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

HPLB University Consortium

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DOE Project DE-EE0000203

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Overview

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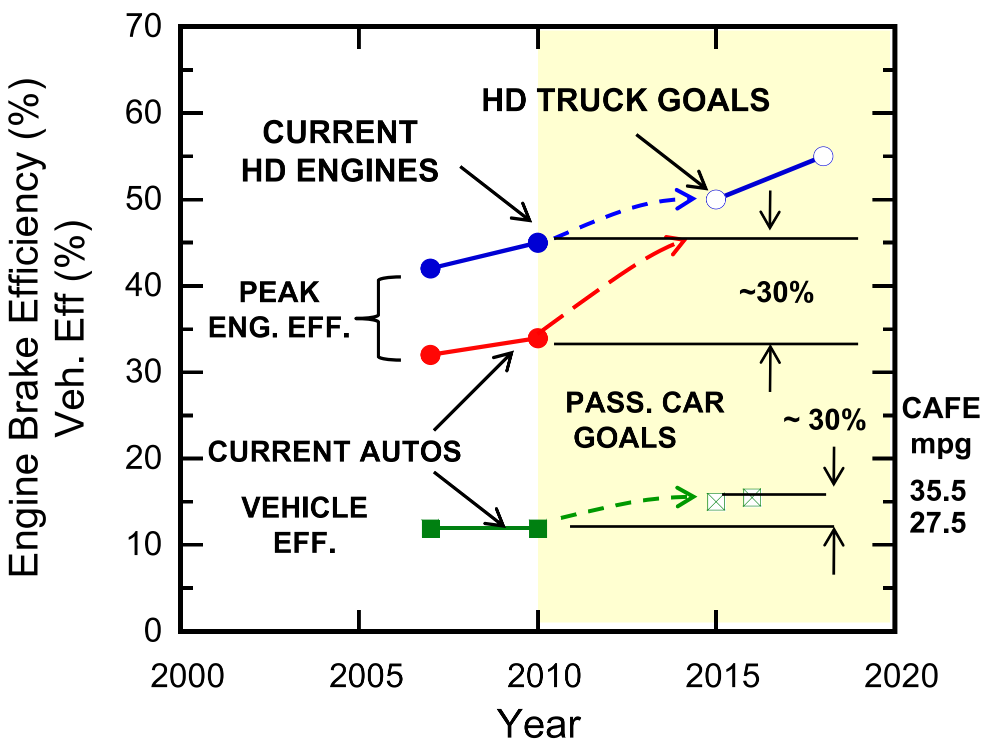
- TIMELINE
  - Start - Oct 2009
  - Finish – Dec 2012
  - 15% completed
- BUDGET
  - Total project funding
    - DOE - $3,000k
    - Contractors - $750k
  - Rec'd FY09 - $614k
  - Rec'd FY10 - $1,000k
- BARRIERS ADDRESSED
  - Fundamental knowledge of engine combustion (B)
  - Emissions control (C)
- PARTNERS
  - Universities – UCB, MIT
  - Collaborations – SNL, LLNL, ORNL, ANL
  - Industrial – GM, BW, Bosch, Ford, BP

Objectives

- Previous Consortium FY09
  - Expand the operating range of LTC engines at both high and low loads
  - Develop models of critical combustion phenomena, and engine-vehicle systems
  - Acquire knowledge of new fuels
- Present Consortium FY10
  - Demonstrate path to achieve 20-40% engine efficiency gain, with 25% vehicle FE improvement.
  - Explore advantages of stratification, new combustion modes, and novel fuels in high pressure, lean burn engines.

DOE Vehicle Technologies Technical Targets

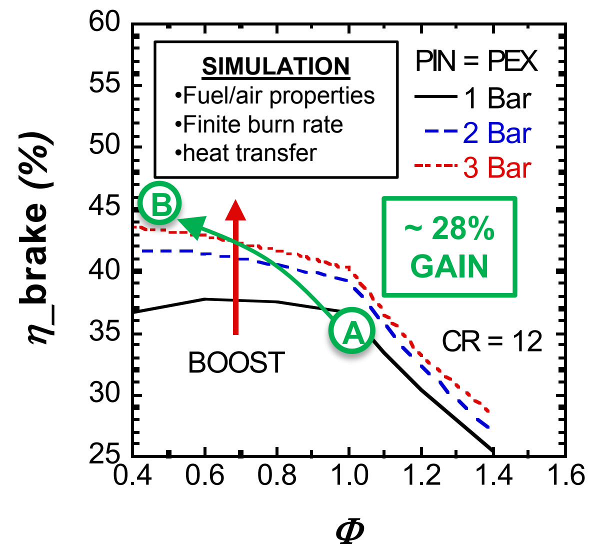
Characteristic	DOE/VTP Passenger Car Target
Peak Eng. Eff.	from 34% to 45% brake eff.
Vehicle Eff.	25% improvement
Emissions	Tier 2, bin 5



