# BOOSTED HCCI OPERATION ON MULTI CYLINDER V6 ENGINE

**Jacek Misztal, Mirosław L Wyszyński*, Hongming Xu, Athanasios Tsolakis**

*The University of Birmingham, Department of Mechanical Engineering*
*Edgbaston, Birmingham B15 2TT, United Kingdom*
**e-mail: M.L.Wyszynski@bham.ac.uk*

**Jun Qiao, Trevor Wilson**

*Jaguar and Land Rover Research*
*Abbey Road, Coventry CV3 4LF, UK*

***Abstract***

*This paper is an extension of work done with boosted 1-cyl Homogenous Charge Compression Ignition (HCCI) engine. As has been proven in the authors' laboratory on a single cylinder research engine, applying boosting can enable an increased load range with a decreased NOx emission. During the tests which are covered in this paper, a Jaguar V6 research engine with a negative valve overlap facility has been used. The engine is equipped with a mechanically coupled supercharger, which supplies the required amount of air. The introduction of a higher amount of air allows the cylinder mixture to be kept on a highly diluted level; this enables autoignition to be controlled and improves NOx emission. Finally, more air introduced into the cylinder enables more fuel to be injected, which in turn provides for a higher load. This fact is useful as one method to increase the upper load limit for HCCI. Boosted HCCI operation is very sensitive to exhaust gas residuals. It has been proven that valve operation, whether advancing or retarding away from the optimum point will affect NOx emission. This paper will demonstrate that the optimisation of valve timing in connection with lambda value and boost pressure can produce lower NOx emission for the same or even a higher load.*

***Keywords:*** *road transport, combustion engines, HCCI, NOx emissions*

## 1. Introduction

HCCI combustion is an attempt to combine and make best use of the characteristics of two different kinds of engine, the spark ignition and the compression ignition. The main idea is to obtain the benefits from both within a single engine, at least for part of the load – speed range. Another potential advantage of using this technology is that a variety of fuels can be used as a power source. For instance, with standard gasoline used the result can be that the engine has a higher efficiency rate than a standard SI engine (closer to diesel engines), while at the same time producing lower NOx emission. Lower NOx emission is reached by running HCCI engines with cylinder mixtures that are near-homogeneous and highly diluted and this prevents high temperatures. The main disadvantages of using HCCI are: generally higher HC emissions; higher rate of pressure rise and a smaller operating range than SI. The higher rate of pressure rise makes the engine very noisy and in some extreme cases can damage it. The two most common roads to decrease the rate of pressure rise are to supply excess air and to introduce exhaust gas retention. Exhaust gases reduce pressure rise better than excess air because they decrease combustion temperature and reduce oxygen concentration. In order to keep the cylinder mixture diluted, the maximum load attainable for HCCI is lower than for SI. One of the solutions to increase the maximum load is to use boosting as a means of introducing more air into the cylinder. More air will allow feeding in more fuel to maintain the same load with a low NOx. However, supplying more air will affect the rate of pressure rise because it increases the oxygen concentration. To prevent that phenomenon more exhaust gases will be required. On the other hand, increasing the amount of fresh air without increasing the retention of hot exhaust gases will not produce a sufficient amount of energy for auto-ignition and will cause misfires. This requires that the engine is operated with more advanced exhaust cams. Employing internal EGR also makes an engine suffer from breathing problems. By reducing the volumetric efficiency, EGR will limit load range compared with a fully breathing SI operation that employs positive valve overlap.

In this work, the Jaguar V6 direct injection research engine has been used. The main goal is to obtain the maximum load possible during the HCCI operation with a supercharger. The variable experimental conditions are engine speed, inlet and exhaust valve timing, lambda and boost pressure. For the purpose of present comparison between this work and the work performed previously on a single cylinder engine, one engine speed is considered – 1500 RPM. Three values of boost pressure will be considered, 0 (no boost) 0.2 and 0.4 bar gauge.

The work that is the base for this paper is part of the CHASE (Controlled Homogeneous Autoignition Supercharged Engine) project at Birmingham University. The CHASE project is a collaborative research within the Foresight Vehicle programme funded by the Department of Trade & Industry and by Engineering & Physical Science Research Council of the UK in cooperation and co-funding with Jaguar Cars Ltd, Johnson Matthey plc and other partners. The main goals of the project are to develop the technology to extend the lower (by adding hydrogen) and upper (by boosting) range of HCCI. The final point of the project will prove that the HCCI engine can be a self-sufficient on board unit.

