Co-Optimization of
Fuels & Engines

Boosted SI and Multimode SI / ACI Combustion, Part 1

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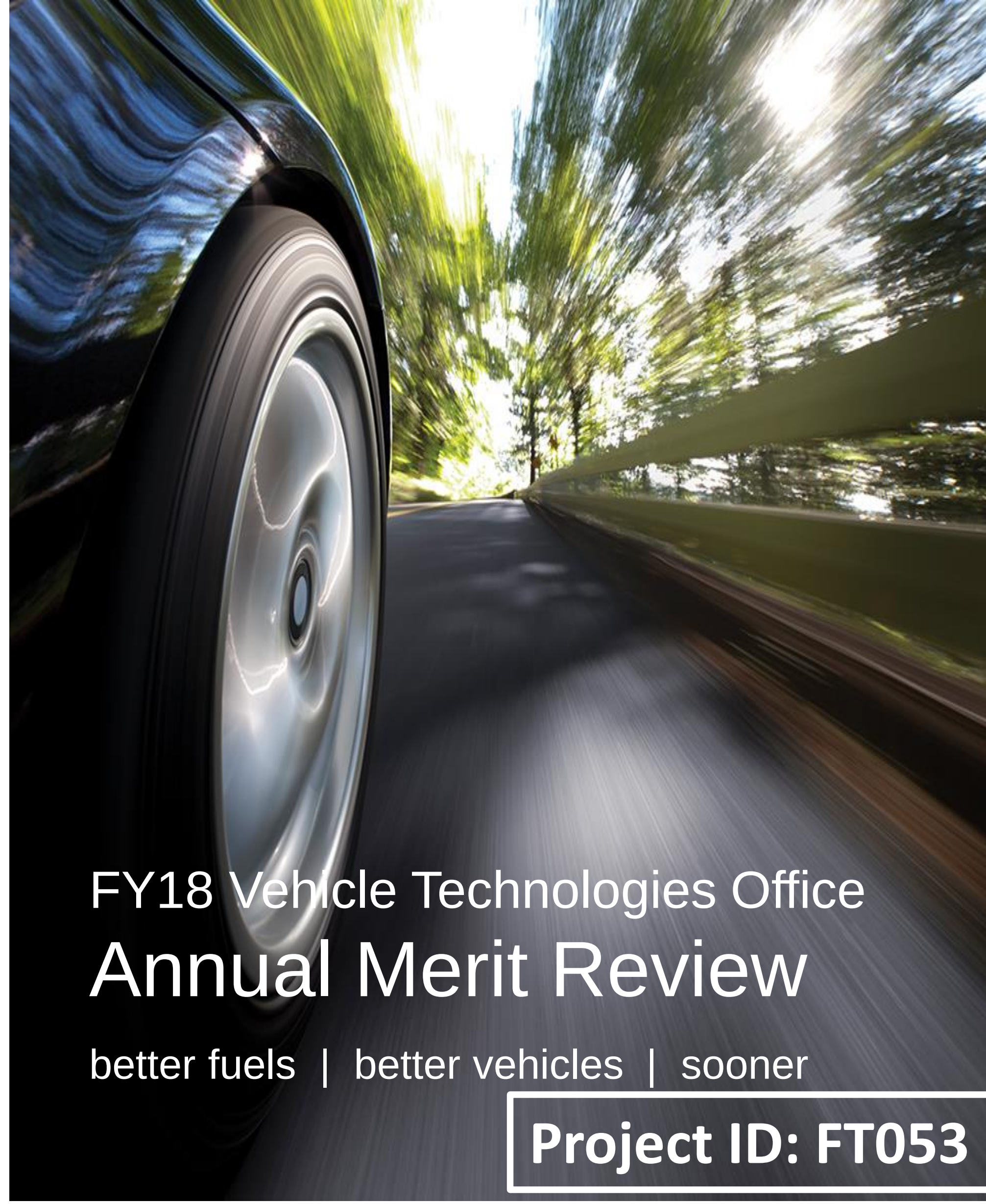
June 20, 2018



FY18 Vehicle Technologies Office
Annual Merit Review

better fuels | better vehicles | sooner

Project ID: FT053

Overview

Timeline

- Project start date: 10/1/2015
- Project end date: *9/30/2018
- Percent Complete: 90%

*Start and end dates refer to three-year life cycle of DOE lab-call projects; Co-Optima is expected to extend past the end of FY18.

Budget

Budgets will be presented for the 8 individual projects included in this presentation; total FY18 budget is $1.655M.

Barriers (ACEC Roadmap)

Knock: At high loads and speeds, knock is a limiting condition that needs to be addressed through combustion chamber design, ignition strategies, and fuel composition tailoring.

Models: Understanding and robust modeling tools for rapidly screening proposed designs based on sound metrics are lacking.

Partners

- 9 national laboratories
- 13 universities
- External advisory board
- many stakeholders and collaborators (145 individuals from 86 organizations)

Relevance

- Co-optima boosted SI and multimode SI/ACI efforts provide improved understanding in several areas critical for progress on:
  - Fuel chemistry – property relationships
  - How to measure and predict fuel properties
  - ***The impact of fuel properties on engine performance.***
- <u>Continual improvement is important in these areas</u> because internal combustion engines will continue to dominate the fleet for at least several more decades.
- Research into better integration of fuels and engines is critical to <u>accelerating progress</u> towards our economic development, energy security, and emissions goals.

Approach

- Experimental and computational approach of the tasks in this presentation is to execute studies into whether the correct fuel properties are identified, properly weighted, and in alignment with the Central Fuel Hypothesis.
- Work with researchers across Co-Optima initiative to develop organizing principals

Central Fuel Property Hypotheis

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 efficiency.

Quantitative Merit Function for Boosted SI Engines

$$Merit = \frac{(RON_{mix} - 91)}{1.6} - K\frac{(S_{mix} - 8)}{1.6} + \frac{0.085[ON/kJ/kg_{mix}]\cdot((HoV_{fuel}/(AFR_{stoich}+1)) - (415[kJ/kg_{fuel}]/(14.3[-]+1)))}{1.6}$$
$$+ \frac{((HoV_{fuel}/(AFR_{stoich}+1)) - (415[kJ/kg_{fuel}]/(14.3[-]+1)))}{15.38} + \frac{(S_{Lmix} - 46[cm/s])}{5.4}$$
$$- H(PMI - 1.6)[0.7 + 0.5(PMI - 1.4)] + 0.008\,^{\circ}C^{-1}(T_{c,90,conv} - T_{c,90,mix})$$

Milestones

Milestone	PI	Status
Complete evaluation of potential fuel economy benefits for 4 Co-optima phase 3 fuel blend candidates with increased octane rating.	Sluder	On Track
Draft journal article highlighting new AFIDA-based experimental capability with pure compounds and/or surrogate blend studies.	Zigler	On Track
Complete an experimental campaign to quantify autoignition propensity with a fuel set containing 6 fuels over a variety of pressure-temperature and K value trajectories in an IC engine.	Szybist	On Track Dashboard
Complete experiments with fuels of modest RON and high S to determine whether the OI predictions remain valid or whether limits to the OI predictions are encountered.	Szybist	On Track
Validated CFD based engine data maps provided to the Autonomie group for the ORNL multi-cylinder engine.	Som	On Track
Provide ANL with boosted SI fuel maps for vehicle fuel economy studies with state-of-the-art and optimized hardware.	Edwards	Completed
Quantify the vehicle energy benefits of Co-optima.	Rousseau	On Track

Technical Accomplishments Outline and Budget

Title	PI	Lab	FY18 Budget
Engine Efficiency Potential of High-Octane Renewable Fuels in Multi-cylinder Engines	Sluder	ORNL	$440,000
Fuel Autoignition Behavior	Zigler	NREL	$180,000
Fuel Property Effects on Abnormal Combustion	Splitter	ORNL	$200,000
Developing a Better Understanding of Octane Index	Szybist	ORNL	$280,000
Characterizing BOB Impacts and Limits within OI	Szybist	ORNL	$200,000
Multi-cylinder CFD Engine Simulations	Som	ANL	$165,000
Multi-cylinder Engine Simulation	Edwards	ORNL	$90,000
Vehicle Fuel Consumption Analysis	Rousseau	ANL	$100,000

Multi-cylinder engine studies used to estimate potential vehicle-level impact of engine efficiency improvements.

Objective:

Develop estimates of vehicle fuel economy, energy use, and tailpipe CO_2 emissions on regulatory drive cycles to inform technoeconomic and life cycle analyses of co-optima blendstocks and provide data to aid in predictive engine model development and validation.

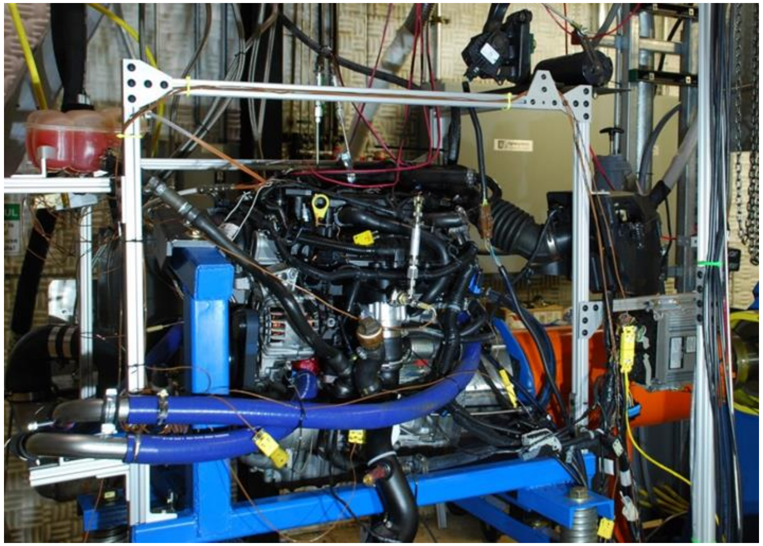
Approach:

Investigate anti-knock performance and fuel efficiency of full-boiling range fuel blends in a multi-cylinder engine. Couple engine studies with vehicle modeling using Autonomie to estimate vehicle-level impacts.

