COMBUSTION RESEARCH FACILITY

Advanced Lean-Burn DI Spark Ignition Fuels Research

Magnus Sjöberg

Sandia National Laboratories

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Project ID: FT006

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. Dilute and mostly premixed charge with advanced ignition.

Budget

- Project funded by DOE/VT via Kevin Stork.
- FY13 - $650 K
- FY14 - $700 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).
- W. Zeng (post-doc)
- Z. Hu (long-term visitor from Tongji Univ.)
- USC-LA (Gundersen *et al.*) – Advanced Ignition.
- LLNL (Pitz *et al.*) – Mechanisms and Flame-Speed Calculations.
- USC-LA (Egolfopoulos *et al.*) – Flame Measurements.

Objectives - Relevance

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

- Determining fuel characteristics that enable current and emerging advanced combustion engines that are as efficient as possible.

1. DISI with spray-guided stratified charge combustion system
   - Has demonstrated strong potential for throttle-less operation for high efficiency.
   - Mastering NO_x / Soot / Combustion Stability trade-off is key to success.
   - These processes are strongly affected by fuel properties (*e.g.* ethanol content).
2. DISI with well-mixed/dilute combustion system
   - Also strong potential for improved efficiency.
   - High combustion stability and combustion efficiency are keys to success.

- 1. Develop a broad understanding of spray-guided SI combustion (*i.e.* conceptual model, including fuel effects).
- 2. Identify and explain combinations of fuel characteristics and ignition strategies that enable stable and efficient well-mixed dilute operation.

- Current focus is on E85 and gasoline, and blends thereof.
  - Flex-fuel vehicles need to function with 0 – 85% ethanol in the fuel tank.
- Shift toward mid-level E0 - E30, and watch for emerging bio-components.

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 all-metal engine over wide ranges of conditions to identify critical combinations of operating conditions and fuels.
  - Speed, load, intake pressure, EGR, and stratification level.
- Second, apply a combination of optical and conventional diagnostics to develop the understanding needed to mitigate barriers.
  - Include full spectrum of phenomena; from intake/compression flows, fuel injection, fuel-air mixing, spark development and ignition, to flame spread and burn-out.

<u>Supporting modeling and experiments:</u>

- Conduct chemical-kinetics modeling of flame-speed and extinction for detailed knowledge of governing fundamentals.
  - Collaborate on validation experiments and support mechanism development.
- Seeking CFD collaborators.

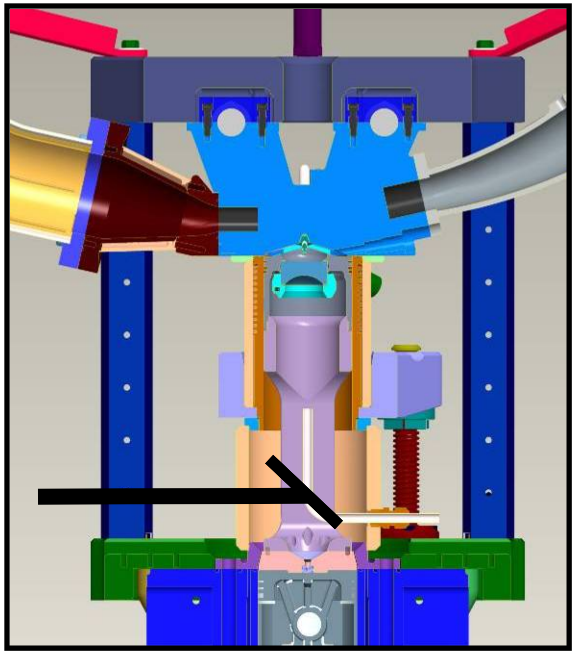
- Addresses barriers to high efficiency, robustness, and low emissions by increasing scientific knowledge base and enhancing the development of predictive tools.

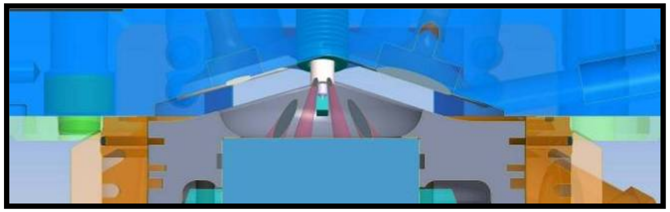
Approach - Research Engine

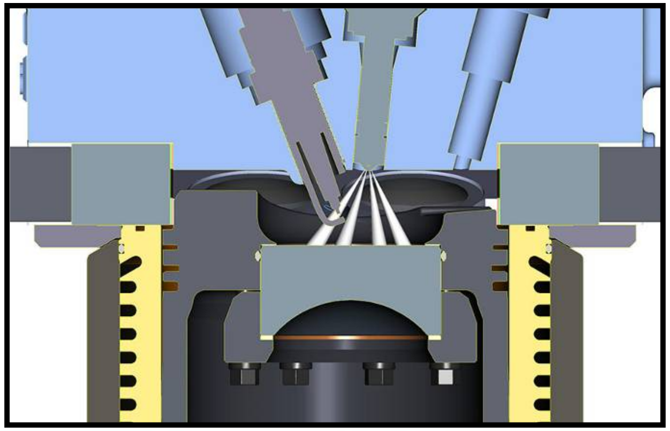
Two configurations of drop-down single-cylinder engine.

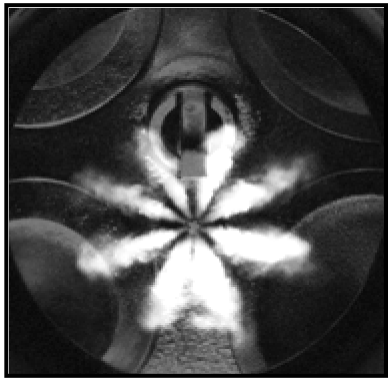
Bore = 86.0 mm, Stroke = 95.1 mm, 0.55 liter swept volume.

