A University Consortium on Low Temperature Combustion (LTC) for High Efficiency, Ultra-Low Emission Engines

Participants

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Acknowledgements

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Sandia National Labs
Lawrence Livermore National Laboratories
Industry Partners: Borg Warner, Bosch, BP, Ford Motor Company, General Motors

DOE Vehicle Technologies Program Annual Merit Review
Washington, D.C., May 18-22, 2009

Overview

TIMELINE

- Start – Jan 2006
- Finish – June 2009
- 85% finished

BUDGET

- Total project funding ($3,748k)
- Funding FY08 ($1,240k)
- Funding FY09 ($947k)

BARRIERS ADDRESSED

- Extend operating range of LTC
- Develop strategies for exploiting LTC for optimal FE benefits
- Investigate ignition timing control
- Explore fuel effects on LTC operation

UNIVERSITY PARTNERS

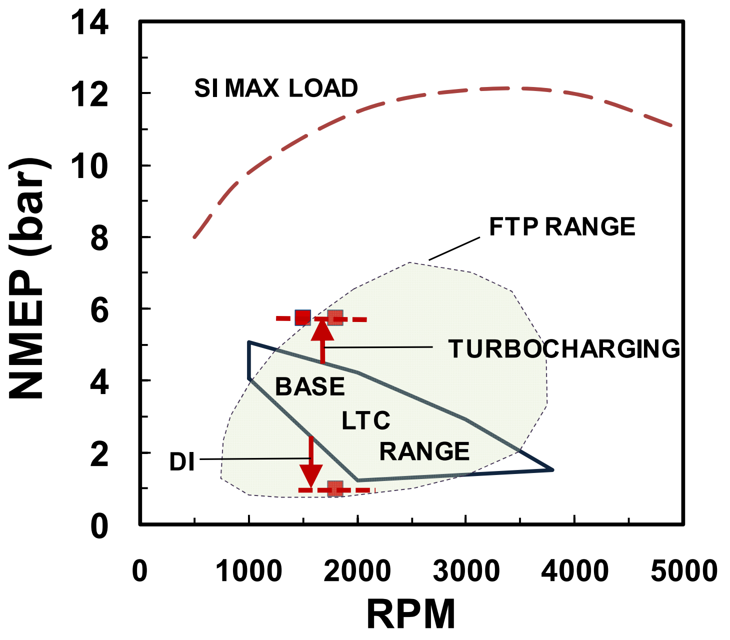
- UM (lead)
- MIT
- UCB
- STANFORD

COLLABORATION

- Sandia National Lab
- Lawrence Livermore National Laboratories
- General Motors
- Borg Warner
- Bosch
- Ford Motor Company
- BP

Objectives

- Expand the operating range of LTC engines at both high and low loads
- Investigate methods of achieving improved combustion control
- Investigate effects of stratification on autoignition and combustion
- Determine kinetics of alternative fuels and blends and optimize HCCI operation with such fuels.



Milestones

ENGINE MODELING
- Kiva – burn correlations
- Develop GT model
- Applications

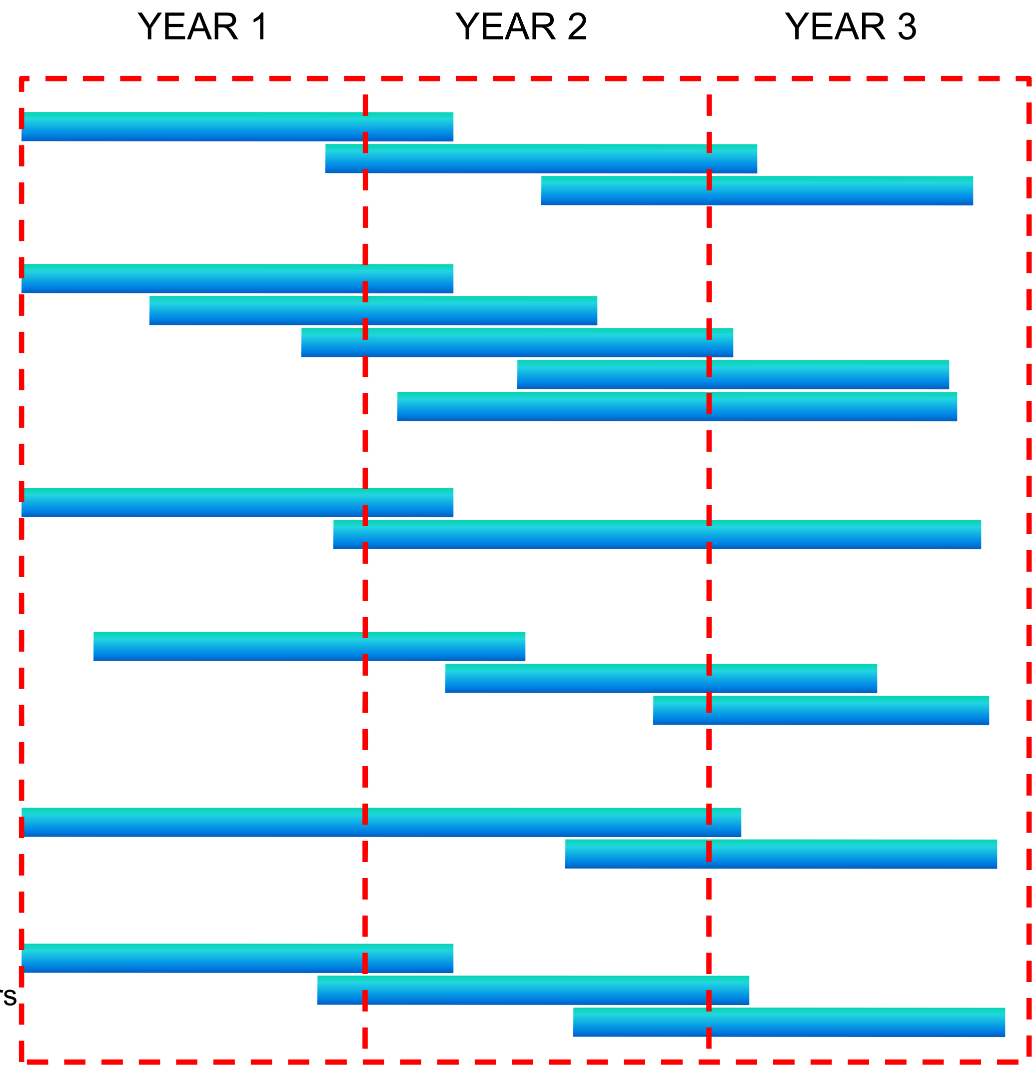
HCCI LOAD LIMITS
- Establish N.A. limits
- Low load – DI effects
  - -- Kinetic modeling
- High Load - Boosted

