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Developing Low Gasoline Particulate Emission Engines through Improved Fuel Delivery

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Abstract

Particulate emissions are of growing concern due to health impacts. Many urban areas around the world currently have particulate matter levels exceeding the World Health Organisation safe limits. Gasoline engines, especially when equipped with direct injection systems, contribute to this pollution. In recognition of this fact European limits on particulate mass and number are being introduced. A number of ways to meet these new stringent limits have been under investigation. The focus of this paper is on particulate emissions reduction through improvements in fuel delivery.

This investigation is part of the author's ongoing particulate research and development that includes optical engine spray and combustion visualisation, CFD method development, engine and vehicle testing with the aim to move particulate emission development upstream in the development process. As part of this work, a spark eroded and a laser drilled injector were fully characterised in a spray vessel under key engine running conditions. Injector nozzle geometries and mass flow data were also measured in great detail.

This paper demonstrates using both steady state and transient engine testing that very significant improvements in particulate emissions can be made. Control strategies enabling multiple injections of smaller volumes of fuel per injection are the most promising technology. The MAHLE Flexible ECU (MFE) combined with injector testing allowed early stage development and demonstrated these effects for a number of key engine operating conditions. Most notably it was found that particulate matter emissions could be reduced by 80-90% during the catalyst light off phase. A new approach was developed (MASTER) to simultaneously assess the effects of calibration changes on all emissions to increase testing efficiency and hence get to more optimised solutions faster. This approach was successfully tested on a production engine comparing two injectors achieving 82% reduction in particulate number emissions during the first 200seconds of the NEDC relative to the EU5b baseline.

Finally it was found that both fuel properties and injector deposits can have a significant effect on particulate emissions.

Introduction

Particulate emissions are of growing concern due to their negative health impacts. The World Health Organization (WHO) estimates that ambient air pollution, in terms of fine particulate air pollution (PM2.5), causes about 3% of mortality from cardiopulmonary disease, about 5% of mortality from cancer of the trachea, bronchus, and lung, and about 1% of mortality from acute respiratory infections in children under 5 year, worldwide. This burden occurs predominantly in developing countries; 65% in Asia alone [1].

But this issue is not limited to Asia. In Europe for example PM10 pollution is estimated to cause 510 to 1150 premature deaths per million inhabitants in the EU-27 alone [2]. A number of countries have therefore issued new regulation limiting the yearly and daily exposure to PM2.5 and 10. Limits in Europe are amongst the lowest with a yearly average of 25 microgram per cubic meter for PM2.5.

A report commissioned by the ICCT [3] estimates the contribution of motor vehicle exhaust to concentrations of ambient fine particulate matter in the PM2.5 range from 22 percent in Beijing to 53 percent in Barcelona. With exposure rates highest within 300 to 500 meters of a major roadway.

This same report also attempts to predict what effects worldwide adoption of limits on road transport particulate emissions would have [3].

Legislation

Gasoline engines, especially when equipped with direct injection systems, are known to contribute to particulate matter pollution. In recognition of this fact European new limits on particulate mass and number are being introduced earlier this year. The particulate number limit currently stands at 6*E12 effectively, and will be further reduced to 6*E11 in 2017. Figure 1 shows the particulate mass and number emissions of a number of production vehicle powered by gasoline PFI and DI engines across the legislative New European Drive Cycle (NEDC).

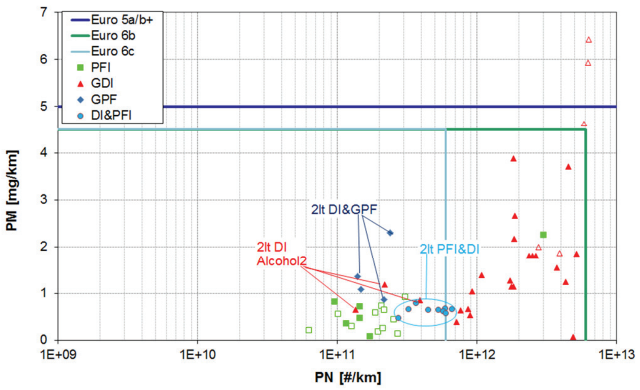

Figure 1. Particulate mass and number emissions from a number of Gasoline DI and PFI vehicles completing the NEDC

In the US, legislators have so far only focused on particulate mass in the understanding that particulate number and mass are intrinsically linked.

