

HCCI Engine Application on a Hydraulic Hybrid Bus

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ABSTRACT

After initial trials on Homogeneous Charge Compression Ignition (HCCI) engine design and tests pursuing feedback control to avoid misfire and knocking over wide transient operation ranges, Engineers at the US Environmental Protection Agency's (EPA) National Vehicle Fuel and Emissions Laboratory identified the crucial engine state variable, MRPR (Maximum Rate of Pressure Rise) and successfully controlled a 1.9L HCCI engine in pure HCCI mode [1]. This engine was used to power a hybrid Ford F-150 truck which successfully ran FTP75 tests in 2004. In subsequent research, efforts have been focused on practical issues such as improving transient rate, system simplification for controllability and packaging, application of production grade in-cylinder pressure sensors, cold start, idling and calibration for ambient conditions as well as oxidation catalyst applications for better turbine efficiency and HC and CO emissions control. A 6.4L V8 HCCI engine and control system was then developed for a hydraulic hybrid shuttle bus as a demonstration platform. The bus has been tested in the laboratory against various driving cycles and driven on city streets, country roads and highways.

This paper summarizes the system approach in developing the HCCI engine and its application on the hydraulic hybrid bus.

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INTRODUCTION

The benefits of HCCI engines have been well studied and recognized. However, using the technology in real world application has been difficult because of obstacles such as transient controllability, cylinder to cylinder and cycle to cycle variations, limited operating range and high HC and CO emissions. There are also issues with cold start, idling, noise control and calibration for varying ambient conditions.

There have been news reports about HCCI powered test vehicles but few technical papers have been published to describe them. General Motors (GM) has successfully demonstrated two test vehicles with HCCI-SI engines. The engines operate in HCCI mode within certain power ranges and switch into SI mode when the engine speed and load increase to a certain threshold. In HCCI mode, an engine controller adjusts multiple actuators to maintain optimal combustion timing or crank angle position at 50% complete combustion (CA50) [2]. GM engines feature variable valve lift and phasing and a central direct-injection fuel system.

HCCI engine development at US EPA has been aimed as a power plant for hydraulic hybrid drive trains which tend to be medium to heavy duty vehicles. The engines run HCCI mode on full operating map while running SI for cold start or as a limp home mode. Hybrid application allows the engine to avoid most low to medium load operations. It also reduces the frequency of the transient operations as compared with a conventional drive train, even though quick transient capability is still desirable for better vehicle efficiency. A basic structure of the HCCI engine/hydraulic hybrid drive system for the shuttle bus is shown in [Figure 1](#). The EPA series hydraulic hybrid technology is able to maximize fuel efficiency by using high rates of regenerative braking (up to 70 percent energy recovery), by nearly always running the engine at its best efficiency, and by shutting the engine off when it is not needed. A detailed description of the system can be found at the EPA website by following the link: <http://www.epa.gov/otaq/technology/research/research-hhvs.htm>.

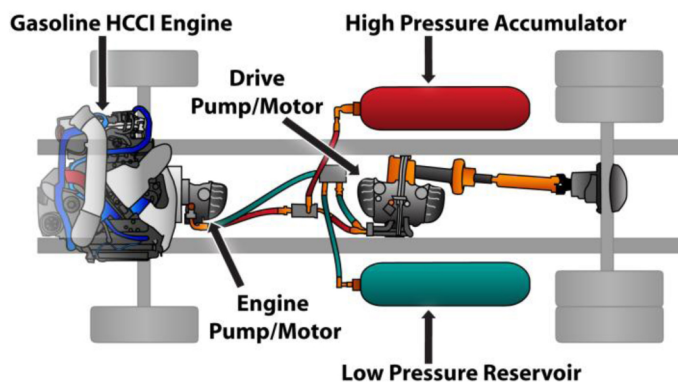


Figure 1. Hydraulic Hybrid Drive System

The EPA HCCI engine is managed by an engine controller with MRPR as the main feedback parameter. MRPR is not used as an indicator of NVH and knock limit but a state variable which describes, qualitatively and quantitatively, the robustness of the combustion. It not only maintains normal combustion against any disturbance, but also balances cylinders and directs optimal response for the next combustion event when the direction and the rate of transition are commanded. The method using MRPR as a feedback control parameter is described in detail in a companion paper [3].