FY 18 Objectives (Ongoing investigations):

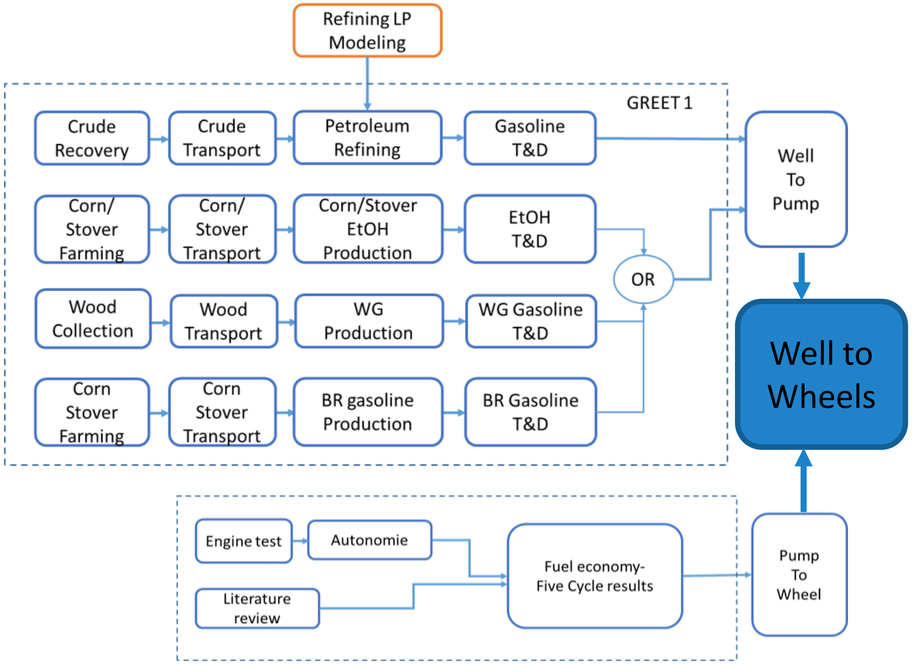
Conduct evaluation of Co-optima tier 3 blendstocks to establish estimates of engine and vehicle efficiency when these blendstocks are used.

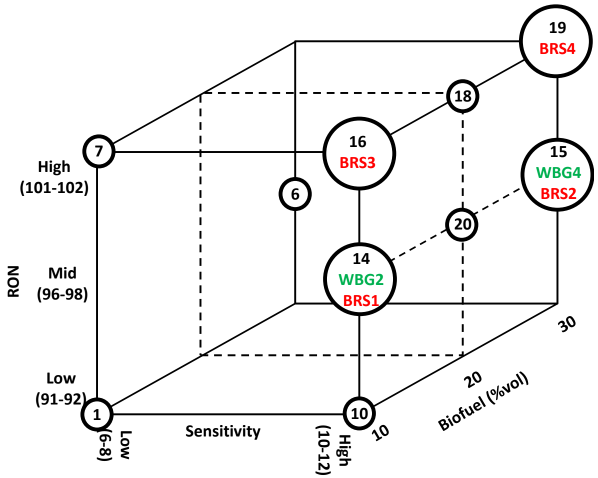
Complete synergistic U.S. DRIVE Fuels Working Group high-octane fuel well-to-



Multi-cylinder engine activities have been supporting a related U.S. DRIVE study.

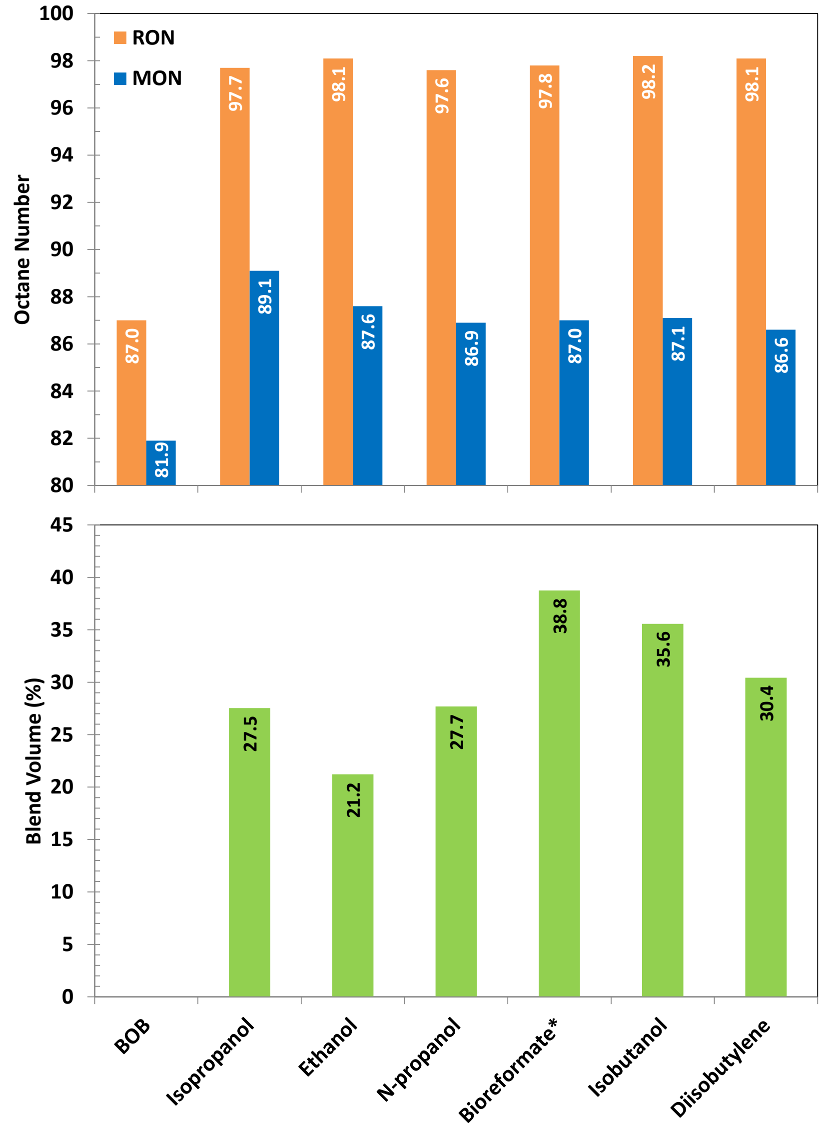
- U.S. DRIVE Fuels Working Group Study investigating well-to-wheels impact of multiple high-octane fuel formulations.
- Collaborative effort with industry, DOE, ORNL, ANL.
- ORNL supported the study with engine studies and vehicle modeling.
  - Energy use reductions are possible with all study fuels.
  - Volumetric fuel economy and tailpipe CO_2 emissions potential benefits depend on fuel formulation.
- Project final report is nearing completion.





Multi-cylinder engine studies currently focusing on evaluation of Co-optima Tier 3 blendstocks.

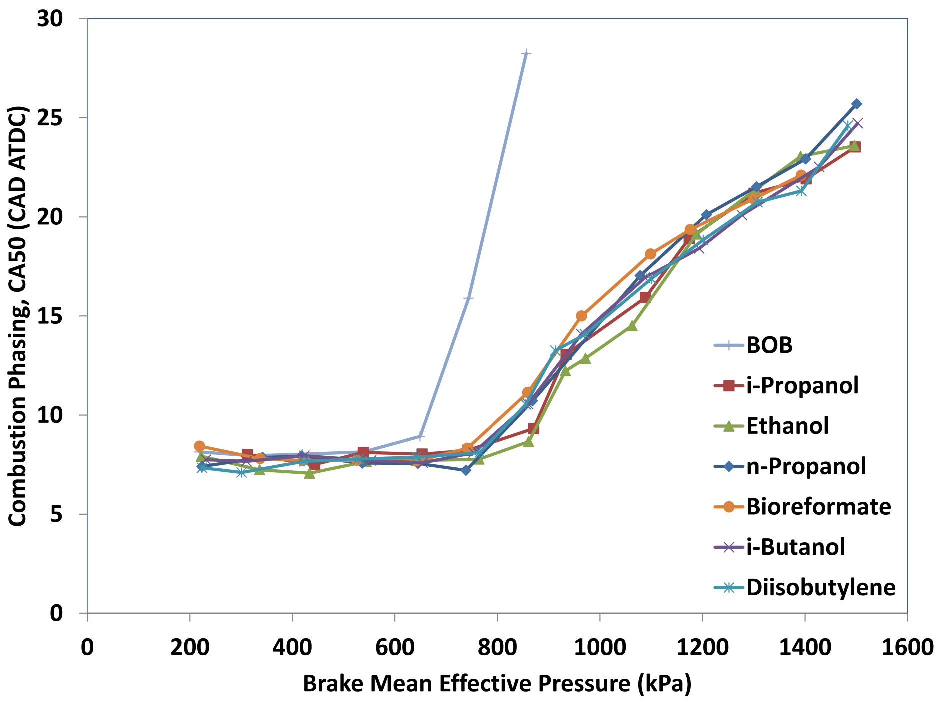
- Fuels blended using 85 AKI BOB.
- Consistent RONs within 1 ON.
- Sensitivity ~11±0.5, except isopropanol (8.6).
- Volume fractions ranging from 21.2% for ethanol to 38.8% for the bioreformate surrogate.
- Fuel distillation reveals challenges:
  - T10 too high for several fuels for vapor classes C-E.
  - Bioreformate surrogate T50 too high for vapor classes C-E.



*Bioreformate surrogate was produced from petroleum to mimic a bioreformate formulation.

Fuels blended using tier 3 blendstocks have similar combustion phasing, consistent with similar RON and MON.

