Ignition Control for HCCI

Project ID – ace_18_edwards

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2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

20 May 2009

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Objectives

Project Objective

A multi-year CRADA between ORNL and Delphi to demonstrate a practical application of HCCI in a production-level, light-duty gasoline engine.

FY2008-2009 Objectives

- **Benchmark multi-cylinder engine in SI operation with stock hardware –** Complete
- **Evaluate designs for hardware upgrades**
  - » Delphi cam phasers – Installed
  - » Low-lift cam designs for HCCI operation – Near completion
  - » Delphi fuel injectors with finer resolution and less shot-to-shot variability – Installed
- **Fabricate and install Delphi 2-step valve-lift hardware –** Summer 2009
- **Develop spark-assisted HCCI (SA-HCCI) model for real-time diagnostics and control –** Development complete, calibration underway

Overview

Timeline

- **Start Date: Oct 2006**
- **End Date: Oct 2009**

Budget

- **FY 2007 – $300k**
- **FY 2008 – $300k**
- **FY 2009 – $300k**

Partners

- **CRADA between ORNL and Delphi**
- **Collaboration with LLNL**

Barriers Addressed

- **Market Challenges and Barriers from OVT MYPP:**
  - ***A. Cost.*** "…Better use of advanced LTC modes to reduce the formation of emissions in-cylinder will reduce aftertreatment system requirements and associated costs."
    - **HCCI to reduce in-cylinder production of NOx**
    - **Demonstration of practical variable valve actuation system**

- **Technical Challenges and Barriers from OVT MYPP:**
  - ***B. Fundamental knowledge of engine combustion.*** "Engine efficiency improvement [and] engine-out emissions reduction … are inhibited by an inadequate understanding of the fundamentals of … in-cylinder combustion/emission formation processes … as well as by an inadequate capability to accurately simulate these processes."
    - **Improving understanding of SA-HCCI through experiments and model development**
  - ***D. Engine controls.*** "Effective sensing and control of various parameters will be required to optimize operation of engines in advanced LTC regimes over a full load-speed map similar to that of a gasoline or diesel engine."
    - **Development of real-time diagnostics and controls to stabilize SA-HCCI and smooth SI-HCCI mode transitions**

Milestones and Project Timeline

FY2009 Milestone: Characterize cyclic-dispersion mechanisms on Delphi multi-cylinder engine (30 Sept 2009)

Status: On track

Update: Analysis of SA-HCCI data from multi-cylinder engine is underway. Adapting models and analysis techniques for the single-cylinder engine to this engine.

Phase 1	***Phase 2***	***Phase 3***
Model debug, Baseline OEM system	Steady-state HCCI mapping, Cam lift/duration evaluation	SI/HCCI Transitions
Jan 2007 – **Sept 2008**	**Sept 2008** – **Aug 2009**	**Aug 2009** – **Dec 2009**

Phase 1 (Jan 2007 – Sept 2008)

- **Single-cylinder experiments**
  - SI/HCCI mode transitions
  - SA-HCCI dynamics
- **Baseline development**
- **Modeling**
  - Initial SA-HCCI model development
  - GT-Power simulation
  - GT-Power cam profile comparisons
- **Component build**
  - Cams, 2-step VVA prep, DICP
  - Low-flow DI injector design

Phase 2 (Sept 2008 – Aug 2009)

- **Component selection**
  - DICP, Low-flow DI injectors
- **HCCI domain evaluation**
  - HCCI fixed cam profile evaluation
  - Map control parameters' influence coefficients
  - Characterize SA-HCCI dynamics
- **Modeling**
  - GT-Power HCCI modeling
  - SA-HCCI model calibration and integration with GT-Power
- **Component build**
  - 2-step VVA

Phase 3 (Aug 2009 – Dec 2009)

- **Transition testing**
  - 2-step w/ DICP
  - SI/HCCI mode transitions
- **Modeling**
  - GT-Power HCCI/SI transition modeling
- **EMS development**
  - Cycle/cycle control implementation
  - SI/HCCI mode transitions
  - HCCI domain optimization
- **Optimization vs. baseline**
  - Fuel consumption
  - Emissions