WALL EFFECTS
- Twall/Tin effects
- Deposit effects

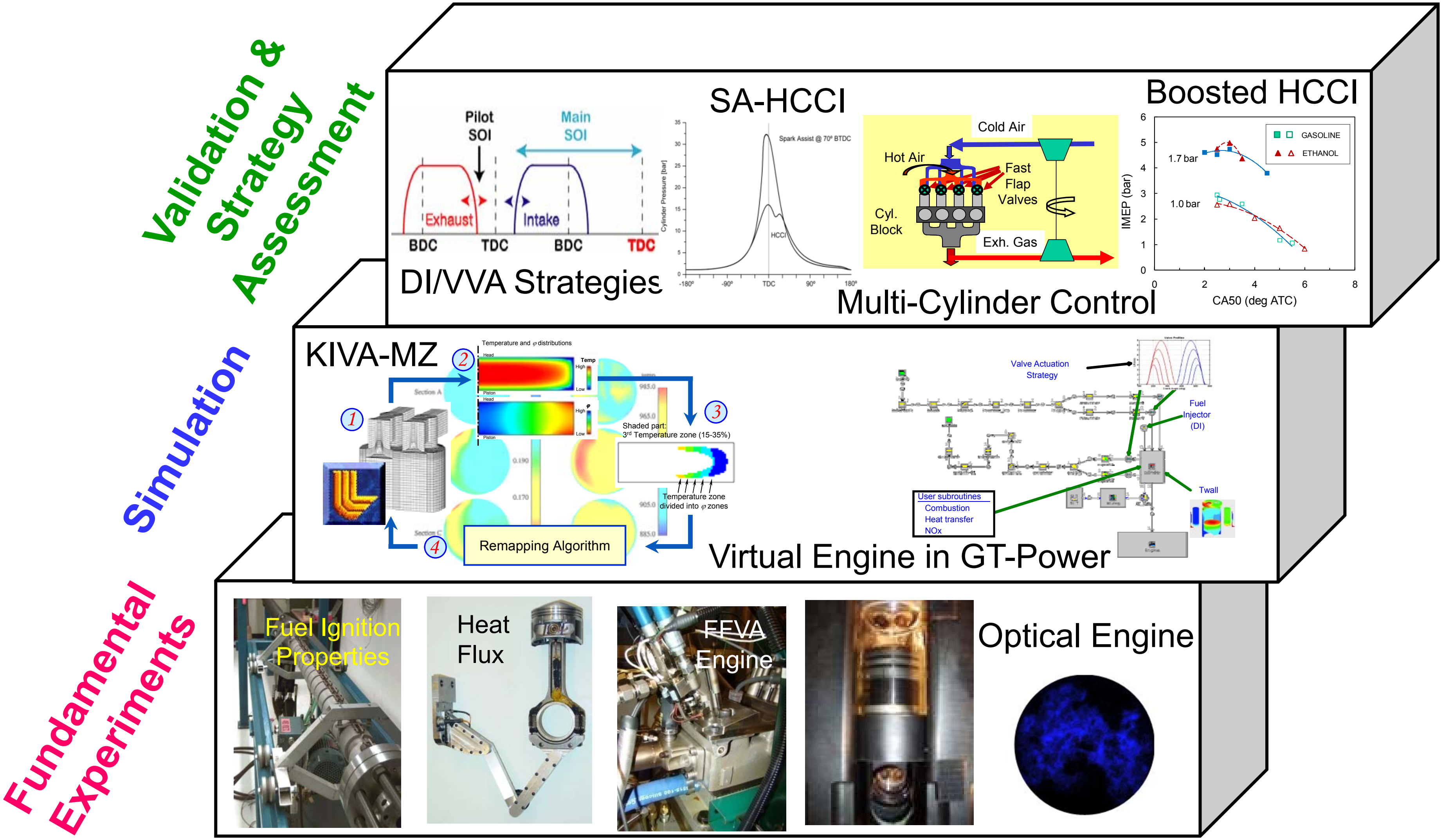
SPARK ASSIST
- Acquire images with SA
- Model lean, high T lam. Flames
- Develop KIVA SACI model

DI - STRATIFIED CHG MODELS
- Flamelet modeling
- DNS studies

CHEMISTRY/KINETICS
- Measure Ignition delay for biofuels
- Validate LLNL model for small esters
- Sampling valve experiments



Approach



Validation & Strategy Assessment
Simulation
Fundamental Experiments
Pilot SOI
Main SOI
Exhaust
Intake
BDC
TDC
BDC
TDC
DI/VVA Strategies
SA-HCCI
Spark Assist @ 70° BTDC
HCCI
Cold Air
Hot Air
Fast Flap Valves
Cyl. Block
Exh. Gas
Multi-Cylinder Control
Boosted HCCI
GASOLINE
ETHANOL
1.7 bar
1.0 bar
IMEP (bar)
CA50 (deg ATC)
KIVA-MZ
Temperature and φ distributions
Shaded part: 3rd Temperature zone (15-35%)
Temperature zone divided into φ zones
Remapping Algorithm
Valve Actuation Strategy
Fuel Injector (DI)
User subroutines
Combustion
Heat transfer
NOx
Twall
Virtual Engine in GT-Power
Fuel Ignition Properties
Heat Flux
FFVA Engine
Optical Engine

Unique Range of Engine Facilities

UM Optical Engine
(SA-HCCI and Fuels)

UM Heat Transfer Engine
(Thermal Management)

UM Camless Engine
(Multi-Mode Combustion)

Stanford Camless Engine
(DI and Controls)

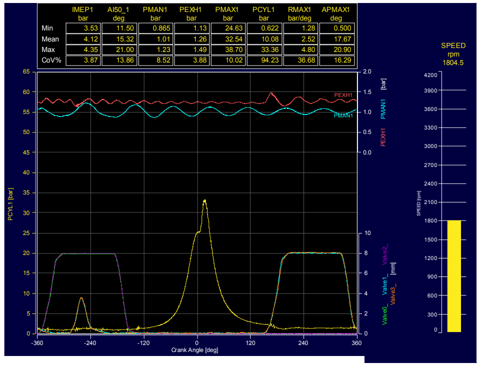
MIT Camless Engine
(Boost and Mode Transitions)

UCB Multi-cylinder Engine
(Boost and Controls)

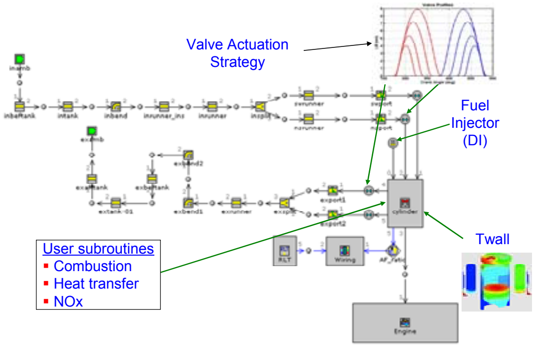
Integrated high fidelity model and camless engine test cell for HCCI FE assessment

- Developed a fundamentally based HCCI combustion simulation model for use with GT-Power®.
- Model was used to compare different valve strategies for a naturally aspirated HCCI engine subject to NOx, knock and misfire constraints.
- Camless SCTE has been setup and is being used for model validation and strategy assessment.