## 2. Experiment Setup

### THE V6 ENGINE

The experimental engine is the Jaguar V6 direct injection, 4 valve per cylinder and 3 litre capacity research engine. To switch between SI and HCCI operation, cam profile switching (CPS) is in use. This system allows on-line switching of valve lifts from 9 mm (SI operation) to 3mm (HCCI operation). The variable cam timing system makes it possible to change the cam timing for the inlet and exhaust cams within 60 crank angle degrees range. The HCCI operation is achieved by internal EGR produced by negative valve overlap, which traps exhaust gases in order to deliver enough energy for autoignition. Valve timings are defined here by inlet and exhaust mean opening point (MOP), which is a crank angle measured from TDC gas exchange denoted as 720 (0) deg. Exhaust valve timing is degrees before TDC and inlet valve timing after TDC. Table 1 shows all engine details.

The fuelling system is DI wall guided and the end of injection was set on 350 deg before TDC combustion. The supercharger used in the experiment is the Eaton M24 model, mechanically coupled with the engine through a fixed gear ratio 2.8. The boost pressure was adjusted by opening the by-pass loop valve. Such system causes a fuel consumption penalty, but this penalty will occur as well in a production engine. Gharahbaghi et al. [1] has shown that HCCI operation is very sensitive with regards to the size of the supercharger. This happens because a bigger supercharger will produce a higher fuel consumption; on the other hand the large amount of fresh air introduced into a cylinder will cause a problem with delivering enough EGR for stable HCCI combustion. This can result in misfires.

*Table 1. Engine specification summary*

| | | | |
|---|---|---|---|
| Engine type | Jaguar research V6, 24-V, GDI | Compression ratio | 11.3 |
| Engine speed | 1500 rpm | Intake valve timing | variable |
| Bore | 89mm | Exhaust valve timing | variable |
| Stroke | 79.5mm | Intake temperature | ~ 335K |
| Fuel | Commercial Gasoline | Air/Fuel ratio | variable |

## CONTROL AND DATA ACQUISITION SYSTEM

In order to control the engine an in-house MATLAB / SIMULINK model is employed in connection with a DSpace system. The system is a fully computer-controlled unit, which enables users to control and record all engine data. Kistler 6125A pressure transducers fitted into the wall of the combustion chambers measure in-cylinder pressures in all 6 cylinders with 1 crank angle degree resolution. The amount of fuel injected is adjusted separately to each engine bank. During tests, a single injection strategy was used. A Pierburg gas analyser has been used to measure emissions taken from one bank of engine.

## TEST CONDITIONS

Table 2 shows an extract from a set of test conditions that has been chosen to show some of the most important results. Two different inlet valve timings are presented to show the influence of inlet cam phasing on combustion. The first two Cases (1 and 2) for Inlet Valve MOP = 150 deg aTDC prove that there is a possibility to obtain the same load with increasing boost pressure but at the same time the NOx emission will decrease significantly. Cases 3, 4 and 5 for inlet valve MOP=160 deg aTDC show that further optimisation of valve timing events can provide an even higher load with a significantly decreased NOx emission. During the tests, the value of the rate of pressure rise was kept within 2 to 7 bar/deg range. No fuel consumption or other aspects of boosted HCCI operation are considered in this paper.

*Tab. 2. Test conditions*

| Conditions | Boost Pr. (bar gauge) | Inlet valve MOP (CAaTDC) | Exhaust valve MOP (CAbTDC) | Conditions | Boost Pr. (bar gauge) | Inlet valve MOP (CAaTDC) | Exhaust valve MOP (CAbTDC) |
|---|---|---|---|---|---|---|---|
| Case1 | - | 150 | 160 | Case3 | - | 160 | 150 |
| Case2 | 0.2 | 150 | 175 | Case4 | 0.2 | 160 | 165 |
| | | | | Case5 | 0.4 | 160 | 175 |

## 2. Results and Discussion

Table 3 summarises the test results details. As has been proven by Yap et al. [2] during the work on a single cylinder engine, applying boosting can lead to decreasing NOx emission for the same load.