Approach

CRADA between ORNL and Delphi

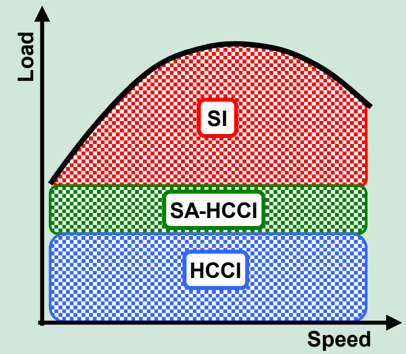
- Delphi provides hardware expertise
- ORNL provides expertise in analysis and control of nonlinear systems

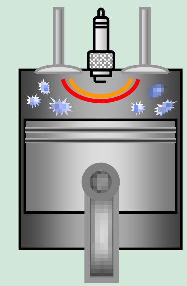
Multi-cylinder, production-level engine platform

- GM Ecotec, DI gasoline, 2.2-L, 4-cylinder
- Delphi cam phasers and 2-step valve-lift hardware
- Delphi CPDC high-speed controller



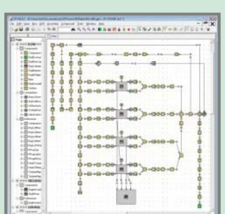
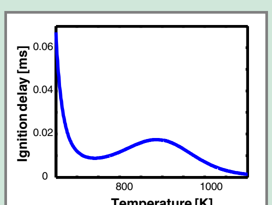
Multi-mode operation and spark assist for full coverage of speed-load range

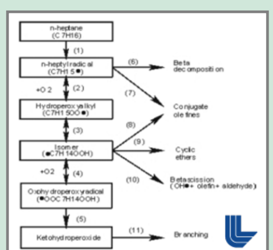




Engine and combustion modeling

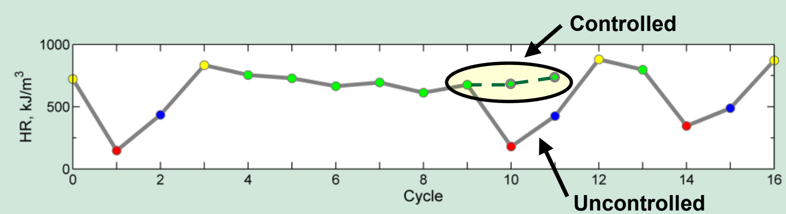
- GT-Power model for initial hardware design and evaluation
- Phenomenological model for real-time diagnostics and control
- Detailed HCCI kinetics model



Real-time predictive models and control strategies

- Smooth combustion mode transitions
- Stabilize SA-HCCI



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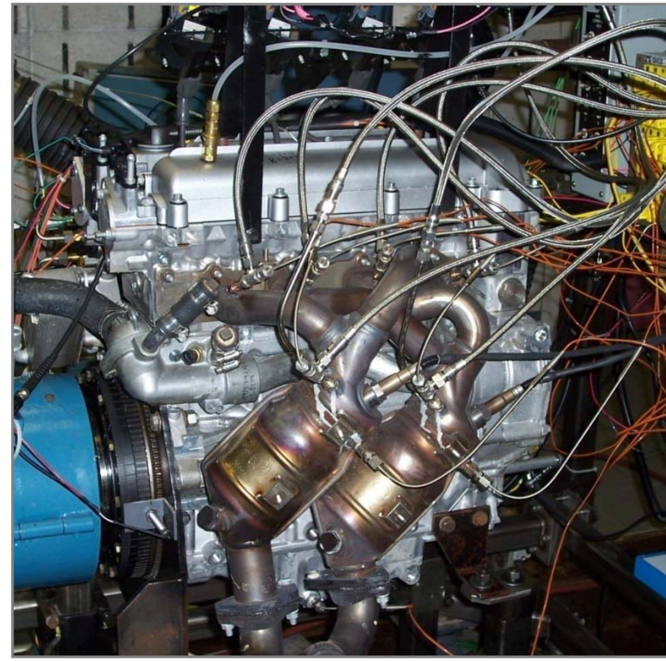
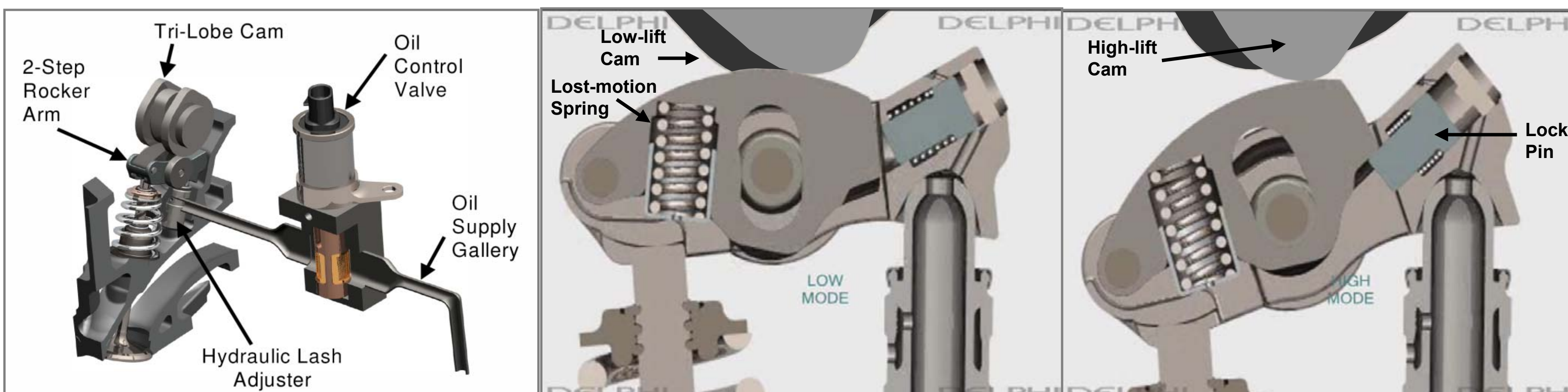
Engine hardware

