Fuel Effects on Multimode Engine Operation

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Overview | Timeline

Multimode Funding
Fraction of Co-Optima

- Multimode SI/ACI
  - Light-duty
  - Boosted SI
  - Mixing controlled
  - MD/HD ACI

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TODAY

Co-Optima 1.0

Co-Optima 2.0

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Focus is on Light-duty Multimode (MM) engine operation. MM uses advanced combustion at lower loads in combination with boosted SI at high loads. Here, sampling from Co-Optima efforts on MM.

- Highlight the role of important fuel properties.

MM fuels need to enable Boosted SI.

Provide quantitative example of how MM can provide fuel-economy benefits.
Contributions from Across Co-Optima Teams

Only a small fraction of all Multimode work is featured in this presentation.

This research was sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies and Vehicle Technologies Offices.
Benefits and Challenges with Lean Operation

- **Increased thermal efficiency.**
  - Increased $\gamma$, reduced pumping losses and heat transfer.
- **Combustion instability.**
- **Excessive burn duration.**
- **Lean NO$_x$ aftertreatment.**
- **Dilute well-mixed SI:**
  - 3-way catalyst can be used.
  - Slow combustion and limited FE gain.

**LLNL (W. Pitz and M. Mehl)**

**SNL (M. Sjöberg) – [1]**
Benefits and Challenges with Lean Operation (2)

- Increased thermal efficiency.
  - Increased $\gamma$, reduced pumping losses and heat transfer.
- Combustion instability.
- Excessive burn duration.
- Lean NOx aftertreatment.
- Dilute well-mixed SI:
  - 3-way catalyst can be used.
  - Slow combustion and limited FE gain.
  - Fuels with inherent high flame speed are beneficial, but limited opportunities with the maximum 30% blend level of Co-Optima.
- ACI (advanced compression ignition) techniques can enable fast burn even for very lean conditions.
- Also fully stratified-charge (SC) SI enables lean burn.
  - Multiple bioblendstocks provide fast combustion.

Regular Gasoline - RD5-87
Ethanol - E30
Di-isobutylene
Iso-Butanol
2-butanol

USC (R. Zhao & F. Egolfopoulos)

SNL (M. Sjöberg)
Overcoming Challenges with Lean Operation; Role of Fuel Properties for Stratified-charge (SC) SI

- Superior thermal efficiency.
- Load can be smoke limited, especially when EGR is used to suppress $\text{NO}_x$.
- Fuels with low sooting propensity are desirable.
- But common sooting metrics not always applicable.
- New sooting metrics are being considered.
  - Collaboration with Yale (C. McEnally) and LLNL (S. Lapointe [23]).

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SNL (N. Kim) – [9]
Overcoming Challenges with Lean Operation; Role of Fuel Properties for HCCI

- Low NO\textsubscript{x}.
- Requires high reactant temperatures, which decreases $\gamma$ & increases heat transfer.
- Combustion-phasing control challenge.
- RON & MON often inadequate for $K > 1 \Rightarrow$ use compositional constraints or newly developed CFR HCCI rating.

**Graphs and Tables**

- **Graph 1:** Performance of alkanes and alcohols aligns with octane index expectations.
  - Aromatics require higher temperature than is predicted by octane index.
  - Olefins require lower temperature than is predicted by octane index.

- **Graph 2:** Intake Temp. [°C] for CA50 = 5 CA aTDC.

- **Graph 3:** Intake Manifold T [°C] for CA50 = 5 CA aTDC, showing ORNL and ANL data with different intake manifold temperatures.

**Tables**

- **Table 1:** Octane Index [\text{°}]
  - Alkylate
  - Amylene
  - Aromatic
  - Bioreformate
  - Cycloalkane
  - Diisobutylene
  - E30
  - E22
  - Iso-propanol
  - Iso-octane
  - MCP
  - n-propanol
  - Olefinic
  - Prenol
  - PRF 96.9
  - Tier 3 EEE
  - TSF 96.9

**Equations**

- $R^2 = 0.9649$
- $R^2 = 0.333$

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Overcoming Challenges with Lean Operation; Role of Fuel Properties for PFS-ACI

- Uses stratification to aid combustion control.

- Requires high boost pressure for CRs suitable also for boosted SI.
- Limited load range.
- Lower load limits (defined by CE > 92.5%) varies with fuel.
  - Di-isobutylene and Aromatic fuels best at maintaining high combustion efficiency (CE).
  - Fuel properties do not explain these differences.
- RON & MON generally applicable in terms of autoignition timing, see next slide.
Overcoming Challenges with Lean Operation; Role of Fuel Properties for SACI

- Spark-timing controlled.
- Moderate reactant temperature requirement.
- Superior load range compared to PFS and HCCI.
- Relatively high NOx levels (but EGR helps).
- Mixed-mode combustion speeds up burn-out phase.
- RON and MON describe autoignition reactivity using Octane-Index (OI) framework for K < 1

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**ORNL (F. Chuahy) – [18]**

- **PFS vs. SACI**

  ![Graph showing temperature comparison between PFS and SACI](image)

**ACI Operability at 1500 RPM**

- **ORNL (T. Powell) – [20]**

![Graph showing operability comparison between SACI and PFS](image)
• Mixed-mode combustion speeds up burn-out.
• Deflagration $\Rightarrow$ end-gas autoignition
• Ensures sufficiently short burn duration.
• For a given spark timing, induction of end-gas autoignition depends on the fuel.
• However, spark-timing adjustments can compensate for differences in fuel reactivity.

