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

University of Michigan (UM):
Dennis N. Assanis (PI),
Aris Babajimopoulos, Stani V. Bohac, Zoran S. Filipi,
Hong G. Im, George A. Lavoie, Margaret S. Wooldridge

Massachusetts Institute of Technology (MIT):
Wai Cheng

University of California, Berkeley (UCB):
Jyh-Yuan Chen, Robert Dibble

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DOE Project DE-EE0000203

Overview

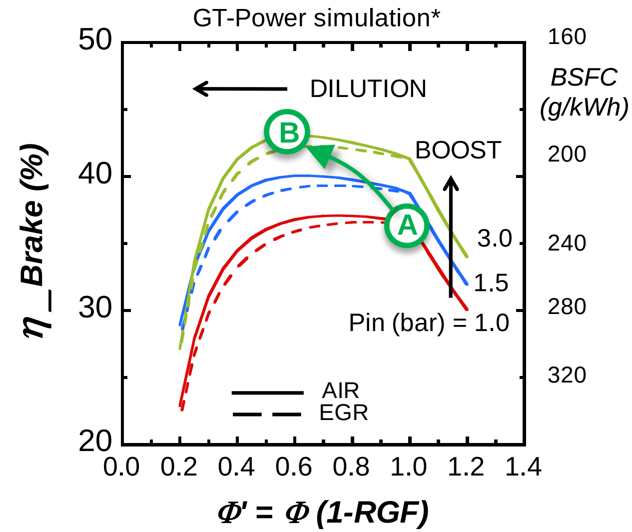
HPLB University Consortium

- TIMELINE
  - Start - Oct 2009
  - Finish – Dec 2012
  - 50% completed
- BUDGET
  - Total project funding - $3,000k
  - Rec'd FY10 - $1,000k
  - Rec'd FY11 - $ 500k
- 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, BP, 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 <u>dilute, high pressure combustion</u> modes and <u>fuel properties</u> as enablers to achieve FE targets

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

* GT=Power simulation includes: heat transfer, friction, CR = 12, and constant B10-90 = 25 °, CA50 = 10 °ATC

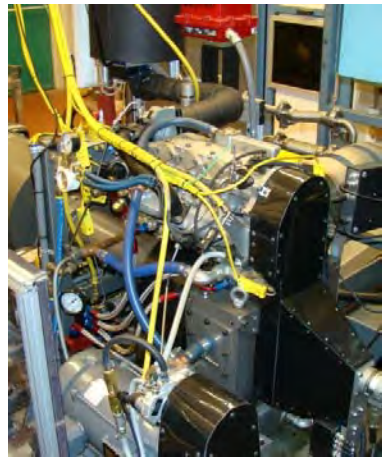
Approach

- Task 1: System and FE analysis tools
  - Establish link between advanced combustion modes and potential vehicle FE gains with GT-power and Matlab simulations (UM)
- Task 2: Stratification as a means to control combustion
  - Carry out experiments in RCM and gasoline fueled boosted diesel (MIT)
  - Apply numerical modeling to study turbulent autoignition modes (UM)
- Task 3: Multi-mode combustion
  - Conduct engine experiments on SACI in FFVA DI engine (UM)
  - Use CFR engine to test combustion limits with MWASP (UCB)
  - RCM and Optical Engine experiments on SACI (UM)
  - Use 1-D modeling of laminar flames in high preheat, high dilution mixtures to develop correlations for multi-dimensional models
  - Develop CFD model of SACI with KIVA (UM)
- Task 4: Fuel properties for optimum FE
  - Explore low octane and other gasoline based fuels in FFVA engine (UM)
  - Gather fundamental ignition and kinetic data for alternate fuels in RCF (UM)

Consortium Experimental Facilities

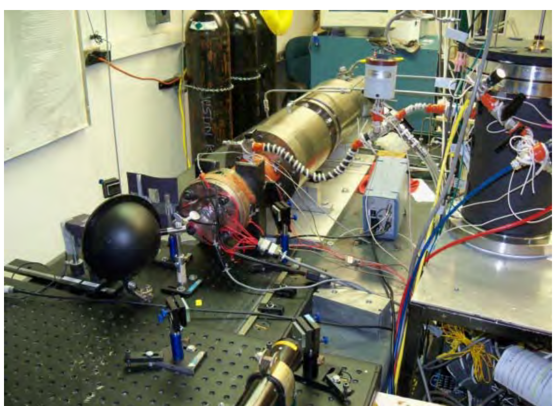
UM optical engine (SACI and fuels)

UM diesel engine (fuels)



UM camless FFVA engine (multi-mode combustion)

MIT rapid compression machine (fuel ignition)



UCB CFR engine (MWASP)

MIT boosted Diesel (stratification)

UM RCF (ign. chemistry)

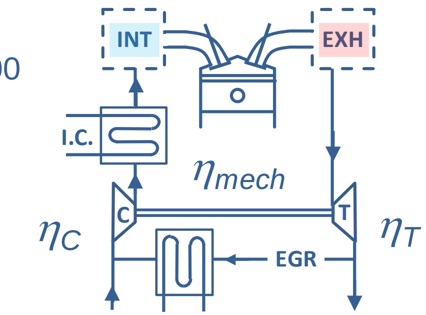
Technical Accomplishments (highlights)

