

Characterization of Engine Control Authority on HCCI Combustion as the High Load Limit is Approached

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ABSTRACT

In this study the authority of the available engine controls are characterized as the high load limit of homogeneous charge compression ignition (HCCI) combustion is approached. A boosted single-cylinder research engine is used and is equipped with direct injection (DI) fueling, a laboratory air handling system, and a hydraulic valve actuation (HVA) valve train to enable negative valve overlap (NVO) breathing. Results presented include engine loads from 350 to 650 kPa IMEP_{net} and manifold pressure from 98 to 190 kPa. It is found that in order to increase engine load to 650 kPa IMEP_{net}, it is necessary to increase manifold pressure and external EGR while reducing the NVO duration. While both are effective at controlling combustion phasing, NVO duration is found to be a “coarse” control while fuel injection timing is a “fine” control. NO_x emissions are low throughout the study, with emissions below 0.1 g/kW-h at all boosted HCCI conditions, while good combustion efficiency is maintained (>96.5%). Net indicated thermal efficiency increases with load up to 600 kPa IMEP_{net}, where a peak efficiency of 41% is achieved. Parametric investigations reveal that increasing exhaust gas recirculation (EGR) at a constant intake manifold pressure (MAP) and increasing MAP at a constant external EGR rate both retard combustion phasing. It is also found that combustion phasing becomes increasingly sensitive to NVO duration as engine load increases. Finally, comparisons are made between commonly used noise metrics. It is found that compared to the AVL combustion noise meter, ringing intensity (RI) significantly underestimates combustion noise under boosted HCCI conditions.

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INTRODUCTION

This work investigates the characteristics of load expansion in gasoline fueled HCCI operation. HCCI has yet to achieve its promise of high efficiency and low NO_x emissions in a production engine despite the first published research papers appearing over 3 decades ago [1,2,3]. While there are numerous barriers to implementation, one is that HCCI combustion is limited to a relatively light operating load of approximately 400 kPa IMEP_{net} in a naturally aspirated engine [4,5,6].

The load limitation is becoming even more critical for the relevance of HCCI combustion given the trends of engine downsizing and electric hybridization of for vehicle fuel economy improvements. Downsized engines utilize turbo-machinery for higher specific power, allowing the engine to operate at higher loads with higher efficiency than a larger naturally aspirated engine at the same power. Hybrid electric technologies aim to minimize the use of the engine at the lightest load conditions. In both cases, the duty cycle of the engine is changed under normal driving conditions, resulting

in a reduced amount of time spent at the conditions applicable to HCCI combustion.

There are two primary strategies being researched to extend the high load limit of HCCI combustion. The first is using a hybrid mode of combustion in which a portion of the fuel energy is consumed by a propagating flame front initiated by a spark, with the remainder of the fuel energy being consumed by a volumetric HCCI-like combustion event, known both as spark-assisted HCCI (SA-HCCI) and spark-assisted compression ignition (SACI) [7,8,9,10,11]. The second is to implement a boosted air handling system so that the required dilution for HCCI can be maintained as the engine load is increased [12,13,14,15,16,17]. This study focuses on the latter strategy of load range expansion, specifically with the use of DI fueling and a NVO valve train strategy used to control combustion phasing and noise.

The NVO valve train strategy allows the temperature of the intake charge to be raised to achieve auto-ignition at or near TDC of the compression stroke while providing the necessary dilution to moderate combustion noise. NVO is achieved by closing the exhaust valves earlier than in conventional engines, thereby trapping a portion of the exhaust gases in-cylinder and recompressing them for the remainder of the exhaust stroke. The intake valve is then opened later than in a conventional engine so that the recompressed exhaust can be expanded. The NVO valve train strategy is common in HCCI research.

