A University Consortium on Efficient and Clean High-Pressure, Lean Burn (HPLB) Engines

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DOE Merit Review
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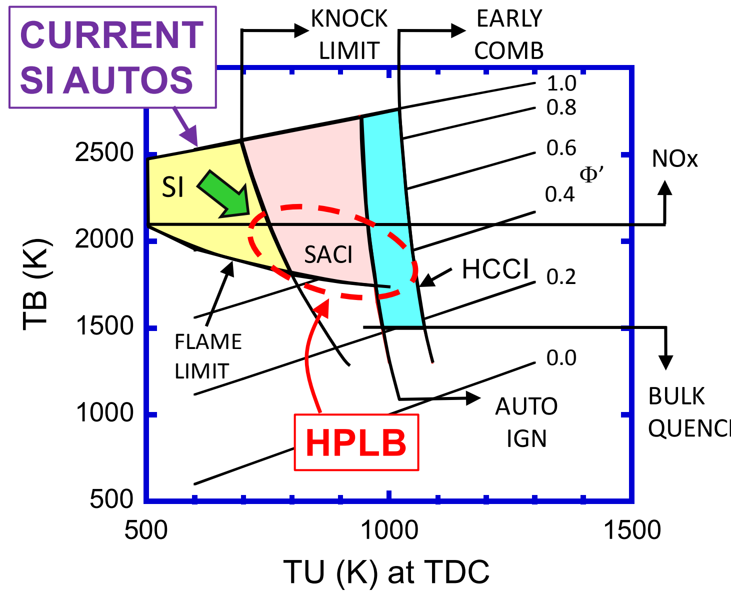
DOE Project DE-EE0000203

Background

History:

- 2002 – 2005 Consortium on HCCI – Basic understanding
- 2006 – 2009 Consortium on LTC – Beyond HCCI: expanded to other combustion modes
- 2010 – 2012 High Pressure Lean/Dilute Burn – Focus on fuel economy



Lavoie, G., Martz, J., Wooldridge, M., and Assanis, D., (2010) "A Multi-Mode Combustion Diagram for Spark Assisted Compression Ignition," Combustion and Flame, 157, pp. 1106-1110.

Overview

- TIMELINE
  - Start - Oct 2009
  - Finish – Dec 2012
  - 70% completed
- BUDGET
  - Total Funding - $3,000k
  - Rec'd FY10 - $1,000k
  - Rec'd FY11 - $ 1,000k
  - Rec'd FY12 - $ 830k
- BARRIERS ADDRESSED
  - Improved fuel economy in light duty gasoline engines
  - Fundamental knowledge of advanced engine combustion
- PARTNERS
  - Universities – UCB, MIT
  - Collaborations – SNL, LLNL, ORNL, ANL
  - Industrial – GM, Conoco-Phillips, Ford

Objectives and Relevance

DOE VTP Technical Target:

- Demonstrate path to achieve 45% peak engine efficiency with 25 - 40% potential vehicle fuel economy (FE) gain

Project Objectives:

Explore advanced dilute, high pressure combustion modes and fuel properties as enablers to achieve FE targets

1. Develop analytical link between engine combustion results and potential in-vehicle FE gains
2. Investigate benefits of stratification
3. Explore multi-mode combustion: Spark Assisted Compression Ignition (SACI), and Microwave Assisted Spark Plug (MWASP)
4. Determine potential of novel fuel properties for improved FE

Approach

ANALYTICAL TOOLS

TASK 1.

Fuel Efficiency of Advanced HPLB Cycles (UM)

- Develop analytical link between combustion and fuel economy benefits
- Assess potential FE gains of advanced combustion cycles

TASK 2.

Investigate the benefits of stratification (UM, MIT)

- DNS and combustion subgrid scale modeling of mixing effects
- RCM and engine experiments

TASK 3.

Advanced multi-mode combustion (UM, UCB)

- Metal engine, optical engine, RCF Experiments
- SACI, MWASP
- CFD – flamelet+AI

TASK 4.

Fuel properties for optimal fuel economy (UM, MIT)

- Metal and optical engine and RCF experiments
- Explore NTC, ON, Gasoline/ethanol blends, alkanes, esters, etc.
- Chemical kinetic models

MODELS, EXPERIMENTS

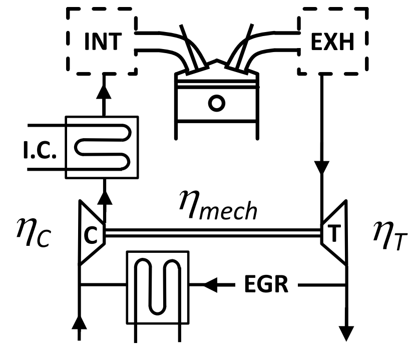
Path to in-vehicle FE improvement

Technical Accomplishments and Progress

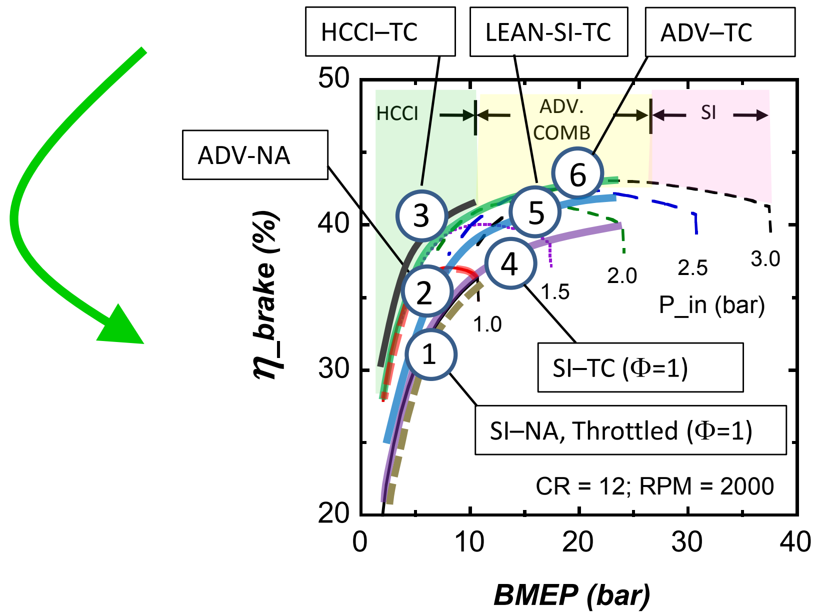
Task 1. Fuel Efficiency of Advanced HPLB Cycles (UM)

