

Particle Emissions from a 2009 Gasoline Direct Injection Engine Using Different Commercially Available Fuels

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ABSTRACT

Total and solid particle mass, size, and number were measured in the dilute exhaust of a 2009 vehicle equipped with a gasoline direct injection engine along with an exhaust three-way-catalyst. The measurements were performed over the FTP-75 and the US06 drive cycles using three different U.S. commercially available fuels, Fuels A, B, and C, where Fuel B was the most volatile and Fuel C was the least volatile with higher fractions of low vapor pressure hydrocarbons (C10 to C12), compared to the other two fuels.

Substantial differences in particle mass and number emission levels were observed among the different fuels tested. The more volatile gasoline fuel, Fuel B, resulted in the lowest total (solid plus volatile) and solid particle mass and number emissions. This fuel resulted in a 62 percent reduction in solid particle number and an 88 percent reduction in soot mass during the highest emitting cold-start phase, Phasel, of the FTP-75, compared to Fuel C. Fuel B also resulted in the lowest particle formation during acceleration events. A complimentary modeling work [10] using the same fuel tested on this program showed a good correlation between the decrease in fuel high boiling point aromatics and double-bond equivalent value and the decrease in soot emissions.

Total PM mass emissions with all fuels, except the less volatile fuel, Fuel C, met the CARB proposed LEV III limit for 2014 and 2017, using the FTP-75. Engine operation with Fuels A and B met the CARB LEV III optional solid particle number limit for 2014, but the engine failed such limit using Fuel C and also failed the 2017 optional solid number limit

using all fuels. This suggests a discrepancy between total PM mass limit and the solid particle number limit, with the latter limit being more stringent. A larger discrepancy also existed between the Euro 6 total PM mass limit and the solid particle number limit. Although the Euro 6 limit is based on the New European Driving Cycle (NEDC) and not the FTP-75, this GDI engine met the Euro 6 PM mass emissions over the FTP-75 and failed the solid particle number limit by a factor of 3 to 10 with the different fuels. This gross failure based on Euro 6 solid particle number limit, while passing the total PM limit, suggests that the Euro 6 PM regulations are mainly driven by the solid particle number emissions limit, with the total PM mass limit becoming less relevant.

This work showed that gasoline fuel physical and chemical properties play an important role in reducing PM emissions from a GDI engine. It also showed that cold-start and acceleration events dominated PM formation. Furthermore, this work highlighted discrepancies between solid particle number emissions limits and total PM mass emissions limits using the proposed optional CARB LEV III standard and the Euro 6 standard.

INTRODUCTION

The drive for improved fuel economy and reduced “green house gas” CO₂ emissions from passenger cars has made gasoline direct injection (GDI) engines an attractive option for light-duty vehicles. To keep taking advantage of the three-way-catalyst (TWC) to reduce gaseous regulated pollutants, automobile manufacturers have used near-premixed charge GDI engines with an overall stoichiometric mixture of fuel and air. Lean-burn stratified charge GDI engine provides

even a better fuel economy, but it requires a different aftertreatment system than the TWC, such as an oxidation catalyst and a lean NO_x trap, besides other combustion improvements. GDI engines are expected to be a key player in providing fuel-efficient cars with reduced CO₂ emissions, however, it will be challenging for this engine technology to meet future particulate matter (PM) emissions standards, particularly in Europe.

