2021 DOE Vehicle Technologies Office
Annual Merit Review

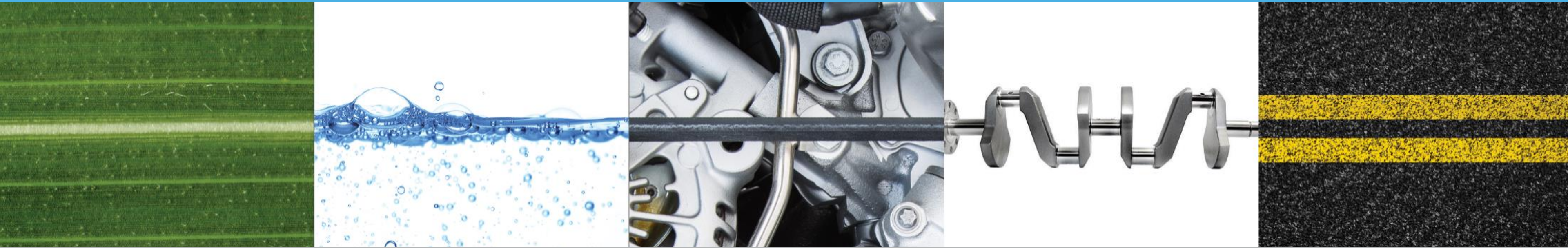
Fuel Effects in Boosted, Spark-Ignition Combustion

Presenter: James Szybist (ORNL)
Project ID #FT091

June 24, 2021

CO-OPTIMIZATION OF
FUELS & ENGINES

better fuels | better vehicles | sooner



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- Many others on the Co-Optima Team

Note on Presentation Structure

The purpose of this presentation is to provide a multi-year overview of the boosted spark-ignition research rather than a 1-year progress update. As a result, this presentation does not adhere to the typical AMR template.

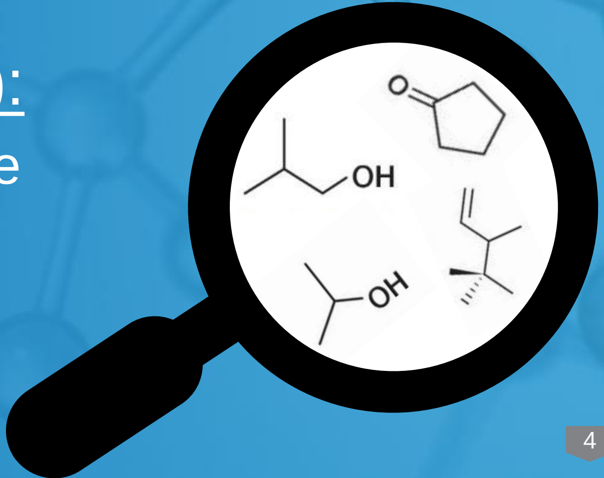
Governing Hypotheses Link Fuel Properties to Engine Efficiency

Central Engine Hypothesis:

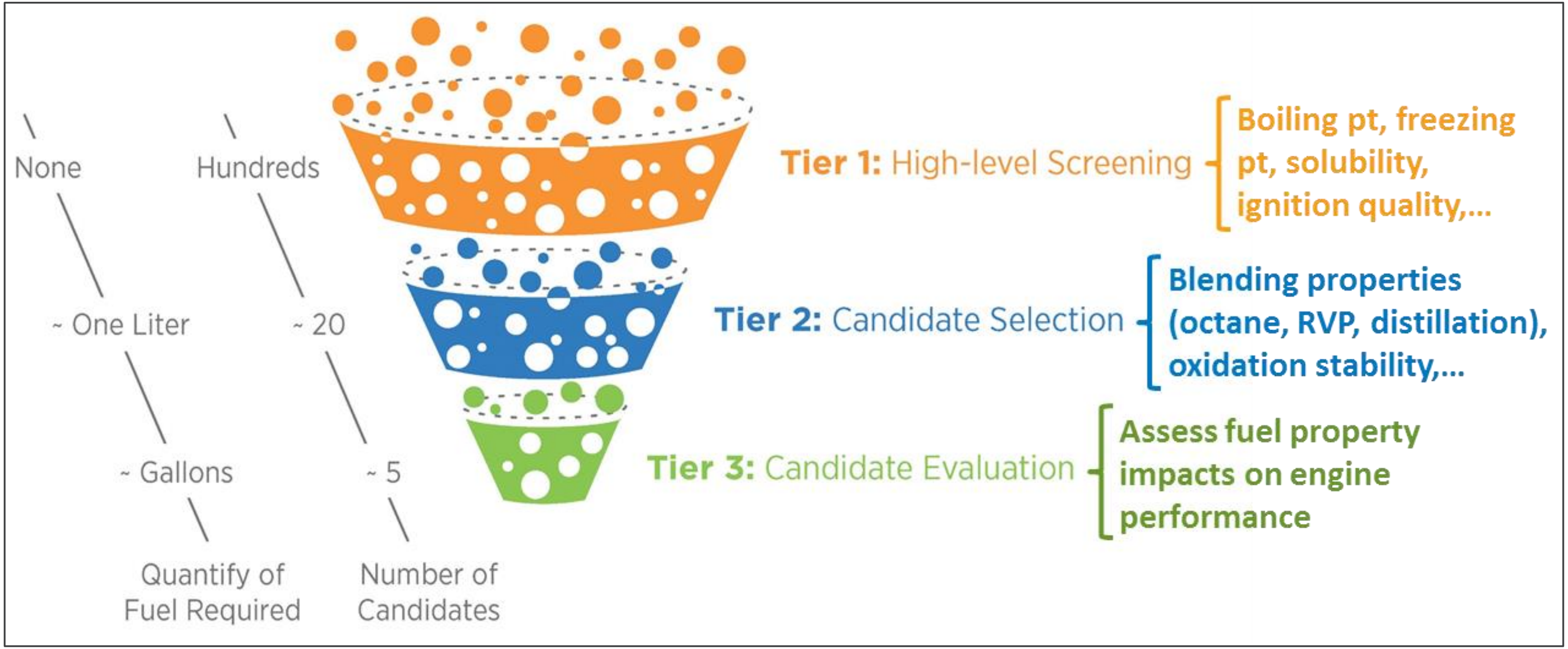
There are engine designs and operating strategies that can improve efficiency. Improved fuels can enable the use of these designs and operating strategies.

Central Fuel Property Hypothesis (CFPH):

Equivalent fuel properties will result in equivalence performance, regardless of the composition

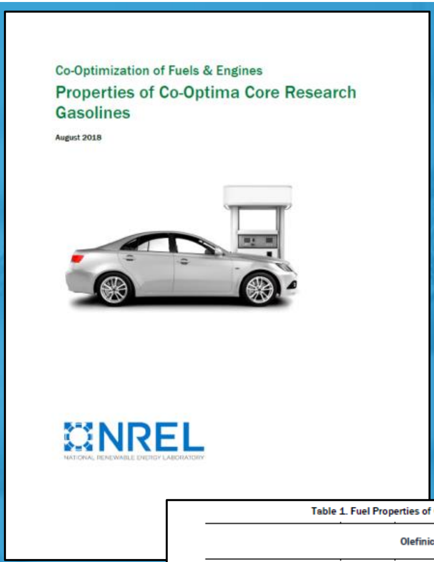


Tiered Screening Approach to Down Select from Hundreds of Candidates



Accomplishment

Matrix of Core Fuels Designed to Challenge CFPH was Used Widely Across Co-Optima


Co-Optimization of Fuels & Engines

Properties of Co-Optima Core Research Gasolines

August 2018

NREL

NATIONAL RENEWABLE ENERGY LABORATORY

Table 1. Fuel Properties of Co-Optima Core Research Gasolines

		Olefinic	E30	Aromatic	Alkylate	High cycloalkane
Specific gravity	D4052	0.7231	0.7529	0.7575	0.6969	0.7557
Density @ 15°C (g/mL)	D4052	0.7229	0.7527	0.7572	0.6968	0.7555
Index of refraction @ 20°C [4]		1.409	1.401	1.431	1.391	1.426
RON (R)	D2699	98.2	97.4	98.1	98.0	98.0
MON (M)	D2700	88.0	86.6	87.8	96.6	87.1
Octane rating	R+M/2	93.1	92.0	93.0	97.3	92.6
Octane sensitivity	R-M	10.2	10.8	10.3	1.4	10.9
Reid vapor pressure (psi)	D5191	6.10	7.66	7.17	4.15	8.00
Gross heating value (MJ/kg)	D4809	47.148	41.096	45.735	47.877	46.018
Net heating value (MJ/kg)	D4809	44.071	38.170	42.952	44.524	43.208
HOV (measured) (kJ/kg)		337	565	412	309	393
HOV (calc. from DHA) (kJ/kg)		330	532	361	308	370
PMI		1.004	1.275	1.803	0.221	1.491
Yield sooting index [11]		80.95	47.86	114.9	60.91	97.92