- **Engine installed at Delphi Technical Center in Rochester, NY**
  - » GM Ecotec, 2.2-L, 4-cylinder, DI gasoline
  - » Delphi cam phasers with 80^{o} authority
  - » Delphi fuel injectors for improved injection control
- **Successfully achieved *SI*, *SA-HCCI*, and *HCCI***
- **Evaluating cam designs for 2-step valve-lift hardware**
  - » SI baseline with stock cams (10-mm lift) complete
  - » Evaluation of low-lift cam designs for HCCI near completion



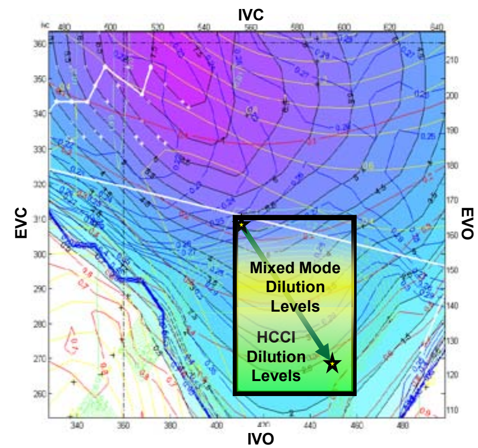


SAE 2007-01-1285

Engine development strategy

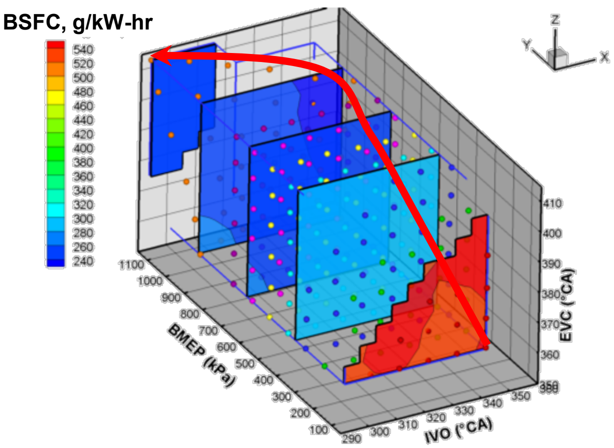
Simulations are guiding engine component selection and design

- **GT-Power engine model**
  - » Identify cam-phasing window to allow proper dilution for SI and HCCI operation
  - » Evaluate potential cam designs (lift & duration) for SI and HCCI operation



Experiments are guiding refinement and optimization of hardware

- **Cam phasing sweeps**
  - » Identify timings for optimum efficiency over speed/load range
- **Selection of 2-step cam design using fixed cams**
  - » Stock cams (10-mm lift) for SI operation
  - » Low-lift cams (4, 5.6, & 6 mm lift) being evaluated for HCCI operation
- **Injector evaluation and development of injection strategy for HCCI**
  - » Single vs. multiple injections (with pilot during recompression)



