Control-Oriented Modeling for HCCI Combustion and Multi-Cylinder HCCI Experimental Activities

The Ohio State University Center for Automotive Research

Motivation for the Control-Oriented Approach

- HCCI with Diesel fuel has been experimentally demonstrated by many groups to be a worthwhile combustion regime:
  - Very low NO_x emissions
  - Very low PM emissions
  - Reasonable efficiency
- One of the major challenges in the implementation of HCCI in practice is combustion control:
  - Unlike SI and CIDI, there is no command having direct control of ignition timing (like spark timing or injection timing.)
  - Maintaining control over combustion timing and burn rate is critical for achieving high efficiency operation and reasonable engine loads with acceptable cylinder pressure levels.
- Combustion timing and burn rate are dictated by the time/temperature/pressure history of the air-fuel-residual charge as well as the composition of the charge.
- With the loss in direct control over combustion, the engine control algorithm is forced to rely on actuators that act on the parameters that influence combustion indirectly: external EGR, trapped residual, charge temperature, boost pressure, and valve timing.
- These indirect factors have many interrelations and overlap in their ability to control HCCI combustion, therefore achieving the desired outcome can be achieved by many different paths
- Just as Control-Oriented Modeling is increasingly vital for advanced gasoline engines with similarly complex actuator sets, it will have similar application to HCCI combustion control.

The work presented here is the early result of developing a control-oriented approach to HCCI combustion control.

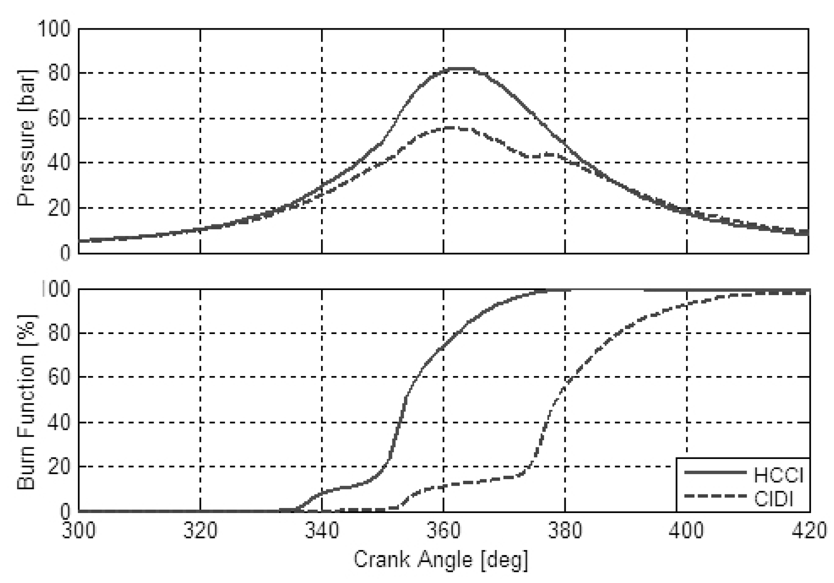

Figure 1: Conventional CIDI versus HCCI Combustion

1

Goals of Research and the Approach

- The goal of the research is to develop a *simple* engine model that is capable of capturing the *relevant* behavior of the engine:
  - A "Simple" Model: The model must be capable of running in real-time or faster
  - "Relevant" Behavior: The model must accurately capture the dynamic, mean-value behavior of the intake and exhaust system; the combustion model must accurately predict the heat release of the fuel with specific attention to combustion phasing
- With a model of this type, it is possible to rapidly investigate the impact of actuators on HCCI combustion, the sensitivity of the combustion to various factors, and explore control concepts

- The approach taken to achieve the goals builds on the successes of two-decades of similar modeling in the gasoline engine field:
  - Mean-Value Engine Modeling: It has been demonstrated that models representing the bulk flow characteristics of the intake and exhaust are sufficiently accurate for control needs. Such mean-value models, such as the classic manifold filling model with volumetric efficiency, are present in some form in virtually every gasoline engine control algorithm.
  - Single-Zone Combustion Models: It has also been demonstrated by OSU and others, that the traditional method of modeling heat release using Wiebe functions can be extended to HCCI combustion.
  - Coupling of the Above: A MVEM can give the conditions at intake valve closing, which then feed the initial conditions for the combustion model.

