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

Participants

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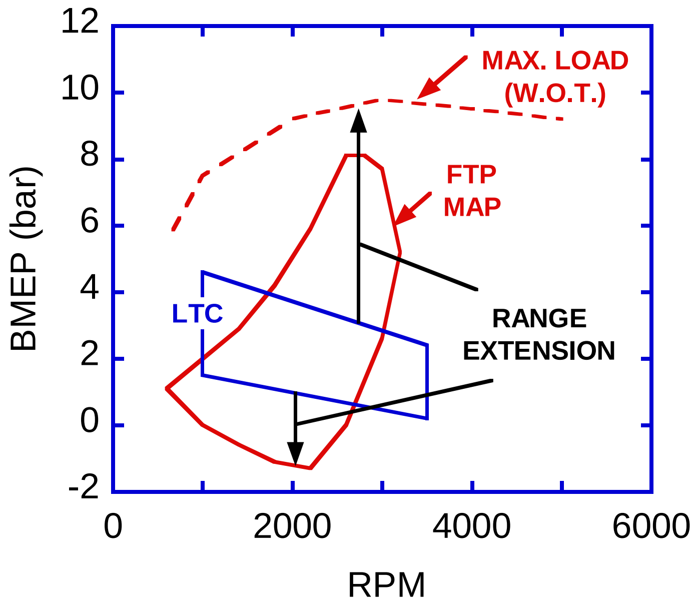
University of California, Berkeley (UCB): Jyh-Yuan Chen, Robert Dibble

Acknowledgements

DOE LTC Consortium project DE-FC26-06NT42629
Sandia National Labs
Lawrence Livermore National Laboratories
Industry Partners: Borg Warner, Bosch, BP, Ford Motor Company, General Motors

Purpose

- Expand the operating range of LTC engines at both high and low loads
- Improve LTC system fuel economy benefits subject to emission constraints and new fuel requirements
- Implement HCCI in gasoline engines and overcome barriers to their use
- Explore transient issues and controls
- Use fundamental understanding and insights to develop practical solutions and transfer to industry
- Develop and use virtual HCCI model to identify most likely path for efficient stable HCCI operation and focus on that path



Response to Previous Year Reviewer's Comments

- "How will modeling be used to investigate the proposed ideas and which models will be used?"
  - Fundamental understanding has been captured in models: KIVA-MZ for predictions of combustion efficiency, burn rates and emissions. GT-power based HCCI system model for strategy assessment.
- "Need to focus on specific select solutions in addition to providing wide understanding"

  "Beyond identifying barriers, what can be done to expand the operating range"

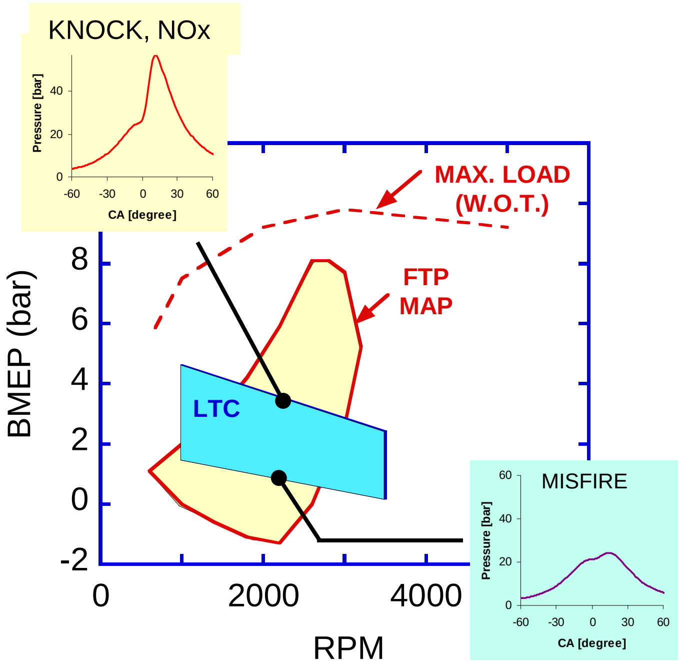
  "Show the strategy and estimates for what the technology will achieve"
  - We are focusing on advanced strategies for expanding the HCCI operating range: DI, VVA, Spark-Assist, Thermal Management , Boosting, Fuel Blending. Recent model and experimental developments will allow fuel economy estimates over driving cycles.
- "Need to collate and compare information from the various test rigs"
  - There is division of labor for the experimental setups and simulation tools are used to integrate the knowledge gained in the labs.
- "Emphasize multicylinder controls"
  - Being addressed at UCB.
- "Need to strengthen connection with industry and technology transfer"
  - Industry connection and tech transfer have been significantly strengthened. Monthly meetings with GM, Bosch and Borg Warner. Students hired by industry (e.g. 5 by GM, 2 by ORNL, 1 by Sandia).
- "How can the program be leveraged to help with diesel fuel work and what might transfer?"

