Ignition Control for HCCI

Agreement 9285

Presented by K. Dean Edwards

Robert M. Wagner
C. Stuart Daw
Charles E.A. Finney
Johney B. Green, Jr.
Oak Ridge National Laboratory

Keith Confer
Delphi

DOE Management Team:
Steve Goguen, Gurpreet Singh
U.S. Department of Energy
Office of Vehicle Technologies

Office of Vehicle Technologies 2008 Annual Merit Review
Bethesda, Maryland – 25-28 February 2008

This presentation does not contain any proprietary or confidential information

Purpose of Work

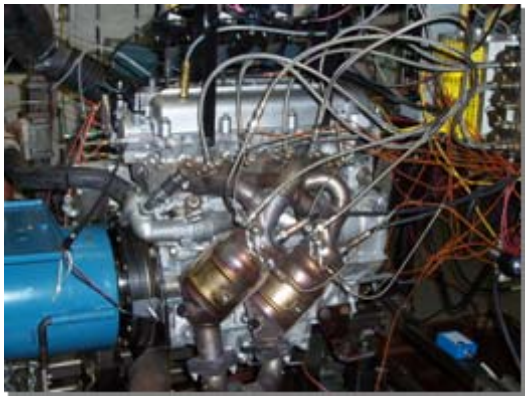
Project Overview

A multi-year CRADA agreement between ORNL and Delphi to demonstrate a practical application of HCCI in a multi-cylinder gasoline engine for improved fuel efficiency and reduced emissions.

FY2007-2008 Objectives

- **Build, instrumentation, and benchmarking of multi-cylinder engine – complete, baseline mapping underway**
- **Equip engine with Delphi variable valve system – Spring 2008**
- **Map HCCI operating range – Spring 2008**
- **Develop GT-Power model of the base engine – complete**
- **Initial development of spark-assist HCCI combustion model based on single-cylinder tests – near completion**
- **Incorporate combustion model into GT-Power model and calibrate with engine data – Summer 2008**

DELPHI



OAK RIDGE National Laboratory

Activity addresses multiple barriers

- **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 spark-assisted 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 spark-assisted HCCI and smooth SI-HCCI mode transitions**

OAK RIDGE National Laboratory

Guidance from FY 2007 Merit Review

Reviewers felt the goals and approach were novel, targeted important barriers, and were well-aligned with DOE objectives, but they expressed the need for more rapid progress. One reviewer questioned the focus on non-diesel applications.

The CRADA agreement with Delphi has provided a better focus on practical implementation of spark-assisted HCCI.

The multi-cylinder engine is now in operation, and we are well-positioned to make rapid progress as we enter the main phase of the project.

The DOE R&D portfolio is fuel neutral and includes activities that utilize gasoline and diesel fuel technologies.

- **Relevance:** all positive comments
  - "… in direct support of [DOE] efficiency/emissions goals."
  - "… successfully handling transitions between spark ignition and HCCI would be a key enabler for this technology."
  - "… the models are directly oriented to enabling control."
- **Approach:** all positive comments
  - "… spark-assisted HCCI approach represents a novelty [among] the DOE programs."
  - Appreciated efforts "… to show the viability of HCCI with near-term technologies."
- **Accomplishments:**
  - "… hardware changes are painfully slow…."
  - Need for more "… accomplishments that lead to overcoming barriers."

  With the multi-cylinder engine now in operation, pace of the project is expected to accelerate.
- **Technology Transfer:** mostly positive comments
  - CRADA agreement with Delphi seen as a positive step forward
- **Future Plans:**
  - "… well-aligned with DOE goals."
  - "… analysis of cyclic variations and [their] cause [is] useful …."
  - "… transient cold plans [are] ambitious but [are] essential for implementation."

