Advanced Lean-Burn
DI Spark Ignition Fuels Research

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Project ID: FT006

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Overview

Timeline
• Project provides science to support industry to develop advanced lean/dilute-burn SI engines for non-petroleum fuels.
• Project directions and continuation are reviewed annually.

Barriers
• Inadequate data and predictive tools for fuel property effects on combustion and engine efficiency optimization.
• Evaluate new fuels and fuel blends for efficiency, emissions, and operating stability with advanced SI combustion.
  1. Lean, unthrottled DISI with spray-guided combustion.
  2. Well-mixed charge and high boost.

Budget
• Project funded by DOE/VT via Kevin Stork.
  • FY11 - $650 K
  • FY12 - $750 K

Partners / Collaborators
• PI: Sandia (M. Sjöberg)
• 15 Industry partners in the Advanced Engine Combustion MOU.
• General Motors - Hardware.
• D.L. Reuss (formerly at GM).
• LLNL (Pitz et al.) – Mechanisms and Flame-Speed Calculations.
• LLNL (Aceves et al.) - CFD Modeling.
• Sandia Spray Combustion & Heavy-Duty Diesel Labs (Pickett & Musculus).
• USC-LA (Egolfopoulos) - Flame Measurements.
Objectives - Relevance

Project goals are to provide the science-base needed to understand:

- How emerging future fuels will impact the combustion systems of new highly-efficient DISI light-duty engines currently being developed.
- How the fuels and combustion systems can be tailored to each other to maximize thermal efficiency.
- Current focus is on E85 and gasoline. Expand to other fuel blends (e.g. E15-E30) and components (e.g. butanol and iso-pentanol) based on industry interest.

DISI with spray-guided stratified charge combustion system
- Has demonstrated strong potential for throttle-less high-efficiency engine operation.
- Plagued by misfires and partial burns, especially for low-NO\textsubscript{x} operation.
- Mastering NO\textsubscript{x} / Soot / Combustion Stability trade-offs is key to success.
- These processes are strongly affected by fuel properties.

- Study performance and exhaust emissions for lean stratified operation and examine the effects of fuel properties.
- Develop / employ high-speed optical diagnostics to understand advanced combustion and mitigate potential barriers (e.g. ensure robust combustion).
- Conduct supporting modeling for understanding of governing fundamentals.
Approach

• Combine metal- and optical-engine experiments and modeling to develop a broad understanding of the impact of fuel properties on DISI combustion processes.

• First, conduct performance testing with a state-of-the-art all-metal engine configuration over wide ranges of operating conditions and alternative fuels.
  – Speed, load, intake pressure, EGR, and stratification level. Quantify engine operation and develop combustion statistics.

• Second, apply a combination of optical and conventional diagnostics to develop the understanding needed to mitigate barriers to high efficiency, robustness, and low emissions.
  – Include full spectrum of phenomena; from intake flow, fuel-air mixing and ignition, to development of flame, and endgas autoignition (knock).

Supporting modeling:

• Conduct chemical-kinetics modeling of flame-speed for detailed knowledge of governing fundamentals.
  – Collaborate on validation experiments and mechanism development.
  – Collaborate on the thermodynamics of fuel-air mixing and vaporization.

• Collaborate on CFD modeling of in-cylinder flows and combustion.
Two configurations of drop-down single-cylinder engine.
Bore = 86.0 mm, Stroke = 95.1 mm, 0.55 liter swept volume.

• All-metal: Metal-ring pack and air/oil-jet cooling of piston.
• Optical: Pent-roof window, piston-bowl window, and 45° Bowditch mirror.
• Identical geometry for both configurations, so minimal discrepancy between performance testing and optical tests.
• 8-hole injector with 60° included angle ⇒ 22° between each pair of spray center lines.
  Spark gap is in between two sprays.
Technical Accomplishments

• Performed a comparative study of stratified operation with E85 and gasoline, examining the potential to accomplish low NO\textsubscript{x} / PM operation.
  – Demonstrated the use of near-TDC fuel injection to enable ultra-low NO and soot with E85.

• Optical engine experiments:
  – Commissioned optical version of the engine.
  – Performed high-speed imaging studies of stratified E85 operation.
  – Natural luminosity, Mie-imaging of fuel-spray development, and initial fuel-PLIF.
    – Identified ignition and flame-spread issues leading to partial burns.
    – Characterized laser-sheet quality of high-speed PIV laser.

• Used CHEMKIN to investigate the influence of E85’s strong vaporization cooling on the laminar flame speed for wide ranges of $\phi$.