This paper focusses on Europe and particulate number generation although the methodology applies for any low particulate matter emissions engine.

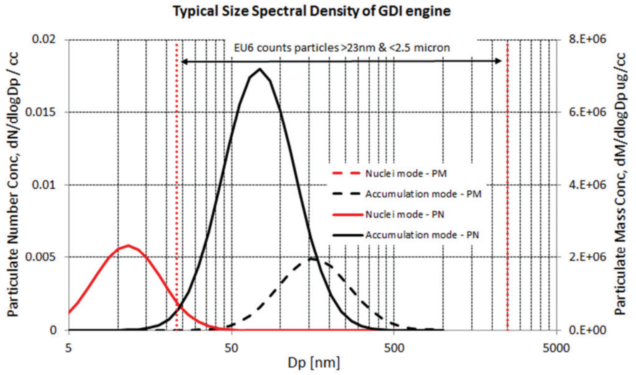

Figure 2. Particulate number and mass versus particle diameter including the EU6 legislated window for a typical modern GDI engine

Figure 2 shows a typical number and mass distribution of a modern GDI engine and is similar to the one presented by Kittelson [4]. The "Nuclei Mode" is a significant contributor to particulate number emissions. This mode consists largely of Volatile Organic Compounds (VOC). Partly due to the difficulties of measuring particulate number emissions accurately, the European limits are set for the larger solid particles of between 23nanometer and 2.5micrometer meaning that mainly particles formed in the "Accumulation Mode" are considered. The larger particles in this mode are responsible for the particulate mass emissions.

Currently the legislative drive cycle in Europe consists of four urban cycles followed by an extra urban cycle. With its cold start and four repeats of the urban cycle parts it is a good drive cycle to understand the effects of engine warm-up on particulates.

Tail pipe particulates mass and number measurements at in-house facilities show that in most vehicles the first 200 seconds of the NEDC is the most significant for particulate number emissions. This is graphically shown in figure 3.

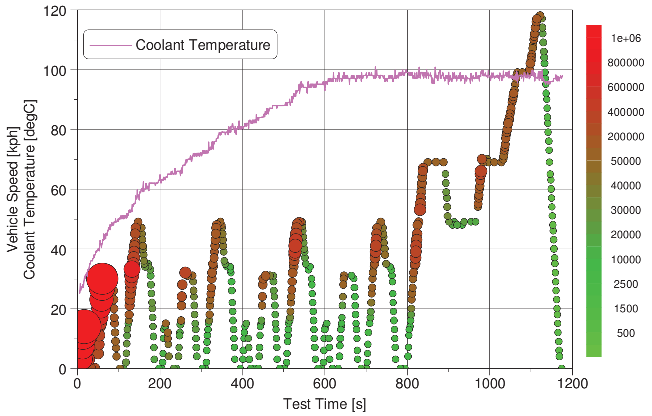

Figure 3. Particulate number emissions and coolant temperature during the NEDC

Particulate Emissions Reduction Technologies

Three main technologies are proposed for particulate emission control. These are:

1. Gasoline Particulate Filters
2. PFI & DI
3. DI improvements

Gasoline Particulate Filters (GPF) are essentially the same technology as the well-known and proven Diesel equivalent. Installation, monitoring and regeneration methodologies are all well understood, but would need adapting to gasoline engines. Although particle filters have excellent filtration properties of both legislated and non-legislated particles, the increased exhaust back pressure together with the increased part count and cost makes this a less favourable option.

The authors have researched PFI and DI injector combinations and have found that this option could also offer small CO_2 benefits as well as meeting particulate emissions legislation. It is particularly well suited for engines with high specific power outputs. The added part complexity and associated cost means that it will be most attractive for premium brand products.

Most EU5 gasoline port fuel injected engines are capable of meeting EU6c particulate number and mass limits and are hence excluded from the legislation. This demonstrates that the direct injection of fuel has a negative effect on particulate emissions and improvements to direct injection fuelling systems are required to reduce particulate matter generation. It is well known that particulate formation is due to diffusion type combustion where the fuel is partly oxidized in oxygen poor conditions. Fuel injected directly is clearly not as well mixed with the available air as is the case with port fuel injection. Apart from the reduced available time to mix it is well known that component wetting occurs due to the spray penetration and targeting. Pool fires especially on the piston and valves have been demonstrated [5] to be a significant contributor to particulates.