OAK RIDGE National Laboratory

Approach

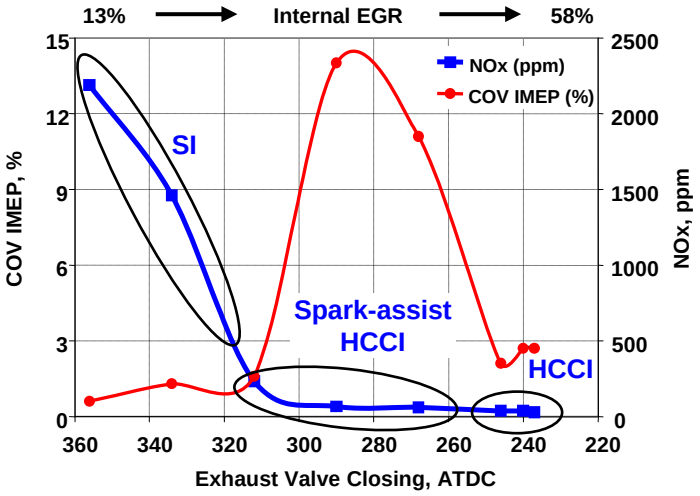
GOAL: Demonstrate practical application of HCCI in a production-level engine platform for improved fuel efficiency and reduced emissions.

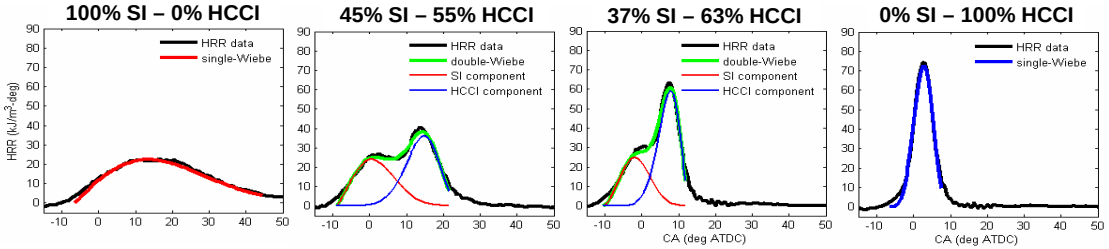
- **CRADA agreement between ORNL and Delphi**
  - **Delphi provides hardware expertise**
  - **ORNL provides expertise in analysis and control of nonlinear systems**
- **Multi-cylinder production-level engine platform with Delphi CPDC high-speed controller**
- **HCCI achieved using negative valve overlap (NVO) strategy to increase internal EGR**
  - **Cam phasers and 2-step valve-lift hardware developed by Delphi**
- **Multi-mode operation to allow full coverage of speed-load range using spark assist**
- **Development of real-time predictive models and control strategies to stabilize spark-assisted HCCI combustion and smooth transition between combustion modes**

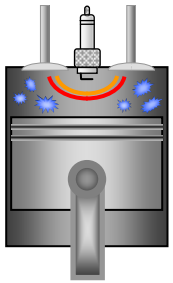
OAK RIDGE National Laboratory

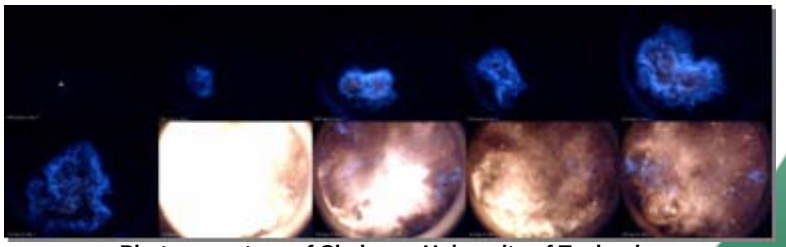
Brief History of the Project

- **Began in 2003 with work on AVL research engine with fully variable valve actuation examining the use of spark-assist to expand the HCCI operating window.**
- **Analysis confirmed that cyclic variability at intermediate internal EGR levels is deterministic and predictable suggesting possibility of control to smooth SI-HCCI transition.** (2006 Merit Review, SAE 2006-01-0418)
- **Spark-assisted hybrid combustion mode identified.** (SAE 2006-01-0418)
  - **Mixed-mode combustion with varying levels of SI and HCCI within the same cycle**
  - **Low NO_x, low pressure rise rate, requires limited intake-charge preparation**
- **CRADA agreement signed between ORNL and Delphi.** (Jan 2007)