Approach

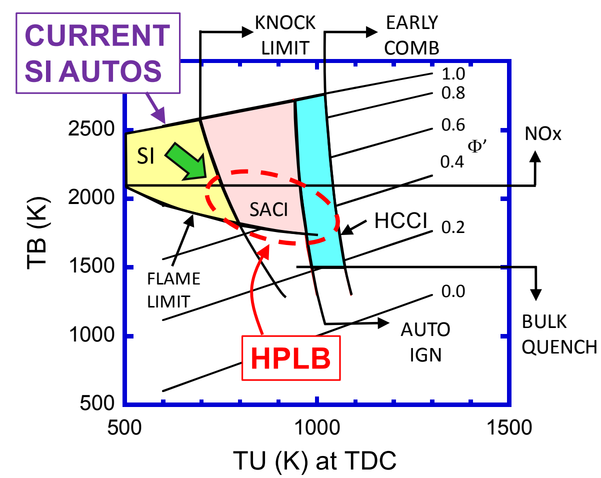
Use tools and knowledge from previous consortium to:

- Focus on *High Pressure – Lean Burn* path toward engine fuel economy gain of 20+%
  - Application to downsized and boosted, high compression ratio engines
  - Lean burn and high unburned temperature for thermodynamic gains



- Assess *final, in-vehicle fuel economy* results; (goal: 20 – 40% gains).
  - Mixed mode
  - Load shifting
  - Start Stop Alternators, Hybrids

Mulit-Mode Combustion Diagram (MMCD)



Lavoie, et al. (2010) Combustion and Flame, Vol. 157 No., 1106–1110

Approach - tasks

- Fuel Efficiency of Advanced HPLB Cycles (UM)
  - Characterize new combustion regimes and assess their potential to improve engine fuel economy in combination with novel engine cycles
- Charge Stratification Strategies (UM, MIT)
  - Experimentally study stratification strategies for HPLB engines and the interaction between fuel properties, heat transfer and stratification
- Maximizing Engine Efficiency via Multi-Regime Ignition Strategies (UM, UCB)
  - Investigate the fuel economy and combustion control potential of mixed modes under high load and highly boosted conditions
- Fuel Chemistry Opportunities for Improved engine Efficiencies (UM, MIT)
  - Provide a quantitative understanding of the potential to enhance engine efficiency through deliberate use of distinct chemistry characteristics under HPLB conditions

Approach – task interaction

MODELS, EXPERIMENTS

ANALYTICAL TOOLS

TASK 2.

Charge Stratification (UM, MIT)

- Explore fuel and thermal stratification and its interaction with fuel properties and heat transfer (RCM at MIT, CFD at UM)

TASK 3.

Multi-Regime Ignition (UM, UCB)

- Carry out SACI metal and optical engine experiments (UM)
- Continue CFD model development of SACI (UM)
- Carry out MWASP experiments and modeling (UCB)

TASK 1.

Fuel Efficiency of Advanced HPLB Cycles (UM)

- Develop models of engines and engine-vehicle cycles in advanced combustion modes
- Make ongoing assessment of potential FE gains

TASK 4.

Fuel Chemistry Opportunities (UM, MIT)

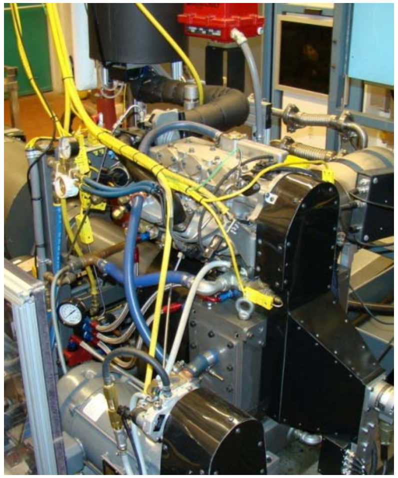
- Explore fuel/stratification interactions in RCM and RCF.
- Assess novel fuel opportunities for improved efficiency in modified diesel engine: Gasoline/diesel/ethanol blends

In-vehicle FE improvement

Consortium experimental facilities

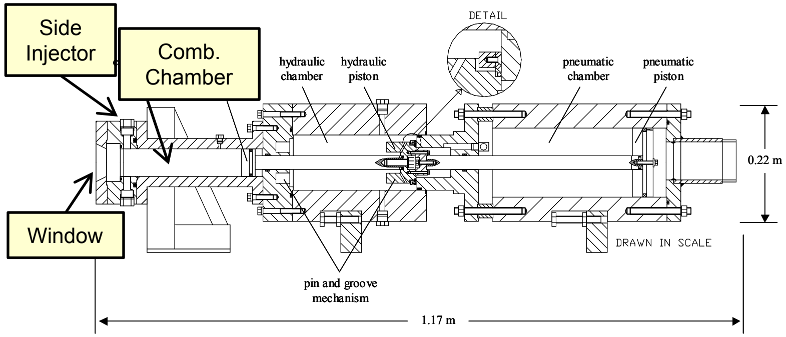
UM optical engine
(SA-HCCI and fuels)