Fuel injection timing is also a well-established control for combustion phasing and noise. Under light load lean-burn conditions that utilize a pilot fuel injection before gas exchange TDC, the primary effect is thought to be the result of an exothermic partial oxidation, although the products of partial combustion can play a role in altering chemical kinetics [18, 19]. An alternate explanation for why the timing of fuel injection into the NVO is able to control phasing has to do with thermodynamics of expansion. When fuel is injected at a more advanced phasing, the ratio of specific heat (γ) is reduced earlier in the cycle, causing the temperature to be higher at the end of the NVO period.

The purpose of this study is to clarify the sensitivity and control authority of available engine controls on combustion phasing, stability, noise, and NO_x emissions. Specifically, parametric investigations are performed. Type equation here in an attempt to isolate the effects of NVO duration, intake manifold pressure, and external EGR relative to fuel injection timing.

EXPERIMENTAL METHODOLOGY

Single Cylinder Engine

A highly modified 2.0 L GM Ecotec engine with DI fueling is used for the study. The engine geometry is listed in Table 1. Three of the cylinders of the production engine are disabled to allow single-cylinder operation and a custom piston is installed to increase compression ratio to 11.85.

Table 1. Engine geometry

Bore [mm]	86
Stroke [mm]	86
Connecting Rod [mm]	145.5
Compression Ratio [-]	11.85:1
Fuel Injection System	Direct Injection, wall guided

Machining modifications have been made to the cylinder head to accommodate the small research module HVA system from Sturman Industries. Modifications include using custom intake and exhaust valves with longer valve stems. While the valve material is different than the production valves, the combustion chamber geometry is unchanged. Other changes to the engine include a Kistler sparkplug with an integrated piezoelectric pressure transducer. In the production configuration from the original equipment manufacturer (OEM), the high pressure fuel pump for the DI fueling system is driven by the intake cam shaft. However, because the camshafts are removed, the fuel is supplied by an externally powered fuel pump. A picture of the engine facility used in this investigation is shown in Figure 1.

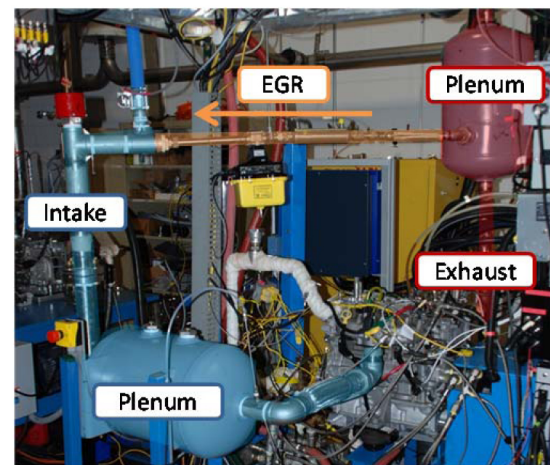


Figure 1. Single cylinder engine equipped with HVA valve train and laboratory air handling system.

The HVA system allows independent control of each of the two intake and two exhaust valves, including opening and closing crank angle, opening duration and valve lift, including the option to disable a valve. While this makes it a very versatile research tool for this type of research, it is limited by the fact that the valve opening profile differs from a cam-based valve train. The rapid valve opening, dwell at maximum lift, and rapid valve closing give the valve events the appearance of a square wave rather than a conventional cam profile. A comparison of this HVA valvetrain and cambased valve events was made while investigating the low load limit of HCCI with this engine in a previous study [20].

In order for this study to be as relevant as possible to production-intent cam-based valve trains, the intake and exhaust valve lift are held constant at 4 mm and opening and

duration is held constant at 98 CA deg (measured at a valve lift of 0.8 mm). The exhaust valve phasing is changed throughout the study as needed, with a total required range of 27 CA deg. This range of valve phasing is within the range of current technology cam-based valve trains with cam phasing. Figure 2 shows the details on the intake and exhaust valve events.

