

HCCI Load Expansion Opportunities Using a Fully Variable HVA Research Engine to Guide Development of a Production Intent Cam-Based VVA Engine: The Low Load Limit

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ABSTRACT

While the potential emissions and efficiency benefits of HCCI combustion are well known, realizing the potentials on a production intent engine presents numerous challenges. In this study we focus on identifying challenges and opportunities associated with a production intent cam-based variable valve actuation (VVA) system on a multi-cylinder engine in comparison to a fully flexible, naturally aspirated, hydraulic valve actuation (HVA) system on a single-cylinder engine, with both platforms sharing the same GDI fueling system and engine geometry. The multi-cylinder production intent VVA system uses a 2-step cam technology with wide authority cam phasing, allowing adjustments to be made to the negative valve overlap (NVO) duration but not the valve opening durations. On the single cylinder HVA engine, the valve opening duration and lift are variable in addition to the NVO duration.

The content of this paper is limited to the low-medium operating load region at 2000rpm. Using different injection strategies, including the NVO pilot injection approach, the single-cylinder engine is operated over a load range from 160-390 kPa net IMEP at 2000 rpm. Changes to valve opening duration on the single-cylinder HVA engine illustrate opportunities for load expansion and efficiency improvement at certain conditions. For instance, the low load limit can be extended on the HVA engine by reducing breathing and operating closer to a stoichiometric air fuel ratio (AFR) by using valve deactivation.

The naturally aspirated engine used here without external EGR confirmed that as operating load increases the emissions of NO_x increases due to combustion temperature. NO_x emissions are found to be one limitation to the maximum load limitation, the other being high pressure rise rate. It is found that the configuration of the production intent cam-based system represents a good compromise between valve lift and duration in the low to medium load region. Changing the extent of charge motion and breathing via valve deactivation prove beneficial at moderating the pressure rise rate and combustion stability and extending the low load limit at 2000rpm on the HVA engine. It also confirms that strategies using a pilot fuel injection are beneficial at low operating loads but that as operating load is increased, the benefits of multiple injection diminish to the point where a single injection offers the best performance.

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INTRODUCTION

In recent years a number of combustion concepts have been researched in order to reduce engine-out emissions and increase efficiency. These methods concentrate on low temperature premixed combustion to alleviate the engine-out emissions of both NO_x and soot while simultaneously increasing engine efficiency. One such concept,

homogeneous charge compression ignition (HCCI) has demonstrated significant potential but is faced with a number of implementation barriers. In order to achieve HCCI combustion in a 4 stroke engine there must be some method of raising the intake charge temperature to achieve auto-ignition at or near the TDC of the compression stroke. This can be achieved with the use of variable valve timing to produce negative valve overlap (NVO). 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 re-compressed exhaust can be expanded.

HCCI operation is limited to part-load conditions due to high rates of in-cylinder pressure rise rate, making it applicable to only a small portion of the engine map. The higher efficiency at part-load conditions is challenged by the growth of hybrid-electric powertrains in production vehicles, which minimize the use of the engine at the lowest engine loads and operate the engine at more efficient higher-load conditions whenever possible. Thus, if HCCI is to remain a relevant means of increasing efficiency, there is a need for a greater emphasis on expanding the operating regime both to lower loads and to higher loads. More recently it has been shown that operating loads approaching idle speed conditions can be achieved using recompression effects combined with late fuel injection and spark-assistance [1]. The achievement of high load HCCI operation continues to be investigated using methods such as intake charge boosting, stratification and spark-assisted operation [3,4,5,6,7,8].

The requirement for a complex combustion control system combined with the need for an advanced valvetrain possessing a large degree of freedom has been confirmed in many HCCI studies. At the same time the sophistication of cam-based variable valve actuation (VVA) technology has progressed significantly and it is now feasible for a valve train with both intake and exhaust valve timing phasing as well as 2-step lift to be used on a production-intent engine platform [9].

The work presented in this paper explores the mechanism of multiple injection in a HCCI engine, then examines the effect of changing the valve train parameters in terms of valve lift, valve timing and NVO duration. Finally the effect of intake valve deactivation is investigated on HCCI combustion at the low load limit. The experimental investigation presented here is performed using a naturally aspirated single-cylinder engine with fully variable hydraulic valve actuation system supplied by Sturman Industries. The valve train approach is based around the design-space envisaged in a production-intent VVA multi-cylinder engine. The same compression ratio, fuel injection equipment (FIE) and fuel (E10) being used in an ongoing study on the multi-cylinder platform is used on the single-cylinder platform presented in this paper.