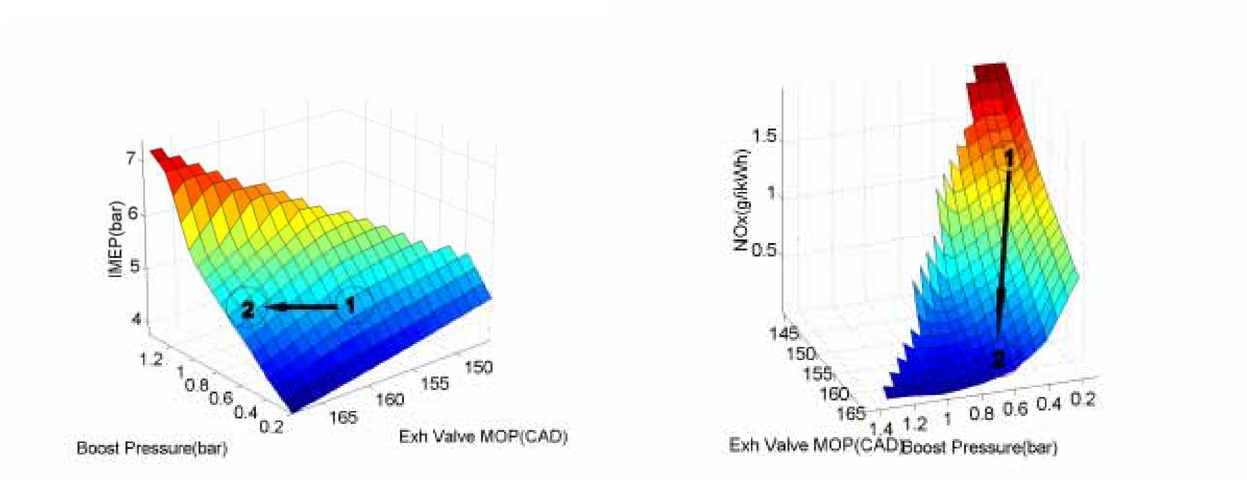

***Figure 1.*** *NOx emissions for various exhaust valve timings and boost pressures. Points "1" and "2" represent the same IMEP [2].*

Figure 1 shows that on a single cylinder engine for the same load one can adjust the boost and exhaust valve setting to obtain much lower NOx emissions [2]. It has been shown as well that each inlet valve setting will have an optimal exhaust valve timing. That optimal point will result in the lowest NOx emission. During tests, it has been found that HCCI operation produce very low NOx emission for a low load but with an increased load the NOx emission increases rapidly. Table 3 shows emissions, load (NMEP), rate of pressure rise, coefficient of variation (COV) and mass fraction burnt for one bank of the engine and Figure 2 presents an average of 100 cycles in cylinder pressures for engine bank B. Generally, the appearance of unpredictable misfires can cause a higher cylinder to cylinder variations on load and rate of pressure rise. It is clear that cylinder B1 has consistently highest COV of NMEP and gives a lower average pressure which suggests misfires during sample time. The average pressure in cylinder B1 in supercharged operation (CASE2, represented by S2) is even lower than the combustion pressure for NA HCCI (CASE1 represented by S1). The occurrence of any misfires will affect not only one cycle, because EGR in the next cycle will have a lower temperature. This temperature in low load condition can cause further misfires and consequently other cylinders will have a tendency to stop working as well. The working HCCI range as presented here is limited to COV of NMEP ≤ 5% (with one value in Table 3 at 5.3%), thus even occurrence of unpredictable misfires will not have unduly affected the results.

*Table 3. Test results (B1,B2 and B3 denote cylinders 1,2 and 3 in the B bank)*

| | λ | HC | NOx | NMEP | | | RATE OF p RISE | | | COV of NMEP | | | MFB (cylA1) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | B1 | B2 | B3 | B1 | B2 | B3 | B1 | B2 | B3 | 5% | 50% | 95% |
| | [-] | [ppm] | | [bar] | | | [bar/CA] | | | [%] | | | [CA] | | |
| CASE1 | 1.0 | 208 | 74 | 4.42 | 4.54 | 4.32 | 4.44 | 5.48 | 4.20 | 1.8 | 1.5 | 1.5 | 361.6 | 368.9 | 374.9 |
| CASE2 | 1.3 | 211 | 27 | 4.51 | 4.67 | 4.58 | 1.99 | 3.01 | 3.43 | 5.3 | 3.0 | 2.2 | 360.1 | 370.1 | 377.9 |
| CASE3 | 1.0 | 190 | 276 | 4.79 | 4.93 | 4.75 | 5.99 | 6.15 | 4.39 | 1.7 | 1.3 | 1.2 | 363.6 | 372.3 | 378.8 |
| CASE4 | 1.3 | 211 | 100 | 4.85 | 4.98 | 4.86 | 2.41 | 3.47 | 4.79 | 4.8 | 2.6 | 2.3 | 362.2 | 372.5 | 379.0 |
| CASE5 | 1.3 | 118 | 64 | 5.73 | 5.71 | 5.47 | 5.81 | 7.07 | 7.43 | 2.6 | 2.5 | 2.3 | 361.2 | 369.8 | 377.1 |