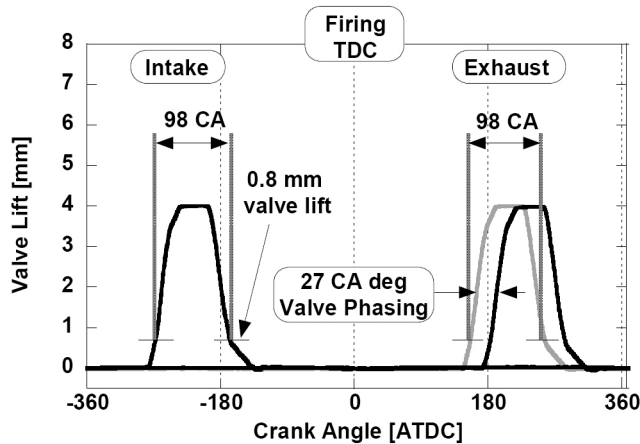


Figure 2. Intake and exhaust valve events.

Crank-angle resolved data acquisition and combustion analysis is done using the combustion analysis toolkit (DCAT) from DRIVEN. These measurements include cylinder pressure, valve lift feedback from each of the four valves and the command signal sent to the fuel injector. Crank-angle resolved data is recorded at 0.2 degCA intervals. TDC for indicated measurements is set dynamically using an AVL 428 instrument which uses a capacitive method to measure piston location. Cylinder pressure is an average of 300 individual cycles. Heat release and maximum pressure rise rate (MPRR) are calculated for each cycle and then averaged. Neither the cylinder pressure nor the heat release is filtered.

Engine emissions are measured using a standard emissions bench. NO_x is measured using a chemiluminescence analyzer, CO and CO_2 are measured using infrared analyzers, oxygen is measured using a paramagnetic analyzer and unburned hydrocarbon emissions (HC) are measured with a flame ionization detector. Exhaust air-to-fuel ratio (AFR) is measured using both gaseous emissions and a wideband exhaust lambda sensor. Fuel flow is measured using a coriolis-effect based flow meter. Fuel rail pressure is regulated to a constant 100 bar and engine coolant is maintained at 90°C.

The engine is operated with a laboratory air handling system. Pressurized air is metered to the engine using a mass air flow controller. The engine is equipped with separate electromechanical valves for backpressure and external EGR, allowing independent control of intake manifold pressure, exhaust manifold pressure, and EGR. Cooled EGR mixes with fresh air upstream of an air heater, followed by the intake plenum and then the intake manifold. EGR is

measured using an EGR 5230 system from ECM, an instrument that uses pressure-compensated wideband oxygen sensors in both the intake and exhaust to non-intrusively measure EGR.

A constant intake manifold temperature of 52°C is maintained at all operating conditions. The exhaust temperature is measured in the exhaust manifold directly after the exhaust port. Combustion noise is measured using an AVL 450 combustion noise meter.

At all boosted operating conditions, a constant pressure differential of 10 kPa is maintained between the intake and exhaust manifolds. For example, an intake manifold pressure of 140 kPaa has an exhaust manifold pressure of 150 kPaa. This is similar to the methodology used in previous investigations [15, 16, 21]. This method allows external EGR to be driven into the intake, but it does have limitations because it does not consider whether the required turbocharger efficiency and turbocharger sizing are realistic. The implications of this are considered further in the Discussion section.

Fuel Properties

The single cylinder engine is operated using gasoline containing nominally 10% ethanol (E10) with the specifications given in Table 2. This fuel is representative of regular-grade E10 fuel found at the majority of fueling stations in the U.S. The specific fuel consumption values presented in this paper are calculated using IMEP_{net} and are normalized to a typical lower heating value for gasoline, 43.7 MJ/kg, and are therefore presented on the basis of gasoline equivalent net indicated specific fuel consumption ($\text{net ISFC}_{\text{geq}}$) in order to make these results more directly comparable to the results reported by other researchers for gasoline with no ethanol content.

Table 2. Fuel properties.

