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Dilution effects on ultrafine particle emissions from Euro 5 and Euro 6 diesel and gasoline vehicles

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HIGHLIGHTS

- Dilution and temperature effects on particle number emission.
- Comparison between tailpipe and CVS for particle number emission.
- Over-emission of particles from the CVS because of nucleation, condensation and coagulation.
- Tailpipe measurement as a complementary method to the CVS for exhaust particle sampling.

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ABSTRACT

Dilution and temperature used during sampling of vehicle exhaust can modify particle number concentration and size distribution. Two experiments were performed on a chassis dynamometer to assess exhaust dilution and temperature on particle number and particle size distribution for Euro 5 and Euro 6 vehicles. In the first experiment, the effects of dilution (ratio from 8 to 4 000) and temperature (ranging from 50 °C to 150 °C) on particle quantification were investigated directly from tailpipe for a diesel and a gasoline Euro 5 vehicles. In the second experiment, particle emissions from Euro 6 diesel and gasoline vehicles directly sampled from the tailpipe were compared to the constant volume sampling (CVS) measurements under similar sampling conditions. Low primary dilutions (3–5) induced an increase in particle number concentration by a factor of 2 compared to high primary dilutions (12–20). Low dilution temperatures (50 °C) induced 1.4–3 times higher particle number concentration than high dilution temperatures (150 °C). For the Euro 6 gasoline vehicle with direct injection, constant volume sampling (CVS) particle number concentrations were higher than after the tailpipe by a factor of 6, 80 and 22 for Artemis urban, road and motorway, respectively. For the same vehicle, particle size distribution measured after the tailpipe was centred on 10 nm, and particles were smaller than the ones measured after CVS that was centred between 50 nm and 70 nm. The high particle concentration ($\approx 10^6$ #/cm^3) and the growth of diameter, measured in the CVS, highlighted aerosol transformations, such as nucleation, condensation and coagulation occurring in the sampling system and this might have biased the particle measurements.

1. Introduction

Vehicle exhaust emissions represent a major source of particle matter in urban environments. On regional and global scales, atmospheric particles play an important role in human health and climate change (Ning, 2010; Kulmala et al., 2000; Pope III, 2000). Particles emitted from diesel and gasoline engines are ultrafine particles with size ranges of 20–130 nm and 20–60 nm, respectively (Karjalainen et al., 2014; Morawska et al., 2008; Burtscher, 2005; Jamriska et al., 2004). The ultrafine particles represent only

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Abbreviations

G-DI	Gasoline with Direct Injection
DPF	Diesel Particulate Filter
Cat	Catalysed Filter
PMP	Particle Measurement Programme
CVS	Constant Volume Sampler
FPS	Fine Particle Sampler
NO_X	Nitrogen Oxides
NO_2	Nitrogen Dioxide
NO	Nitric Oxide
PN	Particle Number
CPC	Condensation Particle Counter
ELPI	Electrical Low Pressure Impactor
SMPS	Scanning Mobility Particle Sizer
FMPS	Fast Mobility Particle Sizer Spectrometer
HEPA	high-efficiency particulate air

0.1–10% of the total particulate mass, but it might represent more than 90% of the total particle number (Giechaskiel et al., 2010; Kittelson, 1998). Particle emission depends on the engine technology, fuel and aftertreatment devices. Liang et al. (2013) and Köhler (2013) showed that the gasoline direct injection (G-DI) technology induced an increase in the particle number concentration compared to the standard gasoline passenger cars. Moreover, the dilution process (dilution ratio, dilution gas temperature and sampling residence time) has been established as a factor influencing ultrafine particle formation (Manoukian et al., 2016; Wei et al., 2016; Ranjan et al., 2012; Fujitani et al., 2012; Mamakos and Martini, 2011; Grieshop et al., 2009a; Vouitsis et al., 2008; Rönkkö et al., 2006; Mathis et al., 2004). After the tailpipe, the exhaust undergoes high and fast atmospheric dilution ratio that could reach up from 1 000 to 4 000 in 1–3 s (Fujitani et al., 2012; Zhang and Wexler, 2004). The exhaust temperature (around 200 °C) decreases rapidly at ambient temperature level within few seconds after emission due to the high dilution ratio. The rapid decrease in temperature has significant implications in terms of thermodynamics of particles and semi-volatile compounds (Kim et al., 2016; Huang et al., 2014; May et al., 2013; Wang and Max Zhang, 2012; Kozawa et al., 2012; Mamakos and Martini, 2011; Casati et al., 2007; Morawska et al., 2008; Zhang et al., 2004) leading to a drastic change in particle number concentration and size distribution (Huang et al., 2014; Wang and Max Zhang, 2012; Uhrner et al., 2011; Grieshop et al., 2009b). Although several recent studies have focused on that issue, uncertainties still remain regarding the experimental determination of ultrafine particle emissions from vehicle exhaust and the impact of dilution and temperature during their sampling (Wei et al., 2016; Manoukian et al., 2016; Ranjan et al., 2012; Fujitani et al., 2012; Grieshop et al., 2009a).