UM GM diesel engine
(fuels/thermal stratification)



UM camless FFVA engine
(multi-mode combustion)

MIT rapid compression
machine (fuel/stratification)



UCB single cyl. engine
(MWASP)

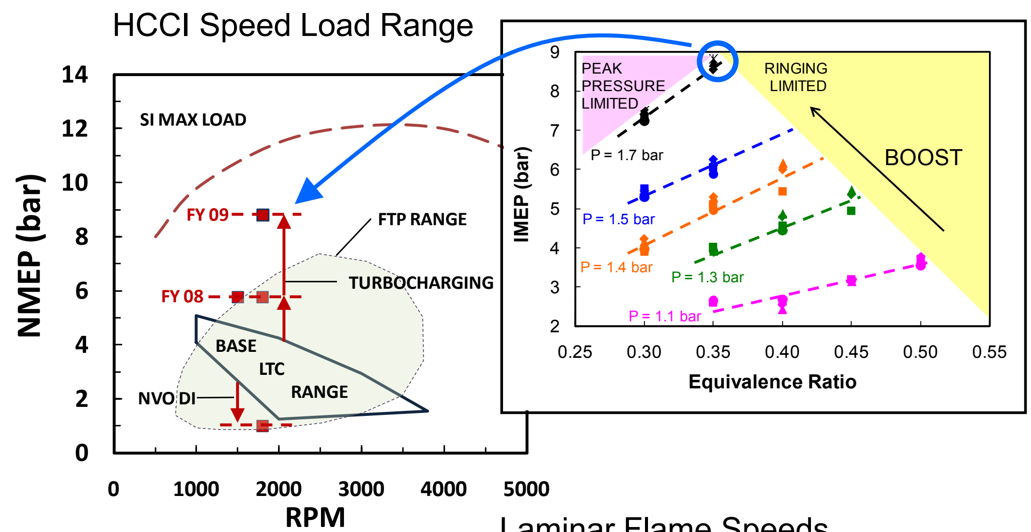
UM rapid compression
facility (ign. chemistry)

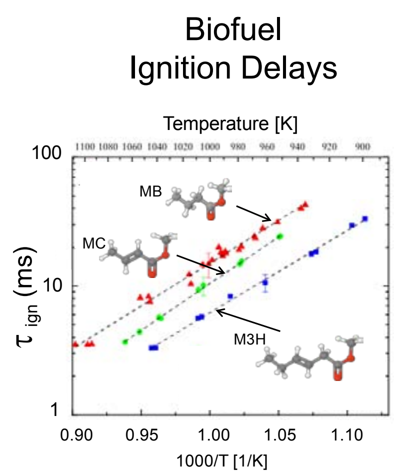
Modeling tools available

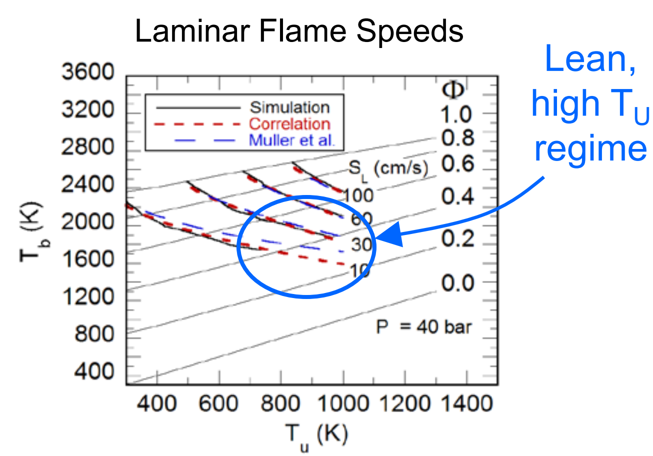
- KIVA-Multi-Zone CFD simulation – (homogeneous and light stratification)
- KIVA- RIF-ER model including effect of evaporation (strong stratification)
- Matlab/Simulink - GT-Power engine and drive cycle simulator with UM developed combustion correlation – includes turbo/supercharger models
- HCT – Transient flame code (laminar flame and ignition)
- CFMZ – Coherent Flamelet Multi Zone (SACI model)

Technical accomplishments (previous consortium – FY09)

- Demonstrated increased high load HCCI limit (8.6 bar NMEP) with boosted, lean operation (agrees with J. Dec experiments).
- Developed HCT dataset of laminar flame simulations in targeted HPLB combustion regime
- Obtained RCF ignition data for several surrogate biofuel fuels for improved kinetic modeling