- Departure from MBT region varies ~100 kPa BMEP among fuels.
- Differences of ~2 CAD as BMEP increases.
- Some differences evident in 800-1200 kPa BMEP range; further investigation is underway.
- Supports central fuel hypothesis: properties determine anti-knock performance.
- Analysis of results to estimate potential fuel economy and CO_2 benefits for these fuels is also being completed.



ORNL is using multi-cylinder engine simulations to investigate efficiency opportunities with flexible hardware.

Objectives:

(FY17) Develop model capable of accurately capturing fuel impact on knock limits.

(FY18) Map predicted engine performance with flexible hardware and advanced fuels.

Approach:

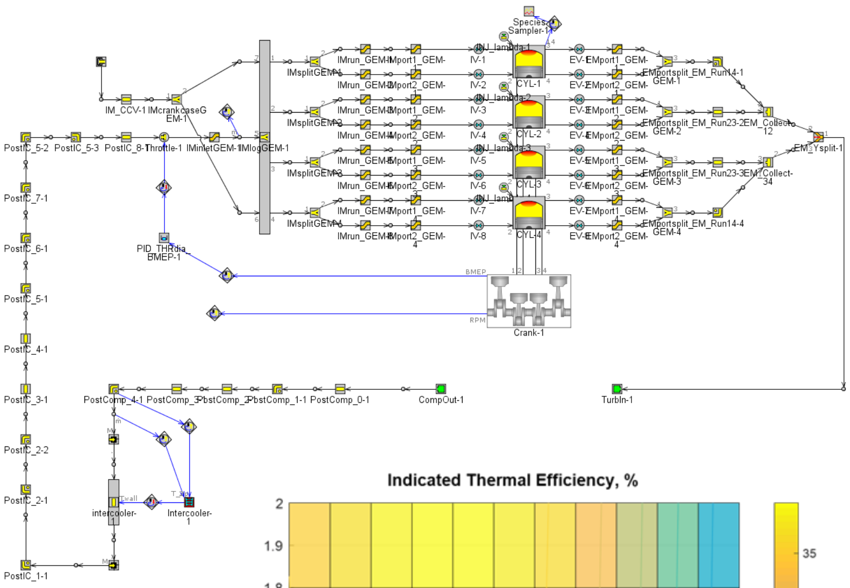
Multi-cylinder GT-Power engine model validated (including KLSA prediction) with experimental data for multiple fuels.

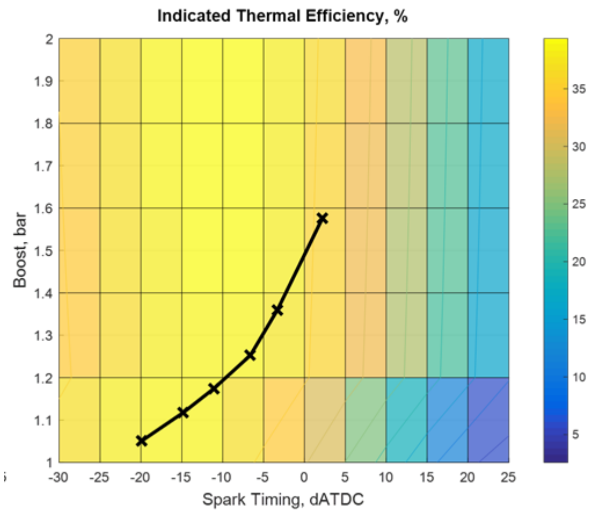
Explore opportunities for efficiency improvement and operating-range expansion with flexible hardware (variable CR, electric-assisted boost, etc.).

FY 18 Objectives (Ongoing investigations):

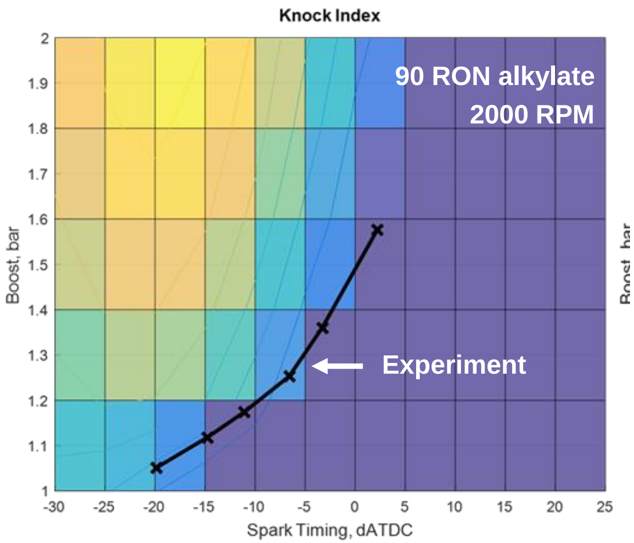
Refine approach and develop fuel maps for additional fuels.

Develop models to support multi-mode and ACI efforts.

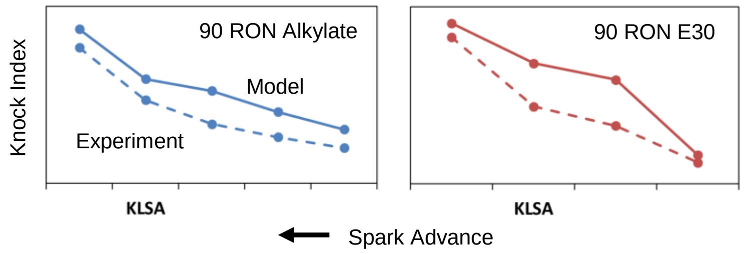




Validated model enables exploration of performance with flexible hardware and candidate fuels.

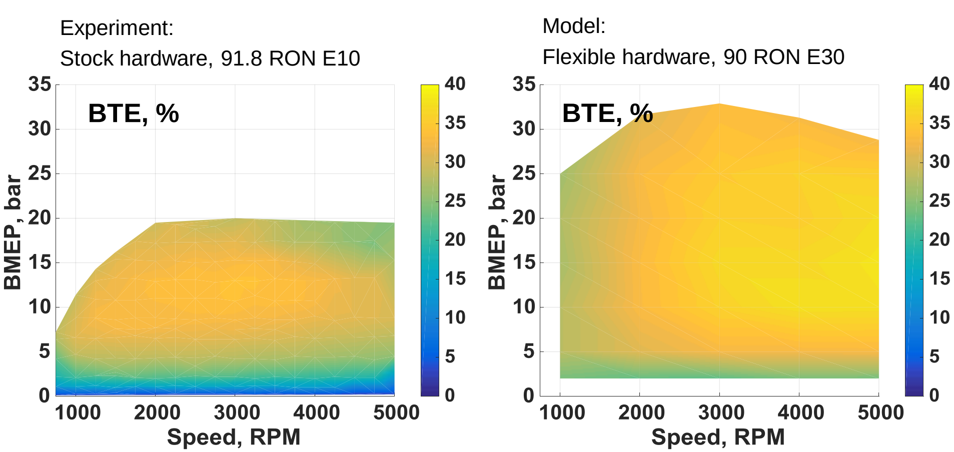


Model (contours) captures experimentally observed knock transition



- Developed GT-Power multi-cylinder model using experimental data from 1.6-L GDI engine at ORNL (Sluder)
- Validated ability of model to capture KLSA for multiple fuels (meeting FY17 Q4 milestone)

- Used validated model to explore efficiency and load expansion opportunities with flexible hardware
  - Variable compression ratio
  - Electric-assisted boost
- Developed fuel map for 90 RON, E30 fuel with limited optimization (meeting FY18 Q2 milestone)
  - Considers KLSA, max PCP, max PRR, max boost
- Map will be delivered to ANL for fuel economy simulations
  - Additional maps being developed for other candidate fuels
- Abstract submitted for ASME ICE Fall Meeting



ANL is using CFD studies of the multi-cylinder engine at ORNL to investigate numerical knock prediction and KLSA timing.

Objective:

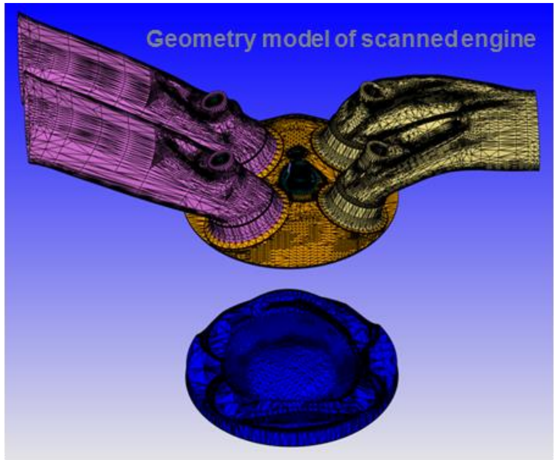
Study the fuel property impact on engine knock and thermal efficiency in a boosted SI engine.

Approach:

Use computational fluid dynamics (CFD) to predict the location and timing of autoignition using the 1.6L GTDI engine at ORNL as a typical boosted SI engine platform.

FY 18 Objectives (Ongoing investigations):

Develop a new approach to predict KLSA in CFD simulation and investigate the fuel property impact on KLSA prediction.