Photos courtesy of Chalmers University of Technology

OAK RIDGE National Laboratory

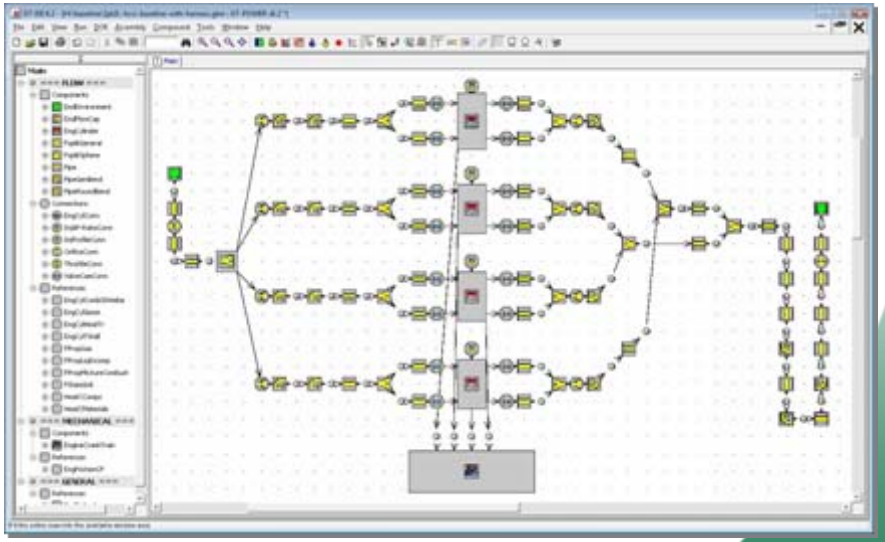
Technical Accomplishments (since 2007 Merit Review)

- **Multi-cylinder engine platform installed and operational at Delphi.**
- **Initial GT-Power model of the engine complete.**
- **Combustion metric developed to detect initiation of HCCI and gauge relative strengths of SI and HCCI in spark-assisted HCCI mode.**
- **Single-cylinder experiments performed to gain further insight into the role of residual composition on combustion stability of spark-assisted HCCI.**
- **Model for real-time diagnostics and control which accurately predicts the cyclic variability of spark-assisted HCCI is near completion. Model will require calibration with data from the multi-cylinder engine.**