Developed framework for cycle fuel economy assessment – FY10

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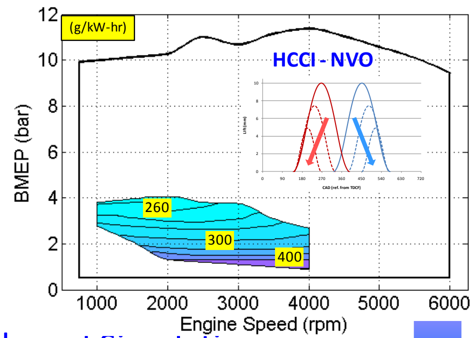
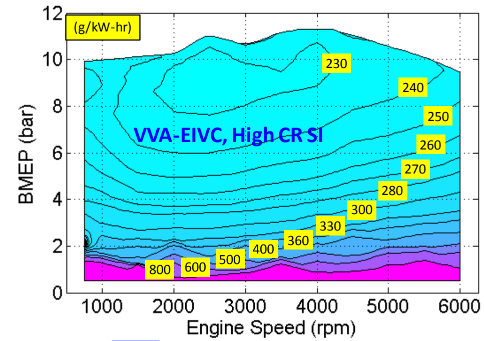
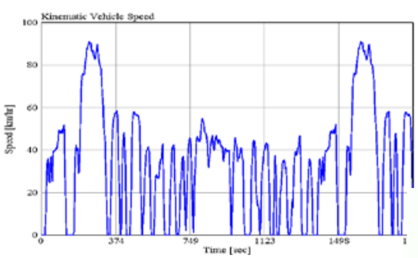
- Comparison of SI/HCCI mixed mode configurations



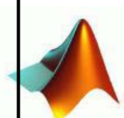


Drive-Cycle

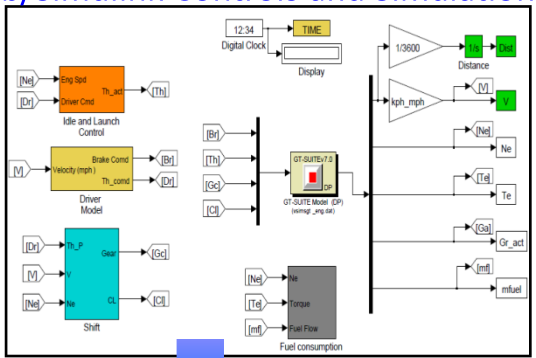


Vehicle Parameters

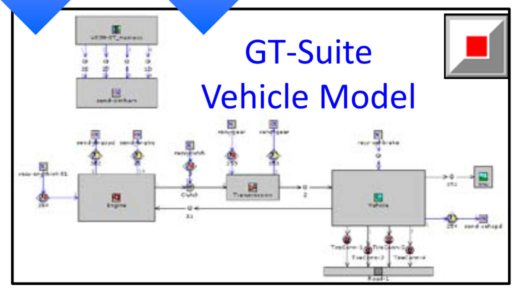
Mid-Size Sedan
2.5L Engine, 3285 lb
6-Speed A/T (w/o TC)