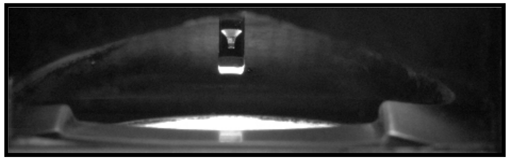
- <u>All-metal:</u> Metal-ring pack and air/oil-jet cooling of piston.
- <u>Optical:</u> Pent-roof window, piston-bowl window, and 45° Bowditch mirror.
- Identical geometry for both configurations, so minimal discrepancy between performance testing and optical tests.
- 8-hole injector with 60° included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





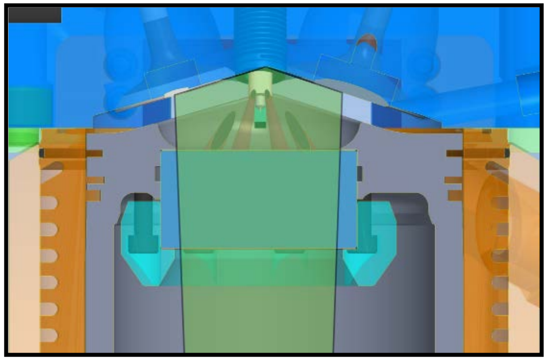


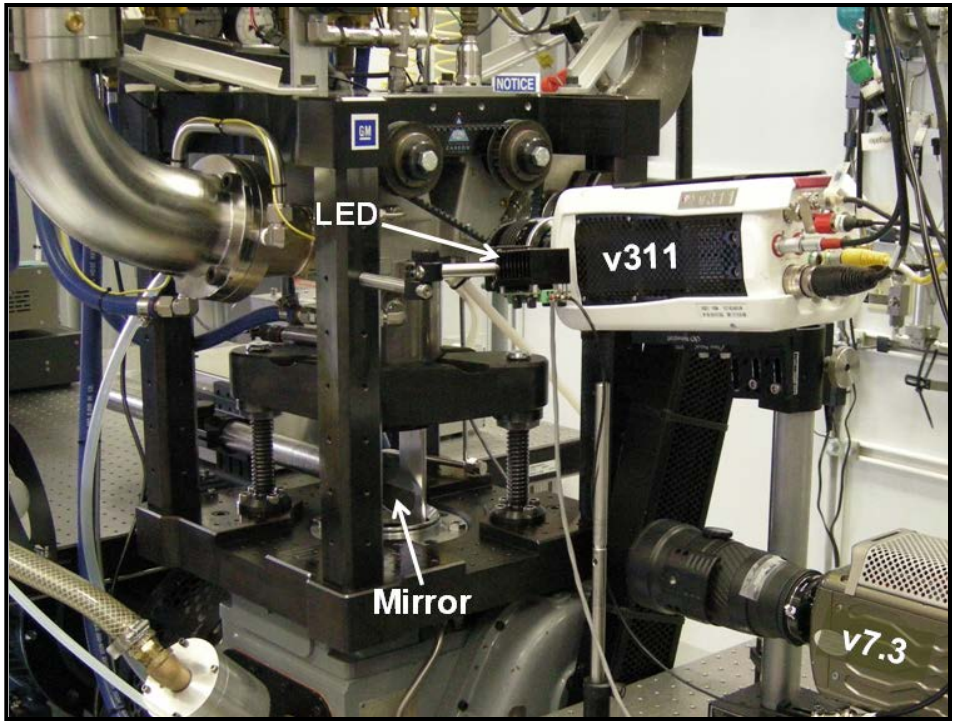


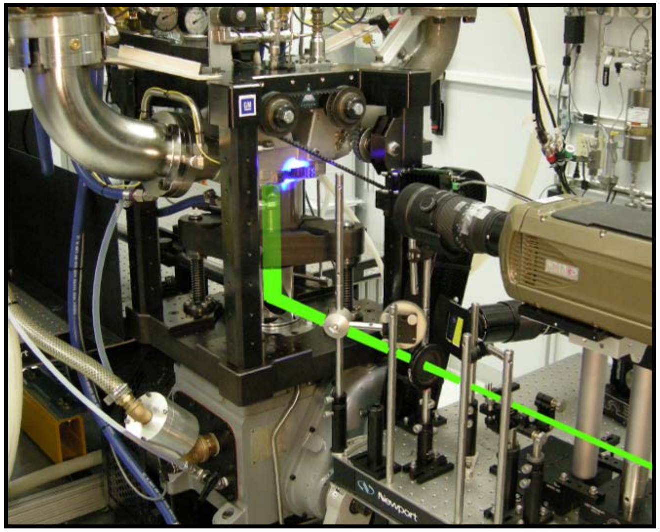


Approach - Optical Diagnostics Setups

- Dual-camera setups.
- Mie & natural luminosity imaging via Bowditch mirror and side window.
- PIV high-speed 532 nm laser - Quantronix Dual Hawk.
  - Vertical laser sheet near spark-plug gap.
  - Horizontal laser sheet at spark-gap elevation.







Approach - Milestones

- ✓ **November 2012**
  Determine the potential for low emissions of NO_x and PM, using stratified combustion of E85 and gasoline.
- ✓ **March 2013**
  Identify important fuel properties and effects that enable or inhibit stable ignition of E85 and gasoline fuel sprays.
- ✓ **December 2013**
  Determine the role of ethanol/gasoline mixture proportions on soot emissions across load ranges for stratified operation.
- ✓ **March 2014**
  Quantify statistically the relationship between the in-cylinder flow field, spark-plasma development, and combustion variability.
- ✓ **June 2014**
  Determine the role of the intake flow for both well-mixed and highly stratified operation.
- **September 2014**
  Quantify the role of ethanol/gasoline mixture proportions on stability of stratified ignition for wide ranges of spark timings.

Technical Accomplishments

1. **<u>DISI with spray-guided stratified charge combustion system</u>**

➔ • Continued examination of effects of fuel blend (E0 to E100) on stratified operation.

➔ • Examined in detail what governs heat-release rate and its variability.

A) Highly stratified <u>E70 or E85</u> operation with "head-ignition".

B) Less stratified <u>gasoline</u> operation with "tail ignition".

- Effects of engine speed, swirl and injection pressure.
- Optical measurements of spray variability, flow field and flame development.

• Examined statistically the effects of in-cylinder flow field variations on spark-plasma development and combustion variability for highly stratified E85 operation.

➔ 2. **<u>DISI with well-mixed/dilute combustion system</u>**

• Compared lean stability limits and fuel-efficiency gain of E85 and gasoline.

• Examined and explained strong beneficial effect of intake heat on lean limits.

- Compounding effects of intake heat, spark timing, and endgas autoignition.