The first stand alone EPA HCCI engine was described in a 2004 SAE Paper [1]. This engine was later used to power a hybrid Ford F- 150 truck which successfully ran FTP75 tests in 2004. Findings and conclusions from this study led to the subsequent research with focus on practical issues such as identifying boost system, improving transient rate, system simplification for controllability and packaging, application of production grade in-cylinder pressure sensors, cold start, idling and calibration for ambient conditions as well as oxidation catalyst applications for better turbine efficiency and HC and CO emissions control. The feasibility and method of building MRPR observers from engine output variables to remove in-cylinder measurement for production purpose was considered as well.

The 6.4L V8 HCCI engine and control system was then developed for a hydraulic hybrid shuttle bus as a demonstration platform incorporating advances made in each area listed above. A Navistar-IC PC5 HC Series shuttle bus was selected for the conversion. The bus was originally equipped with a 2008 International® MaxxForce™ 7 diesel engine and conventional drivetrain. After modifications and installation of the HCCI engine and hydraulic hybrid drive system, the shuttle bus weights 9250 kg. Pictures of the HCCI engine powered bus and truck are shown in Figure 2.



Figure 2. HCCI engine powered vehicles

The hybrid bus has been tested in the laboratory against various driving cycles and driven on city streets, country roads and highways. This paper describes the engine system, its calibration in the test cell and application on the bus.

6.4L V8 HCCI ENGINE SYSTEM

An International® MaxxForce™ 7 engine, the same type of engine originally used for the base bus, was modified for this study. The stock diesel fuel system was removed. An intake manifold was custom designed to accommodate gasoline port injectors which are Delphi injectors from a production engine. Stock pistons were modified to yield a compression ratio of 16.5:1. A low-pressure EGR loop was used in place of the stock high pressure EGR system. Two small catalysts were placed in the exhaust runner from each cylinder bank leading to the Variable Geometry Turbocharger (VGT). Apart from these changes, the engine is in its production configuration. Table 1 lists the basic specifications of the engine as tested.

Table 1. Engine Specifications

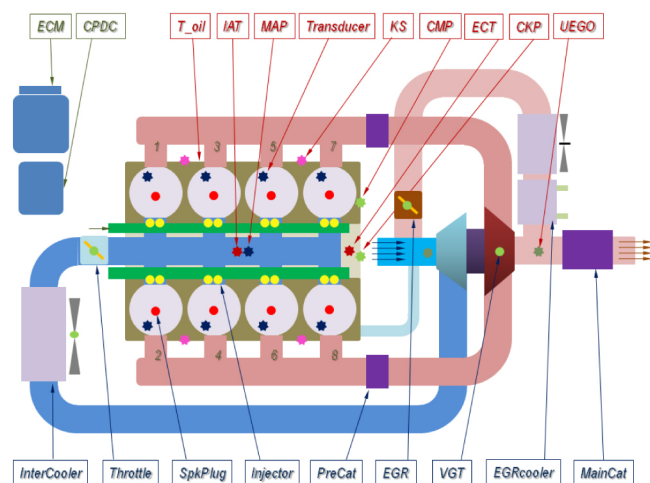
Engine Type	V8
Displaced volume	6.4 L
Stroke	105 mm
Bore	98.2 mm
Connecting Rod	255 mm
Compression ratio	16.5:1
Valve Timing	Fixed, Stock
Port Injectors	Delphi
Cylinder Pressure Sensor	Beru PSG
Knock Sensor	NGK Wide Band

Commercial regular 87 Octane pump gasoline was used for this study. The specification of the fuel is listed in Table 2.

Table 2. Fuel Specifications

	Unit	
Carbon	wt %	87.28
Hydrogen	wt %	12.72
Heating Value	MJ/kg	42.8
Specific Gravity		0.7594 @ 15.5°C
Octane #	(RON+MON)/2	87
Sensitivity	RON-MON	7.6
Vapor Pressure	kPa	66.883
Density	g/cm ³	0.7581 @ 15.5°C

The systems of the HCCI V8 engine are shown in Figure 3. Rapid changes in intake charge flow rates, boost level and charge temperature are desirable for transient operations. However, since there is no variable valve timing mechanism available on this engine, these variables cannot be changed on a cycle to cycle basis. Intake boost level and EGR content of the cylinder charge are controlled by adjusting the VGT vane position and the EGR valve. Adjusting intercooler fan speed provides some modulation of intake charge temperature. Radiator fan speed is adjusted to maintain the desired coolant temperature.