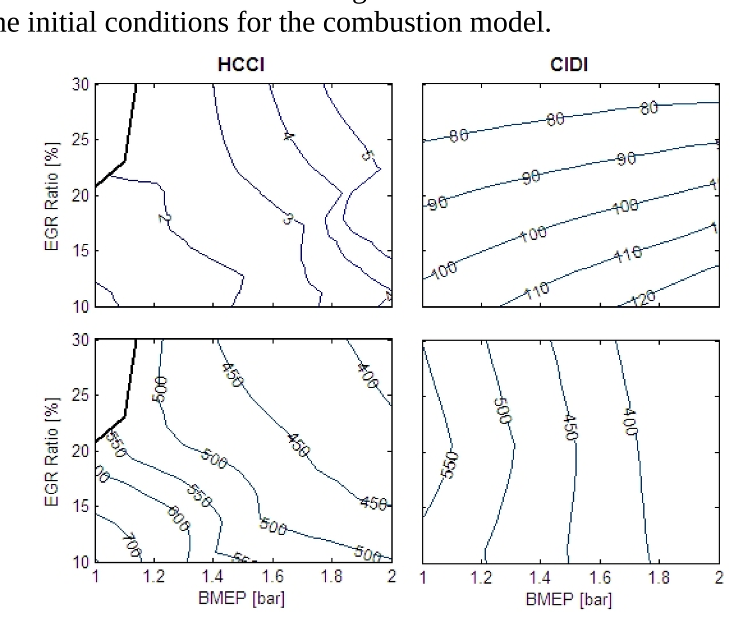

Figure 2: Experimental Results Show Drastic NOx Emissions Improvements (top) with Negligible Impact on BSFC (bottom) for HCCI Combustion at Low Idle vs. CIDI Combustion (Even with CR = 17.5)

2

Experimental Setup

- Experimental facilities for this project are housed at the OSU Center for Automotive Research (see Figure 3.)
- Experiments conducted on 2.5L CIDI engine with the following minor modifications:
  - The intercooler and EGR cooler of the engine were maintained
  - The EGR valve was upgraded to a higher flow, electronically controlled model
  - A VGT was retrofitted onto the engine in place of the stock, waste-gated model
  - The stock cam-timing was maintained
  - The engine maintained a stock compression ratio of 17.5:1
- HCCI fuel injection is made externally using the OSU Atomizer, which creates a "fog" of sub-micron Diesel fuel droplets (see Figure 4)
  - Fuel is injected into the intake manifold at a single location.
- It is well known that reduced compression ratio (via engine geometry or cam timing) has a positive impact on HCCI combustion, by delaying the start of combustion; this results in improved ISFC and maximum BMEP
- The current work focuses on what is essentially a retrofit of a stock CIDI engine

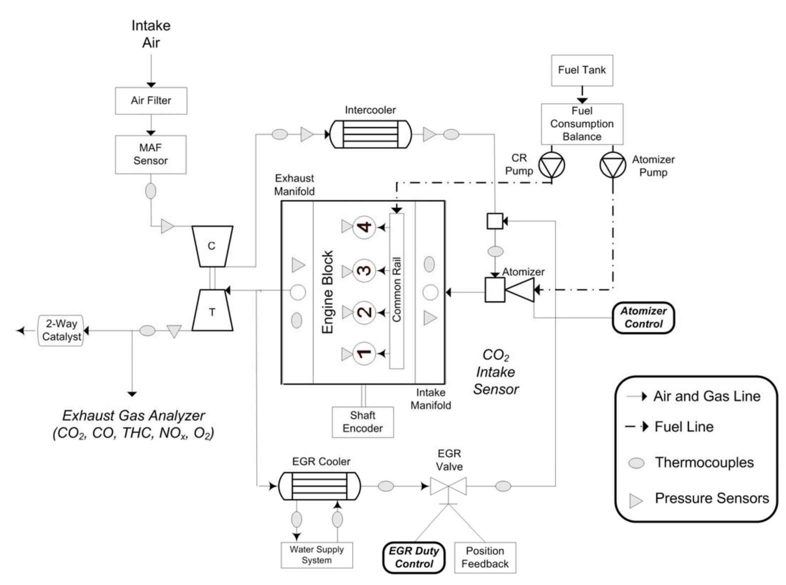

Figure 3: Engine Instrumentation for Combustion and

Figure 4: Top: Atomized Diesel Fuel from Atomizer; Middle and Bottom: Time Lapse of Atomized Diesel in 2 L Flask