Fully flexible valve actuation (mechanism by Sturman Industries)



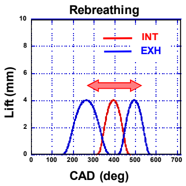
GM STURMAN INDUSTRIES BorgWarner



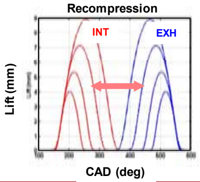
MODEL PROJECTIONS

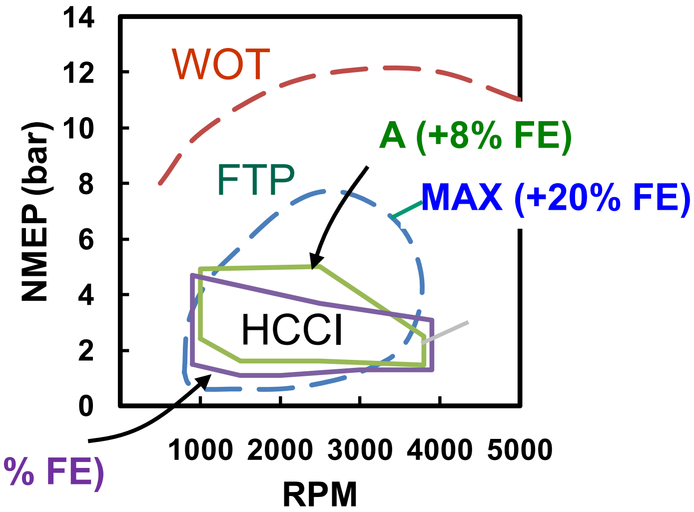
VALVE STRATEGY	TYPE	GAIN
A	Rebreathing	~8 %
B	Recompression	~11 %
MAX	Max. potential	~20 %

A



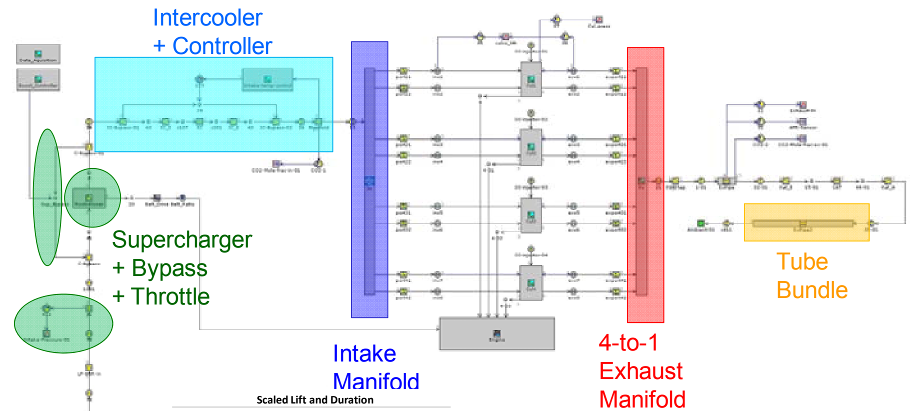
B

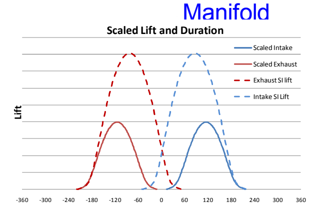




Explored effect of intake pressure on high load limit

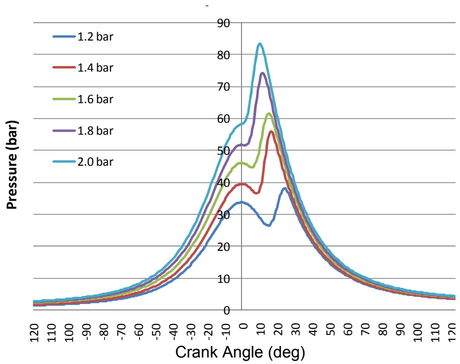
- Used GT Power model with UM developed combustion correlation to investigate the potential of increased intake pressure for extending high load range.
- Ringing intensity criterion can be satisfied by decreasing Φ as boost pressure is increased

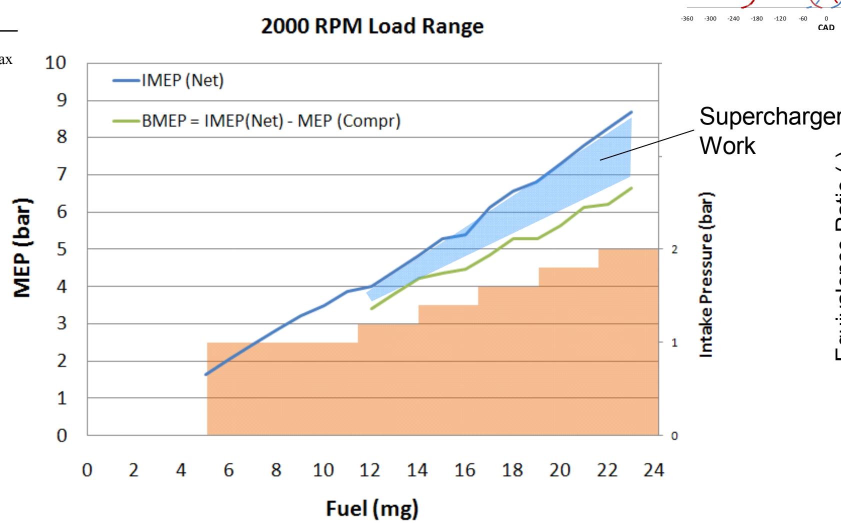


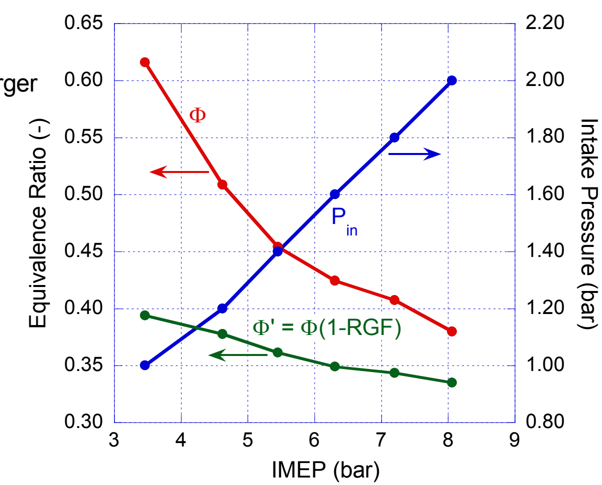


Recompression for residual gas retention and combustion phasing control

$$\text{Ringing intensity} \approx \frac{1}{2\gamma}\frac{\left(\beta \frac{dP}{dt}_{max}\right)^2}{P_{max}}\sqrt{\gamma R T_{max}}$$