Ethanol content [vol%]	11.54
Carbon [wt%]	83.01
Hydrogen [wt%]	13.38
Oxygen [wt%]	4.21
Density [kg/m^3]	754
Antiknock index, $(\text{RON} + \text{MON})/2$ [-]	88.7
RON [-]	93.6
MON [-]	83.8
Octane sensitivity $\text{RON} - \text{MON}$ [-]	9.8
Lower heating value [MJ/kg]	41.2
Stoichiometric air/fuel ratio [-]	14.0

Engine Modeling

The GT-Power modeling tool from Gamma Technologies is used to model a subset of engine operating conditions. Experimental data is used as inputs into the model, including operating temperatures, intake and exhaust valve profiles, and air flow. The experimental heat release profile is prescribed

as the heat release in GT-Power, and the chemistry of fuel injection into the NVO is not modeled. Thus, no attempt is made to use GT-Power as a predictive tool for HCCI combustion. Instead, a reasonable match between the model and experimental is primarily used to determine the trapped residual mass in the NVO, overall dilution, and cylinder temperature.

RESULTS

The results are presented in three sub sections. The first presents a data overview showing the engine loads that can be achieved, emission trends, and boost requirements. The second presents the parametric sweeps using subsets of operating conditions. Combustion noise comparisons are presented in the final results subsection.

Data Overview

Operating loads of 350 to 650 kPa IMEP_{net} are investigated in increments of 50 kPa IMEP_{net}. Each engine load is operated over a range of NVO duration, external EGR rate, fuel injection timing, intake manifold pressure, equivalence ratio (Φ), and dilution. All operating points are discussed together during the Data Overview subsection, and the effect of each of these operating parameters is investigated in more detail below in the Parametric Investigations subsection.

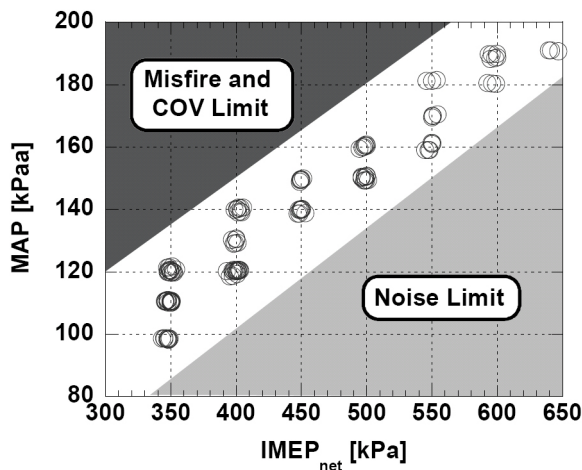


Figure 3. Manifold pressure as a function of engine load.

Within this range of operating loads, only the 350 kPa IMEP_{net} load can be achieved under naturally aspirated conditions while staying below the engine noise limit of 94 dB. Intake manifold boosting is required to increase operating load, as is illustrated in Figure 3. The sharp increase in manifold pressure, up to 190 kPa at 600 and 650 kPa IMEP_{net}, is consistent with results obtained in previous studies [12,13,14]. This illustrates one of the major challenges with implementation of HCCI combustion on a production-intent platform: it is not trivial to achieve these

levels of boost pressure at relatively low engine flow rate and low exhaust temperature, especially with turbo-machinery that must also perform well at high engine load conditions.

The thermal, or Zeldovich mechanism is the primary pathway of NO_x formation in internal combustion engines [22], and reducing the peak temperature reduces NO_x emissions. As a result, charge dilution through boosting is not only effective at reducing noise as engine load increases, but is also effective at reducing NO_x emissions. Dilution with excess air is quantified by the equivalence ratio, Φ , in accordance with Equation 1. Φ is not representative of the overall dilution, though, because it does not consider the internal and external EGR. Thus, a dilution parameter, Φ' , is described in Equation 2 in a manner consistent with Lavoie et al. [23].

$$\Phi = \frac{(Air/Fuel)_{stoich}}{(Air/Fuel)} \quad (1)$$

$$\Phi' = \frac{(Air/Fuel)_{stoich}}{((Air + external\ EGR + internal\ EGR)/Fuel)} \quad (2)$$