• Set up and validated GT-Power model over wide ranges of speed and boost.
  – Used high-speed imaging of valve motion as model input.

• Continued the examination of the direct effect of vaporization cooling on the thermal efficiency for E85 and gasoline.
  – Quantified the effects of injection timing and pressure.
Emissions Study

- The traditional SI engine has poor thermal efficiency at low loads.
- Overall lean but stratified combustion can improve fuel economy.
- Low engine-out NO$_x$ and PM is required to avoid expensive lean-NO$_x$ aftertreatment and particulate filter.
- The parameter space is huge.
- Grouped as hardware, static parameters & operating variables.
- Relatively low in-cylinder temperatures.
- Acquired data for 500 cycles per steady-state operating point.
- Unless noted, stratified cases have spark timing (ST) for lowest standard deviation (SD) of IMEP$_n$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>12</td>
</tr>
<tr>
<td>Piston Bowl</td>
<td>$\varnothing$ 46 mm</td>
</tr>
<tr>
<td>Swirl Index</td>
<td>0 or 2.7 (most data)</td>
</tr>
<tr>
<td>Valve Timings</td>
<td>For Minimal Residual Level</td>
</tr>
<tr>
<td>Injector &amp; Spray Targeting</td>
<td>Bosch 8 x 60° Straddling Spark</td>
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<tr>
<td>Injection Pressure</td>
<td>170 bar</td>
</tr>
<tr>
<td># of Injections</td>
<td>Single</td>
</tr>
<tr>
<td>Spark Energy</td>
<td>106 mJ</td>
</tr>
<tr>
<td>$T_{\text{coolant}}$</td>
<td>60°C</td>
</tr>
<tr>
<td>$T_{\text{in}}$</td>
<td>26-28°C</td>
</tr>
<tr>
<td>Engine Speed</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Intake Pressure</td>
<td>95 kPa</td>
</tr>
<tr>
<td>$P_{\text{exhaust}}$</td>
<td>100 kPa</td>
</tr>
<tr>
<td>IMEP$_n$</td>
<td>250-380 kPa</td>
</tr>
<tr>
<td>Start of Injection (SOI)</td>
<td>-37 to -5°CA</td>
</tr>
<tr>
<td>Spark Timing (ST)</td>
<td>-36 to 1°CA</td>
</tr>
<tr>
<td>EGR / [O$<em>2$]$</em>{\text{in}}$</td>
<td>21 – 14.5% O$_2$</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>E85, Gasoline</td>
</tr>
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</table>
• Apply N\textsubscript{2} dilution to examine potential for low NO\textsubscript{x} operation.
• Gasoline shows clear trade-off. Engine-out soot is governed by soot burn-out?
• Low NO is possible, but at the expense of soot and stability.

With E85, can reach inside the US2010 NO/PM box, using near-TDC injection.
- NO\textsubscript{2} contribution may be substantial.
- Future study.

With E85, SOI = -31°CA, IMEP\textsubscript{n} = 370 kPa
- E85, SOI = -23°CA, IMEP\textsubscript{n} = 370 kPa
- E85, SOI = -23°CA, IMEP\textsubscript{n} = 250 kPa
- E85, SOI = -6°CA, IMEP\textsubscript{n} = 260 kPa

\textbf{Reaching Inside the NO/PM Box}
**Effects of Injection Timing Retard**

- **a.** SOI retard strongly reduces NO emissions.
- **b.** Lower average peak combustion temperatures.
- **c.** Later CA50, so less time for thermal NO formation.
- **d.** Closely-coupled injection and combustion.
  - Higher mixing rates may limit time spent at NO-producing temperatures.
- **e.** Compared to gasoline, E85 generally requires earlier spark for highest stability.
  - This difference is accentuated for SOI retard.
  - For near-TDC injection, spark discharge starts well before fuel is present in the cylinder!
- **f.** How can this help stability?
  - Use high-speed imaging.
- **•** Spark at SOI or earlier counteracts CA50 retard with SOI retard.
  - Spark of gasoline is near EOI, so does not allow much SOI retard.
N$_2$-sweep for SOI = -6°CA

- SOI = -6°CA can provide single-digit NO.
- N$_2$-dilution sweep shows trade-offs between NO-Stability-CE-TE.
- The NO-Stability trade-off is superior to other conditions with earlier SOI.
- Study 19% point further.
- Has very low NO, but increased combustion efficiency and stability would enable more fuel-economy gain.
  - Up to +27% relative stoichiometric operation.
Imaging Setup / Spark-Sweep