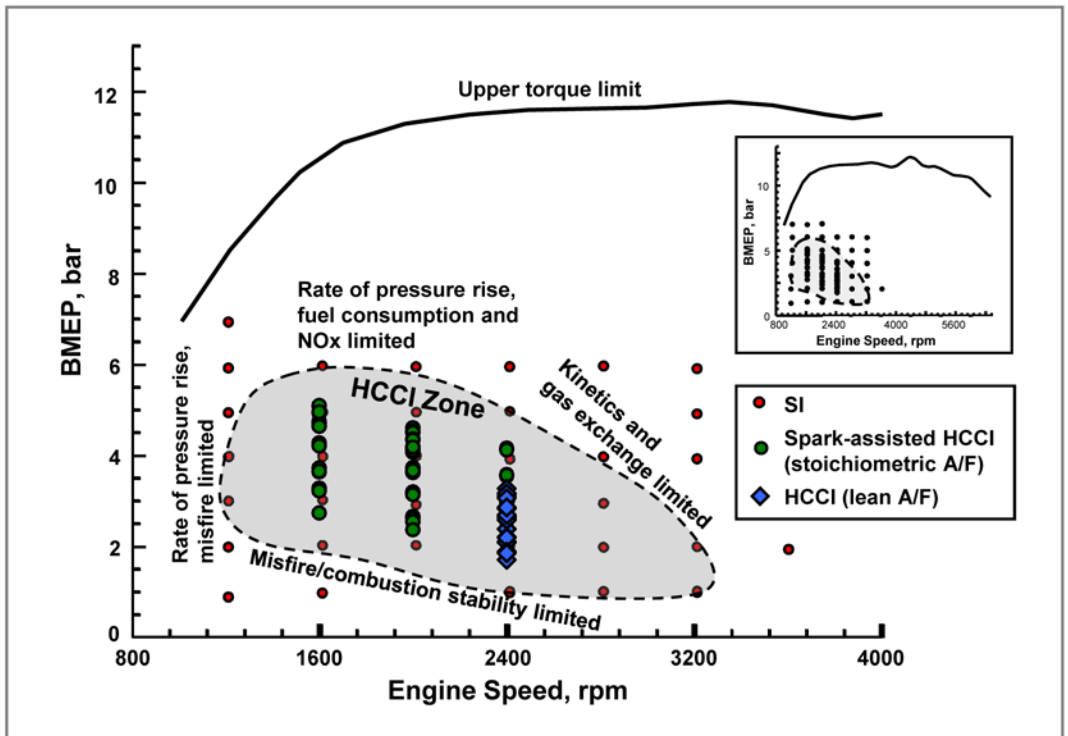
Exploration of engine operational range

Demonstrated engine operation in *SI, SA-HCCI,* and *HCCI* modes

- **Initial HCCI operating window is limited, even with spark assist**
- **Currently exploring potential opportunities for expanding this window**
  - » Lower-lift (5.6-mm, 4-mm) cams
  - » Higher-resolution injectors with multiple injection strategy
  - » Control to reduce combustion instability

Range of engine operation explored to date using:

- 10-mm lift cams (SI)
- 6-mm lift cams (HCCI)



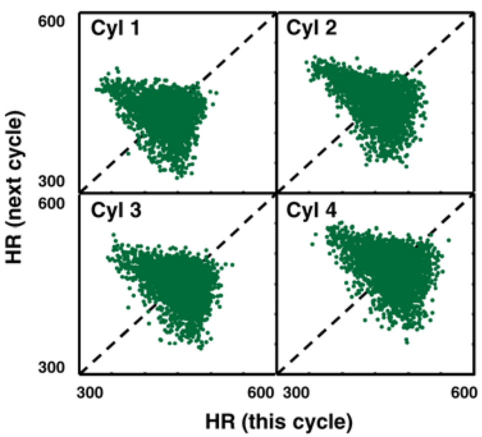
Analysis of combustion instabilities in the multi-cylinder engine

Confirms unstable SA-HCCI has significant deterministic component

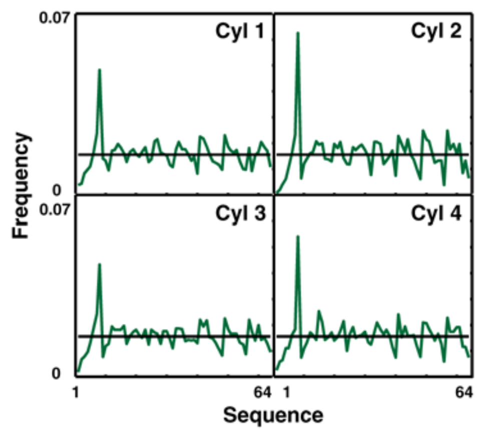
- **Implies predictive control could extend operating window**
- **Patterns superficially similar to lean-limit combustion**
- **Cylinder cross-talk appears to be minimal at conditions analyzed to date**
- **Adapting previous models and control strategies based on multi-cylinder data**

