

Measures to Reduce Particulate Emissions from Gasoline DI engines

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ABSTRACT

Particulate emission reduction has long been a challenge for diesel engines as the diesel diffusion combustion process can generate high levels of soot which is one of the main constituents of particulate matter. Gasoline engines use a pre-mixed combustion process which produces negligible levels of soot, so particulate emissions have not been an issue for gasoline engines, particularly with modern port fuel injected (PFI) engines which provide excellent mixture quality.

Future European and US emissions standards will include more stringent particulate limits for gasoline engines to protect against increases in airborne particulate levels due to the more widespread use of gasoline direct injection (GDI). While GDI engines are typically more efficient than PFI engines, they emit higher particulate levels, but still meet the current particulate standards. In Europe there is a proposal for the Euro 6 standard to require GDI engines to meet the particulate number (PN) standard introduced at Euro 5 for diesel engines. In the US, more stringent particulate mass (PM) limits have been proposed by CARB and EPA. Testing has shown that current Euro 5 GDI engines would exceed the proposed Euro 6 PN standard and that additional effort may be required to meet the proposed US standards.

While a particulate filter could be used to reduce both particulate mass and number, the preferred approach would be to reduce engine-out particulates which may be possible through combustion system, controls and calibration improvements.

This paper describes an investigation where combustion system improvements and control strategies were developed then applied to provide a significant particulate number reduction from a gasoline turbocharged direct injection engine (GTDI). The mechanisms of particulate formation are described and countermeasures for reduction are discussed. In particular, particulate formation resulting from interactions between the fuel and the combustion chamber walls (liner, piston) are investigated, and it is shown how multiple injection strategies can be used to minimize these interactions and reduce particulates. The effects of component temperature on particulates are discussed and the particulate reduction benefits of a control strategy to provide rapid piston heating are shown. The development of injector technology for particulate emission reduction is also discussed.

The potential for a turbocharged GTDI engine to meet the proposed Euro 6 PN standard without the use of a particulate filter is demonstrated.

INTRODUCTION

Until recently, particulate emissions have not been a significant issue for manufacturers of gasoline engines.

In the US, the current PM limit for Tier 2 and LEV 2 light duty vehicles is 10 mg/mile, whereas a typical PFI gasoline engine will emit less than 1 mg/mile [1]. PM emissions from GDI engines are typically higher than for a PFI engine, however the 10 mg/mile standard is relatively easy to meet with a GDI engine without significant additional calibration effort. In Europe a PM limit of 5 mg/km was introduced at Euro 5, and similarly, this standard is relatively easy to meet.

