 2016. American Society of Mechanical Engineers. 2016.
7. Gehmlich, R.K., Dumitrescu, C.E., Wang, Y., and Mueller, C.J., "Leaner Lifted-Flame Combustion Enabled by the Use of an Oxygenated Fuel in an Optical CI Engine," *SAE Int. J. Engines* **9**(3), 2016, doi:10.4271/2016-01-0730.

- **Presentations**
  - 16 presentations from this project since last DOE Annual Merit Review (AMR) meeting, 3 invited.
- **Patents**
  - Non-provisional appl. #15,363,966: "Ducted Fuel Injection" filed Nov. 29, 2016.
  - Non-provisional appl. #15,364,002: "Ducted Fuel Injection with Ignition Assist" filed Nov. 29, 2016.
- **Award**
  - Coordinating Research Council (CRC) Advanced Vehicles, Fuels, and Lubricants (AVFL) Committee Special Recognition Award (Feb. 7, 2017).