

EU6c Particle Number on a Full Size SUV - Engine Out or GPF?

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ABSTRACT

This paper describes the findings of a design, simulation and test study into how to reduce particulate number (Pn) emissions in order to meet EU6c legislative limits. The objective of the study was to evaluate the Pn potential of a modern 6-cylinder engine with respect to hardware and calibration when fitted to a full size SUV. Having understood this capability, to redesign the combustion system and optimise the calibration in order to meet an engineering target value of 3×10^{11} Pn #/km using the NEDC drive cycle. The design and simulation tasks were conducted by JLR with support from AVL. The calibration and all of the vehicle testing was conducted by AVL, in Graz.

Extensive design and CFD work was conducted to refine the inlet port, piston crown and injector spray pattern in order to reduce surface wetting and improve air to fuel mixing homogeneity. The design and CFD steps are detailed along with the results compared to target. The redesigned high tumble combustion system enabled the engine to meet challenging combustion stability targets at low Pn-levels.

The ECU software was optimised in order to allow for calibration strategies leading to minimised wall interaction of injected fuel.

The Pn optimisation by calibration measures with the improved combustion system followed a specific development process.

Physical testing and calibration optimisation was conducted on a state of the art chassis dynamometer with rapid cooling capability and full combustion and emissions measurement capability.

In addition, optical combustion diagnostic equipment was used to determine sources of soot formation within the combustion chamber during dynamic testing on a cycle resolved basis. Within this testing environment a Pn - optimised injection strategy with special focus on dynamic, cold and high load operation was developed. This strategy allowed reducing surface impingement as a source of diffusion combustion, under all operating conditions, to an absolute minimum.

The results of the project showed that the engineering target could be achieved with a margin of robustness. The performance of the hardware and calibration was also assessed over the WLTP, FTP 75 and a real world driving cycle (AVL RDE cycle). This showed that the excellent Pn optimisation of this engine did not result in any significant detrimental effects on gaseous emissions and actually delivered a small improvement in fuel consumption. The paper concludes with a summary of considerations outside the original scope of the project which would be important for further Pn reduction.

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1. INTRODUCTION

Whereas in the past, revisions of the exhaust gas legislation were focused primarily on the reduction of gaseous emissions within an established test scenario, the next legislative step will contain several new challenges, [Figure 1](#). The biggest challenge will be the limitation of particle emissions. Within this scenario, the limitation is of particle number rather than particle mass based on the current legislative requirements of Diesel approximately 1 order of magnitude (90%) is required between EU6b and EU6c for petrol engines.

A modified test cycle for the chassis dyno - the WLTC drive cycle - will be adopted for emissions and CO₂ measurement. Finally, vehicles will be tested using real world drive cycles - RDE. In addition, more stringent CO₂ fleet average limits result in further challenges. Despite the fact that some essential parts of the future legislation are not yet fixed, potential solutions have to be developed and evaluated, not only in the current NEDC drive cycle, but also in future WLTC and RDE cycles [1].

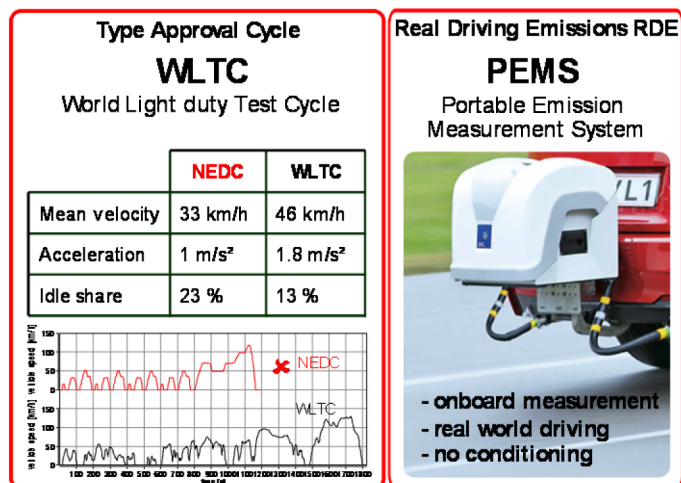


Figure 1. European emission legislation for passenger cars: expected changes for EU6: WLTC / RDE + PEMS