GDI engines are known to emit more particulate matter (PM) than the widely used homogenous-charge port fuel injection (PFI) spark-ignited gasoline engines [1, 2, 3, 4, 5] and diesel engines equipped with diesel particle filters (DPFs) in the exhaust system [1,2,6]. Although the engine-out PM emissions remain high in modern diesels, the use of high efficiency DPFs in the exhaust system drastically reduces tailpipe PM emissions. PM formation in spark ignited gasoline engines is very sensitive to the fuel air mixture during combustion. Previous work using a 1994 homogenous-charge PFI spark ignited gasoline engine showed that PM emissions is very low and increase almost exponentially with the increase in fuel to air equivalence ratio [7], particularly above stoichiometric. The equivalence ratio is defined as the actual fuel to air mass over the fuel to air mass required for stoichiometric combustion. Recent work performed with a modern PFI gasoline engine showed a similar phenomenon [8]. In GDI engines, the fuel is injected directly into the combustion chamber and full droplet evaporation and mixing with air may not take place before the start of combustion. Previous work [9] showed that fuel composition may have an influence on the rate of droplet evaporation. Slow droplet evaporation rate can retard full fuel-air mixing and lead to soot formation due to the presence of droplets and/or locally rich fuel-air mixtures. Recent complimentary work [10] to this work also showed that the presence of high boiling point aromatics with a high double-bond equivalent value increase the tendency of soot formation.

Stringent Euro 6 solid particle number regulations and the proposed California Air Resources Board (CARB) LEV III PM mass and optional solid particle number standard will force substantially varying degrees in PM reduction from GDI engines, depending on whether the engine is sold in the European Union (EU) or the United States (U.S). Substantial reduction in solid particle number emissions from GDI engines will be required to meet Euro 6 solid particle number standard of 6×10^{11} part./km, by 2014 [11,12]. However, there is a discrepancy between Euro 6 solid particle number standard and total PM mass standard of 4.5 mg/km. Recent work [11] showed that in order to meet the EU solid particle number standard, the PM mass emissions will almost be a factor of 10 lower than the Euro 6 regulatory limit. Thus, the Euro 6 PM regulation is mainly driven by the solid particle number requirement and not the total PM mass. The CARB

LEV III proposed standard, on the other hand, appear to have some level of synergy between total PM mass regulation and the optional solid particle number regulation. For LEV III, CARB proposed a total PM mass limit of 3.8 mg/km and 1.9 mg/km by 2014 and 2017, respectively, down from a current limit of 6.2 mg/km. CARB also proposed an optional solid particle number standard of 3.8×10^{12} part./km and 1.9×10^{12} part./km, respectively, making an argument that meeting such limit will not be more stringent than meeting the PM mass limit. More work, however, is needed to ensure that such relationship holds across different engines and using different fuels.

Another layer of potential regulations that may affect PM emissions from GDI engines is the U.S. House of Representatives Black Carbon Emissions Reduction Act of 2009 [13]. This Act requires U.S. EPA to report to Congress on black carbon emissions sources, and formulate a plan to measure and control black emissions through regulations under the Clean Air Act by April 2011. Besides the effect of black carbon on human health, black carbon is considered a major candidate of global warming second to CO₂ [14]. Thus, there is a strong possibility for EPA to regulate black carbon mass emissions from combustion sources including direct injection gasoline engines.

This paper focuses on total (solid plus volatile) and solid particle mass, size, and number emissions from the exhaust of a 2009 vehicle equipped with a GDI engine along with a TWC in the exhaust. Emissions measurements were taken over the FTP-75 and the US06 cycles using three commercially available gasoline fuels. A chassis dynamometer facility along with a full flow constant volume sampler (CVS) dilution tunnel were used to conduct this study. Total PM mass was collected in accordance with the code of federal regulations CFR Part 1065 [15]. Organic carbon and elemental carbon mass was measured using Sunset Laboratories semi-continuous instrument [16]. Particle size distribution and number concentration were measured using TSI Engine Exhaust Particle Sizer (EEPS) [17]. Black carbon mass was measured using AVL micro-soot sensor (MSS) [18]. The measurement of solid particles was facilitated using SwRI solid particle sampling system (SPSS) [19]. Limited solid particle number measurement in accordance with the EU protocol was performed using the AVL Aerosol Particle Counter (APC) [20].

