

Evaluation of Solid Particle Emissions from Hybrid and Conventional Gasoline Vehicles

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ABSTRACT

Solid particle emissions from a modern gasoline hybrid electrical vehicle (HEV) and a conventional gasoline vehicle were studied under diverse transient drive cycles on a chassis dynamometer.

It is found that solid particle emissions from the conventional gasoline vehicle which has a 3.8-liter engine are sensitive to vehicle temperatures. Over 90% of solid particles are emitted during the first 250 seconds of transient cycles. Spikes for solid particle emissions from the HEV during a transient cycle are mainly caused by engine starts, hard accelerations after engine starts, and the engine running harder at high vehicle speeds. The engine and vehicle temperature status on the HEV doesn't show a strong correlation to the solid particle emission.

While the conventional gasoline vehicle is cold, it emits over 2 times less solid particles than the HEV although it is larger and has heavier curb weight; and, while it is fully warmed up, it emits over 30 times less solid particles than the HEV. It is likely that frequent engine starts and a relatively higher percentage of maximum engine torque and power caused by engine downsize are contributing factors to increasing solid particle emissions from the HEV.

INTRODUCTION

The solid particle is one of the main components of the soot emitted from internal combustion engines. The soot causes adverse environmental and human health issues. It contributes to global warming [1]. It is a carcinogenic substance and causes diseases affecting the human respiratory system [2]. The US Environmental Protection Agency (EPA) confirmed that engine exhaust increases mortality and

morbidity. Therefore, it is necessary to reduce soot emissions from combustion engines and vehicles.

On-highway diesel engines and vehicles were major sources of the soot particle emissions. A stringent emission standard for on-highway heavy-duty diesel engines has been in effect since 2007 in the USA. And, some other similar standards have been enforced at other parts of the world. These emission standards cut roughly 90% of diesel particulate matter (PM) emissions from the previous emission standards. It is likely that the fraction of the on-road PM emitted from gasoline vehicles may be increased significantly in that strict PM emission regulations have been applied for diesel vehicles and reduces the on-road PM largely.

To further reduce PM emission from on-road vehicles, it is critical to reduce PM emissions from gasoline vehicles in the future. Studies found that new engine technologies reduce vehicle CO₂ emissions significantly but may increase PM emissions from gasoline vehicles simultaneously [3, 4, 5]. To reduce PM emissions from light and medium-duty vehicles and not increase emissions from future engine technologies, California Air Resource Board (CARB) proposed a Low Emission Vehicle (LEV) III emission standard. PM emissions for the LEV III are reduced greatly from the current LEV II emission standard, and are proposed to be measured either by the gravimetric mass approach or solid particle number approach. Moreover, Black Carbon (BC) which is the main component of the soot is proposed to be added for the CO₂ equivalency calculation [1]. The LEV III standard will be phased-in in 2014 and 2017 for 2014-2022 model years.

The proposed LEV III standard is the first regulatory proposal to allow the PM emission being certified in particle number in the United States. The Solid Particle Counting System (SPCS) which is similar to that recommended by

European Particle Measurement Programme (PMP) may be used to measure number emissions from LEV III vehicles although the PMP approach may neglect a large number of solid particles smaller than 23 nm [6, 7, 8, 9]. Comparing the number measurement to the mass measurement based on the gravimetric filter, it should be noted that the number measurement has advantages such as good sensitivity, being a real-time measurement system, wide dynamic range, etc.

In this study, we evaluated solid particle emissions from a conventional gasoline vehicle and a hybrid electrical vehicle (HEV) powered with an advance gasoline engine on a chassis dynamometer. One objective of the study is to investigate the feasibility of the PMP compliance solid particle counting system for the solid particle number measurement from gasoline vehicles. The other objective for this study is to understand characteristics of solid particle emissions from gasoline vehicles. Findings from this study are discussed in the paper.