The authors have investigated all of these technologies and have found that each of the three systems have their individual merits. Since improvements to the injection system hardware combined with optimisation of the calibration does not increase the part count, complexity and little to no part on-cost it is expected that this technology will be the preferred route for many vehicle manufacturers.

Although being seen as one of the preferred options, optimisation of the injection system only in order to meet the EU6c limits robustly requires careful development and calibration. This extra level of complexity in engine optimisation would therefore benefit significantly from a robust methodology that can be implemented sufficiently early in the development process.

A few of the tools and methodologies used in the development of low particulate emissions engines are described in this paper.

Methodology

The previous paragraph indicates that DI injector hardware, installation and its operation needs significant work in order to improve mixture preparation and reduce levels of in-cylinder wall wetting and mixing. A thorough understanding of multi-hole injectors and the spray they produces is therefore required.

Injector geometry and testing

The detailed geometry of injector nozzles largely determines the spray characteristics, but also its propensity to fouling. The injectors used in this study were therefore scanned to 4μm accuracy using X-ray tomography techniques to obtain accurate nozzle dimensions. A 3D surface model was created of the data cloud, which can then also be used for CFD simulation as shown in figures 4 and 5. In this case two 7-hole injectors of similar flowrate and spray orientation were compared. Figure 3 shows the baseline spark eroded injector and figure 4 shows the laser drilled replacement injector. It is clear from these figures that not only the manufacturing method is different but that there were also significant differences in injector nozzle geometry.

The L/D of the injectors is 2.5 and 1.5 for the spark eroded and laser drilled injector respectively. The laser drilled nozzle also has a degree of taper. Full nozzle dimensions are given in [6].

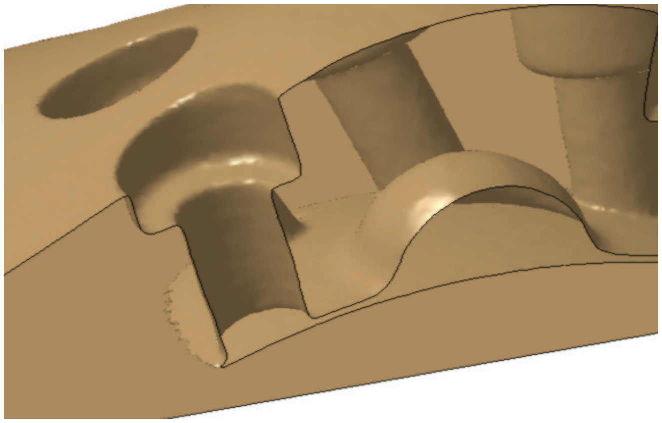

Figure 4. Injector 1 – seven hole spark eroded injector

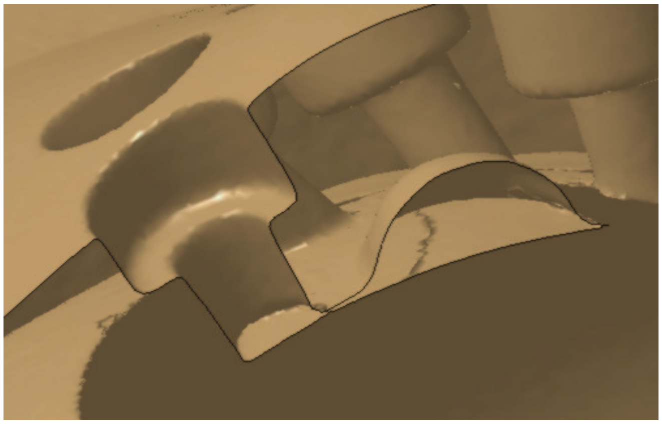

Figure 5. Injector 2 – seven hole laser drilled injector

The injector sprays were then fully characterised using optical techniques. Spray penetration and total cone angle was measured using the MIE scattering technique. Penetration and cone angle data shown here was at 1ms after the injector was actuated. Phase Doppler Particle Anemometry (PDPA) is a well-established technique to determine droplet distributions of sprays and hence this technique was used here. A single beam was measured in this instance 25mm away from the nozzle tip. Spray data using EN228 RON95 fuel is shown here. A full description of the measurement techniques used as well as more results can be found in Behringer et.al [6]. The injectors were tested in a clean condition to enable direct comparison.