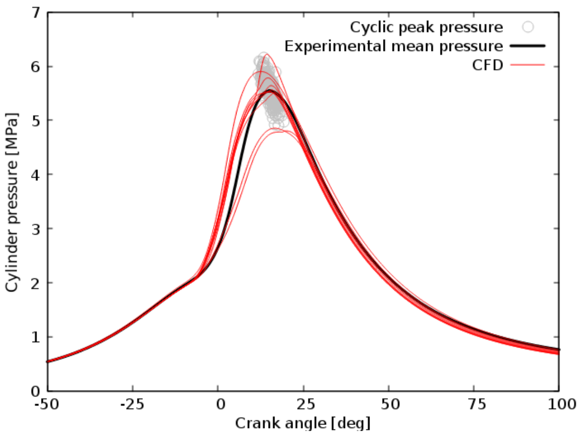
CFD model setup in Converge 2.3

Turbulence	Re-Normalization Group (RNG) k-ε model
Spray	Model constant validated against Engine Combustion Network (ECN) Spray G
Computational mesh	• Adaptive Mesh Refinement (AMR) w/ Minimum cell size: 0.5 mm; • Peak cell count: ~1.3 millions
Mach CFL	50 (turn-around time at ~1 day)
Turbulent premixed combustion model	G-equation combustion model (w/ tabulated flame speed model developed at Argonne[1]) End gas heat release and auto-ignition: Well-Mixed (WM) model with chemical kinetics
Fuel surrogate for Co-Optima Alkylate	Physical: 4-component surrogate recommended by Co-Optima fuel team (1% n-butane, 2% 1,2,4-trimethylbenzene, 4% n-pentane, 93% iso-octane by volume) Chemical: PRF97 (ERC PRF mechanism, 109 sp., 543 rxn.)

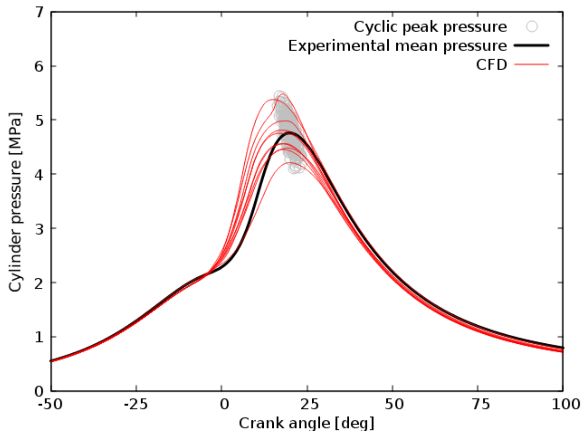
Engine operating conditions

	Medium Load	**Low Load**
Engine speed [rpm]	2000	2000
IMEP [bar]	11.5	7.5
Manifold Pressure [bar]	1.12 / 1.29 (intk. / exh.)	0.79 / 1.14 (intk. / exh.)
Spark timing [° aTDC]	-10.18, -13.47, **-14.23 (KLSA),** -15.21	**-23 (KLSA)**
Fuel mass [mg/cycle]	27.4	18.2

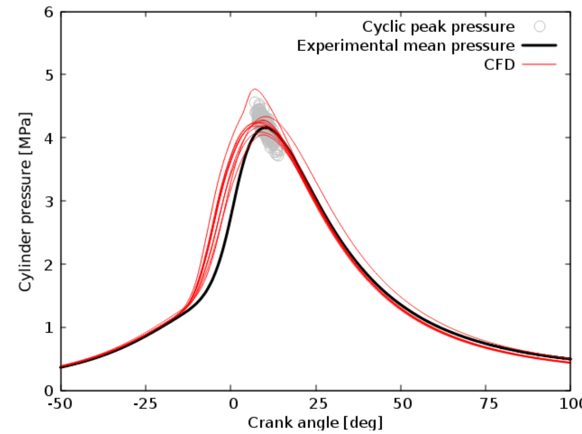
Simulations of 10 consecutive engine cycles show good agreement between the CFD model and experimental data.



Medium load, SI = -14.23 º aTDC (KLSA)

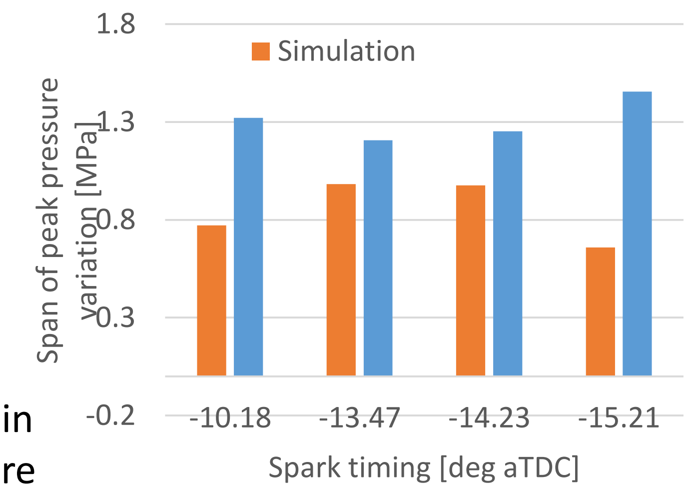


Medium load, **SI = -10.18 º aTDC**



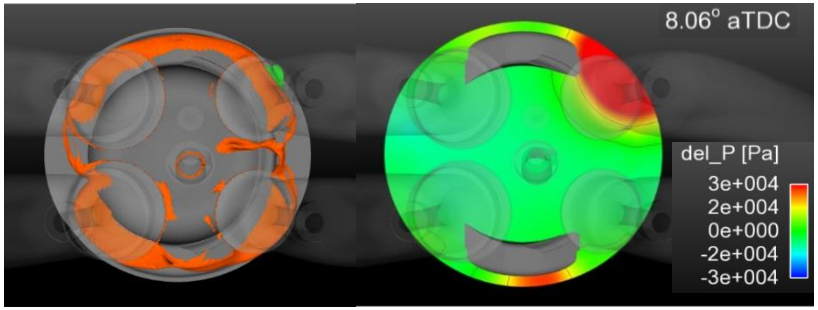
Low load, SI = -23 º aTDC (KLSA)

- ✓ Peak pressure location and magnitude
- ✓ Change in combustion phasing w/ spark timing
- ✓ Span of the cyclic variation in peak pressure
- RANS simulation represents some level of CCV
  - ✓ Refined mesh resolution with AMR and 2nd order accuracy preserve disturbance from cycle to cycle, such as variations in flows around spark, and variations in residual gas and mixture dilution rate.



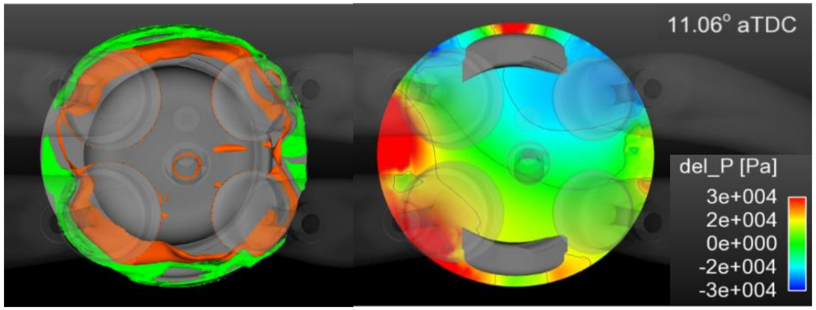
Knock onset is determined by monitoring the MAPO at 16 locations around the perimeter of the cylinder.

- Example showed for medium Load, SI = -16.2° aTDC (Experimental knock limit spark advance: -14.23° aTDC)
- Knock onset occurs at 8 ° aTDC

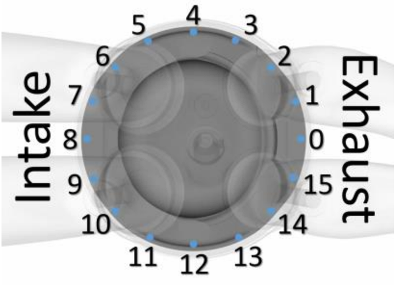


Spark-ignited flame (orange iso-surface) and end-gas ignition (green iso-surface) Pressure oscillation

- Significant pressure oscillation following knock onset

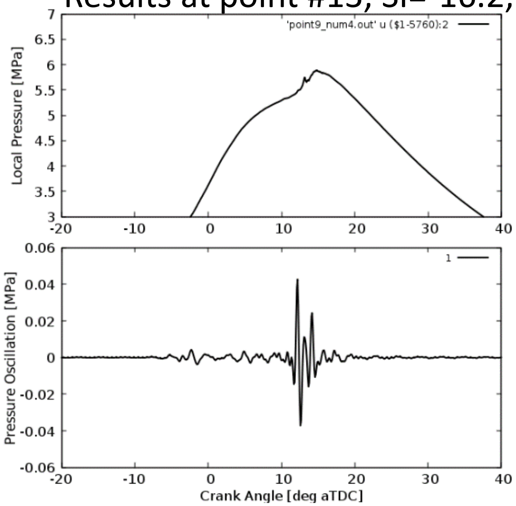


- 16 monitor points are set up along the liner to record local pressure oscillation in simulations