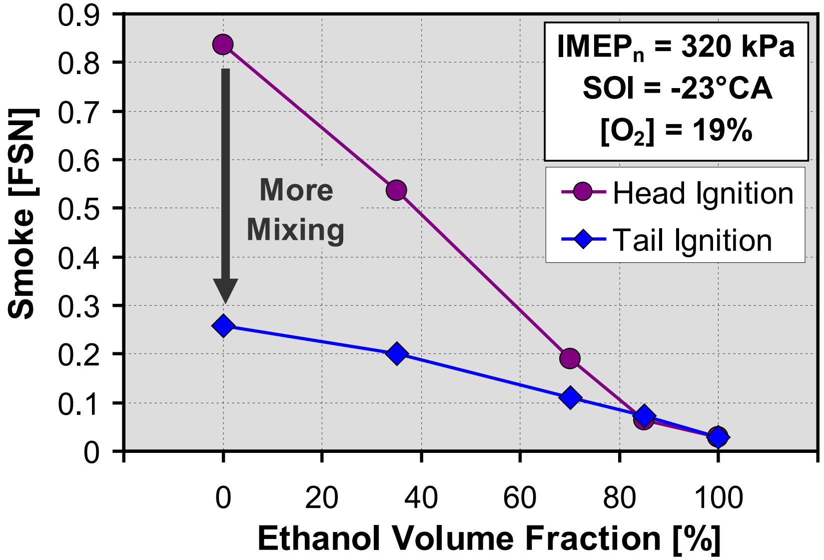
• Conducted a combined optical/performance study of multi-pulse transient plasma ignition for E85.

<u>Lab Development.</u>

• Designed and installed an intake-air heater with fuel-premixing capabilities.

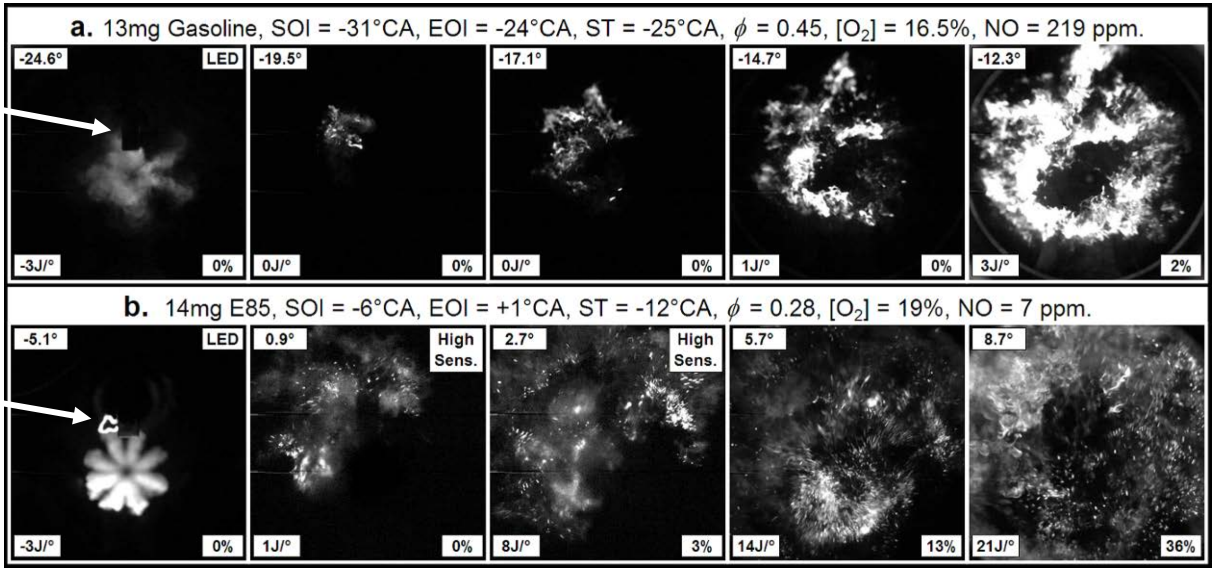
Smoke vs. Fuel Type & Ignition Strategy

- Sooting tendency generally decreases with more ethanol.
  - Oxygenated fuel & strong vaporization cooling suppresses rich combustion.
- Highly stratified operation is not suitable for gasoline.
  - Smoke mandates tail ignition.
- Different combustion characteristics.
  - Factors controlling HRR and cycle-to-cycle variability.



Gasoline Tail Ignition

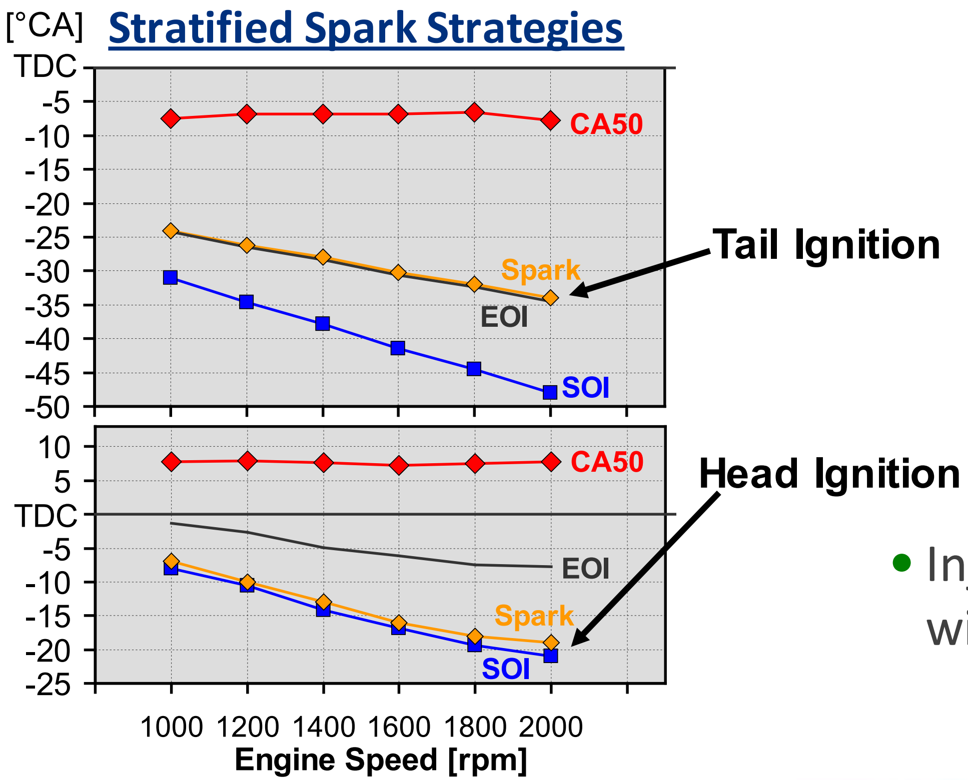
E85 Head Ignition



Parameter Space

- Grouped as hardware, static parameters & operating variables.
- Gasoline – ethanol blends.

- Low to moderate loads.
- Strive towards unthrottled operation.
  - Higher efficiency.