**Figure 3. HCCI V8 engine systems**

The only quantity which can be changed from cycle-to-cycle and cylinder-to-cylinder is fuel quantity, which has been used as the main variable that controls engine navigation through the operating map while the other controlled variables, e.g. boost level, intake temperature and EGR, reach desired levels at a relatively slow pace.

For a practical system, cylinder pressure based control requires production grade sensors, which are accurate enough for the control, robust enough for reliability and durable and low enough cost for market feasibility. Such sensors have been discussed in the literature [4]. A Beru production grade glowplug type cylinder pressure sensor was installed for each cylinder. The cylinder pressures are collected and processed, on a cylinder by cylinder, cycle by cycle basis, by a Delphi Cylinder Pressure Development Controller (CPDC), a pre-production experimental device [5]. The output of the CPDC, information on combustion quality Maximum Rate of Pressure Rise (MRPR), is provided to a Pi Shurlok® (now Pi Innovo®) G850 engine controller module (ECM) as feedback. It is important to note that the numerical value of MRPR can vary depend upon how it is derived. It is not an absolute value. The value of MRPR calculated by the CPDC is up to 1 bar/deg higher than that by the test cell combustion analyzer (MTS ADAPT-CAS™). The engine test cell data reported in this paper were by CAS and data collected in vehicle testing were from the CPDC.

Four NGK knock sensors were installed on the engine, with each sensor observing two cylinders' MRPR estimation. The locations of the sensors were chosen to yield the maximum signal gains. The knock sensor signals were processed to yield a quantity called KSmetric for each cylinder on a cycle by cycle basis. This information is sent to the ECM via Controller Area Network (CAN) signals. There is significant correlation between KSmetric and MRPR. KSmetric could act as a proxy of MRPR thus significantly reducing the overall engine cost. The correlation between KSmetric and MRPR and the usage of KSmetric as a feedback control parameter is described in details in a companion paper [3]. For this application, KSmetric is only used in limp home mode as a backup to MRPR in case of a pressure sensor failure.

One of the major problems with HCCI engines is high HC and CO emissions, especially during starting, idle and light load operations [1]. With the V8 configuration and two exhaust manifolds leading to a single VGT, there are spaces available to place the catalyst before the turbine. This is a logical choice as it not only removes HC and CO but improves turbine efficiency with elevated exhaust gas temperature. However, increased volume in the exhaust system also increases the turbo lag which negatively affects the engine transient rate. As a compromise, two small pre-turbine catalysts (diameter 80 × length 80mm, 200cps straight foil) were installed and one main catalyst (diameter 174 × length 240mm, 300cps LS type foil) was placed after the turbine and downstream from the EGR port. The substrates are metallic and made by Emetec. The LS type foil substrate used for the main catalyst has been shown to have better performance compared with ceramic substrate in terms of hydrocarbon conversion, heat-up, and pressure drop [6]. The substrates were coated with an oxidation catalyst by Umicore.

ENGINE CONTROL STRATEGY

In an HCCI engine, the start of combustion and the rate of heat release are determined by the charge composition and its time-temperature-pressure history, which depends upon a combination of many factors, such as air/fuel ratio, humidity, engine speed, residual gas fraction, EGR, boost level and temperatures of charge, coolant and lubricating oil. For a given combination, there is a limited range the fuel quantity can vary to yield a “normal” combustion, i.e. free of misfire or knock. There is an optimized combination of these parameters at each given speed and load to yield the best efficiency with acceptable cycle-to-cycle variation and combustion noise. In real world applications, only fueling rate, boost level and EGR rate can be actively, accurately, quickly and effectively controlled. Intake air temperature is highly dependent on the weather conditions, road grade and vehicle speed, as are oil and coolant temperature.

The basic core of the control strategy is to use the controlled variables to compensate for the uncontrolled variables and to use a controlled variable which can be changed quickly to compensate for those controlled variables which change more slowly in order to keep HCCI combustion state staying within a healthy range. Since many of the variables are inter-related, a study was performed to understand the relationship between MRPR and a multi-variant matrix using techniques such as response surface method [7]. Such an understanding formed the knowledge based optimal model in the control flow chart shown in [Figure 4](#). There are two basic criteria which serve as general guidance. One is to adjust fuelling rate on a cycle to cycle and cylinder to cylinder basis to maintain a target of MRPR. The target is set to around 6 to 8 bar/deg throughout the map except at idle. The second criterion guides the choice of fuel/air/EGR which is based on the response of MRPR to fueling change. A positive slope should be maintained by adjusting the boost level and EGR rate [3]. For steady state map calibration, the boost was kept as low as possible and EGR rate as high as possible for a given load request while meeting the two criteria. This leads to the best thermal efficiency achievable. Transient controllability must insure that fueling changes fall within the range from cycle to cycle. Quick transient response requires the range to be large, i.e. a large fueling step change from cycle to cycle.