EXPERIMENTAL SETUP

SINGLE CYLINDER ENGINE

A highly modified GM 2.0L Ecotec engine with direct fuel injection 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, a custom piston is installed to increase compression ratio to

11.85, and the engine is operated naturally aspirated without external EGR.

The single cylinder engine is equipped with a hydraulic valve actuation (HVA) system, allowing independent control of each of the two intake and two exhaust valves, including opening and closing 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 event the appearance of a square wave rather than a conventional cam profile. This is discussed further in the [appendix](#).

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 custom exhaust system and 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 gasoline direct injection (GDI) fueling system is driven by the intake cam shaft. However, because the cam shafts are removed, the fuel is supplied by an externally powered fuel pump. A picture of the engine is shown in [figure 1](#).

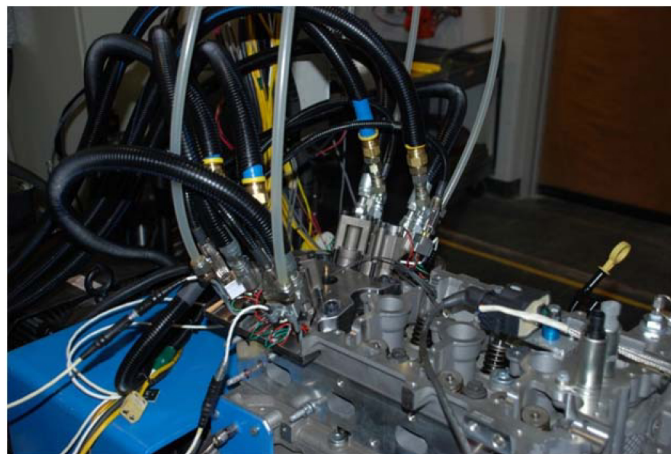


Figure 1. Single cylinder engine.

Table 1. Engine geometry.

Bore x Stroke	86mm x 86mm
Conrod length	145.5mm
Compression ratio	11.85:1
Fuel injection system	Direct injection, wall guided

Drivven Combustion Analysis Toolkit (DCAT) performs the crank-angle resolved data acquisition and combustion analysis. 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 0.2degCA intervals over 300 consecutive cycles, and all references to indicated mean effective pressure (IMEP) refer to net IMEP.

Engine emissions are measured using a standard emissions bench. NO_x is measured using a chemiluminescence analyzer, CO and CO₂ are measured using infrared analyzers, oxygen is measured using a paramagnetic analyzer and unburned hydrocarbon emissions (HC) are measured with a flame ionization detector. Smoke measurements are performed using a filter smoke number (FSN) instrument. Exhaust air-to-fuel ratio (AFR) is measured using both gaseous emissions and a wideband exhaust lambda sensor.

Air mass flow is measured using a laminar flow element device and fuel flow is measured using a coriolis-effect based flow meter. Fuel rail pressure is regulated to a constant 100 bar. Engine coolant is maintained at 90°C. The air supplied to the engine intake manifold is externally conditioned to 55% relative humidity and 25°C using an air supply conditioning unit. The intake air temperature in this paper is measured inside the intake manifold before the intake port. The exhaust temperature is measured in the exhaust manifold directly after the exhaust port.

FUEL PROPERTIES

The single cylinder engine is operated using E10 with the specifications given in Table 2. The ISFC values presented in this paper are calculated using the net IMEP and the fuel mass flow rates measured by the coriolis fuel meter and are not normalized to the energy value of an E0 gasoline.

Table 2. Test fuel.

Ethanol content vol/%	11.54
Carbon wt/%	83.01
Hydrogen wt/%	13.38
Oxygen wt/%	4.21
Density/kg/m ³	754
Octane nr (R+M)/2	88.7
RON/-	93.6
MON/-	83.8
(RON-MON)/-	9.8
Lower heating value/MJ/kg	41.2
Stoichiometric AFR/-	14.0

ENGINE OPERATING STRATEGY

SINGLE CYLINDER ENGINE

A baseline HCCI operating point is defined at 300 kPa IMEP and 2000rpm. At this operating load we first investigate effects of fuel injection parameter variation and valve characteristics before increasing or decreasing operating load to the limits of operation.

