

Evaluation of a Gasoline Particulate Filter to Reduce Particle Emissions from a Gasoline Direct Injection Vehicle

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ABSTRACT

Gaseous compounds, particle number and size distribution measurements on a gasoline direct injection (GDI) vehicle and a port fuel injection (PFI) vehicle were conducted over the U.S. Federal Test Procedure 75 (FTP-75) and US06 Supplemental Federal Test Procedure (US06) on Tier 2 certification gasoline (E0) and a 10% by volume ethanol (E10). Overall the GDI test vehicle was observed to have lower fuel consumption than the PFI test vehicle by 6% and 3% for the FTP-75 and US06 drive cycles, respectively. When using E10, this GDI vehicle had a better fuel consumption than the PFI vehicle by 7% and 5% for the FTP-75 and US06 drive cycles, respectively. For particle emissions, the solid particle number emission rates for the GDI, equipped with a 3-way catalyst in its original equipment manufacturer configuration (i.e., stock GDI), were 10 and 31 times higher than the PFI vehicle for the FTP-75 and US06 drive cycles, respectively. However, when a non-catalyzed gasoline particulate filter (GPF) was installed, the solid particle number emission rates were only 2 and 8 times higher than that from the PFI vehicle. For the GDI vehicle, the number-weighted geometric mean particle diameters over both FTP-75 and US06 cycles were in the range of 50-70 nm. The situation was similar for the PFI vehicle over the FTP-75, however, over the US06, most of the emitted particles were ultrafine particles with a diameter of about 10 nm. E10 had little impact on particle diameter for both the GDI and PFI vehicles. The use of E10 fuel generally led to a reduction in particle number emissions on the PFI vehicle over both cycles. For the GDI vehicle, the use of E10 led to a reduction in particle emissions over the FTP-75 but the opposite was observed for the US06 drive cycle. Based on the test results, the unconditioned GPF had a particle filtration efficiency of 82 and 76% for the FTP-75 and US06 cycles, respectively. Results also revealed that the GPF filtration efficiency was strongly linked to the exhaust temperature and continued soot regenerations were the reason for the lower filtration efficiency being observed for the US06 drive cycle.

CITATION: Chan, T., Meloche, E., Kubsh, J., Rosenblatt, D. et al., "Evaluation of a Gasoline Particulate Filter to Reduce Particle Emissions from a Gasoline Direct Injection Vehicle," *SAE Int. J. Fuels Lubr.* 5(3):2012, doi:10.4271/2012-01-1727.

INTRODUCTION

Gasoline direct injection vehicles are currently receiving increased attention by auto manufacturers because of their better fuel economy as compared to traditional port fuel injection gasoline vehicles [1, 2]. With the use of

turbocharging on GDI vehicles, the same driving performance can be maintained with downsized engines, which further reduces vehicle fuel consumption. According to the U.S. EPA, among other technologies, such as a diesel engine, turbocharging, and downsizing, the GDI engine was considered as one of the technology paths for meeting future

emission regulations for reducing greenhouse gases [3]. Based on current data and estimation of compliance with federal requirements, in North America GDI vehicles could reach up to 60% of the light-duty vehicle fleet by 2016 [4].

Despite the benefits of reduced fuel consumption and CO₂ emissions, GDI vehicles have relatively higher particle emissions than PFI vehicles [1, 5]. This is because GDI engines often run lean and stratified as opposed to stoichiometric and homogeneous like in traditional PFI engines [6]. Also, cylinder wall wetting is another factor that contributes to higher particulate matter emissions in GDI engines [7, 31]. On the other hand, when GDI engines are operated under homogenous charge mode, fuel is injected early during the intake stroke and this allows better mixing of the fuel and intake air. In this case, particle emissions could approach to near PFI vehicle levels [8]. Similar to diesel engines, exhaust particles from GDI vehicles contain a large fraction of soot with typical mean particle diameters ranging from 60 to 100 nm [5, 6, 9, 10, 11]. However, due to the very different operating conditions, soot particles emitted from GDI engines vary significantly. During the homogeneous charge mode, the better fuel mixture yields soot particles with much smaller primary particle size, similar to those observed from PFI vehicles [12, 13]. During stratified charge mode, air/fuel ratio may vary from very rich near the spark plug to very lean near the cylinder wall. The soot particles produced at the fuel rich region have a much larger primary particle size similar to those emitted from diesel engines [12].

