

On the High Load Limit of Boosted Gasoline HCCI Engine Operating in NVO Mode

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ABSTRACT

The high load limit of a boosted homogeneous-charge-compression-ignition (HCCI) engine operating on negative-valve-overlap (NVO) was assessed. When operating under stoichiometric condition with no external dilution, the load, as measured by the net indicated mean effective pressure (NIMEP), increased with increase in manifold absolute pressure (MAP), and with decrease in trapped amount of residual gas. The maximum pressure rise rate (MPRR), however, also increased correspondingly. When the MAP and the amount of residual gas were adjusted so that the engine operating point could be held at a constant MPRR value, the NIMEP increased with the simultaneous decrease in MAP and residual until the misfire limit was reached. Therefore if a MPRR ceiling is imposed, the high load limit of an HCCI engine is at the intersection of the constraining MPRR line and the misfire line. Dilution with cooled exhaust gas recirculation (EGR) shifted both the MPRR line and the misfire line so that the intersection point would be at a higher MAP and a higher level of dilution. The NIMEP value at this new intersection point, however, did not change substantially. Thus using cooled EGR dilution strategy, the MPRR constrained high load limit is approximately neutral to boosting.

INTRODUCTION

Gasoline homogeneous-charge-compression-ignition (HCCI) engines could offer substantial gain in fuel economy [1]. The operating range, however, is rather limited with respect to driving requirements [2, 3]. Consequently, there is significant interest in extending the HCCI engine load range. Since at the same stoichiometric ratio, the amount of fuel burned is proportional to the amount of air trapped in the cylinder, boosting should, in principle, increase the engine output load (as measured by the Net Indicated Mean Effective Pressure -

NIMEP). In practice, the Noise-Vibration-Harshness (NVH) and engine durability concerns pose a significant limit on the high load limit of boosted HCCI engines [4,5,6,7,8].

This paper concerns the high load limit of operating an HCCI engine with boosting. It is a continuation of the previous work [4] in studying the high load limit of a boosted single cylinder HCCI engine operating in the negative-valve-overlap (NVO) mode using electromagnetically activated intake and exhaust valves. In that work, the maximum pressure rise rate (MPRR) was used as a metric for NVH. External cooled exhaust gas recirculation (EGR) was found to be effective in reducing MPRR in a boosted engine. However, the trapped charge temperature also decreased with EGR so that at some point, the charge was not hot enough for HCCI, and the engine misfired. Therefore, it is of interest to understand the relationship between the high load NVH limit and the misfire limit in a boosted HCCI engine operating with NVO.

The scope of this paper is as follows:

- (i). To determine the gross impact of the engine operating variables on HCCI engine MPRR.
- (ii). To assess the impact of cooled EGR on the HCCI engine misfire limit at high load (here and in subsequent references, load is measured by the NIMEP value).
- (iii). To understand the relationship between the high load limit and misfire limit, and the impact of EGR on the MPRR-constrained high load limit.

EXPERIMENTAL SET UP AND TEST CONDITIONS

The details of the engine with an electromagnetically activated variable valve timing system [2] and the intake system with boost and cooled EGR [4] have been reported previously. The experimental set up is briefly described here

for completeness. The engine and fuel parameters are shown in Table 1.

Table 1. Engine and Fuel Parameters

Bore	80.26 mm
Stroke	88.9 mm
Connecting rod	158 mm
Displacement	449.8 cc
Compression ratio	10.2
Fuel	Certification fuel UTG91
Octane #	RON 91, MON83
Injection pressure differential for PFI	2.7 bar

The engine used a Ricardo Hydra Diesel Crankcase and a VW TDI (model year 2001) head. Fuel is introduced by port fuel injection. The original diesel injector was replaced by a small racing car spark plug. Pressure was measured by a Kistler 6125 transducer through the original glow plug hole.

The boosted air supply and cooled EGR system are shown in Fig. 1. The compressor was a production supercharger from a BMW Minicooper vehicle, and was driven by an electric motor. The manifold absolute pressure (MAP) could be adjusted up to 1.7 bar by varying the motor drive speed. The exhaust pressure was maintained by a close-loop controlled throttle to be 0.03 bar above MAP to enable EGR. The EGR was water cooled. The EGR temperature was above the dew point to prevent water condensation. The cooled EGR flow was then reheated to the same temperature of the fresh air, which was also temperature controlled by a heater.