The limits of operation for the purposes of the single cylinder experiments are an upper limit of the coefficient of variance (COV) of IMEP of ≈5% and a maximum ringing intensity of ≈5 MW/m². The RI relation proposed in [3] is applied in this paper and is reproduced below.

$$RI = 2.88 \times 10^{-8} \times \frac{(MPRR \times RPM)^2}{PP}$$

The limit of RI corresponds to a maximum pressure rise rate (MPRR) of 300 to 400 kPa/degCA given the range of peak pressure (PP) encountered at an engine speed of 2000 rpm. This is a conservative limit that would take into account the production intent limitations placed on a light duty engine. When multiple injection is used, the mass fraction between the pilot and the main injection event reported in this paper is measured by injecting fuel at the same operating condition without pilot injection while the engine is motoring. The fuel injection mass is measured by the coriolis fuel meter and the mass fraction is then determined. The large separation of the two injection events reduces the likelihood of injector interference and pressure wave effects to a minimum.

RESULTS

SINGLE CYLINDER

The baseline HCCI operating point uses 4 valve operation and 3mm lift. The HVA valve lifts are shown in figure 2. Here the characteristic rise and fall of the HVA system is evident which possesses some inherent asymmetry as indicated. The choice of HVA valve duration was based upon the profile of the production intent HCCI cam profile shown in figure 2.

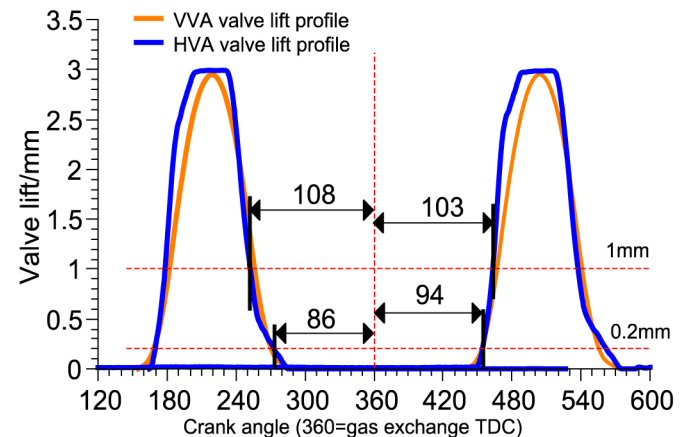


Figure 2. HCCI operating entry point : HVA valve lift profile and VVA cam profile.

The negative valve overlap (NVO) duration of the baseline HCCI operating point is 180 degCA with intake and exhaust valve event durations of 104 degCA assuming 0.2mm lift. For a HCCI engine operating with NVO, the

effect of direct fuel injection parameters is highly significant in contrast to a PFI engine where there is effectively no way to either adjust mixture stratification or to take advantage of fuel interactions during the NVO period. Numerous studies into the effects of direct injection in HCCI engines exist with most proposing the use of a pilot fuel injection before or during the NVO period followed by a main injection event after the NVO period has passed. A comparison of single and multi-injection in the single cylinder engine follows.

Single Injection Event Operation (4Valve - 3mm Lift)

The effect of first using a single injection event is examined using the valve timing shown above while adjusting fueling to maintain 300 kPa IMEP load. The fuel injection parameter varied is DI timing and its variation can be seen in terms of secondary variables in figures 3, 4 and 5. Spark assist is applied with a -20degATDC spark event for stability.

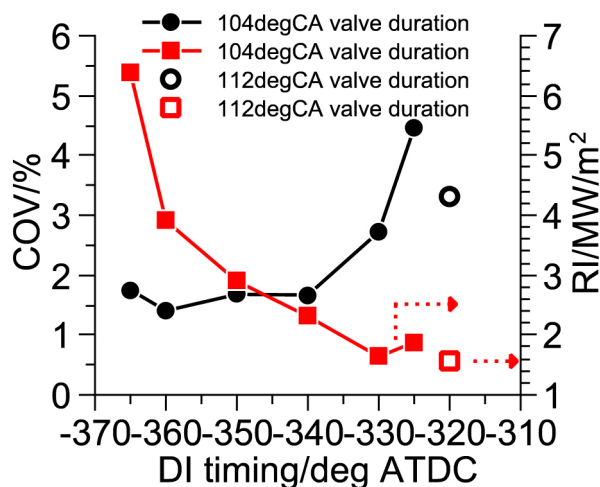


Figure 3. Single injection SOI (COV of IMEP and RI).

