2016 Annual Merit Review
Vehicle Technologies Program
Project ID# FT042

UTILIZING ALTERNATIVE FUEL IGNITION PROPERTIES TO IMPROVE SPARK-IGNITED AND COMPRESSION-IGNITED ENGINE EFFICIENCY

PI: Margaret Wooldridge
Presenter: André Boehman
University of Michigan
June 9, 2016

Overview

Timeline

- Project start date: 9/1/15
- Project end date: 9/30/16
  (No-cost extension to 8/30/17)
- Percent complete: 75%

Barriers

- >40% BTE SI Engine
- >50% BTE CI Engine

Budget

- Total project funding
  - DOE share: $874,024
  - Contractor share: $240,000
- Funding received in FY 2015
  - DOE share: $536,222
- Funding for FY 2016
  - DOE share: $337,802

Partners

- Project lead: University of Michigan
- Partner: Bosch, LLC
- Collaborator: NREL
- Collaborator: Ford Motor Company
- Collaborator: Sandia Engine Combustion Network
- Collaborator: Horiba

Relevance and Project Objectives

Overall Objective: To demonstrate the combination of fuel selection, fuel injection strategy, and mixture preparation that enables meeting the DOE targets for brake thermal efficiency of greater than 40% for spark-ignited engines and greater than 50% for compression-ignited engines.

Task 1.1: auto-ignition and spray studies of fuel blends

Objectives: to develop ignition and fuel spray correlations that can be used to guide injection and spark timing strategies and can be used in the engine simulations.

Task 1.2 engine simulations

Objectives: to evaluate the impact of knock and flame limits of alternate fuels and combustion strategies on engine efficiency.

Task 1.3: single cylinder engine studies

Objectives: to develop spray and spark timing strategies for different fuel compositions and and EGR blends that quantify sensitivity to extending knock limits and enabling higher engine efficiencies

Task 1.4: multi-cylinder ethanol/gasoline SI studies

Objectives: to demonstrate spray and spark timing strategies from single cylinder engine studies on multi-cylinder engine; to assess impact of multiple injection pulses on the knock mitigation and the PM emission for different fuel blends with production and production-intent hardware

Task 1.5: multi-cylinder DME/propane CI studies

Objective: 50% BTE CI demonstration (via dual-fueling of DME and propane)

Milestones and Go/No Go Metrics

Year 1

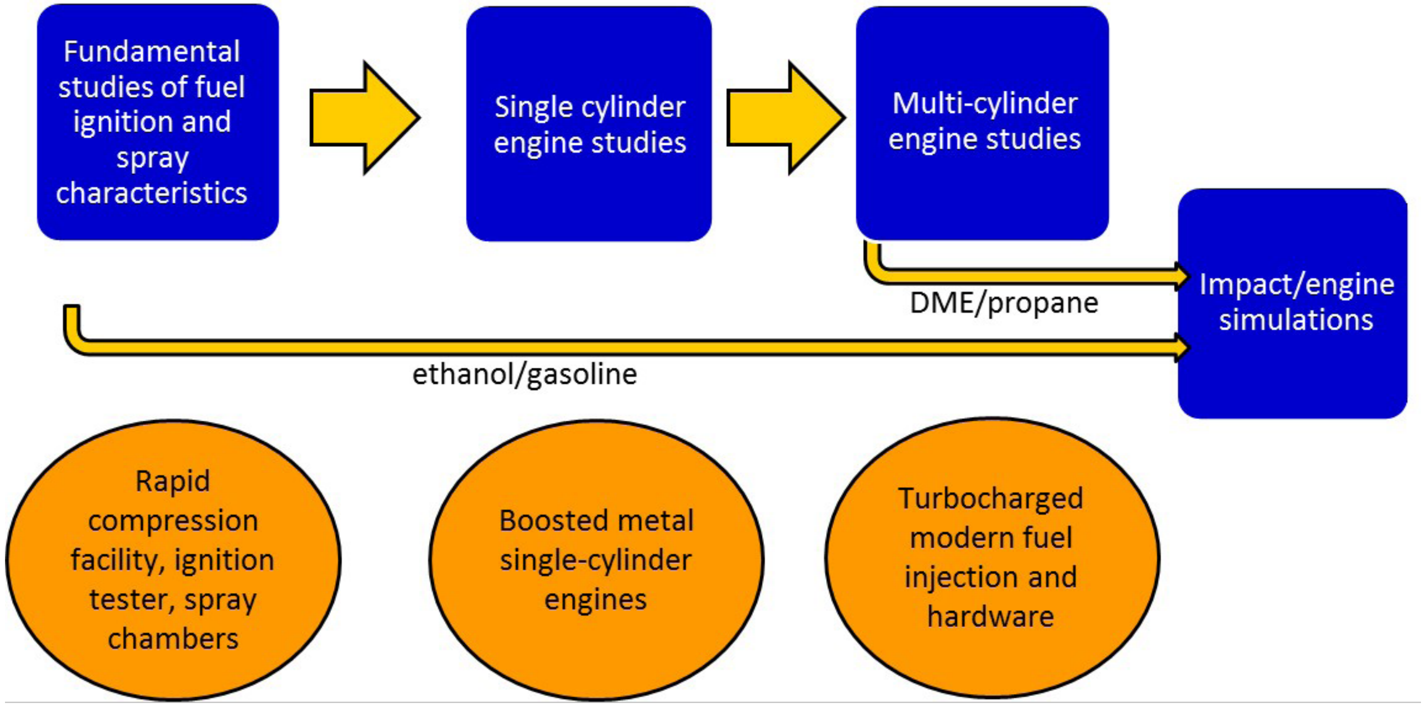
Milestone	Description	Completion Date	Status % complete	Type
Dual-Fuel Studies	Initiate Dual-Fuel Studies	1/15	100	Milestone
Single-Cylinder Engine Upgrade	Configure and install upgraded single-cylinder engine operation	4/15	100	Milestone
Multi-Cylinder Engine Upgrade	Configure and install upgraded multi-cylinder engine operation	6/15	100	Milestone
Fuel Strategies	Develop dual fuel strategies leading to 50% BTE or greater	9/15	100	Milestone
50% BTE CI Demonstration	Demonstration of 50% or greater BTE in a multi-cylinder CI engine	9/15	100	Go/**No Go**

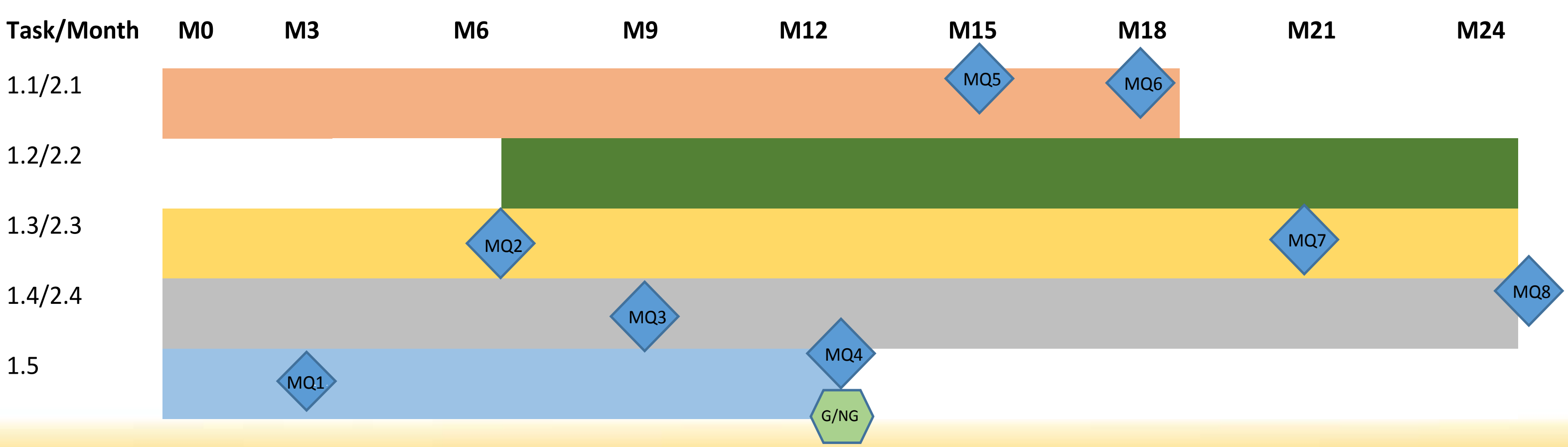
Year 2

Milestone	Description	Completion Date	Status % complete	Type
Ignition data	Experimental ignition data corresponds with database	1/16	100	Milestone
Rapid compression facility data	Experimental data from rapid compression facility corresponds with database	4/16	100	Milestone
Knock limits	Demonstration of knock limit extension	6/16	25	Milestone
40% BTE SI Demonstration	Demonstration of 40% or greater BTE in a multi-cylinder SI engine	9/16	25	Milestone

Approach/Strategy

Extend the knock limit through fuel blending and quantify the fuel specific contributions.