The amount of EGR was determined by a CO₂ measurement at the intake port and in the exhaust line. The in-cylinder residual gas fraction was determined by the exhaust temperature and pressure measurements; the method had been verified by direct in-cylinder CO₂ sampling measurement using a fast CO₂ meter from Cambustion Ltd. as described in a previous study [4].

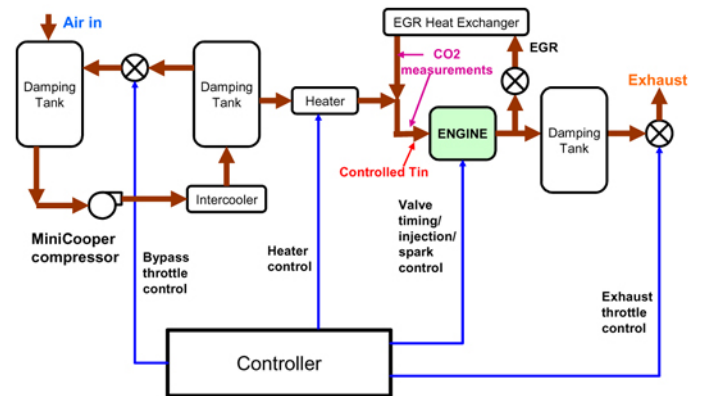


Fig. 1. Engine set up for boosted operation with cooled EGR

The valve timing strategy is shown in Fig. 2. The timings for IVC and EVO were fixed (see Fig. 2 caption for values). The timings for EVC and IVO were set symmetric with respect to TDC-intake so that the amount of negative overlap was determined by the NVO half angle θ_0 ; the amount of NVO determined the amount of trapped burned gas retained for next cycle.

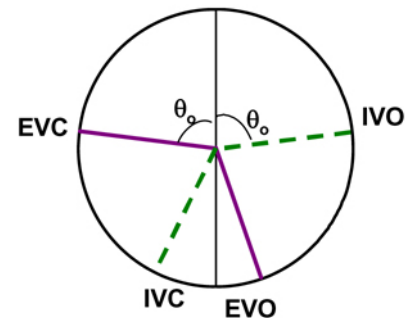


Fig. 2. Valve timing strategy: IVC fixed at 29° ABC-compression; EVO fixed at 15° BBC-expansion; NVO symmetric about TDC exhaust; NVO half angle is θ_0 .

All the data were taken at the engine speed of 1500 rpm with a stoichiometric mixture except for the experiments which compared the dilution by burned gas and by air, for which there was excess air. The exhaust pressure was set to MAP +0.03 bar. The amount of EGR was set by the EGR valve as shown in Fig. 1. The experimental parameters are shown in Table 2.

Table 2. Range of operating conditions

MAP	1 to 1.7 bar
Intake temperature	30 to 120° C
EGR dilution without excess air (stoichiometric condition)	0-30% by moles of EGR gas
Dilution with excess air(lean condition)	0-30% by moles of excess air
Residual burn gas	30 -60%, depending on NVO setting

HCCI ENGINE OPERATING VARIABLES IMPACT ON MPRR

A large data set was collected with the range of parameters varied according to Table 2. Some of the results were previously reported [4]. The task here is to develop a correlation based on that data so that the *gross* dependence of MPRR on engine operating condition could be established. We have put emphasis on the *gross* dependence because in general, the MPRR depends on the detailed charge temperature and concentration stratifications. As a matter of fact, stratification is often used as a strategy to control MPRR [9, 10]. Quantifying stratification is difficult since such data are difficult to generate and since a simple metric for stratification has not been devised. Furthermore, the spatial distribution changes during the engine process. Nevertheless, quantifying the gross dependence of MPRR on engine parameters, not withstanding the effects of stratification, is useful because such a correlation would give an estimate to the change in MPRR due to the gross change of operating condition (such as MAP or intake temperature), all other things kept “equal.”

The pertinent observations from the data set are [4]:

- At fixed NVO, the NIMEP increased with MAP and decreased with intake temperature. The latter was a volumetric efficiency effect. The corresponding MPRR increased with both MAP and intake temperature.
- Comparing at the same total dilution (see Definition/Abbreviation section for detailed definition), dilution by EGR was effective in lowering MPRR by lowering the charge temperature. However, at high EGR level, the charge would be too cold for HCCI operation and led to misfire.
- With air dilution (operating lean at the same dilution ratio, intake temperature, and MAP), MPRR did not improve; instead, it deteriorated. The effect was due to the increase of oxygen concentration, which promoted reaction, and also to the increase in compression temperature due to the higher specific heat ratio.