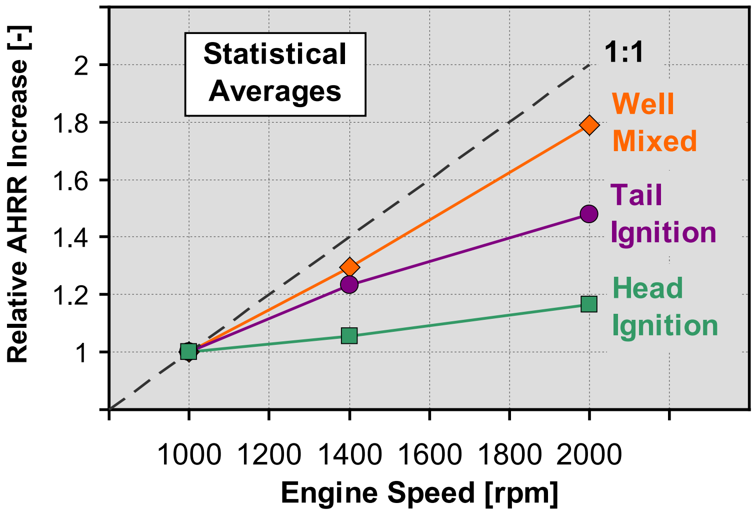
Parameter	This Presentation
CR	12
Valve Timings	For Minimal Residual Level
# of Injections	Single
Injection Pressure	56 - 170 bar
Spark Energy	106 mJ
$T_{coolant}$	75°C
Fuel Type	Gasoline (E0) – E100
Engine Speed	1000 - 2000 rpm
$IMEP_n$	250 - 430 kPa
Intake Pressure	37 - 96 kPa
Swirl Index	0 or 2.7
Tumble Index	0.27 or 0.62
T_{in}	26 - 100°C
EGR / $[O_2]_{in}$	21 – 19% O_2

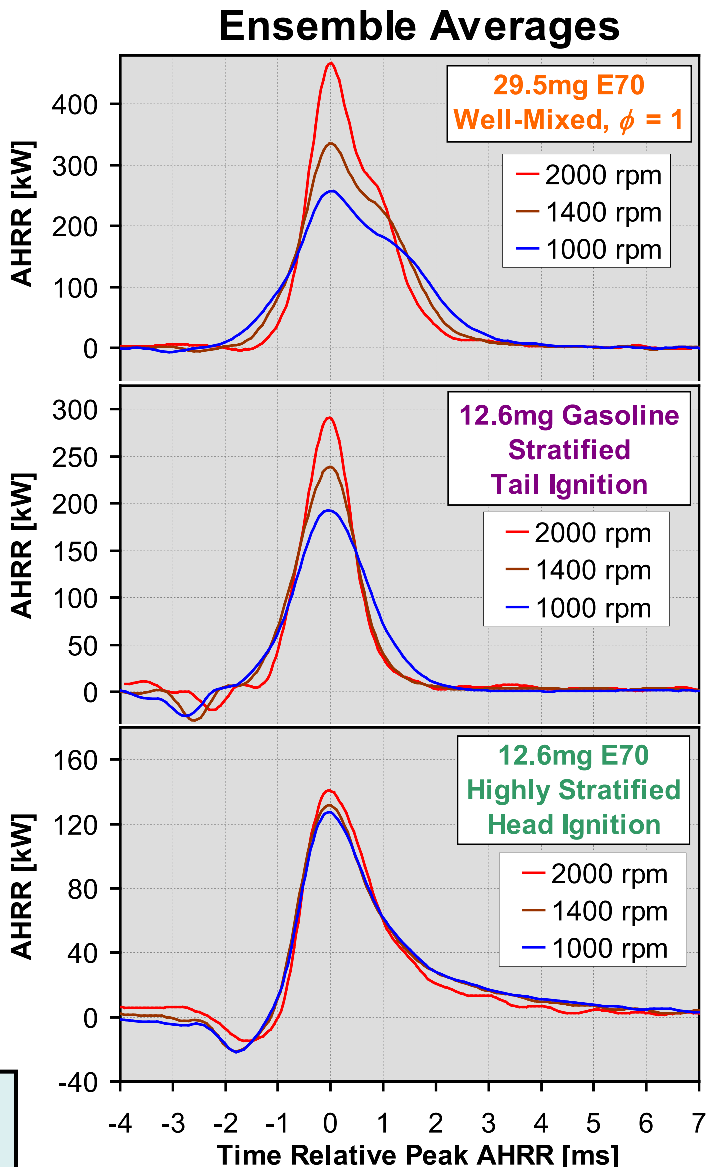
- Injection and spark must be advanced with increasing engine speed.
  - Maintain constant CA50.

HRR Scaling with RPM

- Well-mixed $\phi = 1$ scales with speed.
  - Deflagration $\propto$ turbulence level.

- Gasoline with tail ignition scales moderately with speed.
  - HRR controlled by combination of spray and intake flows.





- E70 with head ignition does not scale with rpm.
  - HRR controlled by spray-induced mixing.

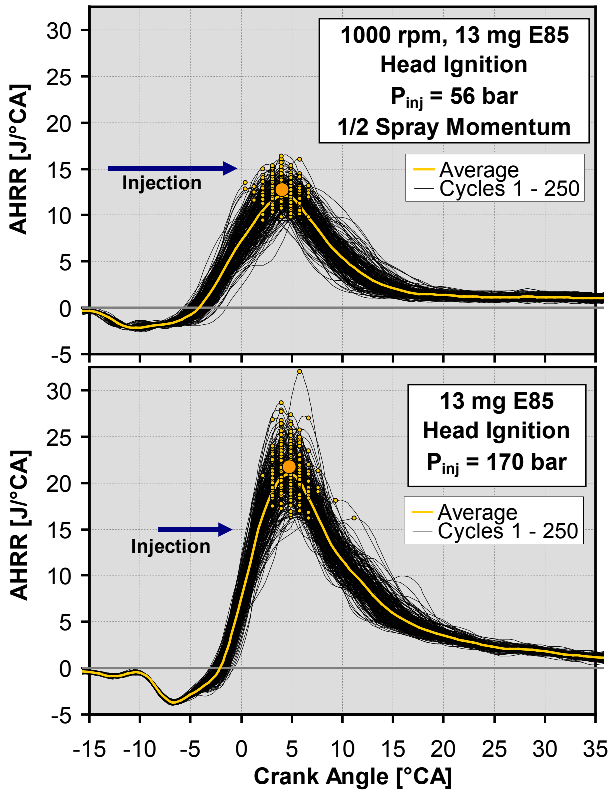
HRR-Controlling Factor for Head-Ignition Operation

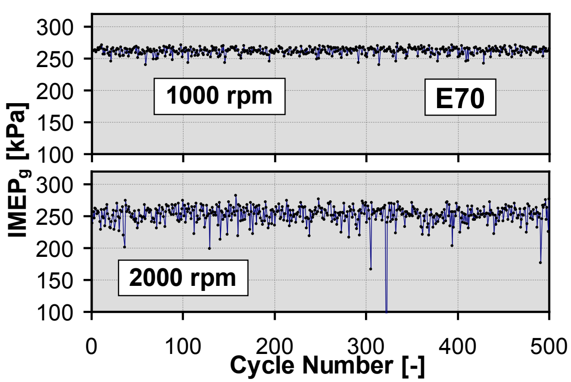
- Investigated in two SAE papers by developing hypotheses and testing against experimental data.