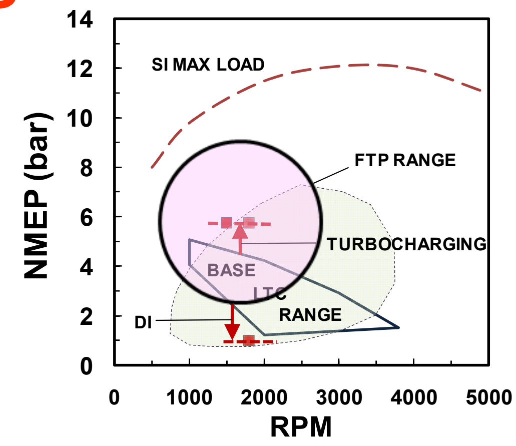






Demonstrated increased load limit in engine experiments

- Net IMEP's of above 6 bar achieved in the lab
- CA50 must be retarded to decrease ringing intensity, while avoiding misfire
- Further load gains may be possible through leaner operation at higher boost



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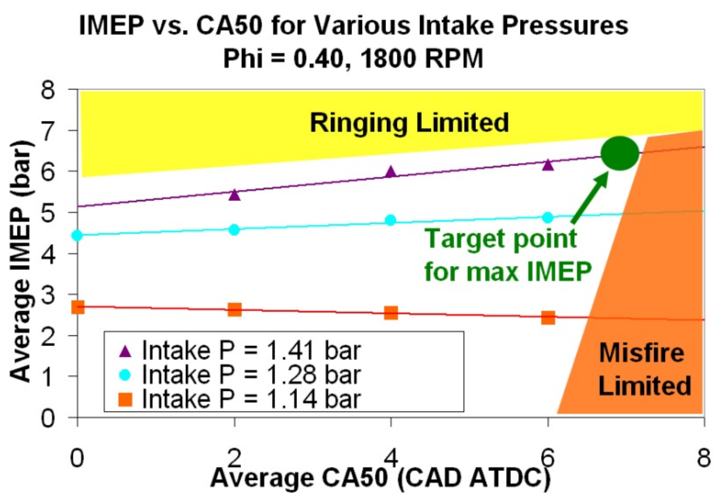
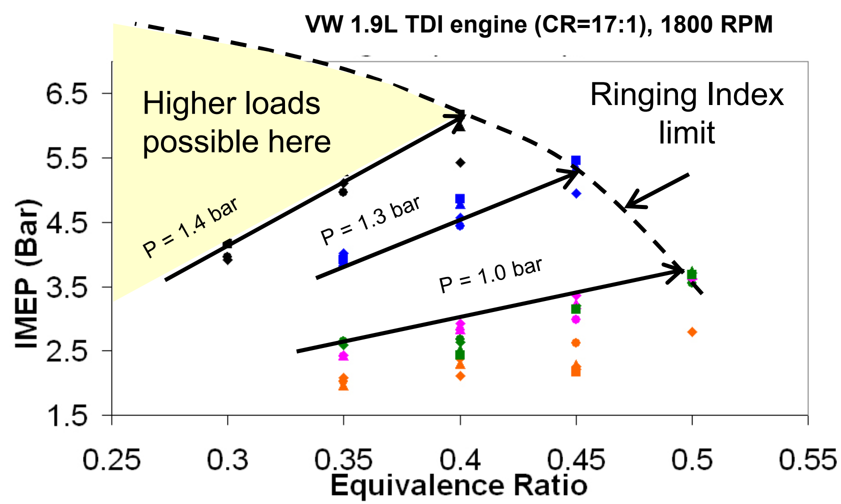


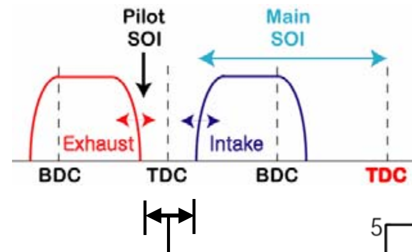


More fuel, but even more air!

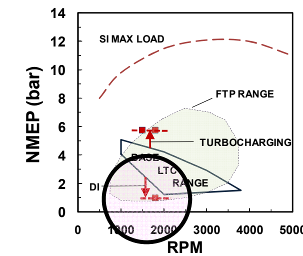
Extended low load limit with DI during NVO

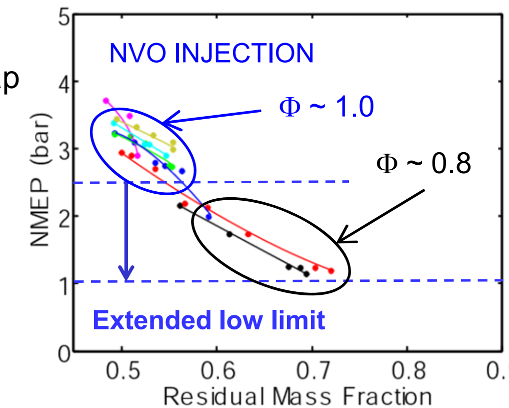
- Low load extended to 1 bar NMEP by injecting fuel during negative valve overlap (NVO) and leaner operation to induce recompression reactions
- Observed advanced combustion phasing and better cycle stability
- Model studies show maximum effect on ignition occurs with $\Phi \sim 0.8$ and moderate exothermicity