NO_x, NVO duration, 10-90% combustion duration, Φ , Φ' , and bulk gas peak cylinder temperature are all shown as functions of load in Figure 4. NO_x, NVO duration, 10-90% combustion duration, and Φ are measured experimentally whereas Φ' and bulk gas peak cylinder temperature are outputs from the subset of points that were modeled using GT-Power. It is observed that the highest NO_x emissions occur under naturally aspirated conditions at the lowest load investigated in this study, 350 kPa IMEP_{net}. NO_x emissions are much lower under boosted conditions at all boosted conditions, from 350 to 650 kPa IMEP_{net}. This is because as load increases, dilution also increases, with Φ' being at or below 0.4 for all modeled operating conditions at a load of 450 kPa IMEP_{net} or higher.

NVO duration decreases with load, indicating that the internal trapped residual fraction decreases with increasing load. This occurs while Φ' increases, so hot internal residuals are being replaced by cooler external EGR. The 10-90% combustion duration increases only slightly as load increases, from a minimum of 7.5 CA to a maximum of 12 CA.

Figure 5 shows that the range of combustion phasing investigated is relatively narrow, as measured by the CA50 combustion timing. Advanced combustion phasing is limited by combustion noise and retarded combustion phasing is limited by combustion stability and/or misfire. It is observed that the range of combustion phasing for lower operating load is larger than for higher operating load. For example, the engine load of 350 kPa IMEP_{net} has a combustion phasing range of 6.5 to 11 deg aTDC_f, whereas the range for 600 kPa IMEP_{net} is only from 9.5 to 11 deg aTDC_f. This is a result of multiple factors. First, the lower operating load conditions are operated over a wider range of intake manifold pressure and equivalence ratios, as shown in Figure 3 and Figure 4.

Secondly, it illustrates that the sensitivity of engine operating increases as engine load increases, producing a narrower range of CA50 with acceptable behavior.