In Europe, the proposed Euro 6 Particle Number (PN) limit for GDI light-duty vehicles is 6.0×10^{11} particles/km with a Particle Mass (PM) limit of 4.5 mg/km. The proposed Euro 6 GDI PN limit would not come into effect until three years after the introduction of Euro 6 emission standards in Europe (starting in September 2017). In North America the current Tier 2/LEV II PM limit is 10 mg/mi (6.2 mg/km) over the FTP-75 test cycle. California recently approved their LEV III light-duty emission limits and this program includes the phase-in of a 3 mg/mi (1.9 mg/km) PM limit starting in 2017 and a 1 mg/mi (0.6 mg/km) PM limit starting in 2025 over the FTP-75 test cycle. Several recent studies suggested that the stoichiometric GDI and lean stratified GDI engines typically have PN and PM emissions higher than and close to the proposed Euro 6 limits, respectively [14]. Therefore, it is important and necessary to address the particle emission issues from GDI vehicles in order to meet current and future emission regulations.

Reduction in particle emissions from GDI vehicles can be achieved through improving engine combustion parameters, such as air/fuel ratio, fuel injection strategy (e.g., timing, number of injections, and injection pressure), combustion phasing, as well as coolant and engine temperatures [14, 15, 31]. Another solution is to utilize a particle emission control device, such as a gasoline particulate filter (GPF) [2].

The GPF concept is equivalent to a gasoline version of a diesel particulate filter (DPF), its general operating principle

has been outlined elsewhere [16, 17]. Although the basic design between a GPF and DPF may be similar, their performance could be different due to the differences between gasoline and diesel exhaust. Some of these characteristics were summarized by Saito et al. [2]. For example, due to the lower soot emissions from GDI engines compared to diesel engines, there may be much less soot being accumulated in the GPF and thus lower GPF particle filtration efficiency. Also, exhaust temperature and flow rate for gasoline exhaust could be higher and may lead to higher pressure drop across a wall-flow GPF. Since the exhaust temperature from a gasoline engine is generally higher than that from a diesel engine, a GPF with passive soot regeneration may suffice in any applications although the oxygen level in the gasoline exhaust could be lower compared to the diesel exhaust.

This work compares the gaseous compounds, particle size distributions and number emission rates between a GDI and PFI vehicles over the U.S. Federal Test Procedure 75 and the US06 Supplemental Federal Test Procedure at ambient temperature. In addition, this work also investigates the effectiveness of a GPF in reducing particle emissions from a GDI vehicle on Tier 2 certification gasoline (E0) and gasoline blended with 10% ethanol by volume (E10). Data on how the soot accumulation in the GPF affects the particle filtration efficiency is also discussed.

MEASUREMENT PROCEDURE AND TECHNIQUE

Vehicles, Mileage Accumulation, Fuels, and GPF

The test vehicles were a wall-guided, stoichiometric GDI vehicle (2011 Hyundai Sonata) and a PFI vehicle (2010 Volvo S40). The mileage accumulation on both the GDI and PFI vehicles were conducted following the procedure outlined in 40 CFR 86.1831 [18]. The accumulated mileage on the GDI and PFI vehicles prior to the emission tests were 3220 and 6523 km, respectively. The engine specifications for the two vehicles are provided in [Table 1](#). All emission tests were conducted at standard temperature on either U.S. EPA Tier 2 certification gasoline (E0) or a splash blended 10% by volume ethanol (E10). Selected fuel properties of the two fuels are given in [Table A1](#) in the [Appendix](#).