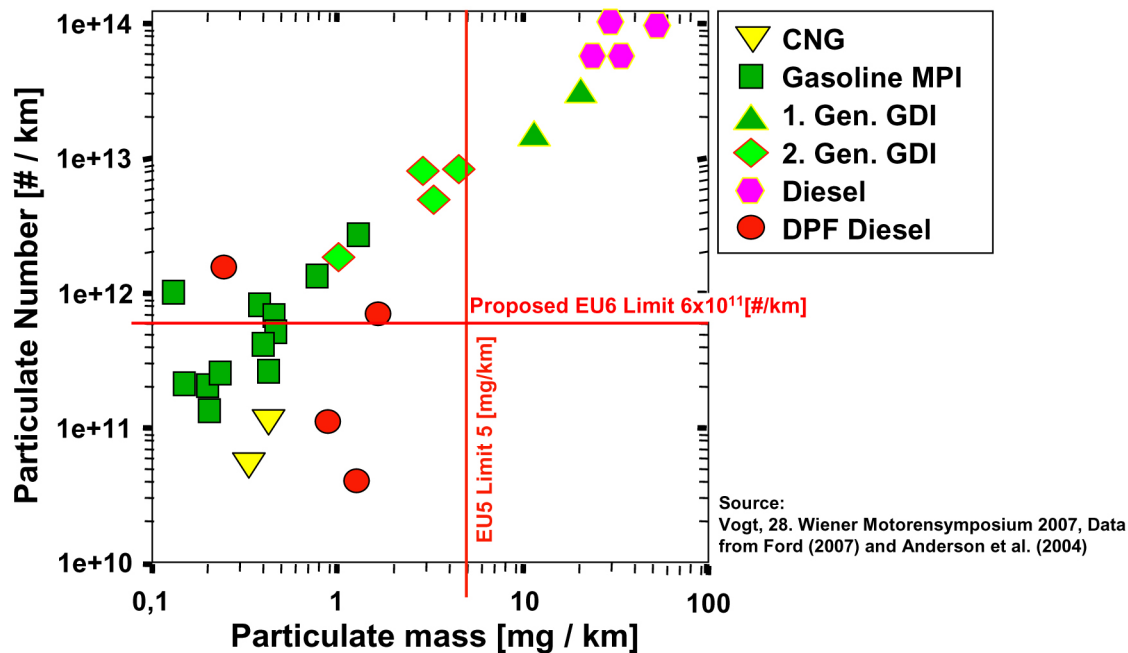


Figure 1. Comparison of Particulate Number and Particulate Mass Emissions for Gasoline and Diesel Engines

With GDI based technology becoming more widespread as manufacturers work to reduce vehicle fuel consumption and CO₂ emissions, the regulatory authorities have proposed more stringent particulate emissions standards for gasoline vehicles to ensure that airborne particulate levels do not increase.

In the US, CARB is considering a reduced PM limit of between 6 and 3 mg/mile while in Europe a proposal is being considered to require gasoline engines to meet the Euro 5 Diesel PN limit of 6.0×10^{11} particulates/km for Euro 6.

The new limits may require a significant increase in calibration effort, probably combined with combustion system improvements - particularly to meet the proposed Euro 6 limits. The important question is whether these improvements will be sufficient to allow compliance through engine-out particulate reduction or whether a particulate filter will be required. There is also the question of whether the new standards are stringent enough to present issues for PFI engines. In addition to the increased engineering effort and the development of new control algorithms, additional instrumentation will be required for development and certification.

This paper describes work conducted by AVL to develop methodologies to achieve engine-out particulate levels below the proposed Euro 6 PN limit with a GTDI engine through combustion and control system improvements and calibration optimization.

OPPORTUNITIES FOR PARTICULATE EMISSIONS REDUCTION

Figure 1 compares particulate number and mass emissions from a number of GDI and PFI gasoline engines and Diesel engines both with and without diesel particulate filters. PM levels from PFI gasoline engines are low - at or below 10% of the current Euro 5 PM standard. Most of these PFI engines also achieve PN levels below the proposed Euro 6 PN limit.

The earlier (Gen 1) GDI engines exceed both the PM and PN standards by a considerable factor, whereas the later (Gen 2) GDI engines meet the Euro 5 PM standard but exceed the proposed Euro 6 PN Standard. The main difference between the Gen 1 and Gen 2 engines is advancements in GDI fuel system technology.

With the diesel engines, engine-out PM and PN emissions are orders of magnitude higher than for the gasoline engines; however the diesel particulate filter is very effective in reducing both tailpipe PM and PN emissions. This would also be an effective solution for reducing tailpipe PM and PN levels for the gasoline engines, but with cost, complexity, durability, performance and fuel economy concerns.

Figure 2 shows a comparison of chassis dyno measured PN emissions for I4 1.6l Euro 5 PFI and GDI gasoline engines in the same vehicle during the NEDC drive cycle. For both engines the highest PN levels are produced during the cold start and during transient operation while the engine is cold. Once the PFI engine is warmed-up (after 300 s) the PN spikes

