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Particle number emission factors and volatile fraction of particles emitted from on-road gasoline direct injection passenger vehicles

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HIGHLIGHTS

- Particle emission rates are proposed for on-road gasoline direct injection vehicles.
- More semi-volatile particles are produced during initial stages of the acceleration.
- The emission factor is higher in urban driving cycles compared to highway cycles.
- Emission rates increase as tractive power increases for the entire range of speed.

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ABSTRACT

Particle number emission factors, and the volatility of the particles, are measured on-road for five gasoline direct injection vehicles over a wide range of operating conditions including urban and highway driving conditions. Two condensation particle counters (CPC) were used to measure nascent and non-volatile (thermodenuded) particle concentrations for transient urban and highway tests. To measure the non-volatile concentration and also the volatility of the particles, a thermodenuder was employed to remove the semi-volatile material from the aerosol sample. Rapid accelerations were also studied in more detail by measuring the particle size distributions in real-time using a differential mobility spectrometer (DMS). The ratio of semi-volatile particles to total particle number is generally higher during acceleration followed by the idle operating mode. The number emission factors (for particles larger than 2.5 nm) ranged between 5.46×10^{11}–3.50×10^{12}/km for freshly emitted (nascent) particles and between 2.87×10^{11}–3.31×10^{12}/km for non-volatile (thermodenuded) particles. More particles per kilometer are produced during acceleration compared to cruise conditions where the non-volatile particle number emission factor for acceleration is 2.3 and 1.8 times higher than vehicle cruise for urban and highway driving cycles, respectively. Particle number emission factor models are also presented in terms of particle emission rate as a function of vehicle tractive power and also as a function of vehicle specific power as defined for the US Environmental Protection Agency's MOVES model.

1. Introduction

In recent years, gasoline direct injection (GDI) engines have been widely used on passenger vehicles and trucks. GDI engines have better fuel economy and higher power output compared to port fuel injection (PFI) gasoline engines, however, they produce more particulate emissions in terms of both number and mass (Zhao et al., 1999). Concerns about the health effects of the particles emitted from these vehicles have resulted in particle mass emissions limits, and more recently, particle number emission limits defined in the Euro 6 standard for GDI vehicles (Commission Regulation (EC) No 459/2012). According to the standard, emission factors are measured on a chassis dynamometer using standard driving cycles. Only non-volatile particles larger than 23 nm are included in the particle number limit according to the particle measurement programme (PMP).

Several studies have been done on chassis dynamometers to examine the effect of air-fuel mixing method (Choi et al., 2012), gasoline particulate filters (Chan et al., 2012; Mamakos et al., 2013), fuel volatility (Khalek et al., 2010; Liang et al., 2013) and ambient temperature (Chan et al., 2013; Mamakos et al., 2013) on particulate emissions from GDI vehicles. However, it has been shown that

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particle emission factors measured from vehicles on the road, under real-world driving conditions, can differ from laboratory tests due to differences in vehicle power requirements, sampling systems, and background particle concentration (Li et al., 2013). Moreover, it has been shown that on-road gas phase emissions are also substantially different to laboratory tests (Pielecha et al., 2010; Weiss et al., 2012). For instance, Weiss et al. (2012) reported that diesel cars that pass emission tests using the New European Driving Cycle (NEDC) might produce more NO_X than the emission limits on the roads and they suggested that complementary test procedures which are more representative of real world driving conditions should be developed. Several options, including portable emissions measurement systems (PEMS), may be introduced to quantify emissions since a single driving cycle is not able to cover a wide range of driving conditions (Vlachos et al., 2014; May et al., 2014).

The U.S. Environmental Protection Agency's (EPA) MOtor Vehicle Emissions Simulator (MOVES) is used for air quality conformity determination and State Implementation Plans outside of California. In locations where the National Ambient Air Quality Standards are not met, MOVES is used to determine whether the transportation emissions projected for that location are within the emission limits established by the State Implementation Plan. MOVES is used to model the direct emissions of $PM_{2.5}$ and PM_{10}, and certain precursors (NO_X, VOC, NH_3, and SO_2). The particulate matter estimates provided by MOVES are on a mass basis; there is no estimate of the number of particles that are emitted. Since particle emissions are currently regulated in terms of number in Europe (and perhaps in the US in new regulatory standards), modeling particle numbers in MOVES is worthwhile.