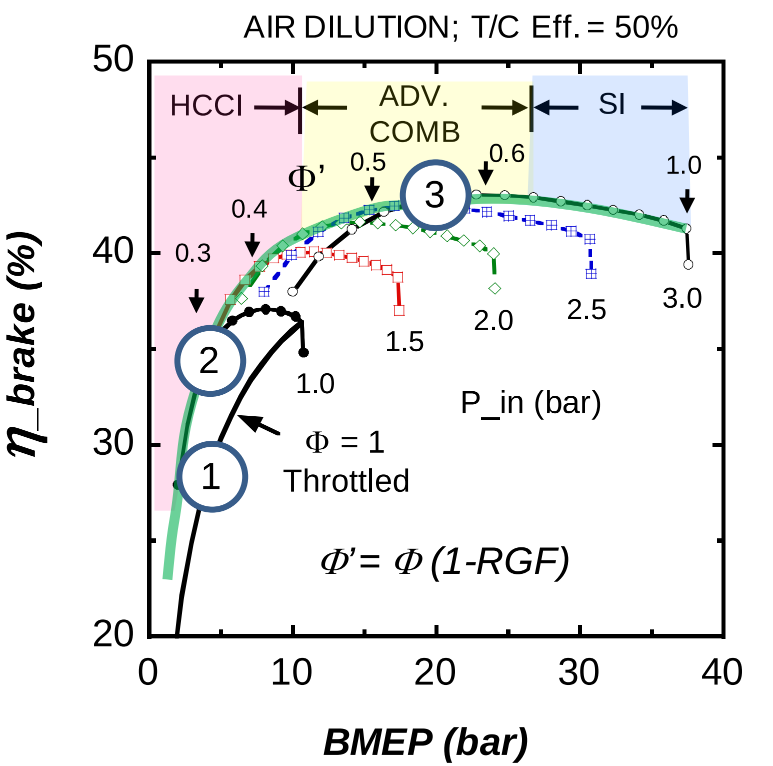
- Task 1: System and FE analysis tools
  - Thermodynamic analysis shows engine efficiency benefits of HPLB (UM)
  - Vehicle FE framework shows potential vehicle-level gains with HPLB strategy (UM)
- Task 2: Stratification as a means to control combustion
  - Stratification moderates heat release rate for gasoline HCCI (MIT)
  - Identified combustion modes with thermal stratification using DNS tools (UM)
- Task 3: Multi-mode combustion
  - SACI extends high load limit in fully flexible valve actuation (FFVA) engine (UM)
  - Microwave-Assisted Spark Plug (MWASP) extends lean limit (UCB)
  - Developed laminar flame speed (SL) correlations for SACI conditions (UM)
  - Developed CFD model of SACI using new laminar flame speed correlations (UM)
- Task 4: Fuel properties for optimum FE
  - Low octane fuel extends HCCI high load limit in FFVA engine (UM)
  - New RCF data obtained on the ignition characteristics of n-butanol (UM)

Task 1: Thermodynamic Analysis Shows Engine Efficiency Benefits of HPLB (UM)

- **Objective:** determine thermodynamic conditions for best FE
- **Approach:** Use GT-Power model with ideal T/C and fixed burn duration
- **Results:**
  - Optimal boosting strategy increases fuel-to-charge equiv. ratio (Φ') as boost is increased
  - Best overall engine efficiency occurs under highly dilute, high pressure conditions, i.e. advanced combustion
  - Peak brake engine efficiency ~ 42%
  - BSNOx < 0.26 g/kWh up to 18 bar BMEP
- **Future Work:**
  - Refine analysis with realistic combustion and T/C constraints; apply simple aftertreatment constraints (T_{EX}) for HC, CO emissions
  - Link FE projections to experimental data in Tasks 2, 3, and 4.

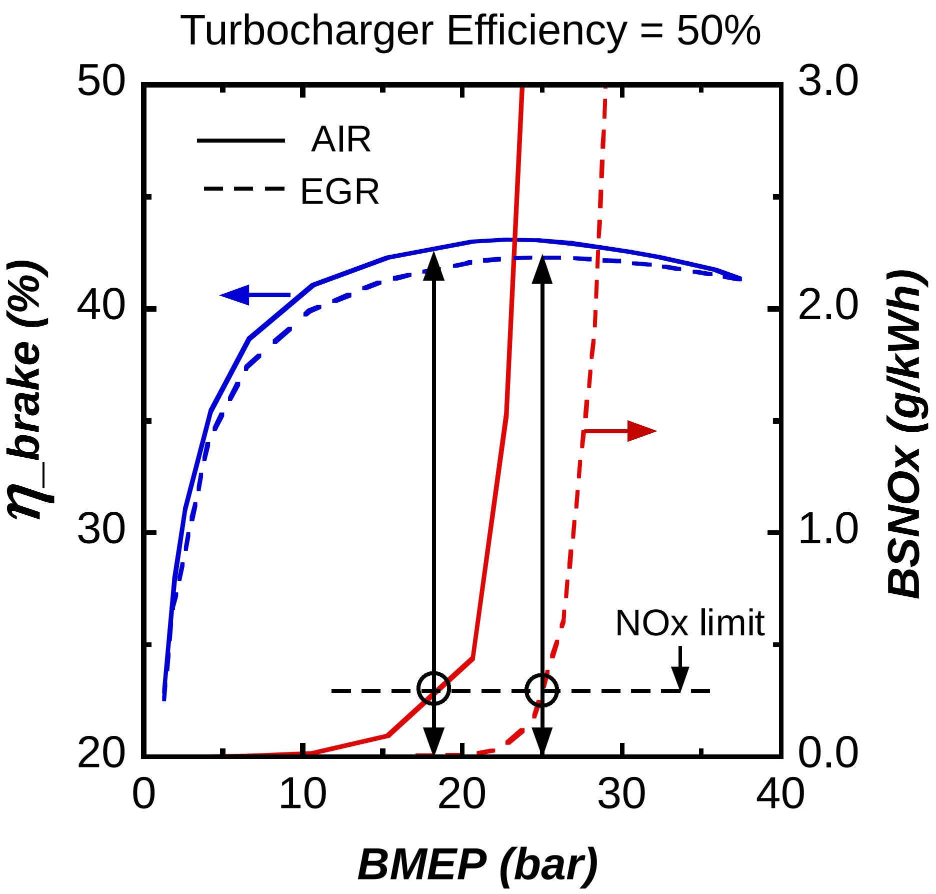
GT-Power model
- CR = 12; RPM = 2000
- Ideal T/C; Eff.=50%
- B10-90 (25°)
- CA50 (10°ATC)
- heat transfer, friction
- 2-zone NOx model