Example analysis for 2400 rpm, 3.0 bar, λ = 1.0, 56% dilution (residual)

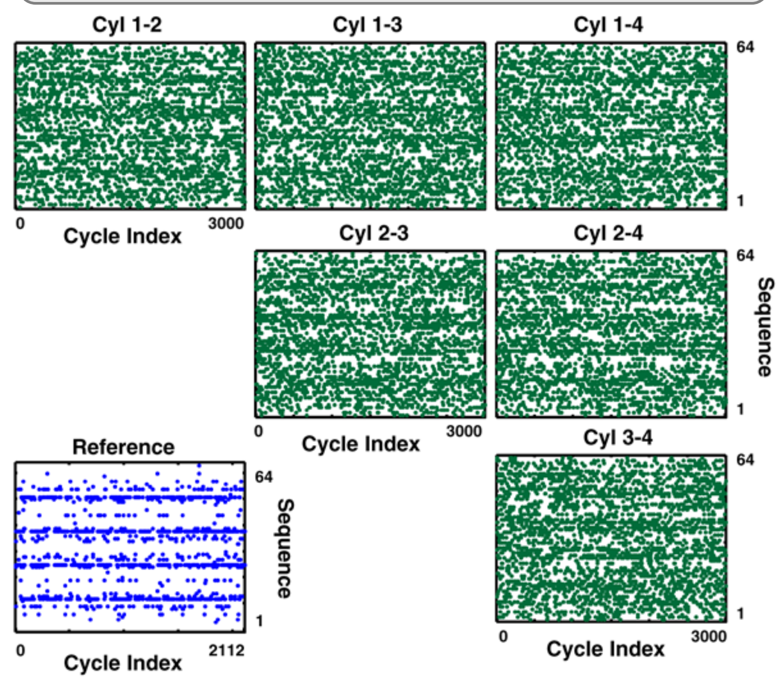
Return maps suggest instabilities are non-random



Symbolization reveals presence of repeating patterns suggesting determinism



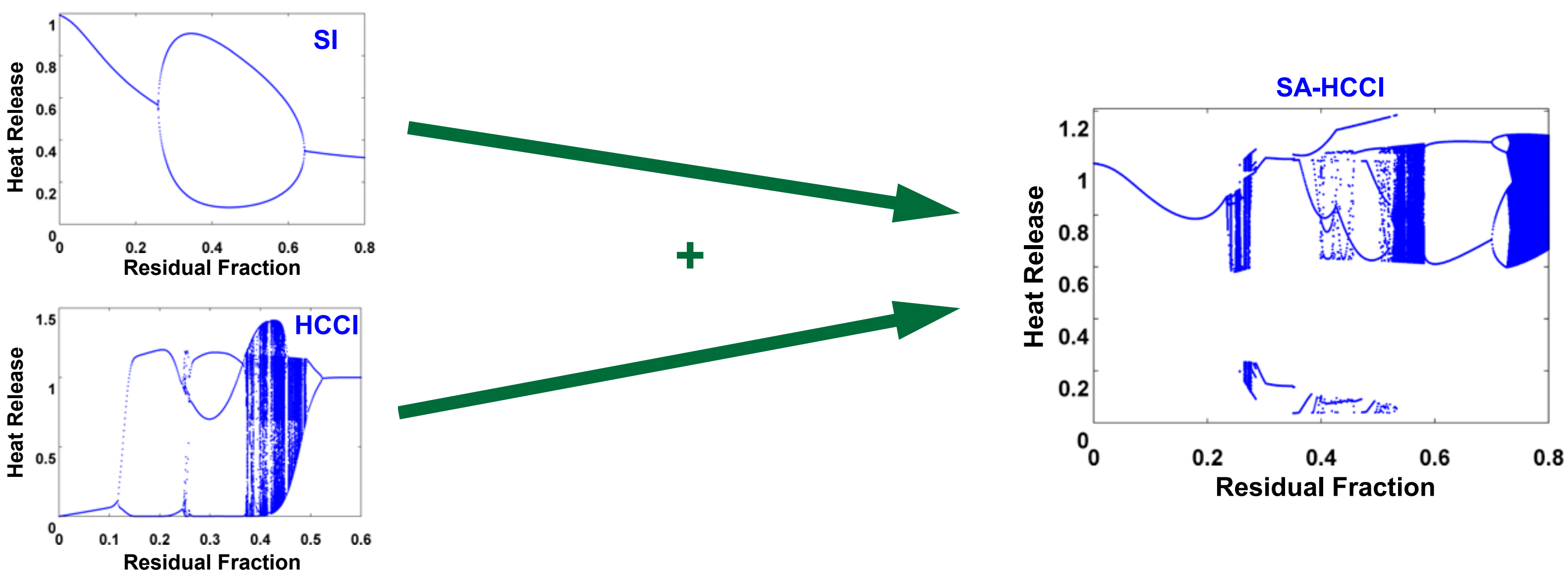
Cross-symbolization spectrograms suggest limited cylinder cross-talk (compare to reference data from another engine)