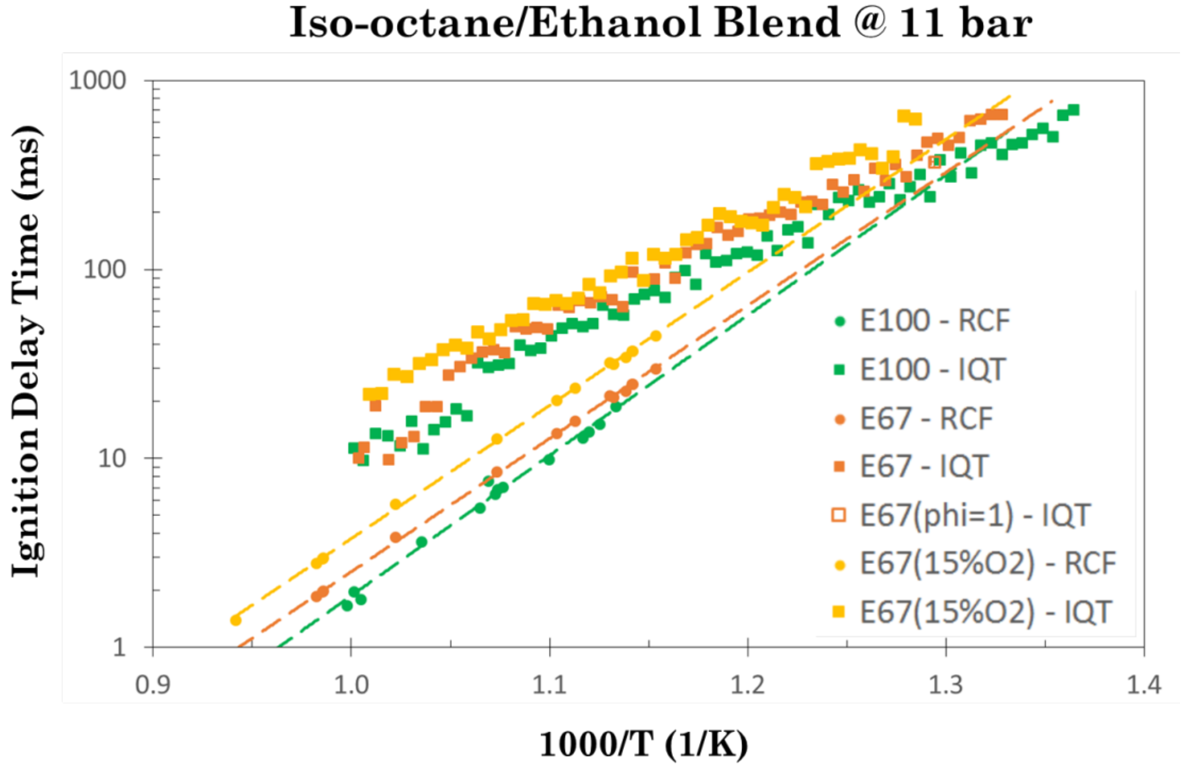




Technical Accomplishments and Progress

Task 1.1: auto-ignition and spray studies of fuel blends: UM RCF and NREL IQT

E100 and E67 ignition delay time results



- Excellent agreement between experimental data and model predictions for E100.
- The UM RCF data cover new conditions, complementing and expanding previous studies
- With advances in multi-injection fuel injection strategies, we need to build confidence over a larger range of state conditions, including temperatures <1000 K and P< 10 atm
- Ignition delay time data for ethanol and ethanol/iso-octane blends from UM RCF and NREL IQT studies at complementary and overlapping conditions.
- Current work: analyzing and comparing ignition data from the “pure chemistry” experiments of the RCF and the spray & mixing data from the IQT

Technical Accomplishments and Progress

Task 1.2 engine simulations: use engine simulations calibrated by experimental results to:

1) determine engine efficiency gains possible with alternative fuels
2) estimate the vehicle fuel economy benefits

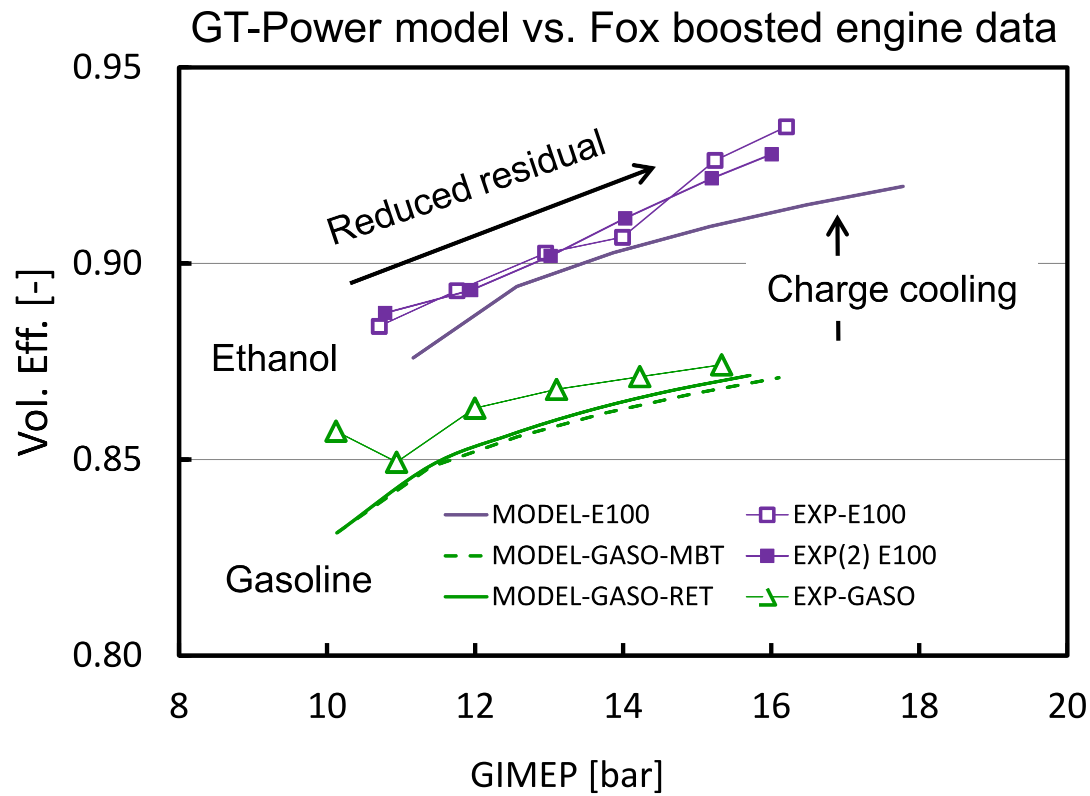
Experimental knock and flammability properties of alternative fuels