A sub-set of the emission experiments was conducted when the GDI vehicle was equipped with a GPF. This non-catalyzed, wall-flow, passively regenerated GPF was provided by the Manufacturers of Emissions Controls Association (MECA) and was optimized for a GDI vehicle with similar or lower horsepower as the test vehicle. The GPF has a dimension of 5.66" in diameter and 6" in length. The GPF cell density is 200 cpsi with 12 mil wall thickness and approximately 50% wall porosity. This GPF typically undergoes regeneration at about 600-650 °C. The GPF was installed in the underfloor position downstream of the



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original equipment three-way catalyst. When the GPF was not used, it was replaced by the original equipment resonator. The catalysts in both vehicles were configured with converters in the close coupled and underfloor positions.

Table 1. Specifications of the tested vehicles.

	GDI	PFI
Accumulated mileage (km)	3220	6523
Displaced volume (L)	2.4	2.4
Engine configuration	GDI I4 DOHC	MPFI I5 DOHC
Rated horsepower (HP)	198	168
Test weight (kg)	1590	1648
Emission control device	3-way catalyst	3-way catalyst
Catalyst configuration	CC-UF	CC-UF

Drive Cycles and Test Procedure

The drive cycles used in this study were the U.S. Federal Test Procedure 75 (FTP-75) and the US06 Supplemental Federal Test Procedure (US06). The two cycles were chosen with the objective to understand the emissions over very different driving conditions. In addition, it is also important to evaluate the GPF performance under these different types of driving scenarios as it may have different implications with regards to exhaust emissions in the real world. Prior to each test date, the vehicle was prepared on the previous test day by running a Los Angeles Route Four (LA4) cycle and then the vehicle was soaked overnight. On each test day, testing began with the cold-start FTP-75, followed by two back-to-back US06 cycles. After that, the test sequence was completed with a LA4 cycle as a preparation cycle for the next day. For all configurations (stock GDI, GDI post-GPF, PFI), at least three repeats were conducted for each drive cycle. At this phase of the program, more than 20 FTP-75 and US06 drive cycles were conducted with each configuration. For emission tests following fuel exchanges either from E0 to E10 or from E10 to E0, two fuel exchange were performed followed by two extra prep cycles before running the LA4 preparation cycle as part of the procedure to ensure minimal contamination from the previous fuel.

Exhaust Particle Sampling

Vehicle exhaust was diluted after the tailpipe and directed to a full-flow Constant Volume Sampling (CVS) dilution tunnel. A schematic diagram of the sampling setup is given in Figure 1. Diluted exhaust over the entire driving cycle was extracted continuously from the CVS tunnel and stored in Tedlar bag for gaseous measurements at the end of the driving cycle. Concentrations for CO₂ and CO were measured by Horiba instruments (AIA-210 and AIA-210LE) based on the Non-Dispersive Infrared Absorption technique (NDIR). NO_x was detected using California Analytical Instruments (400-HCLD) based on the Heated Chemiluminescence detection method. Concentration of the total hydrocarbons (THC) was measured by a California

Analytical Instruments (300-HFID) using the Heated Flame Ionization Detection method (FID).

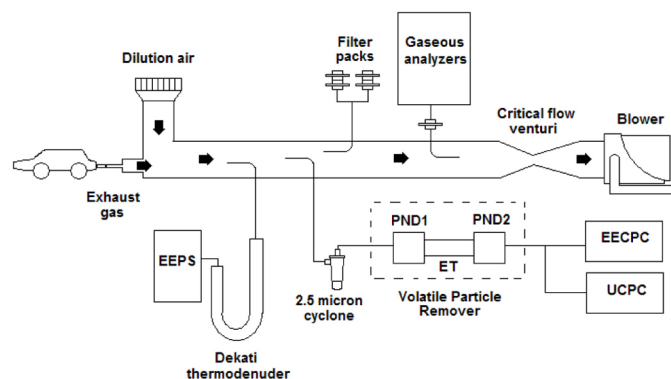


Figure 1. Schematic diagram of the emission testing and sampling system.

