SAE TECHNICAL PAPER SERIES

2007-01-0773

Cylinder Pressure-Based Control of Pre-Mixed Diesel Combustion

H. Husted, D. Kruger, G. Fattic, G. Ripley and E. Kelly
Delphi Corporation

Reprinted From: Electronic Engine Controls, 2007
(SP-2087)

ISBN 0-7680-1636-3

9 780768 016369

2007 World Congress
Detroit, Michigan
April 16-19, 2007

SAE International™

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-0790 Web: www.sae.org

For permission and licensing requests contact:

SAE Permissions
400 Commonwealth Drive
Warrendale, PA 15096-0001-USA
Email: permissions@sae.org
Fax: 724-776-3036
Tel: 724-772-4028

For multiple print copies contact:

SAE Customer Service
Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org

ISSN 0148-7191

Printed in USA

2007-01-0773

Cylinder Pressure-Based Control of Pre-Mixed Diesel Combustion

H. Husted, D. Kruger, G. Fattic, G. Ripley and E. Kelly
Delphi Corporation

ABSTRACT

Implementation of real-time combustion feedback for use in closed-loop combustion control is a technology that has potential to assist in the successful production implementation of advanced diesel combustion modes. Low-temperature, pre-mixed diesel combustion is presently of interest because it offers the ability to lower the engine-out emissions of oxides of nitrogen (NOx) and particulate matter (PM). The need for lowering these two emissions is driven by tighter regulations enacted worldwide, especially the NOx limits in the United States. Reducing engine-out emissions eases the need for additional exhaust aftertreatment devices and their associated cost and mass.

In this paper we will describe an experimental cylinder pressure-based control system and present both steady-state and transient results from a diesel engine employing a pre-mixed type of combustion. Data are presented showing engine operation with the control system enabled and disabled, highlighting the control effectiveness of the real-time cylinder pressure feedback.

INTRODUCTION

The use of an in-cylinder pressure sensor is one means of providing combustion feedback. When sampled in real-time with the appropriate electronics, the resulting cylinder pressure waveform can be analyzed to determine combustion parameters of interest, such as the start of combustion angle, indicated mean effective pressure (IMEP), total heat release quantity, and the angular location of peak pressure (LPP). This combustion feedback can then be used to adjust relevant engine control parameters.

A number of papers have recently been presented about the closed-loop control of combustion using cylinder pressure [1-4]. This closed-loop feedback can be effective in reducing the effects of component variability and aging effects, thus reducing the overall emissions dispersion from engine to engine. This paper deals with a second area where closed-loop combustion control can be useful – that of controlling advanced diesel combustion modes. Low-temperature, pre-mixed combustion in diesel engines consists of injecting the fuel such that it is allowed to vaporize and mix with the intake mixture before combustion occurs. A high level of exhaust gas recirculation (EGR) is often used to reduce the combustion temperature. Since all the fuel is typically injected prior to the start of combustion, the crank angle when combustion starts is controlled by the chemical reaction kinetics of the mixture, which are directly influenced by the pressure and temperature of the mixture (among a number of other factors). This introduces new variability due to factors that are not present in traditional diffusion-burn diesel combustion, where start of combustion occurs a cetane-number-based time delay after the start of the fuel injection.

While pre-mixed combustion is desirable for emissions reduction, a challenge is maintaining the stability of combustion during transient events and transitions between combustion modes. Closed-loop feedback control offers the potential to improve controllability of pre-mix combustion, thus enabling a means of greatly improving engine-out exhaust emissions.

SYSTEM DESCRIPTION

A system was developed to test the functionality of closed-loop cylinder pressure feedback control on a multi-cylinder diesel engine. The system is shown in Figure 1.