A: *The heat-release rate of highly stratified spray-guided combustion is primarily controlled by mixing rates associated with the fuel spray.*

- Test hypothesis by changing spray momentum.

- Reduce injection pressure from 170 to 56 bar to reduce V_0 by 50%.
- Peak AHRR reduced by 42%.
- Strengthens hypothesis A.



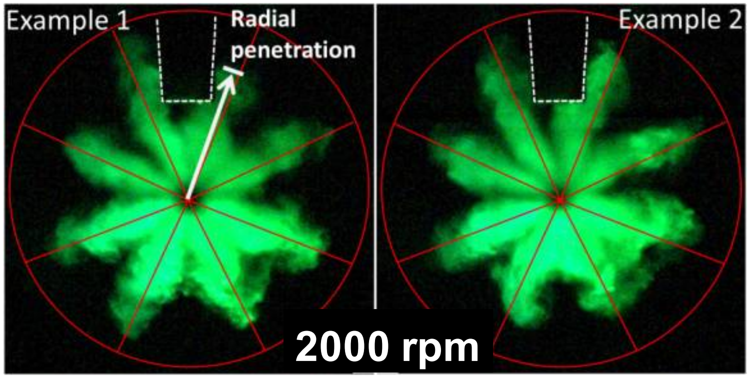


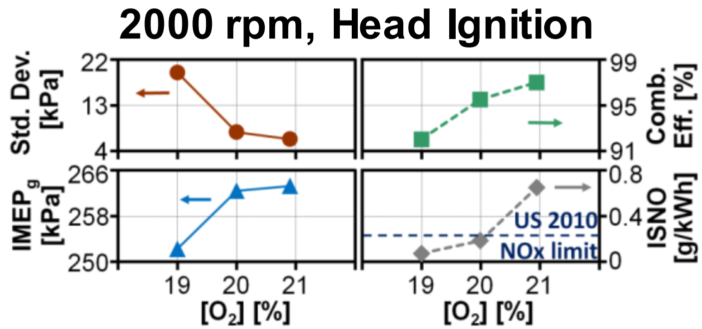
Stochastic Role of In-Cylinder Flow

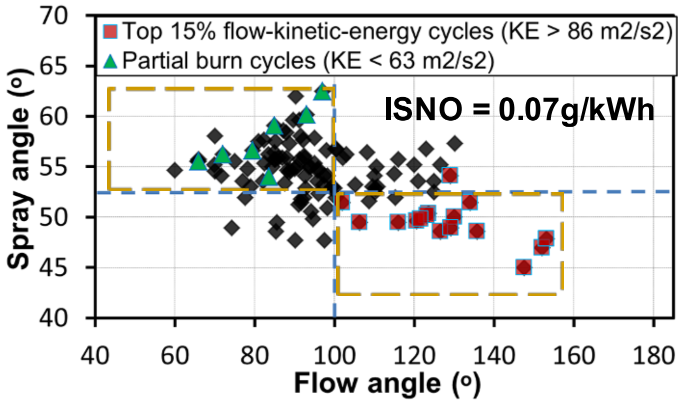
B: RPM ⇑, in-cylinder flow field becomes strong relative to the fuel jets ⇒ unstable combustion.

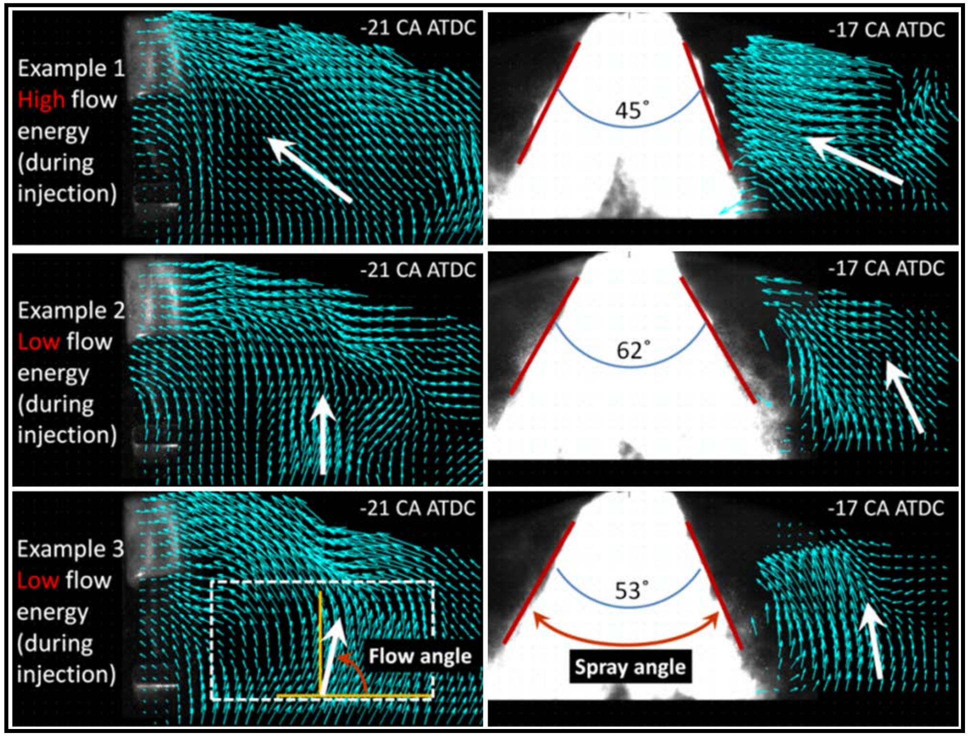
Stochastic Role of In-Cylinder Flow for Stratified E70 Operation

- Combined Mie, PIV and AHRR reveal partial-burn predictors for low-NO_x operation with EGR at 2000 rpm.
- Improper flow direction + wide spray ⇒ low flow energy ⇒ 30% partial-burn frequency.