During transient conditions, based on the vehicle controller request, the engine controller moves the engine operating point from location to location on the state map at the requested rate. Since an HCCI engine is a strong non-linear system, there are multiple paths to achieve the desired power command depending on engine conditions. The knowledge based model gives guidance for the system to assume a new set of state variables and also provides the sequence for adjustment. In response, calculations are made

to drive the actuators so that engine combustion moves accurately in the desired direction. Fuelling changes occur after every combustion event and are managed through an event based loop. All other actuators are managed through a 5 msec time-based loop. Closed-loop control of boost, EGR and, to a lesser extent, temperatures enables the maintenance of optimum combustion and engine efficiency at all times.

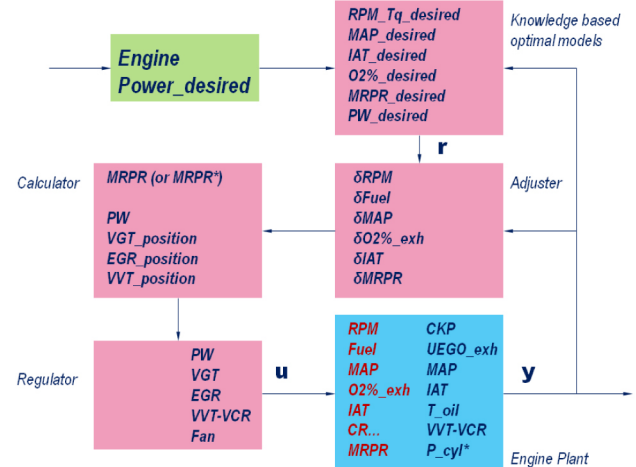


Figure 4. HCCI V8 engine control logic

The HCCI engine is controlled by means of controller area network (CAN) communication between the Hybrid Systems Controller (HSC) and the Engine Control Module (ECM). Speed and load are directly requested via a J1939 Standard TSC1 (Torque Speed Control) message. The ECM informs the HSC of current engine speed and torque limitations in its return copy of the TSC1 message. Also added to this message, in a non-standard way, are fields that express the HCCI engine's current limits on rate of speed change. There are limits on the engine's rate of load change which are handled automatically, although a load limit can be imposed based on certain conditions, such as SI start up mode, and this limit is also communicated via the TSC1 message. An HSC request to provide a “loaded idle” in response to air conditioning activation is also provided in an unused field of the TSC1 message. In response to the HSC request via this message, the ECM makes appropriate modifications to current engine parameters and then returns in its TSC1 message the current percent torque achieved, constantly updated.

Other engine status parameters are communicated by the ECM via CAN message. The current actual engine speed, engine percent torque and confirmation of the HSC's load request are transmitted via an EEC1 message. Current engine coolant temperature and oil temperature are provided by an ET1 message. Engine fuel pressure and oil pressure are transmitted in an EFLP1 message. Fuel rate and estimated fuel economy are sent in a LFE message, while battery

voltage is available in a VEP message. A CM1 message is used by the ECM not to communicate but to respond to an air conditioning startup and turn on the radiator fans if they are currently off in order to cool the A/C coils. And engine protection and shutdown conditions are sent to the dashboard lamp display unit via a DM1 message, with additional information provided in a SHUTDOWN (engine shutdown) message, including support for limiting time the engine is held at idle. All of these messages provide information which can be gathered for diagnostic and calibration purposes but are also used by the HSC to respond to engine conditions.

TEST RESULTS AND DISCUSSION

Steady State Engine Maps

Steady state engine maps were generated in an engine test cell with the engine coupled to a dynamometer. The coolant out temperature was maintained at a maximum of 96 °C. Since oil was mainly cooled by the coolant, its temperature varies from 95 °C at light load to 115 °C at the maximum power. Figures 4, 5, 6, 7 show the maps of engine performance and dependent parameter settings (low load and idle HCCI maps are not included) for hybrid vehicle application. Acceptable HCCI operation is defined as follows:

1. The coefficient of variation (COV) of IMEP for each individual cylinder is less than 5%. The COV of the engine global IMEP is less than 3%.
2. The maximum rate of pressure rise (MRPR), as it is defined by the combustion analyzer (MTS ADAPT-CAS™) is less than 10 bar/deg. The standard deviation of MRPR was kept below 1 bar/deg over 25 cycles. The map of average MRPR is shown in Figure 5.