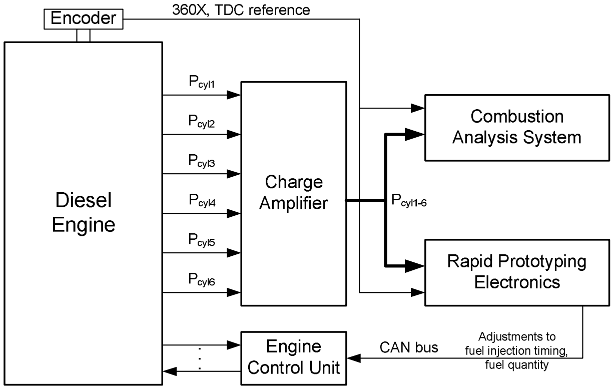

Figure 1: System Diagram

It consists of instrument-grade in-cylinder pressure sensors, a high resolution position encoder, a dSPACE AutoBox rapid prototyping unit, and an A&D Technology Redline Combustion Analysis System (CAS). The engine was equipped with a Delphi engine controller and a Delphi DFI-1 fuel injection system. The signals from the piezoelectric pressure sensors were processed by a charge amplifier and then routed to both the rapid prototyping system and the CAS, where simultaneous cylinder pressure samples on all cylinders were taken at 1° crankshaft intervals. The purpose of connecting the CAS and rapid prototyping unit in parallel was to allow comparison of the resulting calculated parameters that are based on the cylinder pressure samples.

PROTOTYPING HARDWARE CONFIGURATION

A dSPACE Autobox was used as the platform for rapid prototyping. The hardware configuration is shown in Figure 2. A 900MHz DS1005 PowerPC Board is the main processor for the system, and it proved to have enough calculation through-put for real-time feedback control. A DS5001 Digital Input Board was used to read the engine position signals, and the DS2003 Analog to Digital Board was used to simultaneously capture the pressure sensor signals from each engine cylinder. The DS5101 Digital Output Board was used for diagnostic state indication. The DS4302 CAN board was used for communications to an external electronic control unit.

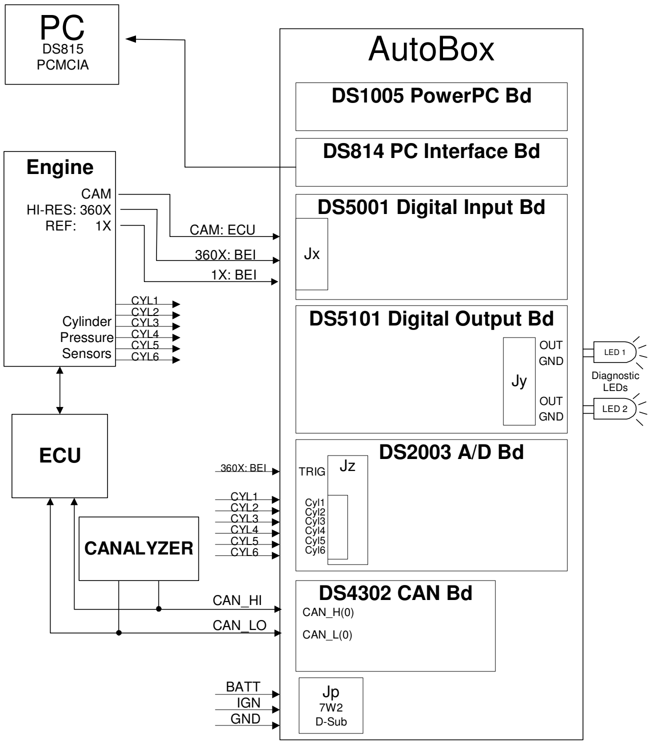

Figure 2: Rapid Prototyping Configuration

PROTOTYPING SOFTWARE CONFIGURATION

The signal processing and closed-loop control algorithms were developed in a block-diagram-oriented modeling and simulation environment which allowed offline simulation prior to hardware implementation. Once the algorithms performed as desired in the offline simulation environment, they were converted to code that could be executed by the rapid prototyping hardware. The executable model was divided into two major sections, data collection and data processing, as shown in Figure 3. The two major sections were each 720 engine degrees long and were controlled using an external reference trigger. First, for 720 degrees, data were collected for all cylinders at one-degree intervals. Then, for the next 720 degrees, calculations were performed and feedback sent to the electronic control unit (ECU).