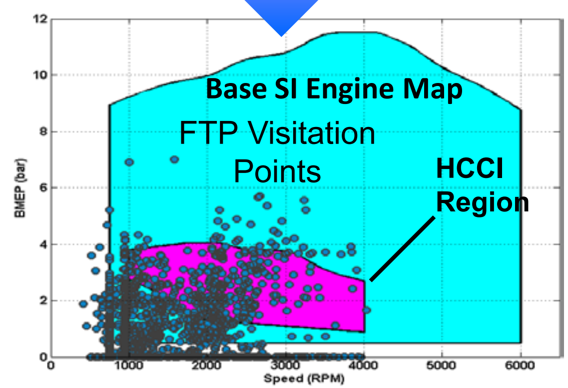


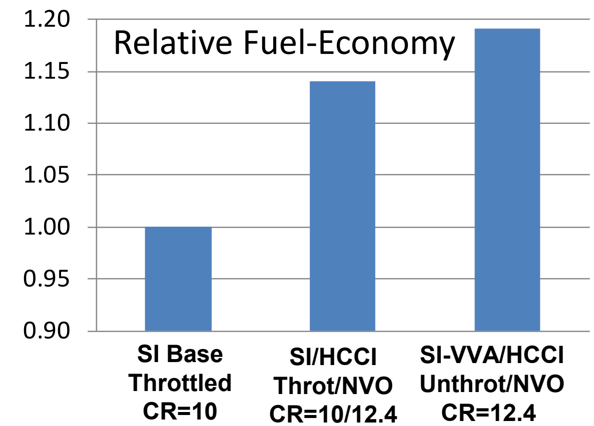
Matlab/Simulink Controls and Simulation



GT-Suite Vehicle Model







Developed new wall function for CFD heat transfer

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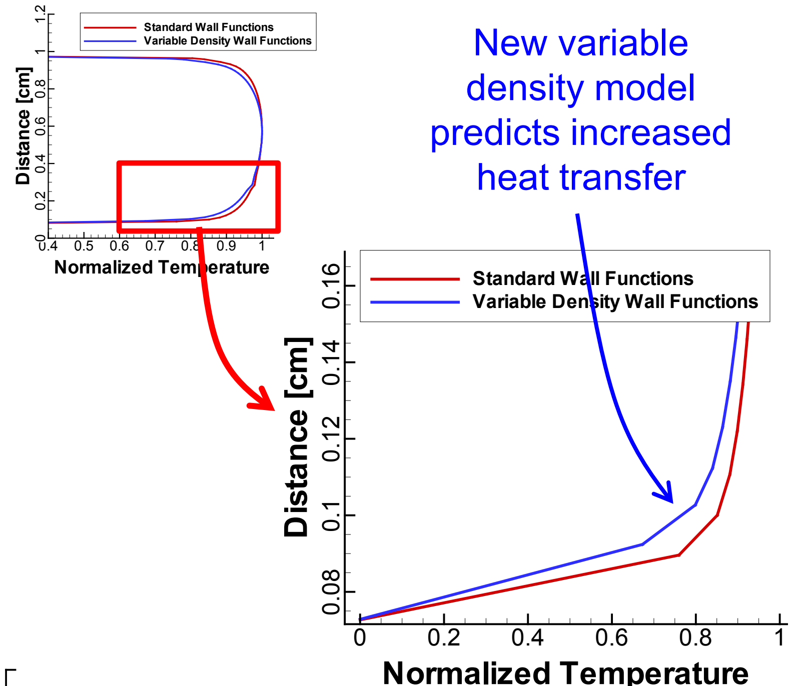
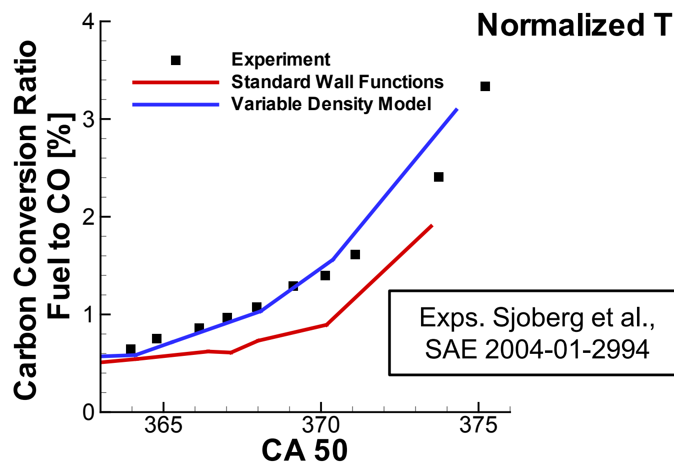
- Model takes into account density variation in wall cell

Within wall layer	Standard Model	New Model
Temperature	Constant	Varies
Density	Constant	Ideal gas law
ν^+ / Pr_t	Based on incompressible flow	Corrected with temperature