https://www.nrel.gov/docs/fy18osti/71341.pdf

- Core fuels represent the major chemical families of fuel candidates

Alkane	Aromatic	Alcohol	Olefin	Naphthene

  - Same nominal research octane number (RON): 98
  - Four fuels with same nominal octane sensitivity (S_{octane}): 10.5
  - Range of heat of vaporization (HoV)
  - Range of particulate matter index (PMI)

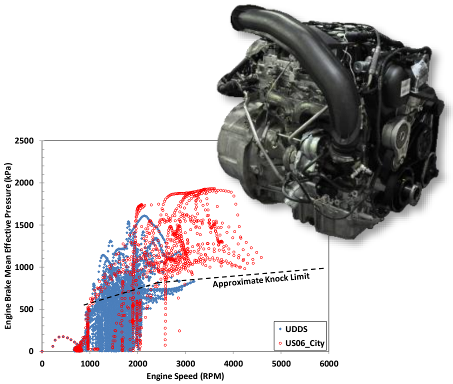
- Heavily used throughout Co-Optima initiative
  - Used at 6 national labs, numerous universities
  - LLNL developed a kinetic model and surrogate formulations for each core fuel
  - >20 publications

Accomplishment

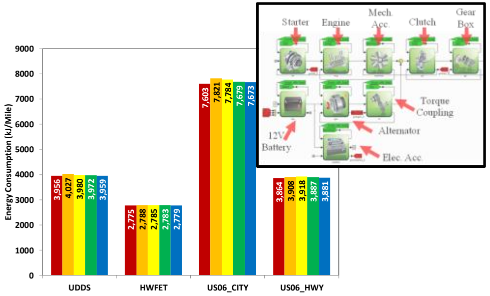
Fuel Effects of Biofuels Evaluated in Collaboration with Industry

Produce Fuels

Generate Engine Maps



Project Fuel Economy



- Quantified efficiency benefits of up to 9.9% in collaboration with industry
  - Affirmed central engine hypothesis
  - Affirmed CFPH

Projected Engine Efficiency Increase (%)	Ethanol	n-Propanol	Isopropanol	Isobutanol	Diisobutylene	Bioref. Surr.
95 RON						
Leone et al.	3.1	2.9	2.9	2.8	2.4	2.4
Co-optima Merit	3.3	3.7	2.6	3.7	3.3	3.3
97 RON						
Leone et al.	4.6	4.3	4.3	4.1	3.6	3.6
Co-optima Merit	5.6	6.1	4.4	6.0	5.4	5.2
100 RON						
Leone et al.	6.4	6.1	6.0	5.8	5.0	5.0
Co-optima Merit	9.3	9.9	7.1	9.6	8.7	7.8

Projected Volumetric Fuel Economy Increase (%)	Ethanol	n-Propanol	Isopropanol	Isobutanol	Diisobutylene	Bioref. Surr.
95 RON						
Leone et al.	1.9	2.7	1.8	2.7	6.0	9.9
Co-optima Merit	2.1	3.5	1.4	3.6	6.8	10.9
97 RON						
Leone et al.	1.5	2.7	1.4	2.7	7.2	12.4
Co-optima Merit	2.6	4.4	1.6	4.6	9.1	14.1
100 RON						
Leone et al.	0.0	1.4	-0.2	1.9	8.6	15.8
Co-optima Merit	2.7	5.0	0.8	5.6	12.4	19.0

Projected Tailpipe CO_2 Emissions Decrease (%)	Ethanol	n-Propanol	Isopropanol	Isobutanol	Diisobutylene	Bioref. Surr.
95 RON						
Leone et al.	3.0	2.8	3.1	2.9	2.0	-2.0
Co-optima Merit	3.2	3.5	2.7	3.7	2.8	-1.1
97 RON						
Leone et al.	4.3	4.0	4.4	4.2	3.1	-2.1
Co-optima Merit	5.3	5.6	4.6	5.9	4.8	-0.5
100 RON						
Leone et al.	5.9	5.7	6.2	5.8	4.2	-2.8
Co-optima Merit	8.4	8.9	7.2	9.1	7.5	0.0

https://www.energy.gov/eere/vehicles/downloads/us-drive-fuels-working-group-high-octane-reports

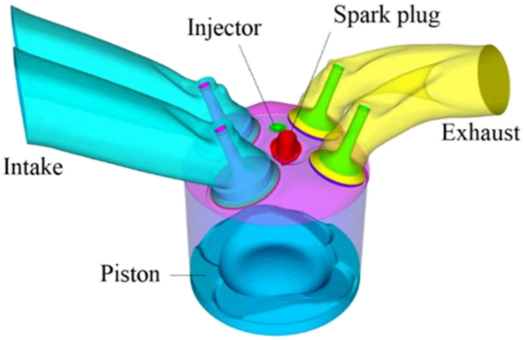
Accomplishment

Transported Livengood-Wu Modeling Methodology Developed

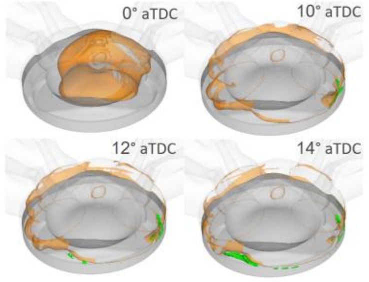
An accurate and low-cost CFD modeling approach developed for KLSA prediction

- G-equation for efficient combustion modeling
- Transported Livengood-Wu (LW) integral for knock modeling
- Automatically switch between single- and two-stage LW integrals for fuels with simple and complex ignition behaviors
- **Key advantage**: no detailed chemistry or Mach CFL constraint are needed → Low computational cost

ORNL Engine Geometry

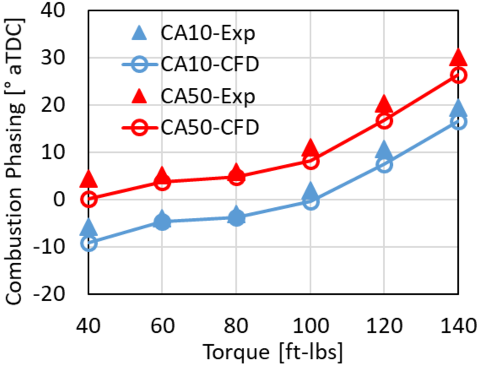


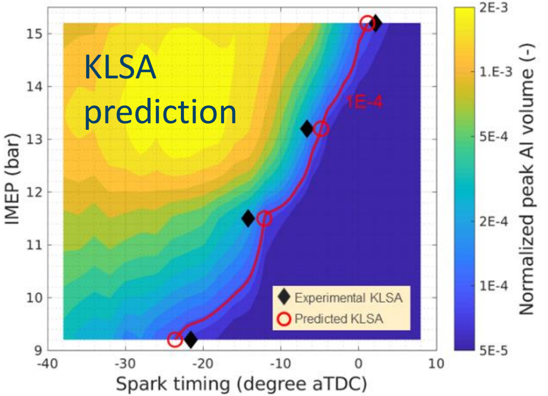
Livengood-Wu model predictions



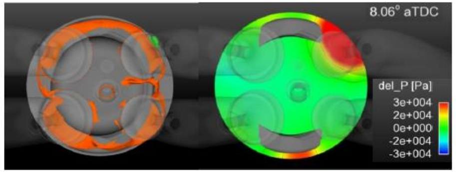
Orange: flame front
Green: end-gas auto-ignition

