

Comparison of Different Boosting Strategies for Homogeneous Charge Compression Ignition Engines - A Modeling Study

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ABSTRACT

Boosted Homogeneous Charge Compression Ignition (HCCI) has been modeled and has demonstrated the potential to extend the engine's upper load limit. A commercially available engine simulation software (GT-Power®) coupled to the University of Michigan HCCI combustion and heat transfer correlations was used to model a 4-cylinder boosted HCCI engine with three different boosting configurations: turbocharging, supercharging and series turbocharging. The scope of this study is to identify the best boosting approach in order to extend the HCCI engine's operating range. The results of this study are consistent with the literature: Boosting helps increase the HCCI upper load limit, but matching of turbochargers is a problem. In addition, the low exhaust gas enthalpy resulting from HCCI combustion leads to high pressures in the exhaust manifold increasing pumping work. The series turbocharging strategy appears to provide the largest load range extension. Single turbocharging is the most efficient but is limited by increased mass flow rates at increased engine speeds. Supercharging helps avoid the backpressure problem but the mechanical work of the supercharger reduces useful work affecting overall brake efficiency.

INTRODUCTION

As emissions legislation becomes ever more stringent, engine research is directed towards achieving improved combustion characteristics and therefore better balance between performance, fuel economy and emissions. Homogeneous

Charge Compression Ignition (HCCI) engines have shown the potential to provide an alternative in this effort, by being able to achieve the high efficiency of Compression Ignition (CI) engines and the low NO_x and soot emissions of Spark Ignition (SI) engines.

The HCCI combustion process is initiated by compression of a homogeneous fuel and air mixture, leading to autoignition of the bulk charge and subsequent fast combustion. It is widely accepted that ignition timing and combustion rates are primarily controlled by the chemical kinetics of the mixture [1,2,3,4]. The low peak cylinder temperature during combustion and the absence of fuel rich zones in the homogeneous mixture, result in significantly reduced NO_x and soot emissions respectively. Furthermore, the lean mixtures result in higher ratio of specific heats, thus improving the thermal efficiency of the engine, while the unthrottled operation aids low-load efficiency by reducing pumping losses.

The commercial automotive application of HCCI engines faces two major challenges. First, the control of combustion phasing that helps avoid knock. Second, the limited operating range resulting from the high rates of heat release, which lead to knock and limit the upper attainable load. From the very first studies regarding HCCI engines, researchers have identified the problem of controlling the combustion phasing, and various approaches have been proposed. One of the most promising methods proposed is the use of Variable Valve Actuation (VVA) strategies. VVA strategies aim to control combustion phasing by modulating the in-cylinder

temperature. This can be achieved by controlling the amount of residual gases trapped in the cylinders. Two major residual-controlling strategies have been investigated: The first one is an exhaust gas retention strategy usually referred to as recompression, and the second one is an exhaust gas reinduction strategy usually referred to as rebreathing [6, 7]. Recompression employs negative valve overlap in order to trap exhaust gases in the cylinders, while rebreathing employs a secondary exhaust valve event after the main exhaust valve event to allow the reinduction of exhaust gases into the cylinders. VVA strategies have helped to improve control of HCCI combustion phasing and also improve low load operation [8, 9].

Intake charge boosting has been investigated for more than a decade and has shown that it can help extend the HCCI engines' upper load limit. One of the first studies by Christensen et al. showed that intake boost can help increase the IMEP of the engine with small benefits in combustion efficiency, NO_x and HC emissions [13]. A later study by Olsson et al. suggested that a turbine for an HCCI engine be smaller and operating on a higher pressure ratio than a turbine for a similarly sized SI engine [14]. This study also identified the pumping problem in boosted HCCI due to high backpressures and suggested the use of a Variable Geometry Turbine (VGT) for higher flexibility on boost control. A later experimental study by the same group confirmed the backpressure problem, but showed an increase in engine efficiency with boosting despite the higher pumping work penalty [15]. Hyvonen et al. studied a supercharged Variable Compression Ratio (VCR) HCCI engine and showed that the operating range can be extended with boosting. They also showed a reduction in burn rate and knock development, but the supercharger suffered from low brake efficiency and was suggested that a turbocharger be used instead [16]. Yap et al. applied boost to a single cylinder Port Fuel Injected (PFI) HCCI engine and concluded that there was substantial load increase without the need for intake air preheating. They also noted that with 1.4 bar of boost, 75% of the maximum SI engine load can be attained, with the equivalence ratio being the main form of combustion phasing control [17]. Cairns and Blaxill investigated a 4-cylinder boosted HCCI engine, showing that load can be increased with boosting and that the reduced heat release rates result in greater combustion stability, lower NO_x, HC but higher CO emissions [19]. Wilhelmsson et al. experimented on a 6-cylinder HCCI engine and they showed that the use of a VGT helped reduce pumping losses. They also commented on the effect of early combustion on increasing the backpressure [20]. Martins and Zhao tested a 4-cylinder 1.6L HCCI engine coupled to a small turbocharger and verified that matching is a problem. They concluded that boosting helps realize the high load extension, but the gas exchange process is compromised as engine speeds rise and there is a need for a highly flexible valvetrain. Finally, they noted that the use of a wastegate for the turbocharger can help extend the low load limit.