Spark-assisted HCCI model status

Targets real-time diagnostics and control of SA-HCCI

- **Simple phenomenological model uses global kinetics to predict cycle-resolved combustion performance based on knowledge of recent combustion history**
  - » Integration with GT-Power for study of mode transition dynamics
  - » Simple form allows computation in real-time for diagnostics and control
- **Couples simple sub-models for SI and HCCI**
  - » Diluent-limited (EGR) flame propagation (SI) **[Rhodes, Keck. SAE 850047.]**
  - » Temperature-driven residual combustion (HCCI) **[Daw, et al. *ASME J.Eng.Power&GT.* 130(5).]**
- **Will be calibrated specifically with multi-cylinder engine data**

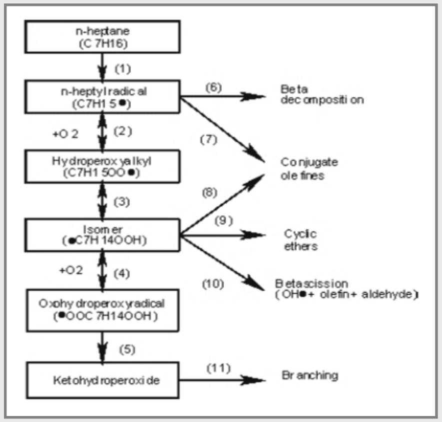


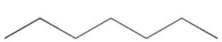
Collaboration with Lawrence-Livermore National Laboratory

Modeling of High-Efficiency Clean Combustion Engines

- ORNL providing single-cylinder SA-HCCI data
- LLNL developing detailed models of kinetic mechanisms for SI, HCCI and SA-HCCI combustion
- Modeling of (many) consecutive cycles to investigate development of combustion instabilities
- ACE 12, 16:15 Tues 19 May 2009, Crystal City E&F (Aceves, Havstad, et al.)

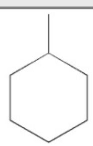
Detailed HCCI kinetics modeling and surrogate fuel blend development