  "It is unclear where the team is going with the bio-fuels work"

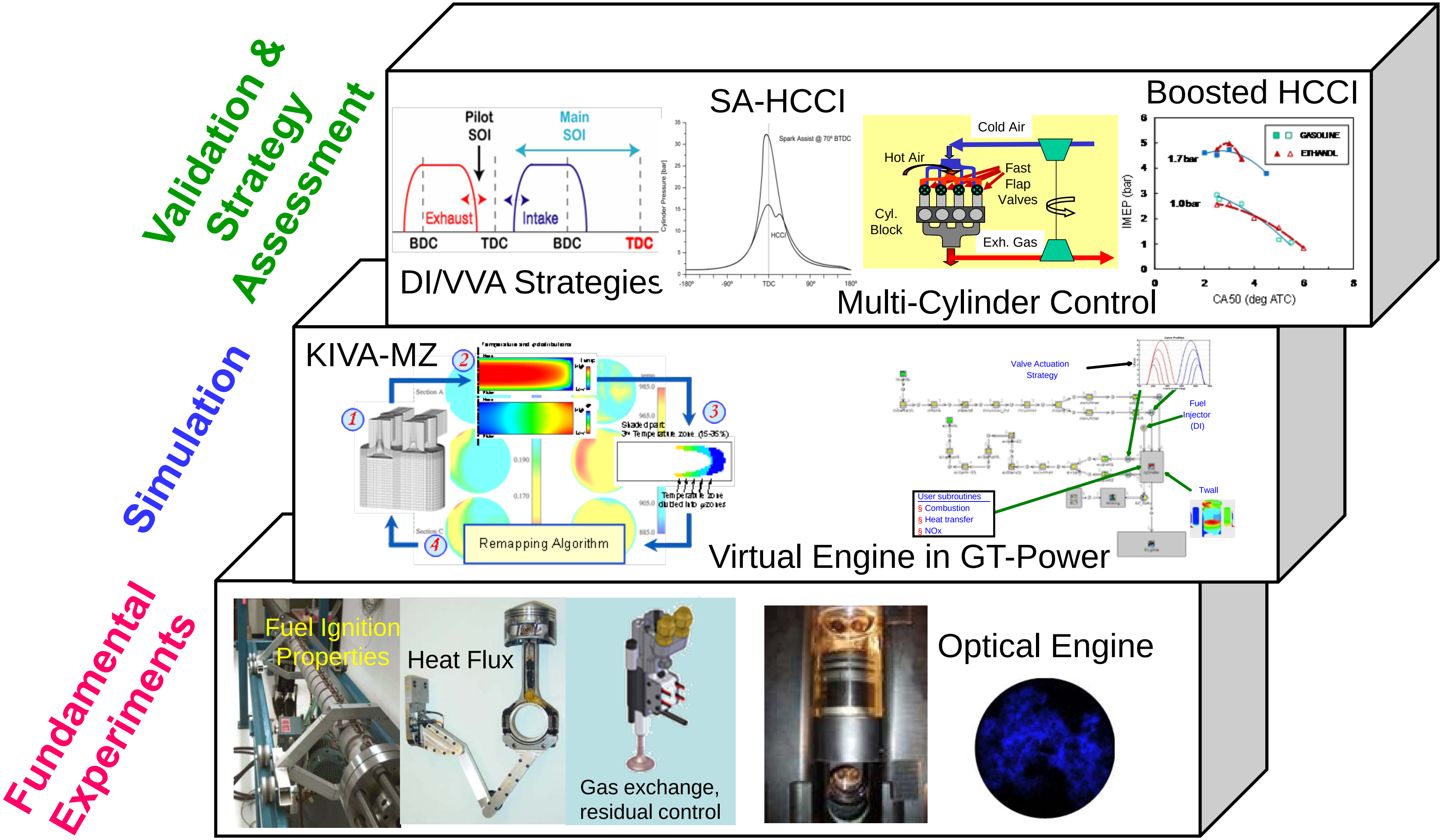
  "Why is aftertreatment modeling in the program?"
  - Bio-fuels kinetics and aftertreatement modeling work has been published and is directly relevant to Diesel LTC. Gasoline HCCI would benefit from blending with oxygenates. Dual-mode SI-HCCI engine would still require a TWC; will HCCI exhaust temperatures be sufficient for effective HC aftertreatment?

Barriers

- Operating range of LTC is limited by:
  - Knock and NOx (high loads)
  - Misfire/unstable combustion (low loads)
- LTC operation is sensitive to engine thermal environment, which affects combustion and engine controllability:
  - Load transients
  - Mode transitions
- Ignition characteristics depend on fuel composition



Approach



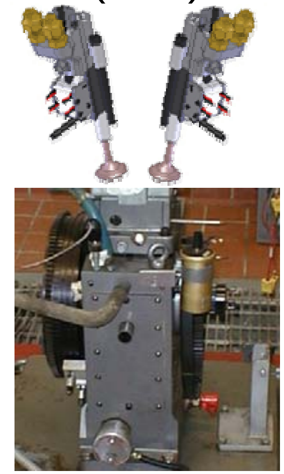
LTC University Consortium

Unique Range of Experimental Facilities

UM Optical Engine
(SA-HCCI and Fuels)

UM Heat Transfer Engine
(Thermal Management)

UM Camless Engine
(VVA)