Task 1: Low NOx Emissions Are Achievable with Optimum Boosting Strategy

- Optimum boosting strategy and T/C efficiency of 50% result in BSNOx < 0.26 g/kWh
  - Up to 18 bar BMEP (Air dilution)
  - Up to 25 bar BMEP (EGR dilution)
  - Peak η_{brake} ~ 42%



Task 1: Vehicle FE Framework Shows Vehicle Level Gains with HPLB Strategy (UM)

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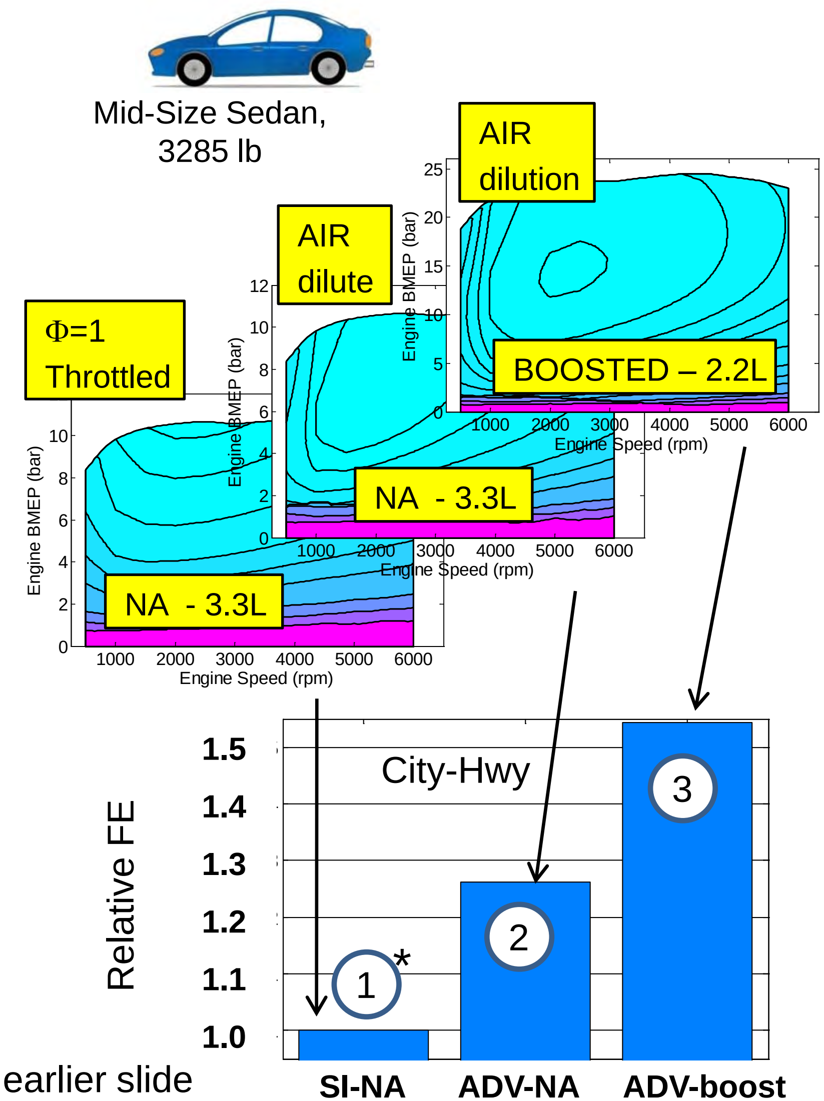
- **Objective:** Provide projection of vehicle FE gains achievable with advanced combustion
- **Approach:** combine GT-Power generated BSFC maps of 3 ideal engine strategies (previous slide) with Matlab drive cycle simulation
- **Results:**
  - (1)*→(2) dilution (N. A.) ~ 25% gain (assumes optimum combustion at all points, and 100% comb. Efficiency)
  - (2)→(3) dilution + boosting + downsize ~ 50% gain (assumes T/C eff = 50%)
- **Future Work:**
  - Include more realistic combustion characteristics and constraints



* Circled numbers refer to engine combustion strategies on earlier slide

Task 2: Stratification Moderates Heat Release Rate for Gasoline HCCI (MIT)

