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Exhaust particles of modern gasoline vehicles: A laboratory and an on-road study

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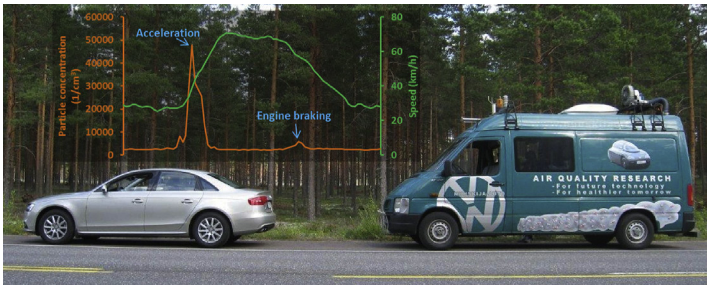
HIGHLIGHTS

- Four types of exhaust particles were observed in the exhaust of GDI vehicles.
- Nonvolatile particle size distribution consisted of two modes.
- GDI vehicles emitted particles also during engine braking conditions.
- Semivolatile nucleation particles were in the exhaust at high load conditions.
- Particle emissions were in real-world qualitatively similar as in the laboratory.

GRAPHICAL ABSTRACT



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ABSTRACT

Vehicle technology development and upcoming particle emission limits have increased the need for detailed analyses of particle emissions of vehicles using gasoline direct injection (GDI) techniques. In this paper the particle emission characteristics of modern GDI passenger cars were studied in a laboratory and on the road, with the focus on exhaust particle number emissions, size distributions, volatility and morphology. Both during acceleration and steady conditions the number size distribution of nonvolatile exhaust particles consisted of two modes, one with mean particle size below 30 nm and the other with mean particle size approximately 70 nm. Results indicate that both of these particles modes consisted of soot but with different morphologies. Both in laboratory and on the road, significant emissions of exhaust particles were observed also during decelerations conducted by engine braking. These particles are most likely originating from lubricant oil ash components. The semivolatile nucleation particles were observed in the laboratory experiments at high engine load conditions. Thus, in general, the study indicates that a modern gasoline vehicle can emit four distinctive types of exhaust particles. The differences in particle characteristics and formation should be taken into account in the development of emission control strategies and technologies and, on the other hand, in the assessment of the impact of particle emissions on environment and human health.

1. Introduction

In the development of gasoline passenger cars the increased attention on global warming and the greenhouse gas emissions has

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led to a widespread use of gasoline direct injection (GDI) engines (Alkidas, 2007). In general, GDI technologies offer better fuel economy compared to port fuel technologies and thus lower emissions of CO_2. Also the use of alternative fuels is increasing, both in diesel and in gasoline vehicle fleets. New technologies most likely affect both the regulated emissions like NO_x, hydrocarbons and particulate mass, and unregulated emissions like the amount or characteristics of emitted nanoparticles. The changes in the emissions other than CO_2 can be either advantageous or harmful (see e.g. Heikkilä et al. (2009) and Lähde et al. (2011)). In the case of the GDI technology, the direct fuel injection can increase the risk for increased particulate emission due to incomplete fuel volatilization, partially fuel rich zones, and impingement of fuel to piston and cylinder surfaces (Maricq et al., 1999b; Bonandrini et al., 2012; Sementa et al., 2012).

Particle emissions of vehicles are restricted by emission standards which have significant variation depending on the country. In the US, since 2004 same standards have been applied to vehicles regardless of the fuel and thus the limits for the particulate mass emission have covered also the gasoline vehicles. In the European Union, a particulate mass emission limit for direct injection gasoline engines took effect in 2009 (Euro 5), and the first restrictions for particle number emissions will come into effect in 2014 (Euro 6). Thus, globally the particle emission limitations for gasoline vehicles are under strong development (Dieselnet, 2014). Especially the European particle number emission limit for GDI engines may enforce the vehicle industry to change their emission reduction technologies and methods.