Engine & vehicle testing

Spray characterisation, CFD simulation and optical engine testing are all good tools to provide detailed insight. To assess particulate emissions in more detail however, engine testing is the only option. The results shown in this paper were taken from the authors own state of the art steady state, transient and vehicle testing facilities for this particulate matter testing in order to develop low particulate emission engines.

Steady state engine testing

In order to meet the strict EU6c particulate matter limits, engine programmes incorporate particulate number and mass optimisation testing early in the combustion system development phase. During this early phase various new hardware and control strategies are often evaluated. The MAHLE Flexible ECU (MFE) control module is typically used in these cases to provide a flexible platform to develop new control strategies quickly.

In this case a control strategy was implemented to gain injector control in the typically uncontrolled or “ballistic” region of injector needle lift. The injector flowrate was measured under typical engine operating conditions using gasoline, and is shown in figure 6. The measured flowrate curve was used in the MFE with the objective to enable delivery of small volumes of fuel to the cylinder in a controlled and consistent manner. This would enable multiple injections and hence minimise fuel penetration [7]. Similar technology is being developed by all main fuel injection suppliers [8-10], but was not yet available for assessment and development during this project.

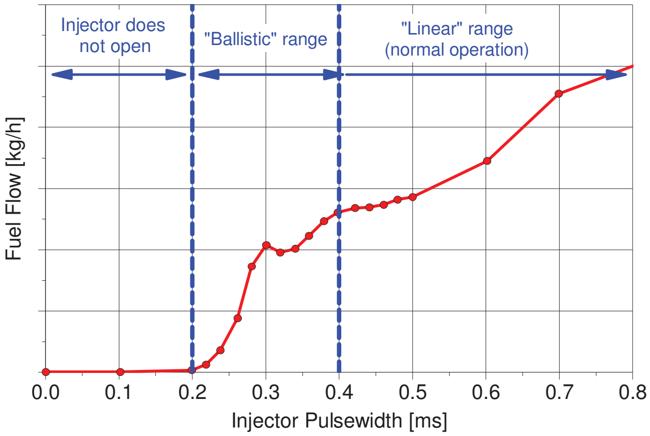

Figure 6. Measured fuel flow characteristic for a modern DI injector

A single cylinder engine was used for this experiment. The engine had a swept volume of 0.5l, a central DI injection system and was operated at a typical catalyst light off mode.

Table 1. Engine test conditions

Parameter	Value	Unit
Engine speed	1350	rpm
Load (NMEP)	2.7	Bar
Fluid Temperatures	25	°C
Lambda	1	#
Spark timing	17	°aTDCf
Number of injections	2	#
Cam phasing	Minimum Overlap	
Fuel	RON95 EN228	
Injector	6 hole solenoid	

Two injections were used for this testing. The first injection was during the induction stroke. The second pulse width was than reduced from 0.5ms to 0.25ms while increasing the first injection pulse to maintain lambda. The second injection timing was varied by ± 5° around the fixed spark timing.

Injector deposits

With the same engine set-up a test was conducted using two particulate measurement tools that have different operating principles simultaneously. The first was an AVL Condensing Particle Counter [14] which was developed to measure only the portion of particles that correspond to the legislative range. This system operates by diluting the exhaust gas and removing the volatile content, after which it condenses butanol on the particles present to enable direct counting. The Cambustion DMS500 [12] is a size spectrometer and number density measurement device that measures both volatile and non-volatile particles in the exhaust gas down to 5nanometer. The volatile contribution can then mathematically be removed in the software. Only solid particle contributions above 23nm are shown in this paper and can therefore be directly compared to the AVL CPC.