In-situ particle measurements were conducted by two systems. The first system was the European Union Particle Measurement Programme (PMP) solid particle system. The PMP system was developed to focus on solid particle detection from diluted exhaust [19]. Briefly, coarse particles were removed by a 2.5 µm cyclone and then the remaining particles were introduced into a Volatile Particle Remover (VPR), which consisted of a sequence of two dilution systems with an evaporation tube operated at 300°C in between. The VPR removed the majority of the volatile materials on the soot particles as well as other volatile liquid particles. Any particles surviving that process and larger than 23 nm were considered as solid particles by definition and the number concentration was measured in real time by the TSI 3790 Engine Exhaust Condensation Particle Counter (EECPC) with a 50% counting efficiency at 23 nm. A second TSI 3776 ultrafine CPC (UCPC), with a minimum detection limit of 3 nm, was included in the PMP system to detect the existence of any ultrafine particles that were not detected or measured by the PMP system. In the second particle measurement system, the particle number size distributions (5-600 nm) were monitored in real time using a TSI 3090 Engine Exhaust Particle Sizer (EEPS). In the EEPS, particles were electrically charged by a corona and then exposed to a uniform electric field where positively charged particles were expelled towards different electrometers based on their electrical mobility. Charges on the particles were transferred and measured upon the contact of the particles onto the electrometers. The measured current at all electrometers were converted to particle number concentration based on an internal algorithm considering the ultrafine particle diffusion losses.

Detaching the EEPS from the PMP system allows the two systems to use different dilution ratios. A higher dilution ratio used in the PMP system minimized the chance for the particle counter to under estimate number concentration due to particle coincidences occurring at high concentrations. On the other hand, a lower dilution ratio used for the EEPS lowered

the impact of electrical noise onto the measurement signals which optimized the size distribution measurements. As the PMP system was designed to remove volatile component on the particles, a Dekati thermodenuder (ELA-111) was installed upstream of the EEPS to ensure measurements from both systems were comparable. The thermodenuder included the heater and absorber sections. The heater section was operated at 300 °C to evaporate most of the volatile fractions, particularly the organic materials on the particles as well as other liquid particles. In the absorber section, the gaseous phase compounds, particularly the hydrocarbons, were removed from the airstream by active charcoal to prevent re-condensation on the soot particles. At the same time, the airstream was cooled by ambient air operated at a flow rate of 100 l/min [13].

Particles were also collected on Teflon and fired quartz filters. The former samples were used for gravimetric analysis and selected samples were sent for metal analyses using an Inductively Coupled Plasma Mass Spectrometry (ICP-MS) technique. The quartz filters were sent for thermal analysis to determine the organic and elemental carbonaceous fractions on the particles. These analyses were not completed at the time this manuscript was completed. Therefore the PM results will be presented together in future publications.

RESULTS AND DISCUSSION

Gaseous Measurements and Fuel Consumption

The gaseous emission rates from both the GDI (with and without GPF) and the PFI vehicles are provided in [Tables A2 and A3](#) in the [Appendix](#) for the FTP-75 and US06 drive cycles. All regulated gaseous emissions from the two vehicles were below their current certified Tier 2 Bin 5 emission standard. NO_x and THC emissions from both vehicles and from various configurations were so low that they were not statistically different. On average, the stock GDI vehicle on E0 had lower CO₂ emissions than the PFI vehicle by about 6% and 4% over the FTP-75 and US06 drive cycles, respectively. Slightly higher reductions were observed for E10. On the other hand, the CO emissions from the stock GDI on E0 were higher than the PFI vehicles by about 3 and 7 times over the FTP-75 and US06 drive cycles, respectively. Interestingly, the average CO₂ and CO emissions for the GDI post-GPF configuration were somewhat lower than the stock GDI configuration. It is speculated that the presence of a GPF may increase the exhaust back pressure compared to the original resonator and this could have an impact on the exhaust gas recirculation (EGR) in the vehicle. As a result, it could affect other vehicle parameters and led to changes in both CO₂ and CO emissions. Some have suggested that EGR may reduce fuel consumption in a GDI engine and thus should be reflected in the CO₂ and CO exhaust emissions [20,

21]. However, better experimental design will be needed to confirm if these speculations were true in this case.