EXPERIMENTAL SETUP AND PROCEDURES

This section describes the vehicle, fuel, instrumentation, sampling system, and test matrix used to perform this work. During this work NO_x, CO, NMHC, and CO₂ were measured in addition to PM. However, the focus of this paper is on PM emissions only.

VEHICLE

The vehicle was a 2009 model year with automatic transmission. The vehicle meets California LEV II standard. It was equipped with a two-liter turbocharged GDI engine with a wall-guided injection system, where by the fuel injectors were not centrally located in the combustion chamber. The vehicle was also equipped with a TWC in the exhaust. The odometer reading was 915 miles before official testing began.

FUELS

Fuel Properties

Table 1 shows the three different fuels used. Fuel A is similar to an EPA certification gasoline that SwRI uses in emissions testing. Fuel B is a commercially available summer fuel that was obtained from a gas station in Fairbanks, Alaska. Fuel C is a commercially available summer fuel that was obtained from a gas station in Las Vegas, Nevada. Fuel A has the lowest sulfur content of 3 ppm, compared to 80.2 ppm with Fuel B, and 19.4 ppm with Fuel C. Fuel C contains 10.1% oxygenates (ethanol) compared to no oxygenates with Fuels A and B. Fuel C has higher olefins, compared to Fuel A and Fuel B, and Fuel A has the highest aromatics content. Fuel volatility can have a major influence on evaporation and mixing of the fuel being injected into the combustion chamber of a GDI engines. Thus, it is important to examine the evaporation characteristics of the fuel to have a better understanding of their effects. Figure 1 shows a comparison of the fuel evaporation curve for all three fuels. Fuel B has the lowest final boiling point temperature of 151°C, compared to a temperature of 197°C for Fuel A, and 210°C for Fuel C. Similar trends are observed for the 90 percent evaporation temperature, suggesting that Fuel B is the most volatile followed by a less volatile fuel, Fuel A, to the least volatile fuel, Fuel C. Figure 2 shows the carbon number distributions. Fuel C contains higher percentages of C9 to C12, compared to Fuel A and Fuel B. Fuel A has higher percentages of C9 to C12, compared to Fuel B. Fuel B has no molecular structure with carbon number higher than C10, reflecting its higher volatility, compared to other two fuels.

Table 1. Fuel Properties

ASTM Method	Name	Unit	Fuel A	Fuel B	Fuel C
D5191	RVP	psi	8.97	14.7	8.96
D2622_07	sulfur	ppm	3 ^a	80.2	19.4
D3831	Manganese	mg/l	N/A	<0.2	<0.2
D86	IBP	°C	33.9	23.0	35.3
	Evap_5	°C	N/A	29.8	48.0
	Evap_10	°C	44.4	34.7	51.6
	Evap_15	°C	51.7	38.9	54.4
	Evap_20	°C	65.0	43.2	57.4
	Evap_30	°C	78.9	53.4	62.5
	Evap_40	°C	94.4	66.9	67.0
	Evap_50	°C	105.0	83.2	89.3
	Evap_60	°C	111.7	100.4	114.4
	Evap_70	°C	117.8	112.7	131.6
	Evap_80	°C	129.4	121.6	152.9
	Evap_90	°C	158.9	131.5	175.3
	Evap_95	°C	167.2	138.6	190.6
	FBP	°C	197.2	151.0	209.8
	Recoverd	mL	98.1	98.1	98.5
	Residue	mL	0.8	0.5	0.8
	Loss	mL	1.1	1.4	0.7
D6729					
	Paraffins	% Wgt	54.809	46.224	41.647
	Aromatics	% Wgt	40.939	43.888	31.55
	Olefins	% Wgt	0.05	0.142	6.875
	Oxygenates	% Wgt	0	0	10.131