The relative importance of particle emissions of gasoline vehicles has increased because of forthcoming particle emission regulations, and because port-fuel injection (PFI) has been widely replaced by GDI technologies. On the other hand, the significance of gasoline particle emissions is now higher because of low emission level of modern diesel passenger cars. The fraction of the GDI vehicle in vehicle fleet is forecasted to grow significantly during the next years (CARB, 2010). It is known that the GDI technologies offer lower fuel consumption and NO_x emission (Alkidas, 2007). However, the knowledge related to gasoline vehicle exhaust particles is not at the same level as the knowledge of diesel exhaust particles. The disadvantage of GDI technologies is an increase in particle number emission compared to PFI technology (Aakko and Nylund, 2003; Mohr et al., 2006; Braisher et al., 2010). If compared to diesel exhaust particle number concentrations, the GDI exhaust number concentrations are typically significantly lower than the concentration of diesel engine exhaust particles without a diesel particulate filter (DPF) but higher than concentrations with a DPF (Mathis et al., 2005). The study of Maricq et al. (2012), conducted for exhaust particles of a light-duty truck with a GDI engine, indicates that the particulate matter emission of a GDI engine is dominated by elemental carbon (EC) whereas organic carbon (OC) constitutes only a small fraction. Several studies (e.g. Maricq et al., 1999a; Harris and Maricq, 2001; Khalek et al., 2010) indicate that the GDI exhaust particles are (in number) mainly in particle sizes below 100 nm. In addition, the size distribution has been observed to be bi-modal (Barone et al., 2012; Sementa et al., 2012; Sgro et al., 2012; Maricq et al., 1999a). The mode of smaller particles (mean particle size between 10 and 20 nm) has previously been observed to consist of spherical amorphous carbon (Sgro et al., 2012; Barone et al., 2012) and to be partly charged indicating their formation at high temperatures (Sgro et al., 2012). Although the volatility characteristics of the smallest particles have not been inspected in all the previous studies, some studies (e.g. Mathis et al., 2005; Li et al., 2013) indicate that the GDI exhaust can contain semivolatile nucleation particles too. In contrast to small amorphous carbon particles (Sgro et al., 2012), and in general, nonvolatile core particles formed during diesel combustion (e.g. Lähde et al., 2009), the entirely semivolatile nucleation mode is formed in the atmospheric dilution and cooling process of the diesel exhaust (Rönkkö et al., 2006; Lähde et al., 2009).

In this study the focus is on the physical characteristics and emissions of particles emitted by modern gasoline passenger cars. Results of particle number emission, size distribution, volatility and morphology are presented. Measurements were conducted not only on a chassis dynamometer in the laboratory but also on the road. On-road studies provide a real-world driving environment and make possible to gather information from real-world exhaust dilution and dispersion processes in the atmosphere. For instance, for diesel vehicles the exhaust nanoparticle concentrations have been reported to be affected by sampling and dilution parameters used in the laboratory study (e.g. Rönkkö et al., 2006). Thus, to get comprehensive and real information on exhaust particles also real-world studies are required. Also, real-world studies produce the most relevant information from the viewpoint of human exposure on particle emission. It should be noted that in the future also the vehicle emission legislation may shift towards the real-world measurements, e.g. due to the requirements for portable emission measurement systems.

2. Experimental

2.1. Experimental procedure on chassis dynamometer

The test vehicle was a modern gasoline passenger car made in 2011 (vehicle 1). The GDI engine of the test vehicle (1.8 l displacement) was turbocharged and used fuel stratified injection below about 3000 rpm. In the stratified mode, the global average air to fuel ratio is stoichiometric but due to stratified operation there are local rich and lean zones in the combustion chamber. The exhaust aftertreatment was performed with a three-way catalytic converter (TWC). The engine ran with low sulfur (<10 mg/kg) 95-octane gasoline–ethanol blend fuel where ethanol concentration was below 10%. The lubricant oil was viscosity grade 5W-30 which contained phosphorus, sulfur, calcium and zinc, 900 mg/kg, 2780 mg/kg, 3200 mg/kg and 920 mg/kg, respectively.

Experimental routine consisted of test cycles and different engine load steady points controlled by the chassis roll resistance. Before the test series, the vehicle was warmed up during a New European Driving Cycle (NEDC). During this warm-up run the emissions were also measured. The NEDC test cycle was repeated in total eight times. Selected steady-state tests were driven at the wheel speed of 80 km/h in fifth gear and at wheel powers 5 kW, 10 kW and 20 kW, controlled by the chassis roll brake.

The exhaust gas sample was extracted from an exhaust transfer tube from a sampling point that located 2 m after the tailpipe end. Exhaust dilution was conducted using a partial exhaust flow dilution system (Ntziachristos et al., 2004) consisting of a porous tube diluter, a short aging chamber and a secondary diluter. The dilution system has been observed to mimic relatively well the real-world cooling and dilution processes, especially from the viewpoint of exhaust nanoparticle formation (Rönkkö et al., 2006; Keskinen and Rönkkö, 2010). The primary dilution ratios of the porous tube diluter and secondary diluter (Dekati Diluter) were approximately 12 and 4.5, respectively. Both the primary dilution ratio and the total dilution ratio (~50) were calculated based on the CO_2 concentrations of the raw exhaust and diluted exhaust. After the secondary dilution the diluted exhaust sample was at room temperature of about 25 °C.

Particles were measured with an EEPS (Engine exhaust particle sizer, model 3090, TSI Inc.), an UCPC (Ultrafine condensation particle counter, TSI Inc. model 3025) and an ELPI (Electrical low