Figure 2 shows that with boosting, more air is introduced into cylinder, resulting in an increased cylinder pressure during the compression stroke. This increase in mass of trapped air requires in the rate of EGR for stable HCCI operation. The higher amount of EGR can be reached by advancing the exhaust valve, which causes a higher in cylinder pressure during the re-compression stroke.

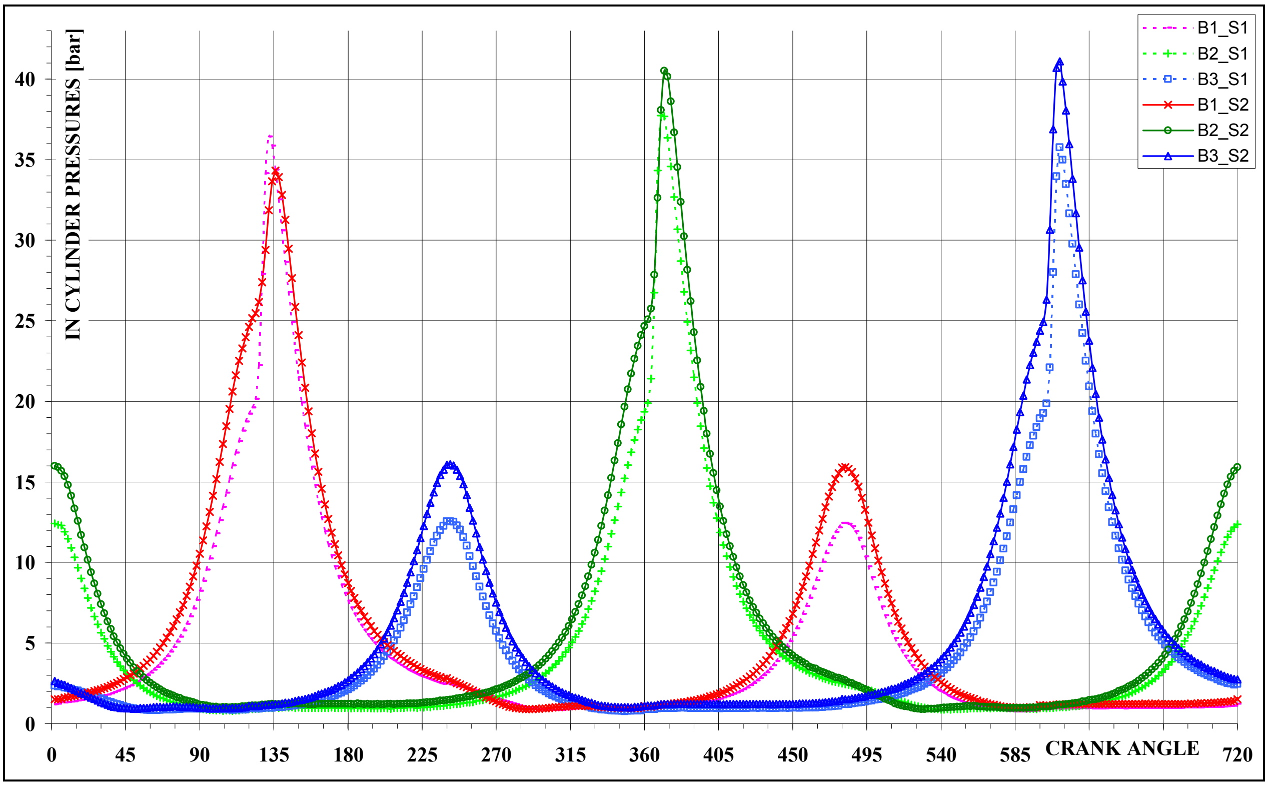

*Figure 2. Average (over 100 cycles) samples of in cylinder pressures for CASE1 (_S1) and 2 (_S2)*