GT-Power Engine simulation

Engine Efficiency Gains

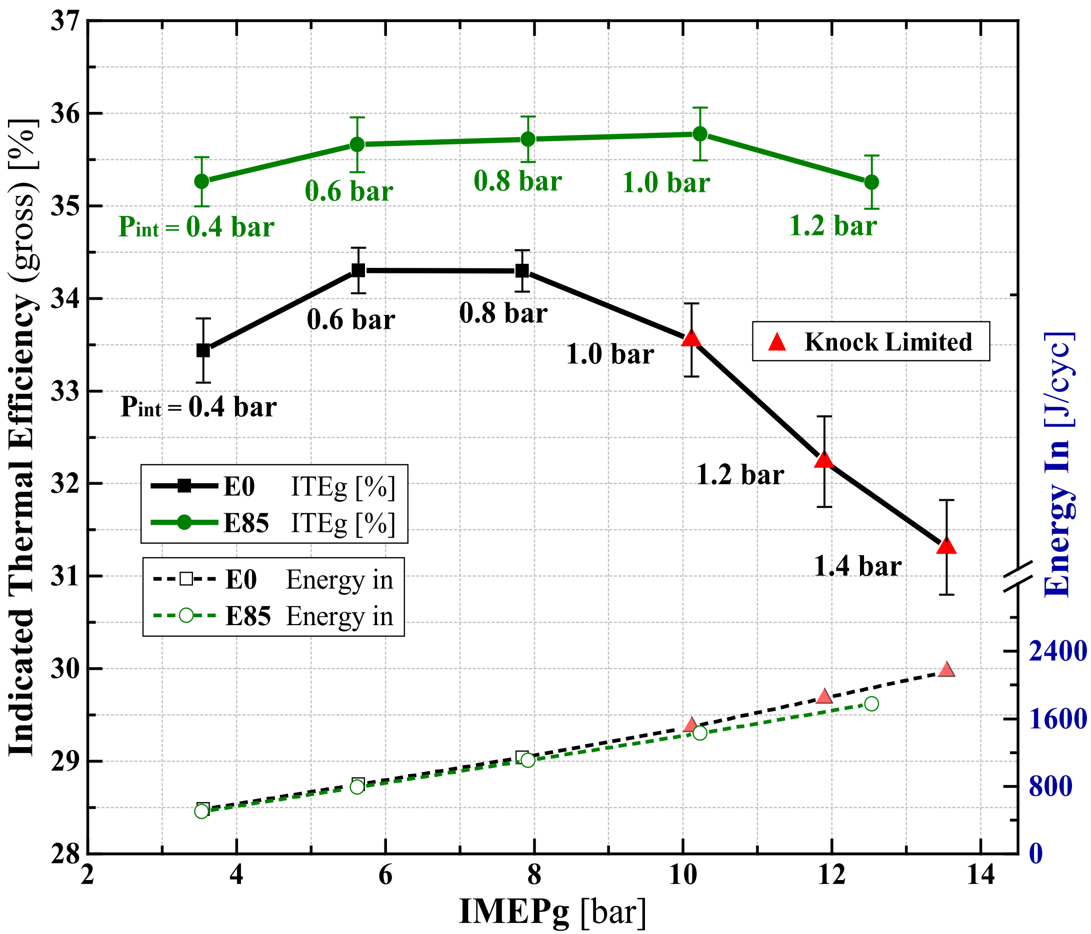
Vehicle Simulation

Vehicle FE Gains

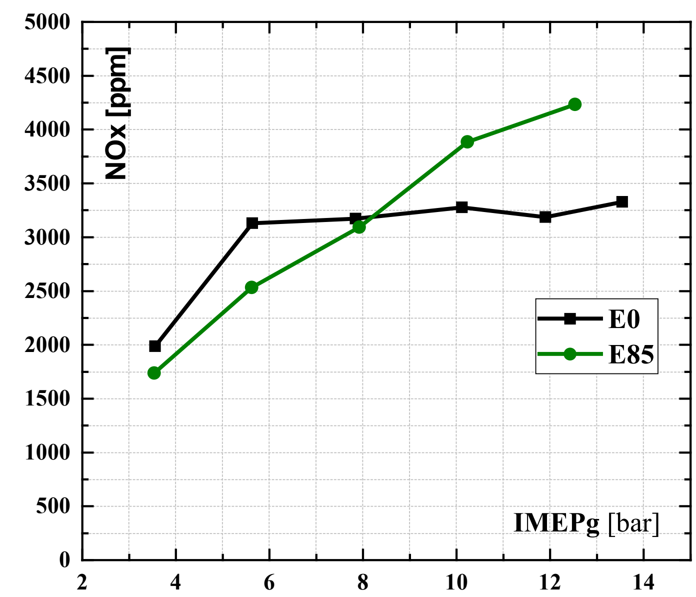


Task 1.3: single cylinder engine studies: Fuel impact on thermal efficiency

- The Indicated Thermal Efficiency of E85 was generally >1% higher than gasoline due to charge cooling of ethanol and reduced heat loss.
- E85 did not show any knocking tendency up to 1.4 bar.



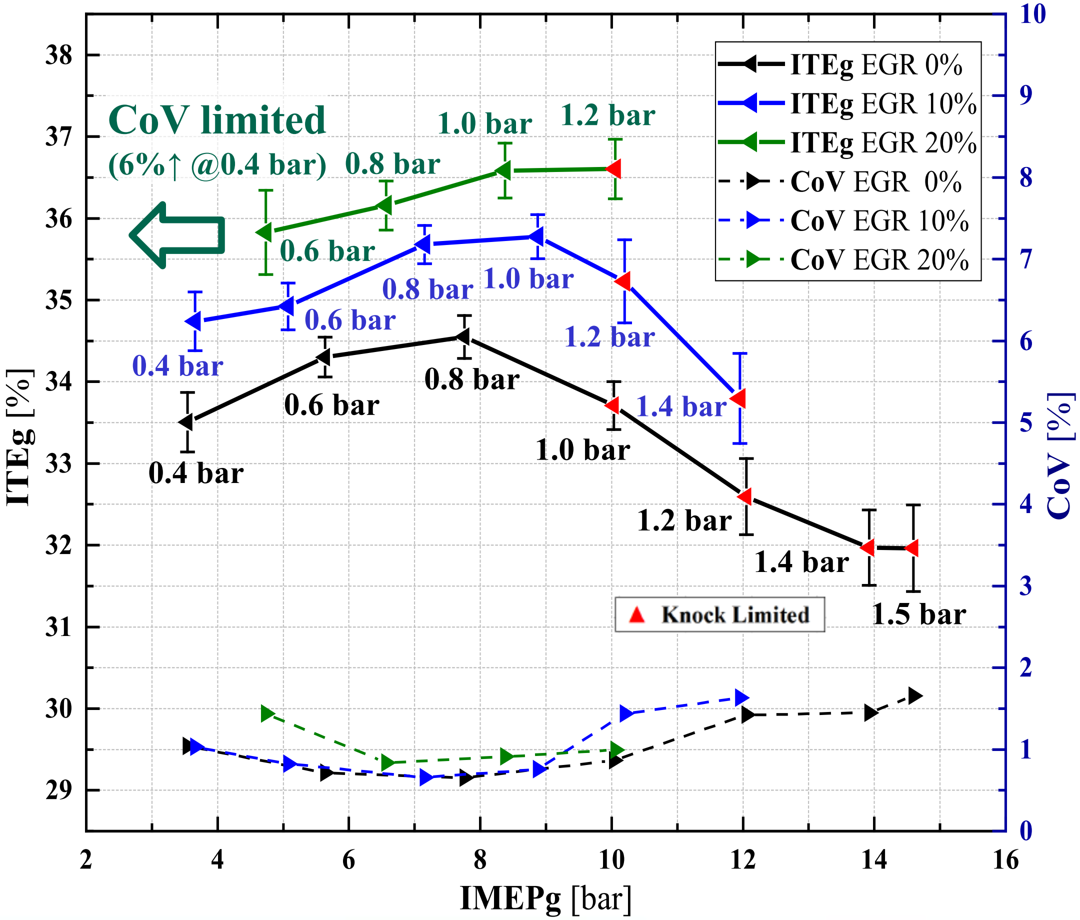
- ✓ All data are at stoichiometric conditions and MBT spark timing except where knock limited.
- ✓ Error bars are standard deviations of 200 cycles.
- ✓ 1500 rpm speed



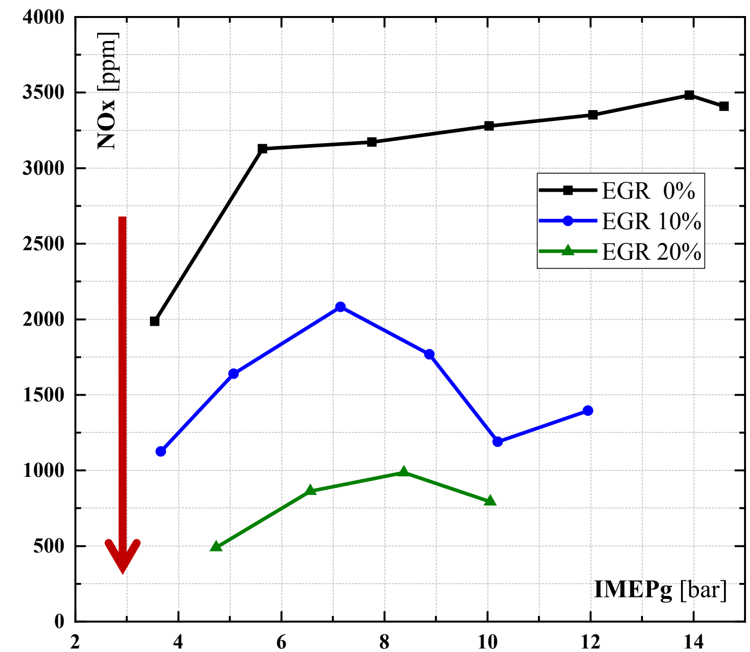
Technical Accomplishments and Progress

Task 1.3: single cylinder engine studies: EGR impact on thermal efficiency

- Indicated Thermal Efficiency increased by approximately 1% with increasing EGR ratios (10%, 20%).
- Higher boosting was possible without being knock limited.
- Nitrogen oxides were drastically decreased with increasing EGR.