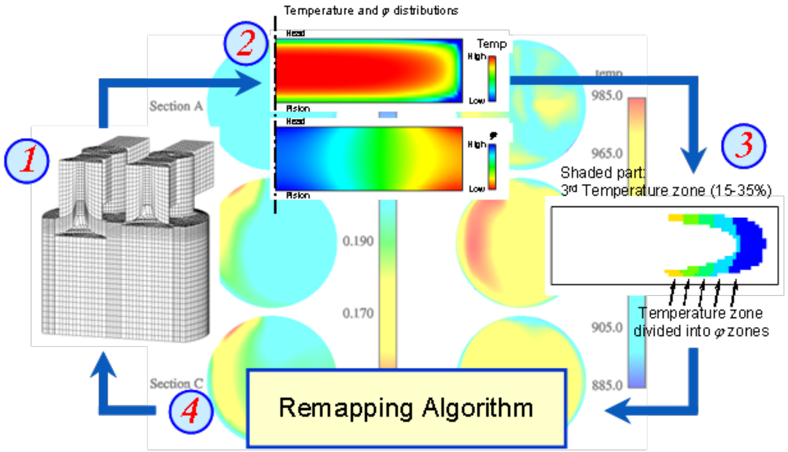
Stanford Camless Engine
(DI and Controls)

MIT Camless Engine
(Boost and Mode Transitions)

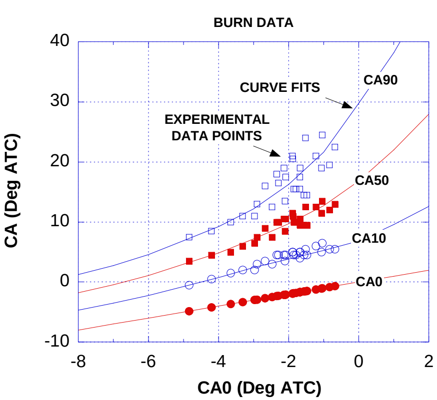
UCB Multi-cylinder Engine
(Boost and Controls)

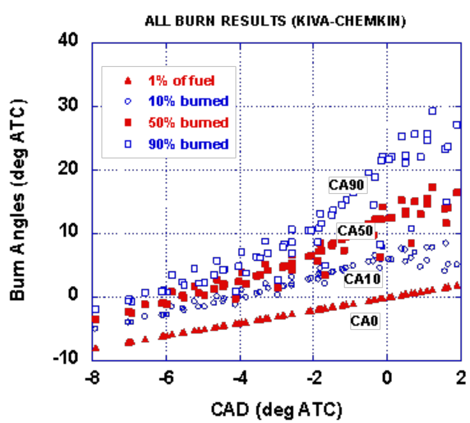
Developed Virtual HCCI Engine Simulator (UM)

KIVA-MZ

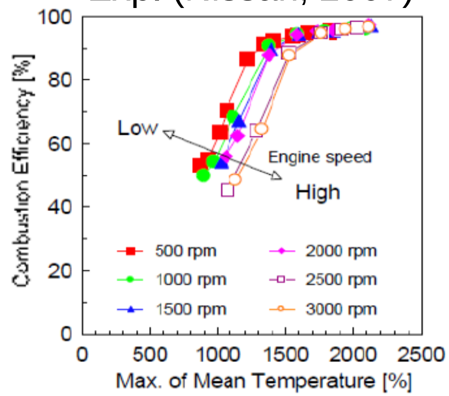


- Developed KIVA-Multi-Zone in collaboration with LLNL
- Used KMZ to develop burn rate and combustion efficiency correlations as a function of ϕ, speed, EGR, geometry
- Validated numerical predictions against experiments
- Incorporated combustion and heat transfer correlation into GT-Power to develop virtual HCCI engine system simulation

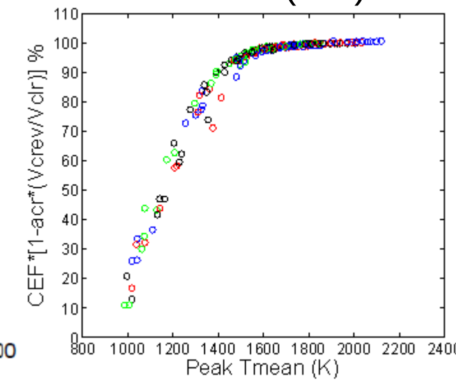




Exp. (Nissan, 2007)



Model (UM)