3

The Need for Control: Experimental Evidence

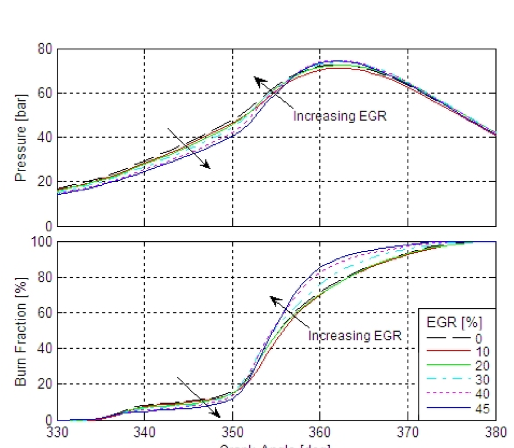

Figure 5: Sensitivity of EGR on Cylinder Pressure and Combustion

- Figure 5 shows experimental results for increasing EGR at a constant fuel rate:
  - Increasing the residual gas has the effect of delaying combustion
  - However, increasing residual gas tends to increase the charge temperature, which can also have the effect of advancing combustion
- Figure 6 shows the high dependence of combustion on a fuel rate increase:
  - Increased fuel rates lead to advanced combustion; this can lead to knocking
- Figure 7 shows the effect of both fueling rate and EGR on indicated efficiency:
  - At low fuel rates, the addition of EGR gives a large improvement in efficiency
  - At higher fuel rates, the addition of EGR is not enough to retard combustion so that the indicated efficiency is dramatically improved.

In order to maintain good efficiency and maintain acceptable cylinder pressures, control is required.

Furthermore, technologies such as variable valve timing must be used to extend the load range and improve efficiency. These technologies require an additional level of control

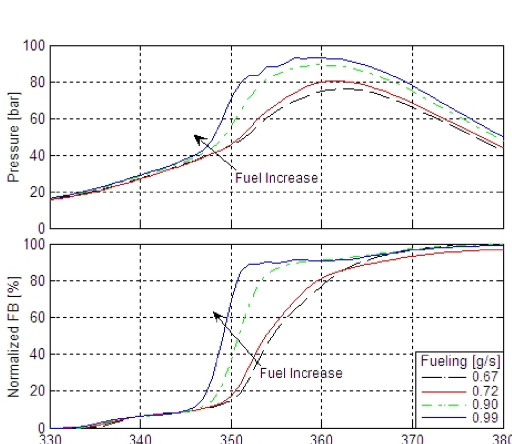

Figure 6: Sensitivity of Fueling on Cylinder Pressure and Combustion

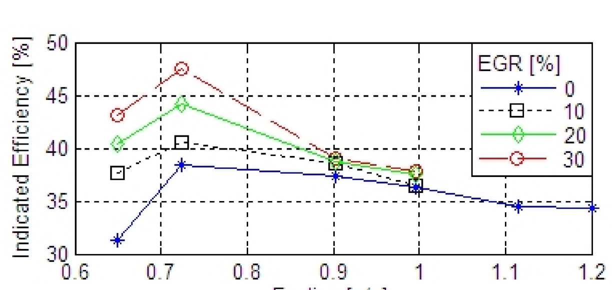

Figure 7: Sensitivity of EGR on Indicated Efficiency for Varying Fueling Rates

4

Cylinder-to-Cylinder Variation

- By using a multi-cylinder engine, it forces the experiments to be constrained to the operable range of a practical engine:
  - For instance, high boost pressures are difficult to achieve with HCCI because of high EGR rates and low load operation.
- The use of a multi-cylinder engine also allows the witnessing of multi-cylinder effects:
  - Non-uniform distribution of air to individual cylinders
  - Non-uniform distribution of fuel to individual cylinders
  - Non-uniform distribution of EGR to individual cylinders
  - Varying levels of heat transfer due to coolant routing through the engine block
- Figure 8 shows the cylinder-to-cylinder variation in IMEP for increases in fueling; note that there is approximately 1 bar of IMEP difference between the lowest and highest cylinder
- Figure 9 shows a variation that the deviation from the highest to lowest efficient cylinder of nearly 10%.