OAK RIDGE National Laboratory

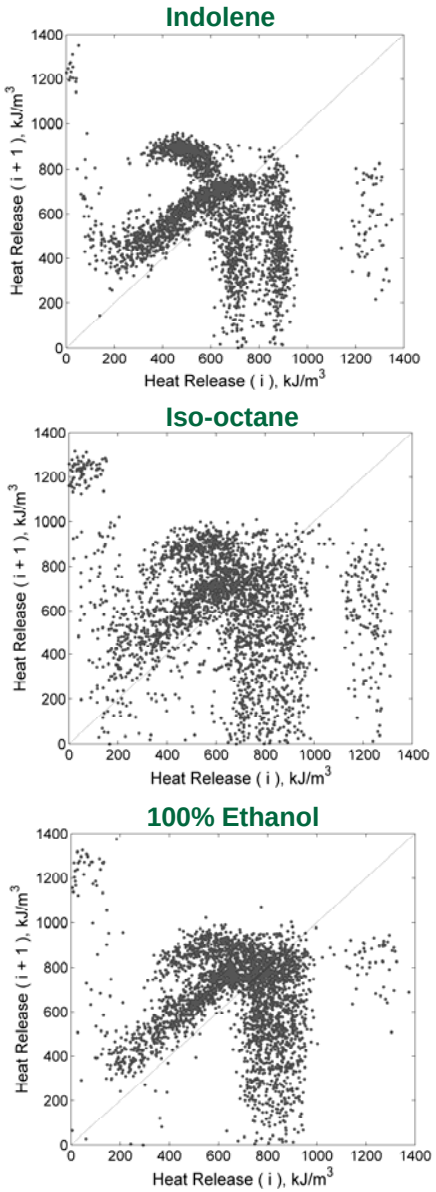
Engine Status Update

- **Experimental platform is a 4-cylinder, 2.2-L gasoline engine with cam phasers and will include a 2-step variable-valve-lift system developed by Delphi.**
- **The base engine has been built, instrumented, and installed in a dynamometer cell at the Delphi facilities in Rochester, NY.**
- **Engine break-in is complete and baseline mapping is underway.**
- **Installation of the variable-valve-lift system is set to begin in Spring 2008. Engineering details of the installation have been completed.**
- **GT-Power model of the engine is complete. Additional calibration will be required using the baseline data.**
- **Engine to be equipped with Delphi CPDC controller. (SAE 2007-01-0774)**

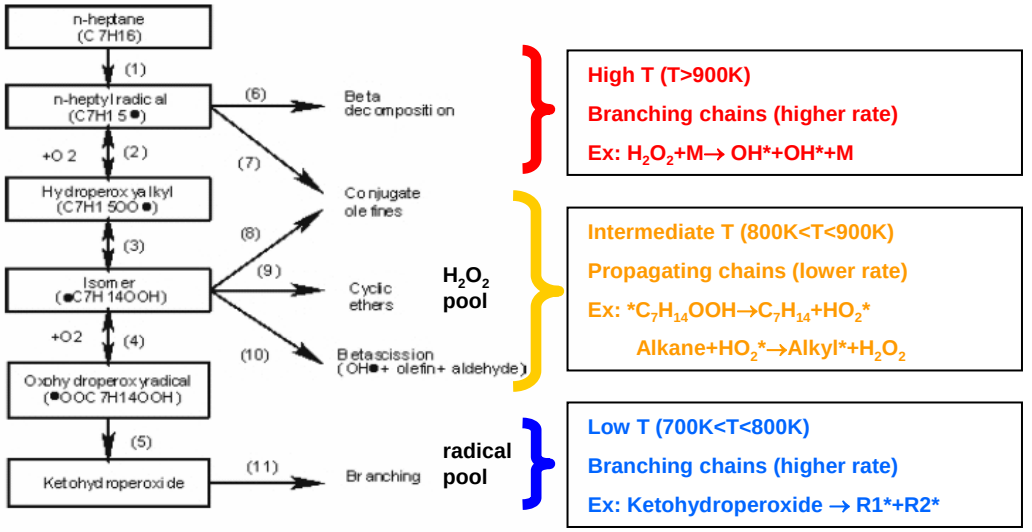


OAK RIDGE National Laboratory

Single-cylinder Experiments – Fuel Effects



- **Global kinetics of late burn reveals that during spark-assisted HCCI operation, the engine alternates between 2 competing combustion modes.**
- **Competition between the 2 mechanisms leads to high COV.**
- **Similar behavior is observed for both fuel blends (indolene, E85) and single-component fuels (iso-octane, 100% ethanol).**
- **This suggests that the modes may be driven by the presence of common intermediate, partially burned species (*e.g.*, H_2O_2).**
- **Data from the single-cylinder experiments are being shared with researchers at Lawrence Livermore National Laboratory in efforts to develop kinetic models for HCCI combustion.**