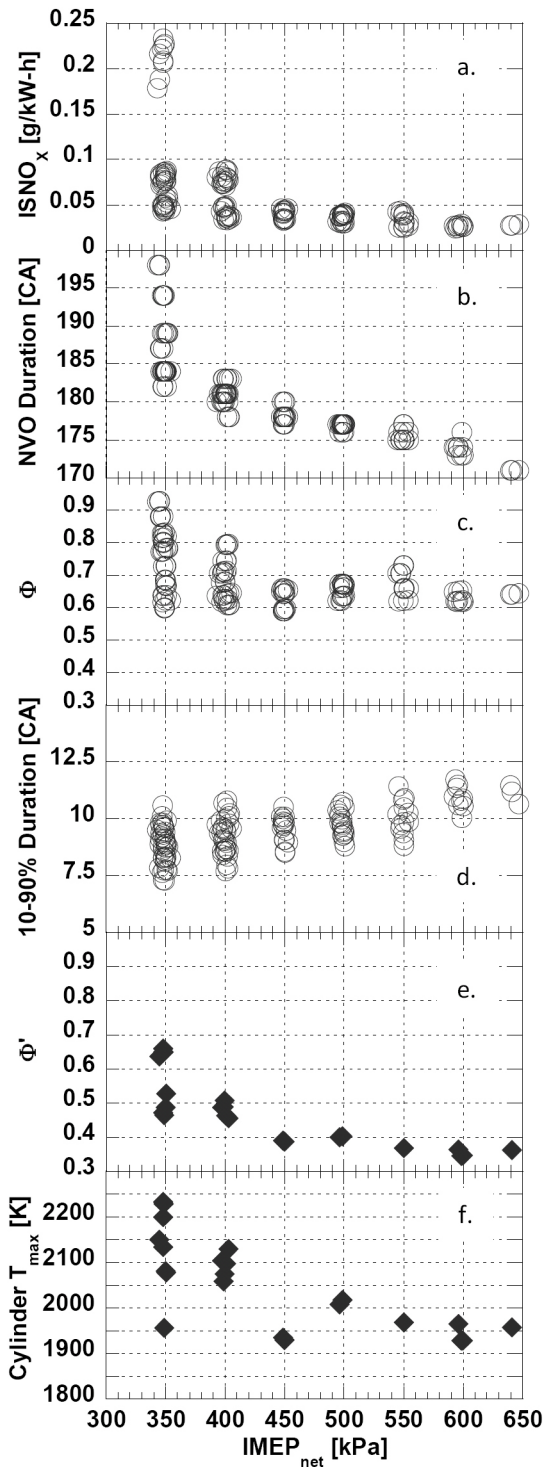


Figure 4. Experimental data for (a) NO_x emissions, (b) NVO duration, (c) Φ , and (d) 10-90% combustion duration, and modeled data for (c) Φ' and (d) peak bulk cylinder temperature as functions of load.

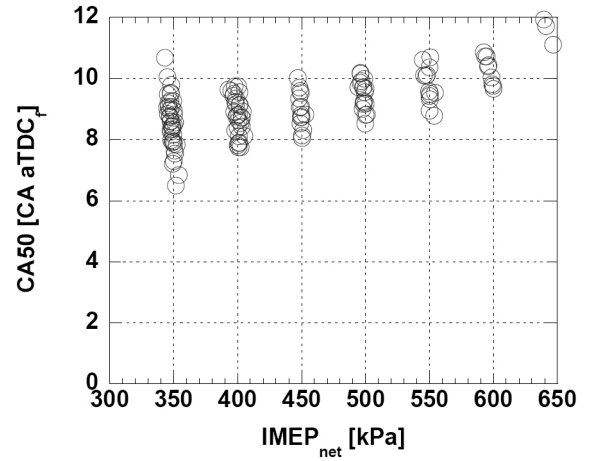


Figure 5. CA50 combustion phasing as a function of engine load.

Figure 6 shows that the combustion efficiency achieved throughout this investigation is high, with all operating points having a combustion efficiency of 96.5% or higher. Thus, within the constraints placed on combustion noise and stability, very low NO_x emissions are achieved without a substantial combustion efficiency penalty compared to conventional SI combustion at the same engine loads.

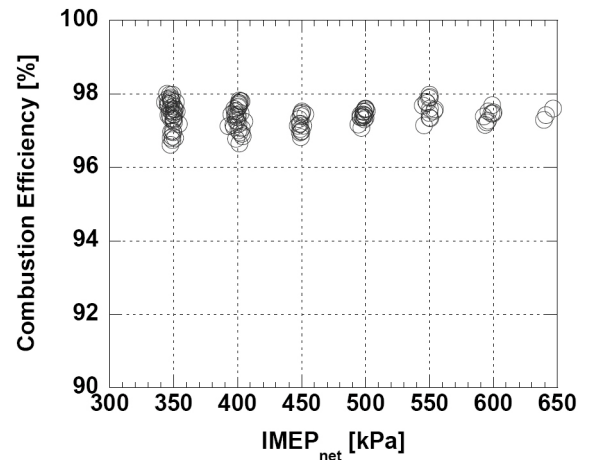


Figure 6. Combustion efficiency as a function of load.

Net indicated thermal efficiency (ITE_{net}) is shown as a function of load in Figure 7. In general, ITE_{net} increases with engine load, but is also dependent on dilution and combustion phasing. The lowest efficiency is produced for the naturally aspirated operating conditions at 350 kPa IMEP_{net}. The efficiencies observed in this study, from 36 to 41.5% correspond to normalized net ISFC_{geq} values of 199 to 228 g/kW-h using the methodology described in the experimental section. This is substantially higher than the 30 to 33% ITE_{net} observed under SI combustion conditions with this engine platform in same speed/load range, reported in a previous study [10]. ITE_{net} is dependent on pumping work and is