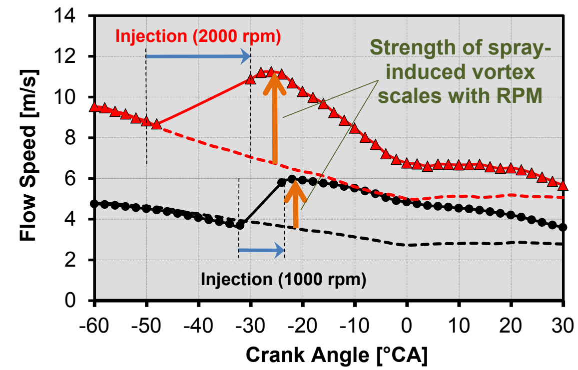








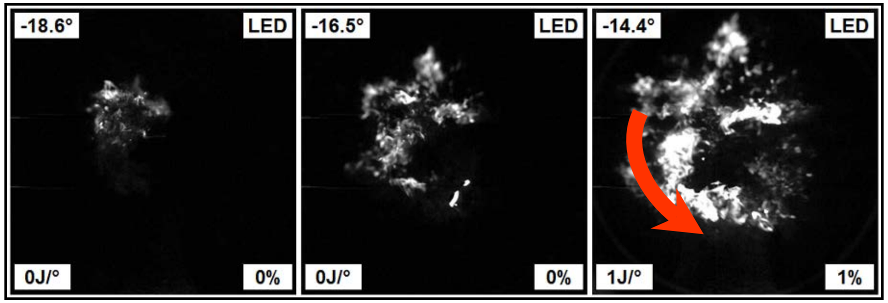
Swirl Stabilization Mechanism

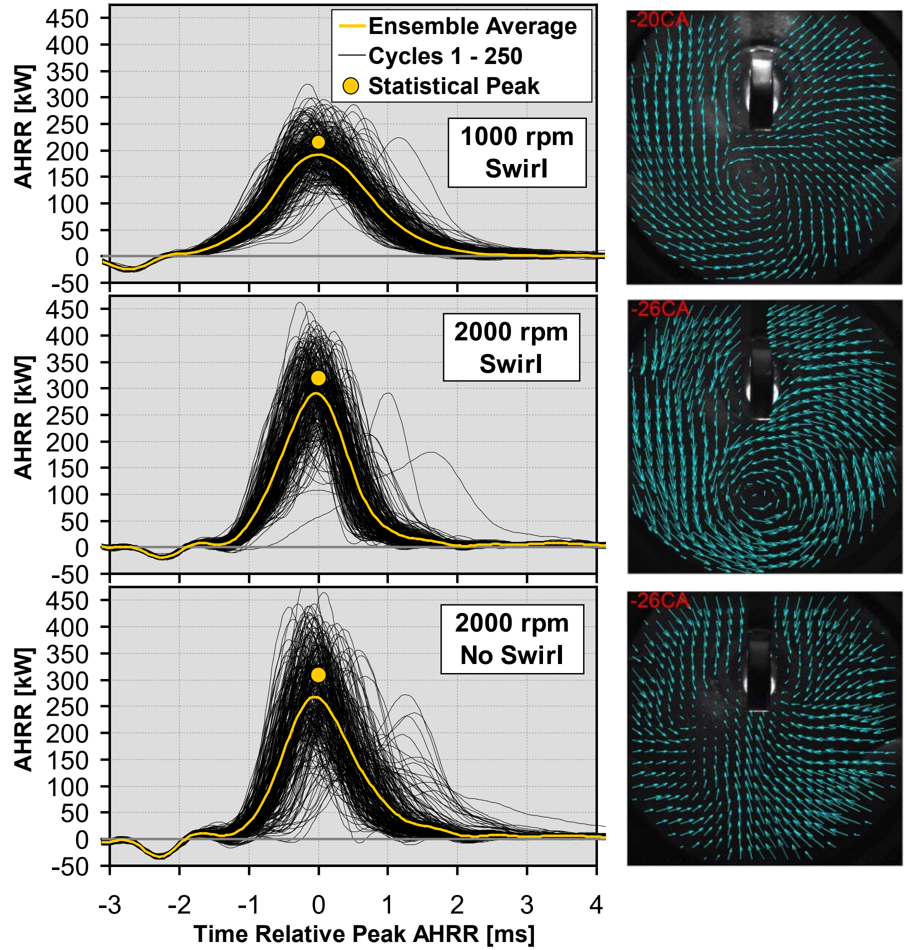


- **Gasoline with tail ignition:** rpm ⇑, ⇒ increased variability without swirl.
- With swirl: rpm ⇑, ⇒ combustion remains stable.

- PIV reveals fluid dynamics of stabilizing mechanism.
- Redistribution of gas flow by sprays creates a strong and very repeatable vortex near center of piston bowl.
  - Vortex strength ∝ RPM

- Important for efficient early flame spread at higher rpm.