- Goals
  - Develop analytical link between combustion and fuel economy benefits
  - Assess potential FE gains of advanced combustion cycles
- Approach
  - Use simple, thermodynamically consistent model of engine
  - Assume combustion is possible at all conditions
  - Evaluate 6 engine-combustion strategies to produce engine maps
  - Estimate vehicle fuel economy with drive cycle simulation

GT-Power model of turbocharged engine



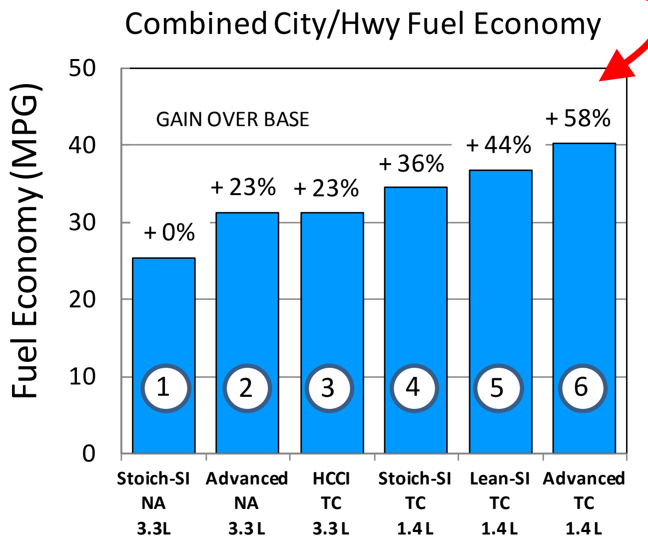
- **Fixed burn duration (25°)**
- **Ideal T/C (OTE=50%)**



Task 1. Fuel Efficiency of Advanced HPLB Cycles (UM)

- <u>Accomplishments/Results</u>
  - Determined that the benefits of advanced combustion and boosting with downsizing appear to be relatively independent
  - Best results obtained by combining both strategies
  - Fuel economy gains of up to 58% are possible

CASE	Combustion Mode	Air Handling	Size	City/Hwy (mpg)	FE GAIN
1	Stoich-SI	NA	3.3 L	25.4	BASE
2	Advanced	NA	3.3 L	31.3	23%
3	HCCI	TC	3.3 L	31.2	23%
4	Stoich-SI	TC	1.4 L	34.5	36%
5	Lean-SI	TC	1.4 L	36.7	44%
6	Advanced	TC	1.4 L	40.3	58%



<u>**Impact**</u>

- Analysis confirms advantages of advanced (mid dilution) combustion strategies under high boost conditions

Lavoie, G. A., Ortiz-Soto, E., Babajimopoulos, A., Martz, J., Assanis, D.N. (2012) Thermodynamic sweet spot for high efficiency, dilute boosted gasoline engine operation, submitted to *Int. J. Engine Res*.

Task 2. Investigate the benefits of stratification (UM, MIT)

High fidelity modeling: effects of small scale mixing on autoignition (UM)

- Understand effects of stratification in Φ, EGR and T on autoignition
- Incorporate effects in engine modeling
- Guide interpretation of experimental observations in RCF, RCM, and optical and metal engines

Experiments on large scale stratification (MIT)

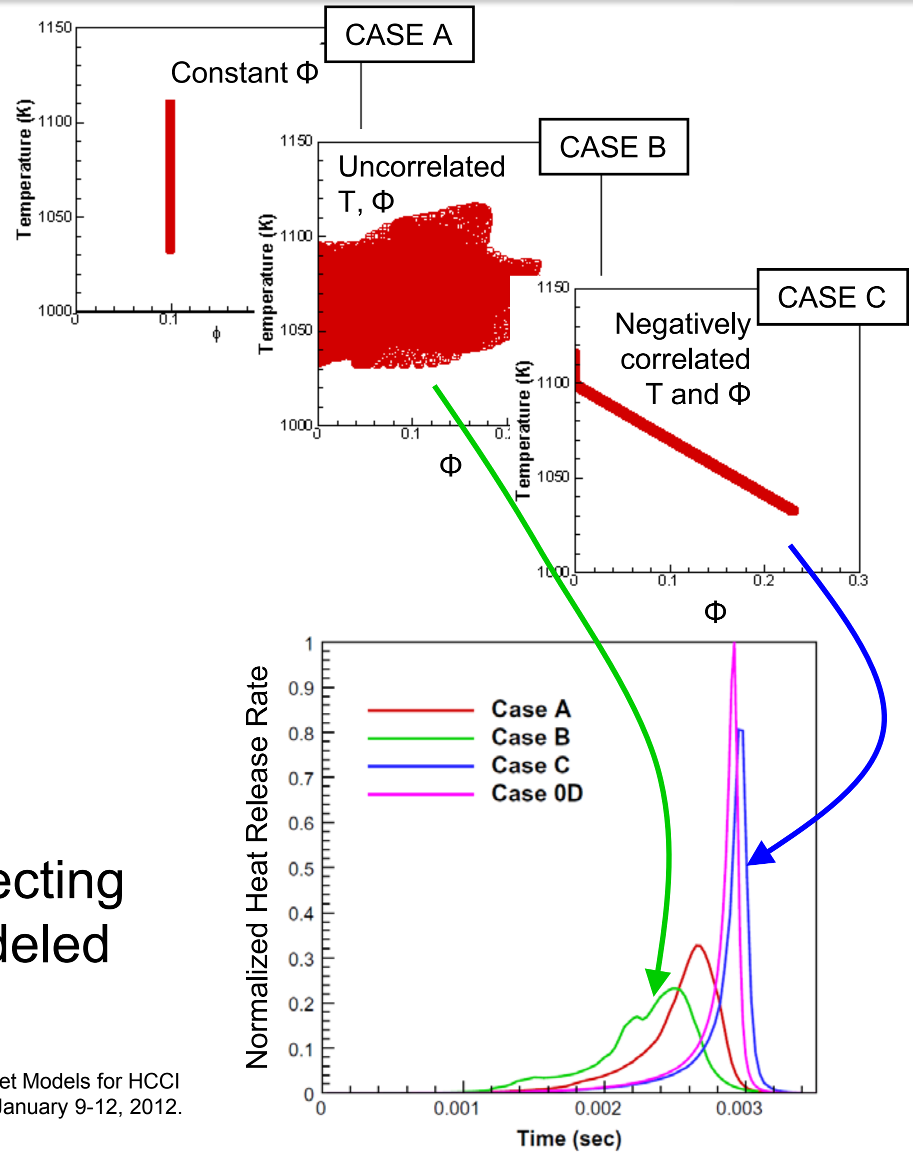
- RCM ignition delay studies integrating heat transfer and using commercial fuels
- Experiments with gasoline in a small bore diesel engine under LTC conditions