^a ASTM D5453 was used

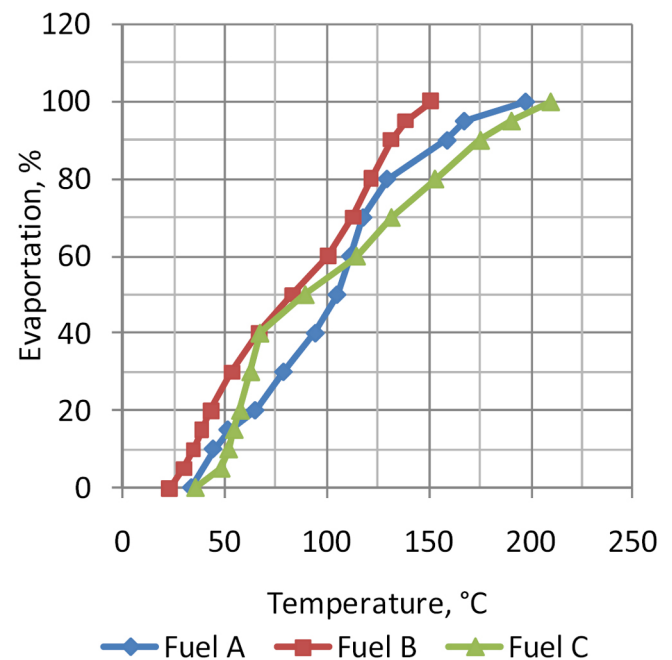


Figure 1. Fuel Evaporation Profile (ASTM D86)

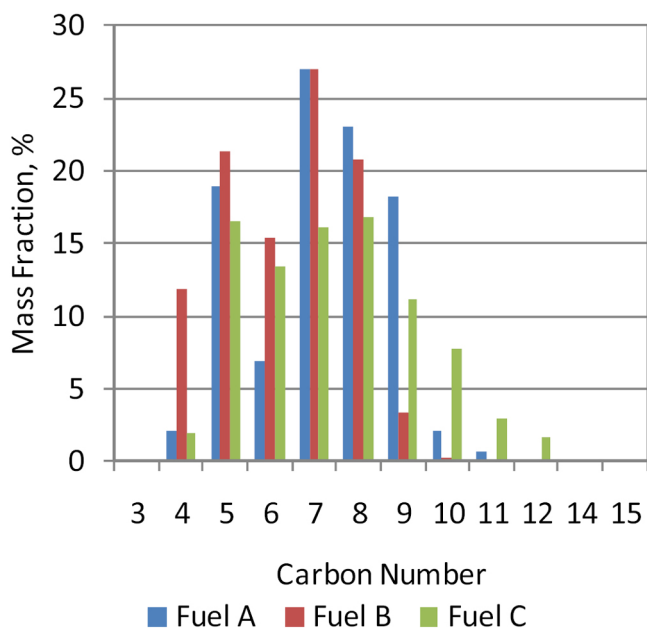


Figure 2. Fuel Carbon Number Distribution

Fuel Flushing Procedure

Before a fuel was used to operate the vehicle on an official test, the fuel tank was thoroughly flushed multiple times. Followed the flush, practice runs on the chassis dynamometer were performed prior to soaking the vehicle for official testing.

PARTICLE INSTRUMENTS AND PM FILTER MEASUREMENT

All particle measurements were taken on every test conducted. A PM2.5 cyclonic separator was used in the sample line upstream of the particle instruments. The particle instruments used on this project were:

- AVL Micro-Soot Sensor (MSS) [18]. The MSS is an instrument that measures soot mass concentration on a one-Hertz basis using a photo-acoustic detection technique.
- AVL Aerosol Particle Counter (APC) [20]. The APC is an instrument that measures solid particle number concentration on a one-Hertz basis in conformance with Euro 6 regulations. This instrument was used with Fuel A only. It was not part of the official program but was added because it was available at SwRI during activities with Fuel A.
- TSI Engine Exhaust Particle Sizer (EEPS) [17]. The EEPS is an instrument that measures particle number concentration and size distribution in the size range from 5.6 nm to 560 nm on a one-Hertz basis. The EEPS was coupled to SwRI Solid Particle Sampling System (SPSS) [19] that facilitates the measurement of solid particle using a catalytic stripper technology, and also has the ability to measure total particles. The system was alternated so that one test with each fuel was

run for total particle number and the other for solid particle number. The SPSS was shown to have a high removal of volatile hydrocarbon, and suppression of any sulfate nanoparticles [19].