Even with a completely homogenous charge introduced into the intake manifold, cylinder-to-cylinder variation is expected due to imbalances in the mass of charge inducted into each cylinder as well as thermal differences between cylinders.

Although these issues were not the purpose of this investigation, they make clear that cylinder-wise control may be necessary to achieve best performance.

With the current experimental setup (manifold injection), individual cylinder fuel trimming is not possible. In the future, port injection will be used to allow a means of allowing cylinder-by-cylinder control.

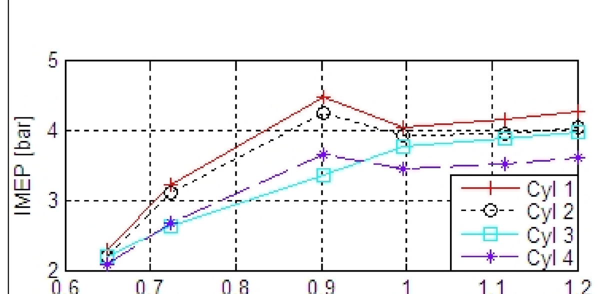

Figure 8: Cylinder-to-Cylinder IMEP Variation

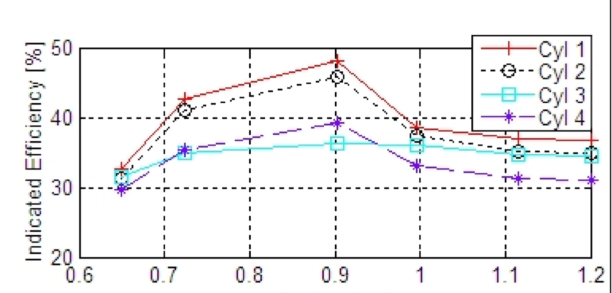

Figure 9: Cylinder-to-Cylinder Indicated Efficiency Variation

5

A Mean-Value HCCI Air-Loop Model

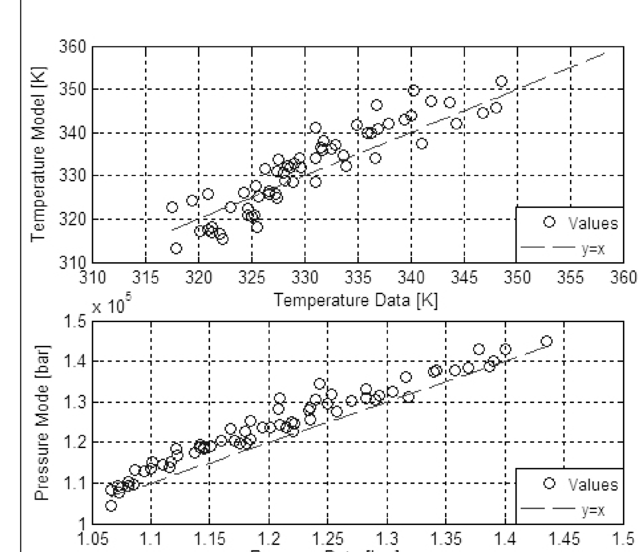

Figure 10: Correlation of Experimental and Model Data for Intake Temperature and Pressure

- Figure 11 shows a schematic of the components of the mean-value model air delivery model; sub-models include:
  - Compressor/Turbine models
  - EGR System model (with cooler)
  - Intake manifold model (with atomized fuel injection)
  - Exhaust manifold model
- Model parameters are determined from physical values and from steady-state and dynamic tests on an engine dynamometer
- Figure 10 shows the agreement between measured data points and model predictions
  - This validation is for the entire model (including combustion) and shows good agreement

The goal of this model is to accurately predict the conditions at intake valve closing for the combustion model.