Task 2. Modeling small scale turbulence effects on autoignition (UM)

- <u>Goals:</u>
  - Understand small scale (subgrid) turbulence and mixing effects
  - Incorporate in CFD modeling
  - Interpret experimental data
- <u>Accomplishments/Results:</u>
  - Modeled H_2-Air turbulent combustion with prescribed T and Φ variation showing effect on heat release using DNS
  - Developed subgrid models

<u>Impact</u>:

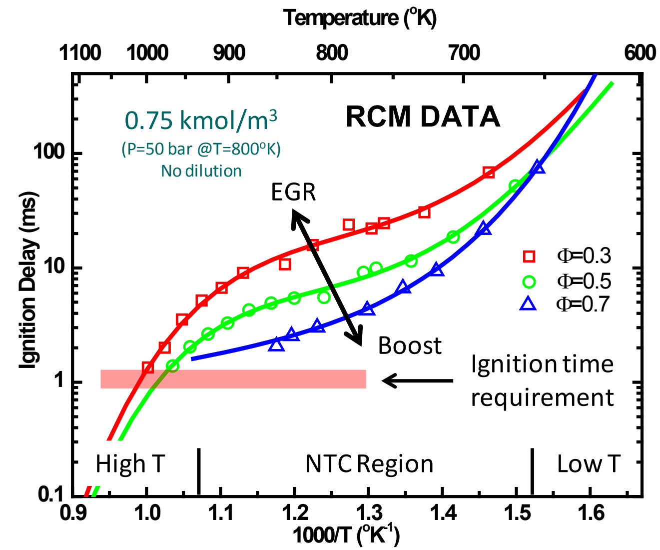
- Bulk gas turbulent fluctuations affecting heat release are not currently modeled by RANS calculations

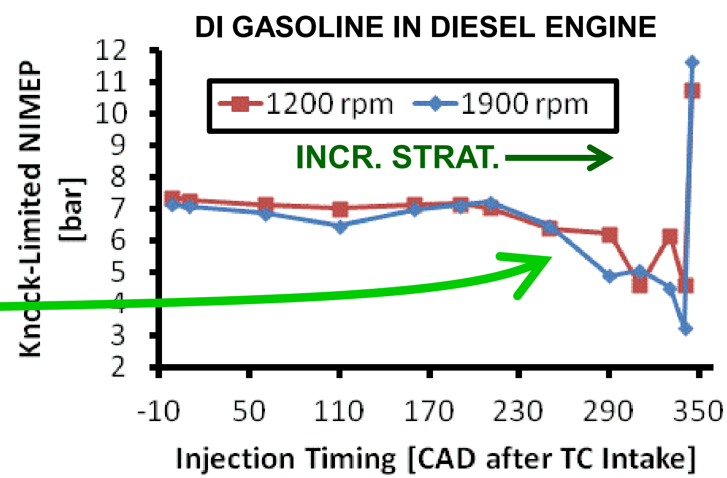


Gupta, S. Keum, S. H., Im, H. G., 2012, "Modeling of Scalar Dissipation Rates in Flamelet Models for HCCI Engine Simulation," 50th AIAA Aerospace Sciences Meeting, Nashville, Tennessee, January 9-12, 2012.

Task 2. Experimental studies of the benefits of large scale stratification (MIT)

- Goals:
  - Acquire RCM ignition delay data for gasoline for varying EGR and Φ
  - Apply to gasoline-fueled diesel engine in stratified mode
- Accomplishments/Results
  - Rapid Compression Machine
    - Ignition delay measurements suggest that the sensitivity to Φ and EGR depends on combustion regime; NTC regime is most sensitive
  - Engine experiments
    - Outside NTC region: stratification increases heat release, decreases maximum load





Impact:

- Stratification is most effective in NTC region; engine parameters (CR, EGR,…) need to be correctly configured

Task 3. Advanced multi-mode ignition and combustion (UM, UCB)

SACI/HCCI in FFVA engine (UM)

- Study multi-mode combustion spark assisted compression ignition (SACI) in well controlled metal engine

Modeling of SACI (UM)

- Laminar flame speed correlations (submodel)
- Coherent flamelet + AI multi-zone (CFMZ) CFD model
- System level model development

Microwave Assisted Spark Plug (MWASP) experiments (UCB)

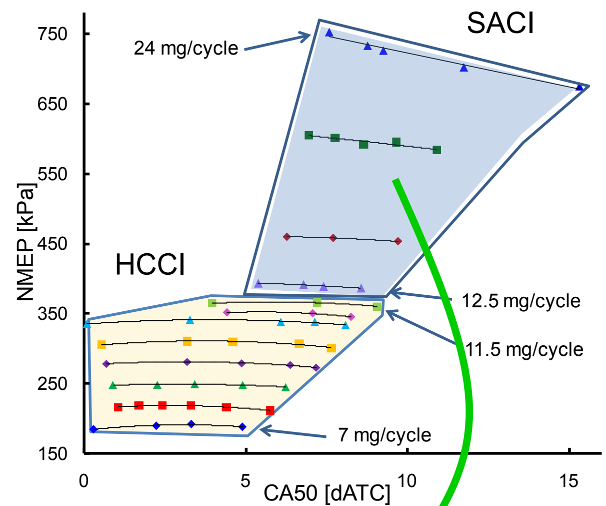
- Feasibility testing in combustion bomb
- Tests in CFR engine
- Modeling of plasma/spark behavior