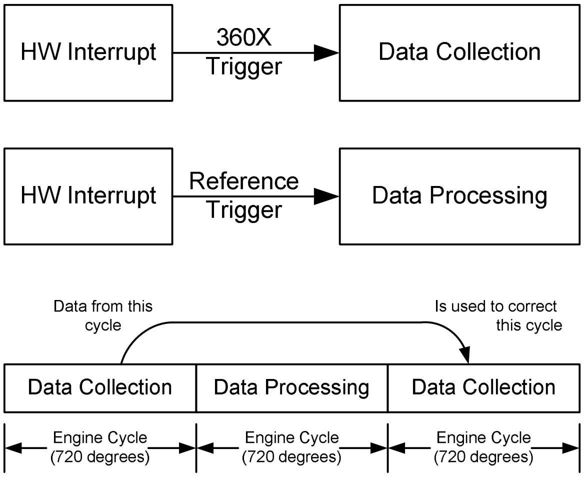

Figure 3: Model Execution Structure

COMBUSTION CALCULATIONS

Once the crank aligned cylinder pressure samples were collected, the pressure waveform offset was referenced to absolute pressure using the manifold absolute pressure sensor reading as an indicator of in-cylinder pressure near bottom dead center after the intake stroke. Next, the combustion calculations were performed in real-time based on the cylinder pressure data and knowledge of other engine parameters need to compute the swept volume, V_{swept}, and the change in volume between samples, dV. A great deal of combustion-related information can be ascertained from the in-cylinder pressure data using these calculations. Numerous researchers have written about the subject [5-7], including Brunt and Eriksson.

From crankshaft angle-aligned pressure data, several combustion parameters may be generated. Of particular interest are indicated mean effective pressure (IMEP), heat release quantity (HR), the angular location corresponding to when 50% of the total heat release has occurred (HR_{50}), maximum cylinder pressure (P_{max}) and the angular location corresponding to maximum (peak) pressure (LPP).

IMEP is a normalized performance measure of an engine's work output and is obtained by dividing the work per cycle by the cylinder swept volume. It is an indication of the torque produced by a cylinder and has the units of force per unit area, or pressure. The definition for IMEP is as follows [5]:

$$IMEP = \frac{\int dW}{V_{swept}} \text{ or } \frac{\int PdV}{V_{swept}} \quad (1)$$

where P and dV represent cylinder pressure and rate of change in cylinder volume, respectively. The angular integration span used in this project included the compression and expansion strokes, making the result the gross IMEP, since it does not include off-cycle pumping work for exhausting the cylinder contents and drawing in the intake gas charge.

The calculation for cumulative net heat release (HR) gives the indicated net amount of heat released from the combustion cycle (ignoring heat lost to the cylinder surfaces and crevice effects.) It is a single-zone model based upon the first law of thermodynamics and is described as follows [8]:

$$HR = \int \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \quad (2)$$

where γ is the ratio of specific heats (c_p/c_v) and P and V represent cylinder pressure and volume at a crankshaft angle of θ.

A sample interval of one crank angle degree was used for the testing and results presented in this paper. Additional information on the electronics and software approaches taken to acquire these data and perform the calculations in real-time can be found in [9].

CLOSED-LOOP CONTROL

Once the combustion parameters have been calculated for a combustion event, these data can be used as the input to a closed-loop feedback control system to adjust relevant engine control variables to influence succeeding cycles. Several parameters were studied for closed-loop control. Of these, two will be presented in this paper.

CLOSED-LOOP COMBUSTION PHASING

The first parameter used for feedback control was the angle of 50% heat release, HR_{50}. It is useful in that it gives feedback on the angular location of the center of the combustion event, often referred to as “phasing”. The phasing of the combustion affects a number of factors including the efficiency at which the released heat is converted to engine work.