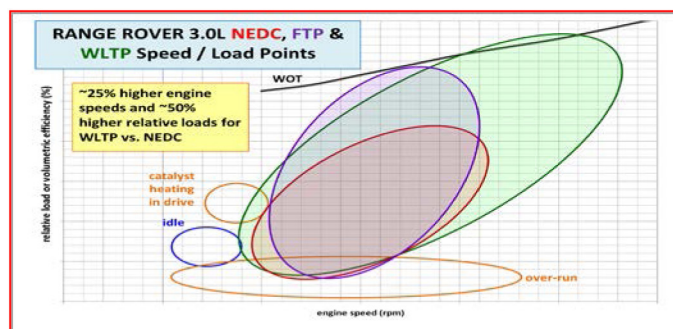


Figure 2. European emission legislation for passenger cars: Cycle comparison WLTC (uses higher speeds / loads, longer duration (reduced effect of warm-up vs. NEDC))

The WLTC test cycle is characterised by heavier accelerations, higher vehicle speeds and less idle share, [Figure 2](#). Real driving emissions will be measured utilising a portable emission measurement device (PEMS) for both gaseous and Pn emissions. The measured emissions will be normalised and weighed in order to make measured emissions from various topographies and driving styles more comparable [2, 3]

2. THE ENGINE

The engine used for this investigation was a supercharged 3.0L V6 GDI engine, [Figure 3](#) [4]. In order to evaluate the worst case conditions the heaviest vehicle application for this engine was chosen - a full size SUV [Figure 4](#) [5]. The V6 combustion chamber was originally optimised for SULEV30 emissions capable with central injection and a relatively small piston bowl to allow compression injection starting. This enabled minimum HC emissions, excellent robustness to low volatility fuels and good combustion stability during the catalyst heating mode. As far as possible commonality between the V6 and existing V8 engines was sought to allow common production lines and maximum flexibility in the build quantities of each engine variant.

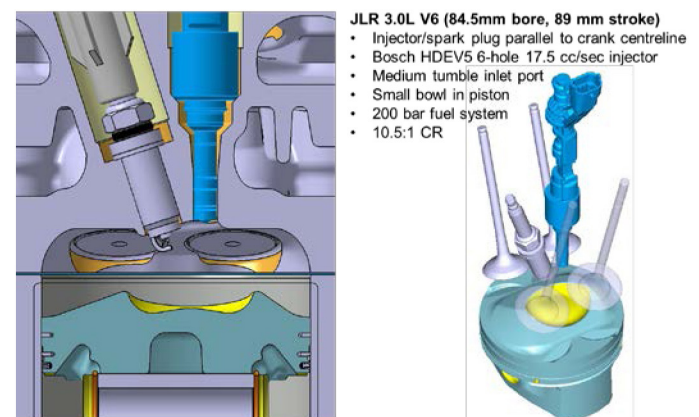


Figure 3. Test engine (baseline configuration: supercharged 3.0L central direct injection)



Figure 4. Test vehicle: Full Size SUV (Range Rover Sport with 3.0L V6 Direct Injection Petrol Engine)

3. REQUIREMENTS FOR EU6C

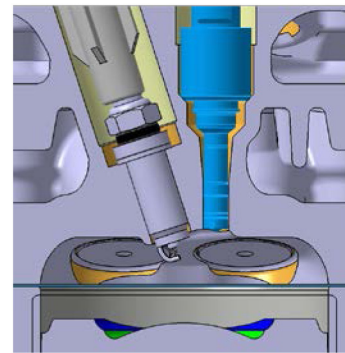
The move from EU6b to EU6c requires several changes to the combustion and injection systems in order to achieve the required improvements in particle number, [Figure 5](#). A higher charge motion level, achieved by more aggressive tumble from the intake port shape, contributes to improved evaporation rates of liquid fuel from cold cylinder walls and also provides better mixing of fuel and air. A large piston bowl to contain most of the fuel spray that impinges the piston during the injection phase helps to avoid fuel being reflected from the piston onto the liner. Low penetration of the injection sprays reduces impingement of cold liner and piston surfaces. Slight spray plume interaction is desirable in order to limit penetration, but has to be carefully developed with relatively equal jet spacing in order to avoid collapsing sprays or increased penetration distances. Small droplet sizes help in the evaporation of the fuel and support good mixing. Spray targeting must avoid liner surfaces and open valves, so far as possible within the chamber design and expected spray penetration distances. The influence of tumble on spray penetration must also be considered. Injector tip coking and its influence on the spray plume is also an extremely important consideration. Engines with centrally located injector often use a pilot injection late in the cycle in order to support stable late burning during catalyst heating. In order to keep the particle number emission at a minimum the injected fuel quantity in this micro pilot injection needs to be minimised. Operation in the ballistic area of the fuel injector is therefore essential. Finally, higher fuel pressures help to reduce the static flow of the injector and thus allow a better operation at low injector pulse widths. Higher fuel pressure improves mixing if the penetration does not exceed the predefined values [6, 7, 8, 9].