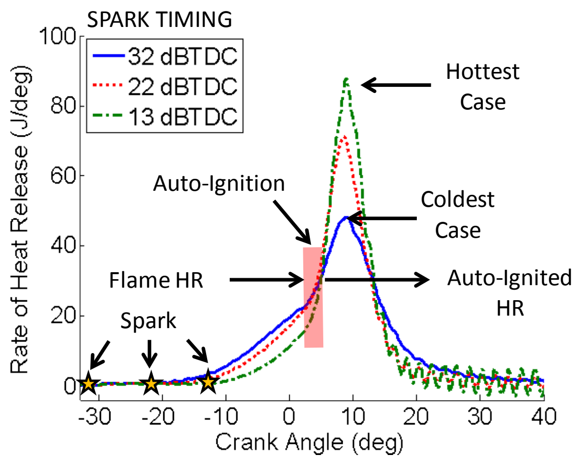
Imaging studies of SACI (UM)

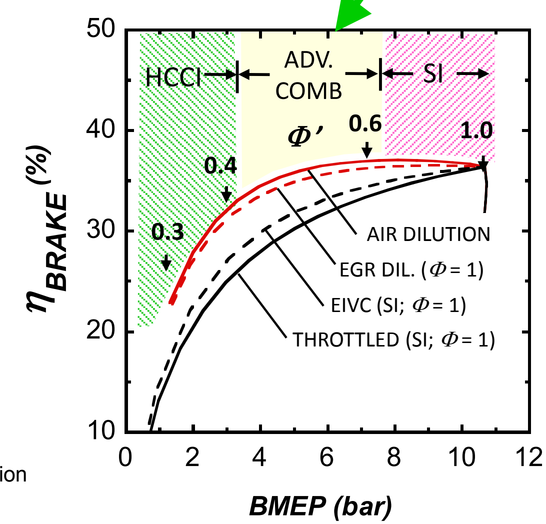
- Optical engine imaging and quantification
- RCF studies of spark + autoignition interactions

Task 3: Load extension with multi-mode combustion (UM)

- Accomplishments/Results
  - FFVA engine demonstrates use of Spark Assisted Compression Ignition (SACI) to moderate HCCI heat release and increase maximum load







Impact:

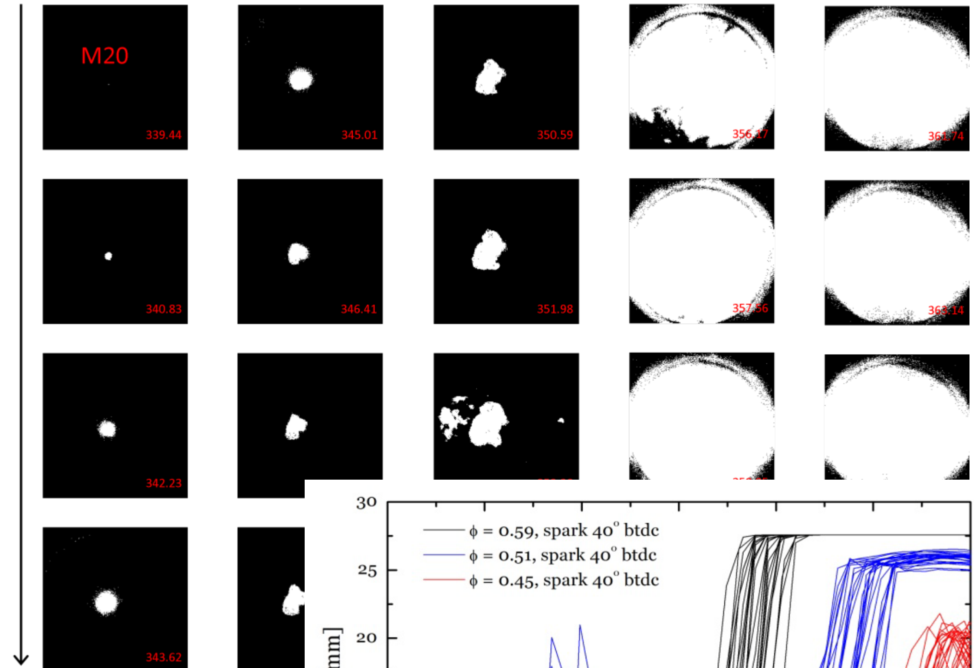
- Demonstrates that SACI can access the advanced combustion region

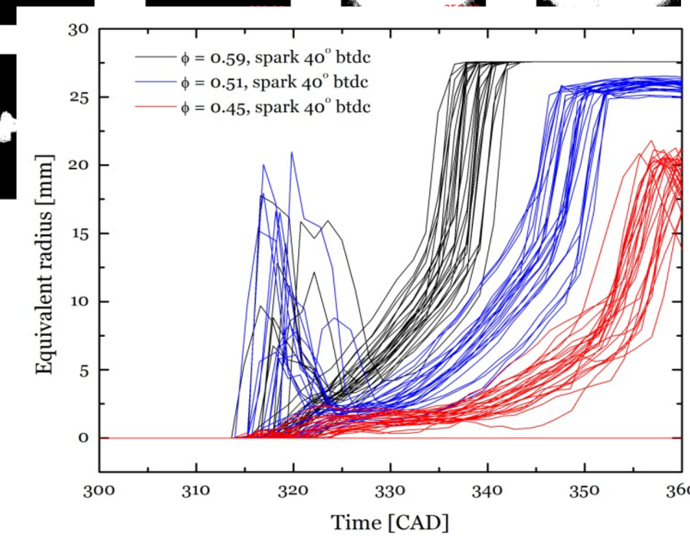
Manofsky, L., Vavra, J., Babajimopoulos, A., and Assanis, D. (2011) Bridging the Gap between HCCI and SI: Spark-Assisted Compression Ignition. SAE Paper No. 2011-01-1179.

