

Achieving Very Low PN Emissions with an Advanced Multi-Hole Injector Functionality and Adapted Spray Targeting Under High Fuel Pressure Conditions

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ABSTRACT

In the near future, emissions legislation will become more and more restrictive for direct injection SI engines by adopting a stringent limitation of particulate number emissions in late 2017. In order to cope with the combustion system related challenges coming along with the introduction of this new standard, Hitachi Automotive Systems Ltd., Hitachi Europe GmbH and IAV GmbH work collaboratively on demonstrating technology that allows to satisfy EU6c emissions limitations by application of Hitachi components dedicated to high pressure injection (1).

This paper sets out to describe both the capabilities of a new high pressure fuel system improving droplet atomization and consequently mixture homogeneity as well as the process of utilizing the technology during the development of a demonstrator vehicle called DemoCar. The Hitachi system consists of a fuel pump and injectors operating under a fuel pressure of 30 MPa.

Revised spray patterns have been developed following an IAV process using optical spray vessel investigations as well as CFD simulation for a specific engine (boosted engine with 1.4L engine displacement and direct injection). For the system evaluation on the engine test-bench and inside the vehicle on the chassis roller dyno, Hitachi Automotive Systems, Ltd. manufactured the new spray patterns accordingly.

The chosen test engine has been equipped with the Hitachi components and has been optimized on the engine test-bench in steady state conditions. Subsequently, the high pressure injection system has been installed onto a DemoCar in order to also improve the calibration in transient operation on the chassis roller dyno. Since injector properties are different from the reference injectors, the injection strategy has been modified and re-calibrated at catalyst heating, warm-up operation and hot condition operation.

The final calibration with 30 MPa maximal injection pressure enabled a reduction by 60% of particulate number over NEDC compared to the reference without a strong penalty on fuel consumption.

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INTRODUCTION

In 2017 and 2018 (2), PN emitted by light duty vehicles will be limited to 6×10^{11} #/km by European legislation (Euro 6c, [figure 1](#)). The current engineering trend for many OEMs is to apply

direct injection to gasoline engines which allows a further downsizing and thus a fuel consumption reduction compared to standard port fuel injection.

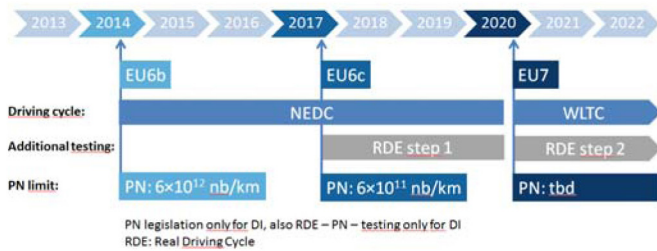


Figure 1. Emissions standards road map (2)

Use of direct injection, even for a homogeneous stoichiometric application, is however bound to a very detailed spray layout and development work to guarantee a good homogeneity and more specifically to prevent from formation of soot particles by the mechanism of pyrolysis under all operating conditions.

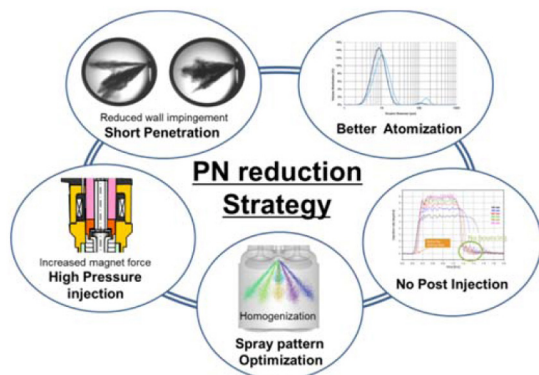


Figure 2. Main measures for reducing particulate number level.

According to (3) soot particles are being formed under locally rich (low oxygen available, as for $\lambda < 0.7$) and hot conditions with a local temperature exceeding 1500K. As the combustion process of homogeneously operated SI engines clearly exceeds these temperatures, and - in case of a globally stoichiometric mixture - there might be not sufficient oxygen left at the end of the combustion to oxidize soot, the only measure to avoid generation of solid particles is to ensure a perfect λ distribution during combustion with locally no richer conditions than 0.7.