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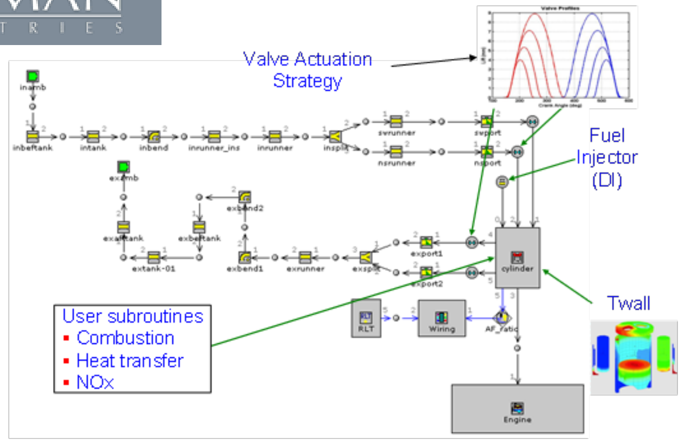
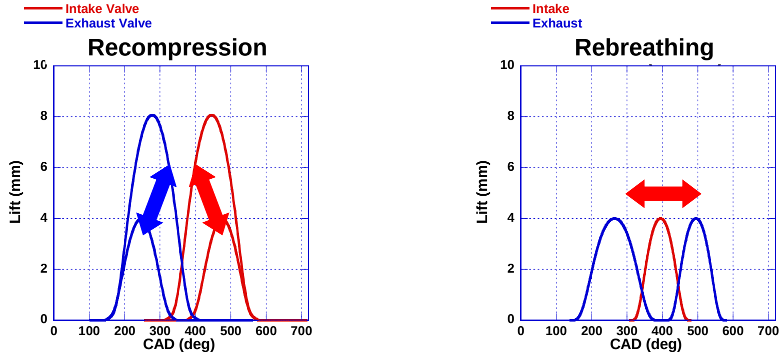
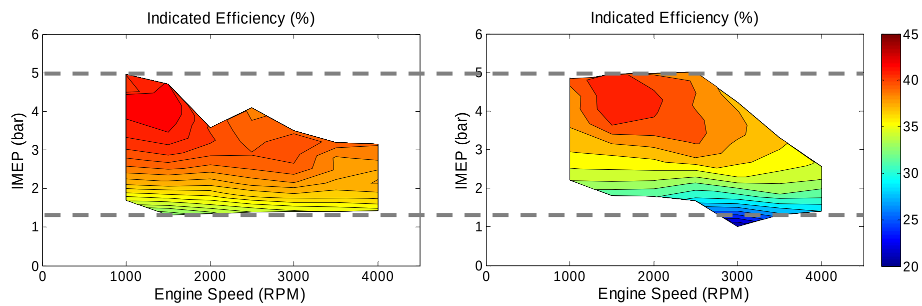
Development of VVA Strategies for HCCI (UM)

GM BorgWarner STURMAN INDUSTRIES

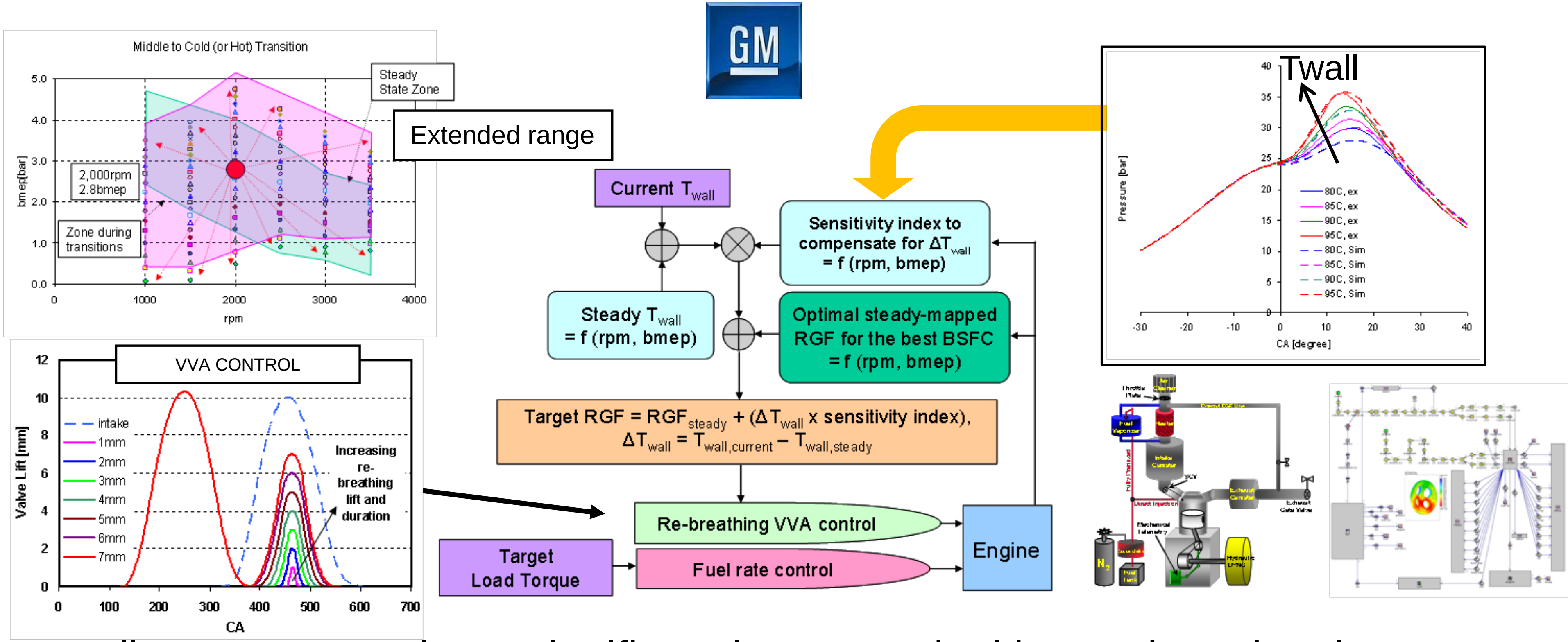
- Developed HCCI engine simulation tool based on experiments and chemistry/CFD modeling
  - Virtual HCCI engine can be used to generate speed/load maps for various operating conditions and VVA strategies
- Explored the potential of VVA strategies to extend the HCCI operating range
  - Demonstrated trade-offs which make recompression the strategy of choice for low load operation
  - Rebreathing is advantageous for high speed operation where it can extend the HCCI load limit to 5 bar NMEP







