

Particulate Emissions for LEV II Light-Duty Gasoline Direct Injection Vehicles

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ABSTRACT

Since the mid-1990s, light-duty vehicles equipped with gasoline direct injection (GDI) engines have been added to the vehicle fleet in increasing numbers. Compared to conventional port fuel injection (PFI) engines, GDI engines provide higher power output for the same size engine, higher fuel efficiency, and lower carbon dioxide (CO₂) emissions. Due to the paucity of particulate matter (PM) emission data for light-duty gasoline vehicles in general and the increasing interest in these emissions relative to climate and air quality concerns, it is important to investigate PM emissions from current-generation GDI technologies. In this study, nine 2007-2010 light-duty GDI vehicles equipped with either wall-guided or spray-guided fuel injection systems were tested using California commercial gasoline fuel containing six percent ethanol by volume. Criteria pollutants including gaseous and PM emissions were measured over the Federal Test Procedure (FTP) transient test cycle. Two real-time particle measurement systems were utilized to measure solid and total particle number emissions.

Test results show that PM emissions for first generation GDI vehicles tested are significantly higher than PFI vehicles certified to California Low Emission Vehicle (LEV) II standards. In phase 1 of the FTP cycle during engine cold-start, PM mass emissions for the nine GDI vehicles ranged from 4 to 35 mg/mi, with an average of 14 mg/mi. The average FTP weighted PM emissions for these GDI vehicles are 10 times higher than LEV II PFI vehicles tested previously [4]. Over the FTP cycle, particle size distribution is bi-modal for the spray-guided GDI vehicle, and accumulation mode particles dominate particle emissions for the wall-guided GDI vehicle.

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INTRODUCTION

Due to its harmful effects on the environment and human health, PM emitted in vehicle exhaust is one of the criteria pollutants regulated under Federal and California emission regulations [1, 2]. Previous studies have shown that PM emissions from light-duty gasoline vehicles equipped with PFI engines are very low when compared to conventional diesel powered vehicles, and are only 10% of the current Federal and California PM emission standards [3, 4]. The PFI vehicles tested were certified to California LEV II emission standards. However, in response to regulations in the U.S. and around the world that demand lower greenhouse gases emissions from mobile sources, advanced engine technologies such as GDI engines have gained popularity with consumers and car makers. With a diesel-like fuel injection system, GDI engines deliver higher power output, improved fuel economy, and lower carbon dioxide emissions when compared with PFI engines. Since the mid-90s, light-duty (LD) gasoline vehicles equipped with GDI engines have

been added to the light-duty vehicle fleet in increasing numbers. Figure 1 shows the trend of GDI engine families certified and vehicles sold in California between 2003 and 2008. During a recent past five-year period, the number GDI engine families certified increased from 1 to 33. The growth of GDI vehicles is expected to continue to increase.

In a conventional PFI engine, fuel is sprayed into the intake manifold and mixed with air during the intake stroke. The fuel and air mixture is then drawn into the combustion chamber of each cylinder and further mixed during the compression stroke. In a GDI engine, highly pressurized fuel is injected directly into the combustion chamber at or near the end of the compression stroke, or during the intake stroke. Wall-guided and spray-guided are the two dominant fuel injection techniques employed in modern GDI engines. For wall-guided fuel injection, fuel injectors are mounted at an angle in the cylinder head. Injected fuel is swirled around depending mainly on the air motion in the cylinder. Swirl is induced to improve fuel-air mixture formation and