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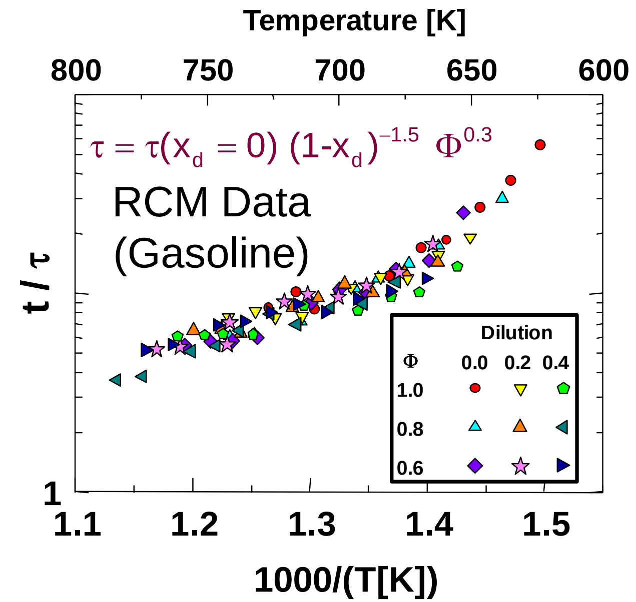
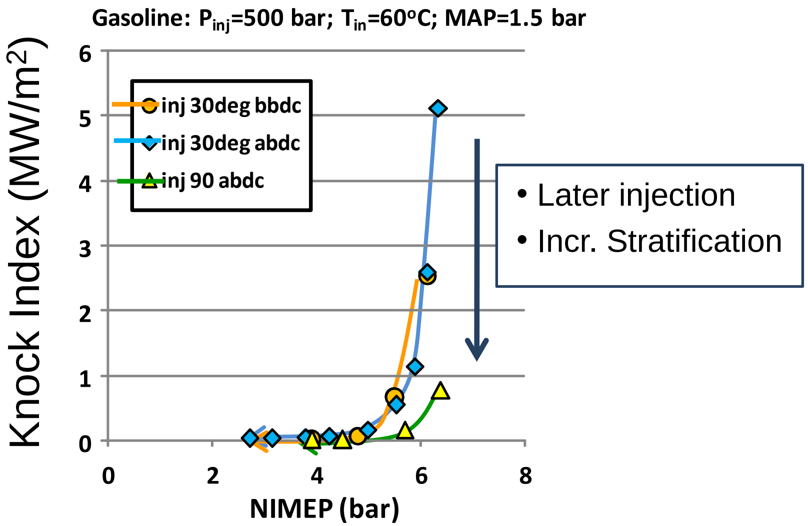
- **Objective:** investigate benefits of interaction between gasoline fuel properties and stratification
- **Approach:**
  - Obtain fuel ignition data in RCM
  - Vary injection characteristics in boosted diesel engine to vary stratification
- **Results:**
  - Correlation developed for τ_{IGN} in RCM
  - In engine, late injection (90° ABDC) is effective in setting up stratification by moderating heat release rate
- **Future work**:
  - Connect RCM results with engine data
  - Vary fuel properties





Task 2: Identified Combustion Modes with Thermal Stratification Using DNS Tools (UM)

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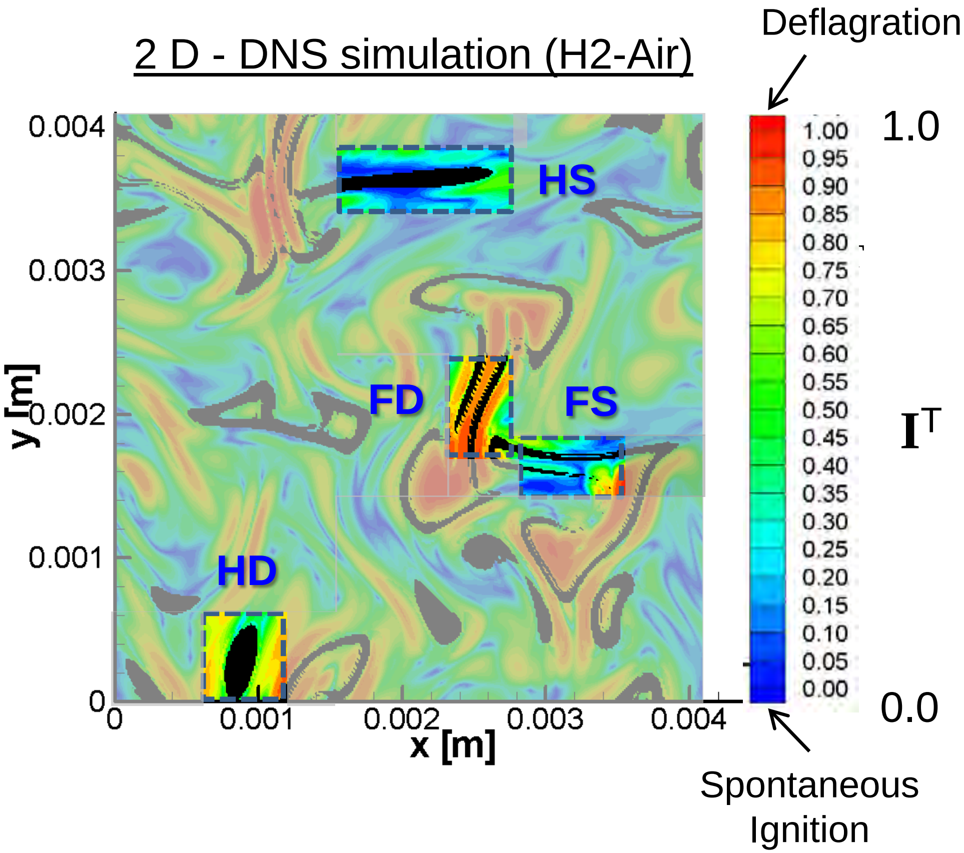
- **Objective:** characterize ignition regimes in thermally stratified HCCI combustion
- **Approach:** Use Computational Singular Perturbation (CSP) analysis of timescales in a reacting flow field to determine Importance Index

$$I^T = \left| I^T_{(T-\text{Diffusion})_{slow}} \right| + \left| I^T_{(T-\text{Convection})_{slow}} \right|$$