As described in figure 2, there are well-known measures existing to improve and control the mechanisms leading to soot formation for both hardware side (injector design and spray pattern) as well as for software side (injection strategy, ECU calibration). This provides then the point of departure for discussing the applied approach to minimize PN emissions in this paper. Basically a reduction of particulate number emissions is governed by:

- a good atomization and spray break-up (higher fuel rail pressure)
- a reduced liquid penetration / wall impingement
- a good homogenization
- no post injection

Hitachi designed and manufactured high pressure gasoline fuel pump (4) and high pressure gasoline injectors (5) that can be used under 30 MPa (figure 3). Both have been tested within this project and will show a strong potential of high pressure direct injection for gasoline engines. Receiving the parts from Hitachi at IAV GmbH, the fuel pump could be used as it was, but the injector spray pattern had to be worked out for the engine dedicated to high pressure injection investigation.



Figure 3. Gasoline direct injection high-pressure fuel pump and injector.

The injector spray pattern is designed to avoid fuel impingement onto the cylinder liner, the valves or the piston under different operating conditions (as catalyst heating, throttled part load operation, full-load operation with multiple injections) as far as possible. The control of fuel impingement is one of the direct levers for PN reduction. Moreover, increasing the fuel injection pressure leads to a distinct enhancement of droplet atomization and consequently a reduction of PN (6). Thus, it's these two items that have been identified to decrease PN for the demonstrator engine: injection spray control and atomization improvement. Both have been applied within this collaboration project in order to design new high pressure injectors (designed with maximum fuel pressure operation at 30 MPa) coupled with high pressure fuel pump, both provided by Hitachi Automotive Systems, Ltd.

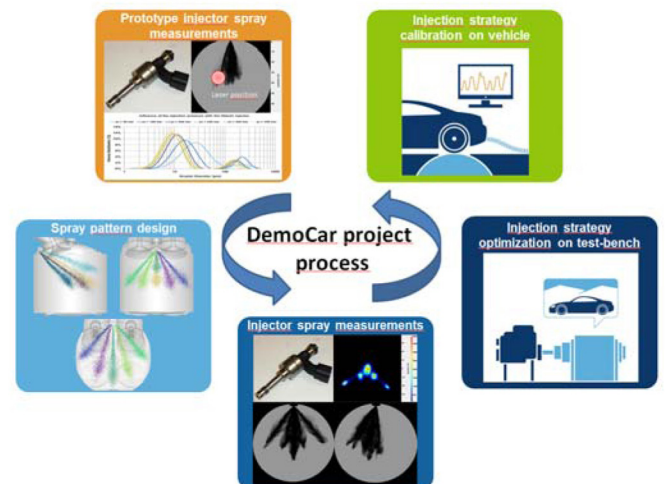


Figure 4. DemoCar project process from prototype injector to validation onto vehicle.

As described in [figure 4](#), the injector spray pattern has been designed and optimized in CFD and then manufactured to be installed on a boosted 1.4 l engine with 4 cylinders. The high pressure fuel system has been mounted onto the engine to be optimized at part load operating points corresponding to NEDC and WLTC. Then, the same system has been installed onto the DemoCar to be calibrated for the several operating conditions during the driving cycles.

SPRAY PATTERN DESIGN

Model Build-Up and Calibration

In order to build up the CFD model, the flow path through cylinder 1 was extracted. The boundaries of the CFD model were equal to the position of the instantaneous pressure sensors that were mounted to the test engine. The base cell size was set to 0.75 mm which leads to an overall cell number of about 1.2 Million cells. The cell size independency was proven and several test runs with mesh quality improvement iteration were performed.

As a turbulence model the k-epsilon model was chosen and calibrated with flow measurements from the component test bench. The residual tolerance was set to 0.001. To get an accurate representation of the initial droplet size, there wasn't any usage of a primary breakup model but the spray measurements of the injector including Laser Diffraction Spectrometry (LDS), Schlieren and hydraulic characteristics were taken to directly define the initial droplet size at the injector tip. The secondary breakup parameter (Reitz) was calibrated to get the correct penetration, spray angle and vapor phase. The calibration was performed for 3 pressure levels and with both injector types (Reference, Hitachi).