- Bowditch: Phantom v7.10 with f = 180 mm lens.
  - Wide-angle view using concave window.
- Side window: Phantom v7.1 with f = 50 mm lens.
- Broadband imaging - CMOS chip.
- Pulsed high-intensity LED for Mie-scattering.
  - 5\(\mu\)s or 10\(\mu\)s pulse length.
  - Skip-illumination for near-simultaneous Mie-scattering and flame imaging.
- 3/12 - skipfire operation for realistic residuals.
- Spark = -12°CA consistently misfire-free.
- Spark during fuel injection leads to high misfire rate.
High-Speed Imaging, SOI = -6°CA

- Statistically selected cycle.
- Combined Mie and natural luminosity.
- Closely coupled injection and ignition leads to highly turbulent combustion.

Spark = -12°CA, Intake [O₂] = 19%, Exhaust NO = 6 ppm
• SOI = -6°CA, spark = -12°CA.
• Correlation with IMEP.
  – Total Burn.
  – Early flame intensity.
• Weak cycles have odd flow near spark gap.
• Shows need to manage stochastic processes for better engine performance.

Imaging of Cyclic Variability

![Graph showing correlation between IMEP and cumulative AHRR](image-url)
Preliminary High-Speed Fuel-PLIF of E85

- High-speed tripled Nd:YAG laser, exciting gasoline components with 355 nm.
- Collecting red shifted fluorescence via 395 nm long-wavelength pass filter.
- Tests indicate strong O$_2$ quenching, so start with inert conditions for decent S/N.
- Cyclic variability is evident, even with the limited view into bowl.
- Combine PLIF with NL & Mie for characterization of combustion mode.
- PLIF: Will perform calibration and spectroscopic characterization.
- Add high-speed PIV diagnostics for identifying sources of cyclic variability.
Fuel Vaporization / Flame Speed

- E85 experiments with near-TDC fuel injection beg for more insights. For example:
  - What enables E85 to be ignited in the head of fuel jet, while gasoline fuel jets misfire?
  - Why are exhaust soot levels so low, despite flame spread prior to fuel/air mixing?
  - Why are NO levels so low?
- Use optical techniques and modeling to answer these questions (future work).
- First, however, examine some of the fundamentals.

- E85’s large latent heat of vaporization and high oxygen content:
  1. Prevents very rich gas-phase mixtures. For E85 $\phi_{max} \approx 5$, whereas $\phi_{max} \approx 15$ for gasoline.
  2. Makes richer zones much cooler. CHEMKIN predicts strongly suppressed combustion activity in these rich zones. Contributes to suppress soot formation.

![Graphs showing Laminar Flame Speed vs. Fuel/Air-Equivalence Ratio and Fuel Jet Mixing Temperature vs. Fuel/Air Equivalence Ratio]
Fuel Vaporization / Thermal Efficiency

- Efficiency study at IMEP_n = 370 kPa shows that TE-gain of stratified operation relative stoichiometric operation is 4% lower for E85.
  - +24% for gasoline, +20% for E85.
- Study SOI-effects on IMEP of non-fired operation.
  - Shows combined effect of fuel vaporization and γ.
- Higher IMEP for early injection.
  - Lower temperature thanks to vaporization cooling, so less heat-transfer losses.
- Lower IMEP for near-TDC injection.
  - Wasting valuable exergy for vaporization.
- Relative magnitude of effects ≈ 4% of fired IMEP_n.
  - Explains 4% lower TE-gain for stratified E85.
- Injection retard towards TDC comes with TE penalty for fuels with strong vaporization cooling.
- Higher injection pressure leads to reduction of IMEP for near-TDC injection.
  - Indicates enhanced heat-transfer losses.
  - Demonstrates one drawback of increased P_{inj}.
Collaborations / Interactions

- General Motors.
  - Hardware, discussion partner of results, and for development of diagnostics.

- D.L. Reuss (formerly at GM, now at UM).
  - Development of optical diagnostics for high-speed PIV and PLIF.

- 15 Industry partners in the Advanced Engine Combustion MOU.
  - Biannual meetings with 10 OEMs and 5 energy companies.

- Sandia Spray Combustion (L. Pickett) & Heavy-Duty Diesel Lab (M. Musculus).
  - Computation of spray penetration, vaporization, fuel/air-equivalence ratio, etc.

- LLNL (W. Pitz and M. Mehl).
  - Chemical-kinetics mechanisms and flame-speed calculations for gasoline-ethanol mixtures.