Combustion system	High tumble
Piston bowl	Sufficient to catch sprays
Injector spray penetration	70-80 mm (= large plume cone angle)
Spray interaction	Equally spaced with slight interactions
Sauter Mean Diameter	<20µm at rail pressures > 60 bar
Min fuel/stroke	1mg (central GDI, micro pilot injection)
Fuel rail pressure limit	20MPa (min; extra Pn benefits if higher)

Figure 5. Requirements of EU6c on combustion and injection system

4. DESIGN CHANGES FOR EU6C

As mentioned in [Figure 5](#), EU6c potentially requires modifications to the inlet port, piston crown and spray pattern. In order to minimise the changes to the base engine, the pent roof and water jacket remained unchanged and the charge motion increases demonstrated were achieved within the existing inlet port envelope. [Figure 6](#) shows the changes that were made to the combustion system for EU6c.



- JLR 3.0L V6 Gen2 Development EU6c Capable**
(84.5mm bore, 89 mm stroke)
- Injector/plug parallel to crank centreline
 - Bosch HDEV5 6-hole 17.5 cc/sec injector
 - Slightly revised fuel spray targeting
 - Improved control at low pulse widths
 - High tumble inlet ports
 - Larger and deeper bowl in piston
 - 200 bar fuel system
 - 10.5:1 CR

Figure 6. Design changes on the engine for Eu6c

Intake Ports

The intake port was optimised in several loops; 25 intake port design iterations were flow tested using steady state CFD in order to give the best possible tumble / flow trade-off with a significantly higher tumble target than the current engine. A sharp edge on the lower port contour leads to flow separation from the port surface of the air entering the combustion chamber, thus increasing tumble motion. The port roof was also modified to guide the air over the top of the inlet valve in order to promote further increases in charge motion. The tumble increase leads to a small reduction in the peak port flow. A GT power model was used to assess the resultant drop in peak power due to increased pumping losses at constant combustion phasing. The result was a 1% lower volumetric efficiency at peak power and 1.8 PS increase in supercharger drive load (due to 0.1 bar higher boost pressure), which equates to approximately a 6 PS reduction in peak power. However, it was felt that this would be counteracted by improved combustion phasing to recover the performance to a neutral status. There was no significant change predicted to the WOT performance below 5000 rpm.

The effect of the design changes was verified in transient CFD, [Figure 7](#). Valve shrouding / masking could have been used to avoid the reverse tumble at the start of the intake stroke at very low valve lifts but the project aimed to minimise the number of changes from the existing V6 engine.

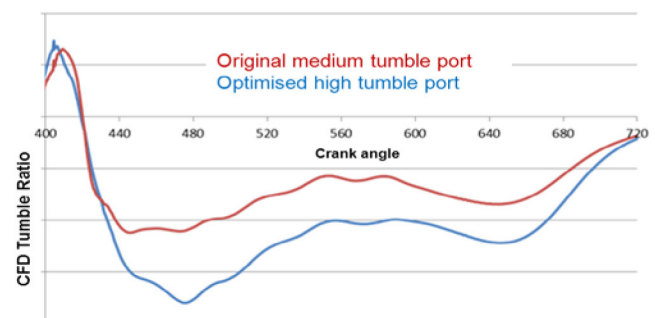


Figure 7. Transient CFD tumble ratio vs. crank angle (showing the increased tumble for Gen2 ports / chamber aimed at improved mixing and evaporation rates)