CFD model validation





Knock detected in end-gas with detailed chemistry



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

Yue et al, *J. Energy Resour. Technol.*, 2019, doi:10.1115/1.4043393
Yue & Som, *Applied Energy*, 2021, doi:10.1016/j.apenergy.2019.114221
Yue et al., *J. Eng. Gas Turbines Power*, 2021, doi:10.1115/1.4050583

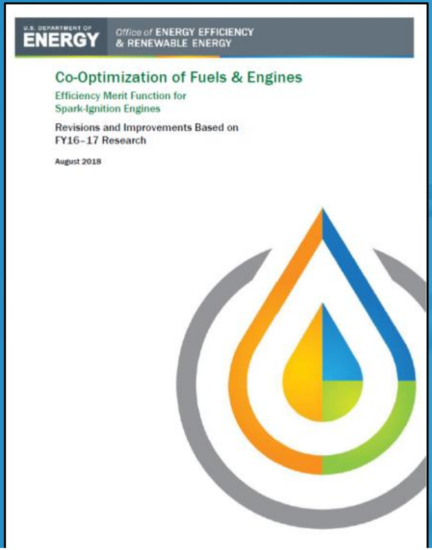
Attributing Efficiency Potential of Individual Fuel Properties using Merit Function

Fuel Properties Quantified for Efficiency

- Research octane number (RON)
- Octane sensitivity (S_{octane})
- Heat of vaporization (HoV)
- Laminar flame speed
- Catalyst light-off temperature
- Particulate matter index (PMI)

Basis for Fuel Property Effects

- Increased compression ratio (r_c)
- Downsizing and downspeeding
- Dilute combustion
- Cold start emissions compliance
- Particulate emissions compliance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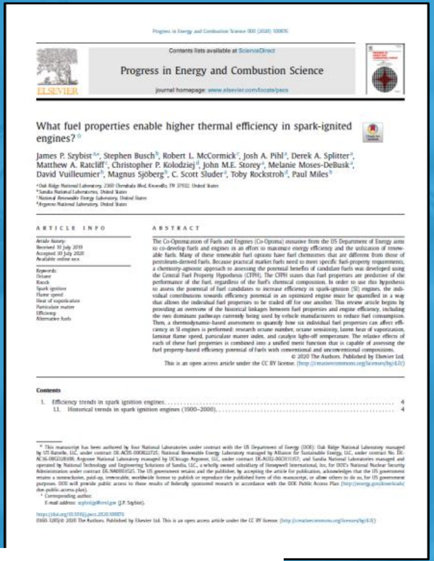
Co-Optimization of Fuels & Engines

Efficiency Merit Function for Spark-Ignition Engines

Revisions and Improvements Based on FY16–17 Research

August 2018

https://www.nrel.gov/docs/fy18osti/67584.pdf


Progress in Energy and Combustion Science

What fuel properties enable higher thermal efficiency in spark-ignited engines?

James P. Szybist, Stephen Busch, Robert L. McCormick, Josh A. Pihl, Derek A. Splitter, Matthew A. Ratcliff, Christopher P. Kolodziej, John M.E. Storey, Melanie Moses-DeBusk, David Vuilleumier, Magnus Sjöberg, C. Scott Sluder, Toby Rockstroh, Paul Miles

10.1016/j.pecs.2020.100876

Accomplishment Octane Index Found to Correlate to Knock

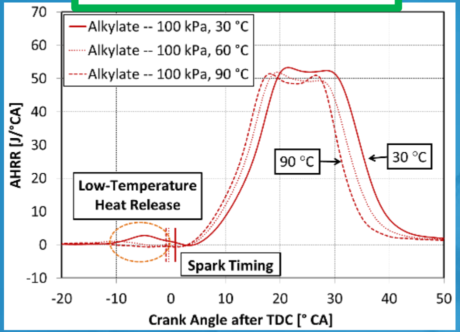
- RON and motor octane number (MON) are not predictive of knock in modern engines
- RON and S_{octane} are combined in the octane index* (OI) to predict knock

$$OI = RON - K*S_{octane}$$

- K is determined through multi-variable linear regression analysis
  - K is physically significant due to low temperature heat release
  - K < 0 corresponds to pressure-temperature conditions kinetically conducive to LTHR
  - S_{octane} indicates fuel-specific propensity to producing LTHR
- Boosted SI engines operate at negative K, making OI and K determination important

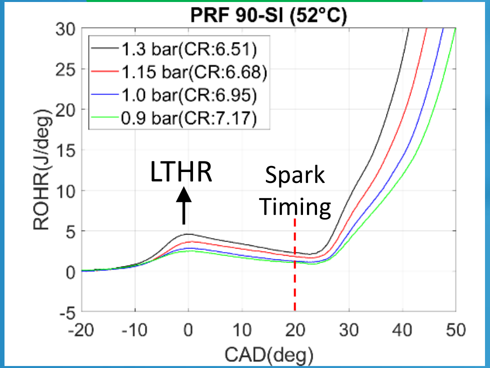
*OI developed by Kalghatgi (SAE 2001-01-3584, 2001-01-3585)

SNL LTHR Data



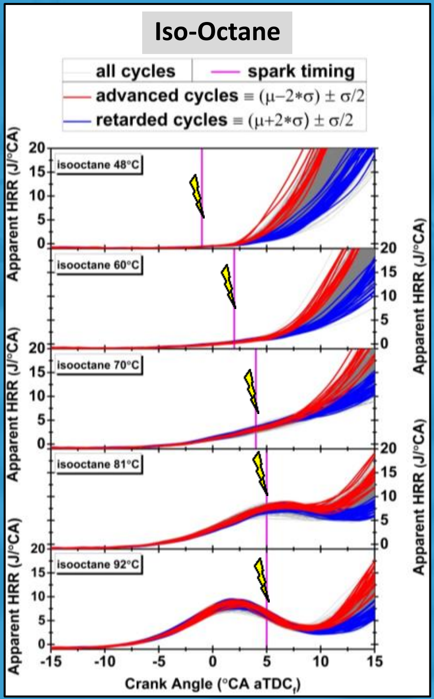
Vuilleumier and Sjöberg, DOI: 10.4271/2017-01-0662

ANL LTHR Data



Waqas et al., DOI: 10.1016/j.fuel.2019.115745

ORNL LTHR Data



Szybist and Splitter,
DOI: 10.1016/j.combustflame.2016.12.002

Accomplishment

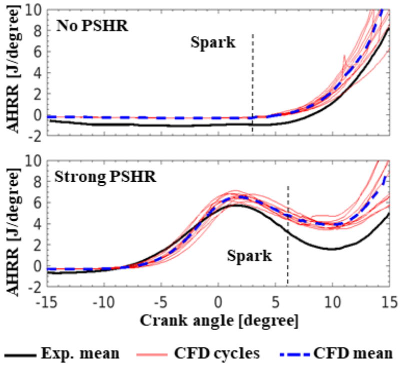
3-D CFD Simulations Reveal Dynamics of Pre-Spark Heat Release

First-of-its-kind study on characterizing low-temperature, pre-spark heat release (PSHR) using 3-D CFD tools