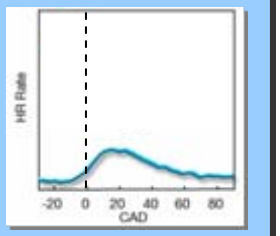


OAK RIDGE National Laboratory

Dynamics of SI-HCCI mode transition with increasing EGR

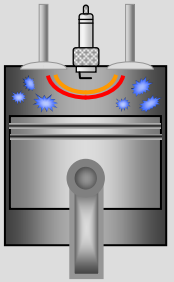
SI
High NOx, Low COV

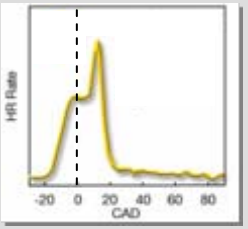
- **At low EGR, combustion is dominated by SI.**
- **As EGR increases, the SI flame speed decreases, reducing combustion efficiency and leaving unburned and partially burned fuel in the exhaust.**



Spark-assisted HCCI
Low NOx, High COV

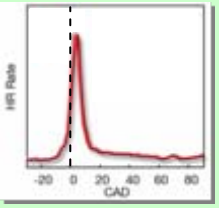
- **At moderate EGR levels, both SI and HCCI occur in the same cycle. The relative strengths of SI and HCCI vary from cycle-to-cycle in a complex but deterministic manner leading to high COV.**
- **Relative strengths of the two modes primarily depend upon concentration of partially burned species in the residual gas with residual temperature and charge stratification also playing important roles.**
  - **Low concentration: SI dominates but with low combustion efficiency producing large amounts of partially burned fuel.**
  - **High concentration: Flame propagation is suppressed and HCCI dominates.**
  - **Moderate concentration: SI begins providing additional heating and compression to end gases which auto-ignite at proper conditions.**





HCCI
Low NOx & COV

- **At very high EGR, dilution significantly reduces flame speed, EGR heat is sufficient to stimulate HCCI without any SI temperature boost, and HCCI out-competes SI.**