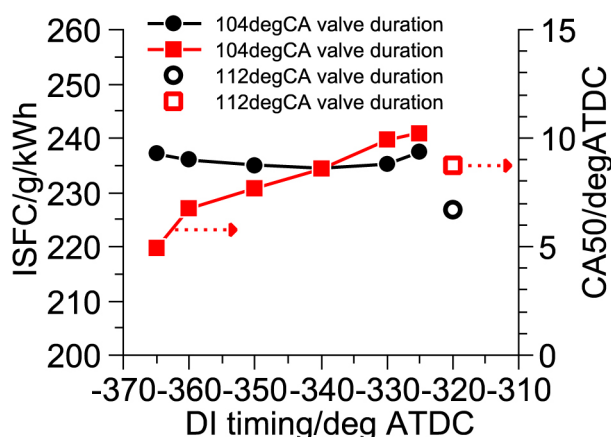


Figure 4. Single injection SOI (ISFC and CA50).

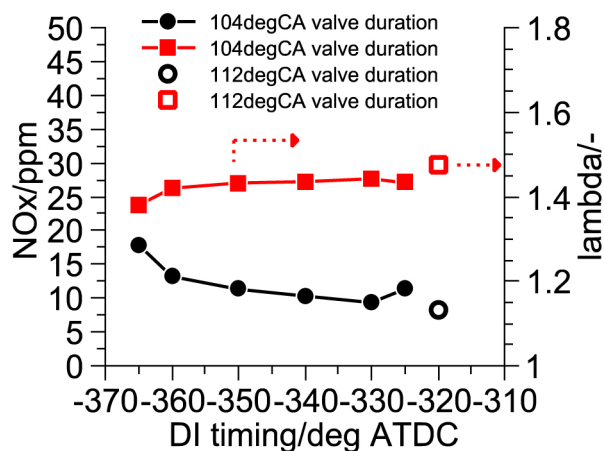


Figure 5. Single injection SOI (NO_x and λ).

The effect of injection timing is significant. The range of stability (COV) and noise (RI) limits can be spanned with a DI timing change from -335 to -365 degATDC SOI parameter variation. At the same time the combustion phasing responds within 5degCA for the same SOI variation and ISFC is minimum at an SOI of -340degCA at combustion phasing of 8degCA ATDC. This does indicate some control scope over combustion phasing and it also shows that operation with less than 2% COV, RI of less than 3 MW/m² and 235 g/kWh can be achieved within this parameter space, while keeping the valve timing constant.

In order to examine the effect of valve duration the previous configuration is re-measured with a valve duration increased from the baseline 104degCA to 112degCA. The valve events are centered around their middle anchor so this means that the duration increase advanced EVO and IVO, and retarded EVC and IVC values. A single direct injection SOI of -320 degATDC is chosen. The effect of spark at this lean operating point is to advance the combustion phasing by 1degCA, leading to a minimal decrease in ISFC of around 1-2 g/kWh compared to the condition where the spark is not used. However, the predominant effect is the change in valve timing. The results are plotted in figures 3,4,5 as single points, where it can be seen that for the optimal combustion phasing of 8-9degCA ATDC, ISFC was reduced to 226 g/kWh while COV was marginally over 3%. NO_x concentration was well below 10ppm.

To summarize, increasing valve duration from 104degCA to 112degCA at this operating point reduces fuel consumption while operating with acceptable combustion stability. This indicates that optimization of valve cam profiles in a production VVA engine can lead to reductions in ISFC. Nevertheless it must be considered that there exist physical limitations to the design of a conventional cam profile in terms of durability and that the effects of engine breathing seen on a HVA valvetrain may well differ from a cam-based VVA system. For these reasons, overall trends

rather than specific optimizations are emphasized in this paper.

Multiple Injection Event Operation (4Valve - 3mm Lift)

The previous section has shown that it is possible to operate with a single injection event occurring after the NVO period and before the intake valve opens. The use of a multiple injection strategy with a pilot event during NVO and a main event after NVO has been investigated in several publications where both exothermic reactions and fuel reforming leading to a greater propensity for auto-ignition to occur have been identified, [10,11,12,13,14,15]. These mechanisms would also be present in the case of a single injection with SOI during the NVO period which explains the change in combustion phasing seen in figures 3,4,5. Comparable effects are seen in spark-assisted HCCI when a single injection event is advanced toward the NVO period, [3].