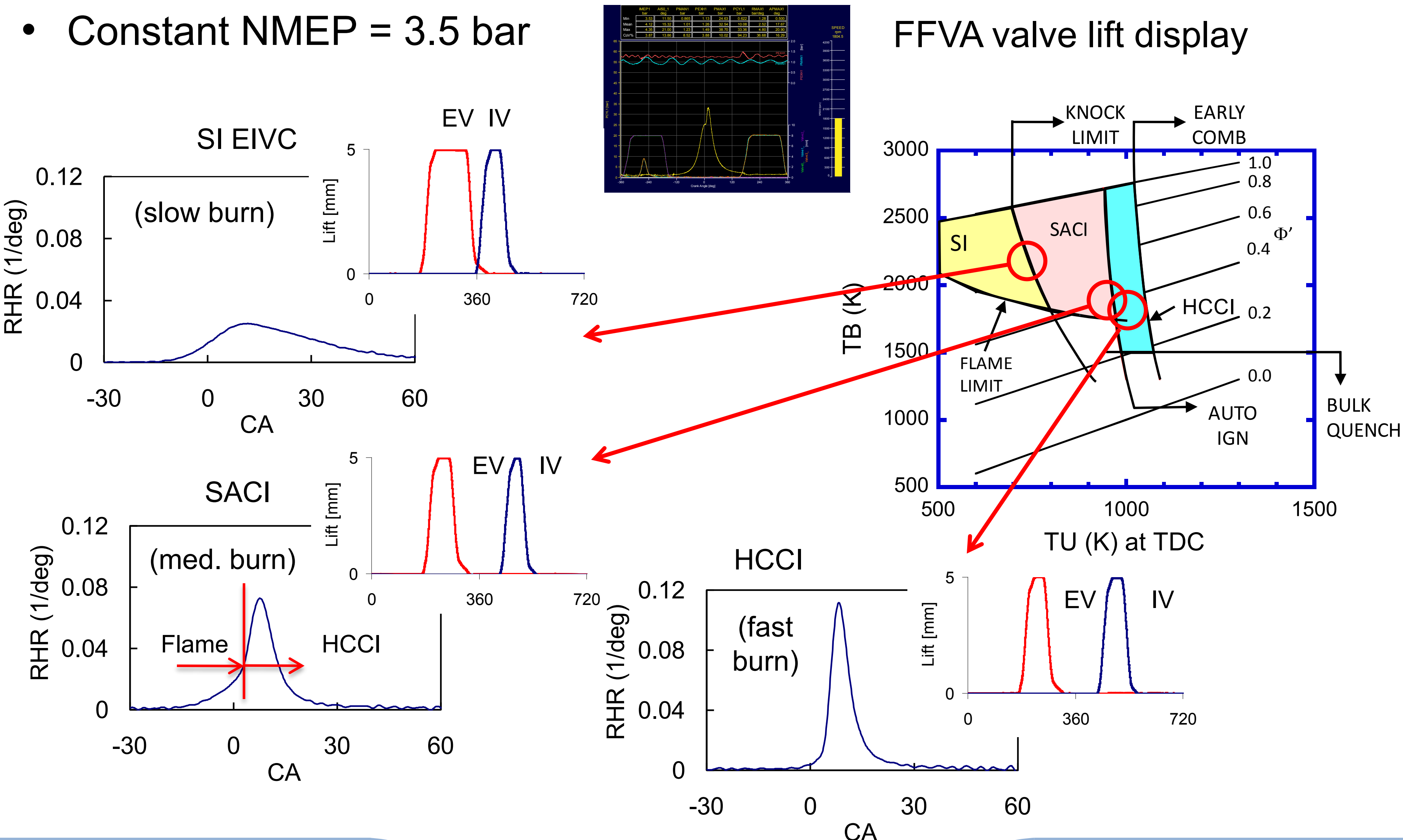


- Results with multi-zone HCCI model show improved agreement with CO trends of Sandia HCCI engine



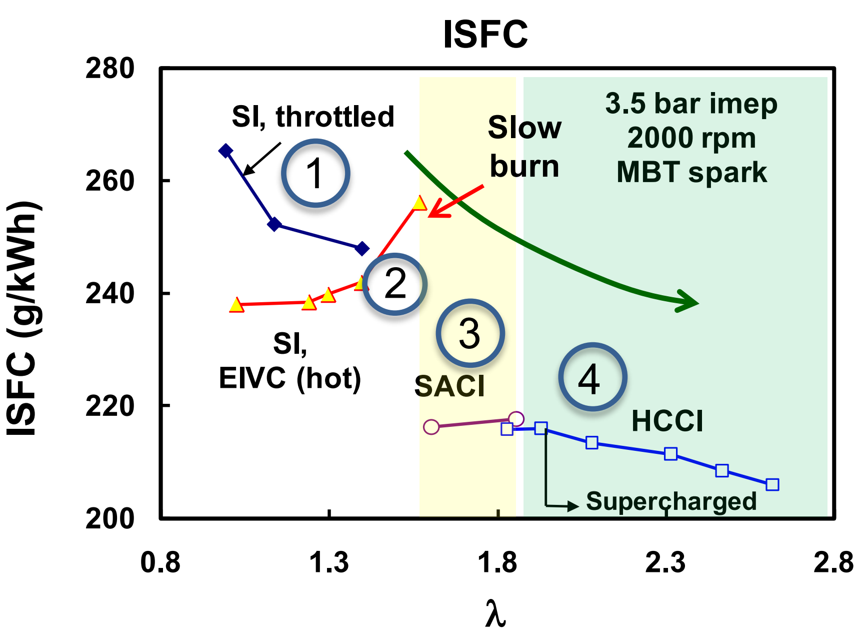
Identified 3 combustion regimes on Multi-Mode diagram with data from UM FFVA engine