Comparing the calculated fuel consumption (based on the carbonaceous measurements) between the two vehicles, the stock GDI vehicle operated on E0 was found to reduce fuel consumption compared to the PFI vehicle by 6% and 3% over the FTP-75 and US06 drive cycles, respectively. When switching to E10, these reductions were improved to 7% and 5%, correspondingly. These observations are consistent with the predictions and are result of a combination of increased compression ratio, lean mixture, reduced throttling losses, and wall heat losses from the GDI engine [1, 22].

Comparison of Particle Measurement Systems

The particle number measurements from the two PN measurement systems were compared to evaluate the consistency of the particle measurements and also the effectiveness of the two VPR systems. [Figure 2\(a\)](#) shows the dilution corrected particle number concentration time series for the stock GDI configuration over a LA4 drive cycle operated on E0 fuel. The orange and blue traces represent the particle number concentrations obtained by integrating the EEPS size distributions (5-600 nm) and measured directly from the UCPC (>3 nm), respectively. Over the duration of the LA4 cycle, particle number concentration varied over three orders of magnitude from 10⁴ to 10⁷ particles/cm³, but the emission patterns from the two systems were highly consistent suggesting the particle emissions were well captured by the two systems. Occasionally at the concentration spikes, the UCPC measurements appeared to report lower number concentration than the EEPS. This is due to the coincidences in the UCPC at high concentrations during which the photometric mode was used to estimate particle number concentration instead of the single particle mode. Under the photometric mode, particle number concentration was inferred based on the magnitude of the recorded analog signal. This method is dependent on factors such as particle type, shape, and composition, and therefore requires special calibration. This often resulted in the under estimation of the particle number concentration despite using dilution in this study. On the other hand, the EEPS does not have a coincidence issue and was capable of detecting much higher number concentration.

[Figure 2\(b\)](#) shows the GDI post-GPF measurements over the LA4 drive cycle. In comparison, the range of the particle number concentration was within the optimum detection range of the two systems and therefore the two sets of measurements were highly correlated. The overall particle emission patterns were comparable to the stock GDI configuration ([Figure 2\(a\)](#)) but number concentration was lower by one to two orders of magnitude indicating the effectiveness of the GPF in removing the exhaust particles. Interestingly, there was a small gradual reduction in particle emissions over the cycle. As will be explained further in

subsequent sections, the exhaust temperature over a LA4 or FTP-75 drive cycle was not suitable for GPF regeneration at ambient temperature and the continued accumulation of soot particles in the GPF led to gradual improvement in particle filtration efficiency over the cycle.

Figure 2(c) shows the corresponding particle number concentration time series for the PFI vehicle. During cold-start, the particle number emissions from the PFI vehicle was at similar or even higher magnitude than from the stock GDI configuration. However, the particle number emissions were reduced rapidly as the engine and emission control system was warmed up. During phase 2 of the cycle, particle number emissions from the PFI vehicle were mostly at the detection limit of the EEPS which could vary from 300 to 1000 particles/cm³ at a 1 second time resolution. As a result, the measured signals were also impacted by electrical noise from the instrument and led to over estimation of particle number concentration during phase 2 and 3 of the FTP-75 drive cycle.