EXPERIMENTAL SETUP

VEHICLES AND CVS SETUP

Two gasoline vehicles which are made by different car manufacturers were evaluated in this study. California phase II reformulated fuel was used on both vehicles. Vehicle A is a conventional gasoline vehicle. It is a 1999 model year mini-van, and has 3.8-liter gasoline engine operated with the conventional Otto engine cycle. Vehicle B is a gasoline powered hybrid electrical vehicle. It is a 2009 model year HEV, and has a 1.5-liter gasoline engine which is operated with the Atkinson engine cycle. The Atkinson engine cycle is an overexpansion engine cycle. It allows the engine to expand completely in expansion stroke to reduce engine pump loss. The engine operated with the Atkinson cycle has larger expansion ratio than engine compression ratio. It has good fuel efficiencies but low power density.

Gasoline engines in both vehicles have the Sequential Fuel Injection (SFI) system. The curb weight of Vehicle A is about 900 kilograms more than that of Vehicle B. [Table 1](#) is the summary for both vehicles.

Two drive cycles, Federal Test Procedure 72 (FTP 72) and Highway Fuel Economy Transient Cycle (HWFET), were operated on those vehicles. For the drive cycle FTP 72, it is designed to simulate urban drive conditions, and has relatively lower speeds and slower acceleration rates. The drive cycle HWFET is designed to simulate highway drive conditions. Thus, it has higher drive speeds, and less acceleration and deceleration events. For all tests with the HWFET cycle in this study, two HWFET cycles were operated in series in a single test.

Table 1. Summary for two vehicles in the study

	Vehicle A	Vehicle B
Vehicle type	Conventional gasoline mini-van, auto transmission	Gasoline hybrid electrical passenger car, auto transmission
Fuel	California phase II reformulated	California phase II reformulated
Model year	1999	2009
Curb weight (kg)	≈ 2700	≈ 1800
Engine cycle	Conventional Otto cycle	Atkinson cycle
Engine	6 cylinders, 3.8 l, SFI	4 cylinders, 1.5 l, SFI
Aftertreatment	Three-way catalyst	Three-way catalyst
Emission certification	California ULEV	California ULEV II

Vehicle exhausts were diluted with a CVS tunnel. A stainless steel transfer line connected the vehicle tailpipe to the inlet of the Remote Mix Tee (RMT) on the CVS system. It was insulated to minimize the heat transfer between the transfer line and the ambient air. A differential pressure transducer installed at the outlet of the transfer line measured the pressure difference between ambient air and the tailpipe. [Figure 1](#) presents the schematic for the experimental setup.

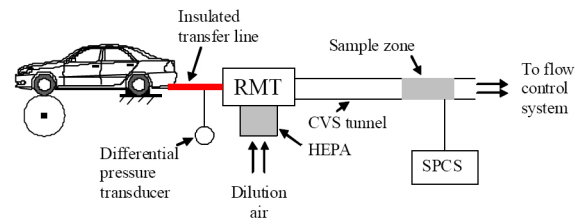


Figure 1. Schematic of the experimental setup

A two-wheel chassis dynamometer was used for vehicle tests. Front wheels of the tested vehicle were placed on the dynamometer, and rear wheels were fixed during the test. The HEV vehicle (Vehicle B) has a traction control function. To make the vehicle be operational in the whole speed range, the traction control function has to be disabled prior to the test start. Thus, the vehicle needs to be operated at the service mode. To switch this vehicle from the regular mode to the service mode, it may take 30 to 90 seconds. For the conventional gasoline vehicle (Vehicle A), the vehicle can be operated in the whole speed range without switching drive modes.

ENGINE STATUS ON THE HEV

For the HEV, the vehicle is driven by either electric motors or the gasoline engine or both the gasoline engine and electric motors. Drive speeds, battery status, etc. determine the

operation mode of the HEV. To understand particle emissions from Vehicle B, it is necessary to monitor the engine status. Communicating to the OBD system or engine ECU with a scanning tool is an approach to be used commonly for obtaining the engine status. However, in this study, we weren't able to access the vehicle OBD system for all tests. Thus, other approaches need to be developed to identify the engine status without modifying the existing CVS tunnel and testing equipments.