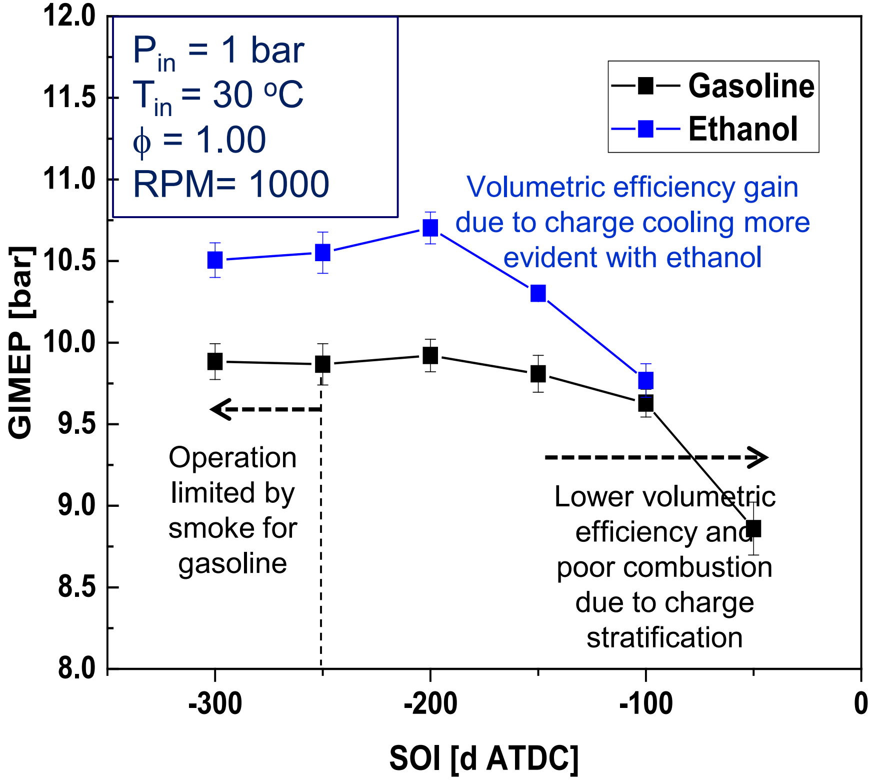


- ✓ Speed: 1500 rpm.
- ✓ All points are stoichiometric condition and at MBT spark timing except knock limited.
- ✓ CoVs are based on 200 cycles.



Technical Accomplishments and Progress

Task 1.3: single cylinder engine studies: Effects of blend composition and injection timing

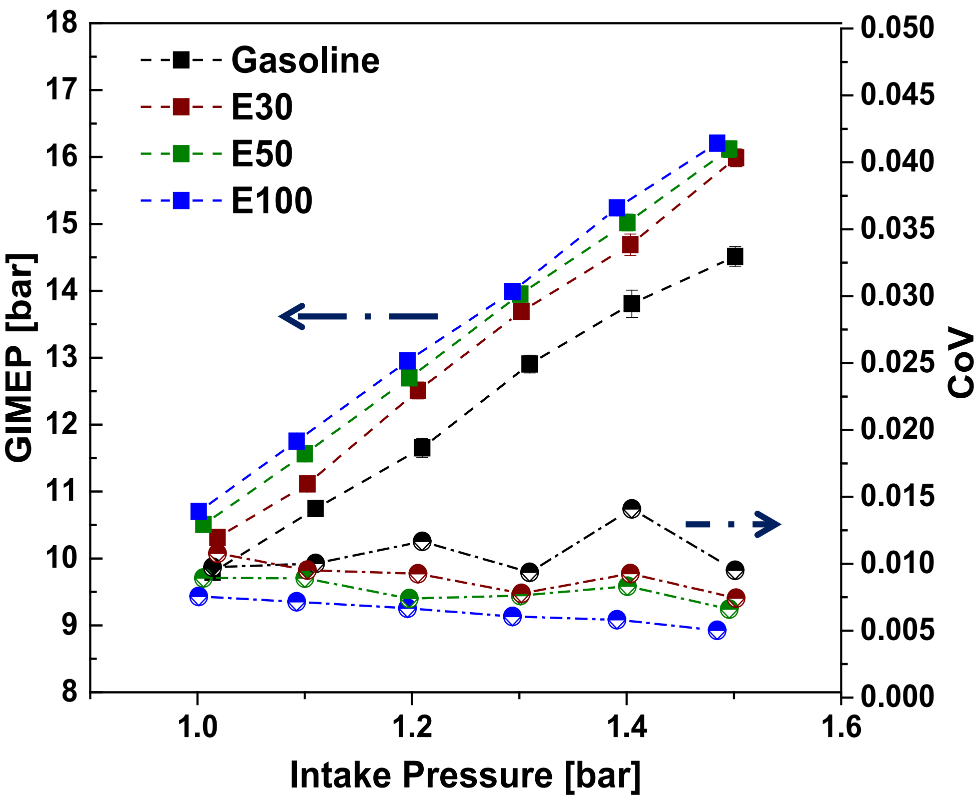


E0: *Gasoline*
E100: *Ethanol (anhydrous)*
GIMEP: *Gross Indicated Mean Effective pressure*
SOI: *Start of Injection*
d ATDC: *Crank angle degrees after top dead center*

- Error bars are standard deviations for 80-90 cycles
- SOI earlier than -250°aTDC led to unacceptable particulate emissions (PM) for gasoline (likely due to fuel impingement on the piston)
- Injection duration increases with increasing ethanol content in the blend, requiring later SOI to prevent smoke for E30 and E50 blends.
- High particulate emissions were observed for SOI retarded to -50° aTDC and beyond for gasoline, E30 and E50. No PM emissions were observed for E100.
- Higher GIMEP observed for earlier injection timing due to gain in volumetric efficiency by the charge cooling effect.

Technical Accomplishments and Progress

Task 1.3: single cylinder engine studies: Effects of blend composition and boosting



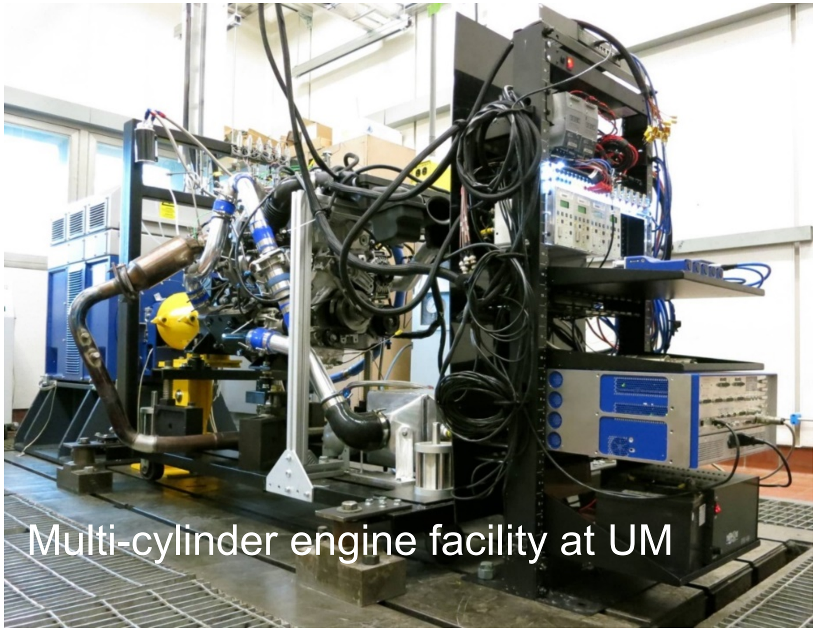
Boosting (from 1 bar to 1.5 bar absolute)

- For P_{intake} ≥ 110 kPa E0 (gasoline) was knock limited
- No knocking was observed for any of the ethanol blends for any of the boosted conditions.
- Large difference in GIMEP from E0 to E30 is because cannot use MBT for E0 due to knocking.
- Further increase in ethanol content results in higher GIMEP for given boost pressure.
- Though the CoV of GIMEP for all conditions was less than ~1.5%, the CoV is systematically lower for ethanol compared with gasoline.

Knock Criteria from König and Sheppard (SAE 902135).
Knock intensity factor KI20:
$KI20 = \sum_{i=1}^{N_{samp}} (P(i) - P_{mean})^2 / N_{samp}$
where P_{mean} is the average pressure after processing with a high pass filter, N_{samp} is the number of pressure samples within 20 degree crank angle range.

Technical Accomplishments and Progress

Task 1.4: multi-cylinder ethanol/gasoline SI studies:



Multi-cylinder engine facility at UM

- State of the art, DI turbocharged engine provided by Bosch: Daimler M274 2.0L
- State of the art piezo-actuated injector capable of multiple closely spaced injection events.
- Optical access via endoscope port.
- Multi-cylinder engine studies mirror the single cylinder studies, with emphasis on practical implications (e.g. vehicle drive cycles, engine transients and emissions regulation compliance)
- Pathway for transition of scientific elements to practical outcomes with production and production-intent hardware

Plan of work:

1. Assess multiple injection strategies with piezo-actuated injector
2. Validate single cylinder optical engine and constant volume chamber spray observations in production engines:
   - Characterization of the spray features for different fuel blends.
   - Evaluation of the in-cylinder soot formation to identify the sources of soot and the effects of alcohols in soot suppression.
3. Characterization of PM emission based on the size distribution and total particle concentration.