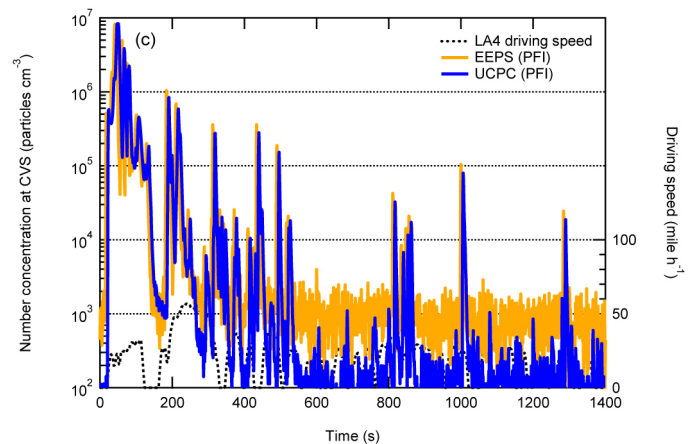
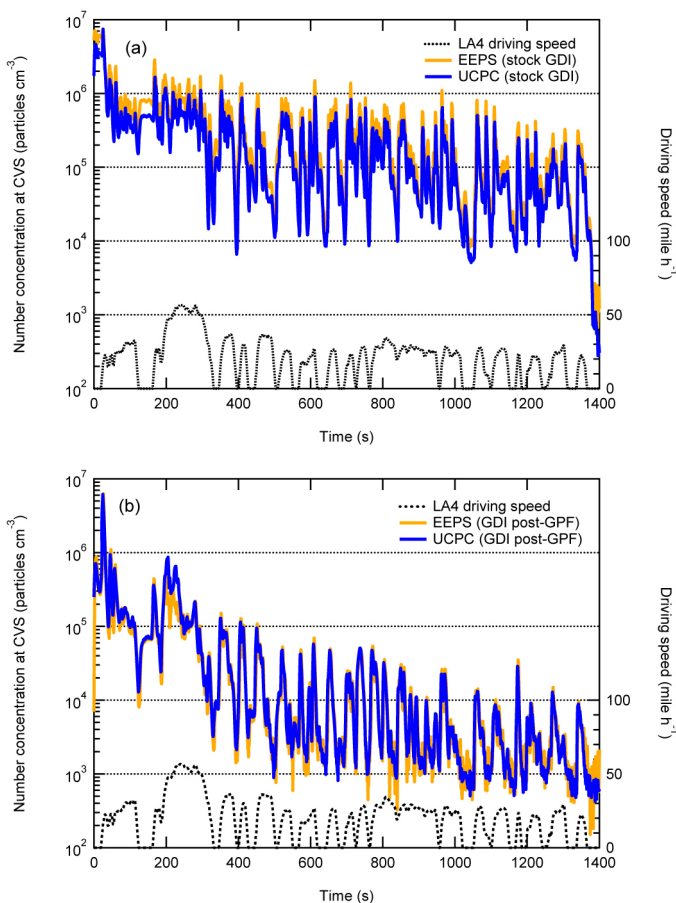


Figure 2. Particle number concentration time series over a LA4 drive cycle for (a) stock GDI, (b) GDI post-GPF, and (c) PFI configurations.



Figures 3(a), 3(b), and 3(c) show the particle number concentration time series for the stock GDI, GDI post-GPF, and PFI configurations over the US06 drive cycle operated on E0 fuel. Over the cycle, particle number measurements for the GDI stock and post-GPF configurations were similar except that the post-GPF case was lower in magnitude due to presence of the GPF. The gradual reduction in number concentration over time observed during the FTP-75 drive cycle was not observed during the US06 drive cycle. Further investigation suggested that multiple GPF soot regenerations occurred during the US06 cycle and therefore the soot layer could not be accumulated to improve the particle filtration efficiency over the cycle. This is discussed in more detail in the GPF soot regeneration section.

Some interesting observations were noted when comparing the EEPS and UCPC data obtained from the US06 drive cycle for the stock GDI, GDI post-GPF, and PFI configurations. For example, the two sets of measurements for the stock GDI configuration over the US06 drive cycle were highly consistent. For the GDI post-GPF configuration (Figure 3(b)), results from all repeats showed that the particle number concentrations from the EEPS were slightly higher than that from the UCPC whereas for the PFI configuration the trend was reversed. It is speculated that these differences observed between the EEPS and UCPC measurements for the GDI post-GPF and PFI configurations over an aggressive drive cycle may reflect the nature of the emitted particles. If the particles were mostly soot and solid in nature (i.e., stock GDI), differences in the VPR performance may have little impact on the particle number concentration measurements. This is because even if particles were coated with volatile materials, removing different amounts of coating has no impact on the absolute number concentration measurements and this will only be reflected on the particle diameter measurements. On the other hand, if the emitted particles contain a significant number of liquid particles, a more effective VPR system may give lower particle number