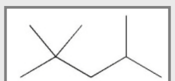


n-heptane

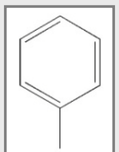
1-pentene



methylcyclohexane

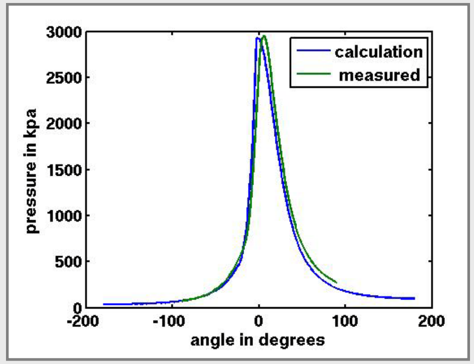


iso-octane

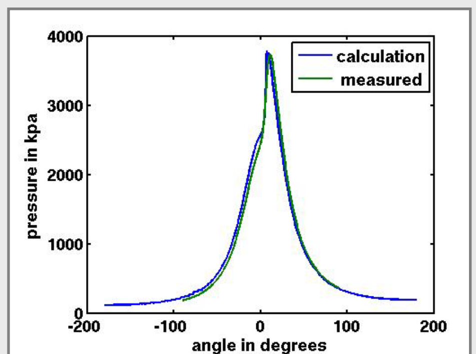


toluene

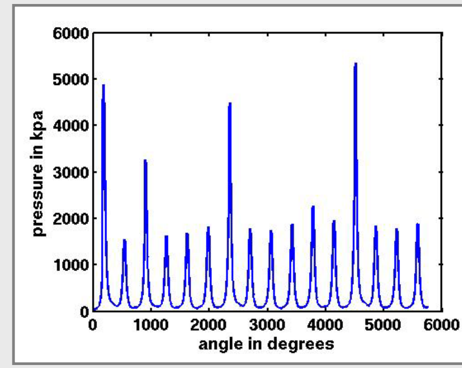
SI

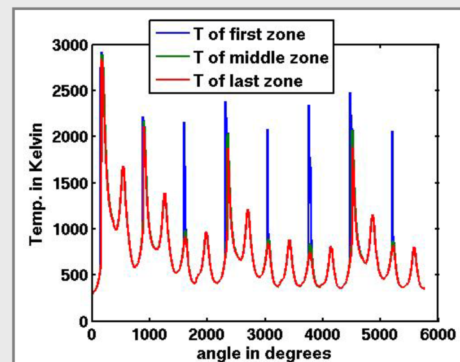


HCCI



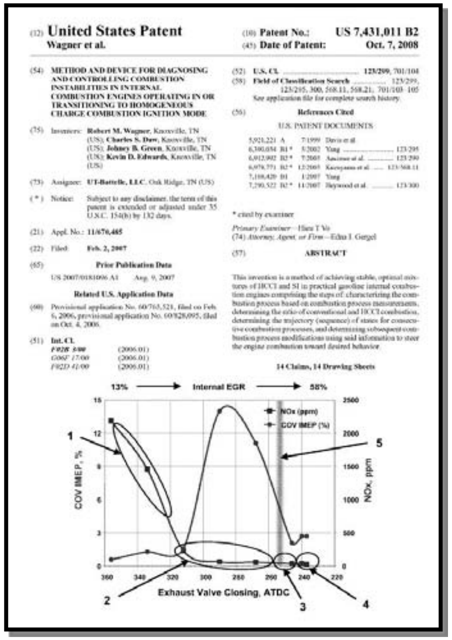
SA-HCCI





Technical Accomplishments – Summary

- **Demonstrated *SI, SA-HCCI*, and *HCCI* on the multi-cylinder engine**
- **GT-Power engine model completed and used to develop initial hardware designs**
- **Hardware evaluations and upgrades**
  - » Delphi cam phasers – Installed
  - » Evaluation of low-lift cam designs for HCCI operation – Near completion
  - » Delphi fuel injectors with finer resolution and less shot-to-shot variability – Installed
- **Cycle-resolved SA-HCCI model for real-time diagnostics and control complete, calibration with multi- and single-cylinder engine data underway**
- **US Patent 7,431,011 issued 7 October 2008 for our techniques to diagnose and control combustion instabilities in HCCI and SA-HCCI operation**
- **Continued collaboration with LLNL to develop detailed kinetics-based model of HCCI and SA-HCCI**


(12) United States Patent
Wagner et al.
(10) Patent No.: US 7,431,011 B2
(45) Date of Patent: Oct. 7, 2008

(54) METHOD AND DEVICE FOR DIAGNOSING AND CONTROLLING COMBUSTION INSTABILITIES IN INTERNAL COMBUSTION ENGINES OPERATING IN OR TRANSITIONING TO HOMOGENEOUS CHARGE COMBUSTION IGNITION MODE

(75) Inventors: Robert M. Wagner, Knoxville, TN (US); Charles S. Daw, Knoxville, TN (US); Johney B. Green, Knoxville, TN (US); Kevin D. Edwards, Knoxville, TN (US)

(73) Assignee: UT-Battelle, LLC, Oak Ridge, TN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 132 days.

(21) Appl. No.: 11/670,485

(22) Filed: Feb. 2, 2007

(65) Prior Publication Data

US 2007/0181086 A1 Aug. 9, 2007

Related U.S. Application Data

(60) Provisional application No. 60/765,521, filed on Feb. 6, 2006, provisional application No. 60/828,095, filed on Oct. 4, 2006.

(51) Int. Cl.

(52) U.S. Cl. 123/299; 701/104

(58) Field of Classification Search 123/299, 123/295, 300, 568.11, 568.21; 701/103–105

See application file for complete search history.