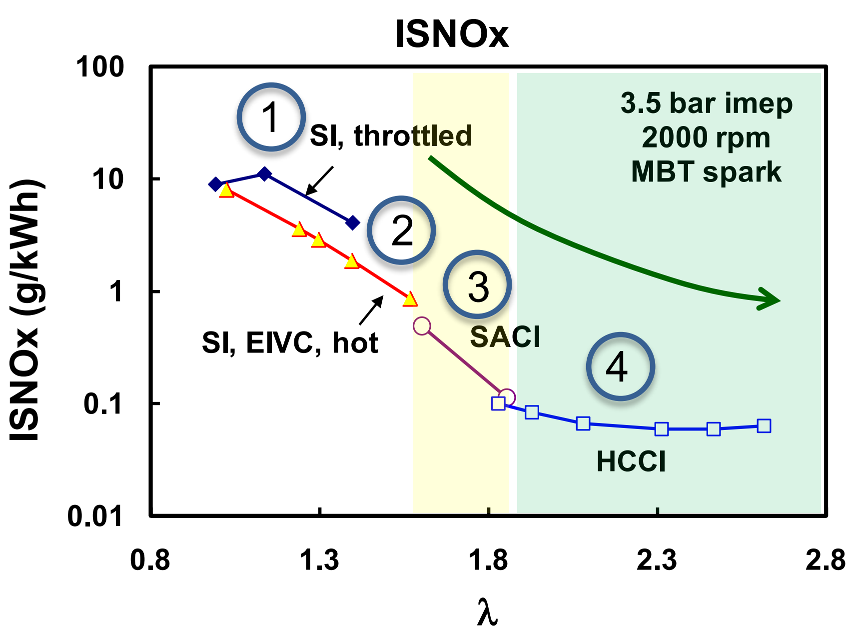
- Constant NMEP = 3.5 bar



SACI can bridge the gap between normal spark ignited combustion and HCCI

- Results confirm the efficiency and emissions benefits of lean combustion





Developed CFD model of SACI using new laminar flame speed correlations

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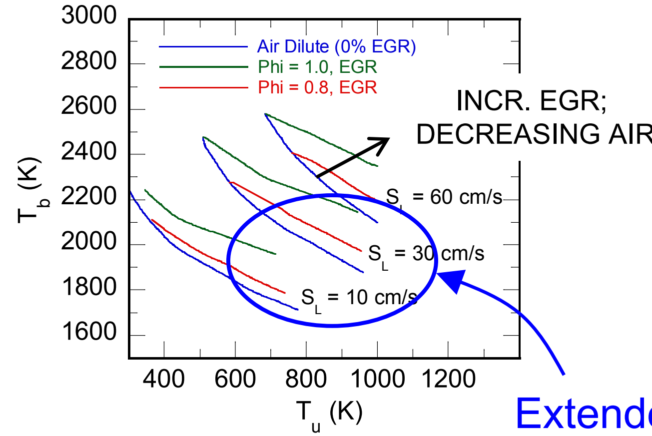
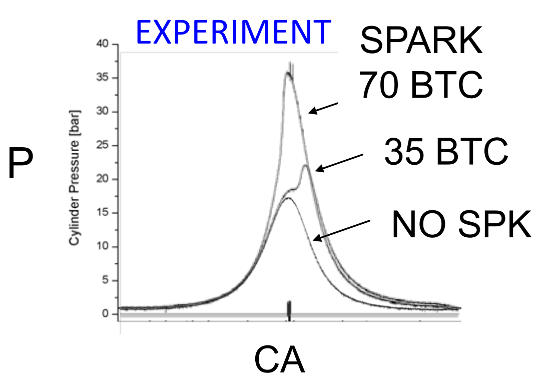
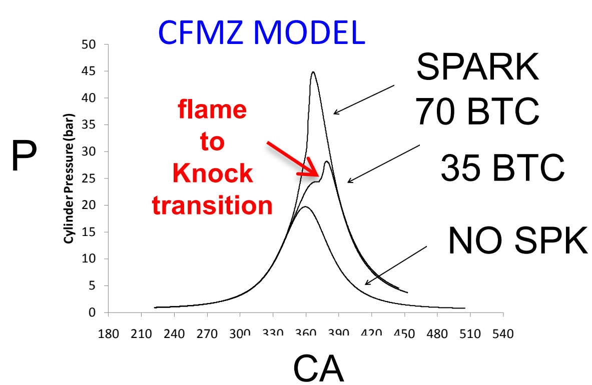
- Extended laminar flame speed data with 1-D unsteady simulations (HCT) and showed that
  - Ultra-lean laminar flames are viable provided the unburned temperature is high enough
  - EGR dilution requires higher T_U than air dilution for same flame speed (higher Cp)
- Developed Coherent Flamelet Multi Zone model (CFMZ) using extended laminar flame dataset
  - Initial results with CFMZ capture the deflagration and knocking combustion seen in previous SACI experiments at UM.