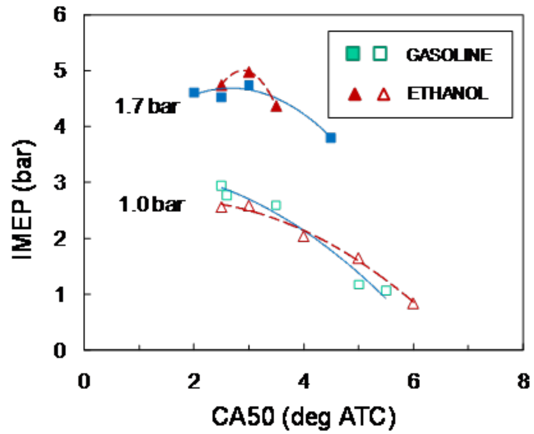
Wall Heat Transfer and Thermal Management (UM)

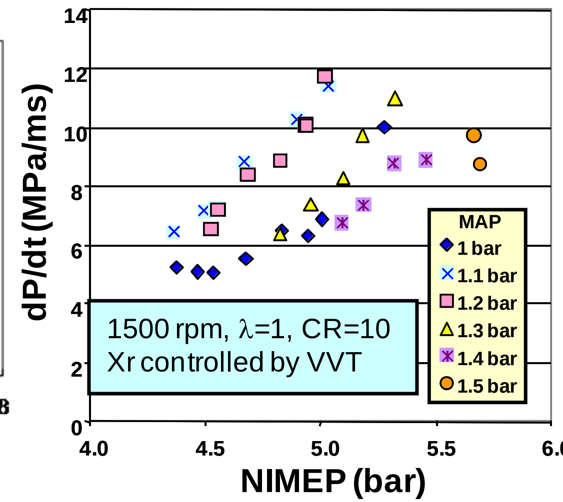


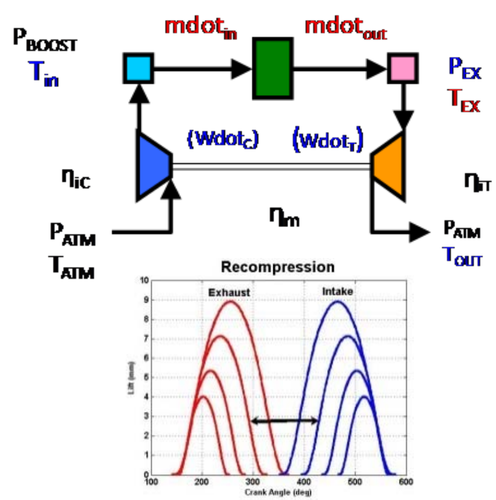
- Wall temperatures have significant impact on ignition and combustion
- Developed predictive simulation tool and used it to design a controller capable of maximizing HCCI operating limits
- Provided open-loop control capable of accounting for instantaneous thermal boundary conditions and avoiding misfire and knock during rapid transitions

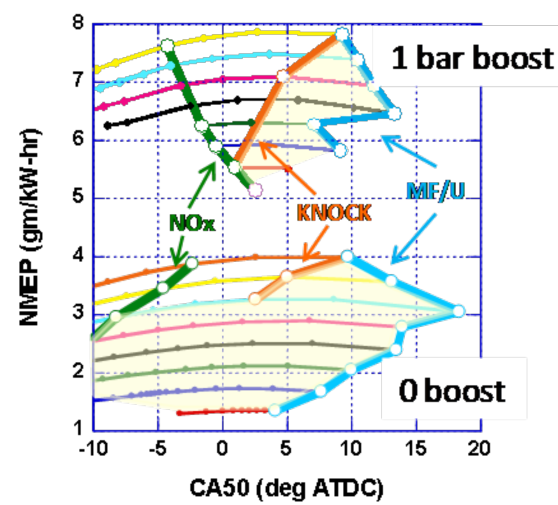
HCCI Operating Range Extension with Boost (MIT, UCB, UM)

- Demonstrated in the lab the potential of turbo-charging to expand the high load HCCI limit
  - Identified factors constraining the Maximum Pressure Rise Rate (MPRR) limit of LTC engines
  - Used gasoline and ethanol
  - Successful mode transition in boosted operation (HCCI→ SI)
- Linked virtual engine with turbocharger model
  - Evaluated performance of various VVA strategies under boosted conditions





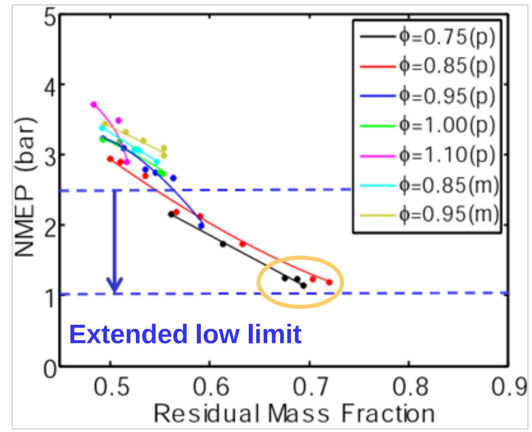


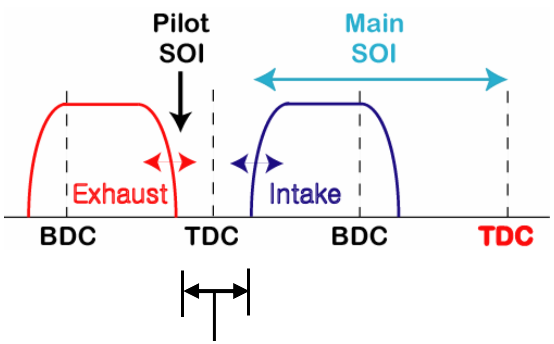


Direct Injection to Extend Low Load Limit (SU)