(56) References Cited

U.S. PATENT DOCUMENTS

* cited by examiner

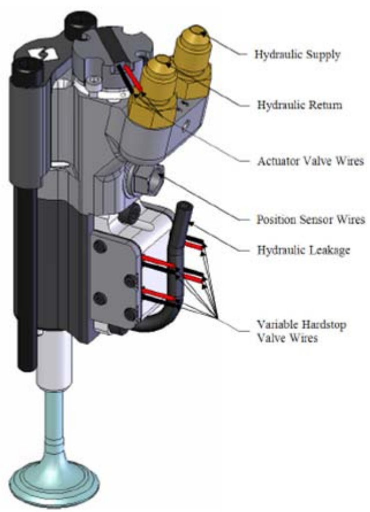
(57) ABSTRACT

This invention is a method of achieving stable, optimal mixtures of HCCI and SI in practical gasoline internal combustion engines comprising the steps of: characterizing the combustion process based on combustion process measurements, determining the ratio of conventional and HCCI combustion, determining the trajectory (sequence) of states for consecutive combustion processes, and determining subsequent combustion process modifications using said information to steer the engine combustion toward desired behavior.

14 Claims, 14 Drawing Sheets

Future Work

- **Continued hardware evaluation and integration of 2-step valve-lift hardware**
- **Additional experiments on single-cylinder VVA engine at ORNL (leveraged activity with internal funds)**
  - » GM Ecotec 2.0-L, one cylinder instrumented with Sturman VVA system (other cylinders deactivated)
  - » Custom pistons for step changes in geometric compression ratio
  - » Additional experiments to characterize SA-HCCI dynamics
  - » Single-cylinder geometry simplifies dynamics by eliminating potential cylinder cross-talk
- **Calibration of the SA-HCCI model with data from multi- and single-cylinder engines**
- **Continued collaboration with LLNL on detailed kinetics models**
- **Implement and evaluate control strategy for multi-mode operation on multi-cylinder engine**



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Schematic of Sturman hydraulically actuated valve hardware

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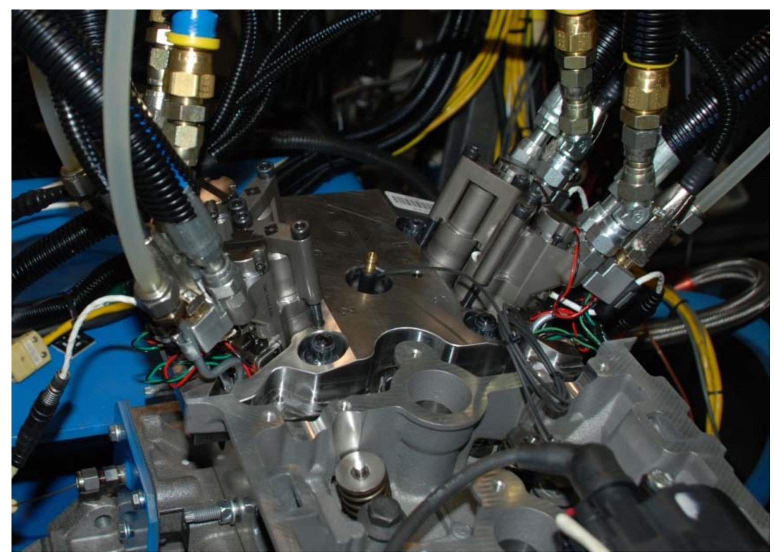
Photo of ORNL engine with hardware installed



Summary

- **Objective**
  - » Develop practical application of HCCI on a production-level gasoline engine for improved fuel efficiency and reduced emissions.
- **Approach**
  - » CRADA between ORNL and Delphi.
  - » Advanced controls to stabilize SA-HCCI and smooth combustion mode transitions to expand speed-load range.
- **Technical Accomplishments**
  - » Demonstrated SI, SA-HCCI, and HCCI on multi-cylinder engine.
  - » Completed basic combustion instability model to guide real-time diagnostics and controls.
- **Technology Transfer**
  - » Collaborating with Delphi through CRADA.
  - » Collaborating with LLNL on development of detailed kinetics model for HCCI and SA-HCCI.
  - » US Patent (7,431,011) on control algorithm for multi-mode operation, several publications and presentations.
- **Future**
  - » Install 2-step valve-lift hardware and fully map HCCI domain of engine.
  - » Incorporate SA-HCCI combustion model into GT-Power and calibrate with engine data.
  - » Implement control strategy to stabilize SA-HCCI operation and smooth combustion mode transitions.

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