  (Shows relative importance of deflagration / flame vs. autoignition)

- **Results:**
  - Turbulent stratified combustion invokes multiple reaction modes
- **Future work**:
  - Application of method to higher hydrocarbon fuels
  - Compositional stratification

2 D - DNS simulation (H2-Air)



M = 1 contour in black [denotes active reaction zone]

H: Homogeneous kernel, **F**: Front
S: Spontaneous Ignition, **D**: Deflagration

In Collaboration With Mauro Valorani, University of Rome, La Sapienza

Task 3: SACI Extends High Load Limit in Fully Flexible Valve Actuation (FFVA) Engine (UM)

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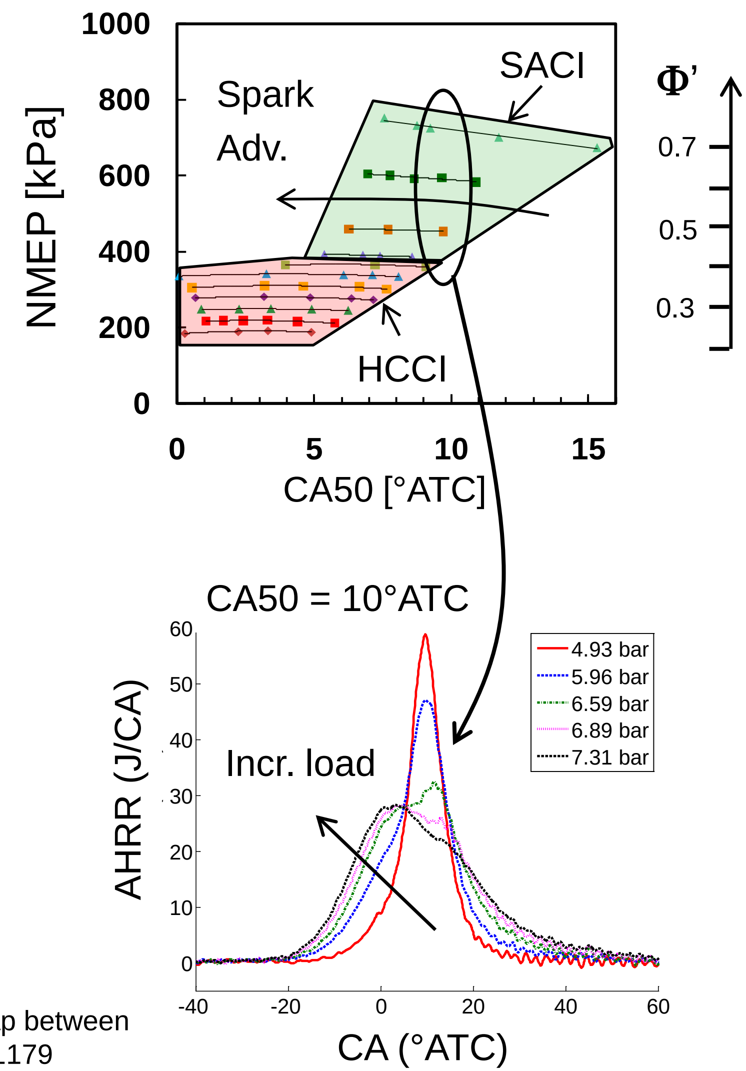
- **Objective:** demonstrate load extension with spark assist
- **Approach:**
  - Increase load by adding fuel and reducing trapped residual gas (NVO) with Φ= 1 (increase fuel-to-charge Φ')
  - Control phasing with spark timing
- **Results:**
  - Heat release rate moderated by SACI
  - Maximum load increased to 7.3 bar
  - Encountered SI knock at highest loads
- **Future Work:**
  - Explore variations in proportion of flame vs. autoignition heat release.
  - Extend work to higher pressures (cell upgrade in progress to provide boost)



Manofsky, L., Vavra, J., Babajimopoulos, A., and Assanis, D. (2011) Bridging the Gap between HCCI and SI: Spark-Assisted Compression Ignition. SAE Technical Paper 2011-01-1179

Task 3: Microwave-Assisted Spark Plug (MWASP) Extends Lean Limit (UCB)