Pilot Injection Quantity and Pilot Injection SOI

The results shown here investigate the effect of pilot injection using the same valve timing as the previous section with 104degCA duration shown in figure 2. In this section the main injection SOI is -240degCA ATDC (occurring during the intake valve event) and the pilot injection quantity and SOI is varied. In these tests a pilot injection event is necessary when the main injection event timing is retarded to this magnitude. This can also be seen by examining figure 3 where single injection retard leads to increased levels of COV of IMEP. Therefore at this level of fueling the interaction (exothermic and/or fuel reforming) between fuel injection (be it single or multiple injection) and NVO is necessary for stable combustion to occur.

The multiple injection strategy used holds the mass fraction of pilot to main injection at 5% and 15% and then varies the pilot SOI. As with all tests the overall fueling is adjusted to maintain a constant load (300 kPa IMEP in this section), involving minor trimming of fuel injection durations. The results are shown in figures 6,7,8. Fuel consumption is approximately constant at 232 g/kWh which shows a reduction of 4g/kWh compared with the single injection used in the previous section and NO_x concentrations below 15ppm. Combustion phasing is affected considerably by pilot SOI in a similar manner to that seen with a single injection in the previous section.

The combustion stability and RI tradeoff seen in figure 6 is comparable again with the single injection results. This confirms that the SOI of the pilot injection does have significant effect over the combustion event. The pilot quantity has a complimentary effect however where it may be possible to use either pilot SOI variation OR pilot quantity variation as a control parameter. This would allow for example the use of a fixed pilot quantity which has certain advantages in terms of FIE hardware linearity and response that will be discussed later in this paper. In terms of pilot

quantity it can also be observed that its effect reduces as the SOI approaches -360 deg ATDC. This would suggest that the exothermic and/or fuel reforming mechanism is reduced when the fuel has less residence time in the NVO high pressure and temperature phase of the NVO period.

By examining figures 6 and 7 it can be seen that the higher pilot quantity advances combustion phasing significantly and leads to an increase in the ringing intensity however operation at a reduced RI of much less than 5 MW/m² is possible with a range of pilot quantity and pilot SOI configurations.

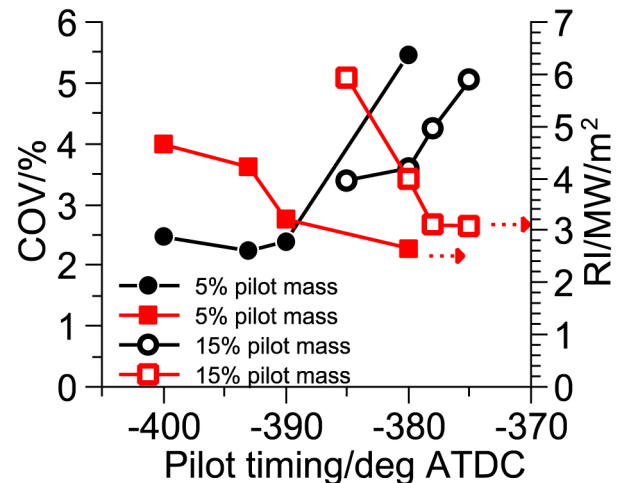


Figure 6. Pilot injection SOI (COV of IMEP and RI).

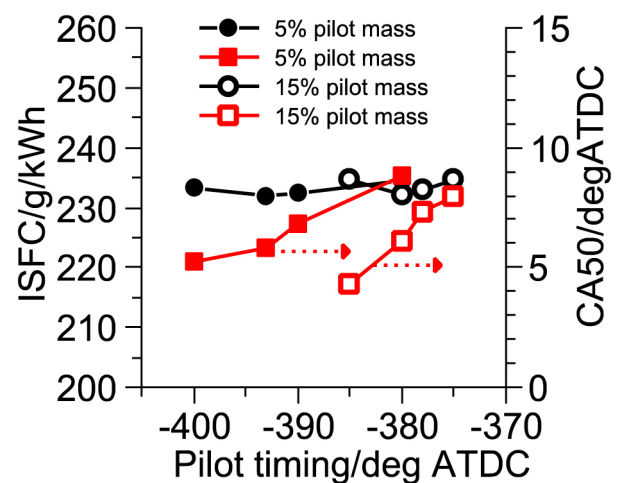


Figure 7. Pilot injection SOI (ISFC and CA50).