Figures 3 and 4 present effect of boost on NOx and engine load for different inlet valve timing. It is clear that even a relatively small boost pressure such as 0.4 bar can give a maximum load close to 6 bar NMEP. As has been shown in Table 3 Cases 1 and 2 represent almost the same load, but NOx emission is much lower for Case 2. This occurs for two different reasons, which were pointed out earlier. Increasing the inlet manifold pressure by pushing more air into the cylinder produces a more diluted mixture (higher lambda = 1.0 in Case 1 but 1.3 in Case 2). On the other hand, maintaining stable combustion requires more EGR to be introduced, and in conjunction with the previous fact, it decreases the in-cylinder temperature and causes lower NOx emission. Another fact, which is worth noting, is that the NOx map for constant inlet valve timing is very sensitive to exhaust valve timing. Yap et al. [3] have shown that every inlet valve timing will have an optimal exhaust valve timing in which the NOx emission will be the lowest. This optimization is the subject of further research. As has been shown in Table 3 and Figure 4, for Cases 3, 4 and 5 increasing the boost pressure extend HCCI to an even higher load without NOx emission penalty. Case 5 proves that keeping the lambda value constant but increasing boost with increasing EGR can extend the load range upwards by 0.8 bar with significant decrease of NOx. Christiansen et al. [4] demonstrate that specific HC emission will decrease with increasing EGR and load, which is observed in Cases 4 and 5. A supercharger is not the only device that can be used to supply required amount of air. There is some work published on turbocharged HCCI [5, 6]. Cairns et al. [5] proved that by using turbocharger, fuel economy and NOx emissions benefits could be reached as well. It was also stated that fuel injection timing is another useful tool to provide control over the combustion phasing and emissions. This has been investigated by the authors for NA HCCI operation and will be presented elsewhere.

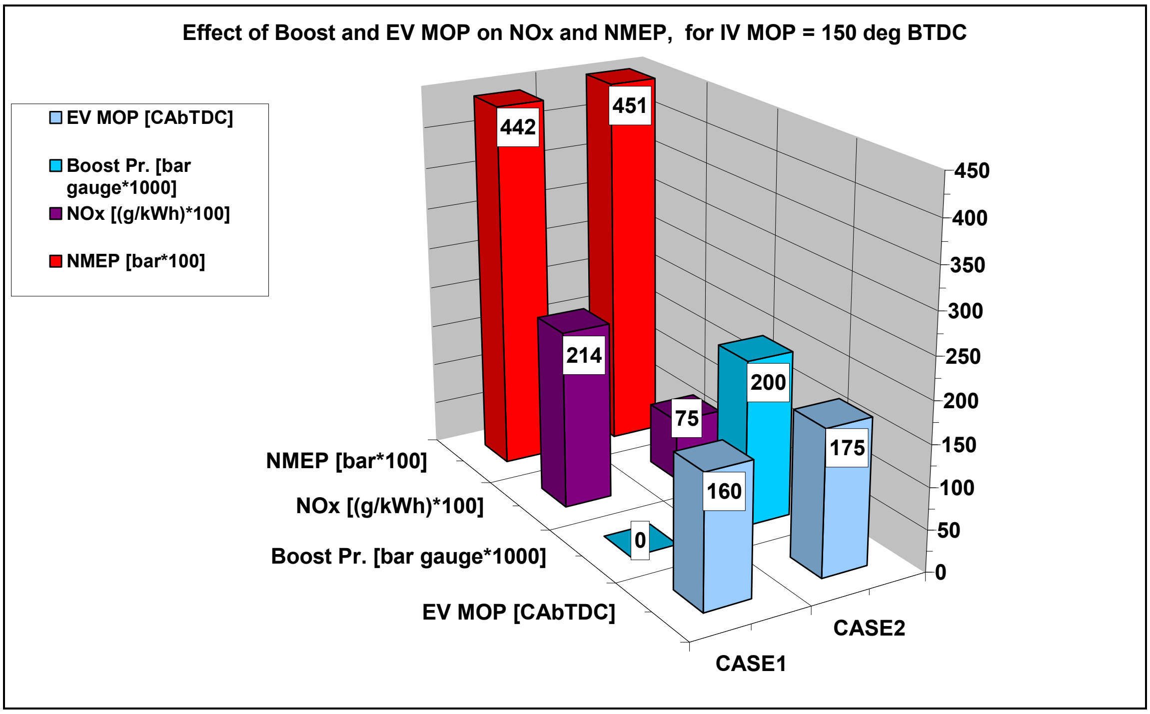

*Figure 3. Effect of boost and EV MOP on NOx and NMEP, for IV MOP = 150 deg bTDC*