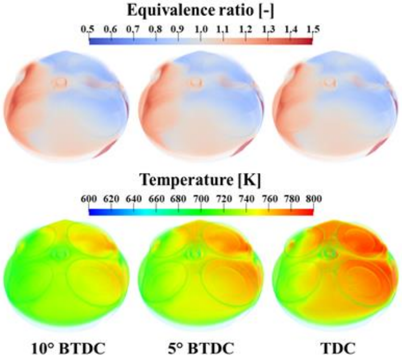
- Developed combustion model best practices to capture the onset of PSHR accurately: the chemistry solver must be kept active during gas exchange.
  - ✓ Previous-cycle residuals are key to the occurrence of PSHR
  - ✓ Simulations integrate chemistry mechanisms by LLNL
- 3-D analyses revealed PSHR begins in the fuel-lean region near the intake, but its effect becomes more significant in the fuel-rich region as time progresses
- P-T trajectories provided further insights in the trends observed for the different levels of PSHR intensity
- Fuel property effects were also examined: heat of vaporization (HoV), laminar flame speed, saturation pressure, liquid specific heat

Guo et al, *SAE Technical Paper,* 2021, doi:10.4271/2021-01-0400
Guo et al, *IJER* (submitted)

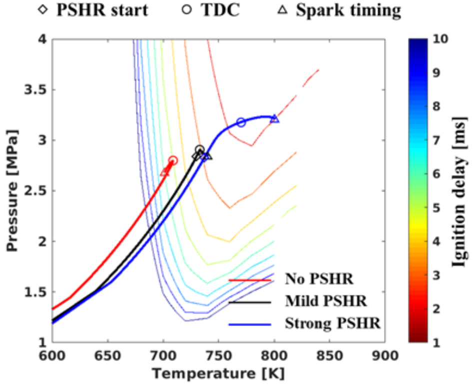
Model validation

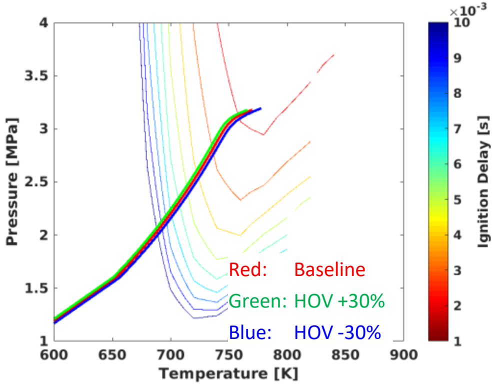


Dynamics of PSHR



P-T trajectory analysis

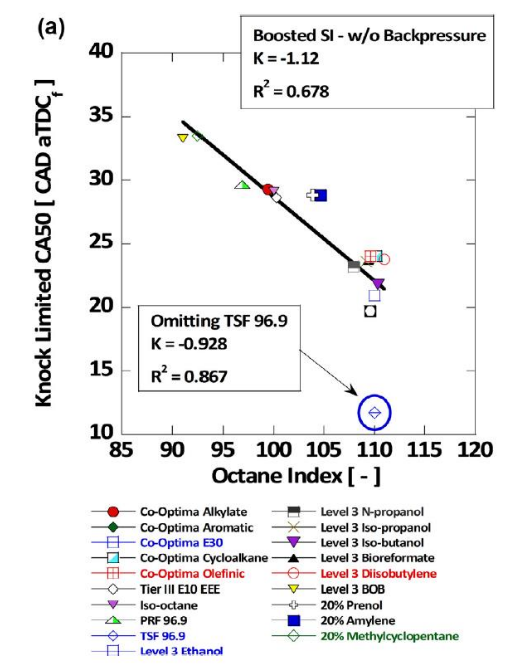




Accomplishment

OI is Superior Metric, But Questions Remain about K Determination

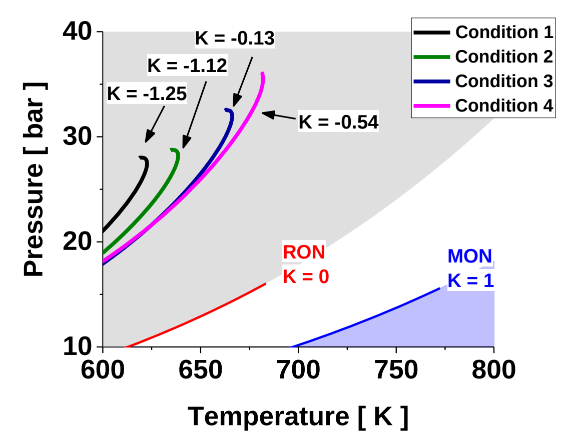
Outlier Behavior of Fuel Under Boosted Operation



Szybist and Splitter, DOI: 10.1016/j.jaecs.2020.100003

Non-Monotonic Behavior of K in Pressure-Temperature Domain

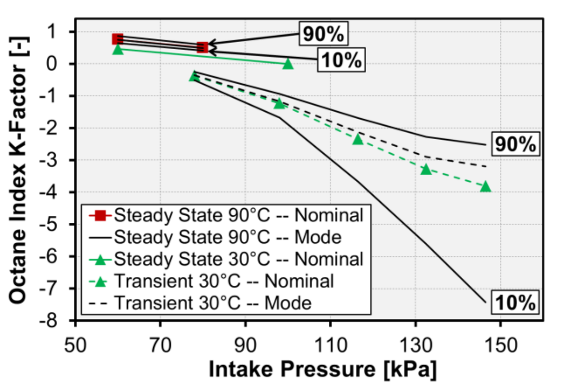
Maximum K Value Does Not Correspond to Highest Temperature Condition



Szybist and Splitter, DOI: 10.1016/j.fuel.2017.12.100

K-Factor Uncertainty Increases with Intake Pressure

K-Factor is Lower Under Transient Conditions Due to Lower Surface T



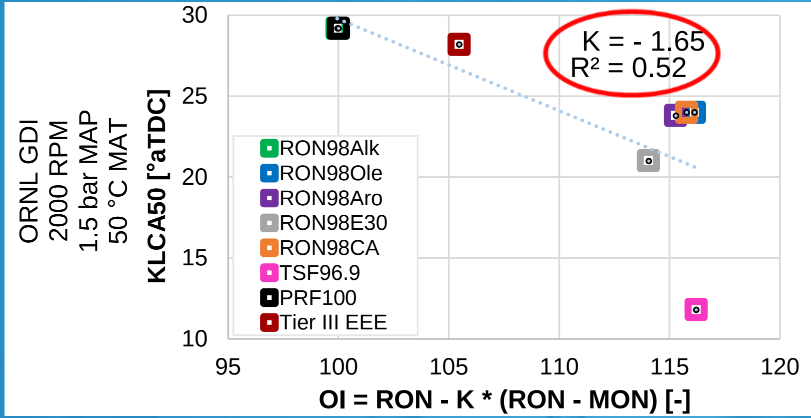
Vuilleumier et al., DOI: 10.4271/04-11-03-0014

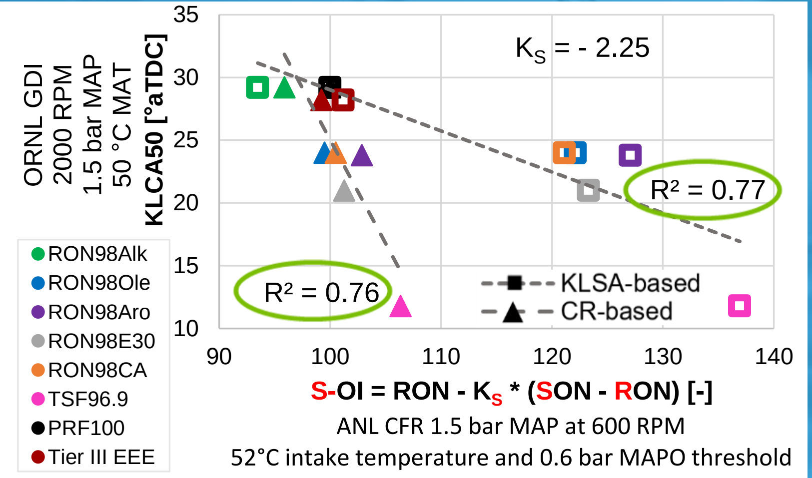
Accomplishment

Supercharged Octane Index (S-OI) improves correlation over Octane Index

- Determination of K values based on RON and MON may have intrinsic uncertainties
- Supercharged octane number (SON), developed under Co-Optima, is more relevant to modern boosted engines
- OI based on RON and SON produces much stronger correlation