Manofsky-Olesky, L., Martz, J.B., Lavoie, G.A., Assanis, D.N.,Babajimopoulos, A., "The Effects of Spark Timing and Pre-Ignition Temperature on Burn Rates in Spark-Assisted Compression Ignition," in review, *The Int. Symp. on Combustion.*

Task 3: SACI measurements in optical engine (UM)

- <u>Accomplishments/Results</u>
  - UM Optical Engine
    - SACI images show distinct flame propagation followed by rapid autoignition
  - Image Analysis
    - Automated methodology developed for quantifying apparent flame speeds.





<u>Impact</u>:

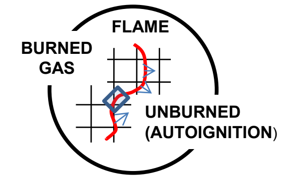
- Insight into early flame development and best practices for SACI
- Validation for turbulent flame model

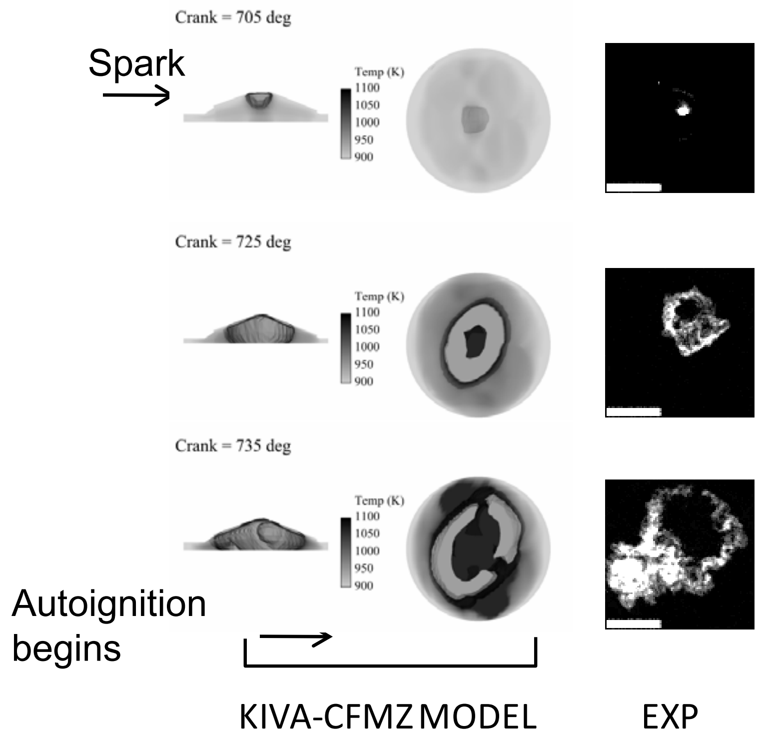
Keros, P., Fatouraie, M., Assanis, Dim., Wooldridge, M. S., (2012) “Quantitative Analysis of High-Speed Optical Imaging of HCCI and Spark Assisted HCCI Events,” submitted to the *ASME Journal of Engineering for Gas Turbine and Power*, January 2012, in review.

Zigler, B. T., Keros, P. E., Helleberg, K. B., Fatouraie, M., Assanis, Dim., and Wooldridge, M. S., (2011) “An Experimental Investigation of the Sensitivity of the Ignition and Combustion Properties of a Single-Cylinder Research Engine to Spark-Assisted HCCI,” *Int. J. Engine Res.* 12, pp. 353-375.

Task 3: Modeling of multi-mode combustion (UM)

- Accomplishments/Results
  - Developed CFD model of SACI
    - Coherent Flamelet Multi-Zone model
    - Extended correlations flame speeds for highly dilute, high preheat flames
    - Multi-zone auto-ignition model
  - Results compare well with optical engine images and experimental heat release





Impact:

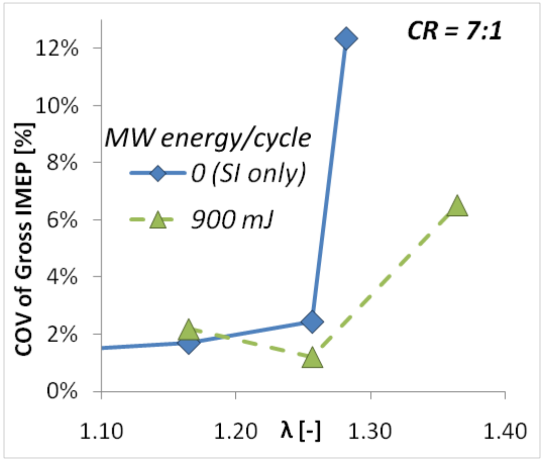
- Tool will enable detailed studies of geometry, turbulence, mixing, combustion limits.

Martz, J. M., *Simulation and Model Development for Auto-Ignition and Reaction Front Propagation in Low-Temperature High-Pressure Lean-Burn engines, Ph.D. Thesis, University of Michigan (2010).*

Martz, J., Middleton, R., Lavoie, G., Babajimopoulos, A., and Assanis, D. (2011) A computational study and correlation of premixed isooctane-air laminar reaction front properties under spark ignited and spark assisted compression igntion conditions. *Combustion and Flame, Vol. 158, No. 6, 1089-1096.*

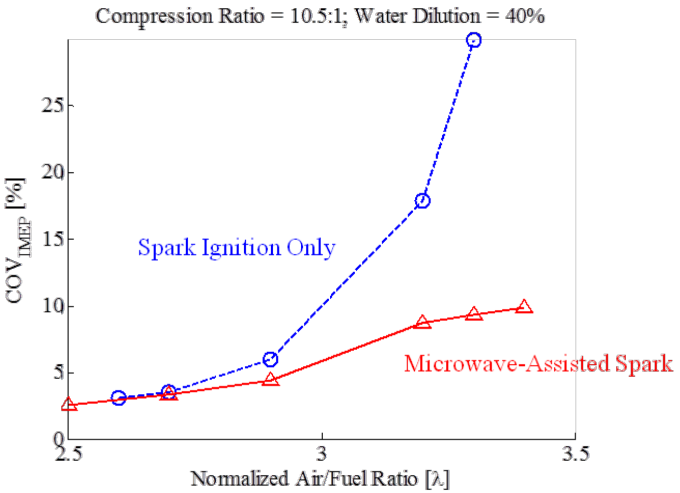
Task 3: Enabling advanced combustion with MWASP (UCB)