The present study focuses on the development of a boosted 4-cylinder HCCI engine model in order to evaluate different boosting strategies and their effects on HCCI combustion. Four different models have been developed; a turbocharged, a supercharged and two series turbocharged engine models. These models are based on a one-dimensional framework (GT-Power® [23]) used to represent the heat flows, heat transfer and energy output of the systems. The models have been used to analyze the behavior of boosted HCCI engines under different boosting configurations using the recompression valve strategy, and to investigate the potential of boosting to extend the upper load limit of the engine. The study also focuses on the factors that limit the operating range at each case and the benefits of the strategies.

MODEL DEVELOPMENT

In order to model different boosting strategies for HCCI engine operation, the whole engine and its components had to be modeled. The simulation tools used in this study were developed in the framework of GT-Power® [23], which is a one-dimensional engine simulation software. It can simulate gas dynamics, heat transfer and thermodynamics in the components of the engine such as the intake and exhaust manifolds, cylinders and turbocharger. It also includes submodels that describe conventional gasoline and diesel combustion but not any that describe HCCI combustion. To address this, new submodels that describe HCCI combustion and heat transfer were developed at the University of Michigan, and were implemented within GT-Power through user subroutines. These submodels include correlations for ignition, combustion rate, combustion efficiency and heat transfer rate and are described in detail by Babajimopoulos et al. [9, 24]. The 4-cylinder engine model was created from a single cylinder engine model, which in turn is based on an experimental engine present at the University of Michigan. The engine geometry parameters are shown in Table 1.

Table 1. Engine geometry parameters

Compression Ratio	12.5
Bore (mm)	86
Stroke (mm)	94.6
Connecting Rod Length (mm)	152.2
Wrist Pin to Crank Offset (mm)	0.8
TDC Clearance Height (mm)	1

The valve strategy used in the model is of the recompression type employing a Negative Valve Overlap (NVO). The need for a flexible valve actuation system pointed towards the implementation of a valve strategy that would not vary NVO through phasing only but through lift as well. For this reason, the valve strategy used and characterized as 'variable'

recompression, keeps constant Exhaust Valve Opening (EVO) and Intake Valve Closing (IVC) timings. In that way, EVO and IVC were used as anchor points, according to which the duration and lift of a high-lift 8mm valve profile were scaled down. [Figure 1](#) shows an example of the scalable lifts. The anchored EVO and IVC prevented the exhaust and intake valve events from significantly entering the expansion and the compression strokes respectively.

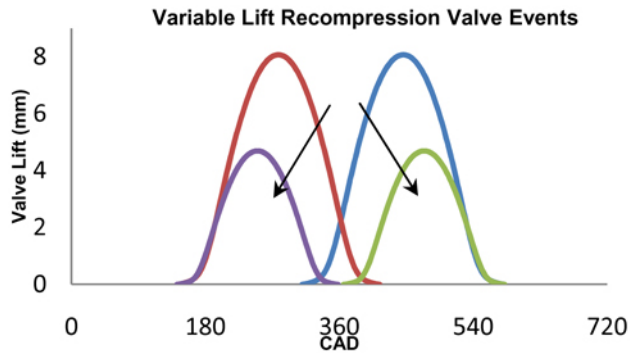


Figure 1. Variable recompression scalable lifts

BOOSTING - In order to identify an efficient boosting strategy for use in HCCI engines, three different boosting configurations were investigated: Turbocharging, supercharging and series turbocharging. The implementation of the turbochargers and supercharger in the GT-Power® framework was achieved by using the turbomachines' maps in each case. There are two turbochargers selected for the present study, a small one sized for a 0.6L engine and a medium one sized for a 2L engine.