Various steady state tests were completed with both measurement devices sampling from the same location in the exhaust system. The tests included a wide variety of part load operation points with cam sweeps, Start of Injection sweeps and AFR sweeps. It also included a catalyst light-off point which tends to emit significant quantities of particulate matter. A control point at 2000rpm, 3.5bar NMEP load was used to monitor changes in particle emissions and measuring capability. The figure below shows the average of the control data points during some of the test sequence. It can be seen that particulate emissions are very stable throughout the test sequence, apart from the significant reduction after the injectors were cleaned in an ultrasonic bath.

Transient engine testing

MAHLE’s Approach for Structured Testing for Emissions Reduction (MASTER) is an approach that was specifically developed to enable engineers to assess all tail pipe emissions and find the optimum more quickly. This process was extended to also include particulate number and mass and is demonstrated here by assessing calibration and hardware changes on an existing engine.

The engine under test was a production engine that was being investigated for its particulate emissions capability compared to its current emissions levels. The objective was to quickly asses a number of calibrations for two injectors and find an optimum balance between all tail pipe emissions including particulate number and mass, while not negatively impacting CO_2 emissions. The engine test facility used here was fully transient and climatic. The engine had rapid cool down facilities to accommodate up to 20 drive cycles a day. Due to the significance of the first 200second after start on particulate emissions, this investigation focused therefore on this part of the drivecycle. The engine was started de-clutched to ensure a representative start profile. The engine speed and load were matched to a pre-recorded NEDC cycle of a representative vehicle. RON95 EU5 reference fuel was used throughout the testing.

The engine was instrumented with pressure transducers in the cylinders and thermocouples and pressure transducers in the exhaust system. Real time emissions pre and post catalyst were provided by a Horiba MEXA 7500DETR. An AVL Microsoot sensor [11] and a Cambustion DMS 500 [12] were additionally used and installed pre-catalyst for fast response and 10Hz sampling frequency of particulate mass and number respectively. The fast response and close proximity of these measurements ensured minimal time lag and “smearing” of the results due to low sample frequencies. This has proved particularly helpful for particulate emission development due to the highly transient nature of engine starts.

The testing programme was a series of mini DOE’s altering injection, ignition and cam timing parameters for the various stages through the warm-up period.

Vehicle testing

Vehicle tests are required as a final step in developing low particulate emission engines in order to validate the results. The authors used the in-house facilities during a fuel research project to understand the impact fuel composition can have on particulate emissions.

It is well known that the composition of the fuel is important to the particulate number and mass emissions of the engine. Honda [15] was the first to attempt to model fuel effect for PFI engines based on the number of double bonds present in and vapour pressure of the fuel. Researchers at Oxford University [16] adapted and improved the model and tested it with respect to direct injection engines. Initial steady state results looked very promising although later transient testing results proved less conclusive [17].

During the research, which is fully described in [17], various fuel blends were tested using a production EU5b vehicle. The vehicle was conditioned before each test for a different fuel to make sure that the fuel trims had adjusted fully. The NEDC cycles were completed three times following the legislative test method.

Results

Injector spray results

It was found that the difference in both penetration length and cone angle between the two injectors tested here was relatively small when compared to the effects of changing operating conditions. Injector 2 seemed to demonstrate consistently smaller fuel penetration rates than injector 1 at 20℃ fuel temperatures and it is therefore expected that this injector would perform slightly better than injector 1.

Figure 7 also shows that penetration length decreased with reduced fuel pressure and increased back pressure. It has to be noted though that increasing fuel pressure would result in a shorter injection pulse width for the same mass of injected fuel which would naturally reduce the penetration length.

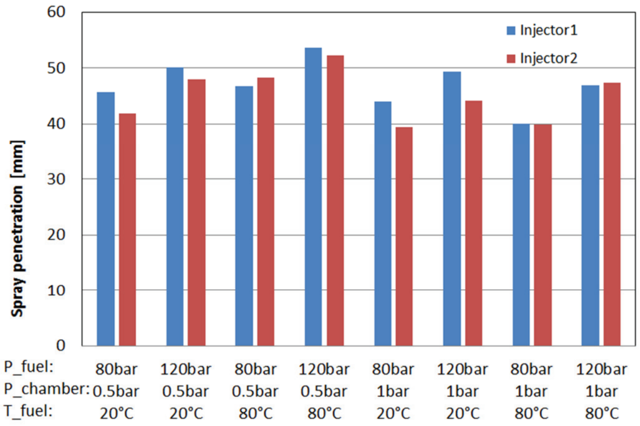

Figure 7. Spray penetration at 1ms after injector actuation

Figure 8 shows the cone angle at 25mm for the same test conditions. Injector 2 seemed to have a slightly wider cone than injector 1 which is most likely caused by the differences in injector nozzle design.