To close the feedback loop, the calculated HR_{50} was compared to a target HR_{50}, and the resulting error was fed into a classical proportional-integral controller as shown in Figure 4 below. The fuel injection control produced a control adjustment to the fuel injection start of injection (SOI) angular timing. By having a pressure sensor in each cylinder, the combustion feedback allowed for combustion phasing on an individual cylinder basis and a resulting ability to correct for cylinder-to-cylinder variations as well as follow a commanded target value. The results of combustion phasing control are shown in the following sections for steady-state and transient conditions.

CLOSED-LOOP CYLINDER IMEP BALANCING

The second parameter used for feedback control was IMEP, on a cylinder-by-cylinder basis. The goal of this control was to equalize or “balance” the IMEP produced by each cylinder. Similarly to the combustion phasing control, proportional-integral control was used to create adjustments in fuel quantity to bring each cylinder’s IMEP into alignment. The results are shown in the following sections for steady-state and transient conditions.

STEADY-STATE TEST RESULTS

The feedback control system was tested on a diesel engine attached to a motoring dynamometer to verify the effectiveness of both the combustion phasing control and the cylinder balancing control at various steady state operating points. Data were taken at several speed-load points within the low-temperature, pre-mixed combustion region and at several points having traditional diesel combustion.

The steady state engine test point presented here was at 2000 RPM and a BMEP of 3.5 bar, with the engine operating using pre-mixed combustion. Figures 5 and 6 show 50 engine cycles of individual cylinder HR_{50} angles with combustion phasing control disabled and enabled, respectively. Note that due to the model execution structure mentioned earlier, the data shown is for every other engine cycle. Cylinder pressure data was only collected every other cycle, with the off cycle being used for calculations with no sampling taking place.

In Figure 5, with closed-loop control disabled, it is

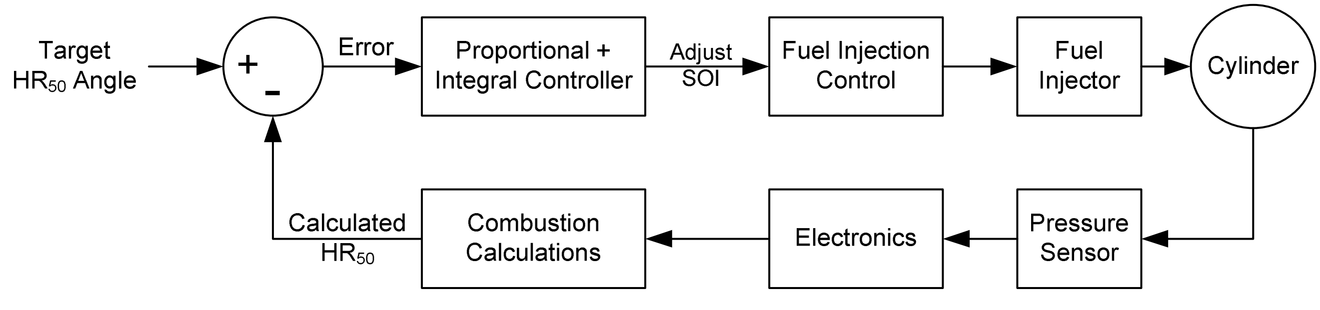

Figure 4: Combustion Phasing Control

apparent that there is some steady-state difference in the HR_{50} combustion angles from cylinder to cylinder, with cylinder 2 being particularly low. Figure 6 shows the same conditions with the closed-loop HR_{50} control enabled. It is clear that the steady-state HR_{50} readings of the cylinders are closer together.

To make evaluation of the control performance more objective, a numerical metric was created. The standard deviation of the means, σ_{means}, as shown in equation (3), is the standard deviation of each cylinder's average value of HR_{50} over every engine cycle in the test, $\bar{x}_{cyl}$, as shown in equation (4). Thus, σ_{means} means gives a numerical evaluation of how closely grouped are the cylinders.

$$\sigma_{means} = \sqrt{\frac{1}{n_{cyl}} \sum_{i=1}^{n_{cyl}} (\bar{x}_i - \bar{\bar{x}})^2} \qquad (3)$$

$$\bar{x}_{cyl} = \frac{1}{n_{cycles}} \sum_{j=1}^{n_{cycles}} x_j \qquad (4)$$

Returning to figures 5 & 6, σ_{means} = 1.7 degrees for the HR_{50} angle with disabled control. With closed-loop control enabled, σ_{means} = 0.017, a 99% reduction in average cylinder-to-cylinder variation. This type of marked improvement was true for all speed-load points tested, with both pre-mixed and traditional diesel combustion. This illustrates the effectiveness of the HR_{50} closed-loop feedback control.