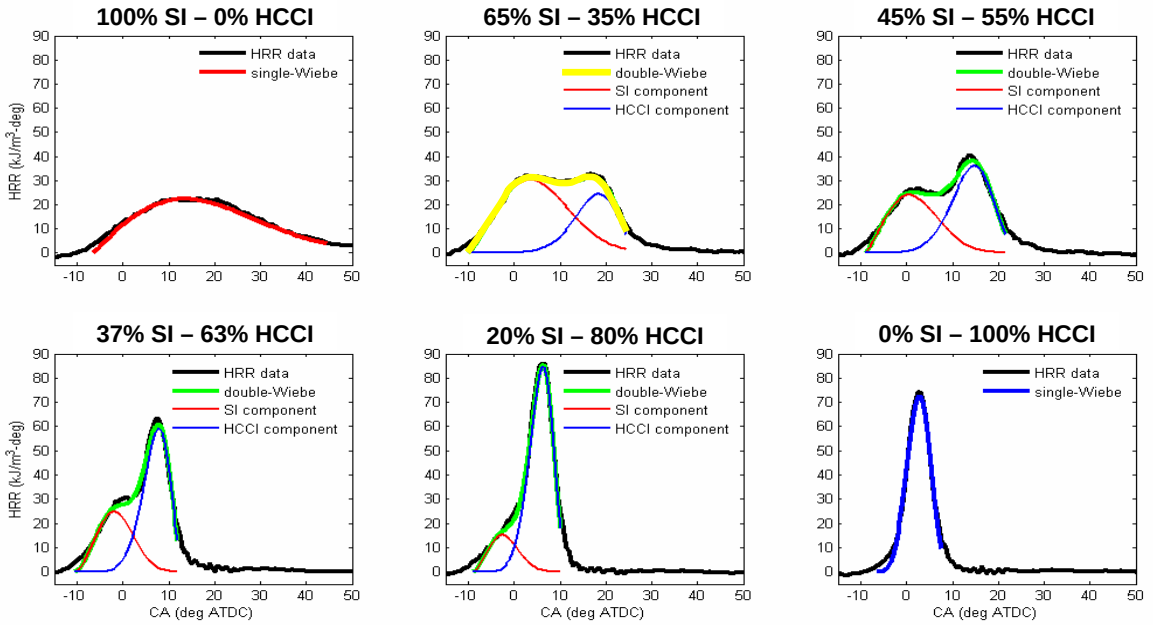


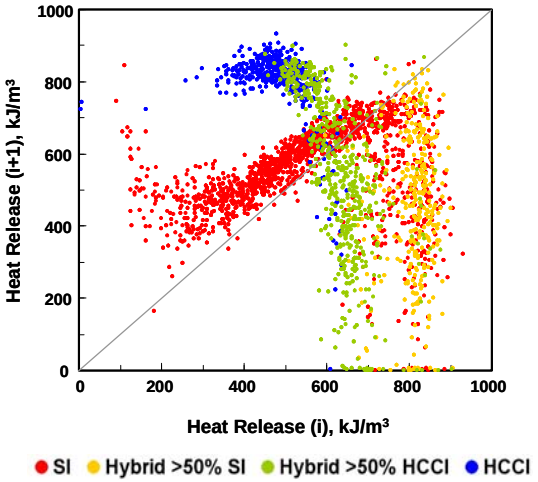
Increasing EGR

OAK RIDGE National Laboratory

Development of combustion metric for spark-assisted HCCI

- **A Wiebe-based combustion metric has been developed to:**
  - **Detect ignition timing of HCCI in spark-assisted HCCI events**
  - **Quantify relative strengths of competing SI and HCCI modes**
- **Method involves using multiple Wiebe functions to approximate the heat-release-rate profile of the different combustion modes.**
- **We are using the metric to visualize in phase space how combustion mode changes affect subsequent cycles through production and consumption of residual species.**
- **The metric can be evaluated quickly based on in-cylinder pressure measurements providing potential use as a trigger for control.**





Glewen, *et al.*, "Analysis of cyclic variability in spark-assisted HCCI combustion using a double Wiebe function"
- The Combustion Institute 2008 Central States Spring Meeting
- 32nd International Symposium on Combustion, submitted

OAK RIDGE National Laboratory

"Low-order" modeling of spark-assisted HCCI for real-time diagnostics and controls

GOAL: Develop a simple model for real-time diagnostics and control which captures the main features of the cyclic variability associated with residual coupling.

- **Mapping functions developed from global mass and energy balances provide predictions for residual mass and temperature from the previous cycle which is used to estimate initial in-cylinder conditions for the current cycle.**
- **Combustion models for SI and HCCI predict a burning rate for each mode based on the initial conditions.**
  - **SI: Flame-speed model accounting for dilution**
  - **HCCI: Combustion kinetics approximated as global reaction rates that depend on temperature and gas composition**
- **The rate constants are used to quantify the balance between SI and HCCI which may occur independently or simultaneously depending upon in-cylinder conditions.**

Status:

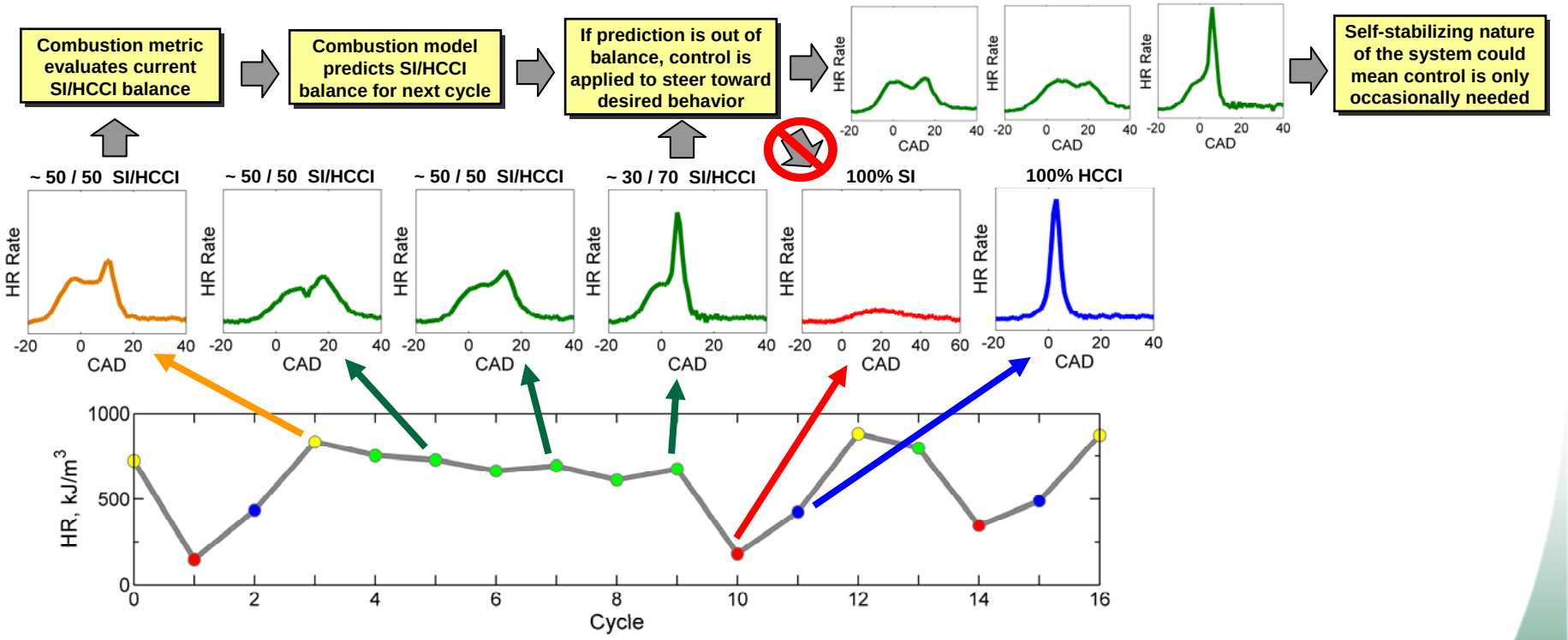
- **Preliminary single-mode components are complete.**
- **Currently working to integrate the SI and HCCI components which includes modeling the competition between the two modes.**
- **Data from multi-cylinder engine will be used for final calibration.**

- **ASME, ICEF-2007-1685**
- **Edwards, *et al.*, Dynamics Days 2008, presentations online soon at www.ddays2008.org**

OAK RIDGE National Laboratory

Integrated Control Approach

- **Preferred operation for stable spark-assisted HCCI involves maintaining a balance between SI and HCCI combustion modes.** (Wagner, *et al.*, 2006 SAE HCCI Symposium)
- **Engine will occasionally stabilize in this mode for short periods of time until slight fluctuations in in-cylinder conditions push SI and HCCI out of balance.**



- **Control is achieved by predicting when the system is about to come out of balance and applying a control perturbation to restore the balance (*e.g.*, varying spark-timing to weaken or strengthen the SI component).**
- **This control approach has been developed based on single-cylinder experiments; however, we anticipate that the fundamental strategy can be applied to other engines with proper calibration.** (US Patent Pending)

- US Patent 5,921,221
- SAE 2001-01-0257

OAK RIDGE National Laboratory

Technology Transfer and Collaborations

- **Part of an on-going CRADA agreement between ORNL and Delphi**
- **ORISE summer student, Will Glewen** (now at University of Wisconsin – Madison)
- **Continued collaboration with Lawrence Livermore National Laboratory toward development of a kinetics model for spark-assisted HCCI** (Today, 10:30AM, this room)
- **Results from this work have been regularly presented in open forums and publications**
  - **Invited lecture at Purdue University**
  - **SAE, ASME, The Combustion Institute, International Flame Research Foundation (IFRF)**
  - **Advanced Engine Combustion (AEC) Working Group**