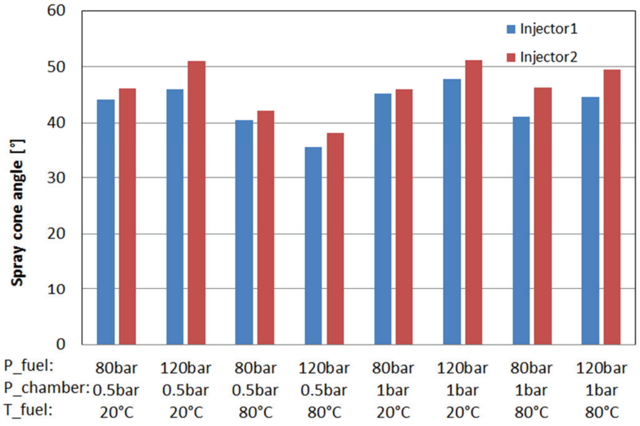

Figure 8. Cone angle at 25mm below the injector nozzle at 1ms after injector actuation

The results show (see figure 9) that the droplet distribution between the two injectors was very similar, and significantly less important than changes in operating conditions. Higher fuel temperature and higher fuel pressure reduce the fuel droplet size as expected.

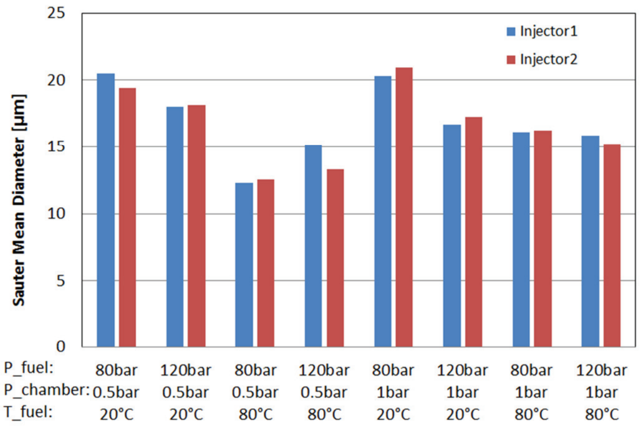

Figure 9. Sauter Mean Diameters

These spray characterisation test results seems to indicate that careful calibration of the operating parameters for a specific engine can be more important than the injector nozzle geometry and method of manufacturing. It has to be noted however that only clean injectors were tested here.

Engine & vehicle testing

Steady state engine testing

Data from steady state tests simulating the catalyst light off period are shown in figure 10. These clearly demonstrate the significant effect of reduced fuel quantities injected around spark timing. A reduction in both particulate number and mass of around 80 to 90% were achieved.

There is also a clear trend showing that later injection timings further reduce the particulate number and mass. This is due to the piston being further down the bore and hence less fuel impinges onto the piston crown.

An interesting observation is that the combustion stability (denoted here as Standard Deviation of NMEP) is also improved by a reduction in the second pulse width. This is thought to be due to the increased turbulence created by the injection outweighing the enriching effect. It means that this effect enables an even more retarded spark timing and hence shorter catalyst light off times which could have a positive effect on hydrocarbon, carbon monoxide and nitrous oxide emissions.