Experiments and simulations of recompression reactions

- Can achieve near idle HCCI operation with low UHC and NO emissions with fuel injected during NVO recompression
- Combustion phasing can be controlled with injection timing
- Exothermic reaction during NVO can be observed with pilot injection
- Simulations show extent of reforming reaction depends mostly on oxygen availability and in-cylinder temperature





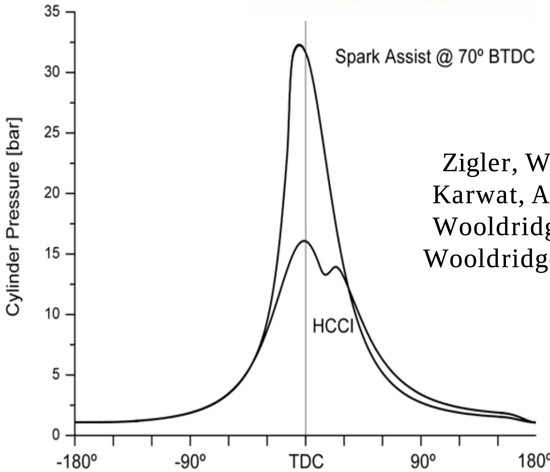
Negative Valve Overlap (NVO)

Stanford Camless Engine

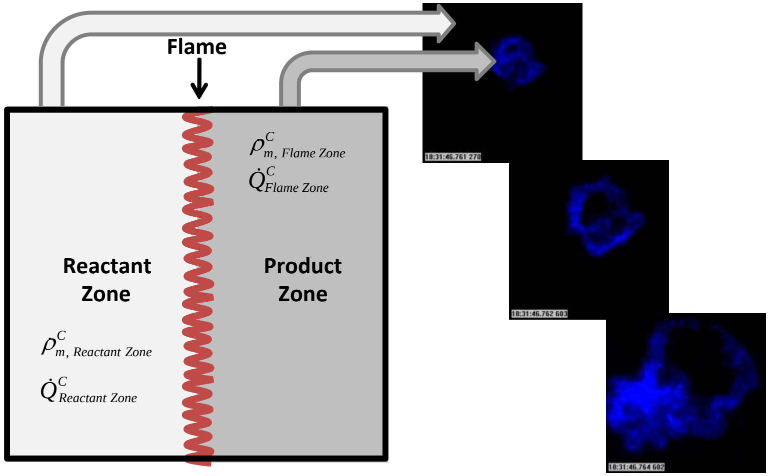
Spark-Assisted HCCI (SA-HCCI) for Enhancing Range and Control of LTC Engine (UM)

SA-HCCI has the potential to combine the thermal efficiency and emissions potential of HCCI with the extended operating range and simpler control of conventional engines

- Investigated spark assist as a means to
  - stabilize HCCI operation at low load
  - trigger volumetric ignition via compression resulting from a propagating flame front
- Single cylinder engine experiments successfully demonstrated that SA can significantly extend low load HCCI operation
  - Optical engine studies identify transitions in ignition regimes and provide speed of propagation of reaction fronts form model validation
  - Sensitivity studies quantified the level of control that can be achieved
- Currently developing sub-grid model for KIVA combining coherent flamelet model with autoignition chemistry



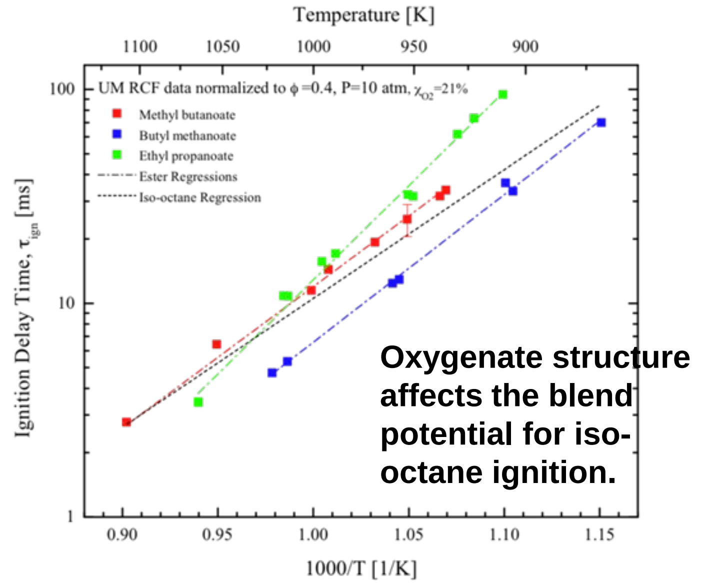
Zigler, Walton, Karwat, Assanis, Wooldridge, and Wooldridge, 2008



Bio-fuels and blends for use in LTC engines (UM)