EXPERIMENT

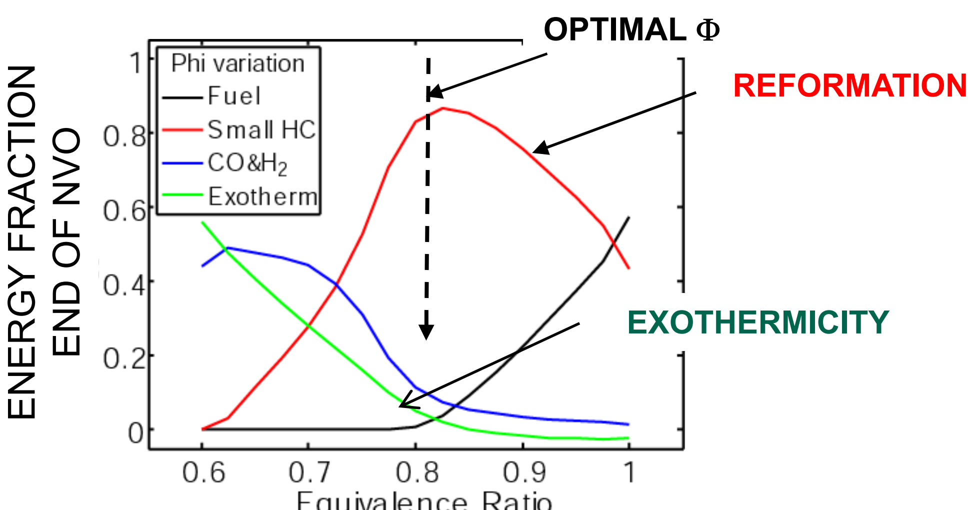


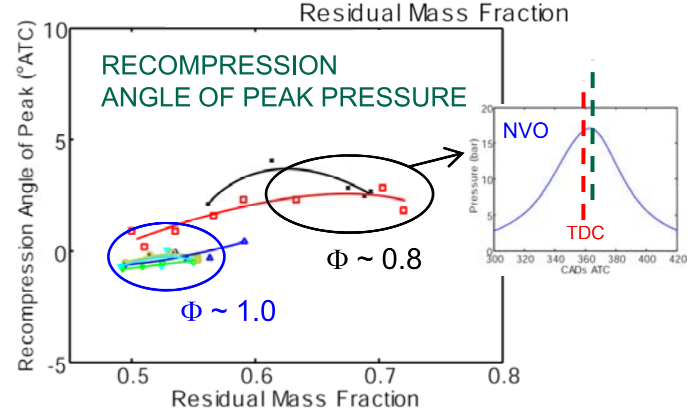
Negative Valve Overlap (NVO)





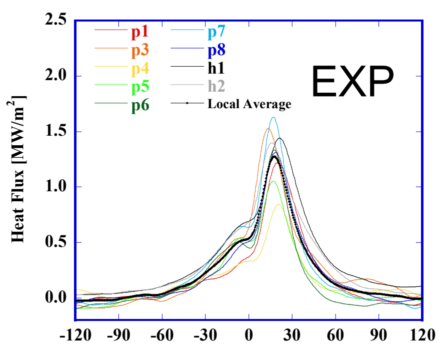
MODELED REACTIONS DURING NVO

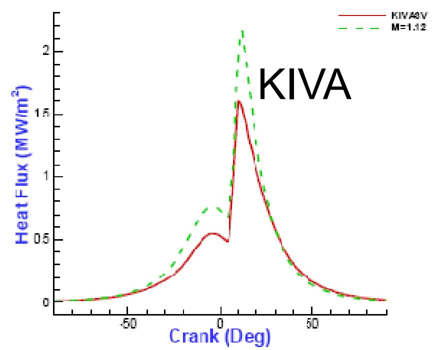




Determined the effect of near-wall thermal conditions on HCCI limits

- Increased combustion chamber wall temperature or presence of the thermal barrier on the wall extends the low load limit
- Surface temperature measurements with fast thermocouples enable determining:
  - Time-varying boundary conditions, with or without deposits

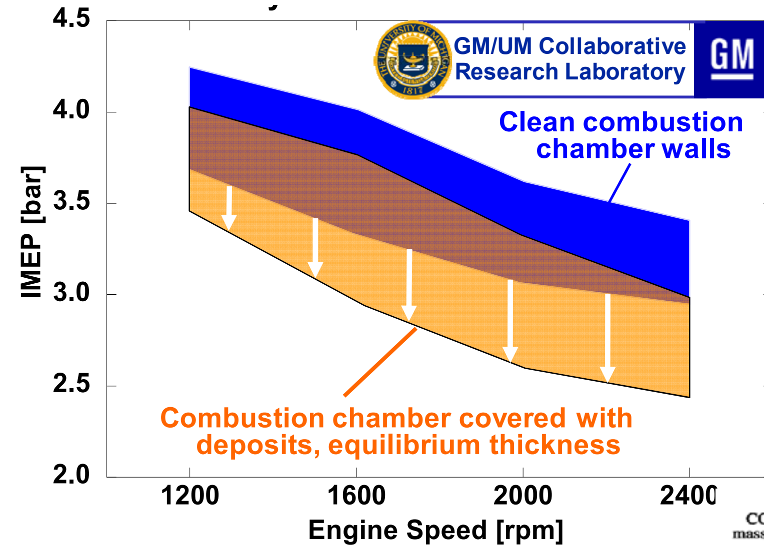


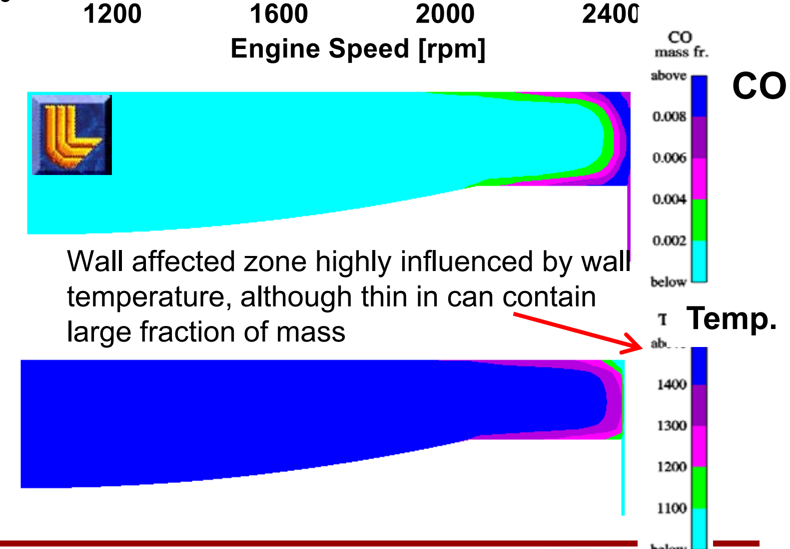


- Coupled heat transfer experiments with CFD modeling of boundary layer effects to provide:
  - In-depth insight into thermal stratification
  - Guidance for developing HCCI range expansion