Particle emissions from on-road vehicles can be measured on the roadside where measurement equipment is placed near the road and samples are taken from the ambient air from passing vehicles (e.g. Jayaratne et al., 2008; Hak et al., 2009). Emission measurement devices can also be placed inside a vehicle and a sample taken from the plume behind vehicles by tracking them on the road (e.g. Minoura et al., 2009; Fruin et al., 2008; Wang et al., 2011). Finally, a sample can be drawn directly from the tailpipe of individual vehicles while the vehicles are driven on the road (Li et al., 2013). The advantage of the last method is that the particle emission factors can be determined as a function of vehicle conditions (e.g. vehicle tractive power and speed) and the emissions from other sources on or near the road do not affect the measurement. However, since the measurement devices must be placed in a small space the instrument options are limited, and it is difficult to test a large number of vehicles.

In this study, particle number emissions are examined for several GDI vehicles on urban and highway roads. The volatility of the particles from GDI vehicles are also studied in real-world driving conditions. The main goal of this study is to quantify GDI particulate emission rates in the real world and to describe how particle number emissions vary during different driving conditions for in-use GDI vehicles. Additionally, two power-based models for particle number emission estimation are derived from the real-world emission data which can be used in emission simulators such as MOVES to estimate the particle number emissions for in-use GDI vehicles.

2. Experimental methods

2.1. Test vehicles and fuels

Test vehicles of model year 2012–2014 were selected from the in-use fleet. The specifications of the evaluated vehicles are shown in the Supplementary information. The test fuel was retail gasoline fuel. The vehicles included three passenger vehicles and two SUVs which were all two wheel drive. The SUVs are the same make but different model years. The vehicles' engine power ranged between 160 and 178 hp. The engines were all naturally aspirated except for vehicle 3 which had a turbo-charged engine. The vehicles were in normal operating condition. Their mileage varied from 17,000 to 85,000 km. All vehicles were equipped with three-way catalysts.

2.2. Test cycles

The measurements were conducted on highways and urban environments in the city of Edmonton, Canada. The ambient temperature was approximately −10 °C and all tests were conducted after the vehicle was fully warmed up. Previously, it has been shown that particle mass and number emission factors are not significantly affected by the ambient temperature when the engine is warm (Mamakos et al., 2013; Chan et al., 2013).

2.2.1. Urban and highway on-road tests

For the urban tests, five different routes with a speed limit of 50–60 km/h were selected in order to cover a variety of driving conditions where all routes included similar proportions of idle, cruise, acceleration and deceleration as defined by Gao and Checkel (2007). The definitions for all four driving modes are summarized in Table 1.

The highway tests were conducted on two urban freeways where the speed limit was 80–100 km/h. Figs. 1 and 2 show examples of urban and highway driving cycles and the distribution of the four driving modes for vehicle 1. The modal distributions for all evaluated vehicles are presented in Table S2 in the supplementary information.

The average speed and energy intensity of the test cycles are reported in Table 2 and compared to common regulatory test cycles. As shown in the table, the average vehicle speed is higher during the urban and highway test cycles compared to the US-Federal test procedure (FTP) and highway fuel economy test cycle (HWFET), respectively. Higher vehicle speed, as well as more aggressive accelerations, are reasons for higher energy intensity during on-road driving in comparison with the FTP and HWFET cycles. The energy intensity of the NEDC is similar to the values for the on-road driving, although the average speed is higher in the NEDC. Energy intensity of the on-road driving cycles are within 8% of each other, which shows that the on-road driving patterns are very similar in terms of tractive energy and consequently the results from different vehicles are comparable. Furthermore, the energy intensity of each driving mode (e.g. highway cruise) is also very similar as shown in Table S2.

2.2.2. Full throttle acceleration tests

Particle size distributions were also measured in real-time during acceleration tests. The acceleration tests consisted of accelerating the vehicle from 0 to 50 km/h using a fully open throttle.

Table 1
Definition of different driving modes.

Driving mode	Vehicle speed (m/s)	Vehicle acceleration (m/s^2)
Idle	≤3	$-0.1 \le a \le 0.1$
Cruise	>3	$-0.1 \le a \le 0.1$
Acceleration	–	$a > 0.1$
Deceleration	–	$a < -0.1$