Technical Accomplishments and Progress

Task 1.5: multi-cylinder DME/propane CI studies
Objective: 50% BTE CI demonstration (via dual-fueling of DME and propane)

- Our BTE results were much lower than a previous study showing 50% BTE with this fuel scheme
- Further analysis of previous study revealed inconsistencies (reported exhaust composition did not match reported air/fuel flow rates)
- Variation of parameters to maximize BTE at one speed/load condition showed maximum BTE of **37.6%,** compared to **36.7%** from conventional diesel combustion (see graph to the right)
- Regression indicates further BTE benefits may be possible beyond limits of our current test matrix

Conclusion: Fuel economy benefits possible, but not at the level of 50% BTE

Go/No Go Decision: No Go

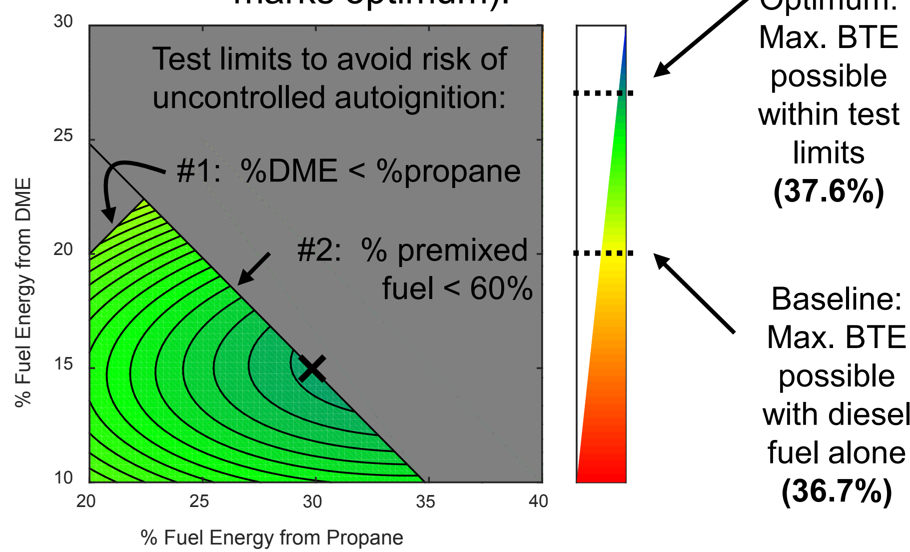
Regression fit optimization results:

BTE	**37.6%**	Premixed DME	15% Fuel Energy
ITE	50.7%	Premixed Propane	30% Fuel Energy
Speed*	1800 RPM	Premixed ULSD**	15% Fuel Energy
Load*	6 bar IMEP	Manifold Pressure	1.00 bar
Lambda	3.04 x stoich.	Main DI start	10 deg BDTC
EGR	29% charge	Rail Pressure	396 bar

*Speed and load not optimized for max BTE

** ULSD: Ultra low sulfur diesel, pilot injected 50 DBTDC

Regression fit BTE contours with different DME/propane blends (X marks optimum):



Collaborations and Coordination with Other Institutions

- Our collaborative industry partner on this project is Bosch, LLC. They are intellectual partners in designing and executing the experimental efforts. Additionally, they are providing 20% cost share, in-kind and direct support, including the instrumented multi-cylinder engine, two single-cylinder DI SI fuel injectors and supporting ECUs, and many other critical hardware components.

- Dr. Bradley Zigler, NREL, hosted the UofM doctoral candidate Mr. Cesar Barazza-Botet to collaborate on IQT and UofM RCF ignition studies of ethanol/gasoline and ethanol/iso-octane blends.

Ford Motor Company

- Ford has provided guidance and support for modifying the production Ford Fox Ecoboost 1.0 L engine for higher compression ratio.

- The Engine Combustion Network (ECN) at Sandia National Laboratory – Livermore provided one of the Spray G fuel injectors for characterization, and spray imaging has been completed in a Ford Zetec single cylinder optically accessible engine.

- Horiba Automotive Test Systems provided a significant discount on the purchase of an emissions analyzer for the project.

Responses to Previous Year Reviewers' Comments

This project is a new start.

Remaining Challenges and Barriers

Task 1.1 autoignition and spray studies of fuel blends

- Develop methodology to incorporate results from IQT and RCF ethanol/iso-octane ignition studies into interpretation and design of DI SI engine studies through integration into GTPower.

Task 1.2 engine simulations

- Complete model calibration and validation for single and multi-cylinder engines.
- Use GTPower to explore specific influences of fuel properties on charge cooling and γ, among other effects, to separate and parse out effects which may limit the benefits of fuels and charge composition.

Task 1.3 single-cylinder engine studies

- Develop method to estimate BTE from ITE using GTPower for the single-cylinder engines.
- Fully harness the knock limit extension tools being used on each single-cylinder engine to extend knock limits to their fullest extent.

Task 1.4 multi-cylinder engine studies

- Demonstrate the effectiveness of knock limit extension to achieve real BTE improvements.

Future Work

Task 1.1 autoignition and spray studies of fuel blends

- Analyze NREL IQT ignition data and develop comparison methodology for UofM RCF ignition data
- Develop ignition delay time correlations for use in engine simulations based on validated reaction mechanism
- Develop correlation of the effects of spray and mixing on ignition delay time based on combined UofM RCF and NREL IQT data

Task 1.2 engine simulations

- Complete model calibration for two single-cylinder and the multi-cylinder engine platforms
- Exercise validated model to identify combination of spray, spark and boosting strategies leading to maximum BTE
- Integrate results of single- and multi-cylinder engine studies into fuel economy predictions.

Task 1.3 single-cylinder engine studies

- Complete test matrix of EGR, syngas, and alcohol/gasoline blends using PFI and DI and boost to quantify BTE sensitivity to fuel properties
- Complete engine modification for higher compression ratio 1.0L Ecoboost engine and complete the test matrix of ethanol and gasoline blends using next generation Bosch fuel injector to quantify BTE sensitivity to fuel properties at higher compression ratio.

Task 1.4 multi-cylinder engine studies

- Complete engine studies of fuel blends, boost, speed, and fuel injection methods, including high fidelity multi-injection events
- Compare and evaluate spray imaging in multi-cylinder engine with results from the different test facilities including previous work with an optically accessible single-cylinder engine and constant volume chamber

Summary

Task 1.1 auto-ignition and spray studies of fuel blends

- Completed ignition studies of ethanol/gasoline and ethanol/iso-octane blends using UM RCF and NREL IQT methods.
- Completed spray imaging study of ECN spray G injector

Task 1.2 engine simulations

- Developed modeling strategy to extrapolate single-cylinder engine results to optimized multi-cylinder engines and evaluate fuel economy benefits.

Task 1.3 single cylinder engine studies

- Installed new single-cylinder engine facility using production Ford Ecoboost 1.0L Fox engine
- Installed new single-cylinder Ricard Hydra engine facility with PFI and DI (upgrade in progress) facility
- Demonstrated improved GITE (Δ4%, 34% E0→ 38% E100) using ethanol blends at equivalent levels of boosted intake air pressure, gasoline was knock limited and ethanol operated at MBT.

Task 1.4 multi-cylinder engine studies

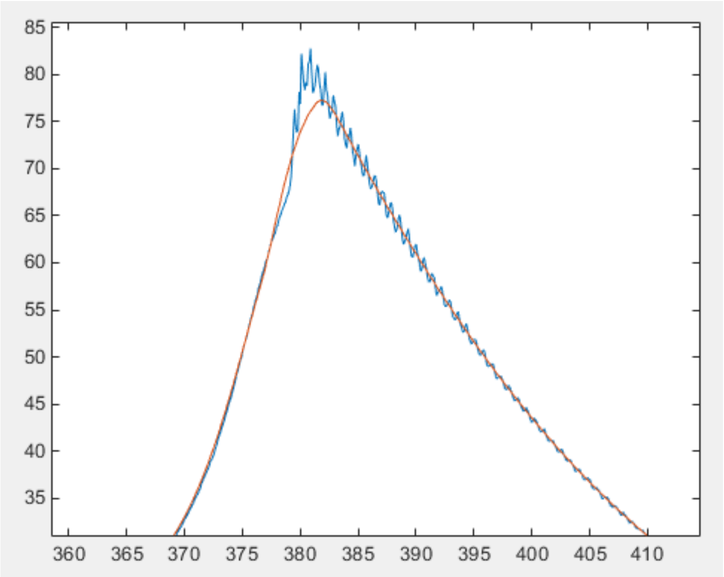
- Installed multi-cylinder Daimler M274 2.0L engine with state-of-the-art piezo-actuated fuel injectors capable of multiple closely-spaced injection per cycle.