Values of MPRR are plotted against NIMEP for all the data in Fig. 3. There was substantial data scatter. To interpret this data, the first law of thermodynamics was applied to the charge [4]:

$$\dot{p} = (\gamma - 1) \left[\dot{q} - \frac{\dot{Q}_L}{V} \right] - \left(\gamma P \frac{\dot{V}}{V} \right) \quad (1)$$

(See Definition/ Abbreviation section for symbol definitions.) Since the heat loss and volumetric expansion terms are small compared to the volumetric heat release term, they may be dropped from Eq. (1); MPRR is then given by

$$\text{MPRR} = (\gamma - 1) \left[\frac{m_f \text{LHV}}{V(\theta) \tau_{\text{reaction}}} \right]_{\text{max}} \quad (2)$$

Here, the volumetric heat release rate $\dot{q}$ in Eq. (1) has been replaced by the average charge fuel energy density at the maximum pressure rise rate point, divided by an overall reaction time τ_{reaction} . To assess whether the data supports an interpretation in the manner of Eq.(2), $V(\theta)$ is approximated by $V(\text{CA}50)$, and τ_{reaction} by $\Delta\tau_{10-90}$. Then the relationship according to Eq. (2) is shown in Fig. 4. The significant reduction of the data scatter (compared to Fig. 3) indicates that Eq. (2) is indeed a valid assessment of the MPRR dependence.

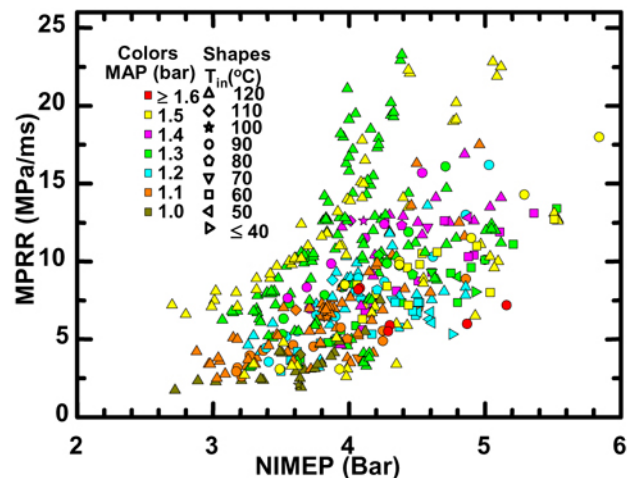


Fig. 3. NIMEP as a function of NIMEP. The colors and symbols represent different operating conditions. The dilution data with both EGR and air were included but not explicitly marked; from [4].

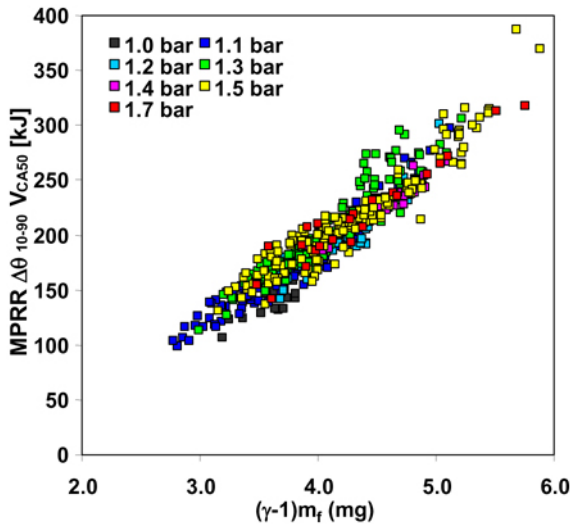


Fig. 4. Correlation plot of MPRR to engine parameters.