- Thus, new fuel property measurements, such as SON, can enable more predictive performance determination



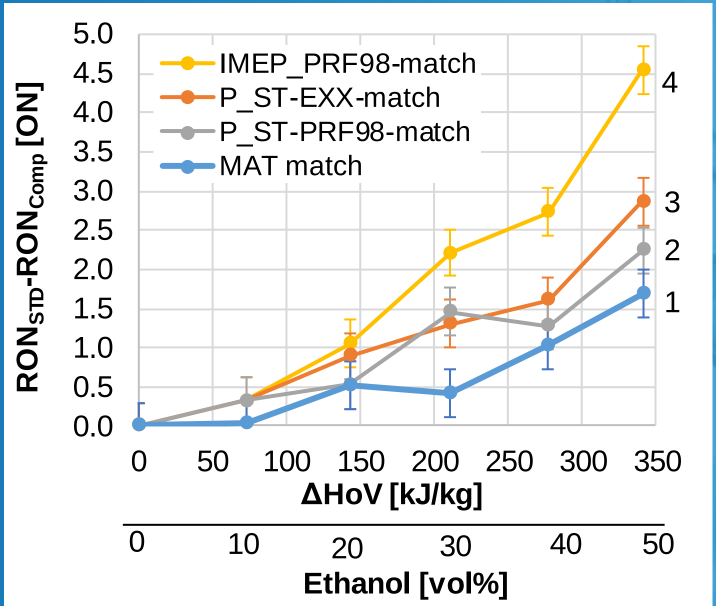


Kolodziej et al., 2020 DOE VTO AMR, FT072

Mechanisms of Efficiency Increase for Higher HoV and Flame Speed Identified and Quantified

HoV Reduces Knock Propensity

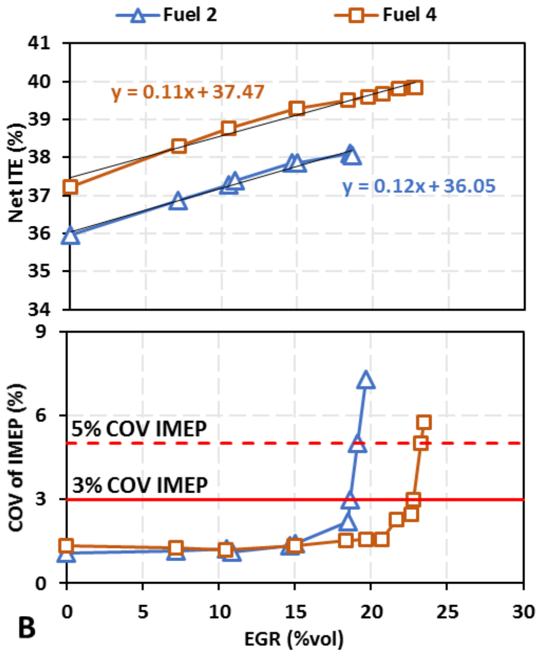
- Only partially accounted for in RON test
- HoV also increases downsizing potential



Szybist et al., DOI: 10.1016/j.pecs.2020.100876

Flame Speed Increased Dilution Tolerance

- Reduced cycle-to cycle variations
- Higher efficiency through increased dilution

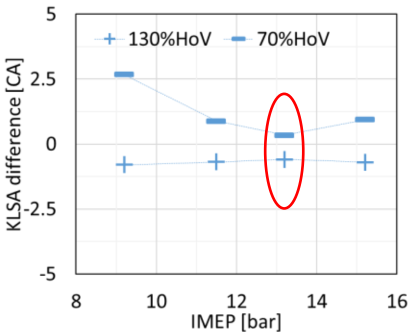


Kolodziej et al., DOI:10.4271/2017-01-0671

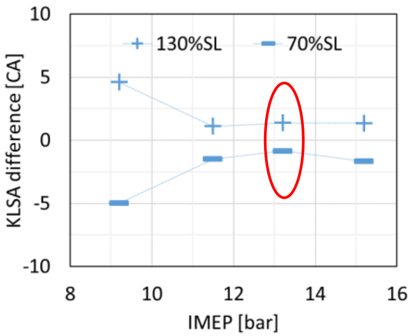
Engine Simulations Provide New Insights for HOV and Flame Speed in Isolation

- HOV affects KLSA and knock tendency through its cooling effect in the end-gas region
- S_L has significant impact on combustion phasing, which in turn affects end-gas auto-ignition and knock onset
- HOV and SL also impact ITE by affecting heat loss and combustion duration, respectively

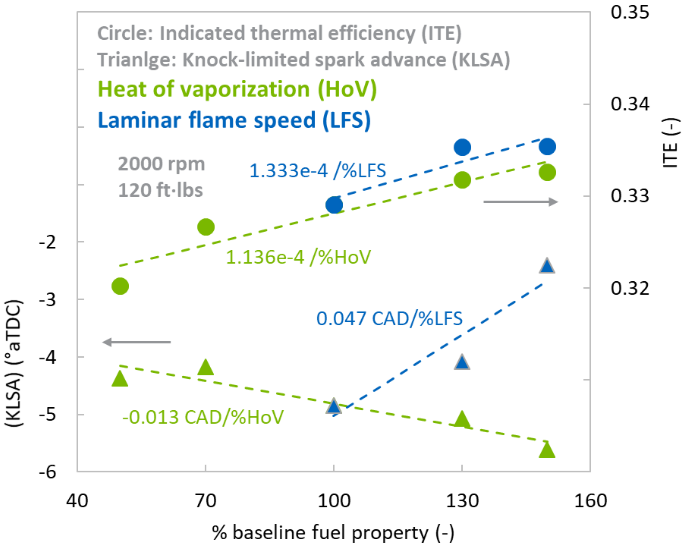
Heat of vaporization (HOV)



Laminar flame speed (S_L)



Effect of HOV and S_L on KLSA and ITE

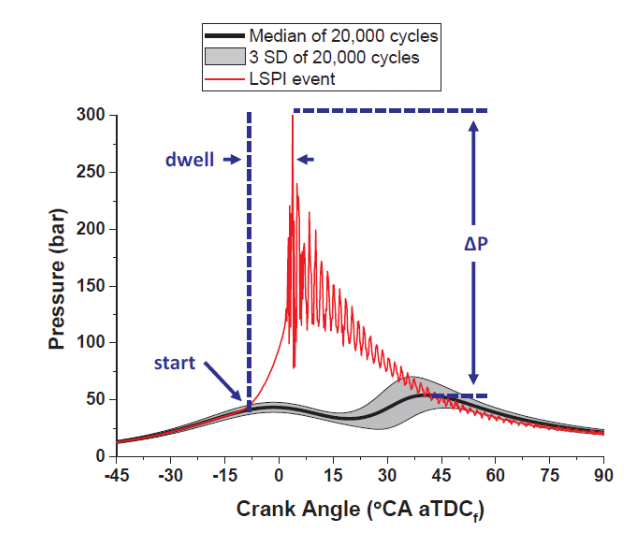


Yue & Som, *Applied Energy*, 2021, doi:10.1016/j.apenergy.2019.114221

IMEP = indicated mean effective pressure, a measure of load

Accomplishment — Stochastic Preignition Correlates to PMI, Quantified through Downsizing Limitation

- There is a multi-step process that leads to damaging superknock
  - Initiation → flame establishment → autoignition → superknock
  - Fuels can effect likelihood and severity of superknock at multiple steps
  - Present analysis focuses on initiation
- Well-established that preignition propensity increases with retained fuel in top ring zone
  - Proportional with increased high boiling point components, particulate matter index (PMI)
  - PMI increases with lower volatility higher double bonds equivalent (DBE)
  - Consistent with recent study by Swartz et al. (SAE 2020-01-0612)