- USC-Los Angeles (Prof. Egolfopoulos) (not VT)
  - Flame speed and extinction measurements for gasoline/ethanol blends.

- LLNL (S. Aceves and R. Whitesides).
  - Converge-CFD.

\[ \text{Entrained gas } (P_a, T_a, \rho_a) \]

\[ \text{Vaporization complete } (x=L) \]

\[ R = \tan(\theta/2)(x+x_0) \]

\[ \frac{d}{dx} = (1+\xi^2)^2 \]

\[ \text{Temp} = 659 \text{ K} \]
\[ \text{Pressure} = 25 \text{ bar} \]
\[ [\text{O}_2] = 18.5\% \]
Future Work FY 2012 – FY 2013

• Examine effects of intake air temperature on stratified low-NO$_x$/soot operation with E85 and gasoline. Study $T_{in}$ effects on stable load range.

• Examine the use of early spark to ignite the head of fuel jet for gasoline.

• Continue the development of the fuel-PLIF technique.
  – Apply PLIF to measure $\phi$-fields for better understanding of low-emissions operation, and sources of cyclic variability.

• Perform initial PIV measurements of intake and compression flows.
  – Examine correlation between flow field and variability of combustion.

• Use CHEMKIN to investigate flame-extinction fundamentals.
  – Compare with measurements at USC-Los Angeles.
  – Provide better understanding of in-cylinder turbulence on flame quenching and ignition of fuel jets.

• Continue examination of fuel-vaporization effects on thermal efficiency.
  – Boosted operation.

• For well-mixed operation, initialize study of fuel effects on endgas autoignition (knock) under boosted conditions.
  – Trade-offs between ethanol content and octane rating of gasoline base fuel.
Summary

• This project is contributing to the science-base for the impact of alternative fuel blends on advanced SI engine combustion.

• Under the current operating conditions (single fuel injection and low residuals) gasoline cannot achieve low NO\textsubscript{x} and soot simultaneously.
  – Using a typical injection timing, neither can E85.

• E85 responds favorably to SOI retard ⇒ enables very low exhaust NO and soot.
  – Lower peak temperatures, and less residence time.

• Stable operation with near-TDC fuel injection is possible for E85.
  – E85 allows and requires spark ignition of the head of the fuel jets, and strong spray/plasma interactions create large amounts of early flame spread prior to onset of main heat release.

• Short delay from injection to combustion likely leads to high turbulence levels.
  – May contribute to low thermal NO formation for operation with late SOI.

• Cycle-to-cycle variations of IMEP can be significant for low-NO\textsubscript{x} operation.
  – Flow variations even prior to fuel injection play a substantial role for the combustion event, as indicated by strong variations of spark-plasma motion.

• Strong vap. cooling of E85 likely limits combustion activity in very rich zones.
  – Contributes to low soot emissions, in addition to the effects of high oxygen content.

• Strong vap. cooling of E85 during intake stroke tends to improve thermal efficiency.
  – Near-TDC injection hurts thermal efficiency, with additional penalty from high P\textsubscript{inj}.
Technical Back-Up Slides
- NO / PM trade-offs are different.
- But none can reach inside NO-PM box.
- Trade-offs between NO and stability are similar for both fuels at this SOI.
- Partial-burn cycles prevent NO\textsubscript{x} compliance.

- Many weak cycles have slow or incomplete flame spread to 5 o’clock position.
Gasoline does not allow SOI retard for these no-EGR conditions. Misfire cycles appear.

IMEP, and TE could benefit from SOI retard.

Better-phased combustion.
SOI-sweep for Gasoline, $O_2 = 16.5\%$

- For $[O_2] = 16.5\%$, gasoline shows decent tolerance to SOI retard.
- Strong NO benefit, but soot increases strongly.
- No TE benefit.
  - Already well-phased combustion.

- Gasoline shows no stable operation for SOI > -23°CA.
Spark Timing for Gasoline

- Earlier ST for 16.5% cases contributes to better success with SOI retard.
- However, no STs were found that provide stable operation for SOIs later than -23°CA.
- “Spark window” is 3°CA wide for 16.5% O₂ and SOI = -31°CA.
- Ignition of head of gasoline fuel jet was not possible under these conditions.

![Graph showing Spark Timing for Gasoline](image)
Spark during fuel injection leads to high misfire rate.

However, if ignition is successful no effect on AHRR is detected in ST = -12° to -4°CA range.

For ST = -4°CA, side-view imaging shows 100% correlation between misfire and lack of plasma formation.