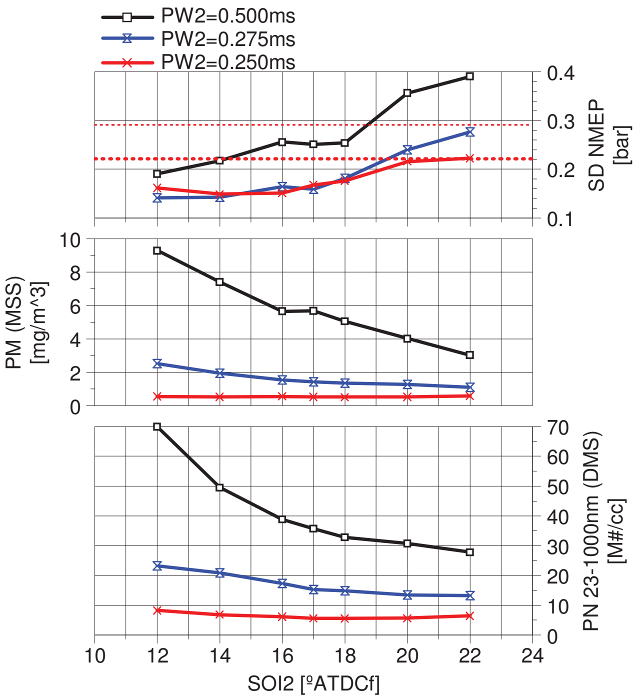

Figure 10. Particulate emissions as a function of second injection timing during simulated catalyst light-off

Although not shown here, similar optimisation processes were repeated for a number of engine operating sites to ensure the best injection timings and quantities were found. These settings were then utilised for the next stage of testing on a fully transient engine dynometer or vehicle testing.

Injector deposits

During testing it was found that injector deposit formation can significantly impact the particulate number emissions as demonstrated in figure 11. This order of magnitude reduction between used and cleaned injectors is of the same magnitude as the limit change from EU6b to EU6c and is hence of great significance. Two independent measurement techniques were used to confirm this result.

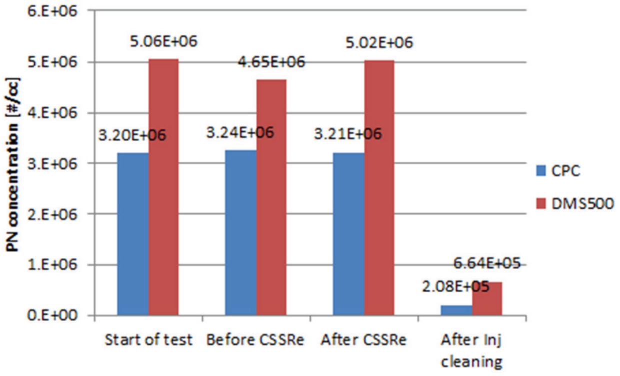

Figure 11. Effect of injector cleaning on particulate number emissions

Logically this significant change in particulate matter generation can be attributed to a change in spray formation which is thought to be due to changes in effective nozzle geometry. The extent and impact of which is currently under investigation at MAHLE Powertrain. Similar findings have also been reported by other researchers [13]. The most significant ones are discussed below in more detail and are being investigated further at MAHLE.

An interesting side observation is the difference in particulate number measurements between the CPC and the DMS500. The authors have conducted a substantial investigation into these differences. It was found that both measurement techniques are repeatable as shown in figure 11, although display a somewhat different magnitude. These differences between the two measurement techniques are understood to be largely due to the different ways of removing the volatile particles. The AVL CPC uses a Volatile Particle Remover which effectively heats the sample to over 300℃ and hence oxidising the volatile particles with a 99% efficiency. The DMS500 measures all the emitted particles including the volatile ones and mathematically removes the volatile content.

Transient engine testing

Figure 12 shows particulate number emissions of injector 1 and 2 using the base (EU5b) calibration. It can be seen that injector 2 performed slightly worse than injector 1 even though it seemed to have a slightly reduced penetration rate at lower fuel temperatures. This effect is not entirely understood, but it is possible that injector deposits changed the spray characteristics of the two injectors differently. The calibration of both injectors was optimised in a systematic manner using the MASTER approach. Figure 10 shows the significant improvement that was made for injector 1 over the first 200 seconds resulting in an 82% reduction of particulate number emissions.