The supercharger selected is a Roots-type blower. In the turbocharging systems the intake pressure is self-regulated by the engine exhaust gas enthalpy and the turbine and compressor performance. In the supercharger case the intake pressure can be set to a desired value. For the present study, the target intake pressure for the supercharged engine model was set at 1.8bar and a bypass valve was used to control the air flow through the supercharger. The series turbocharging configuration was implemented in two different setups. The first one includes a pair of the same small turbochargers connected in series, while the second one is a combination of a small and medium turbocharger connected in the same way. These two systems are going to be denoted as S-S and S-M in the text and plots following. In the second case, the medium turbocharger was the one placed closer to the engine, so that the exhaust gases expand through the larger turbine first and the larger compressor is the last feeding the intake manifold.

The models also employed an aftercooler placed after the compressors or supercharger. The aftercooler was used to control the compressed air intake temperature. The initial mixture temperature is one of the controlling parameters of HCCI combustion, and varying it will have an effect on

combustion phasing and the performance of the engine. In order to reduce the amount of variable parameters of the study, the intake temperature was controlled at 350K. This is only the value of the target temperature though. If the resulting intake air temperature was lower than the target, the aftercooler was bypassed; otherwise the intake air was cooled down at the target temperature.

[Figure 2](#) shows the 4-cylinder turbocharged HCCI model as it appears on the GT-Power® interface. The intake and exhaust ambient can be seen on the right side of the model. Intake air runs through the compressor, aftercooler and intake manifold, which appears on the left part of the model. Next to the intake manifold is the block of the four cylinders connected to the engine cranktrain. The exhaust manifold appears on the middle right, after the engine block and before the turbocharger. The turbocharger is followed by a low pressure EGR loop; however, external EGR was not used in this study.

In order to compare the three configurations, a load sweep at 2000 rpm was performed. In the analysis of the results, several operational constraints were imposed so as to discard unrealistic data. These constraints included maximum cylinder pressure, maximum ringing intensity as a knock criterion, maximum IMEP CoV (Coefficient of Variance) as a cylinder to cylinder variation criterion and maximum specific NOx. Each one of these constraining criteria is described below.

Maximum cylinder pressure - The maximum acceptable cylinder pressure has been set at 200bar to discard cases that would result in extreme mechanical stresses in an actual engine.

Knock criterion - The criterion used for knocking combustion is Ringing Intensity (R.I.) and it was proposed by J. Eng in 2002 [24]. He characterized the pressure pulses in SI and HCCI engines and highlighted the differences between the two combustion modes. Ringing Intensity is a measure of the cylinder pressure acoustic intensity and is given by:

$$R.I. = \frac{1}{2\gamma} \frac{\left(\beta \frac{dP}{dt}\right)_{max}^2}{P_{max}} \sqrt{\gamma R T_{max}}$$

where $\frac{dP}{dt}|_{max}$ is the maximum pressure rise rate (kPa/ms), P_{max} (Pa) is the maximum cylinder pressure, T_{max} (K) is the maximum cylinder temperature, γ is the ratio of specific heats, R (J/kg/K) is the gas constant and β is an empirical coefficient that relates the pressure pulsation amplitude to the maximum rate of pressure rise. In this study the value of β is recommended to be 0.05. The units of R.I. resulting from the