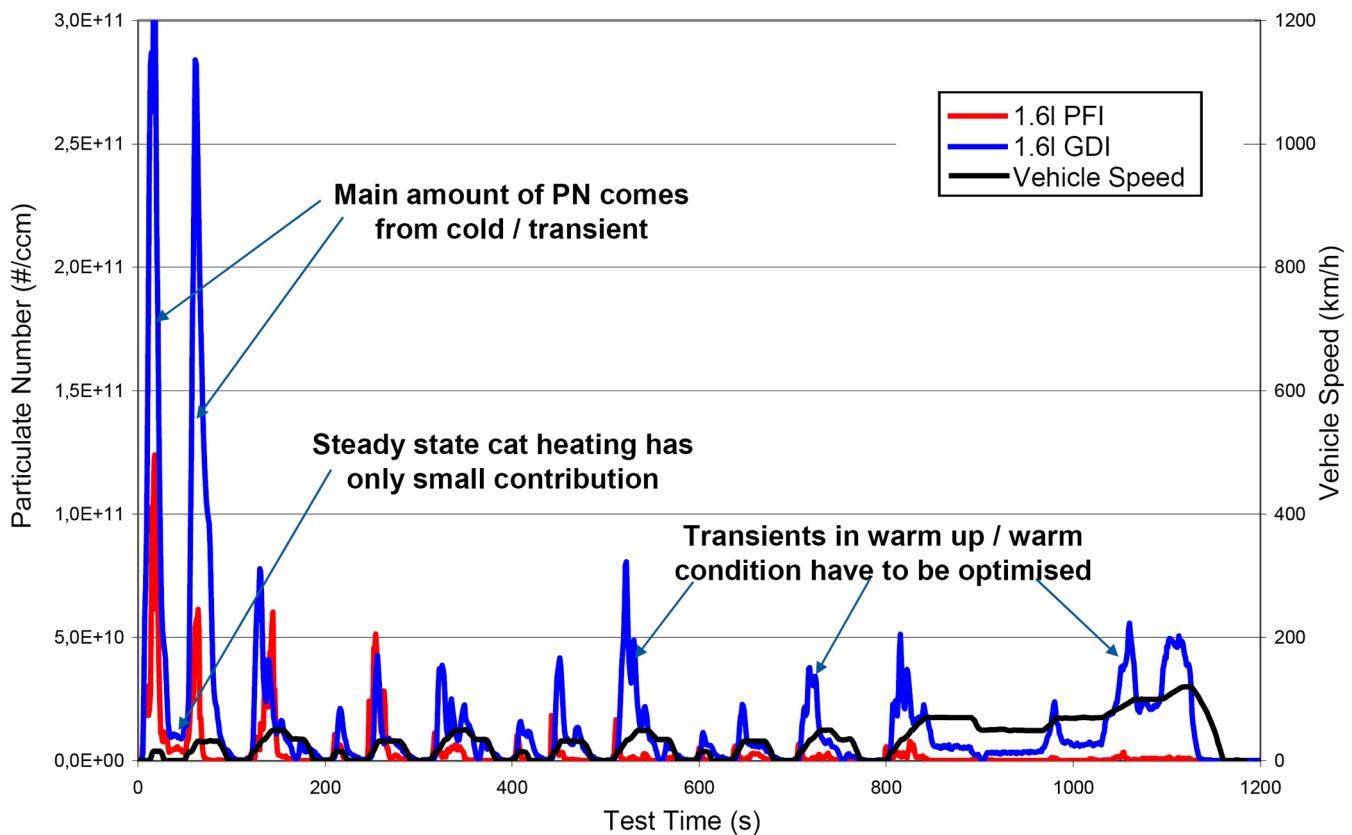


Figure 2. Comparison of Euro 5 PFI and GDI PN Emissions over NEDC Cycle (chassis dynamometer measurements)

are significantly reduced, however the GDI engine continues to produce high PN levels during accelerations.

Particulate formation in a gasoline engine is usually the result of inadequate air-fuel mixing.

With a PFI engine, the fuel injector is targeted at the back of the intake valves and fuel is injected while the intake valves are closed. Under warmed-up operating conditions latent heat for evaporation is taken from the air, valves and port surfaces. When the intake valves open, the fuel vapor and any remaining liquid fuel is carried into the combustion chamber with the charge air and the high charge motion that occurs just after intake valve opening promotes excellent fuel/air mixing. This produces a well mixed homogenous charge which results in a clean burning pre-mixed flame with negligible particulate formation.

During cold operation, the charge air, valve and port surface temperatures do not support the same level of evaporation and liquid fuel accumulates on the valves and port floor. Although the air charge helps evaporate and mix this fuel, mixture quality deteriorates containing pockets of rich mixture and liquid fuel that may be deposited on the combustion chamber walls. During combustion, although the combustion process remains predominantly pre-mixed,

diffusion combustion occurs in the overly rich and liquid fuel regions producing particulates.

With GDI, if the fuel were to be injected early to take advantage of the high charge motion generated after intake valve opening, then the piston would be too close to the injector which would result in severe piston wetting. The liquid fuel on the piston crown would then burn through diffusion combustion generating high levels of particulate. Therefore injection timing has to be retarded to avoid piston wetting, but if injection timing is retarded too far, then due to decaying air motion, the fuel spray will impinge the liner which will again increase particulates and also result in oil dilution. With the injection timing window constrained by piston and liner impingement, the time available for injection, evaporation and mixing of the fuel is limited. Combine this with the missed opportunity for evaporation and mixing that was offered by the air motion generated before start of injection, and mixture preparation is typically worse than for a PFI engine. Again, mixture preparation also deteriorates when the engine is cold and the cold charge air reduces the evaporation rate.

