Ignition Control for HCCI
Project ID – ace_18_edwards

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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
- **Model debug, Baseline OEM system**
- **Baseline development**
- **Component build**
  - Cams, 2-step VVA prep, DICP
  - Low-flow DI injector design

#### Phase 2
- **Steady-state HCCI mapping, Cam lift/duration evaluation**
- **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

#### Phase 3
- **SI/HCCI Transitions**
- **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

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| Model debug, Baseline OEM system | Steady-state HCCI mapping, Cam lift/duration evaluation | SI/HCCI Transitions | }
**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

**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

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

**Real-time predictive models and control strategies**
- Smooth combustion mode transitions
- Stabilize SA-HCCI
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° 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, \( \lambda = 1.0 \), 56% dilution (residual)**

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

Return maps suggest instabilities are non-random

Symbolization reveals presence of repeating patterns suggesting determinism
Spark-assisted HCCI model status

- 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

SI

SA-HCCI

HCCI

n-heptane

I-pentene

methycyclohexane

iso-octane
toluene

Detailed HCCI kinetics modeling and surrogate fuel blend development.
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**
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

Used with permission of Sturman Industries, Inc.

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.

- **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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