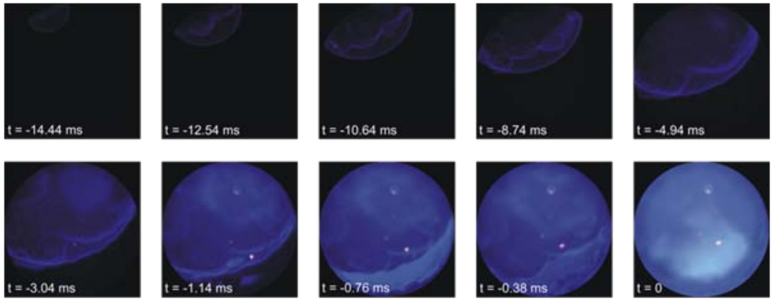
HCCI is tolerant to different fuel types; however, a predictive understanding of the fuel chemistry controlling ignition is critical to maintaining high engine efficiencies. Little is known about the chemistry of fuel blends or oxygenated fuels at low temperatures.

- Developed accurate reaction mechanisms for iso-octane and other key reference fuels and fuel blends in collaboration with LLNL
- Explored reaction kinetics of oxygenated compounds such as esters, that can be blended with gasoline to extend HCCI load limits or as alternative fuels in PCI engines
  - Oxygenated fuels showed dramatically different ignition behavior
  - Experimentally measured ignition times for methyl-butanoate that were 2x slower than original LLNL mechanism predictions and contributed to revised mechanism

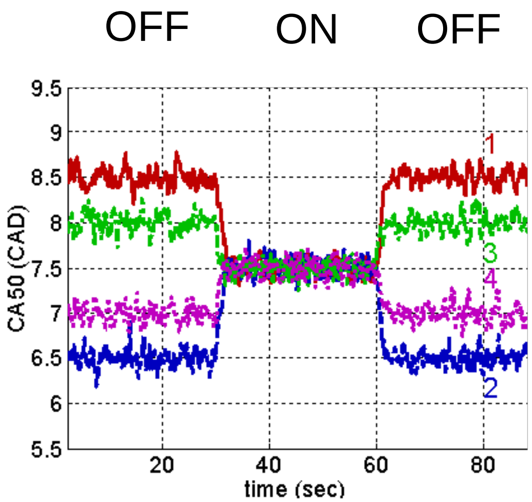


Oxygenate structure affects the blend potential for iso-octane ignition.

Walton, Wooldridge, and Westbrook 2008

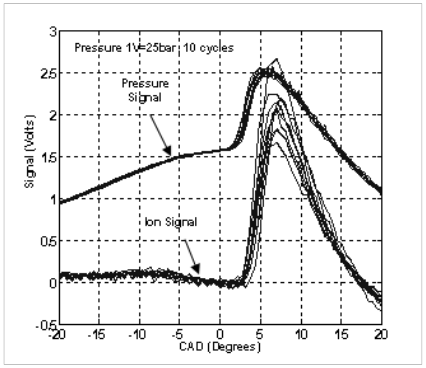


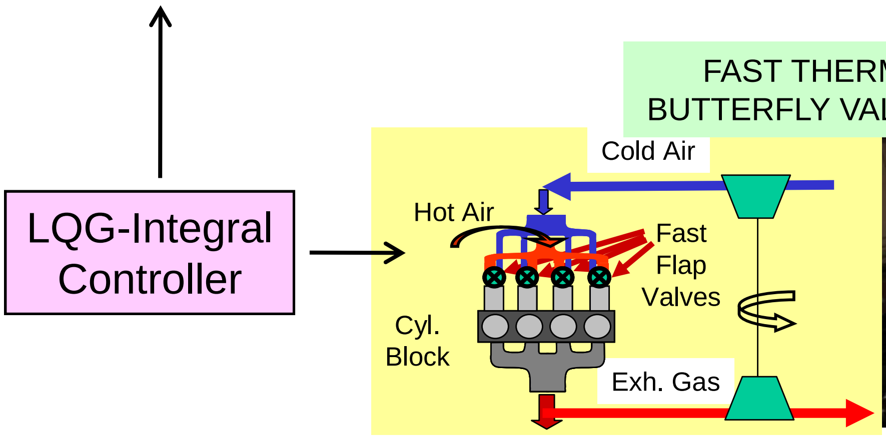
Multi-cylinder LTC Engine Control (UCB)



- Demonstrated individual cylinder control with throttlets and LQG controller
- Controller being applied to new fast thermal management valve system
- Developed and modeled ion-sensor technology for LTC

ION SENSOR





Technology Transfer

Auto engineers from Stanford, GM and Bosch team up to make leaner, cleaner engines

This summer Associate Professor J. Christian Gerdes received $2.5 million to work for three years with **General Motors**, the world's largest automaker, and **Bosch**, a leading manufacturer of automotive technologies, to speed the development of HCCI technology. The engines they develop could find their way into conventional or hybrid vehicles in less than a decade, says Gerdes.

Bosch's role in this partnership will be to focus on the control systems, sensors and actuators.