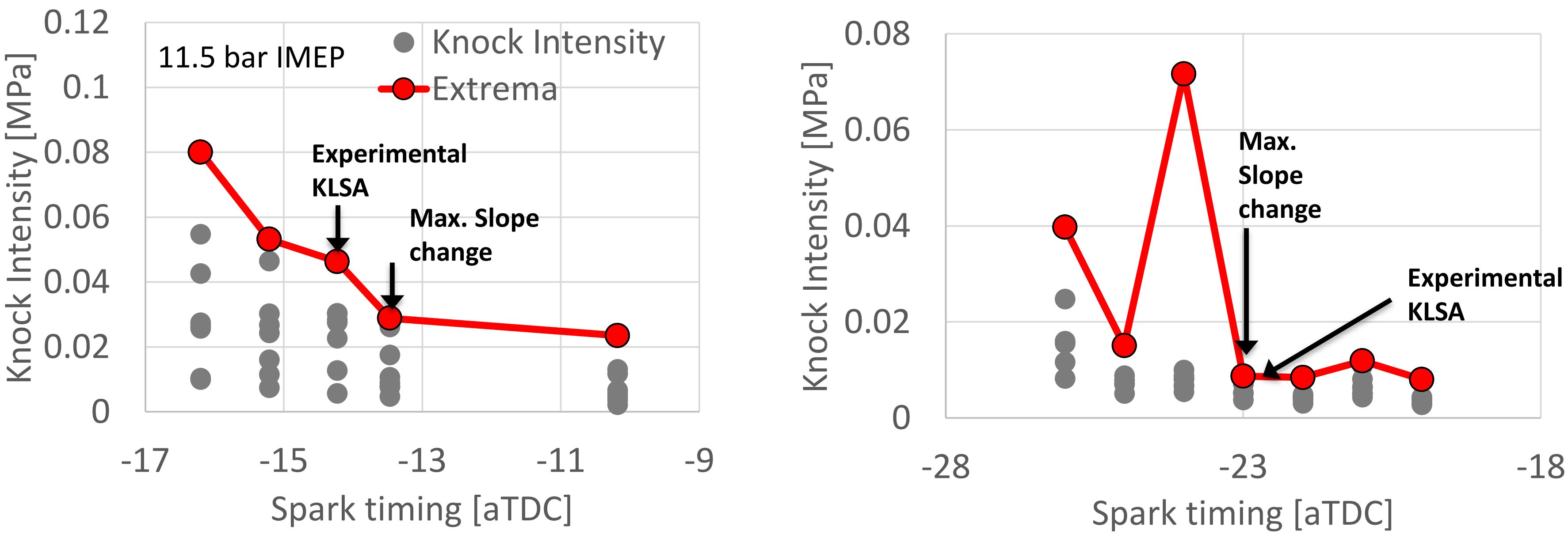
- Maximum Amplitude Pressure Oscillation (MAPO) analysis (4~20 kHz band filter applied in frequency domain)

Results at point #13, SI=-16.2, Cycle 8



A new approach to predict KLSA numerically has been developed and shown to agree well with experimental data.

- Maximum slope change point in the knock intensity extrema is a good indicator for KLSA
  - ✓ Multi-cycle simulation is required to capture the variations in knock intensity
- Less sensitive to time-stepping scheme, allow the use of large CFD time-step to achieve fast turn-around time
  - ✓ Current simulations use CFL = 50, and each engine cycle finishes within ~1 day on 80 cores



[2] Yue et al., submitted to ASME-ICEF 2018

ANL is using Autonomie in to help Co-optima demonstrate progress toward its goals for fuel economy improvement.

Objective:

Estimate vehicle fuel economy impacts of Co-optima program.

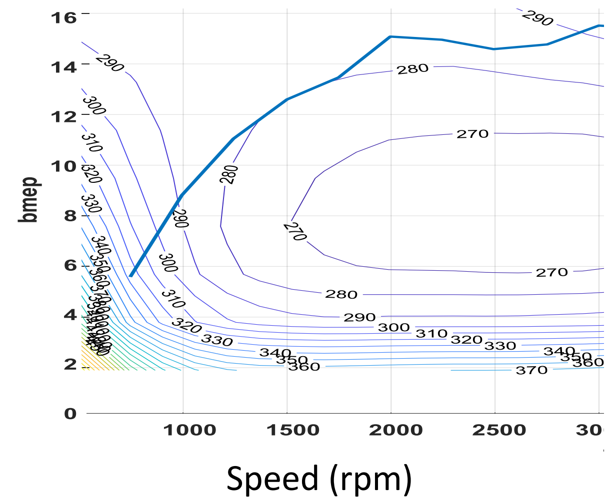
Approach:

Incorporate engine maps developed through Co-optima experiments and modeling in the Autonomie environment to evaluate fuel economy improvements.

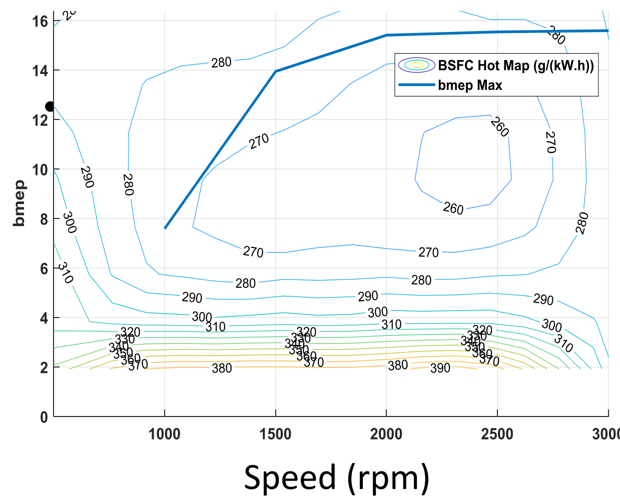
FY 18 Objectives (Ongoing investigations):

Initial evaluations used maps generated at ORNL using engine experiments; subsequent evaluations will make use of maps developed through modeling that reflect a greater degree of co-optimization of fuels and engines.

- 1.6L EcoBoost
- CR10.1
- 91.8 RON E10



Fuel maps are converted to gasoline equivalent values.



- 1.6L EcoBoost
- CR11.4
- 97 RON E20

Co-Optima Engine Technology Provides estimated 8% Improvement in Fuel Economy in a Midsize Sedan.

- Vehicle simulated with Autonomie to estimate the fuel consumption benefits on the US Standard driving cycles under hot conditions
- Results indicate a potential gasoline-gallon equivalent fuel economy improvement of 8% (equivalent to 9.25% fuel consumption) compared to the baseline engine.
- These results are consistent with the overall program targets

Unadjusted mpgge

	UDDS	HWFET	Combined	Condition
Baseline	26.61	38.3	30.85	CR10, 91 RON E10
Co-Optima	29.12	40.5	33.33	CR11.4, 97 RON E20
% Diff	9.4%	5.7%	8.0%	

- Vehicle Characteristics
  - Powertrain: Conventional
  - Gearbox: 6 speed automatic with early lockup
  - Drag: 0.3
  - Roll: 0.009
  - 0-60mph in 9sec

Kinetics Used to Explain Reduced Effectiveness of EGR Under Boosted Operating Conditions

Objective:

Develop a better understanding of the impact of EGR on knock in SI engines

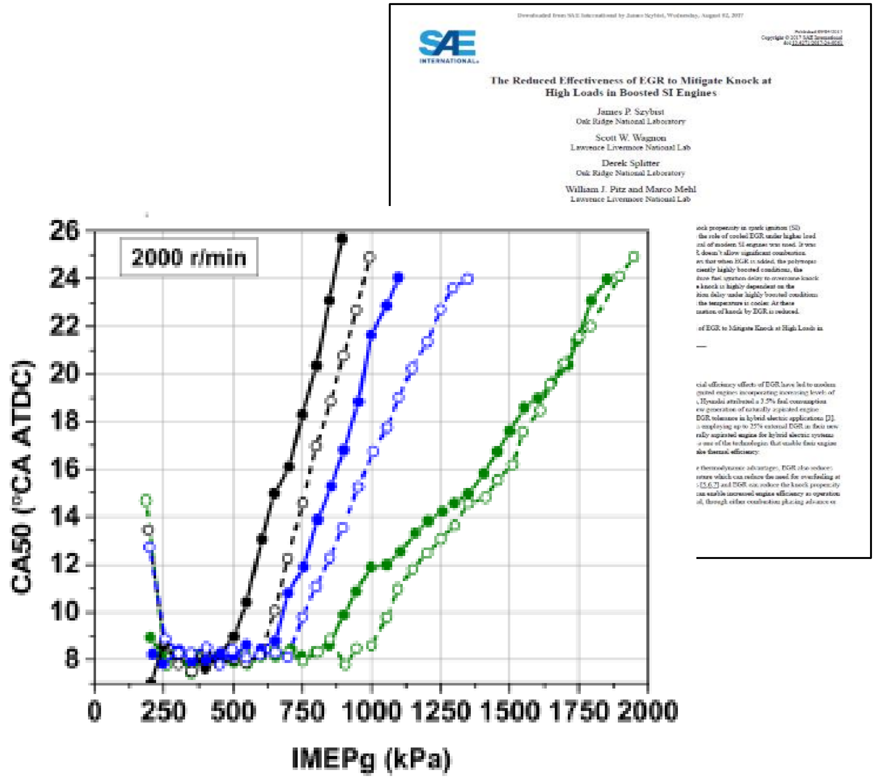
Approach:

Investigate knock-limited phasing under boosted conditions with and without EGR in a single-cylinder DI engine (GM LNF, 0.5 L displacement / cylinder)

Collaborate with LLNL to provide a kinetics-basis for observed trends and establish expectations

FY 18 Objectives (Ongoing investigations):

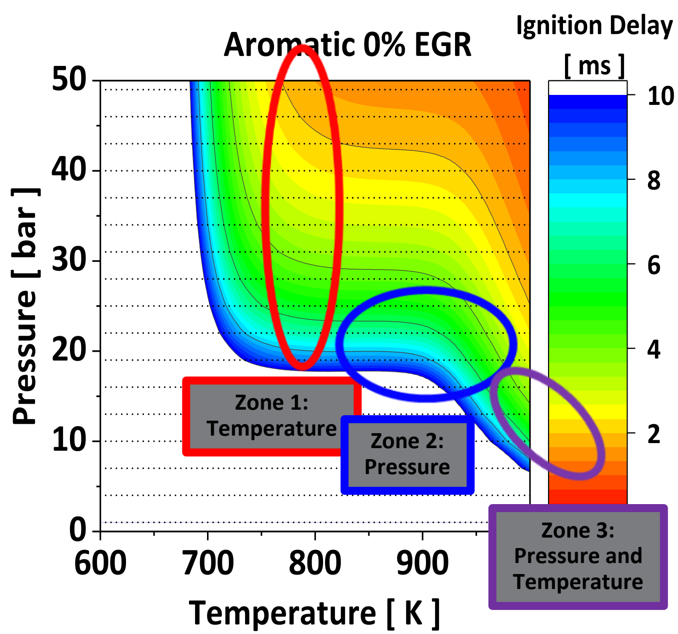
Develop a better kinetics-based understanding of the octane index, including high S BOB with modest RON