Jatana et al., *Fuel. 2018;230:474-82.*

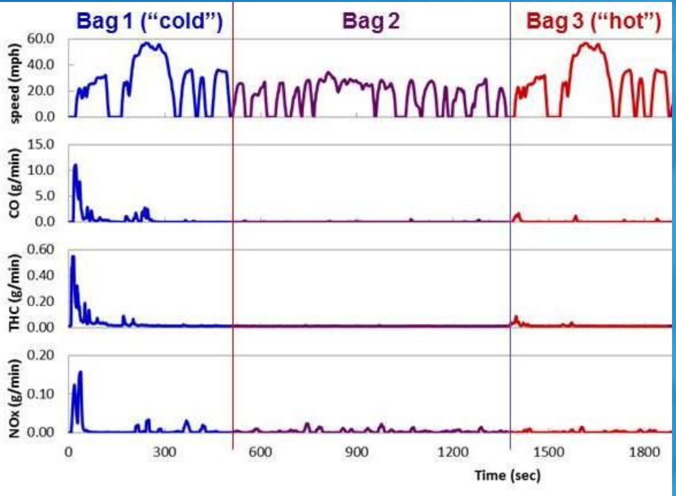
$$PMI = \sum_{i=1}^{n}\left[\frac{(DBE_i + 1)}{VP(443K)_i} \times Wt_i\right]$$

Aikawa et al., *SAE Int. J. Fuels and Lubes. 2010;3:610-22.*

Accomplishment

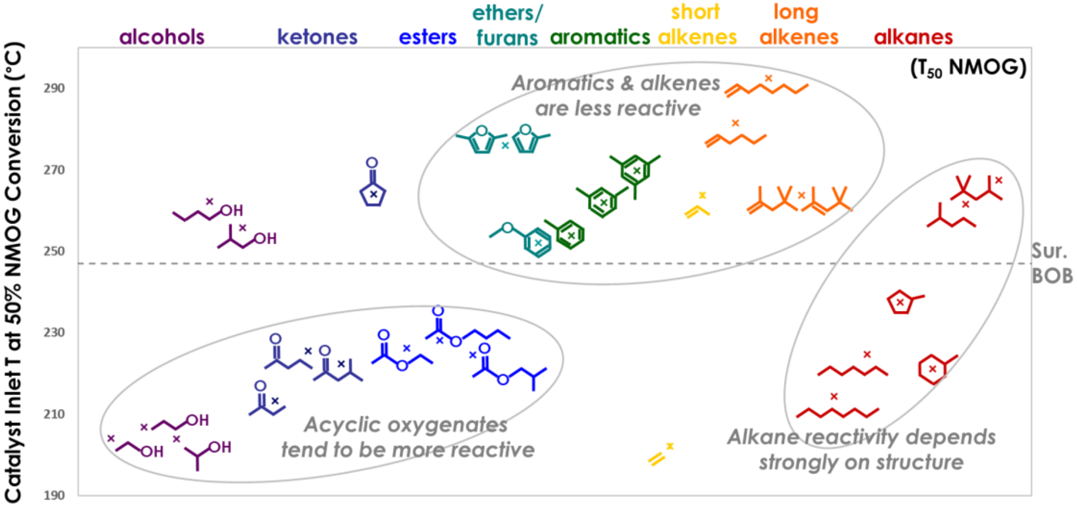
Effect of Catalyst Light-off Temperature Quantified, Fuel Effects Identified

- Cold-start represents a 2-3% fuel consumption penalty over the FTP cycle



Pihl et al., DOI: 10.4271/2018-01-1264

- Fuels with lower light-off temperatures can reduce the cold-start fuel penalty
- Many of the Co-Optima biofuel candidates exhibit reduced light-off temperature

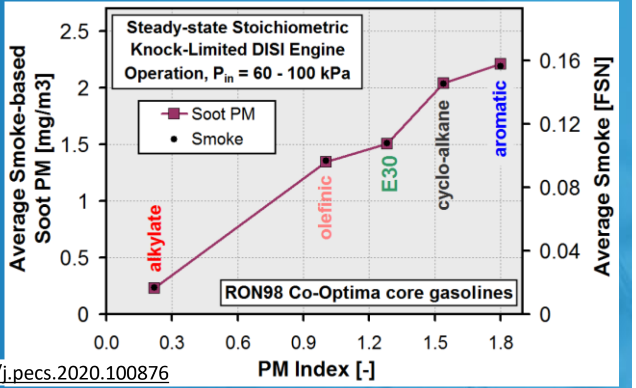


Sinha Majumdar et al., DOI: 10.1016/j.apenergy.2019.113640

Accomplishment

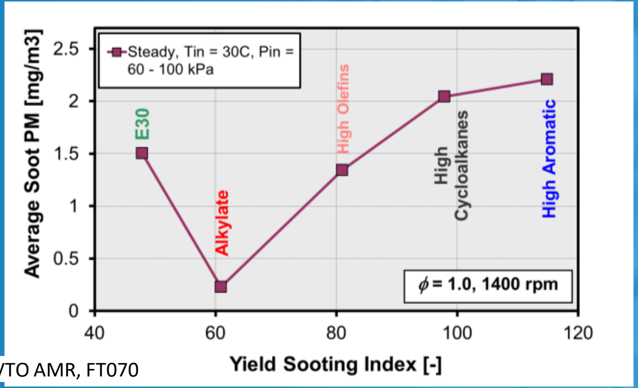
PMI Predictive of Soot Emissions for Wide Range of Fuel Chemistries

Steady-State Soot Emissions Correlate with PMI



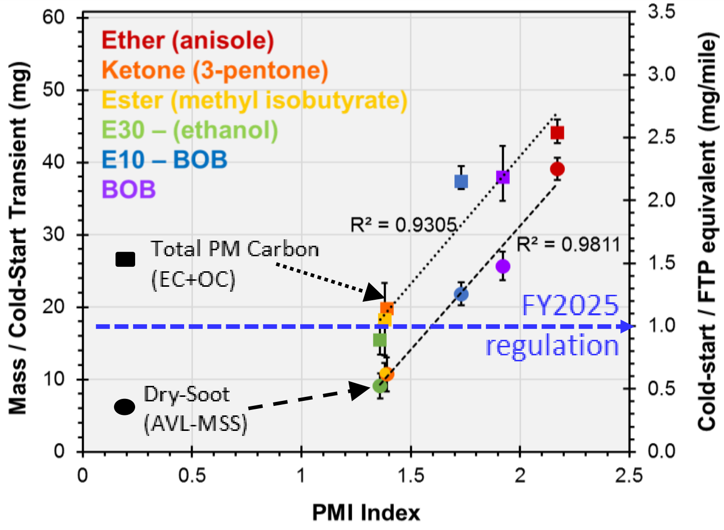
Szybist et al., DOI: 10.1016/j.pecs.2020.100876

PMI is More Robust for Engine-Out than YSI



Sjöberg et al., 2020 DOE VTO AMR, FT070

Soot Emissions Correlate with PMI under 90s Transient Cold-Start Idle Conditions



BOB from Co-Optima E30 was splash blended with 4 oxygenated bio-fuels and EtOH resulting in 70%BOB + 20% bio-fuel +10%EtOH. Also shown was an E10 and the BOB. 4 bio-fuels were an ether, ketone, ester and alcohol.