HCCI Operating Range

Single-cylinder gasoline HCCI with re-induction of residual, fixed exhaust cam lift, 2000 rpm. Experimental work performed with UM/GM CRL funding

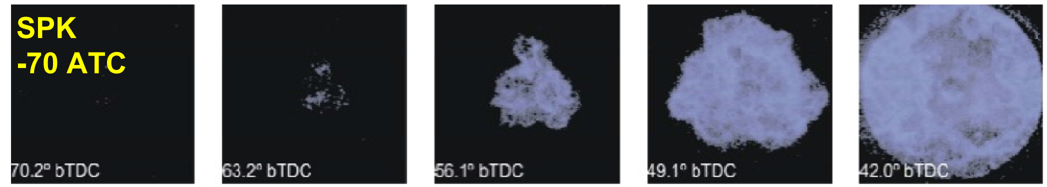




Insight gained on spark assisted HCCI (SACI) with optical engine

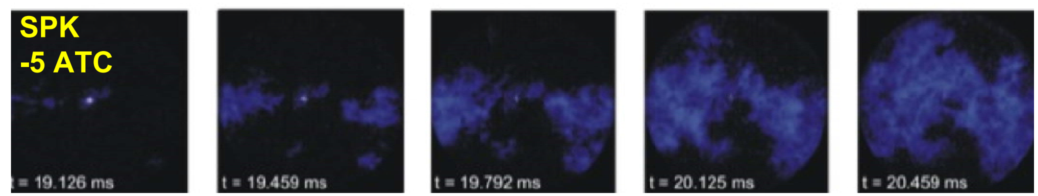
- Spark assist with high load (Φ ~0.6) and low T is dominated by flame type behavior
- Without spark, images show similar reaction fronts but much slower overall combustion

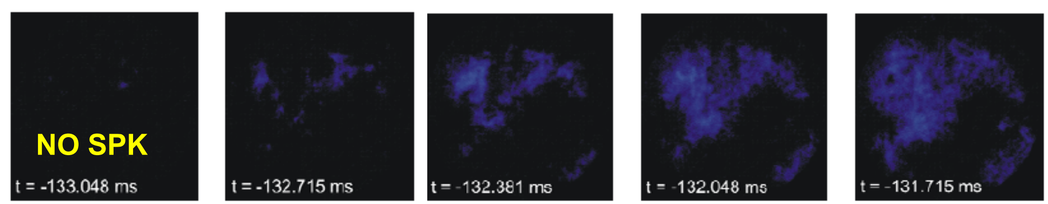
HIGH LOAD (Φ=0.62); LOW Tint (271C)



- Spark assist with low load (Φ ~ 0.4) and high T shows mixed mode combustion
- Without spark, combustion is slower and less stable

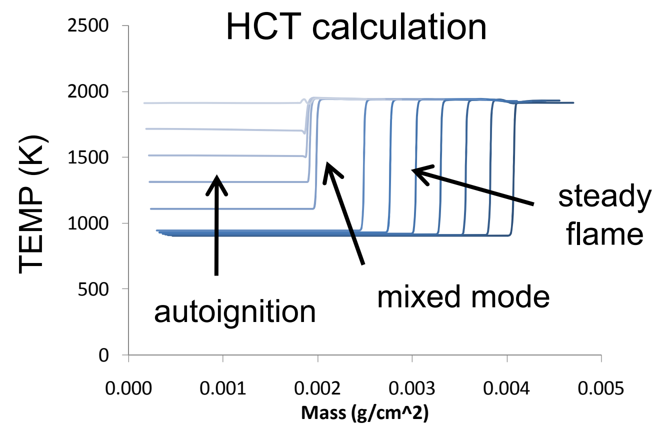
LOW LOAD (Φ=0.40); HIGH Tint (321C)



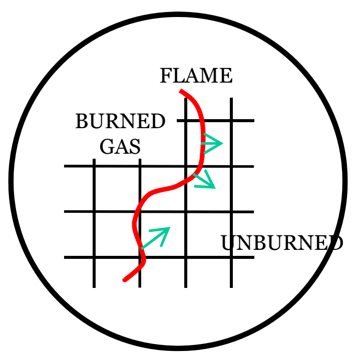


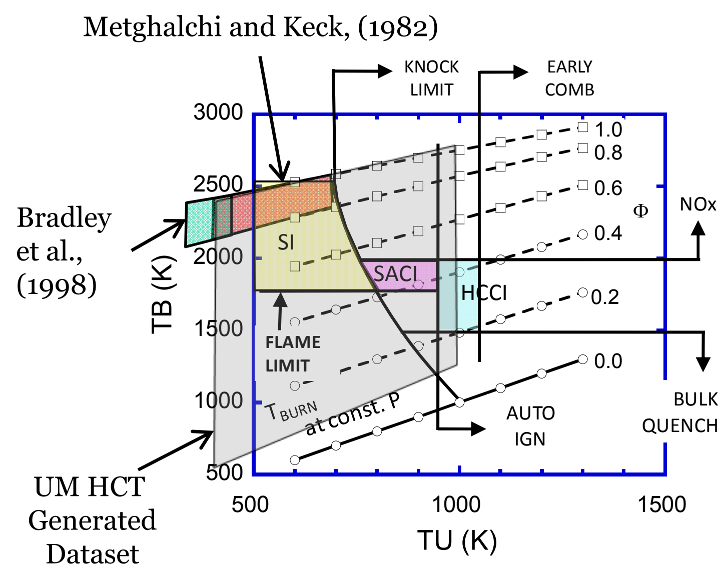
Extended model based laminar flame data for application to HCCI and SACI ranges

- Transient flame code (HCT) showed that autoignition and flame propagation are largely independent processes
- Used HCT to establish database of flame speeds beyond range of available experimental data
- Flame speeds (SL~20-40 cm/s) appear robust enough for flame propagation in SACI and HCCI regions (consistent with optical engine observations)
- KIVA model nearing completion based on wrinkled laminar flame combined with autoignition



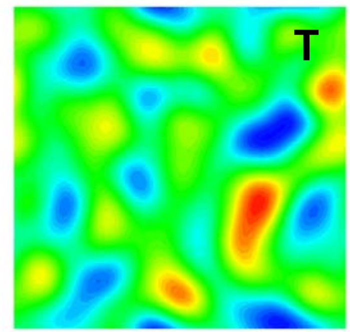
KIVA
SACI
MODEL





Investigated autoignition in LTC engine environments with DNS

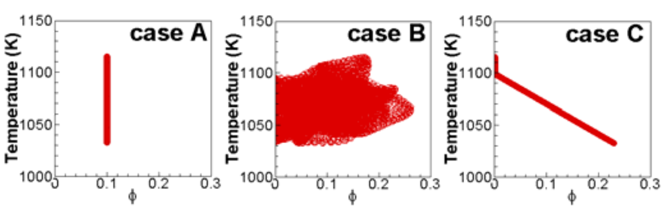
- Small scale effects of T-Φ correlations on autoignition and front propagation studied using DNS
- Most stratified case displays most spatially distributed reactions and burns faster, while homogeneous and uncorrelated cases exhibit reaction fronts and longer burn durations