- Mixed literature on impact of EGR to mitigate knock
- Close examination shows EGR can mitigate knock in naturally aspirated engines, but loses effectiveness under boost
- This study provides kinetics-based explanation of observed trends

Analyzing Constant Volume Ignition Delay Contours Allows Us to Identify 3 Zones of Ignition Chemistry

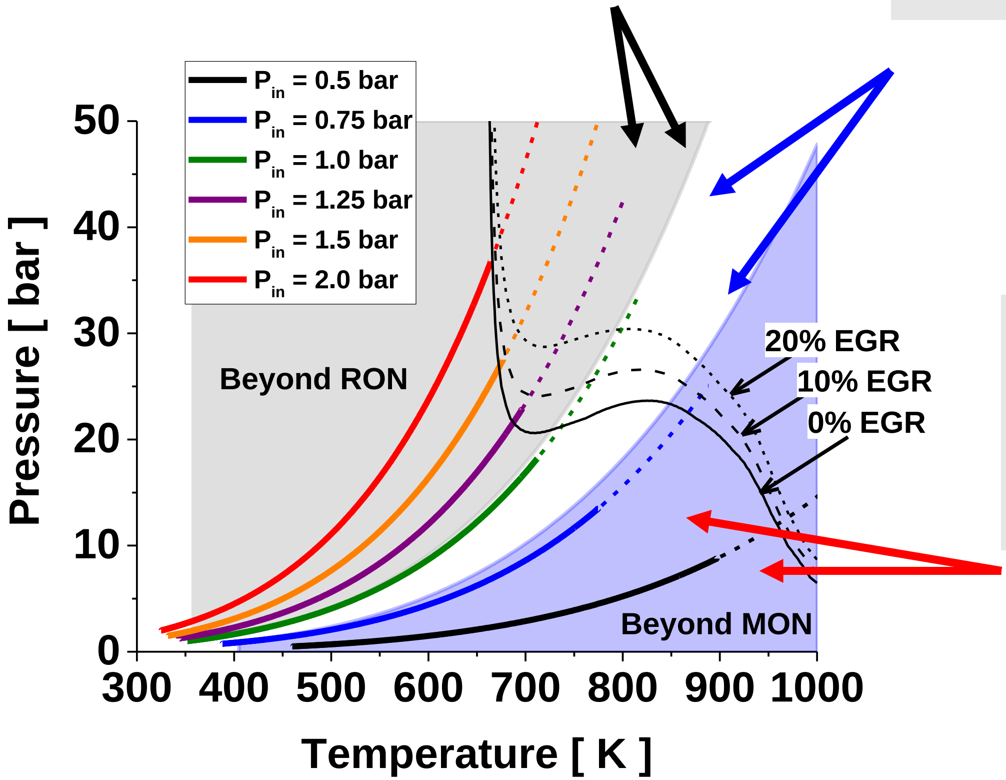
- Ignition delay calculations performed by LLNL team (Scott Wagnon, Bill Pitz, Marco Mehl)
- Zone 1: Ignition delay contours are nearly vertical
  - Very sensitive to temperature, less sensitive to pressure
  - In this region, LTHR is promoted because alkylperoxide and hydroperoxide radicals are relatively stable
- Zone 2: Ignition delay contours are nearly horizontal
  - Sensitive to pressure, less sensitive to temperature
  - In this region alkylperoxide and hydroperoxide radicals are thermally unstable, decreasing LTHR propensity
- Zone 3: Ignition delay is a strong function of both temperature and pressure
  - Exhibits third-body enhanced formation of hydroperoxyl radicals
  - Leads to the formation of hydrogen peroxide



Boosted "Beyond RON" Conditions Interact with Ignition Zone 1, Minimal Impact on Knock

- Higher levels of boost interact with ignition Zone 1
- At these conditions, EGR becomes increasingly ineffective at mitigating knock

- WOT and modestly boosted operation interacts with Zone 2
- EGR is highly effective at knock-mitigation
- Conditions similar to where EGR is shown to be effective at mitigating knock



- Throttled operation interacts with ignition zone 3
- The operating conditions are typically far away from autoignition (i.e., not knock-limited)

Implication: EGR is Effective at Mitigating Knock under Naturally Aspirated and Lightly Boosted Conditions, but Not at Higher Boost

- For engines designed for NA or lightly boosted operation, this work confirms that EGR is reliably effective at suppressing knock across different fuels
  - Knock mitigation allows higher compression ratio and higher efficiency (Toyota is reporting NA engines with high EGR and high CR producing 40% BTE)
  - Currently, the majority of engines are naturally aspirated, but this is a declining market share
- For engines that are aggressively boosted, EGR will not be effective at suppressing knock
  - Pressure-temperature trajectory begins interacting with a different region of kinetics that isn't impacted sufficiently by EGR (LTHR production)
  - These engines can still realize pumping benefits of EGR at light loads, but will be unable to realize the efficiency improvements associated with a higher compression ratio

NREL studies are also focusing on the kinetics of ignition, but with a differing approach.

<u>Objective:</u>

Develop better understanding of how parametric ignition delay measurements may more fully predict SI engine knock limits than octane index.

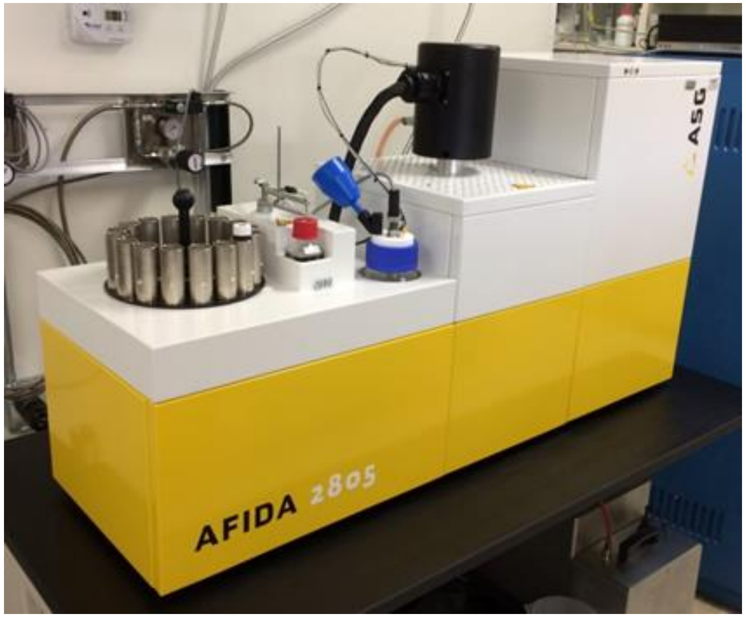
<u>Approach:</u>

Combine AFIDA measurements with single-cylinder engine data and modeling to predict onset of autoignition.

<u>FY 18 Objectives (Ongoing investigations):</u>

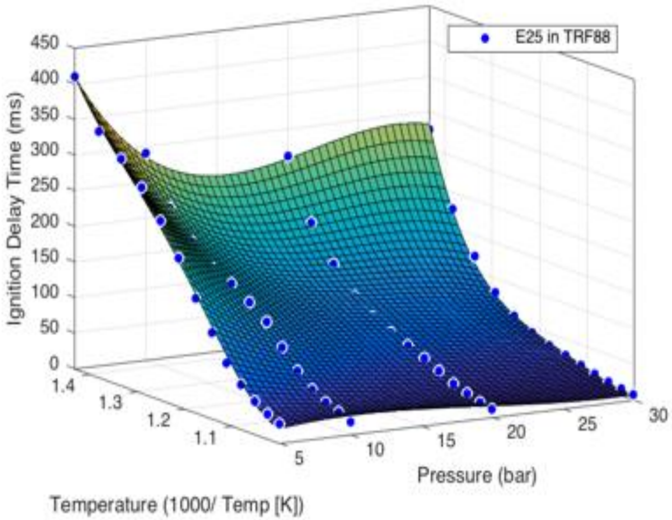
Map ignition delay to Indicated Cetane Number (new AFIDA-based measurement) for mixed mode and ACI fuels, and new RON and S correlation points (developed by NREL in FY18) for SI and mixed mode fuels to provide tie points to engine-based standard tests.

Integrate ignition delay data with engine data to facilitate predictive calculations describing knock limited SI engine operation, plus predicted ignition for ACI strategies (i.e., GCI) using engine data shared from other labs.

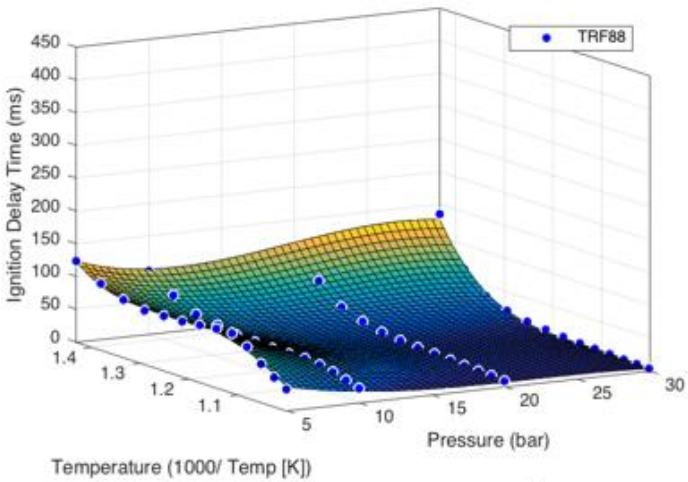


NREL shifted most bench-scale experimental fuel ignition studies to the Advanced Fuel Ignition Delay Analyzer (AFIDA).

- Expands experimental capability beyond the Ignition Quality Tester (IQT)
  - Higher temperatures and pressures (1000 K, 50 bar)
  - Enable study of full boiling range gasoline blends
- Gasoline range surrogate blends with various oxygenates that NREL studied in the single-cylinder GDI engine (examining RON, S, and HOV effects on knock limits) were studied in the AFIDA.
- Parametric (T, P, ϕ, X_{O2}) sweeps of ignition delay were studied, including low temperature heat release analysis of pressure curves.