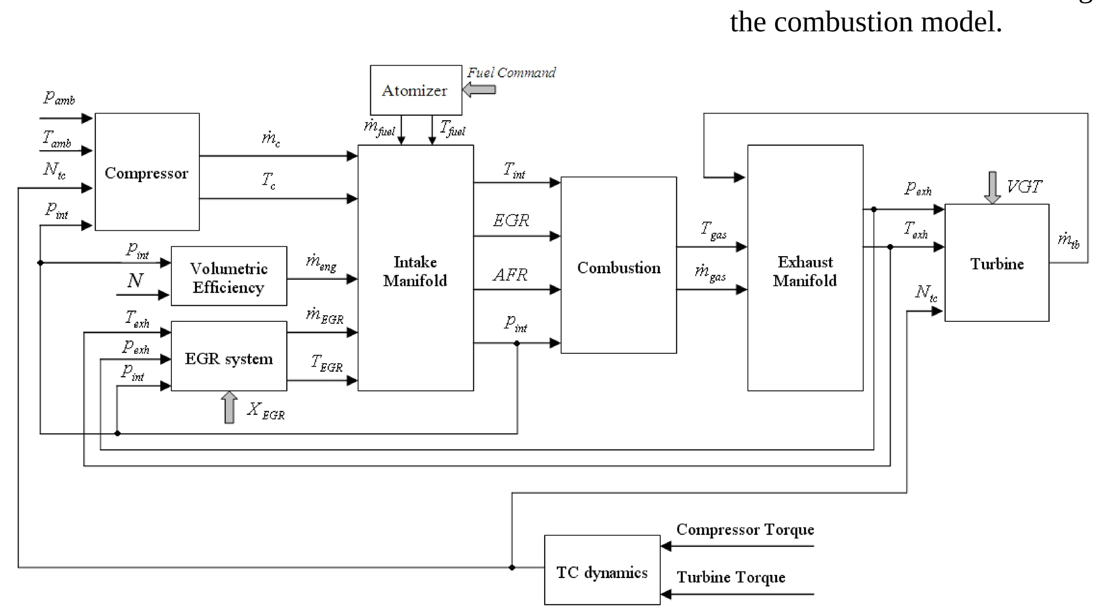

Figure 11: Simulink Implementation of the Multi-Cylinder HCCI Engine

6

Control-Oriented Combustion Model

$$\frac{dT}{d\vartheta} = \frac{1}{Mc_v}\left(\frac{dQ_g}{d\vartheta} - \frac{dQ_w}{d\vartheta} - p\frac{dV}{d\vartheta}\right)$$

$$\dot{Q}_w = h_w A_S(\vartheta)(T - T_{wall})$$

$$\frac{dQ_g}{d\vartheta} = \eta M_{fuel} LHV \frac{dx_b}{d\vartheta}$$

$$x_b(\vartheta) = \alpha x_1(\vartheta) + \beta x_2(\vartheta) + (1-\alpha-\beta)\, x_3(\vartheta)$$

$$x_i(\vartheta) = 1 - \exp\left[-a_i\left(\frac{\vartheta - \vartheta_{0i}}{\Delta\vartheta_i}\right)^{m_i+1}\right], i = 1,2,3$$

$$AR(\vartheta) = \frac{A}{\omega}[O_2]^{-0.53}[Fuel]^{0.05}\rho^{0.13}\exp\left(\frac{E_a}{RT}\right)$$

$$\int_{IVC}^{\vartheta_{SOC}} \frac{1}{AR(\vartheta)}\, d\vartheta = 1$$

Figure 12: Key Equations for the HCCI Combustion Model

- CFD and chemical kinetics routines are too complex for use in a control oriented model.
- The modeling structure used, shown in Figure 12, relies on the use of Wiebe functions which are commonly used for gasoline combustion. Three Wiebe functions were used to capture the characteristics of diesel HCCI:
  - The first Wiebe function captures the cool-flame combustion.
  - The second Wiebe function captures the main combustion.
  - The third Wiebe function captures the long duration combustion that is present in diesel HCCI.
- An "auto-ignition" integral is used to accurately predict the start of the cool flame and temperature threshold was found to accurately model the start of the main flame.
- The values in the model are parameterized by things, such as fuel quantity, air mass, diluent mass, charge temperature, *etc.*
- Figure 14 shows the three phases of combustion, which are each modeled by a single Wiebe function.
- Figure 13 shows typical agreement between the model and experimental data

This simple model has proven capable of modeling HCCI combustion over a range of operating conditions.