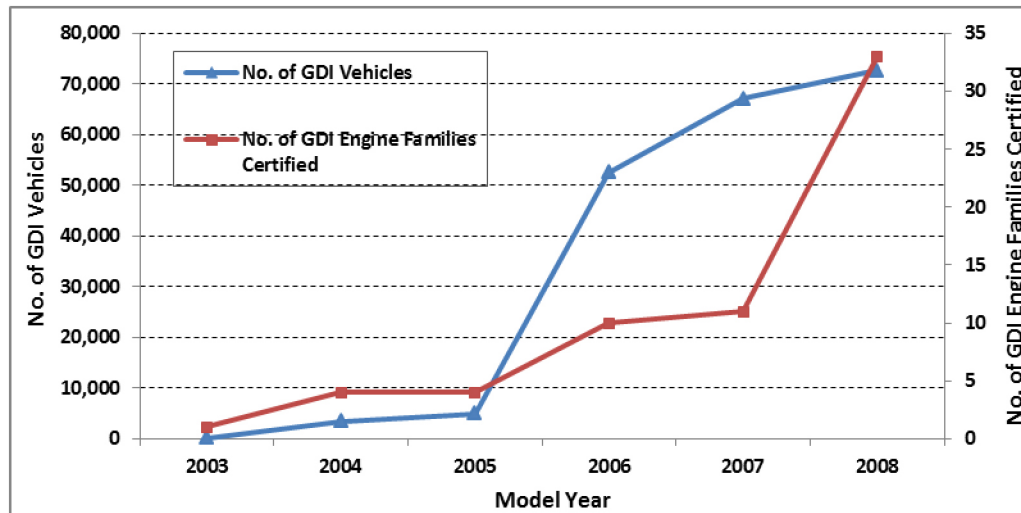


Figure 1. Gasoline Direct Injection Engine and Vehicle Market Trend in California (*CARB's Certification Database)

subsequent combustion. For spray-guided fuel injection, fuel injectors are mounted vertically at center top of the cylinder head. Fuel is injected near the sparkplug so the combustible mixture is brought to the sparkplug with accurate timing. Due to its unique fuel injection process, homogeneous mixing of air and fuel may be more difficult for both wall-guided and spray-guided injection compared to PFI engines.

Historically, PM emissions from light-duty PFI gasoline vehicles have generally been well below the Federal and California PM emissions standards (currently 10 mg/mi), and therefore PM emission measurements are not required for vehicle confirmatory testing [4]. However, various studies investigated PM emissions from GDI technologies and reported elevated PM and particle number (PN) emissions [5, 6, 7]. For example, Braisher *et al.* reported that GDI vehicles emitted higher PM and PN emissions than that of a PFI vehicle [5]. PM emissions for GDI vehicles were over 30 times greater than PFI vehicles. Solid PN emissions for a wall-guided, stratified charge GDI vehicle were one order of magnitude greater than the spray-guided, homogeneous charge GDI vehicle, and over two orders of magnitude greater than the PFI vehicle. Factors leading to higher PM emissions from GDI engines may include reduced time available for homogeneous mixing of air and fuel mixture and increased incidence of fuel impingement on the surfaces of the piston crown, valves and combustion chamber [8]. While GDI technologies provide promising benefits, it is important that PM emissions from GDI engines are investigated and characterized so that benefits of the GDI technologies are not over shadowed by an increase in PM emissions.

In this study, particulate mass emissions from a group of nine late model light-duty GDI vehicles and one PFI vehicle were tested over the FTP test cycle. In addition, real-time total and solid particle number emissions were measured, as

well as particle size distributions for two GDI vehicles and one PFI vehicle.

EXPERIMENTAL SETUP

Vehicles were tested for gaseous and particulate emissions at the California Air Resources Board's (ARB) Haagen-Smit Laboratory Test Cell 7. Test Cell 7 is a light-duty vehicle testing laboratory built to meet the Code of Federal Regulations (CFR) for gaseous and PM emission testing. It is equipped with a 48" single roll chassis dynamometer and a Constant Volume Sampler (CVS) with a 10" dilution tunnel.

TEST VEHICLES

A total of nine GDI vehicles was selected for testing. These vehicles were 2007-2010 light-duty vehicles certified to California LEV II emission standards. Of the nine test vehicles, seven were equipped with wall-guided direct injection (WGDI) and two were equipped with spray-guided direct injection (SGDI). In addition to GDI vehicles, a 2009 LEV II certified PFI vehicle was tested for comparison. Vehicle specifications are listed in Table 1.

TEST CYCLE AND TEST FUEL

All vehicles were tested over the Federal Test Procedure cycle.