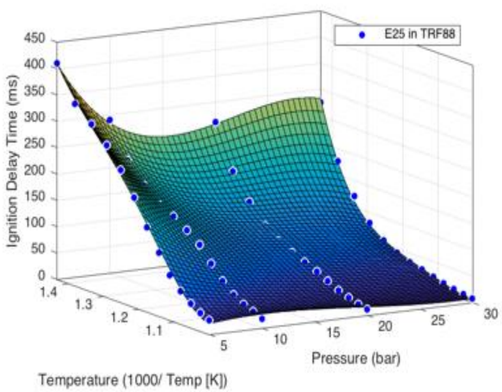
RON=101.6; S=10.7



RON=87; S=5.2

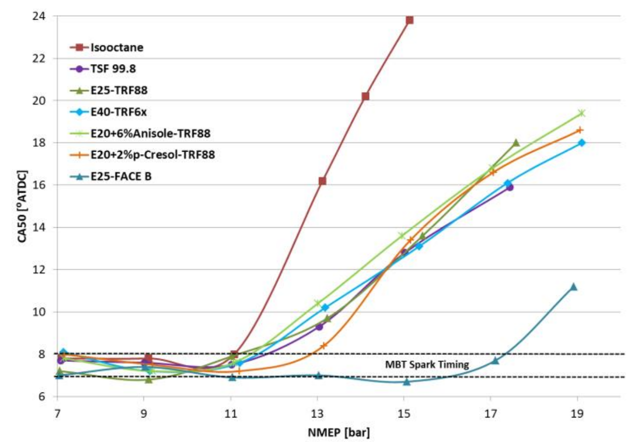
A 0D, two-zone engine simulation integrates bench-scale (AFIDA, IQT) ignition delay data with engine input data.

- Experimental engine pressure trace data is fed to the model to calculate predicted end-gas knock following ignition using a modified Livengood-Wu knock integral calculation.
- Simulation has continued development in collaboration with the Co-Optima Toolkit team (Grout).
- We are beginning to expand this approach to Advanced CI fuels / engine data.

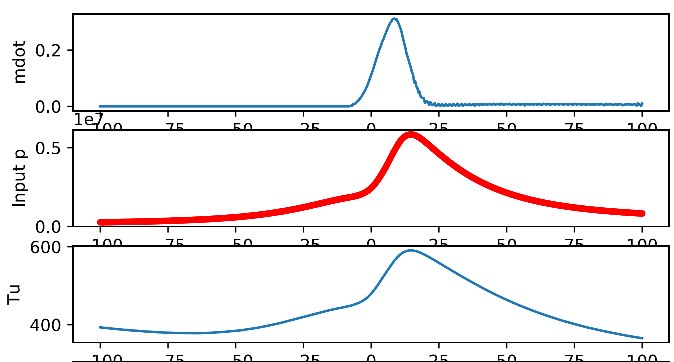


Bench-scale ignition delay data

Knock integral modeling in engine simulations



GDI SCE engine data



Simulations with knock-integral model

Furthering the understanding of pre-spark heat release and its impact on abnormal combustion events in SI engines.

Objective:

Develop a phenomenological understanding of molecular structure and fuel property effects on abnormal stochastic ignition and combustion event frequency and intensity

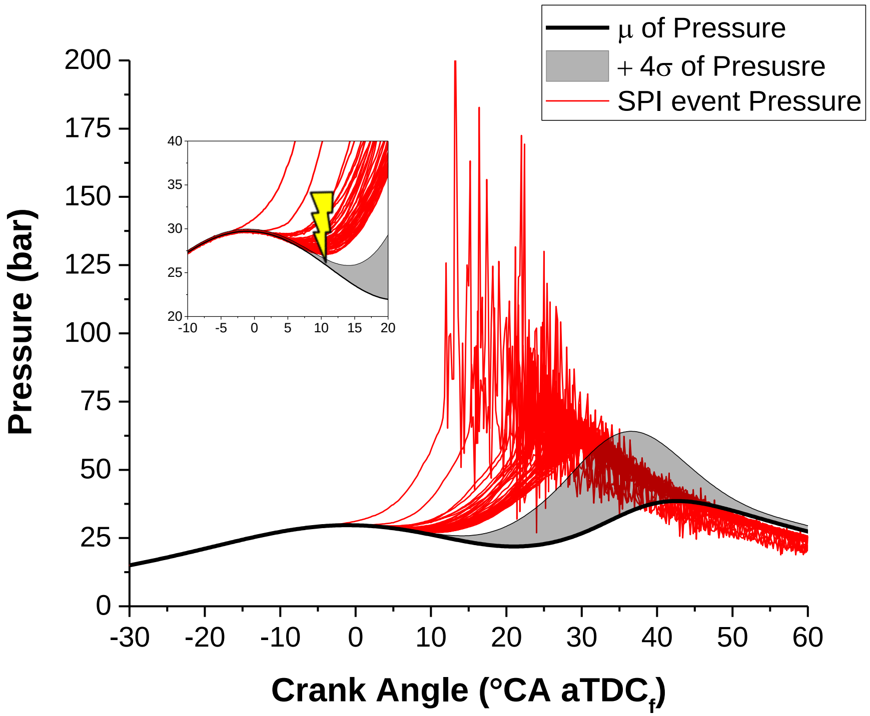
Approach:

Perform combustion experiments at engine conditions relevant to abnormal combustion and ignition in a modern engine(s)

Quantify abnormal combustion tendency and intensity

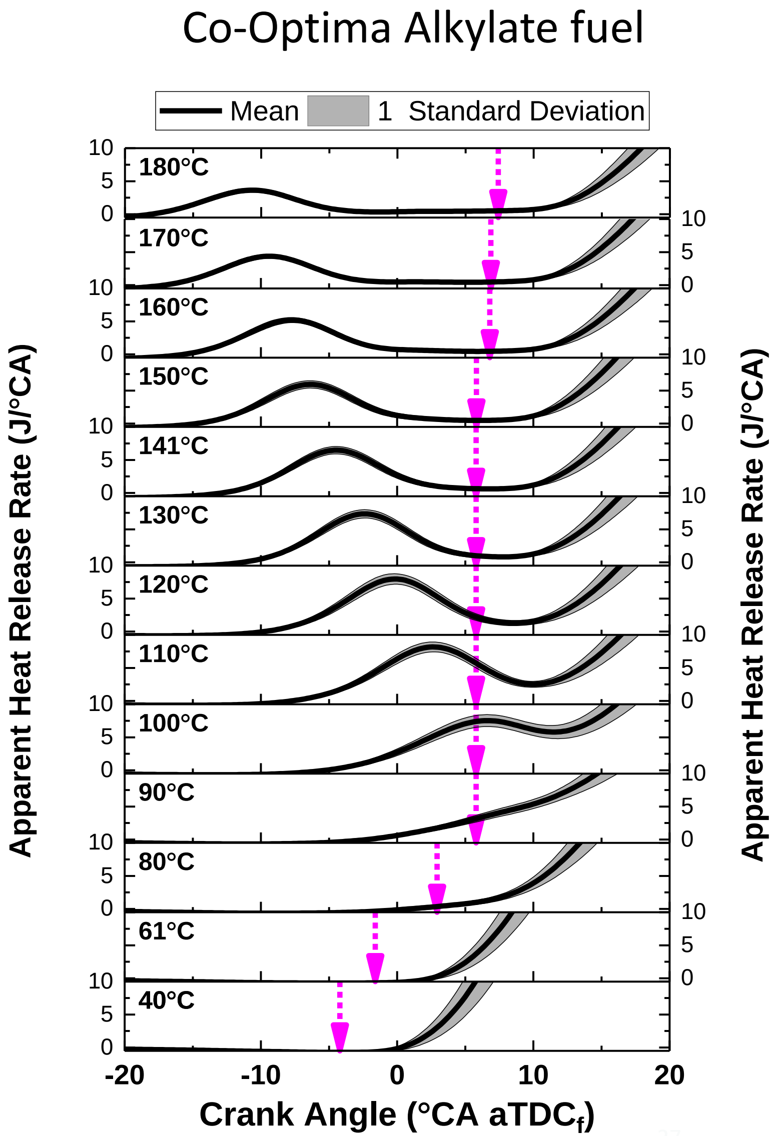
FY 18 Objectives (Ongoing investigations):

Develop an understanding of fuel properties effects on bulk gas kinetic state and abnormal combustion event propensity and magnitude.