It is important to note that while σ_{means} is improved with feedback control, the coefficient of variation (COV) of HR_{50} on an individual cylinder basis was not consistently improved by the closed-loop control. This overall conclusion is based on analysis of the aggregate of the test data over multiple speed-load points. A visual comparison of figures 5 & 6 shows that the cycle-to-cycle variation of each cylinder is roughly the same. For this particular steady-state point, the COV of HR_{50} did degrade from 2.0% to 3.1% on average for all cylinders. However, for some speed-load points it improved. A reduction in the latency of the control associated with the "every other cycle" method employed may allow closed-loop feedback to improve COV.

Cylinder balancing control showed similar effectiveness. Figures 7 and 8 show the test results with control disabled and enabled respectively. With disabled

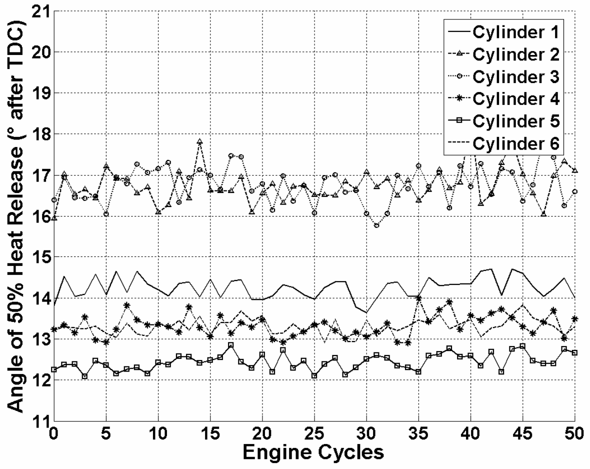

FIGURE 5. HR_{50} with Disabled HR_{50} Angle Control

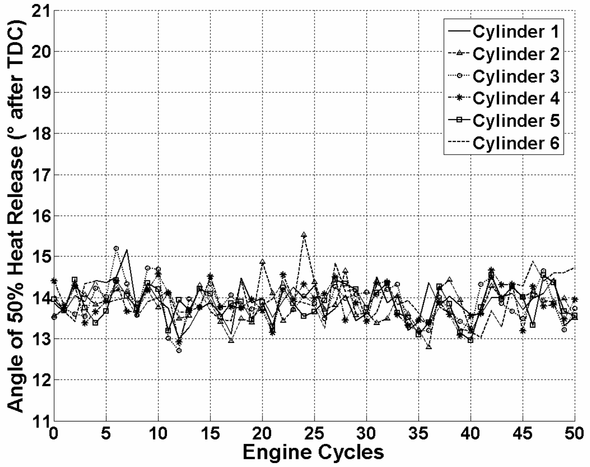

Figure 6. HR_{50} with Enabled HR_{50} Angle Control

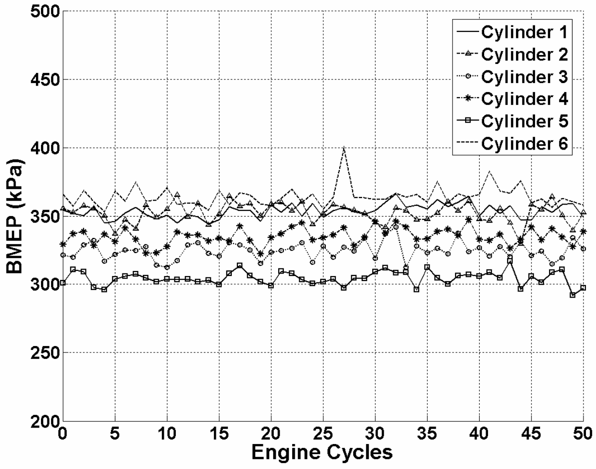

Figure 7. BMEP with Disabled Cylinder Balancing Control

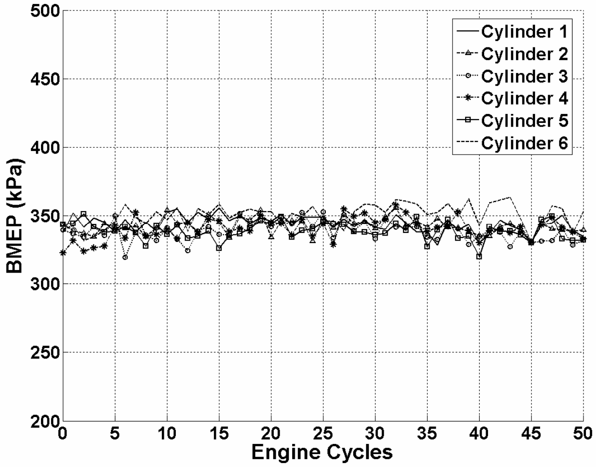

Figure 8. BMEP with Enabled Cylinder Balancing Control

control, $\frac{\sigma_{means}}{BMEP_{avg}}$ = 3.6%, versus 0.73% with enabled control, for a very significant improvement in the agreement of cylinder-to-cylinder work output. Cylinder balancing proved to be very effective for both pre-mixed and traditional diesel combustion. Similar to HR_{50} control, however, the COV of IMEP was not consistently improved on a per-cylinder basis.

TRANSIENT TEST RESULTS