Members of the AEC Working Group
(organized and led by Sandia National Labs)

Oak Ridge National Laboratory

Publications & Presentations (since 2007 Merit Review)

- ***Physical Review Letters***
  - **Daw, *et al.*, "Modeling dynamical instability of homogeneous charge compression ignition in combustion engines", submitted**
- **ASME Internal Combustion Engine Division 2007 Fall Technical Meeting**
  - **Daw, *et al.*, "Modeling cyclic variability in spark-assisted HCCI, ICEF-2007-1685**
  - **Accepted for publication in *ASME Journal of Engineering for Gas Turbines and Power***
- **SAE 2007 HCCI Symposium – invited presentation**
  - **Wagner, *et al.*, "Global kinetics model for spark-assisted HCCI"**
- **2007 American-Japanese Flame Research Committees International Symposium (IFRF)**
  - **Edwards, *et al.*, "Understanding the dynamics of spark-assisted HCCI combustion"**
- **Dynamics Days 2008**
  - **Edwards, *et al.*, "Modeling dynamic instability of HCCI in combustion engines"**
  - **Bifurcation plot of HCCI model selected as conference logo**

- **Invited lecture at Purdue University**
  - **Wagner, *et al.*, "Spark-assisted HCCI combustion modes and the potential for control"**
- **32nd International Symposium on Combustion**
  - **Glewen, *et al.*, "Analysis of cyclic variability in spark-assisted HCCI combustion using a double Wiebe function", submitted**
- **The Combustion Institute – 2008 Central States Spring Meeting**
  - **Glewen, *et al.*, "Analysis of cyclic variability in spark-assisted HCCI combustion using a double Wiebe function"**
- **FY 2007 DOE EERE Progress Report**
  - **http://www1.eere.energy.gov/vehiclesandfuels/resources/printable_versions/fcvt_reports.html**

OAK RIDGE National Laboratory

Activities for FY 2008 and beyond

Remainder of FY 2008

- **Equip engine with 2-step valve-lift hardware – set to begin March 2008**
- **Map engine over HCCI operating range – Spring 2008**
- **Implementation and calibration of combustion model in GT-Power – Summer 2008**

FY 2009 and beyond

- **Continued refinement of combustion models**
- **Development and application of control to stabilize spark-assisted HCCI operation and SI-HCCI mode transitions**

OAK RIDGE National Laboratory

Summary

- **Purpose**
  - Support the development and practical application of HCCI on a production-level gasoline engine for improved fuel efficiency and reduced emissions.
- **Approach**
  - CRADA agreement between ORNL and Delphi.
  - Advanced controls to stabilize spark-assisted HCCI and smooth combustion mode transitions to allow full coverage of speed-load range.
- **Technical Accomplishments**
  - Multi-cylinder engine is installed and in operation. GT-Power model of engine complete.
  - Combustion metric developed to detect HCCI initiation and quantify relative strengths of combustion modes for spark-assisted HCCI.
  - Model for real-time diagnostics and control of spark-assisted HCCI is near completion.
- **Technology Transfer**
  - Direct involvement with Delphi through CRADA agreement
  - Kinetics model development with LLNL
  - Several publications and presentations
- **Future**
  - Installation of 2-step valve-lift hardware and mapping of engine in HCCI operation.
  - Incorporate combustion model into GT-Power
  - Refinement of control strategy to stabilize spark-assisted HCCI operation and smooth SI-HCCI mode transitions

Contact: K. Dean Edwards, edwardskd@ornl.gov, 865-946-1213

OAK RIDGE National Laboratory