- Sunset Laboratories semi-continuous organic carbon and elemental carbon (OC/EC)[16]. The OC/EC is an instrument that collects PM on a quartz filter located inside of it and provides (OC/EC) analysis at the end of filter collection. Because the analysis time will take about 10 minutes, the OC/EC was not used for phase-by-phase collection, it was rather used to collect one filter for the entire FTP-75 followed by the analysis. Quartz filters are known to adsorb artifact hydrocarbon from the gas phase during filter collection from engines [21]. In order to account for such artifact, the testing using this instrument was alternated between collecting PM for an actual test or collecting the PM artifact of an actual test. To collect the PM artifact, a Teflon membrane filter was used in the sample line upstream of the instrument during collection. Thus, any OC that is reported by the instrument during artifact test will be gas phase artifact that are collected by the quartz filter downstream of a Teflon membrane filter. The reader is encouraged to review references [21, 22, 23] for more details.

In addition to the particle instruments described above, PM mass was collected on a Teflon membrane filter using a sample-train that is heated to $47^{\circ}\text{C} \pm 5^{\circ}\text{C}$ in accordance with the Code of Federal Regulations (CFR), Title 40, Part 1065. A PM2.5 cyclonic separator was used in the sample-train before filter collection. PM on a filter was collected for each of the three phases of the FTP-75 as well as for the US06.

SAMPLING SYSTEM

Figure 3 shows the experimental setup on a chassis dynamometer. Chassis dynamometer settings for the vehicle were derived from target road load coefficients as reported in the EPA on-line Test Car List Data Files.

Regulated PM was sampled from the full flow CVS and collected on a filter located downstream of a PM2.5 cyclonic separator. The real-time particle instruments measured the particle concentration in the full flow CVS using a sample line containing a PM2.5 cyclonic separator.

The minimum total dilution ratio between engine exhaust and filter collection was set to six at the maximum exhaust flow rate of the cycle tested, in accordance with 40 CFR Part 1065. The dilution ratio (DR) is defined as:

$$\text{DR} = (\text{Dilution air flow} + \text{Sample flow}) / (\text{Sample flow})$$

The DR between the CVS and filter collection was a constant set to 1.5. The DR between the CVS and the MSS was a constant set to two. The DR between the APC and the CVS was a constant set to 1000. The dilution ratio between the

CVS and the EEPS was a constant set to six. The only variable proportional dilution ratio was between the CVS and engine exhaust. It ranged from a minimum dilution ratio of 6 at maximum exhaust flow to a maximum dilution ratio of 22 for the FTP and 36 for the US06 at idle flow.