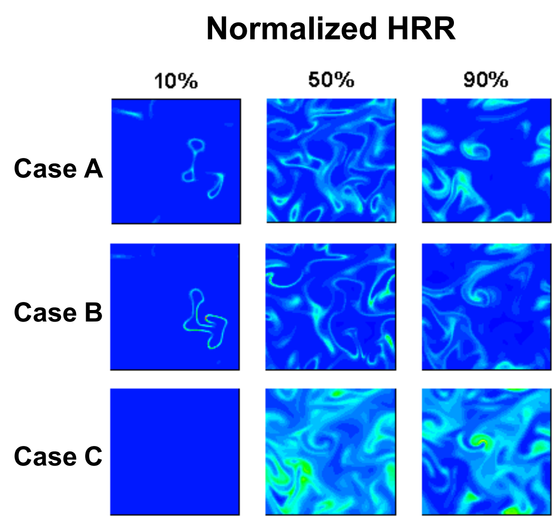
- Domain: 4.1mm x 4.1mm (960 x 960)
- Detailed chemistry of H_2
- P = 41 atm
- Prescribed random turbulence field (u' = 0.5m/s, L_{11} = 0.34mm)
- Prescribed random temperature field (T_{mean}=1070K, T'=15K)

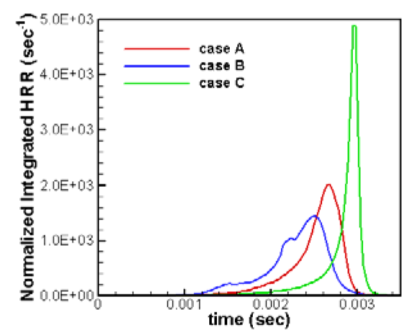
Effects of SOI on mixture formation at TDC:

- Premixed – constant Φ (case A)
- Early SOI – uncorrelated T-Φ fields (Case B)
- Late SOI – negatively-correlated T-Φ fields (Case C)



Initial Conditions





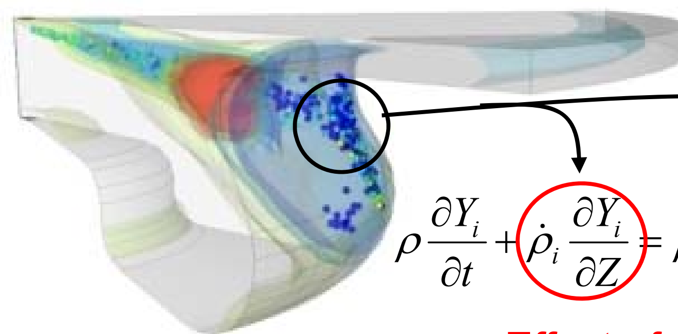
Ignition delay: case C > case A > case B

Peak heat release: case C > case A > case B

Studied effect of DI stratification on LTC

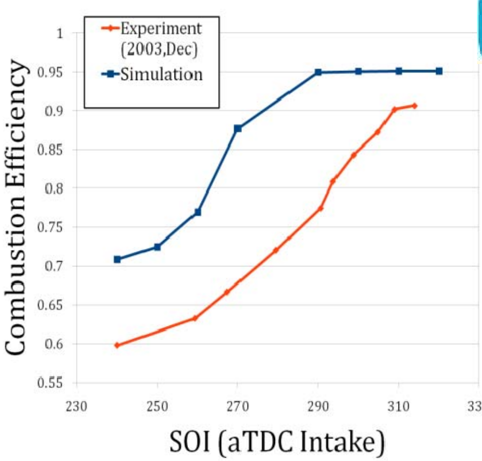
- Developed KIVA- RIF-ER model, which considers the effect of evaporation in the reaction space for accurate modeling of LTC/DI combustion
- Demonstrated model capability by matching experiments (Dec,2003)
- Studied effect of stratification on spatial CO production under low load conditions

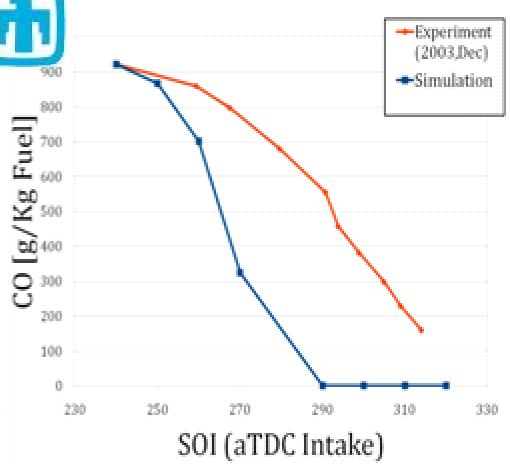
Effect of evaporation included in the reaction space

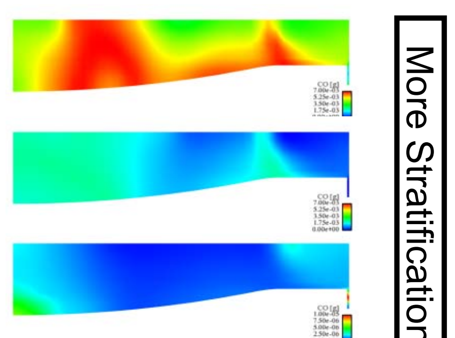


$$\rho \frac{\partial Y_i}{\partial t} + \dot{\rho}_i \frac{\partial Y_i}{\partial Z} = \rho \frac{\chi}{2} \frac{\partial^2 Y_i}{\partial Z^2} + \dot{\rho}_i + \omega_i$$