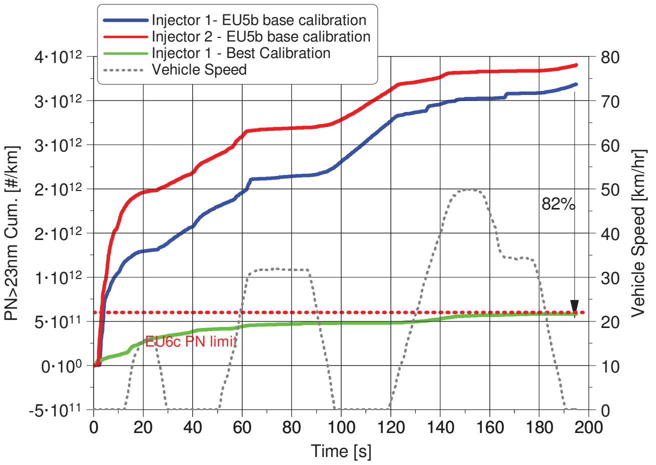

Figure 12. Improvement to pre-catalyst Particulate number emissions relative to the EU5b baseline using the MASTER approach

These significant improvements were achieved by optimising a large number of variables at different stages of engine start, warm-up and transient operation and a full discussion of these falls outside the scope of this paper. Important variables were found to include the start of the first injection, employing split injection strategies, employing catalysts light off strategies, end of second injection, rail pressure and exhaust cam timing. Directionally the changes either are thought to reduce wall wetting or improve atomization and mixing.

Vehicle testing

Figure 13 shows the particulate number results across the NEDC using three different fuels. The results clearly demonstrate that high content alcohol blends can have a very positive influence on particle number emissions. It is thought that this is largely due to the differences in the vapourisation behavior of the three fuels. The Final Boiling Points are 168, 118 and 83℃ for the RON95 EN228, alcohol blend 1 and alcohol blend 2 respectively.

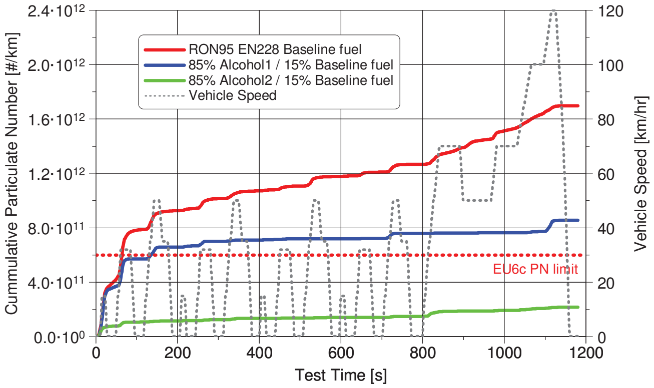

Figure 13. Effect of blends with high levels of alcohol on Particulate emission relative to an EN228 baseline fuel

Further investigations are on-going to understand how some of these effects can be utilised for fuels within the EN228 fuel specification.

Conclusions

Particulate emissions are known to be harmful to human health and hence it is imperative that they are reduced significantly. Gasoline direct injected engine are a source of these small particulates and limits are therefore being introduced in Europe and the US.

Particulate number is a complex emissions component of DI gasoline engine due to the relatively large number and wide range of influencing factors and the inherent difficulties of measuring small particles. It is anticipated that the large majority of vehicle manufacturers will adopt novel injection hardware and control strategies in order to comply with new legislation.

To this end injector nozzle geometries and spray formation have been studied in detail and compared to the particulate matter emissions performance of the same injectors during the NEDC drive cycle. A comprehensive development approach and consistent toolset (MASTER) has been developed, demonstrating that more optimised solutions can be obtained faster. This approach has been successfully tested on a production engine comparing two injectors, obtaining an 82%

reduction in the number of particulates emitted in the first 200seconds of the NEDC.

It was found that significant improvements (of around 80 to 90%) could be made by injecting smaller quantities of fuel more often. This is due to the reduced penetration of smaller injected fuel quantities which would in turn reduce wall wetting and hence particulate matter emissions.

While completing this work it was found that deposits forming on the injector can increase the particulate number emissions by an order of magnitude this deposit formation at the injector tip is very significant for long term stability of low particulate emission engines.

Finally it was found that fuel composition and properties can have a significant effect on the particulate emissions. High volumes of alcohol in a blended fuel with a lower FBP would meet the EU6c particulate number and mass limits.

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Definitions/Abbreviations

NEDC	New European Drive Cycle
EN228	European gasoline fuel specification
PFI	Port Fuel Injection
GDI	Gasoline Direct Injection
CFD	Computational Fluid Dynamics
FBP	Final Boiling Point
SDNMEP	Standard Deviation of Net Mean Effective Pressure
PN	Particulate Number
PM	Particulate Mass
CPC	Condensing Particle Counter