Figure 3 below illustrates the process of particulate formation due to fuel impingement on the piston crown of a GDI engine. The top two images (a & b) are LIF images of the fuel spray looking into the side of the combustion chamber

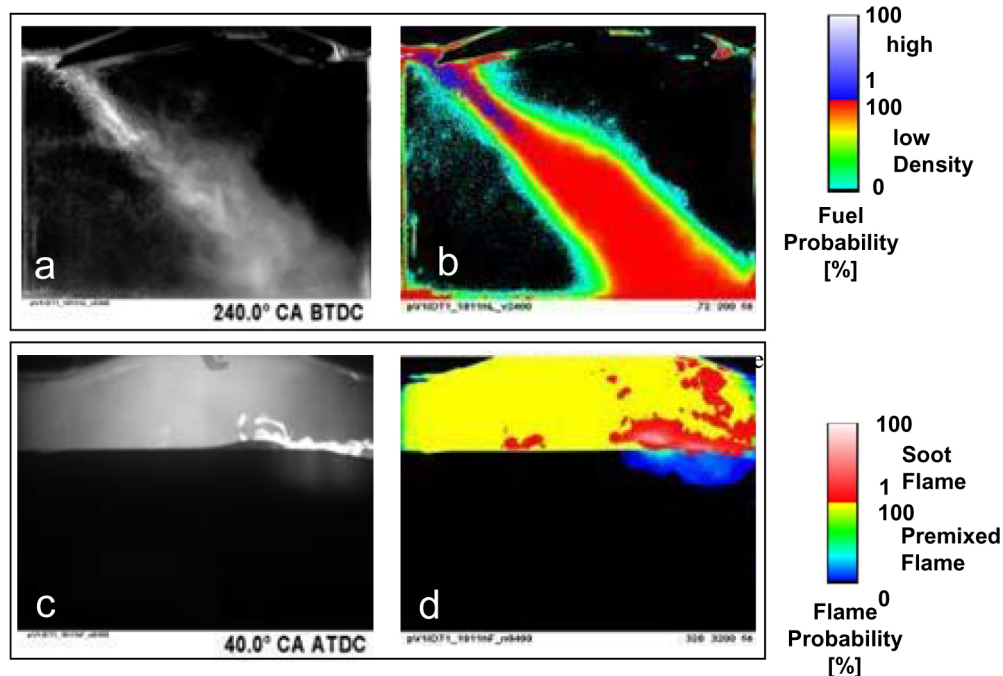


Figure 3. Optical Engine LIF and Combustion Images of Fuel Impingement on the Piston Crown of a GDI Engine Resulting in Particulate Formation

with the injector located on the intake side between the intake valves. The image on the top left (a) is from a single cycle whereas the color image on the top right (b) is a statistical evaluation of 35 cycles at the same crank angle. The fuel spray extends downward and can be seen to impinge the piston.

The lower images (c & d) show photographs of the corresponding combustion event. The image on the lower left (c) is a photograph of a single combustion cycle at 100 deg ATDC. The flame is enveloping the entire combustion chamber volume at this crank angle and is seen as moderately luminous and reasonably homogeneous which is typical for a pre-mixed combustion flame. More interesting however is the highly luminous localized region on the exhaust side of the piston. This is a diffusion flame resulting from the diffusion combustion of liquid fuel that was deposited in this region on the piston crown and liner. Diffusion flames are much more luminous than pre-mixed flames and this useful characteristic helps identify areas within the combustion chamber where particulates may be forming or individual particulate generating cycles can be identified.

The color image on the bottom right (d) shows a statistical representation of 35 cycles at the same crank angle showing the probability of the presence of particulate generating flames as an analog of flame luminosity. With the optical engine, the piston crown and liner can also be inspected for signs of fuel impingement after a measurement is taken.

Piston and liner impingement is particularly problematic during a cold start when the surfaces are cold and cannot provide the heat required to evaporate the fuel. Also, fuel vapor that contacts these cold surfaces may be condensed back into liquid. Injection timings that would have been satisfactory with a warmed-up engine may lead to high particulates when the engine is cold.