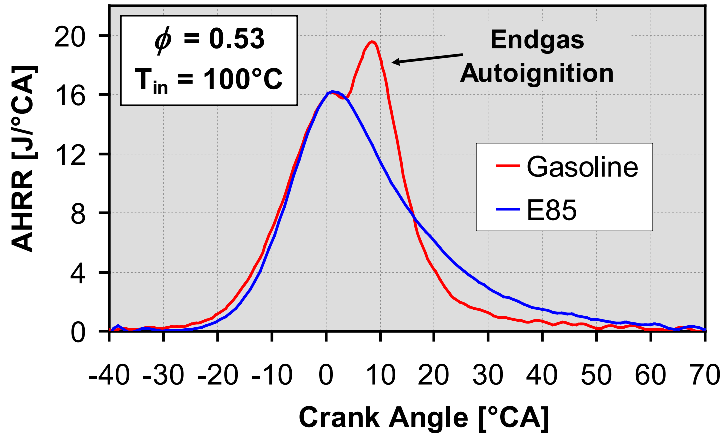


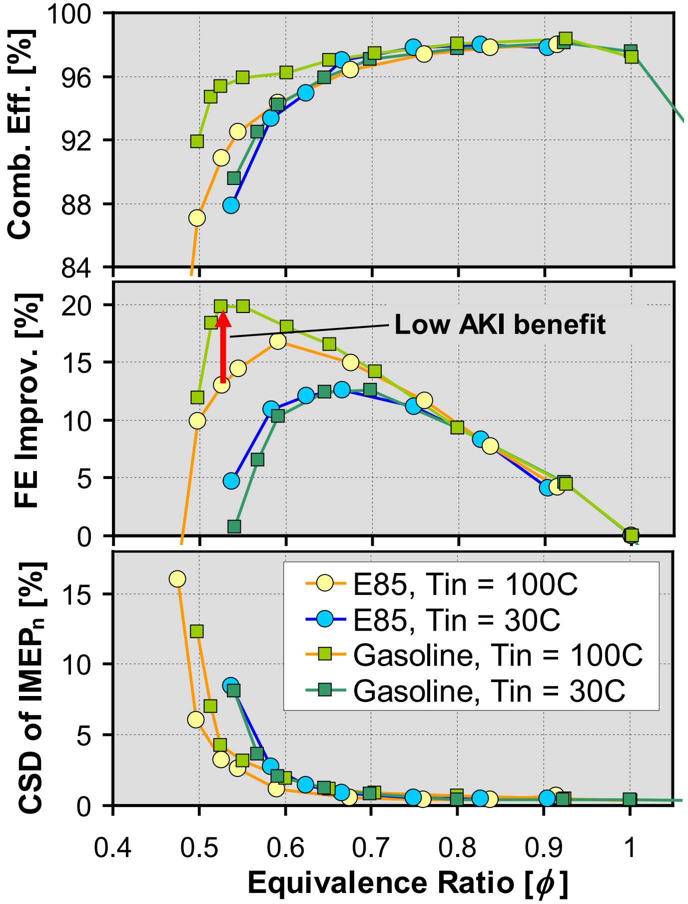


Lean Limits with Gasoline & E85

- Well-mixed lean operation can provide higher fuel economy as well.
- Examine fuel effects and clarify governing fundamentals.
- Gasoline and E85 have very similar lean stability limits for unheated operation.
- Intake heating improves lean limit for both fuels (see Collaboration slide.)

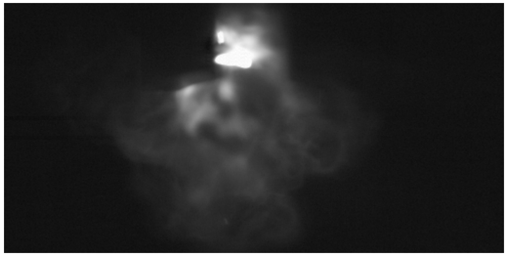
- Gasoline shows extra benefits for heated lean operation.
  - CE > 95% for ϕ down to 0.53.
  - FE improves by 20%.
  - Endgas autoignition.
- Suggests that low AKI fuels are beneficial for exploiting this.

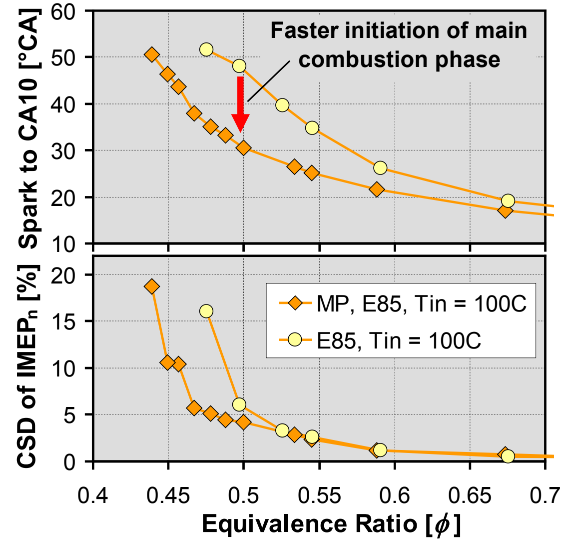


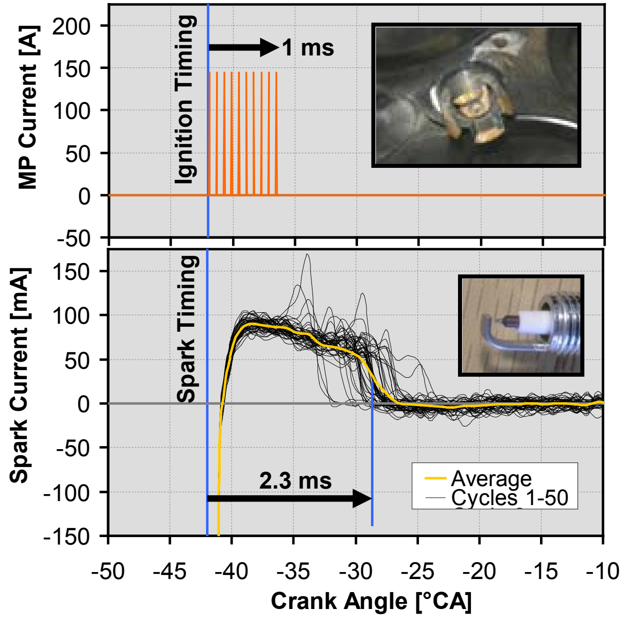


Advanced Ignition of E85

- Traditional spark is very localized.
  - Slow transition from laminar flame kernel to fully turbulent deflagration.
  - Susceptible to local unfavorable conditions (*i.e.* fuel-, temperature-, flow-variations).
  - In addition, spark duration varies.
- Collaboration with USC-LA (Gundersen).
  - Multi-pulse (MP) transient plasma.
  - Semi-open ignition chamber.
  - High-voltage/current, but short pulses.
- Pushes lean limit to $\phi = 0.48$
  - Downward turbulent jet.