The test fuel was California Phase 3 commercial summer fuel containing 6% ethanol by volume (E6). The test fuel was analyzed in-house and fuel properties are listed in Table 2.

PARTICULATE MASS EMISSION SAMPLING

Particulate mass emissions were measured from the CVS dilution tunnel. PM sampling system and filter weighing procedures have been described previously [4]. CVS flow rates ranged from 350 to 650 scfm for this study. Forty-seven

Table 1. Test Vehicle Specifications

Fuel Injection Type	Vehicle No.	Model Year	No. of Cylinder/ Engine Disp. (L)	Vehicle Type	Emission Category	Odometer (mi)
Wall-guided	WGDI-1	2009	V6 / 3.6	LDT	ULEV II	11309
	WGDI-2	2008	L6 / 3.5	PC	ULEV II	11035
	WGDI-3	2009	L4 / 2.3	PC	ULEV II	858
	WGDI-4	2007	L4 / 2.0	PC	ULEV II	20780
	WGDI-5	2009	Flat 6 / 3.8	PC	ULEV II	124012
	WGDI-6	2009	L4 / 2.0	PC	PZEV	2744
	WGDI-7	2010	L4 / 2.0	PC	PZEV	4000
Spray-guided	SGDI-1	2009	L6 / 3.0	PC	ULEV II	2019
	SGDI-2	2009	V8 / 4.4	PC	ULEV II	4000
PFI	PFI	2009	L4 / 2.5	PC	PZEV	28725

Table 2. Test Fuel Properties

Fuel Property	Commercial E6 Summer Fuel	Test Method
Oxygenate (vol %)	5.65 Ethanol	ASTM 4815, GC/FID
Total Oxygen (mass %)	2.09	ASTM 4815, GC/FID
Benzene (vol %)	0.57	ASTM D5580, GC/FID
Total Aromatics (vol %)	23.72	ASTM D5580, GC/FID
RVP, psi	6.73	ASTM D5191
Distillation (°F)		
T10	136	ASTM D86
T50	212	ASTM D86
T90	312	ASTM D86
Sulfur (ppm by wt)	8.1	ASTM 5453, ANTEK
Olefins (vol %)	5.2	ASTM 6550, SFC

(47) mm PTFE membrane filters were used for PM sample collection. Filters were weighed on a Mettler Toledo UMX2 microbalance which is housed in a Class 1000 clean room. Filter conditioning and weighing procedures complied with 40 CFR Part 1065 requirements [9]. Enhanced quality control and assurance procedures were implemented to ensure repeatable and accurate filter weighing. In addition to the NIST traceable metal weights and reference filters weighing requirements in the 40 CFR Part 1065, additional quality control and assurance procedures were implemented. These include weighing a replicate filter for each ten filters during a weighing session, and a trip blank filter was used alongside with sample filters during transport between test cell and the clean room. Tunnel blank tests are conducted as part of the weekly QC verifications of the PM sampling system. During a tunnel blank test, PM samples are extracted from the CVS tunnel PM sampling zone and the exhaust inlet to the tunnel is capped.

PARTICLE NUMBER EMISSIONS MEASUREMENT

Figure 2 shows a schematic of the particle number (PN) emission measurement setup. Diluted exhaust was drawn from the CVS tunnel through a PN sample probe located in the same sampling zone as the PM probe inside the CVS tunnel. A cyclone pre-classifier with a 50 percent cut point of 2.5 μm was connected to the PN probe outside the CVS tunnel. Total and solid particle number emissions in the diluted exhaust were measured using real-time particle instrumentation connected downstream of the cyclone pre-classifier. Total particles in the exhaust stream consist of volatile, semi-volatiles, and solid particles. No further preconditioning of the exhaust stream was applied for measuring total particles. On the other hand, solid particles are operationally defined by the European Particulate Measurement Program as particles that survived the heated dilution and evaporation process with particle sizes at or greater than 50 percent cut point of 23 nm in mobility diameter.

Total particles were measured with a fast response Engine Exhaust Particle Sizer (EEPS) spectrometer from TSI.