Fuel impingement can also be an issue leading to high particulates at high load conditions in a warmed-up engine. Under these conditions, the quantity of fuel injected is high which can increase fuel deposition on the piston. Although the hot piston assists evaporation, there may be insufficient time for all the fuel to evaporate and mix. This is even more problematic with a GTDI engine where the quantity of fuel injected is even higher. GTDI engines are typically designed with very high tumble, which maintains high charge motion later into the intake stroke. This provides improved mixing and also helps deflect the fuel spray from the piston and liner. Low speed, high load operation is particularly challenging for mixture preparation and particulates as fuel quantities are very high but the effective charge motion is low due to the low engine speed.

Therefore it would seem that the key to reducing particulate emissions from a GDI engine is to reduce fuel impingement on combustion chamber components, particularly the piston, and particularly while the piston is cold. Also it would appear that anything that can be done to accelerate warm-up of the piston will help reduce particulates.

COMBUSTION SYSTEM OPTIMIZATION

The design of the injector and fuel spray targeting can have a significant influence on wall wetting and particulate formation. The main factors that can be influenced with the injector design of a solenoid operated multi-hole injector are:

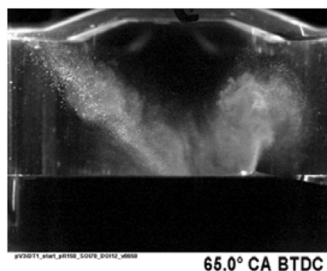
- Number and shape of the injection holes
- Spray pattern, position of the holes relative to one another and injection angle
- Static flow rate
- Minimum duration of injection
- Method of producing the holes and hole geometry (laser cut or erosion, straight or stepped holes)

The injector must not only be designed to meet performance, fuel economy, oil dilution, and gaseous emissions targets, but must also result in low particulate levels. A Euro 6 PN compatible injector must meet high standards regarding spray quality whilst avoiding interactions of the injected fuel jets.

For a given fuel pressure, spray penetration is directly proportional to the duration of injection (DOI), with DOI determined by the fuel mass required to achieve the target IMEP at the required air/fuel ratio with the specified injector flow rate. Increasing fuel rail pressure (FRP) reduces droplet size, thus enhancing evaporation. However, spray penetration is directly proportional to FRP. High fuel spray penetration leads to fuel impingement on the piston and/or liner. This conflict can be resolved by splitting the required DOI - at highest FRP for lowest droplet size - into multiple injections.

Figure 4 shows the benefit that can be achieved when reducing DOI for compression stroke injection. With 1.2ms DOI there is significant impingement of the piston crown and the fuel spray can be seen to bounce off the piston - this will result in significant wetting of the piston crown. With 0.4ms DOI, impingement is significantly reduced as the fuel spray only just reaches the piston. Three 0.4ms DOI injections will provide the same fuel mass as a single 1.2ms DOI injection but with reduced piston wetting and lower particulates.

Duration of Injection
1.2 ms



Duration of Injection
0.4 ms

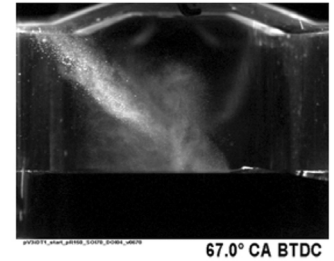


Figure 4. Injection duration reduction through multiple injection is very helpful for transient warmed-up engine operation however it is essential for a low particulate cold start - together with highest fuel rail pressure!

Advancements in injector technology continue to improve spray quality and provide additional flexibility in spray design. One of the latest advancements is laser drilling of the nozzle holes which provides a spray with reduced penetration and improved atomization at the same fuel pressure. This also provides the flexibility to vary the size of each of the individual holes to control the penetration of each individual spray plume as an additional countermeasure to avoid fuel impingement.

By combining injectors with improved atomization and greater control of spray penetration with multiple injection strategies, it is possible to achieve significant reductions in particulate emissions. Figure 5 shows a comparison of particulates from a laser drilled injector compared to an erosion drilled injector for single, double and triple injections under steady state operation. Further particulate reductions were achieved by reducing the fuel flow rate of the laser drilled injector.

Piezo-injectors also achieve good results for particulates. They offer the minimum fuel droplet size at the highest fuel rail pressure and lowest penetration and shortest injection duration but at high cost and only work for a central injection position.

PARTICULATE REDUCTION STUDY

The NEDC cycle can be split into four areas of focus requiring different approaches for particulate reduction from a GDI engine:

- Cold start
- Catalyst heating
- Transients during cold engine operation
- Steady state and transient operation of a hot engine

Methodologies for particulate reduction in these phases will be presented in the following sections. These findings are based on several studies performed by AVL over the past few years through which methodical approaches for particulate