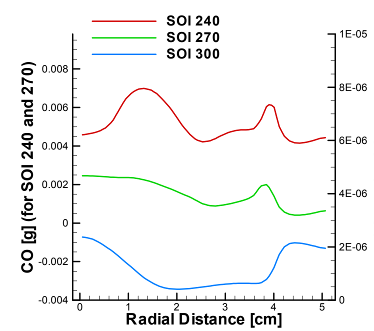
Effect of evaporation







CO Contour at TDC
With different stratification level

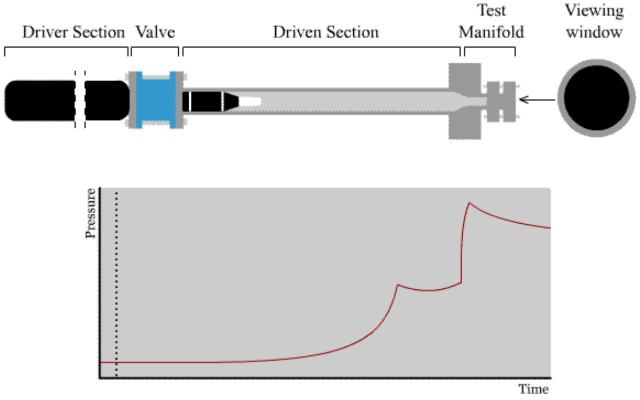


High stratification: Near Wall
Low stratification: bulk gas

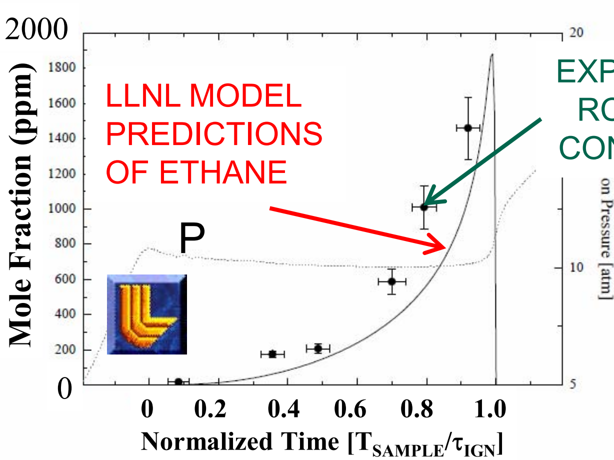
Determined ignition properties of biofuels and fuel blends

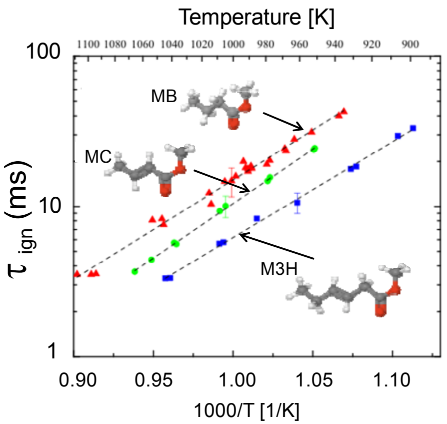
- Measured ignition delays for 3 small biofuel esters (basic components of typical biofuels) and found a factor of 3 variation in delay times
- Speciation studies of the ester methyl butatnoate (MB) were conducted and the key reaction pathways identified.
- There was excellent agreement between the reaction mechanism developed by Westbrook, Pitz and co-workers at LLNL
- Identified non-linear behavior for methyl trans-3-hexenoate (M3H) and n-heptane blends
- Results indicate that biofuel blends could be designed with targeted levels of HCCI reactivity

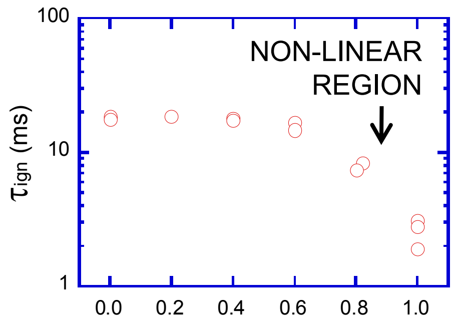
Rapid Compression Facility



METHYL BUTANOATE AUTOIGNITION



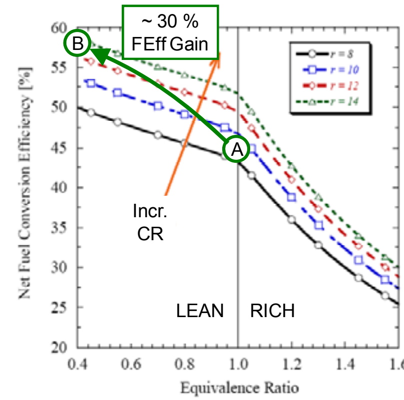


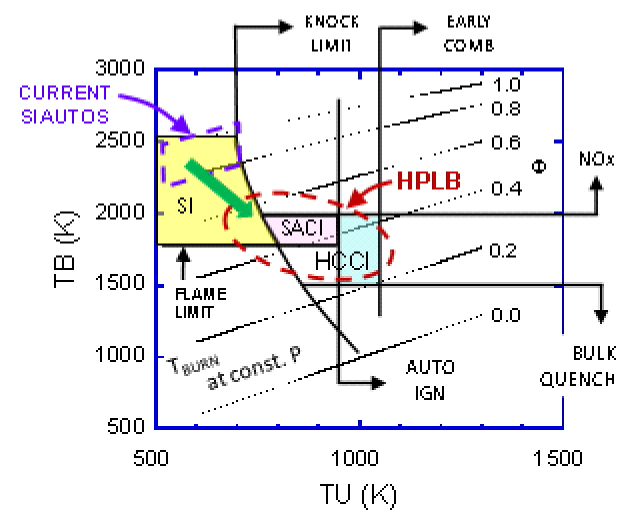


n-Heptane in M3H

Future Work

- Focus on High Pressure – Lean Burn path toward overall fuel economy gain of 20-40%
  - Application to downsized and boosted engines
  - Lean burn and high temperature for thermodynamic gains
- Determine ways to use fuel and thermal stratification interactions for improved combustion
- Explore fuel blends and their effect on combustion limits
- Investigate and demonstrate the benefits of multi-mode combustion methods (SACI, DI) for combustion control
- Use full range of models developed in previous years (CFD, system, etc) to maintain close connection between experimental work and final, in-vehicle results, including thermal and other transients





Summary

- We have a well developed and balanced approach to the research task
  - Full range of modeling tools from fundamental (flame, kinetic, CFD) to system level (GT power)
  - Excellent selection of experimental engine facilities (single cylinder, multi-cylinder, rapid compression facility)
  - Tools now available to fully focus work on achieving large fuel economy benefits
- We have accomplished our objectives for the project so far
  - Demonstrated FE potential of candidate valve strategies
  - Extended low load limit to 1 bar NMEP by DI during NVO
  - Extended high load limit to 6 bar NMEP by boosted, dilute operation
  - Demonstrated controllability improvement with spark assist and showed multi-mode combustion by propagating reaction fronts and autoignition
  - Obtained fundamental ignition data for biofuels and fuel blends for optimizing fuel/engine interactions
  - Used DNS to show that stratification can effect ignition and heat release depending on nature of T, Φ correlation
  - Demonstrated combustion control by fast thermal management on multi-cylinder engine