To make Eq.(2) a useful formula for assessing MPRR, instead of using $\Delta\tau_{10-90}$, the value of τ_{reaction} was calculated directly from the data:

$$\frac{1}{\tau_{\text{reaction}}} = \left[\frac{\text{MPRR } V(\text{CA50})}{(\gamma - 1)m_f \text{LHV}} \right]_{\text{data}} \quad (3)$$

This value was then regressed against the engine thermochemistry variables to produce the following correlation:

$$\left(\frac{1}{\tau_{\text{reaction}}} \right) = 3.32 \cdot x_{\text{O}_2}^{1.88} \cdot x_{\text{fuel}}^{0.35} \cdot P_{10 \text{ BTC}}^{1.92} \cdot \exp\left(\frac{-2560}{T_{10 \text{ BTC}}}\right) \quad (4)$$

(τ_{reaction} in ms; P in bar; T in K)

The choice of x_{O_2} instead of the residual gas fraction as variable was to reflect the significant influence of oxygen concentration (see observation (c) above). The compression pressure and temperature at 10° before-top-center were chosen as the thermodynamics variables because up to that point, there was no significant heat release, and the temperature and pressure there encompassed the effects of the trapped enthalpy of the residual, the intake air temperature, and the heat loss. The value of $T_{10 \text{ BTC}}$ was calculated from $P_{10 \text{ BTC}}$ using the ideal gas law and the residual fraction value obtained from the exhaust temperature and pressure measurements [4].

The result of the regression is shown in Fig. 5. The agreement was satisfactory ($R^2 = 0.71$). The data scatter (bracketed by a factor of 0.5 to 1.5) may be attributed to stratification effects and to error in the charge temperature estimate. Reported ignition delay data targeted to HCCI combustion conditions

indicate that the reaction rate is highly sensitive to temperature [11]. Since the temperature estimate relies on the residual fraction estimate, even a small error from the calculation in the latter could result in significant scatter for the $1/\tau$ correlation of Eq. 4. For example, if the residual fraction is estimated to be 38% instead of 40% - a 5% error, which is realistic - the $T_{10\text{BTDC}}$ value would be 27° K lower. Then there will be a 44% decrease in ignition delay (using the correlation in [11] for iso-octane). Thus the data scatter in Fig. 5 is within the accuracy of the experiment.

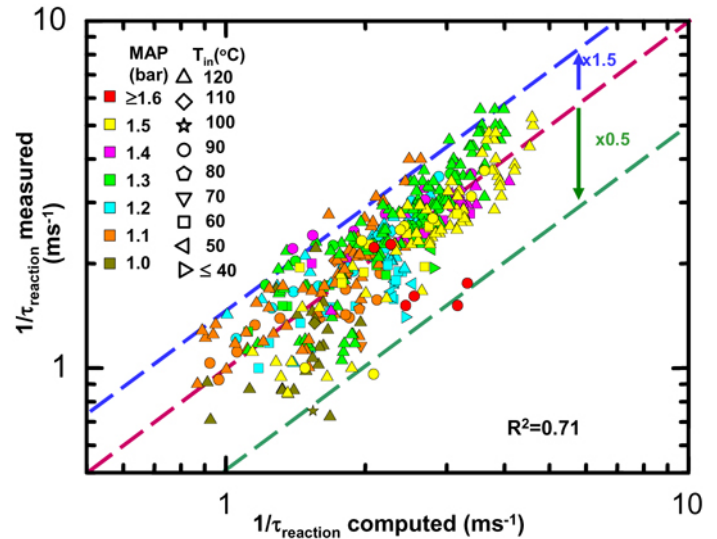


Fig. 5. Comparison between reaction rate obtained from data and from the correlation of Eq. (4).

To assess the stratification factors, it was noted that precise quantitative measures of stratification are difficult. Therefore, the following variables that addressed stratification were added to the regression:

- (1). $(T_{\text{exh}} - T_{\text{in}})$; to represent the temperature non-uniformity due to the mixing between the hot trapped residual and the relatively cool intake fluid.
- (2). $x_r (1 - x_r)$; to represent the concentration non-uniformity due to the mixing between the residual and the fresh charge.
- (3). $(1 - x_{\text{EGR}})$; to represent the concentration non-uniformity due to the mixing between the recirculated exhaust gas and the fresh charge. (Strictly speaking, the expression should be $x_{\text{EGR}} (1 - x_{\text{EGR}})$. However, a significant part of our data set was obtained with $x_{\text{EGR}} = 0$, so such an expression would not work.)

It is recognized that the above variables did not address the stratification profiles, nor did they address any correlation between temperature and concentration stratifications. Nevertheless, assessing the regression by inclusion of these