Data partially published in Szybist et al., DOI: 10.1016/j.pecs.2020.100876

Outcomes

Merit Function Normalizes Efficiency Impact of Each Fuel Property for Common Basis

$$Efficiency = 100 * \frac{\eta - \eta_{ref}}{\eta_{ref}}$$

Octane Index Terms

$$= \frac{(RON[-] - 91)}{1.6 + 0.3 * H(PMI - PMI_{LSPI,crit})} - K[-]\frac{(S_{Octane}[-] - 8)}{1.6 + 0.3 * H(PMI - PMI_{LSPI,crit})}$$

Heat of Vaporization on Knock Mitigation

$$+ \frac{0.085\left[\frac{kJ}{kg}\right]^{-1} \cdot \left(\frac{HoV\left[\frac{kJ}{kg}\right]/(AFR[-] + 1) - 415[kJ/kg]}{14.0[-] + 1}\right)}{1.6 + 0.3 * H(PMI - PMI_{LSPI,crit})}$$

Other Combined Heat of Vaporization

$$+ \frac{HoV[kJ/kg]/(AFR[-] + 1) - (415\left[\frac{kJ}{kg}\right]/14.0[-] + 1)}{15.3\left[\frac{kJ}{kg}\right]}$$

Flame Speed

$$+ \frac{(S_L[cm/s] - 46[cm/s])}{5.4\left[\frac{cm}{s}\right]}$$

Particulate Emissions

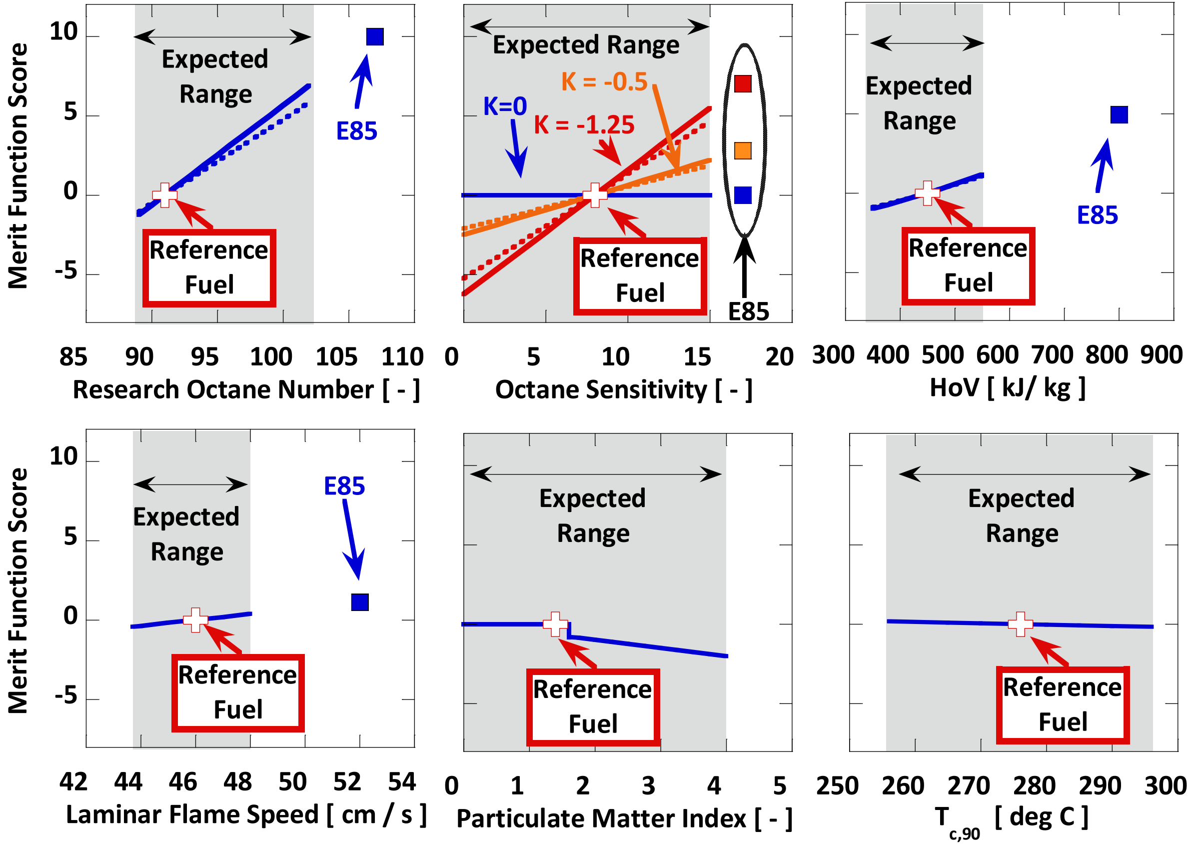
$$- H(PMI - 1.6)[0.7 + 0.5(PMI - 1.4)]$$

Catalyst Light-Off

$$+ 0.008[°C]^{-1}(T_{c,90,conv}[°C] - T_{c,90,mix}[°C])$$

Outcomes

Sensitivity Analysis Shows RON and S_{octane} are Most Important for Efficiency



Szybist et al., DOI: 10.1016/j.pecs.2020.100876

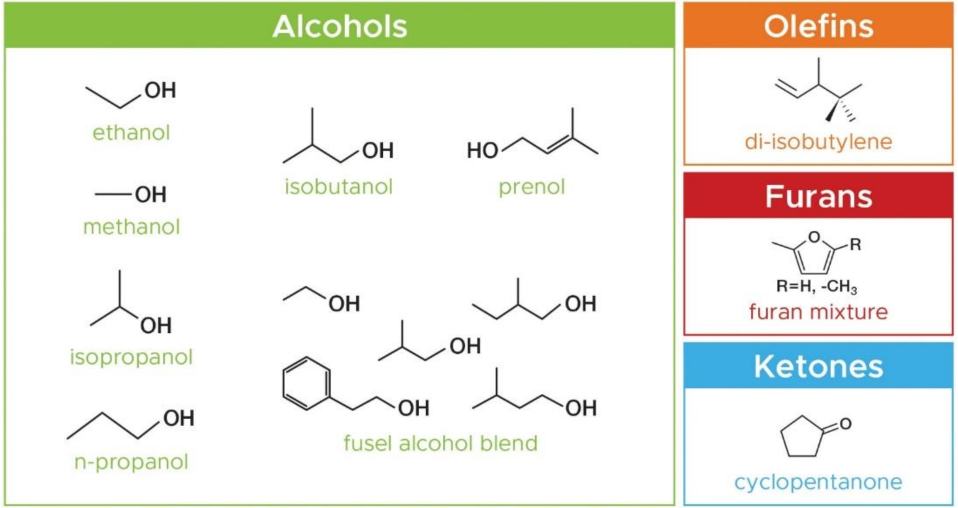
Realistic Ranges of Fuel Properties

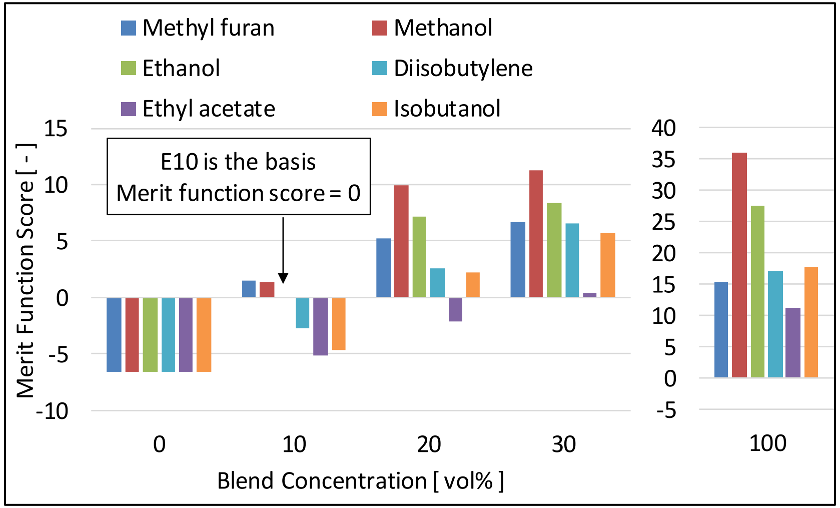
	Realistic Low Value	Realistic High Value	E85 value
RON [-]	89	102	107
S [-]	0	15	17
HoV [kJ/kg]	350	550	800
SL [cm/s]	43.7	48	52
PMI [-]	0.0	4.0	N/A
TC,90 [°C]	261	291	N/A

Note: Merit function calculations assume that engine changes, such as increased compression ratio, are made to take advantage of the fuel potential.