Technical Back-Up Slides

Definition of knock criteria KI20 modified König

$$KI20 = \sum_{i=1}^{N_{samp}} \{P\_cyl(i) - P\_cyl\_smooth(i)\}^2 / N_{samp}$$

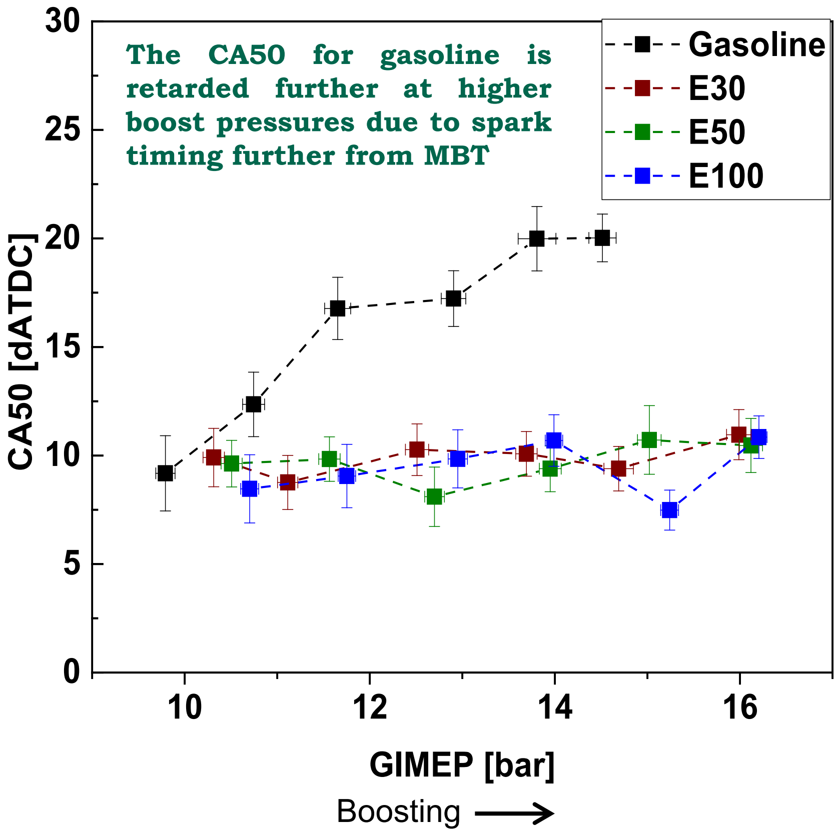
Where, P_cyl = unfiltered cylinder pressure trace
P_cyl_smooth = smoothened filter pressure trace using high pass filter 3.5KHz
N_{samp} = number of pressure samples within the 20 crank angle window

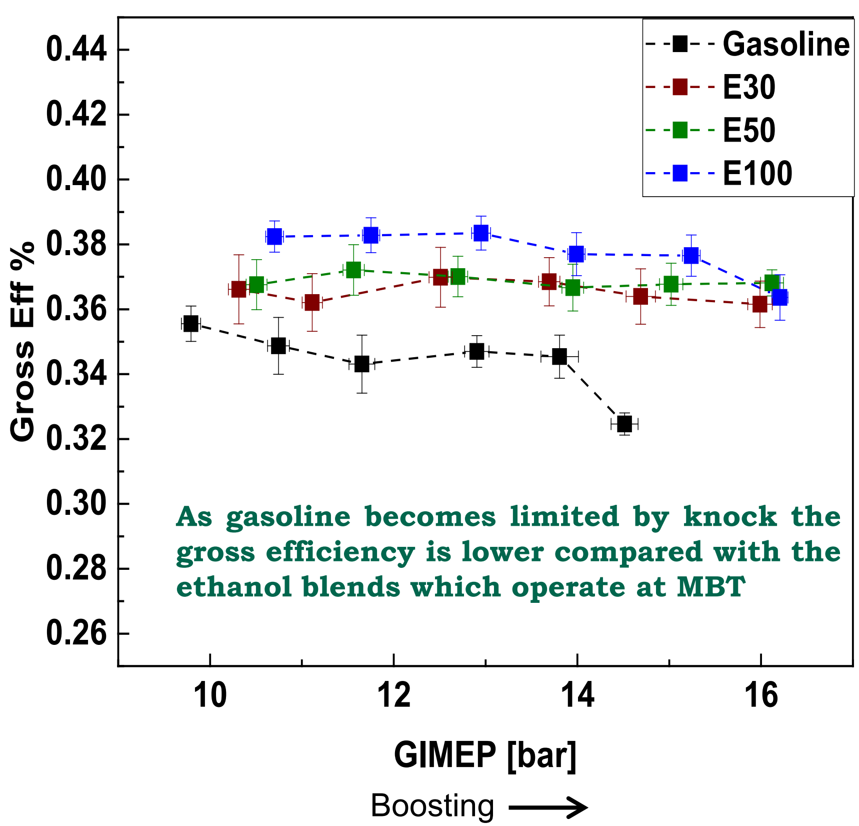


KI20 reference: König, G. and Sheppard, C.G.W, 'End Gas Autoignition and Knock in a Spark Ignition Engine', SAE Paper 902135, 1990

Task 1.3: single cylinder engine studies - results

Effect of blend composition and boosting on CA50 and gross efficiency:

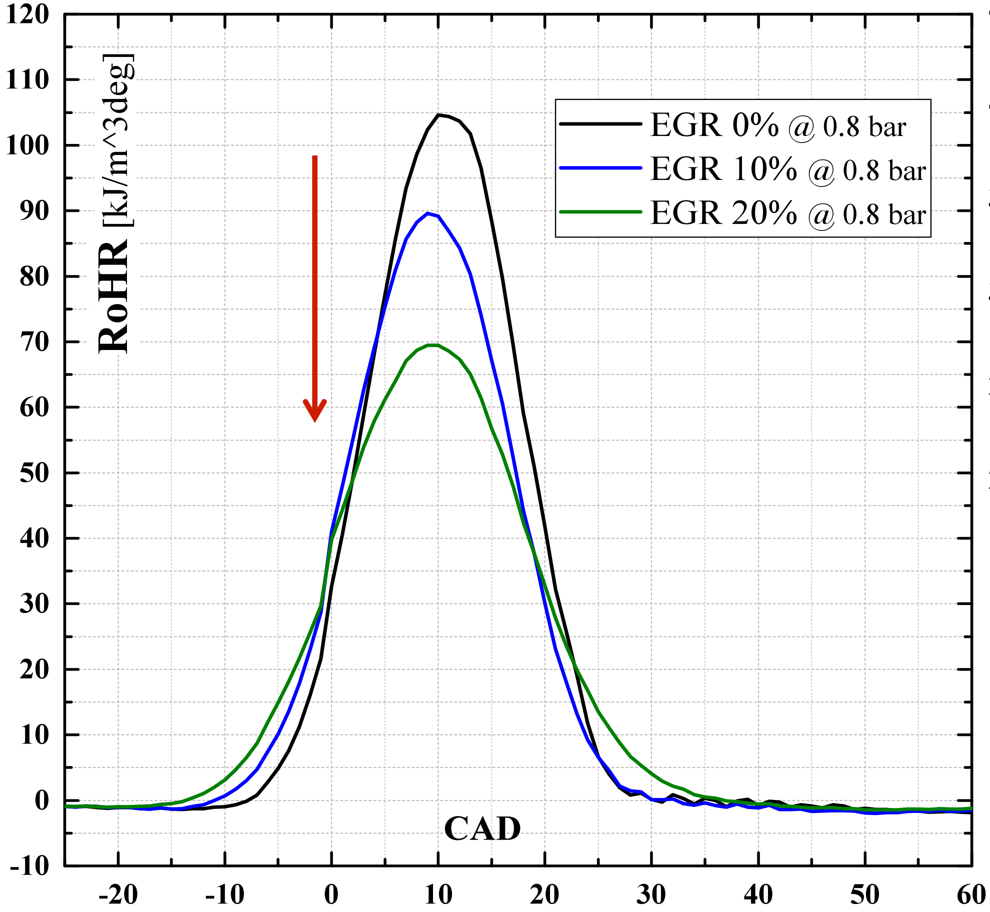


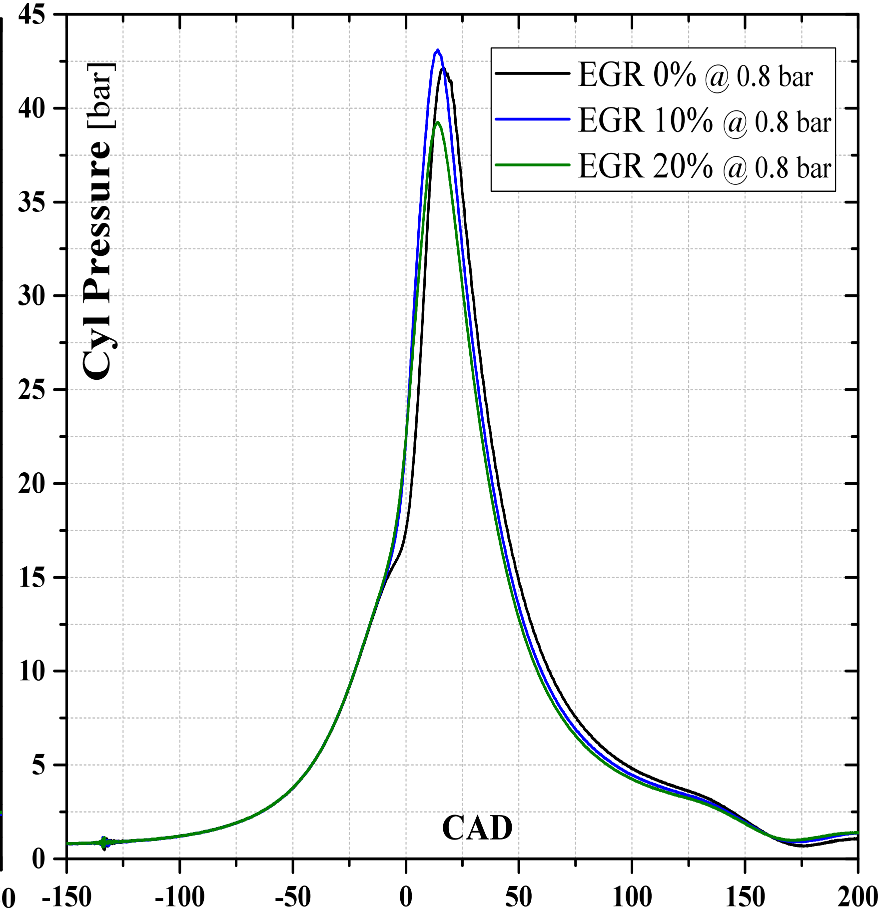


Task 1.3: single cylinder engine studies - results

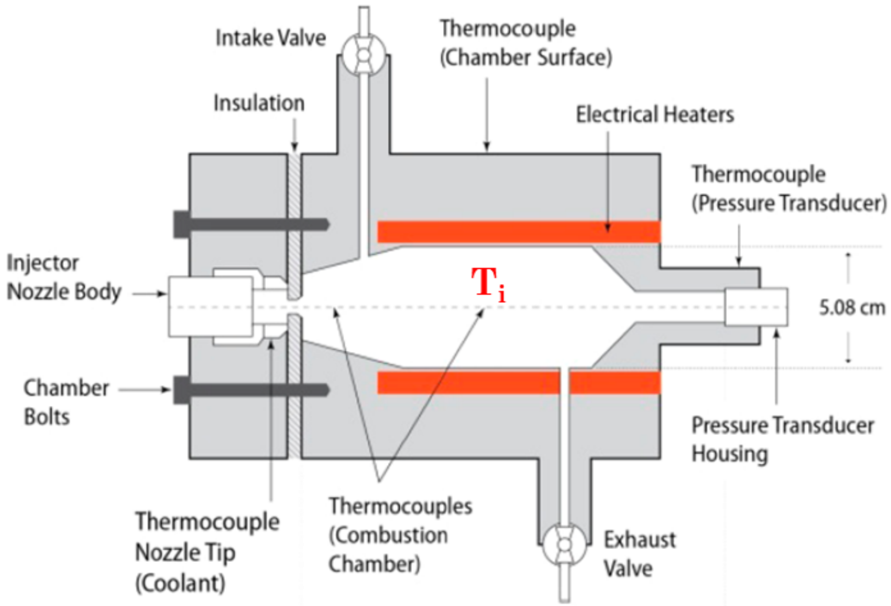
Heat Release and Cylinder Pressure (0.8 bar), Gasoline EGR (0%, 10%, 20%)

→ Maximum rate of heat release decreased with the EGR increasing





Current Work: Autoignition UM RCF – NREL IQT



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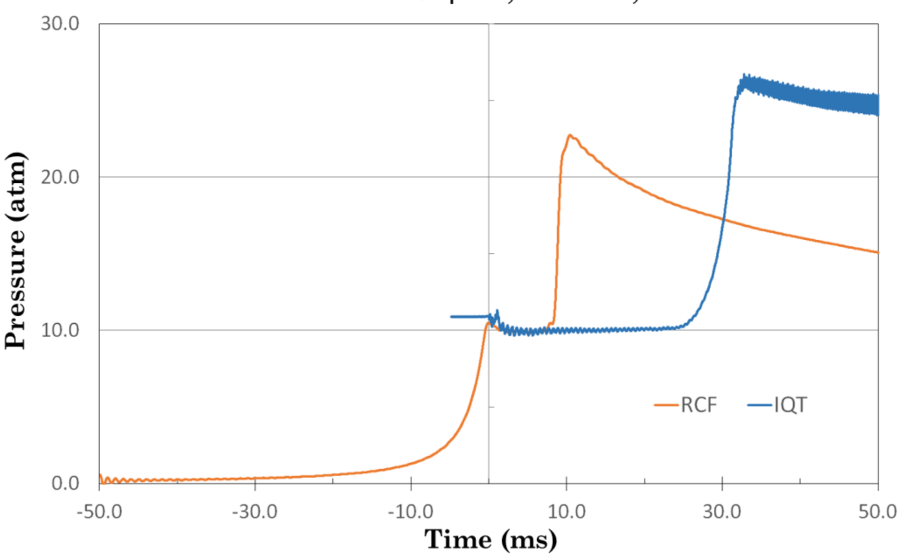
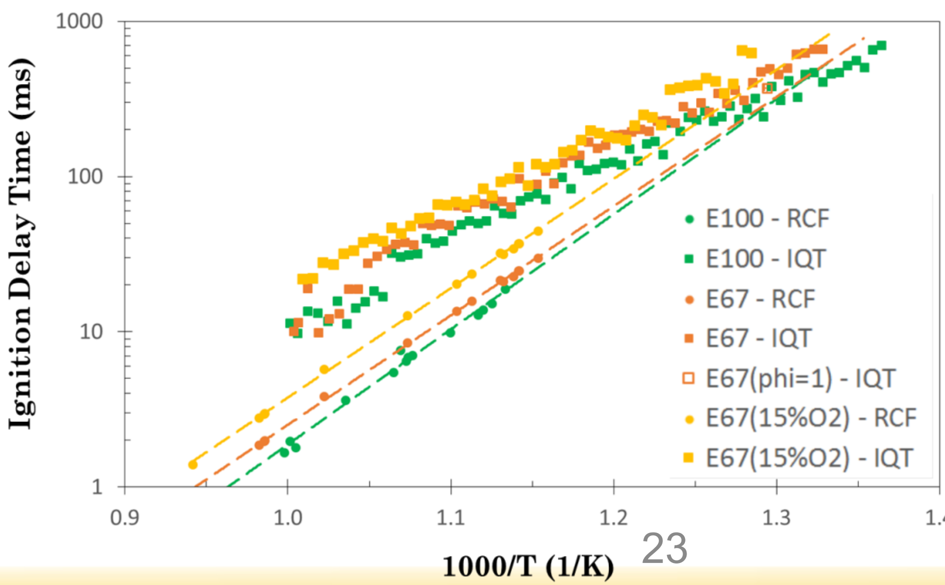
E67 Blend @ ϕ =1, 10 atm, 980 K



Iso-octane/Ethanol Blend @ 11 bar



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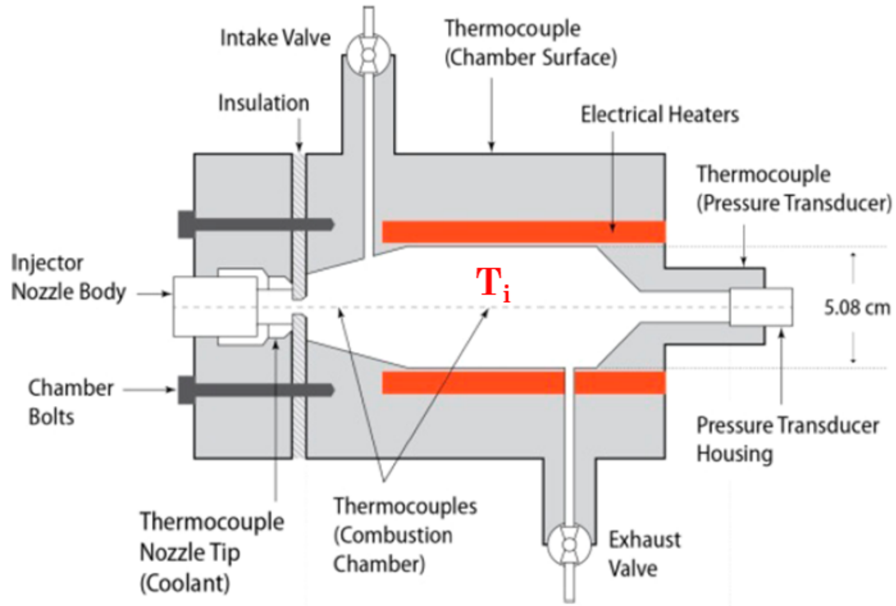

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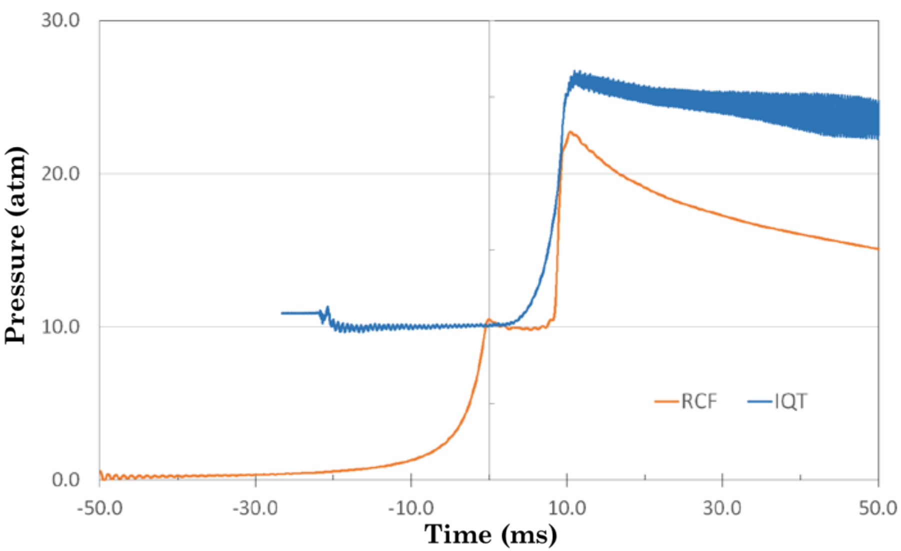