One of the challenges of operating a diesel engine in a low-temperature, pre-mixed combustion mode is maintaining the stability of combustion during transient engine operation since this combustion is more directly influenced by temperature effects. To evaluate the effectiveness of the closed-loop combustion control, several transient maneuvers were performed with the engine dynamometer, using both combustion phasing and cylinder balancing control enabled simultaneously.

The transient test that will be discussed here was a constant-speed transient at 1600 RPM, with the load changed from 1.0bar BMEP to 5bar BMEP and back again. Figure 9 shows the HR_{50} angle response with feedback controls disabled. Notice the unintended late combustion phase of 30 - 40 degrees at approximately engine cycle number 40. This may be associated with a transition in combustion modes. The associated effect on torque production can be seen in figure 10, where a drop in BMEP can be seen near cycle 40.

With both controls enabled, the same test was conducted. Figures 11 and 12 show HR_{50} and BMEP results for the test. In figure 11, note the absence of late HR_{50} at approximately cycle 40 and lack of associated torque drop in figure 12. A comparison of figures 10 and 12 also shows a more consistent cylinder-to-cylinder BMEP output, demonstrating that the cylinder balancing can be effective during transient operation.

While the closed-loop transient control results will be improved through further refinement, these initial test results are promising and show that cylinder pressure-based, closed-loop combustion control offers the potential to help make advanced, low-emissions combustion modes viable for production applications.