Particle number concentration is measured through a specific protocol, derived from the Particle Measurement Program (PMP) through the full-flow Constant Volume Sampler (CVS). This protocol requires the removal of the volatile phase by the dilution stage (150 °C) and a heated tube (at 300–400 °C). The PMP approach only regulates the non-volatile fraction of particles in order to exclude the possible confounding of measurement data by low volatility hydrocarbons manifesting as a nucleation mode present below 20 nm that highly depends on the sampling conditions (Giechaskiel et al., 2008). In the atmosphere, the concentration of aerosols changes rapidly in the first seconds after emission with condensation phenomenon and presence of SVOCs, which strongly depend on the exhaust sampling (length of the sampling line, dilution factor, temperature, etc.) (Albriet et al., 2010). Several studies showed that the ultrafine particle number concentration directly measured from the tailpipe was significantly different than those from the CVS (Kim et al., 2016; Giechaskiel et al., 2010, 2007; Mathis et al., 2005). Giechaskiel et al. (2010) showed that deceleration (from 140 km/h to 120 km/h) induced a higher particle number concentration with higher mean diameter than acceleration (from 90 km/h to 120 km/h) with a Euro 3 diesel vehicle without particulate filter. This observation is in contrast with their previous work (Giechaskiel et al., 2007), which reported a lower particle number concentration during deceleration than during acceleration. This contradiction can be explained by differences in sampling systems. According to Giechaskiel et al. (2007), particles were sampled directly from the tailpipe, while in Giechaskiel et al. (2010), particles were sampled from the CVS. As mentioned by Giechaskiel et al. (2014), the CVS dilution tunnel has several disadvantages such as the inability to control the dilution ratio and the dilution temperature, a long sampling path and a long residence time. This dilution system favours nucleation, condensation and coagulation that could induce the new particle formation or the modification of the particle size distribution.

Based on this evidence, the particle measurement directly from the tailpipe was considered as a complementary sampling method to CVS in order to understand the sampling condition impacts on particle number concentration. This work aimed to investigate the impacts of dilution and temperature on particle emissions after a CVS tunnel system and directly from the tailpipe with Euro 5 and Euro 6 vehicles. Particle number and size distribution between the CVS and the tailpipe were compared under similar dilution conditions to investigate the processes occurring in the dilution tunnel with the Euro 6 G-DI vehicle. Finally, we discussed the nucleation, condensation and coagulation phenomena observed into the CVS dilution system.

2. Materials and methods

2.1. Vehicle characteristics

Four currently in-use vehicles were studied: a Euro 5 gasoline with direct injection system (G-DI), and Euro 5 diesel with catalysed particulate filter (DPF cat), a Euro 6 G-DI and a Euro 6 DPF cat. Technical characteristics of the tested vehicles are shown in Table 1. All the tested vehicles were private vehicles to be as representative as possible of the state of the current French fleet. All experiments were conducted using commercial fuel (sulphur content less than 10 ppm) pumped from the same petrol station to minimise variability of fuel composition and its impact on emissions.

Table 1
Technical characteristics of the tested vehicles.

Vehicle	No. 1	No. 2	No. 3	No. 4
Size class	1.2	1.5	1.0	1.5
Technology	G-DI[a]	Diesel	G-DI[a]	Diesel
Standard	Euro5	Euro5	Euro 6	Euro 6
Empty weight (kg)	1 320	1 090	864	1 087
Mileage (km)	25 844	87 073	2 164	4 700
Gearbox type	Manual (5)	Manual (5)	Manual (5)	Manual (5)
Registration date	27/02/2014	17/02/2012	11/12/2015	31/12/2015
Test date	31/03/2015	15/04/2015	29/03/2016	11/04/2016
Catalyst	Three-way	Oxidation	Three-way	Oxidation
Filter	No	Catalysed DPF[b]	No	Catalysed DPF[b]

[a] G-DI: Gasoline with direct injection system.
[b] DPF: Diesel Particulate Filter.