MODELED LAMINAR FLAME SPEED CONTOURS



Extended LTC regime Lean/dilute; high T_U

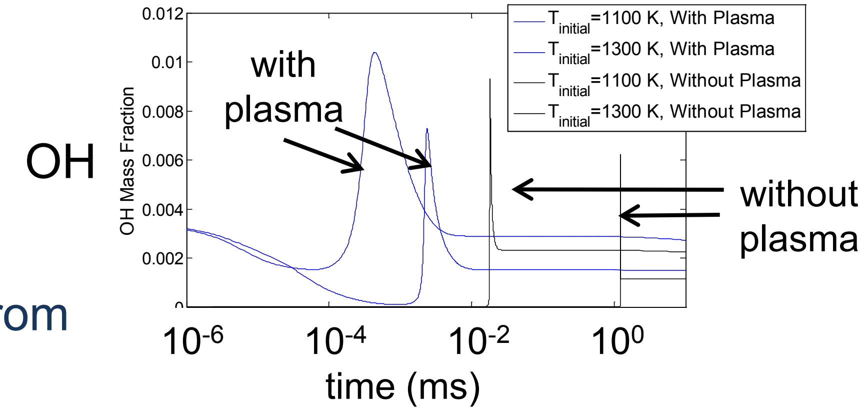




Modeled the effect of plasma on ignition delay

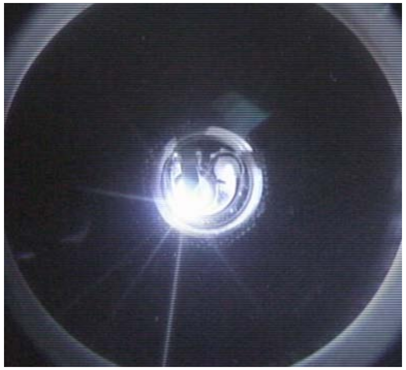
- Microwave Assisted Spark Plug/MWASP (UCB)
  - Modeling work shows that plasma decreases ignition delay.
  - Engine experiments are planned in CFR engine with upgraded igniter from Imagineering, Inc.

Ignition delay predictions with and without plasma



MW Assisted Spark Plug

MW enhanced plasma (0.1MPa)



Obtained RCF and optical engine data on n-dodecane and ethanol/indolene blends

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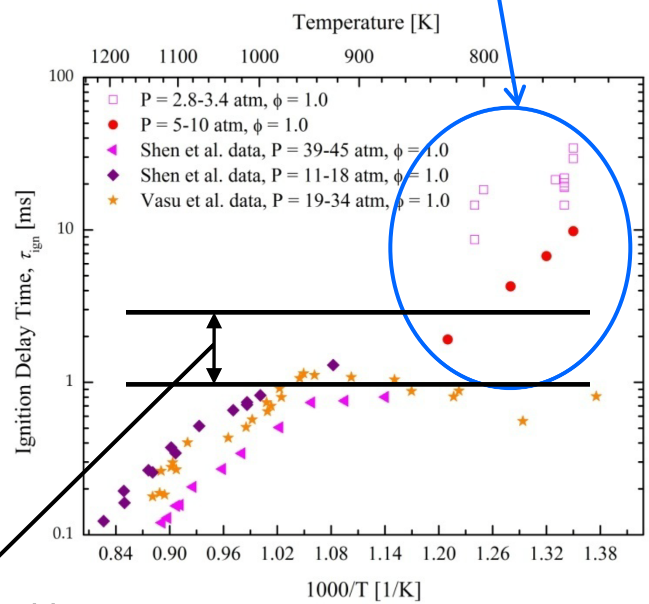
- RCF ignition delays for n-dodecane demonstrate significant negative temperature coefficient behavior (i.e. accelerated low temperature chemistry compared to high temperatures), and significant sensitivity to pressure
- The optical engine data with ethanol/indolene blends show fuel blend chemistry affects phasing
- Energy for ethanol vaporization is a dominant fuel characteristic affecting phasing and HRR.

UM RCF data – ignition delays for n-dodecane at moderate pressures (3-10 atm)



Required Ignition delay time for engines (1-3 ms)

Collaborations

- Initiated four year partnership with Bosch, AVL and Emitec to develop advanced control strategies for multi-mode combustion and associated aftertreatment
- Studying sensitivity of spark-assisted HCCI engines to range of market fuels; with BP and Ford.
- 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
- Collaborated with C. K. Westbrook and Bill Pitz (LLNL) on validating reaction mechanisms for long chain alkanes, small esters
- Currently working with Ford on the next steps towards changing 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.

Proposed work for FY10-FY11

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TASK

- Obtain data from FFVA engine: 1.
  - Calibrate GT-Power burn model for HCCI combustion mode
  - Determine boundaries of SI, SACI and HCCI with external and internal EGR
  - Set up engine for simulated boosted operation
- Set up system level methodology of FE assessment for various combustion modes

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- Set up MIT RCM for stratification studies and obtain first data 2.
- Continue KIVA subgrid modeling of fuel/thermal/stratification effects

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- Complete CFMZ model for SACI and apply to data from FFVA engine 3.
- Test experimental MWASP system and refine kinetic model

- Set up modified GM diesel engine for gasoline/ethanol fuel blends. Obtain initial data set. 4.
- Measure ignition delays of blends of NTC and non-NTC fuels in RCF at high pressures and moderate temperatures.
- Validate reaction mechanisms for blends of HC and oxygenates with Charlie Westbrook (LLNL)

Summary

- Analytical tools and experimental facilities developed in previous years are ready to apply knowledge gained to make progress toward the FreedomCar and VTP fuel economy goals.
- Work over last calendar year has:
  - Demonstrated full engine-in-vehicle fuel economy assessment tool
  - Developed improved CFD models of heat transfer/thermal stratification
  - Developed conceptual diagram to identify high pressure, lean burn combustion regimes for SI, SACI and HCCI.
  - Developed KIVA model of SACI combustion and extended range of computer based laminar flame speed data.
  - Demonstrated SI, SACI and HCCI operation in new FFVA engine
  - Obtained new ignition delay data for n-dodecane and ethanol/indolene blends in RCF