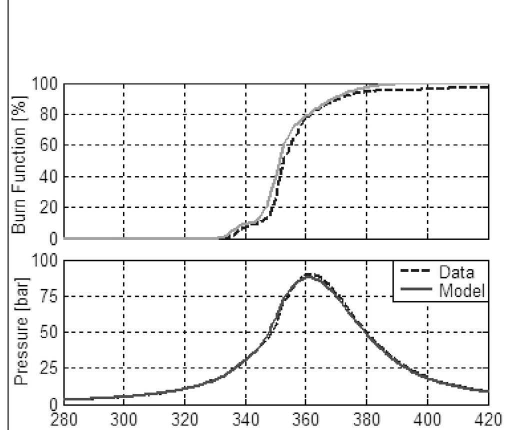

Figure 13: Combustion Model Agreement with Experimental Data

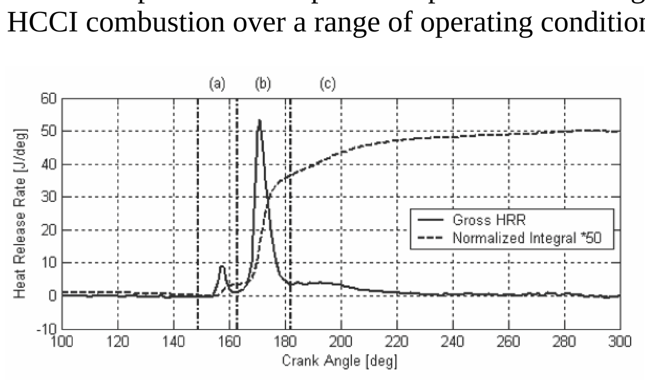

Figure 14: Illustration of the Use of Three Wiebe Functions for Modeling HCCI Combustion