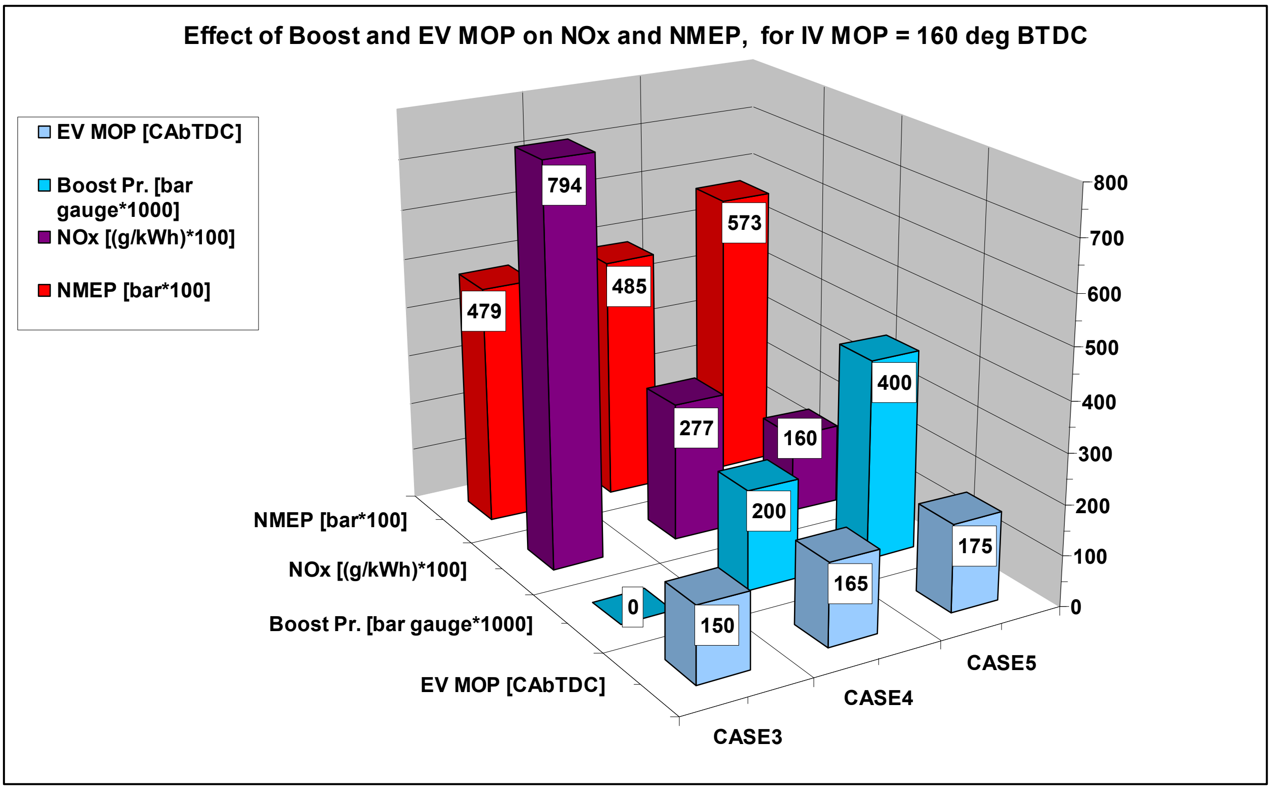

*Figure 4. Effect of boost and EV MOP on NOx and NMEP, for IV MOP = 160 deg bTDC*

## 2. Conclusion

This paper is a continuation of work that published before [2, 3] on a single cylinder engine. It has been shown that during boosted HCCI operation it is possible to obtain a similar or even higher load with much lower NOx emission. This paper confirms that the same behaviour can be obtained with a multi cylinder production engine, which is adapted for HCCI operation. As has been shown above the optimisation of exhaust valve events will be very important for that action in case of high emission sensitivity. To obtain all the benefits which come with HCCI technology it will be very useful to prepare a full map of NA HCCI and boosted HCCI and after that to prepare the optimum map of load-engine speed operation.

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