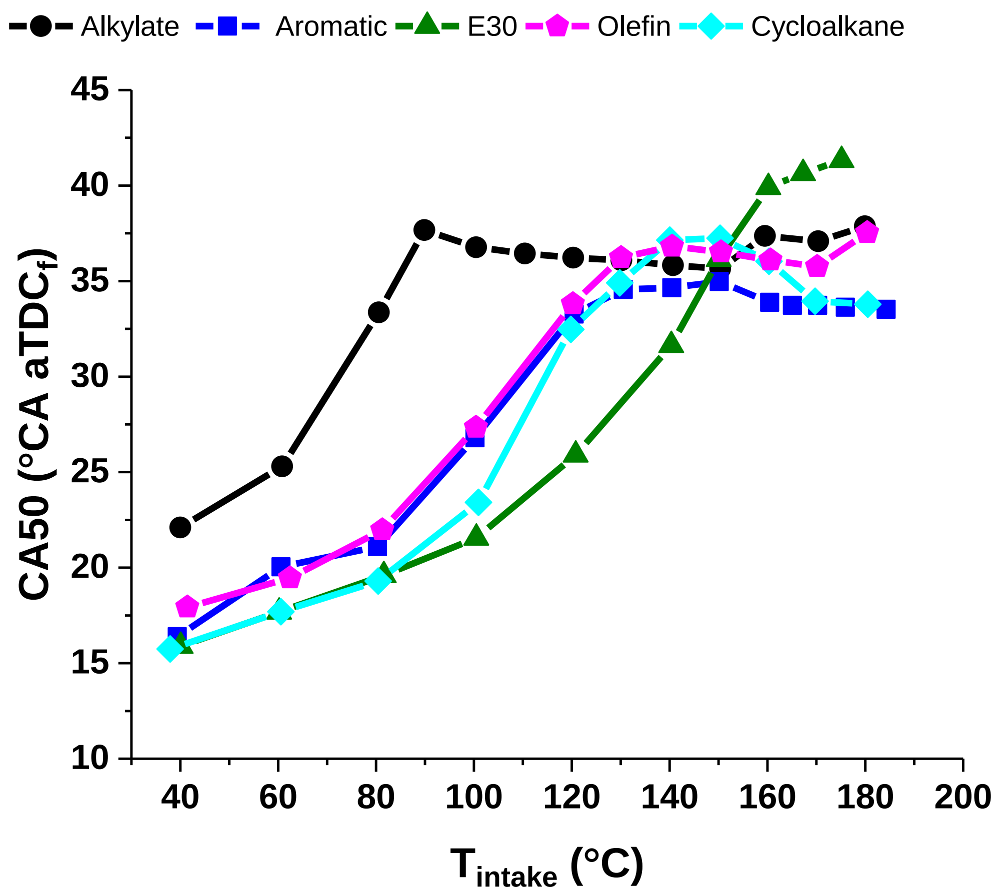
Pre-spark heat release is correlated with abnormal combustion events but its contribution is not well understood.

- Pre-spark heat release (PSHR) can occur at high intake temperatures and loads.
  - PSHR affects in-cylinder composition and temperature.
- Occurrence of PSHR can indicate conditions prone to LSPI or increased knock.
- Combustion phasing retard for knock control was reduced/decoupled once PSHR occurred.
- All Co-Optima core fuels screened for PSHR at KLSA timing at 20 bar IMEP by sweeping intake temperature from 40-180°C.
- All Co-Optima fuels exhibited PSHR at elevated temperatures, but fuel-specific differences were observed.



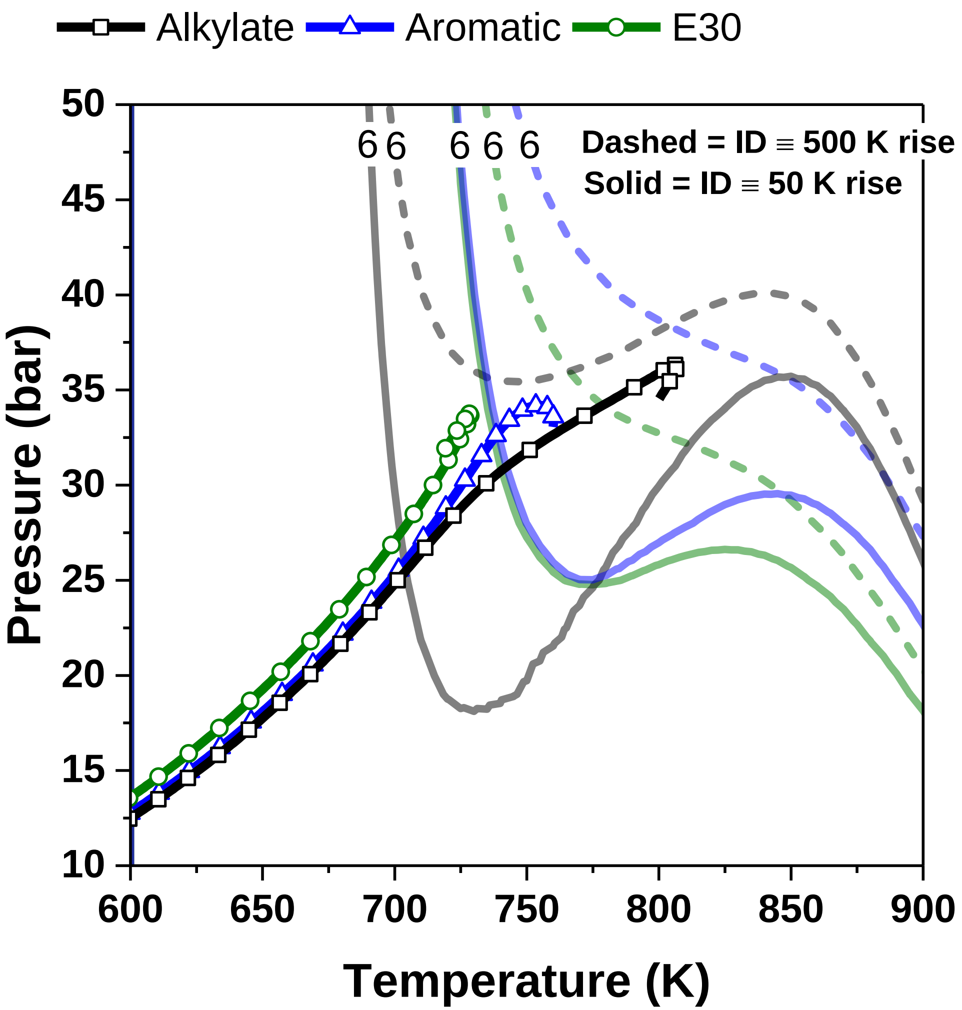
Studies with co-optima "core" fuels show that beyond a threshold temperature, knock-limited CA50 tends to stabilize.

- CA50 is retarded to avoid autoignition as temperature increases, but stabilizes at elevated temperatures.
  - Rate of retard and threshold temperature are fuel-specific.
  - PSHR expression coincided with reduced combustion retard in all fuels.
- Trend observed with alkylate (low-S), Aromatic, Olefin, and Cycloalkane (high-S) fuels.
  - E30 is an exception. Why? Possible HoV effect?
- Stabilization of CA50 reduces rate of change of control input needed to avoid violent abnormal combustion events.



The requirement for rapid CA50 retard for E30 is attributed to fast transition into high temperature heat release.

- E30 transition to high temperature ignition is faster than other fuels.
  - LTHR and PSHR "heating" causes E30 to more closely approach ignition.
- PSHR is more difficult to achieve for E30, but has more dramatic effect on combustion P,T trajectories.
- Study of underlying linkages between PSHR and abnormal combustion (knock and LSPI) are next step.



Responses to Previous Year Reviewer's Comments

- Most comments were positive.
- One reviewer suggested that the program include differing hydrocarbons, whether they are bio-derived or not.
  - *Several of the Tier 3 blendstocks could be produced through multiple pathways, some non-biological. "Co-optima Core Fuels" enable study of multiple HCs (aromatics, olefins, alkanes, cyclo-alkanes).*
- On reviewer highlighted the importance of performance aspects not covered by the merit function. (Driveability, cold start performance, etc.)
  - *A cold start catalyst lightoff term has been added, but the merit function was not intended to cover all aspects of performance. We've taken this suggestion into our messaging about its use.*
- One reviewer highlighted the importance of establishing the impact of octane on typical drive cycles.
  - *We continue to include assessments of potential impact of fuel properties and combustion strategies on multiple drive cycles.*
- One reviewer liked the studies of the impact of manifold temperature, but wanted information on actual values of intake manifold temperature in actual production engines.
  - *Intake manifold temperature is often used to manipulate charge temperature at intake valve closure; while production intake manifold temperatures can be elevated, the IVC temperature is also elevated by retained residuals used to reduce pumping losses.*

Collaborations

- **Co-Optimization of Fuels and Engines** brings together expertise from across the National Laboratory system, working toward a common purpose. This effort has stakeholder engagement at a high level to ensure relevance.
  - 9 laboratories: engines, fuels, kinetics, simulation, biofuel development, LCA & TEA
  - Monthly stakeholder engagement phone calls, industry listening days, external advisory board
- Projects presented at the semi-annual AEC program review meetings, discussed with industry and academia
- Engagement with ACEC Tech Team activities

Additional project-level collaborations with industry and academia

Sluder (ORNL)

Ford

USDRIVE Fuels Working Group

Coordinating Research Council

Szybist (ORNL)

FCA

Splitter (ORNL)

GM

Driven Racing Oil

Zigler (NREL)

ASG Analytik-Service Gesellschaft mbH

Bosch

Ford

GM

Coordinating Research Council

Som (ANL) / Edwards (ORNL)

Convergent Science, Inc.

Rousseau (ORNL)

Remaining Barriers and Proposed Future Research for LD SI and multimode SI/ACI Tasks

For FY19, co-optima boosted SI work will shift to multimode SI/ACI.

- Individual studies will shift focus from "stand-alone" boosted-SI to enabling multi-mode engine operation using ACI to improve part-load efficiency while retaining boosted-SI mode for peak power.
- Detailed project planning for future work was ongoing at the time of AMR slide submission.

Advanced Engine Development Team Multimode SI/ACI Goals for planning specific activities:

- Execute on integrated engine test plan that identifies fuel property and engine parameter impacts (physical experiments using a common fuel set).
- Articulate condition in which fuel property effects could impact feasible range of operation (of ACI / SI)

Any proposed future work is subject to change base on funding level.

Summary

Relevance Research into better integration of fuels and engines is critical to accelerating progress towards our economic development, energy security, and emissions goals.

Approach The co-optimization of fuels and engines program approaches its mission collaboratively among multiple institutions, using both experimental and numerical modeling tasks to further its objectives.

Accomplishments Individual task accomplishments have been presented that demonstrate substantial progress towards meeting Co-optima program goals.

Collaborations Co-optima includes researchers from 9 laboratories and 13 universities and is actively advised by an external advisory board made up of industry experts. Numerous other stakeholders also provide feedback to the program through regular conference calls.

Future Work For FY19, co-optima will shift its focus to multimode SI/ACI and towards full-time ACI for medium and heavy duty applications.

Any proposed future work is subject to change base on funding level.