7

Putting the Models Together

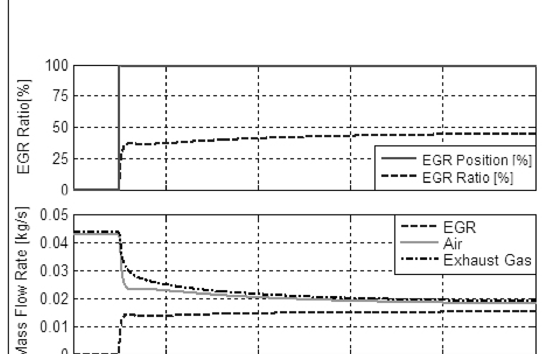

Figure 15: Simulated Air Loop Response to a Step in EGR Valve Position

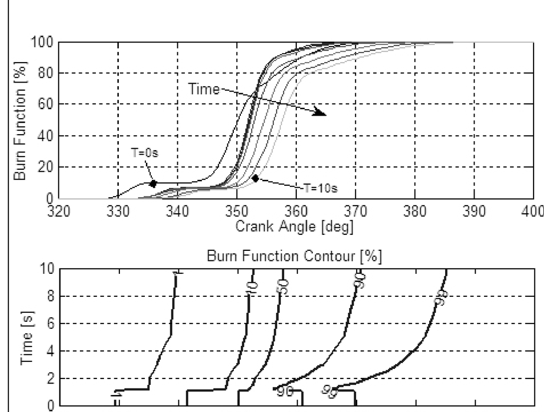

Figure 16: Evolution of Cylinder Pressure during a Step Input in EGR Position

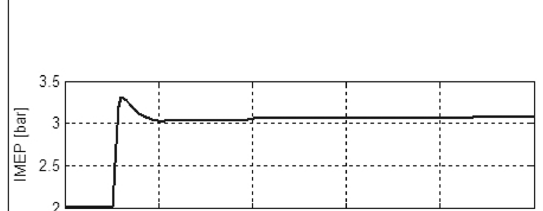

Figure 17: IMEP Response to Step Input in EGR Valve Position

- The Mean-Value Air-Loop model and the combustion model are integrated into a Matlab-Simulink® simulator
  - The air-loop model simulates the intake manifold, exhaust manifold, turbocharger, intercooler, EGR valve, and EGR cooler; this results in the determination of the charge composition, temperature, and pressure at intake valve closing
  - From this point, the combustion model calculates the rate of heat release in the cylinder which leads to cylinder pressure which is used to calculate the torque production of the engine
- The upper plot in Figure 15 shows a simulated step in EGR valve position, from fully closed to fully open
- The lower plot shows an initial rapid change in EGR flow rate, air flow rate, and exhaust gas flow rate; which is followed by a much slower change until steady state is reached
- Figure 16 shows the evolution of cylinder pressure over the ten second transient simulation
  - The upper plot shows the variation in heat release
  - The lower plot effectively shows how the burn fraction varies with respect to time; not an initial rapid change in the metrics
- Figure 17 shows the IMEP response to this open loop step input; the IMEP has an initial overshoot before settling into nearly the steady state value

This simple exercise shows the degree that combustion can change over even a simple EGR maneuver.

Developing a control that can manage the HCCI system during transients is a key challenge for implementing any HCCI strategy.

8

Conclusions and Future Work

The multi-cylinder research has demonstrated that an essentially unmodified diesel engine can be successfully run in HCCI using external mixture preparation. This method of combustion has demonstrated similar BSFC and dramatically improved NO_x emissions at the light loads possible with the current experimental engine. Furthermore, relatively simple models can be used to provide useful models of an HCCI engine.

1. Experimental Investigation and Modeling of a Variable Cam HCCI Engine: Experiments to date have focused on a stock valve timing of a CIDI engine. In order to gain greater control over combustion and extend the load range of the HCCI combustion, it is necessary to allow for variable cam timing. Using the power of mean-value modeling, it is possible to perform experiments using a using a series of static cam positions, and integrating the results into a model capable of dynamic operation. This eliminates the need to perform testing using difficult to obtain variable cam hardware.
2. Load Extension for HCCI Combustion: Using the current, high compression ratio, fixed-cam engine, high loads are not possible with HCCI. The primary method of extending the load range is by delaying the onset or duration of combustion. This can partially be accomplished using cooled EGR and intake charge cooling, however, not to the extent required to achieve practical mid-load operation. In the literature, one of the most favorable methods of delaying the onset and slowing the rate of combustion is through variable valve timing.
3. Actuator Arbitration for HCCI Control: Because of the presence of many indirect and overlapping methods of controlling HCCI combustion, some method of arbitration between what actuators to use under what circumstances must be conducted. For instance, EGR can be used to control combustion phasing as well as valve timing. Each of these options has a varying time response and impacts the engine in a different manner. A rigorous method of arbitration between these different controls must be developed which comprehends the relative cost of actuation (physical cost, energy cost, etc.) against the performance of the actuator (time-response, effectiveness, etc.)
4. Develop Feedback Control Methods for HCCI Combustion: As with any system, feedback control is important for improving the robustness of the control system. With HCCI combustion, this is critical, since it is quite possible to damage an engine through knocking due to slightly incorrect control inputs. Cylinder pressure has been presented as a possible feedback mechanism, provided that low-cost pressure transducers enter the market. Another viable method is the use of crankshaft speed fluctuations, which OSU has demonstrated can be used to reconstruct in-cylinder pressure in real time. Developing an approach for using cylinder pressure (real or virtually measured) for combustion control would be one method of closing the loop on HCCI combustion.

Current work to date has been funded through the CAR Industrial Consortium. We are currently seeking additional funding mechanisms to accelerate the pace and scope of our work.

9

The Ohio State University Center for Automotive Research
930 Kinnear Rd.
Columbus, Ohio 43212

Primary Contact Regarding the Work:
Prof. Yann Guezennec, Dept. of Mechanical Engineering
guezennec.1@osu.edu

Contributing Team Members: Mr. Marcello Canova, Mr. Luca Garzarella, Mr. Marco Ghisolfi, Prof. Yann Guezennec, Dr. Shawn Midlam-Mohler, Prof. Giorgio Rizzoni, Mr. Adam Vosz