The model calibration started with the spray bomb ([figure 5](#)) of the reference injector. It was adjusted to meet the results from the optical spray measurements conducted on the injection test-bench

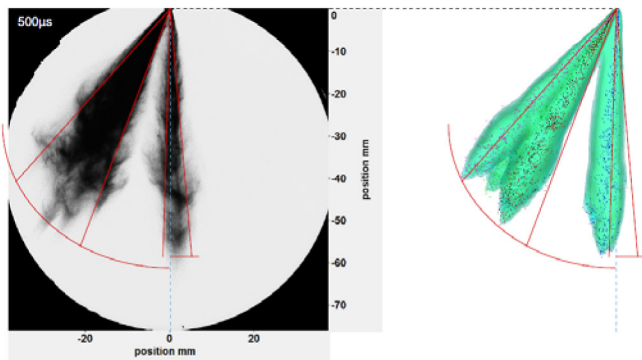


Figure 5. Spray bomb calibration.

After the calibration of the injector model, the baseline simulations were performed. With these initial runs, the performance of the reference injector could be evaluated and finally compared to the Hitachi prototype injectors.

To evaluate the evaporation of the parcels (droplets) and a possible wall wetting over the complete cycle, numerous scalar parameters were observed and analysed, the most important are depicted in [table 1](#).

Table 1. Criteria for mixture analysis.

Lambda statistical distribution in the combustion chamber (homogeneity) to identify overall combustion efficiency	$U_i = \frac{\text{stddev}(\lambda)}{\sqrt{\sum_{\text{cells}} (\lambda_i - \lambda_{\text{mean}})^2}} = \frac{1}{n_{\text{cell}}}$
Lambda value near the spark plug during spark event can be correlated to ignition and combustion stability	$\lambda_{sp} = \text{mean}(\lambda)_{\text{cells} \in \text{Kernel}} = \frac{\partial \lambda_{sp}}{\partial t}$
Global micro-turbulence level (MTL) during the compression stroke is known to influence the combustion overall speed	$u' = \frac{\sum_{\text{cells}} \left(m_i \sqrt{\frac{2}{3}} k_i \right)}{\sum_{\text{cells}} m_i}$
Local (spark area) micro-turbulence level and mean flow velocity during the ignition	$MTL_{sp} = \frac{u'}{U_M} \Big _{sp} = \frac{1}{U_M} \frac{\sum_{\text{cells} \in \text{Kernel}} \left(m_i \sqrt{\frac{2}{3}} k_i \right)}{\sum_{\text{cells} \in \text{Kernel}} m_i}$
Quantity of impinged fuel against wall can be qualitatively correlated to PN and PM emissions	$\sum_{\text{cells near wall}} (m_{\text{fuel}})$

Particular attention was paid to reduce the mass of impinged fuel onto chamber walls as well as the improvement of the global homogeneity and to prevent the formation of locally rich mixture under all operating conditions, including multiple injections at higher engine loads. As for the latter, it is essential to also analyze the interaction of late injection and global charge motion so that the turbulence intensity (both globally and locally around the spark plug) has been observed as well.

Spray Optimization

Basically, there are limitations concerning the degree of freedom for an optimization of the fuel spray - particularly for a lateral injector position. The primary goal is to achieve a close to perfect homogenization, for example by a good air utilization. This might be enabled by an advanced end of injection - in order to leave as much time as possible for evaporation of the fuel - as well as a widest as possible spray targeting with a high number of single spray beams covering a huge fraction of the air inside the cylinder. On the contrary, there are both geometrical boundary conditions of the combustion chamber (spray impingement must be avoided) and limitations related to the spray specifications, so that the design of the spray targeting is a compromise. In [figure 6](#) these geometrical boundaries for the given combustion chamber are exemplarily depicted. From left to right, the spray should not be too wide to avoid cylinder liner impingement, not too high and too low to avoid respectively cylinder head impingement and piston impingement, and finally arranged in a way to avoid fuel impingement on the valves. The final layout of the prototype injector spray pattern takes into account all these conditions and limitations given.