Outcomes

Merit Function can be Exercised to Compare Fuel Candidates





- Co-Optima has been focused on blends with petroleum (BOB) up to 30 vol%
- Fuel properties of the blends are used as input for the merit function
- Many fuel properties, including RON and S_{octane}, blend non-linearly
  - Fuels with synergistic blending show good performance (methyl furan, ethanol, methanol)
  - Fuels with antagonistic blending show poor performance (ethyl acetate)

Top 10 Bioblendstocks for Boosted SI Report: https://www.osti.gov/servlets/purl/1567705

Conclusions

Determined Efficiency Effect of Individual Fuel Properties for Boosted SI Engines

- Central engine and central fuel property hypotheses set baseline expectations, allowing research to proceed in a fuel-agnostic manner
  - Thermodynamic basis for fuel property-based efficiency increases
  - Requires engine optimization for full benefit (r_c, EGR dilution, degree of downsizing, etc.)
- Knock mitigation, quantified by OI, was the most impactful
  - OI correlates to LTHR from the fuel, which is prominent for boosted engines
  - Determination of K for accurate OI remains challenging
- Additional fuel properties considered include HoV, flame speed, catalyst light-off temperature, and two mechanisms for PMI: LSPI and particulate mitigation
- Accurate high-fidelity modeling tools developed to accurately predict fuel effects
- Merit function provides a tool to compare the potential of alternative fuel candidates for both naturally aspirated and boosted SI engines

Publications

More than 280 Publications From Co-Optima Many Applicable to Boosted SI

For a complete record of publications:
https://www.energy.gov/eere/bioenergy/co-optima-publications-library

Select publications on the merit function:

- Szybist, J.P., Busch, S., McCormick, R.L., Pihl, J.A., et al., “What Fuel Properties Enable Higher Thermal Efficiency in Spark-ignited Engines?”, Progress in Energy and Combustion Science, 82, 2021, 100876. https://doi.org/10.1016/j.pecs.2020.100876
- Miles, P. “Efficiency Merit Function for Spark Ignition Engines: Revisions and Improvements Based on FY16–17 Research.” Technical Report. U.S. Department of Energy, Washington, DC. 2018. DOE/GO-102018-5041.
- Gaspar, D., “Ten Blendstocks For Turbocharged Gasoline Engines: Bioblendstocks With Potential to Deliver the for Highest Engine Efficiency,” PNNL-28713, 2019, Pacific Northwest National Laboratory.

Select publications on octane index and LTHR:

- Szybist, J.P., Splitter, D.A., “Impact of Engine Pressure-Temperature Trajectory on Autoignition for Varying Fuel Properties,” Applications in Energy and Combustion Science, 1, 2020, 100003. https://doi.org/10.1016/j.jaecs.2020.100003
- Wauas, M.U., Hoth, A., Kolodziej, C., Rockstroh, T., et al., “Detection of Low Temperature Heat Release (LTHR) in the stancard Cooperative Fuel Research (CFR) Engine in Both SI and HCCI Combustion Modes,” Fuel, 256, 2019, 115745. https://doi.org/10.1016/j.fuel.2019.115745.
- Szybist, J.P., Splitter, D.A., “Understanding Chemistry-Specific Fuel Differences at a Constant RON in a Boosted SI Engine,” Fuel, 217, 2018, pp 370-381. https://doi.org/10.1016/j.fuel.2017.12.100
- Vuilleumier, D. and Sjöberg, M., "Significance of RON, MON, and LTHR for Knock Limits of Compositionally Dissimilar Gasoline Fuels in a DISI Engine," SAE Int. J. Engines 10, 2017, https://doi.org/10.4271/2017-01-0662
- Szybist, J., and Splitter, D., “Pressure and Temperature Effects on Fuels with Varying Octane Sensitivity at High Load in SI Engines,” Combustion and Flame, 177, 2017, pp 49-66. https://doi.org/10.1016/j.combustflame.2016.12.002

Select publications on PMI

- Ratcliff, M.A., Windom, B., Fioroni, G.M., St. John, P., et al., “Impact of ethanol blending into gasoline on aromatic compound evaporation and particle emissions from a gasoline direct injection engine.” Appl Energy, 250, 2019,1618–31. https://doi.org/10.1016/j.apenergy.2019.05.030

Publications (cont.) More than 280 Publications From Co-Optima Many Applicable to Boosted SI

Select publications on heat of vaporization

- Sluder, C., Szybist, J., McCormick, R., Ratcliff, M., Zigler, B., "Exploring the Relationship Between Octane Sensitivity and Heat-of-Vaporization," SAE Int. J. Fuels Lubr., 9, 2016, pp 80-90. https://doi.org/10.4271/2016-01-0836

Select publications on flame speed

- Szybist, J. and Splitter, D., "Effects of Fuel Composition on EGR Dilution Tolerance in Spark Ignited Engines," SAE Int. J. Engines, 9, 2016, pp 819-831. https://doi.org/10.4271/2016-01-0715
- Kolodziej, C., Pamminger, M., Sevik, J., Wallner, T. et al., "Effects of Fuel Laminar Flame Speed Compared to Engine Tumble Ratio, Ignition Energy, and Injection Strategy on Lean and EGR Dilute Spark Ignition Combustion," SAE Int. J. Fuels Lubr., 10, 2017, pp 82-94. https://doi.org/10.4271/2017-01-0671

Select publications on catalyst light-off

- Pihl, J.A., Thomas, J., Sinha Majumdar, S., Huff, S. et al., "Development of a Cold Start Fuel Penalty Metric for Evaluating the Impact of Fuel Composition Changes on SI Engine Emissions Control", SAE Technical Paper 2018-01-1264, 2018, https://doi.org/10.4271/2018-01-1264
- Sinha Majumdar, S., Pihl, J. A., and Toops. T. J., "Reactivity of novel high-performance fuels on commercial three-way catalysts for control of emissions from spark-ignition engines", Applied Energy, 255, 2019, 113640. https://doi.org/10.1016/j.apenergy.2019.113640
- Sinha Majumdar, S. and Pihl, J. A., "Impact of Selected High-Performance Fuel Blends on Three-Way Catalyst Light Off under Synthetic Spark-Ignition Engine-Exhaust Conditions", Energy & Fuels 34, 2020, pp 12900-12910. https://doi.org/10.1021/acs.energyfuels.0c02102

Select publications on modeling

- Yue, Z., Edwards, K.D., Sluder, C.S., and Som S. "Prediction of Cyclic Variability and Knock-Limited Spark Advance in a Spark-Ignition Engine," J. Energy Resour. Technol. 141, 2019, 102201. https://doi.org/10.1115/1.4043393
- Yue, Z. and Som, S., "Fuel Property Effects on Knock Propensity and Thermal Efficiency in a Direct-Injection Spark-Ignition Engine," Applied Energy 281, 2021, 114221. https://doi.org/10.1016/j.apenergy.2019.114221
- Yue, Z., Xu, C., Som, S., Sluder, C.S., Edwards, K.D., Whitesides, R.A., and McNenly, M.J., "A Transported Livengood–Wu Integral Model for Knock Prediction in Computational Fluid Dynamics Simulation," J. Eng. Gas Turbines Power 143, 2021, 091017. https://doi.org/10.1115/1.4050583
- Guo, H., Torelli, R., Szybist, J.P., and Som, S., "Three-Dimensional CFD Investigation of Pre-Spark Heat Release in a Boosted SI Engine," SAE Technical Paper 2021-01-0400, 2021. https://doi.org/10.4271/2021-01-0400
- Guo, H., Torelli, R., Szybist, J.P., and Som, S., "CFD Modeling of Pre-Spark Heat Release in a Boosted Direct-Injection Spark-Ignition Engine," Int. Journal of Engine Research, (submitted).