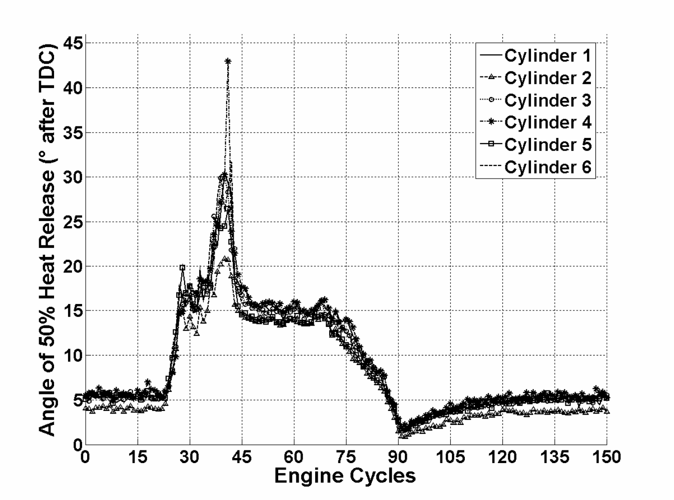

Figure 9: HR_{50}, Disabled Control, 1600 RPM

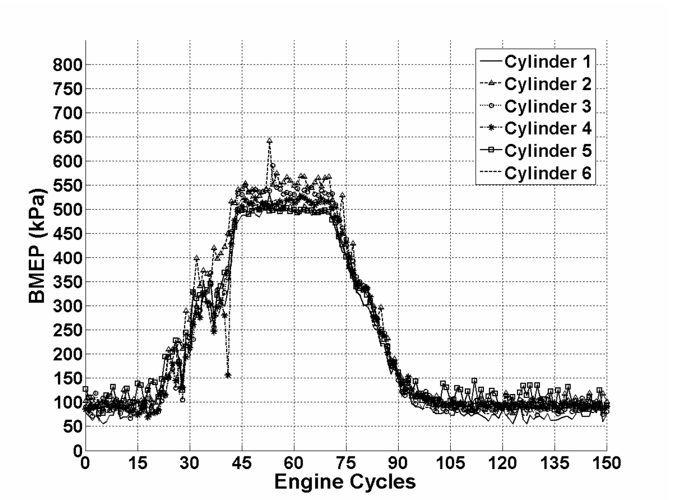

Figure 10 BMEP, Disabled Control, 1600 RPM

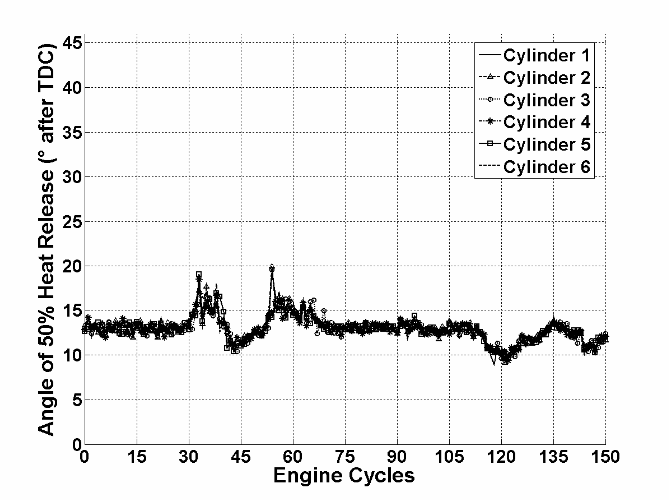

Figure 11: HR_{50}, Enabled Control, 1600 RPM

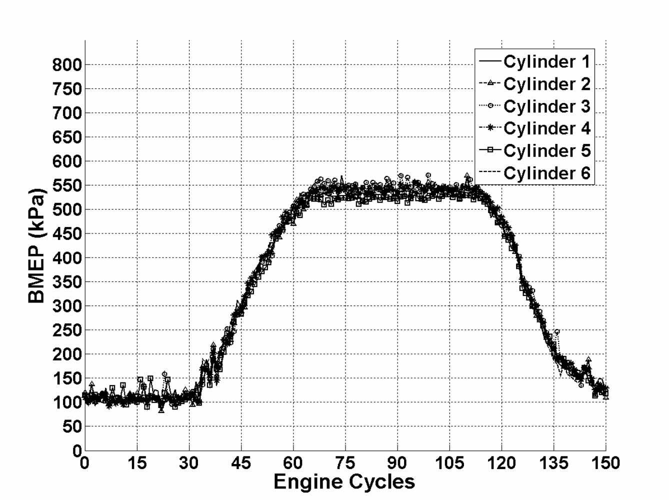

Figure 12: BMEP, Enabled Control, 1600 RPM

NEXT STEPS IN COMBUSTION CONTROL ELECTRONICS

The results discussed in this paper were accomplished using off-the-shelf prototyping hardware, as mentioned earlier. In order to achieve "next cycle" correction of combustion, an automotive-grade electronic control unit was custom-designed by Delphi. This unit, called the cylinder pressure development controller (CPDC), uses automotive temperature-rated components and circuits along with a production-intent microcontroller. In initial testing, this controller has already shown itself capable of executing the combustion calculations and closed-loop control presented in this paper.