E30, RON = 105
$T_{\text{in}} = 100^\circ\text{C}$
$\phi = 0.55$

End-gas Autoignition
Slow Burn-Out

SNL (M. Sjöberg) – [1]
An Examination of SACI; Partial Fuel Stratification (PFS) SI Experiments

- To stabilize lean SACI operation, use pilot injection at the time of spark ⇒ PFS – SACI.

- Creates an enriched region near spark plug.
- Large 3.4 mg pilot in this example.
PFS-SACI; Optical Imaging Experiments

- Smaller 0.7 mg pilot (210μs inj. dur.)
- Liquid fuel vaporizes quickly.

Fundamental Spray Experiments

- PFS-SACI and PFS-ACI require good handle on fuel-air mixture formation.
- Spray-vessel experiments reveal strong influence of distillation curve on spray morphology at lower pressures.
  – Lower sensitivity for late injection.

3D Tomographic Images, P = 0.5 bar

SNL (C. Tornatore) - [12]

SNL (J. Hwang) – [10]
LES-CFD Reveals the Role of Flame Speed for SACI

- Model predicts that PFS operation reduces sensitivity to variations of laminar flame speed.
- May enable PFS-SACI to provide stable operation with EGR to suppress NO$_x$.
- CFD reveals that NO$_x$ formation is closely tied to mixture formation.

![Diagram showing CFD Modeling Results](image)

- NO Mole Fraction @ TDC.
- Chemical kinetics by LLNL (S. Cheng) – [24]
Fuel Effects on Lean Exhaust Aftertreatment

- Important to assess how bioblendstocks impact the performance of emissions control catalysts.
- Multimode engines must meet emissions regulations.
- Measured three-way catalyst (TWC) stoichiometric light-off and lean light-down temp.
- 10-30% blends of ethanol, isobutanol, di-isobutylene, and aromatics mixed into a surrogate BOB (+neat).
- Overall TWC reactivity is controlled primarily by the BOB components rather than the high performance blendstocks.
Developed and Used a Methodology for Determining Octane Requirements of SACI

- Upper load limit is strongly favored by increasing RON and S.
- Lower load limit is nearly invariant with RON and S.

1. Experiments for validation data

2. GT-Power for T-P trajectories

3. CHEMKIN - autoignition

4. Screen for feasibility

5. Quantify load ranges

Chemical kinetics by LLNL (W. Pitz)  
SNL (D. Vuilleumier, N. Kim)
Developed and Used Framework to Predict the Effect of Fuel Type on Fuel Economy; Stoichiometric and Multimode

Exp. Engine Data for many fuels, operating conditions & engine thermal states

SNL (M. Sjöberg, N. Kim)
LLNL (N. Killingsworth, M. McNenly)
LBNL (J. Mueller)
ANL (R. Vijayagopal)
ORNL (S. Sluder)

Determine knock limits for hypothetical fuels

Regression model

KL-CA50

Fuel Consumption Rate

Gaussian Process Regression model

Fuel-Flow Rate Map

Torque, Fuel Flow

Drive Cycle Simulation

Fuel Economy

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**Stoichiometric Knock Limits at Reduced Engine Thermal State**

- High-power SI engine can benefit greatly from enhanced thermal management.
  - Suppression of engine knock. Especially important for downsized engines.
- Boosted knock limits of E30 are highly sensitive to the thermal state of the engine.
- Knock limits of Alkylate are much less sensitive.

**Fundamental Measurements of Fuel Autoignition**

- RCM experiments at ANL show that autoignition becomes more sensitive to changes of charge temperature ($T_c$) for high-S fuels.
- Suppression of NTC behavior.

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Fuel Effects on the Benefit of Enhanced Thermal Management

- Downsizing provides FE benefits for FTP-75 & HWFET, but not for US06.
  - Higher IMEP ⇒ More knock limited.

- Autonomie predicts that enhanced thermal management provides most benefit for more aggressive driving (US06).

- Here, the S=12 fuels provide greatest benefit.

SNL (M. Sjöberg, N. Kim), LLNL (N. Killingsworth, M. McNenly)
LBNL (J. Mueller), ANL (R. Vijayagopal)
Weak Fuel Effects for Cool Stoichiometric Operation - Benefit of Multimode Varies with Drive Cycle and Fuel Type

- Stoichiometric; only most aggressive US06 shows a benefit of increased RON & S.
- Boosted SI Merit Function assumes CR adjustment with fuel type, here CR = 12.
- Multimode shows essentially no benefit for US06 which uses higher engine speeds.
Substantial Fuel-Economy Benefits from Multimode Operation for HWFET & UDDS

- Multimode operation provides 9 – 14% MPG Gains for HWFET & UDDS cycles.
- Mode switching most frequent for UDDS.
- Here, the higher SACI load limit of high-RON high-S fuels provides benefits.
Summary

- Multimode engine operation can provide fuel-economy gains of more than 10% for a conventional powertrain.
- For SACI, increased RON & S enable higher loads.
  - Reduces the mode-switching frequency.
  - Octane appetite of SACI is aligned with that of Boosted SI.
- To a large degree, the Octane Index framework is applicable to LD ACI.
- Emissions regulations must be met.
- Lean operation can result in excessive formation of NO\textsubscript{x}, HC, CO and PM.

Future Work*

- Assess the benefits of multimode engine operation for a hybridized powertrain.
- Determine mode-switching schemes that minimize fuel penalties.
- Determine the role of the fuels’ Heat of Vaporization (HoV) on SACI & ACI.
- Assess how bioblendstocks affect HoV, especially for +30% blend levels.
- Investigate how improved mixture formation can reduce engine-out emissions for ACI.
- Assess the use of advanced lean aftertreatment and potential synergies with future fuels.

* Any proposed future work is subject to change based on funding levels.