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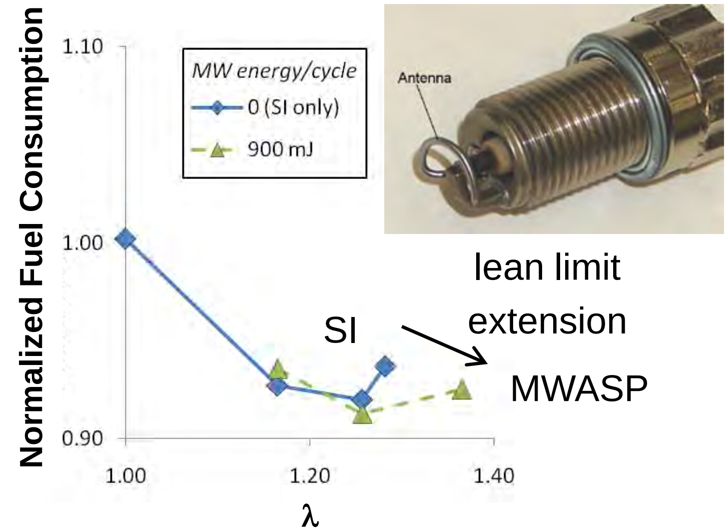
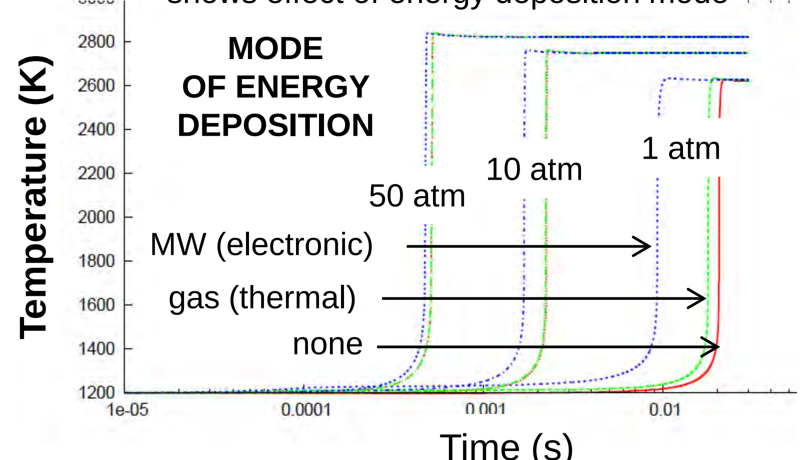
- **Objective**: Evaluate the potential benefits of MWASP for advanced combustion modes
- **Approach**:
  - Use CFR engine (CR = 7, 9) to test ignition under lean limit conditions
  - Model ignition with simplified methane kinetics and electron gas dynamics
- **Results:**
  - Lean limit extension observed
  - Modeling suggests benefit may decrease at higher pressures
- **Future Work:**
  - Extend experiments into SACI range (higher CR, leaner, and more preheat)



Kinetic model of ignition in a WSR shows effect of energy deposition mode



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: Developed Laminar Flame Speed (S_L) Correlations for SACI Conditions (UM)

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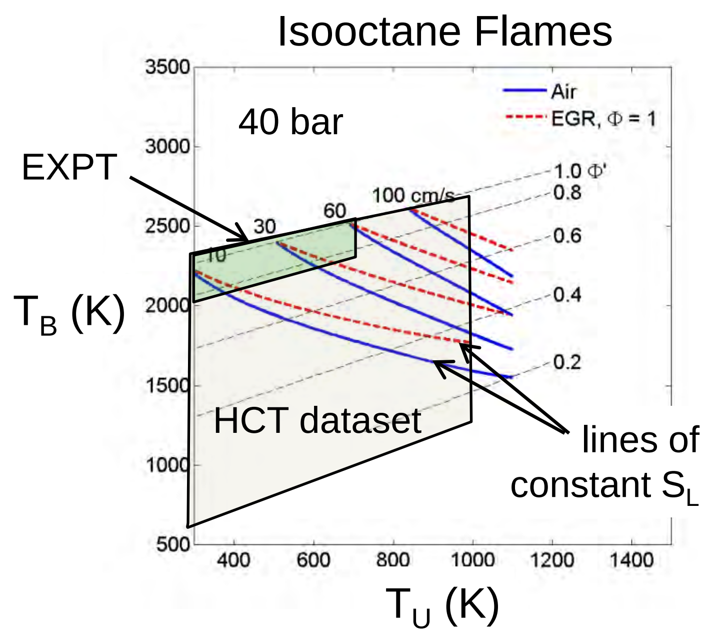
- **Objective**: Understand fundamental flame behavior and properties for highly preheated, highly dilute mixtures
- **Approach**:
  - Use transient flame code HCT to build dataset of flame properties in SACI regime where experimental data is limited
  - Build mathematical correlations for use in turbulent combustion models
- **Results**:
  - Viable flames predicted in regions where SACI observed
  - Correlations made for AIR and EGR dilute flames
- **Future Work**:
  - Validate vs. images from optical engine and in RCF



Form of correlation shows Air and EGR dependence

EGR (O_2 term) AIR only

$$S_L = \left(1 - D_2 Y_{EGR} \Phi\right)^{D_1} F Y_{f,u}^{m} \exp\left(-G/T^0\right)\left(\frac{T_u}{T^0}\right)\left(\frac{T_b - T^0}{T_b - T_u}\right)^{n}$$

Middleton, R.J. et al., "A Computational Study and Correlation of Premixed Isooctane Air Laminar Reaction Front Props. with Combustion Products," In Preparation.

Task 3: Developed CFD Model of SACI Using New Laminar Flame Speed Correlations (UM)