- <u>Goal:</u>
  - Explore the use of a Microwave Assisted Spark Plug (MWASP) with application to SACI combustion
- <u>Accomplishments/Results</u>
  - MWASP extends lean limit and lowers COV of IMEP in CFR engine
  - Plasma modeling shows diminished effects at high pressures



<u>Impact</u>:

- Success with advanced combustion will depend on testing at higher preheat, more dilution and higher pressures

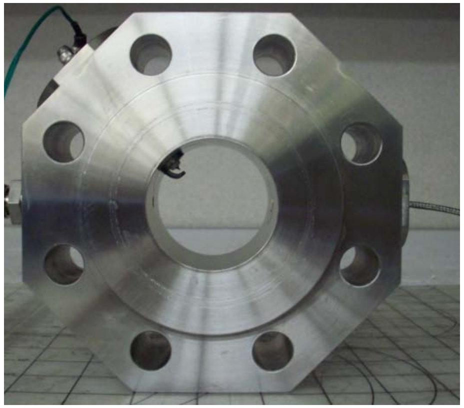


DeFilippo, A., Saxena, S., Rapp, V.H., Ikeda, Y., Chen, J-Y, Dibble, R.W., (2011) Extending the lean flammability limit of gasoline using a microwave assisted sparkplug, SAE Paper no. 2011-01-0663

Task 3: Understanding simultaneous flame + autoignition interactions

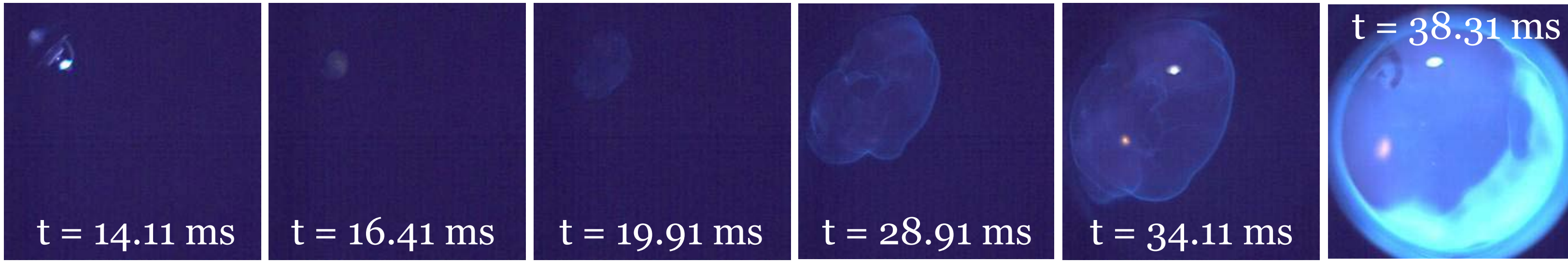
Fundamental need to better understand flame propagation in low temperature (700-1100 K), high pressure (~10 atm), lean (Φ = 0.3 – 0.7) and dilute mixtures

- <u>Goal:</u>
  - Quantify flame + autoignition interactions
- <u>Approach:</u>
  - RCF experiments varying Φ and dilution in premixed iso-octane/O_2/N_2 mixtures
  - Spark to ignite flames
  - High speed imaging to measure flame speeds and autoignition time

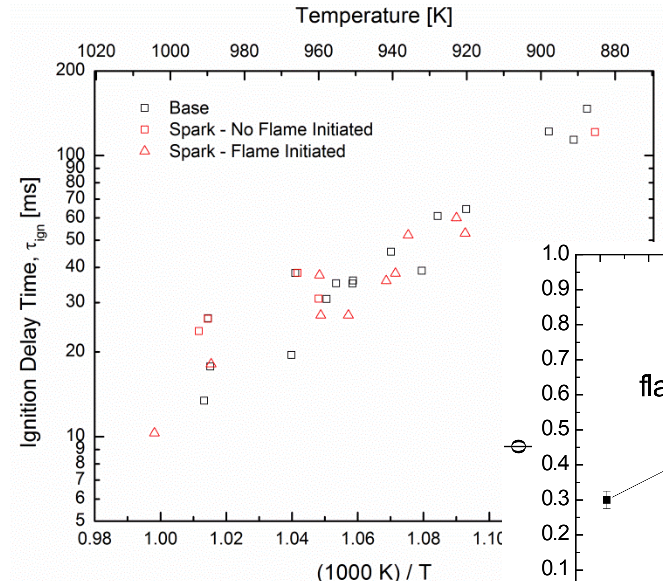


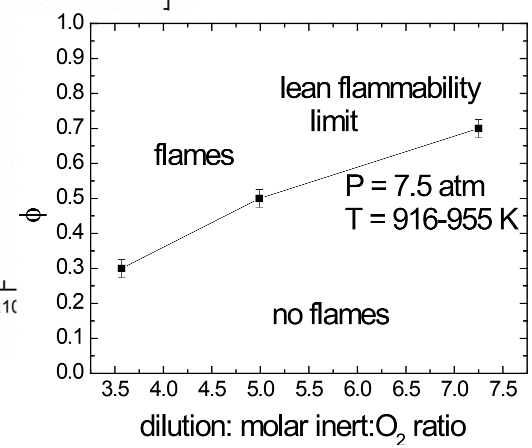
Assanis, Dim., Wagnon, S., Wooldridge, M. S., "An Experimental Study of Flame Propagation into High Temperature High Pressure Premixed Fuel Lean Iso-Octane/Air Mixtures," 7th U.S. National Combustion Meeting, Atlanta, Georgia, March 2011.