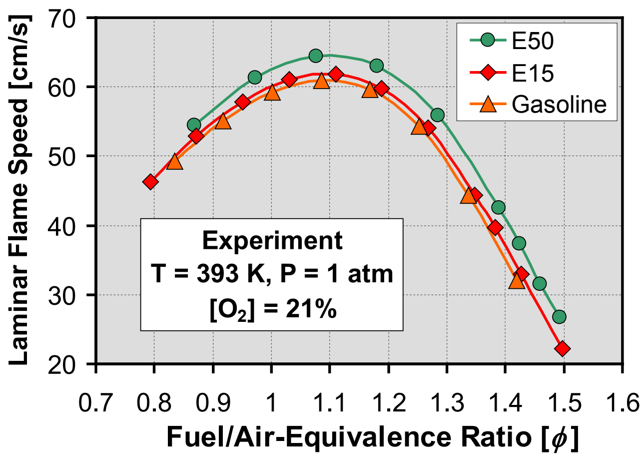




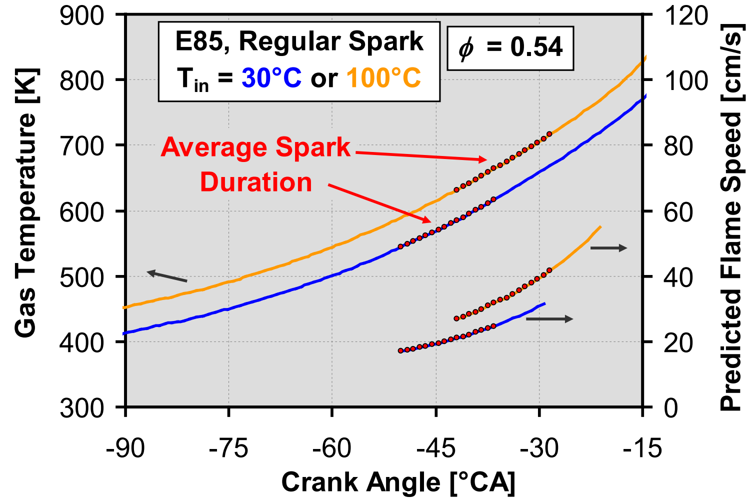
- Improves potential of lean operation by speeding up transition into fully turbulent combustion.

Collaborators / Results from Collaborations

- General Motors.
  - Hardware support, discussion partner.
- D.L. Reuss (formerly at GM, now UM).
  - Optical diagnostics development.
- 15 Industry partners in the Advanced Engine Combustion MOU.
  - Biannual meetings.
- USC-Los Angeles (Egolfopoulos) (not VT).
  - Flame-speed measurements of real gasoline/ethanol blends, and modeling.



- USC-Los Angeles (Gundersen) (not VT).
  - Multi-pulse transient plasma.
- LLNL (W. Pitz and M. Mehl).
  - Prediction of flame robustness for engine-conditions.
  - Development of mechanisms for gasoline-ethanol surrogate blends.
- Intake heat & MP ignition both allow later spark.
  - Flame model shows benefit from later spark due to higher compressed-gas temp.



Address Previous Reviewers' Comments

- **Overall, the evaluations were very positive.**
- **Below are responses to selected areas of concern that the reviewers expressed.**
- *Question 4: "One reviewer explained that for many reasons, there is little chance of engines being purpose-built or even optimized to take advantage of the characteristics of E85/E70, particularly to the extent that they run contrary to the optimization for gasoline operation, which appears to be what this research shows (e.g., retarding spark timing to avoid head ignition, effects of temperature, etc.) unless future engines were to reincorporate fuel sensors that would adjust the spark timing, etc., according to the ethanol content or oxygen content of the fuel, which seems doubtful."*
- **Response:** The purpose of this project is to provide new insights and incorporate this into the scientific knowledge base. When opportunities with alternative fuels are identified, it is up to industry to decide if it is practical to exploit these opportunities. Reasonably, the calibration decisions by OEMs must balance control complexity against fuel savings, while ensuring emissions compliance. By building a solid science base and facilitating development of predictive models, this project helps the OEMs to make informed decisions.
- *Feedback from a reviewer for Question 3: "…results still does not provide predictive tools or models for fuel property effects on engine efficiency optimization. Developing a proper model as a predictive tool will be very valuable for optimizing engine performance."*
- **Response:** Developing predictive tools is outside the scope of this project. This projects examines fuel effects on advanced combustion strategies, and provides data and support for model development. The results and collaboration slides highlight good progress in both flame-model development and the use of these models to gain valuable insights. We are currently seeking to re-establish collaborations with CFD model developers.
- *Question 4: "One reviewer was concerned with the relevance the project believes the E100 range could have. "*
- **Response:** We agree that E100 is not a practical fuel in the US. However, when developing a comprehensive understanding of fuel effects in the E0-E85 range, which is the range of fuel blends encountered in the fuel tanks of flex-fuel vehicles, it makes sense from a scientific standpoint to also include the extreme point of E100 (neat ethanol) fuel. This is particularly true also when providing data to support model development. Undoubtedly, the current thinking around alternative fuels in the US has shifted away from E85 as the most important solution. Hence, going forward, this project will devote more attention to mid-level blends in the E0-E30 range. We are also monitoring the research and debate around other emerging bio-based fuels.

Future Work FY 2014 – FY 2015

- Continue studying effects of fuel blend, E0 to E30 (E100), on stratified operation.
  - Ignition stability, smoke and NO_x exhaust emissions.
- Finish analysis of swirl-stabilization mechanism for stratified gasoline.
  - Examine interaction of center vortex and flame spread for “tail ignition”.
- Continue examination of lean/dilute operation.
  - Multi-pulse ignition and intake heat in combination with E0-E30 gasoline blends.
  - Effects of diluent type (*e.g.* air, EGR, trace species of EGR).
  - Watch for opportunities to collaborate on emerging advanced-ignition hardware.
- Start examination of partial-fuel stratification for lean/dilute operation.
  - Tailor fuel stratification to improve lean stability limit.
- Continue the development of the fuel-PLIF technique.
  - Apply PLIF to measure ϕ–fields for better understanding of both stratified and partially stratified operation.
- Continue using CHEMKIN to investigate fundamentals of deflagration.
  - Combination of fuel type, stratification level, and ignition timing on lean limits.

Summary

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

1. <u>DISI with spray-guided stratified charge combustion system</u>

- Gasoline/ethanol blend proportions influence optimal injection- and spark-timing strategies for stratified operation.
  - More mixing time is required for gasoline to avoid excessive soot formation.
- Factors governing heat release change with fuel type due to different spark strategies.
  - Highly stratified operation with high-ethanol blends: HRR is governed by fuel spray.
  - Less stratified operation with gasoline: HRR is governed by spray and intake-generated flow field.
- Increasing engine speed can challenge combustion stability.
  - Highly stratified operation with high-ethanol blends: Stochastic flow/spray interactions influence spray collapse, fuel-jet strength, and subsequent flame spread.
  - Less stratified operation with gasoline: Spray – swirl interactions create strong and stable vortex.
    - Vortex strength scales with engine speed to aid flame spread.

2. <u>DISI with well-mixed/dilute combustion system</u>

- For unheated operation, lean stability limits are identical for E85 and gasoline.
- For heated-air operation, gasoline shows an advantage due to endgas autoignition.
  - Initial tests exhibit fuel-economy improvement of +20%.
- Multi-pulse transient plasma demonstrates strong benefits to stabilize lean operation.
  - Faster transition to fully turbulent combustion allows later spark timing.