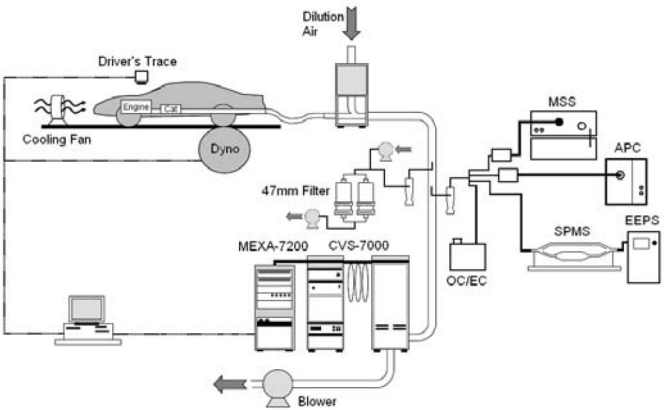


Figure 3. Experimental Setup and Sampling System

TEST MATRIX

Table 2 shows the test matrix. On each fuel, testing was performed over a period of two days. Each day, one run of the FTP-75 followed by one run of the US06 were performed. Over a period of two days, two runs of the FTP-75 and two runs of the US06 were accumulated on each of the three fuels. NO_x, CO, CO₂, non-methane hydrocarbons (NMHC), OC/EC, MSS, and solid or total number concentration and size distributions were measured on every cycle tested. For the OC/EC, PM was collected on primary filter in Run 1 of the FTP and US06 and on a backup filter in Run 2. The backup filter OC was subtracted from the primary filter OC to correct for artifact before reporting the final results. For the size distribution measurements, total particles (solid plus volatile) were measured in Run 1 and solid particles were measured in Run 2.

Table 2. Test Matrix Per Fuel

Test Cycle	Number of Runs Per Fuel				
	PM ^a	OC/EC ^b	Micro-Soot Sensor	Solid Particle Number and Size Distribution	Total Particle Number and Size Distribution
FTP-75 (per phase)	2	2	2	1	1
US06	2	2	2	1	1
^a Particulate matter mass measurement was in accordance with CFR Part 1065					
^b Organic carbon and elemental carbon was taken once per entire cycle. For this method, we collected and analyzed filters using a primary filter and a backup filter. We subtracted the backup filter OC from the primary filter OC to correct for artifact collection by the primary filter					

RESULTS AND DISCUSSION

PARTICLE MASS EMISSIONS

PM mass emissions were measured in accordance with 40 CFR, Part 1065, where the Teflon membrane filter is heated and maintained at 47°C±5°C. A separate filter measurement was taken for each phase of the FTP and the US06. Figure 4 shows the PM mass emissions for Phases 1, 2, and 3 of the FTP, the FTP-composite, and the US06. Several observations can be made about Figure 4:

- The individual FTP-composite PM emissions were in the range of 48 to 88 percent below the Tier 2, Bin 5 limit of 6.25 mg/km
- Fuel B, the highest volatility fuel, showed the lowest PM emissions among all the fuels tested. For the FTP-composite, the average PM emissions with Fuel B were 88 percent lower than the Tier 2 Bin 5 limit.
- Fuel C, the lowest volatility fuel, showed the highest PM emissions among all the fuels tested. For the FTP-composite, the average PM emissions with Fuel C were 55 percent lower than the Tier 2, Bin 5 limit.
- For Phase 1 of the FTP, the average PM emissions with Fuel C were 12 percent higher than Tier 2, Bin 5 limit.
- For the US06, the average PM emissions with Fuel C were 1.8 times the Tier 2, Bin 5 limit for the FTP.
- For all the fuels, the cold-start phase of the FTP-75, Phase 1, shows much higher PM emissions than Phase 2, and higher emissions than the hot-start identical phase, Phase 3.

The choice of fuel can result in an increase or decrease in PM emissions. One expects Fuel C to result in the lowest PM emissions due to the presence of oxygen in the fuel. However, other fuel properties such as fuel volatility played a more important role than the presence of oxygen in the fuel. The presence of oxygen in the fuel should result in lower PM if the base-fuel properties were similar [24]. While the vehicle met the respective PM standard, the PM mass emissions were still a factor of 10 higher than the recently reported [25] PM emissions of LEV II gasoline vehicles equipped with PFI engines, and it was also higher than LEV I vehicles using PFI engines [25].

In relation to CARB LEV III proposed standard of 3.8 mg/km by 2014 and 1.9 mg/km by 2017 using the FTP-75 cycle, this vehicle meets both standards with all fuels, as shown in Figure 4, except with Fuel C for the 2017 requirement. Thus, this current GDI technology seems to be able to meet future CARB PM standard with very minor modification to its PM emissions performance.