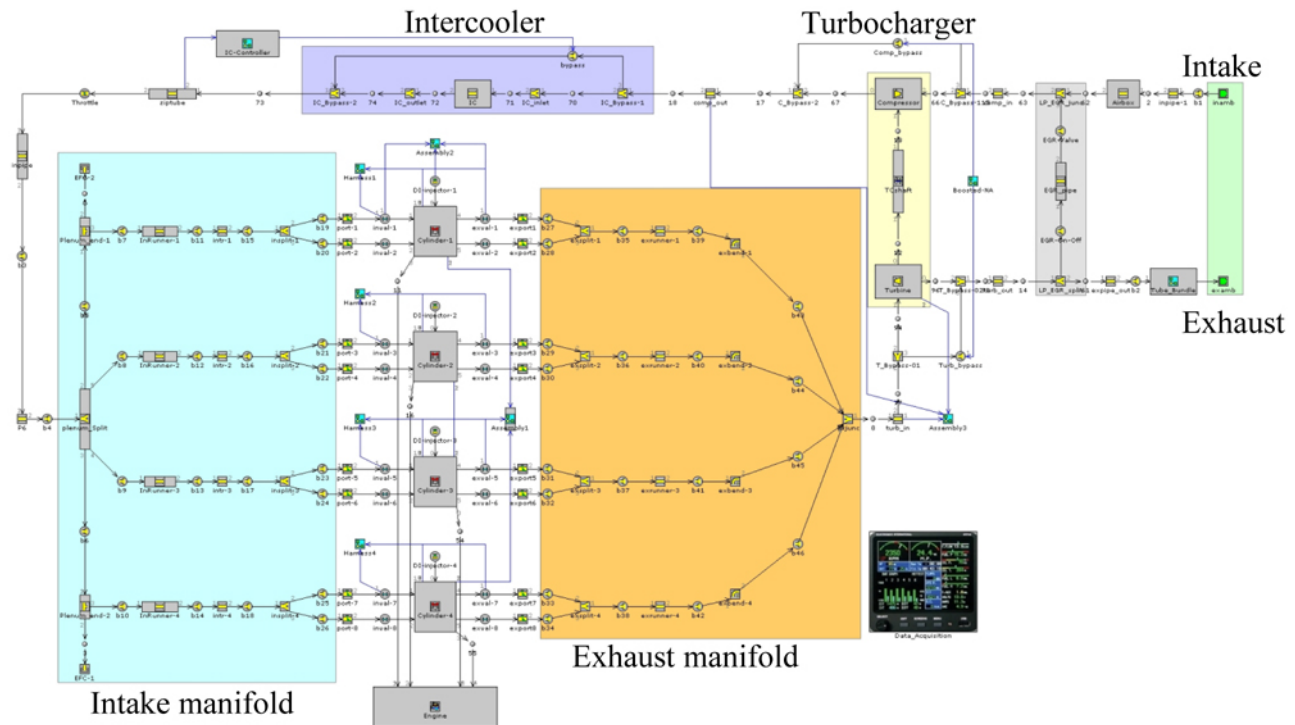


Figure 2. The four-cylinder turbocharged HCCI engine model

definition are $\frac{\text{MW}}{\text{m}^2}$ and the maximum acceptable value for this study has been at $5 \frac{\text{MW}}{\text{m}^2}$.

<figure 2 here>

Cylinder to cylinder variation - Cylinder to cylinder variation is a possible cause of instability in multi-cylinder engines and should be accounted for in HCCI, since there is no direct control of combustion phasing. A constraint has been imposed in the model that accounts for the maximum coefficient of variance (CoV) for individual cylinders' net IMEP. The maximum acceptable value for IMEP CoV is 5%.

NO_x emissions - The University of Michigan HCCI combustion correlation implemented in GT-Power®, employs the extended Zeldovich mechanism to estimate the NO_x formation rate [9, 26]. The integrated NO production in the cylinder is then used in the calculation of NO_x emission index (EI-NO_x), estimating the amount of NO production per unit amount of fuel consumed (g NO/kg fuel). The constraint imposed for the NO_x emission index is 1g NOx/ kg fuel.

In order to assess the performance of the boosted HCCI engine a load sweep was performed at 2000 rpm. Load was controlled through the amount of fuel injected per cycle, and it was varied between 5 and 25mg/cycle with unitary increments. For every load point an NVO sweep was

performed through specifying EVC and its symmetric IVO around gas exchange TDC. After imposing all the constraints in the results obtained from the NVO sweep, the amount of NVO corresponding to maximum net IMEP was selected. Therefore, for every load point there is an NVO value that results in the optimal fuel efficiency point which satisfies all the constraints presented above. These points were selected for the entire load range and presented in the results following. All points with sub-optimal fuel efficiency were ignored in the results following.

RESULTS AND ANALYSIS

This section includes the results obtained from the load sweep as described in the previous section. They are presented in four distinct categories, regarding general efficiency, boosting parameters, aftercooling and in-cylinder effects. The results for the naturally aspirated case are presented along with the boosted operation results. The boosted cases include supercharging, single turbocharging and the two configurations of series turbocharging.

GENERAL EFFICIENCY - The figures of this section display general efficiency results for the four different configurations under investigation and the naturally aspirated case. The parameter NMEP shown is the net indicated mean effective pressure of the engine over the entire cycle (720 CAD).