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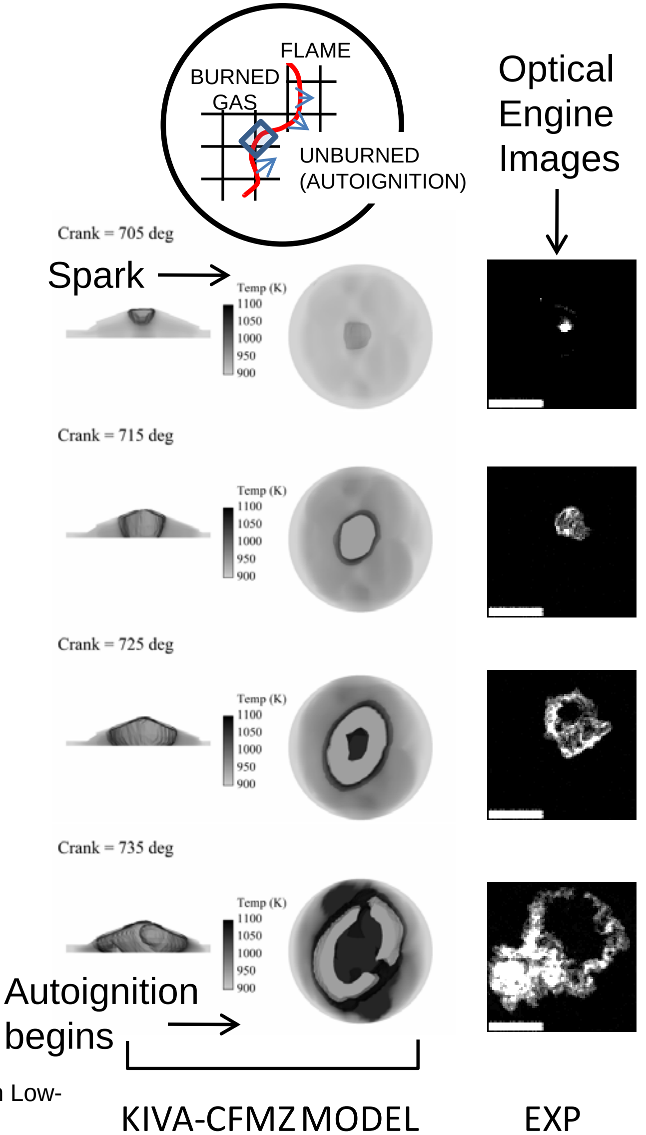
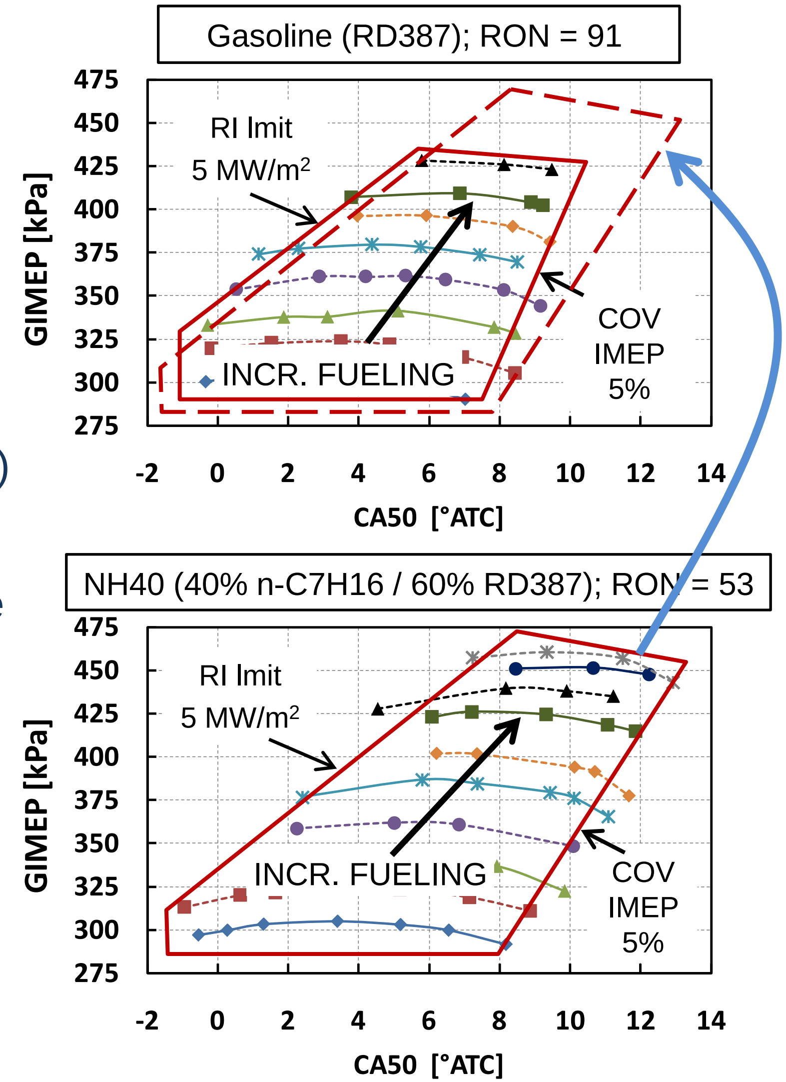
- **Objective**: develop CFD model of SACI and use to explore possible benefits
- **Approach:** combine laminar flame speed correlations with models of coherent flamelet and multizone autoignition (CFMZ model)
- **Results:**
  - Model compares well with images obtained in UM optical engine
  - Good qualitative agreement with heat release curves in metal engine
- **Future work**:
  - Perform parametric studies on variables affecting heat release partition between flame and autoignition and sensitivity to spark timing
  - Validate limits vs. metal engine data



Martz, J. B., (2010) , 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, October 2010.