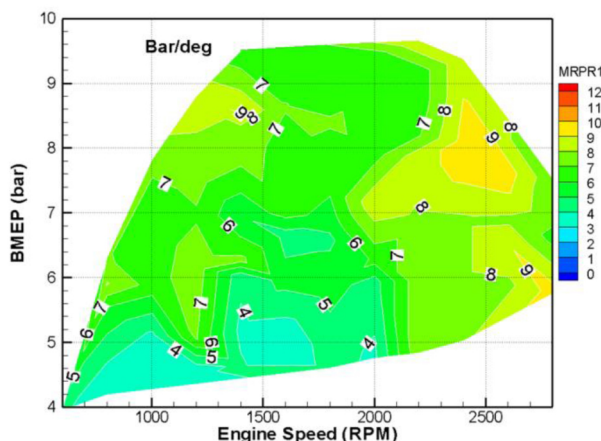


Figure 5. HCCI V8 engine MRPR Map

These criteria were used for the steady state calibration to leave plenty of room for error for the bus application. The upper boundary of the maps was limited by the cooling capability of the test cell. Figure 6 shows a map of the intake temperature, which got quite high at high power because of

the capacity of the test cell air handler. The lower boundary of the steady state maps was limited by the lower end of engine system temperatures. Prolonged operation at lower load would result in lower in-cylinder gas temperature which would cause more fuel to be added to maintain the same MRPR target. Lower BMEP can be achieved by throttling the engine with the VGT, which was found unnecessary and not used in the bus application.

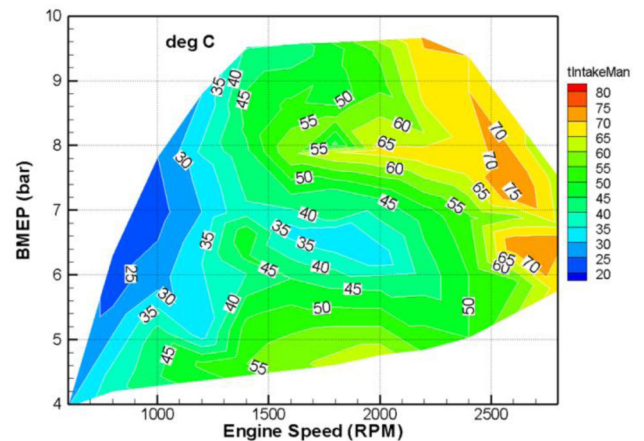


Figure 6. HCCI V8 engine Intake Temperature Map

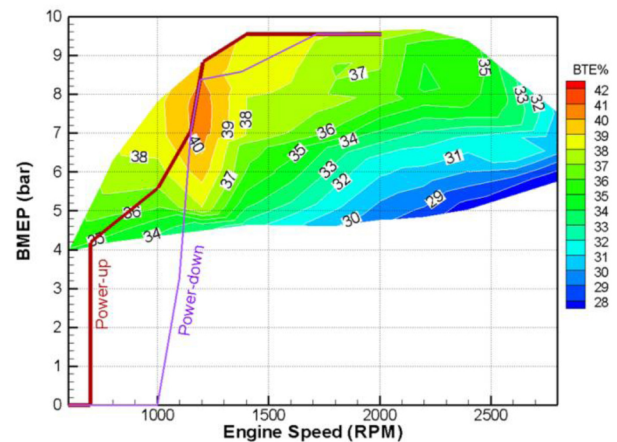


Figure 7. Steady State BTE Map

A maximum shaft torque of 492 Nm (9.6 bar BMEP) was achieved at 2200 rpm. A maximum power output of 120 kW was achieved at 2300 rpm. A best brake thermal efficiency of 40% was achieved around 350 ~ 400 Nm (7 to 8 bar BMEP) @ 1100 ~ 1200 rpm. As the application is a series hybrid drive train, the operating path occupies only a small portion of the map. The solid lines in Figure 7 are the desired operating path for the engine when used for the shuttle bus.