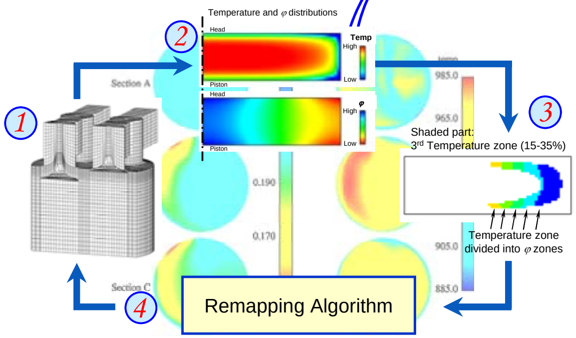
…However, stable and satisfactory operation of an HCCI engine is not possible without further development and sophistication of sensors, actuators and feedback control systems. The goal at the end of the day will be to suggest a complete engine controls solution that is both robust and cost effective.

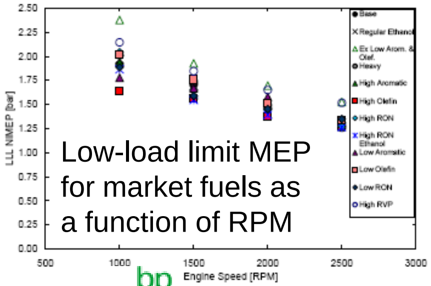
Dr. Rolf Leonhard, executive vice president, Engineering Gasoline Systems Division, **Robert Bosch GmbH**

Fundamental insight from experiments

Predictive simulation tools for control system development and thermal management

BOSCH





New York Times, Aug. 19th 2007

The New York Times

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TECHNOLOGY

Clean or Efficient? An Engine Goes for 'Both of the Above'

By LINDSAY BROOKE
Published: August 19, 2007

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MILFORD, Mich.

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FROM the outside, the dark blue Saturn Aura accelerating to a steady 50 miles an hour on the high-bank oval here at General Motors' proving grounds looked altogether unremarkable.

In fact, it was not much to look at under the hood either, despite an experimental engine using a method of burning gasoline that may prove to be the next major advance in fuel economy and emissions control. Only a couple of stray electrical connectors hinted at the differences distinguishing

Ford

bp

GM Collaborative Research Laboratories

Engine Systems Research

LTC University Consortium

Plans for next fiscal year

- HCCI Modeling and Control
  - KMZ modeling of deposits on heat transfer and thermal stratification
  - Develop controller for fast thermal management of individual cylinders
  - Quantify and validate HCCI fuel economy benefits over operating range
- Thermal effects in LTC engines
  - Quantify the potential impact of precision cooling or surface treatment on LTC low limit
  - Assess critical thermal transients with LTC engine-in-vehicle system simulation
- Explore Strategies for Load Range Extension
  - VVA: Assess tradeoffs associated with alternative strategies for RGF and combustion phasing control, and quantify benefits.
  - Direct Injection: Complete chemical kinetics modeling of recompression reaction to fully understand the mechanisms of low-load extension. Examine medium and high load LTC operation with DI and water injection.
  - Spark-Assisted HCCI: Integrate bulk ignition model with coherent flamelet model for SA-HCCI modeling
  - Boosted HCCI: Model, demonstrate and optimize turbo-charged HCCI engine operation with respect to valve event strategies and alternative fuels.
- Bio-fuels
  - Continue studies of ignition and combustion of bio-fuels and blends in RCF and optical engine.
  - Identify, quantify and optimize biofuel blend strategies to extend HCCI operation (iso-octane/ethanol, iso-octane/ester)

Key Publications

Andreae, M., Cheng, W. K., Kenney, T., Yang, J. (2007) On HCCI Engine Knock. SAE Paper 2007-01-1858, SAE/JSAE Joint Powertrain and Fluid Systems Meeting, Kyoto, Japan, June, 2007.

Angelos, J. P., Andreae, M. M. Green, W. H., Cheng, W. K., Kenney, T. and Xu, Y. (2007) Effects of Variation in Market Gasoline Properties on HCCI Load Limits. SAE Paper 2007-01-1859. SAE/JSAE Joint Powertrain and Fluid Systems Meeting, Kyoto, Japan, June, 2007.

Angelos, J. P., Puignou, M., Andreae, M. M., Cheng, W. K., Green, W. H. and Singer, M. A. (submitted) Detailed Chemical Kinetic Simulations of HCCI Engine Transients. *International Journal of Engine Research*.

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Sampara, C.S., Bissett, E.J., and Chmielewski, M. (2007) Global Kinetics for a Commercial Diesel Oxidation Catalyst with Two Exhaust Hydrocarbons. Presented at the Diesel Engine Efficiency and Emissions Research (DEER) Conference, August 13-16, Detroit, MI.

Song, H.H., and Edwards, C.F. (2008) Optimization of Recompression Reaction for Low-Load Operation of Residual-Effected HCCI. SAE paper 2008-01-0016.

Walton, S.M., Perez, C., Wooldridge, M.S. (2007) An Experimental Investigation of the Auto-Ignition Properties of Two C5 Esters: Methyl Butanoate and Butyl Methanoate. Technical Publication ASME IMECE2007-41944.

Zigler, B.T., Walton, S.M., Karwat, D.M., Assanis, D., Wooldridge, M.S., and Wooldridge, S.T., (2007) A Multi-Axis Imaging Study of Spark-Assisted Homogeneous Charge Compression Ignition Phenomena in a Single-Cylinder Research Engine. Proceedings of ICEF2007, Paper No. ICEF2007-1762.