Task 4: Low Octane Fuel Extends HCCI High Load Limit in FFVA Engine (UM)

- **Objective:** Explore ways to use fuel properties to increase HCCI load limit
- **Approach:**
  - Use NVO in FFVA engine to provide control over combustion phasing
  - Inlet temperature = 45°C
  - Initially compare gasoline vs. a low octane surrogate NH40 (40% n-heptane in gasoline)
- **Results:**
  - NH40 had higher load limit possibly because it had faster 10-90 burn duration and could be retarded more without instability
- **Future Work:**
  - Expand range of test fuels
  - Explore benefit of spark assist



Task 4: New RCF Data Obtained on the Ignition Characteristics of n-butanol (UM)

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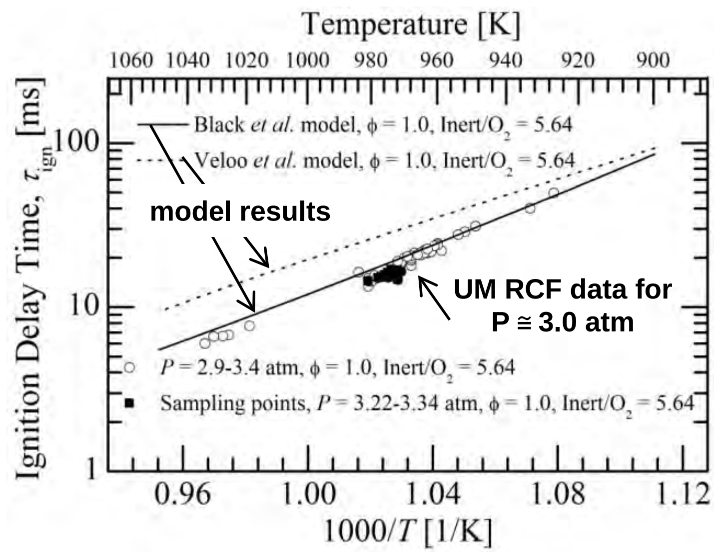
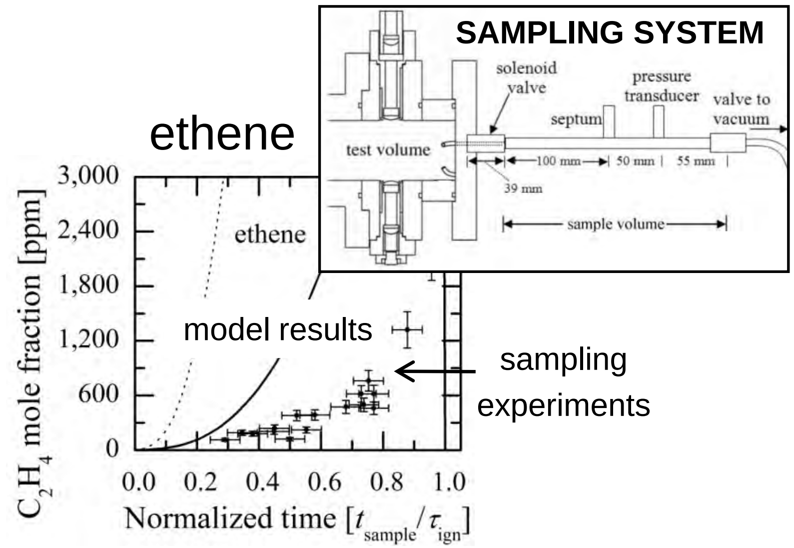
- **Objective:** Investigate ignition of alternative fuels such as n-butanol as a possible infrastructure compatible fuel and blending component for bio-fuels
- **Approach:**
  - RCF provides ignition delay data
  - Sampling system gives intermediate species data
  - Both data are necessary to quantify the impact on fuel reactivity and exhaust emissions
- **Results:**
  - Measured ignition delays are in excellent agreement with Black et al. model
  - RCF speciation data identify weaknesses in reaction pathways important for predicting and mitigating emissions
- **Future work:**
  - Study fuel blends using RCF and optical engine





Future Work FY11-12

- Task 1: System and FE analysis tools
  - Refine analysis of optimum combustion strategy with realistic combustion constraints and turbocharger characteristics. Apply simple T_{EX} constraint for CO, HC aftertreatment. Explore tradeoff between CR and T/C efficiency.
  - Link FE projections to experimental data from Tasks 2, 3, and 4.
- Task 2: Stratification as a means to control combustion
  - Connect RCM ignition results with engine timing data; vary fuel properties
  - Apply Computational Singular Perturbation (CSP) method to higher hydrocarbon fuels and compositional stratification
- Task 3: Multi-mode combustion
  - Explore variations in partition of flame vs. autoignition heat release in SACI in FFVA engine
  - Extend FFVA SACI work to higher pressures (cell upgrade in progress to provide boost)
  - Extend MWASP experiments into SACI range (higher CR, leaner, and more preheat)
  - 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.
- Task 4: Fuel properties for optimum FE
  - Expand range of test fuels, and include spark assist in testing
  - Carry out RCF studies of ignition properties of fuel blends

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)
- Supplied engine maps for HCCI to Argonne National Labs
- Currently working with Ford on the next steps towards changing our optical engine to direct injection.
- Working with Chevron on enhancing the effectiveness of stratification on controlling LTC heat release with fuel (MIT)
- Studying sensitivity of spark-assisted HCCI engines to range of market fuels; with BP and Ford (MIT)
- 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

Summary

HPLB University Consortium

- Task 1: System and FE analysis tools
  - Thermodynamic analysis confirms HPLB strategy; BTE of 42% with BSNOx < 0.26 g/kWh
  - System framework developed for vehicle FE assessment: demonstrated potential vehicle level impact of boosted dilute strategies
- Task 2: Stratification as a means to control combustion
  - Initial experiments carried out with stratified gasoline fueled diesel engine show stratification moderates heat release rate
  - DNS simulation showed multiple combustion/ignition modes in thermally stratified mixture ranging from spontaneous ignition to deflagration front
- 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 carried out in RCF; speciation results show need for improvements to kinetic models