Task 3: Understanding simultaneous flame + autoignition interactions



- <u>Accomplishments/Results</u>
  - Established limits for SACI in range of:
    - Φ = 0.3 - 0.7 ± 0.025
    - T = 900-1000 K; P = 7.3-8.1 atm
    - Inert :O_2 dilution = 3.6 to 7.5:1 (mole basis)





<u>Impact</u>:

- Vital missing link for theory and modeling
- Fundamental limiting conditions for SACI identified for the first time, including flame propagation rates

Task 4. Fuel properties for optimal fuel economy (UM)

Fuel testing in FFVA engines (UM)

- Establish range of combustion with fuels of varying octane number

Optical engine (UM)

- Investigate effects of alcohol blends,
- PRF blends

Rapid Compression Facility (UM)

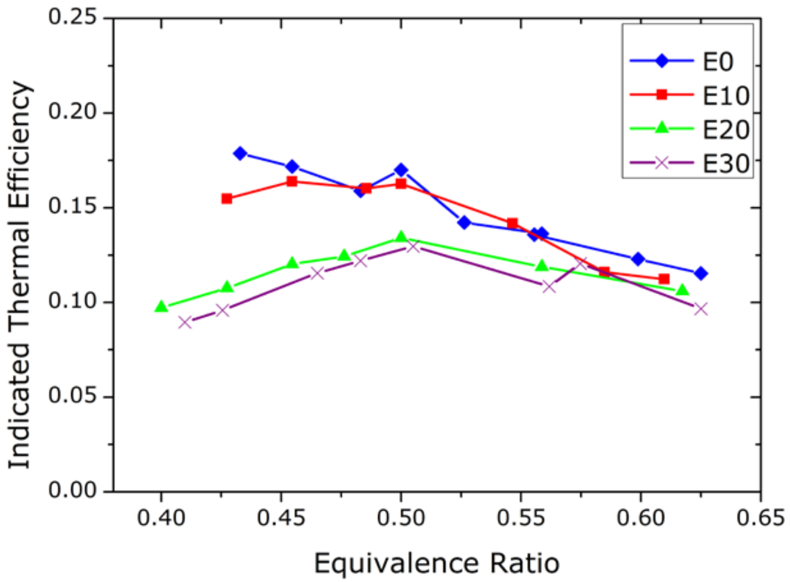
- Ignition delay measurements
- Detailed speciation
- Fuels: (isooctane, esters, alcohols and blends)

Correlations and Modeling

- RCF data used to develop ignition delay correlations for system level models
- Speciation assists development of improved detailed kinetic models

Task 4. Effects of Fuel Blends on LTC Combustion (UM)

- <u>Goal:</u>
  - Identify links between ignition and combustion properties of ethanol + indolene blends and LTC engine performance
- <u>Accomplishments/Results</u>
  - Ethanol content affected power, efficiency, stability, lean limits, and NOx emissions
  - Performance was a strong function of the LTC fueling strategy



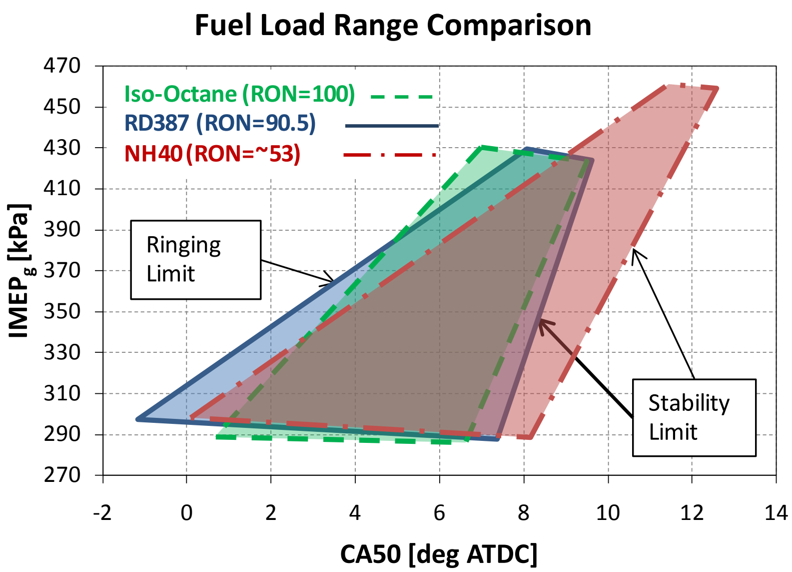
<u>Impact</u>:

- 30% ethanol cannot achieve power, stability and emissions of 100% indolene, even after compensating for charge cooling effects. What is the role of ethanol chemistry?

Fatouraie, M., Keros, P., Wooldridge, M. S., (2012) "A Comparative Study of the Ignition and Combustion Properties of Ethanol-Indolene Blends during HCCI Operation of a Single Cylinder Engine," Society of Automotive Engineers, SAE World Congress, Paper No. 2012-01-1124, pp. 1-17.

Task 4. Fuel properties for optimum fuel economy (UM)

- **Goal:**
  - Determine load limits for different fuels in FFVA engine
- **Accomplishments/Results**
  - Differences in both load limit and burn rate observed
  - Analysis underway to understand this behavior in terms of burn rate, phasing and charge composition

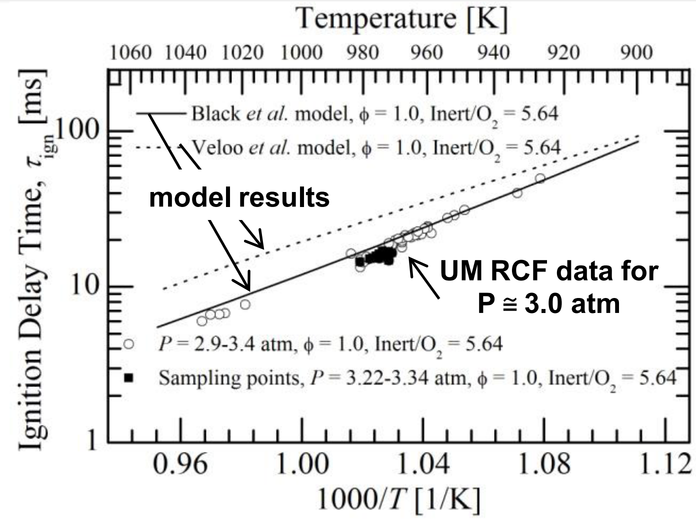


Impact:

- Strategy to characterize and optimize ON
- Results in controlled engine environment combined with Task 1 simulations to determine potential fuel economy effects

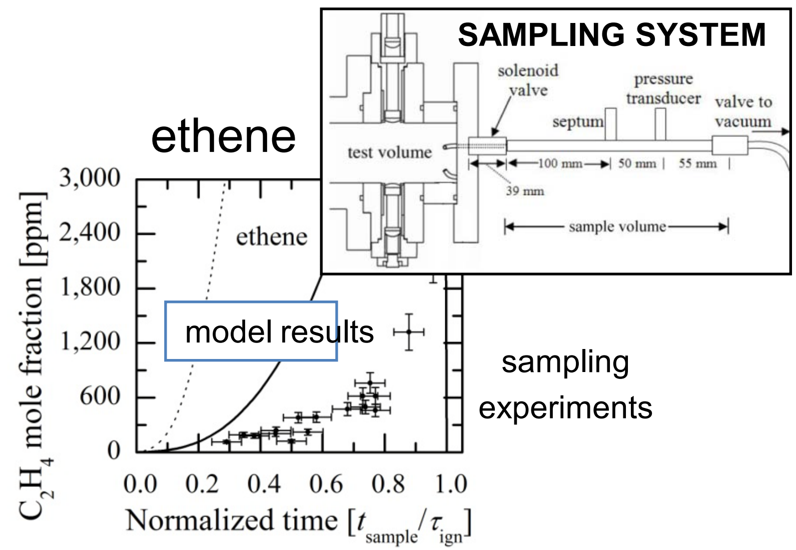
Task 4. Ignition studies in RCF (UM)

- <u>Goal:</u>
  - Quantify autoignition of key reference fuels
- <u>Rapid Compression Facility</u>
  - Ignition delay data obtained for several reference species (e.g. iso-octane, n-butanol, esters)
  - Correlations integrated into engine models
  - Speciation results used to improve kinetic mechanisms (with LLNL)



<u>Impact</u>:

- Developed autoignition models spanning levels of fidelity.
- Identified areas of strengths and weaknesses in rules of reaction chemistry



Wagnon, S. W., Karwat, D. M. A., Wooldridge, M. S., Westbrook., C. K., (2012) “On the Ignition Chemistry of Methyl trans-3-hexenoate,” submitted to the International Symposium on Combustion January 2012, in review.

Karwat, D. M. A., Wagnon, S., Teini, P. D., Wooldridge, M. S., (2011) “On the chemical kinetics of n-butanol: ignition and speciation studies,” Journal of Physical Chemistry A, 115, pp. 4909-4921.

Collaborations and Coordination

- Working on boosted single cylinder HCCI studies with GM
- Working with Microwave Enhanced Ignition device supplied by Yuji Ikeda, Imagineering, Inc., Japan
- Collaborating on SACI and combustion stability with Robert Wagner (ORNL)
- Currently working with Ford to adapt our optical engine to direct injection.
- Working with Jacqueline Chen (Sandia National Laboratories), Ramanan Sankaran (ORNL), Mauro Valorani (University of Rome, La Sapienza), Chris Rutland (UWisc) on mixing effects on HCCI combustion.
- Collaborated with C. K. Westbrook and Bill Pitz (LLNL) on validating reaction mechanisms for long chain alkanes, small esters – now working on alcohols
- Working with Marco Mehl (LLNL) to apply new surrogate fuel kinetics to engine models

Future Work FY12

- Task 1: System and FE analysis tools
  - Refine analysis with realistic combustion constraints and turbocharger characteristics. Explore tradeoff between CR and T/C efficiency in determining optimal efficiency.
- Task 2: Stratification as a means to control combustion
  - Shift engine operating point from non-NTC region where Φ stratification is not effective to NTC behavior where fuel stratification is expected to be important.
  - Develop advanced combustion and mixing submodels to capture stratification effects and mixed mode turbulent combustion.
- Task 3: Multi-mode combustion
  - Complete study of partition of flame vs. autoignition heat release with SACI in FFVA engine
  - Implement a higher-energy microwave system for MWASP testing
  - Compare flame front model results vs. experimental images in optical engine and RCF
  - Use CFMZ model of SACI to investigate variables affecting details of heat release; sensitivity to spark timing; and nature of limits by comparison to metal engine data.
  - Develop system level model of SACI for transient and controls work.
- Task 4: Fuel properties for optimum FE
  - Expand range of test fuels in HCCI load limit studies
  - Carry out RCF studies of ignition properties of fuel blends

Summary

- Task 1: System and FE analysis tools
  - Thermodynamic analysis confirms HPLB strategy; shows importance of advanced combustion
  - System framework refined since last year and FE assessment carried out for additional boosting, downsized strategies: demonstrated potential vehicle FE improvements from 23-58%
- Task 2: Stratification as a means to control combustion
  - Experiments carried out with stratified gasoline fueled diesel engine show fuel stratification increases heat release rate, because combustion is in the non-NTC region.
  - DNS simulation showed multiple combustion/ignition modes in thermally stratified mixture ranging from spontaneous ignition to deflagration front.
  - Provided *a priori* validation of improved mixing model for turbulent combustion.
- Task 3: Multi-mode combustion
  - SACI extends high load limit in naturally aspirated FFVA engine
  - MWASP ignition extends lean limit under NA conditions with potential gains for LTC combustion
  - Laminar flame correlations developed for high dilution / high preheat conditions
  - CFD model of SACI developed; good qualitative agreement with optical engine images
- Task 4: Fuel properties for optimum FE
  - Studies of low octane gasoline fuel shows potential for higher load operation in FFVA (NVO enabled) HCCI operation
  - Initial studies on ignition of n-butanol and esters carried out in RCF; speciation results show need for improvements to kinetic models