As shown in [figure 1](#), the tailpipe pressure for all HEV tests was recorded in a one Hertz data rate. It was compared with the engine speed obtained from the OBD system. [Figure 2](#) shows engine speeds and tailpipe pressures as a function of the test time during two FTP 72 cycles. Small vacuum pressures were detected in the tailpipe and caused by suction from the CVS tunnel. It is found that pressure differences between the tailpipe and ambient air stay at the baseline when the engine in Vehicle B isn't running. The absolute value of the pressure difference is smaller when the engine speed is higher, and it is larger when the engine speed is lower. Spikes for the pressure difference are correlated to engine starts and off. This finding may suggest that it may be an effective approach to obtain the engine status by monitoring exhaust tailpipe pressures.

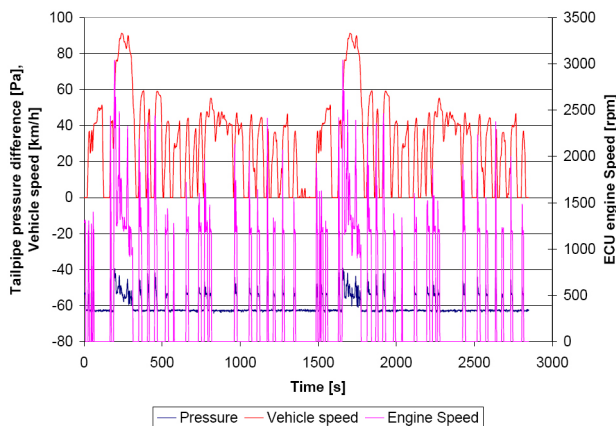


Figure 2. Tailpipe pressure difference and engine speed as a function of the test time on Vehicle B (FTP 72 test)

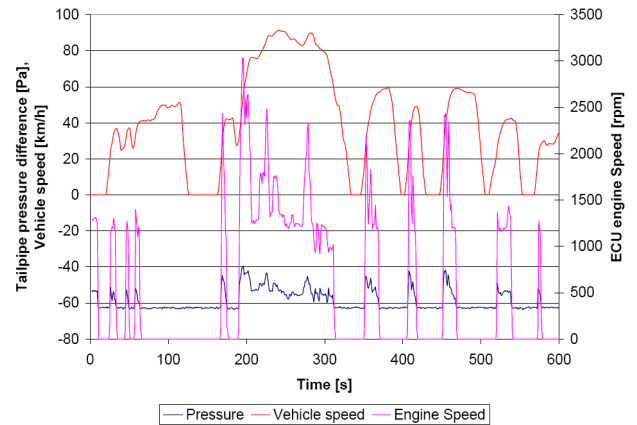


Figure 3. Tailpipe pressure difference and engine speed as a function of the test time on Vehicle B (FTP 72 test, 0 - 600 s)

[Figure 3](#) presents the same data but in 0 to 600 seconds. Generally, the engine doesn't run while the HEV speed is zero or low. However, it is observed from [figure 3](#) that the engine was running and the pressure difference is higher than the baseline when the vehicle speed is zero at the beginning of the test. This is caused by switching vehicle modes from a regular drive mode to a service mode to disable the traction control function prior to the test start. If the traction control function is alive on this vehicle, the vehicle cannot be accelerated to desired high vehicle speeds due to big speed differences of front wheels and rear wheels on the two-wheel chassis dynamometer. Engineers of the vehicle manufacturer suggested that the vehicle emission should be the same under two different drive modes (regular drive mode and service drive mode).

To change the drive mode, the vehicle power needs to be turned on. The engine is started even though the vehicle speed is zero. It is possible that this is a strategy being used by the car manufacturer to warm up the aftertreatment system to reduce emissions from the HEV. As it is mentioned above, it takes 30 to 90 seconds to switch the operation mode prior to the test start. Thus, for some cold start tests on the Vehicle B, emissions for 30 to 90 seconds weren't collected and recorded.

INSTRUMENT

Horiba MEXA-2000SPCS was used in this study. It measures solid particle number emissions from vehicles in real-time. It took sample from the sample zone on the CVS tunnel. It is designed based on the Horiba prototype solid particle counting system (SPCS) [6]. A wide range continuous diluter (WRCD) is used as the particle number diluter 1 (PND1) and gives accurate and wide dilution ratios for the PND1. The particle number diluter 2 (PND2) in the MEXA-2000SPCS is operated at a constant dilution ratio. The MEXA-2000SPCS is fully automated, and conforms to all requirements