The CPDC is capable of "next cycle" correction of combustion, so it will allow testing of cycle-to-cycle variation reduction. This electronic controller is discussed in more detail in another 2007 SAE paper [9].

CONCLUSIONS

A number of conclusions were drawn from this closed-loop combustion control work:

- Real-time closed-loop control of combustion on a multi-cylinder engine using cylinder pressure feedback is possible with present electronics technology. Crank angle-based sampling of cylinder pressure on all cylinders, followed by thermodynamic calculations based on this data, is a demanding task that is helped by specialized electronic hardware and software designs.
- Closed-loop combustion phasing and cylinder balancing are both effective in helping control low-temperature, pre-mixed diesel combustion, especially during transient operation.
- The cylinder-to-cylinder variation metric called σ_{means} was greatly improved for both HR_{50} and BMEP by closed-loop control of combustion.
- Cycle-to-cycle variation of HR_{50} and BMEP on an individual cylinder was not consistently improved by closed-loop control of combustion. This may be due in part to the "every other cycle" latency implemented with the prototyping system used for this project.
- Practical implementation in a production-style electronic controller with an automotive embedded microcontroller is possible and has been achieved.

ACKNOWLEDGMENTS

Assistance from both the Delphi Advanced Powertrain Electronics group and the Delphi Advanced Engine Modeling group was instrumental in helping with the implementation of the prototyping system and in the analysis of data and the understanding of underlying phenomena.

REFERENCES

[1] Hasegawa, Mamoru, Shimasaki, Yuichi, et al, "Study on Ignition Timing Control for Diesel Engines Using In-Cylinder Pressure Sensor", SAE Paper 2006-01-0180.

[2] Beasley, Matthew, et al, "Reducing Diesel Emissions Dispersion by Coordinated Combustion Feedback Control", SAE Paper 2006-01-0186.

[3] Pinson, John, "Bringing the Low NOx Diesel Under Control", Presentation to the Diesel Engine Emissions Reduction (DEER) Conference, August 22, 2006.

[4] William de Ojeda, Alan Karkkainen, "Multicylinder Diesel Engine Design for HCCI operation", Presentation to the Diesel Engine Emissions Reduction (DEER) Conference, August 22, 2006.

[5] Brunt, Michael, et al, "The Calculation of Heat Release Energy from Engine Cylinder Pressure Data", SAE Paper 980152.

[6] Brunt, Michael, Emtage, Andrew, "Evaluation of Burn Rate Routines and Analysis Errors", SAE Paper 970037.

[7] Eriksson, Lars, "Requirements for and a Systematic Method for Identifying Heat Release Model Parameters", SAE Paper 980626.

[8] Challen, Edward and Baranescu, Rodica, Diesel Engine Reference Book. Woburn, MA: Butterworth-Heinemann, 1999.

[9] Schten, Karl, et al, "Design of an Automotive Grade Controller for In-Cylinder Pressure Based Engine Control Development", SAE Paper 2007-01-0774.

CONTACT

For additional information, please contact Harry Husted by email at Harry.L.Husted@Delphi.com.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BMEP	- Brake Mean Effective Pressure
COV	- Coefficient of Variation
CPDC	- Cylinder Pressure Development Controller
EGR	- Exhaust Gas Recirculation
HR	- Total Heat Release
HR_{50}	- Heat Release 50% Angle
IMEP	-Indicated Mean Effective Pressure
LPP	- Location of Peak Pressure
NOx	- Nitrogen Oxides
PM	- Particulate Mater
P_{max}	- Pressure Maximum
RPM	- Revolutions per Minute
TDC	- Top Dead Center