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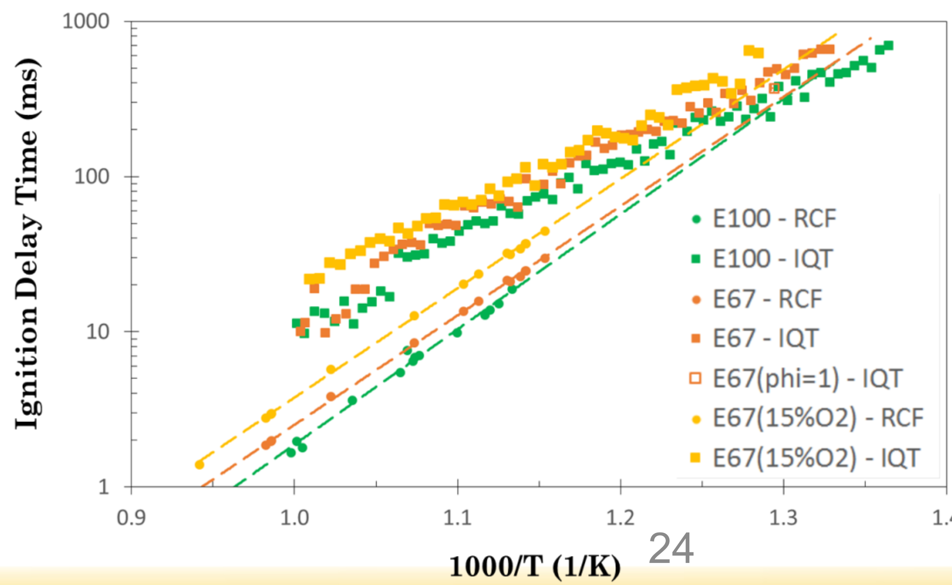

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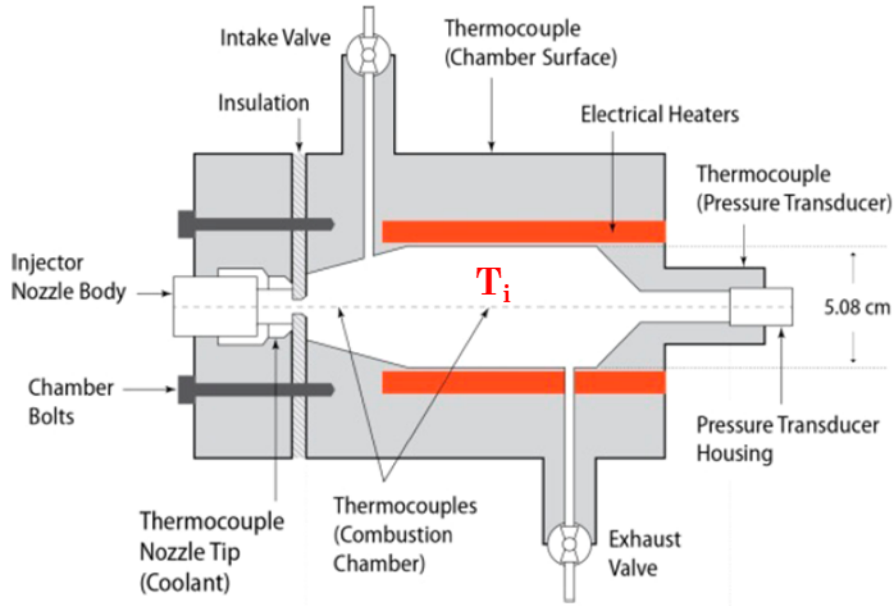

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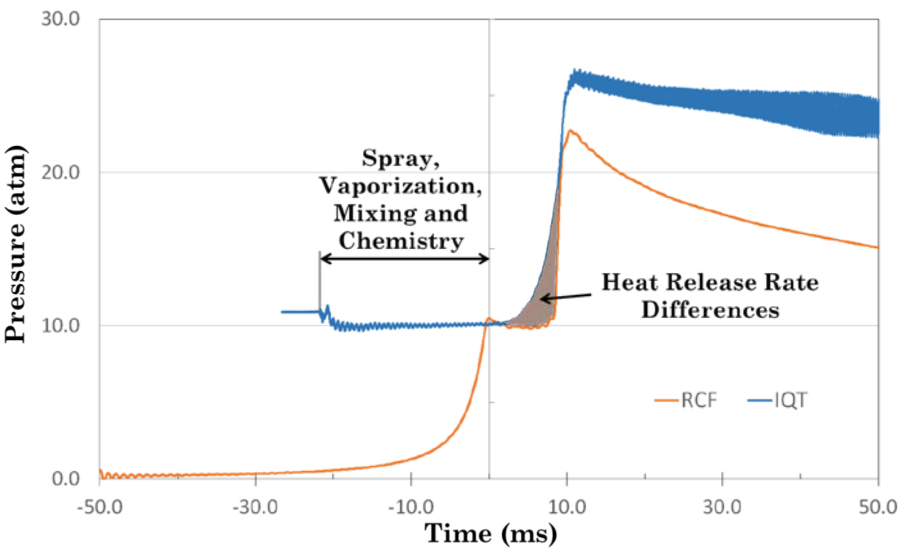

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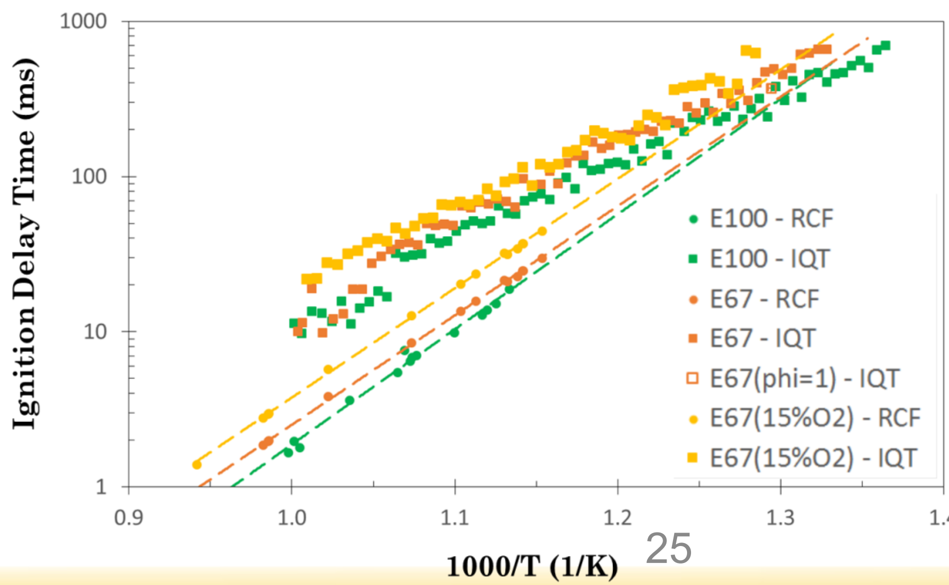
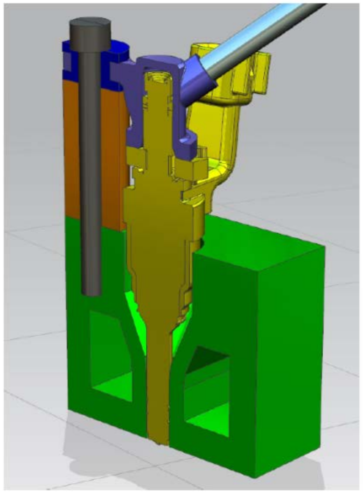


combustion LABORATORY

ECN Spray G Experiments

Objective: to characterize the behavior of Spray G in an engine environment; compare spray development with results obtained in constant-volume chambers.



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Experimental Procedure and Conditions

- The Spray G injector was mounted on an optical engine with visual access through the piston and cylinder liner.
- Spray development was imaged with a high speed camera using Mie-scattering technique to study liquid-phase structure.
- Performed experiments at flash and non-flash-boiling conditions.

Parameter	Flash Boiling	Non-flash-boiling
Fuel	Iso-octane	Iso-octane
Fuel Pressure	20 MPa	20 MPa
Fuel Temperature	90° C	90° C
Ambient Temperature	60° C	60° C
Ambient Pressure	50 kPa	100 kPa
SOI	270° bTDC	270° bTDC
RPM	200,1000, 2000	200,1000, 2000
Camera frame rate	24000 fps	24000 fps