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Particulate emissions of a modern diesel passenger car under laboratory and real-world transient driving conditions

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ABSTRACT
Exhaust emissions from diesel vehicles are significant sources of air pollution. In this study, particle number emissions and size distributions of a modern Euro 5b-compliant diesel passenger car exhaust were measured under the NEDC and US06 standard cycles as well as during different transient driving cycles. The measurements were conducted on a chassis dynamometer; in addition, the transient cycles were repeated on-road by a chase method. Since the diesel particulate filter (DPF) removed practically all particles from the engine exhaust, it was by-passed during most of the measurements in order to determine effects of lubricant on the engine-out exhaust aerosol. Driving conditions and lubricant properties strongly affected exhaust emissions, especially the number emissions and volatility properties of particles. During acceleration and steady speeds particle emissions consisted of non-volatile soot particles mainly larger than ~50 nm independently of the lubricant used. Instead, during engine motoring particle number size distribution was bimodal with the modes peaking at ~10–20 nm and 100 nm. Thermal treatment indicated that the larger mode consisted of non-volatile particles, whereas the nanoparticles had a non-volatile core with volatile material condensed on the surfaces; approximately, 59–64% of the emitted nanoparticle evaporated. Since during engine braking the engine was not fueled, the origin of these particles is lubricant oil. The particle number emission factors over the different cycles varied from \(1.0 \times 10^{14}\) to \(1.3 \times 10^{15}\) #/km, and engine motoring related particle emissions contributed 12–65% of the total particle emissions. The results from the laboratory and on-road transient tests agreed well. According to authors' knowledge, high particle formation during engine braking under real-world driving conditions has not been reported from diesel passenger cars.

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1. Introduction

Traffic emissions are a major concern since the emission sources are in the proximity of population. Large European capitals such as London and Paris are struggling with air quality issues although much effort has been put into updating the vehicle fleets to comply with the latest emission standards. The adverse health effects of ambient particles or particulate matter (PM) are often associated with the concentrations of PM\(_{2.5}\) (mass concentration of particles smaller than 2.5 \(\mu\)m) or PM\(_{10}\) in the ambient air. In addition, black carbon (Janssen et al., 2011) and nanoparticles (Oberdörster et al., 2005) have been proposed as proxies for health risks. The World Health Organization (WHO) has classified diesel exhaust to be carcinogenic to humans (IARC, 2012). Especially, metals, metal oxides and specific semi-volatile organic compounds are considered as the hazardous material in the exhaust related particles. Nevertheless, epidemiological short-term studies on ultrafine particles (UFP) and mortality is still limited due to the lack of continuous monitoring of UFP, while there is abundantly ambient PM data available (Lanzinger et al., 2016 and references therein).

Vehicles increase particle concentrations in urban air by the emissions of primary particles, fresh exhaust PM, and aged exhaust PM (Rönkkö and Timonen, 2019; Maricq, 2007). Primary emissions are formed in the engine during the combustion processes, and the particle number size distribution may consist of two modes; an
accumulation mode in the size range of 30–100 nm and a core mode in sub-10 nm the size range (Rönnkö and Timonen, 2019). The accumulation mode particles are non-volatile soot agglomerates (Kittelson, 1998; Tobias et al., 2001). The core mode particles consist of amorphous carbonaceous compounds (Sgro et al., 2012; Seong et al., 2014) or metallic ash compounds from fuel and lubricant oil (Fushimi et al., 2011; Lähde et al., 2014). Furthermore, exhaust contains semi-volatile compounds that condense onto the surfaces of nonvolatile particles or nucleate forming new particles when the exhaust rapidly cools at the end of the tailpipe (Arnold et al., 2006, 2012; Rönnkö et al., 2013; Shi and Harrison, 1999; Tobias et al., 2001; Schneider et al., 2005; Khalek et al., 2003). The newly formed particles consist of volatile material such as water, sulfate and hydrocarbons. These particles are hereafter called fresh exhaust particles. Secondary organic aerosol (SOA) is formed in the atmosphere from gaseous precursors emitted by vehicles. Photochemistry converts these high vapor pressure organic compounds to low volatility compounds which can form SOA via gas-to-particle conversion (Kroll et al., 2012; Chirico et al., 2010).

Due to the hazardous health effects and climate-warming potential (e.g. Bond et al., 2013), the emissions of light-duty vehicles are regulated. As legislation has brought more stringent emission limits, measuring particle mass emissions was not enough to limit the impact of the fine particles in the air on health and climate. Therefore, the measurement of particulate number (PN) has been introduced in 2014, non-volatile exhaust PN has been regulated for gasoline passenger cars (Davies et al., 2018). In Europe, the PN regulation was introduced as a complement to the PM10 and PM2.5 limits. The objective of non-volatile particles for light-duty (LD) diesel vehicles was to determine whether diesel passenger cars emit particulate matter (PM) when tested under real-world and laboratory driving conditions (Noack et al., 2013; Shi and Harrison, 1999; Tobias et al., 2001; Schneider et al., 2005; Khalek et al., 2003). The non-volatile particle regulation aims to non-volatile particles greater than 23 nm in size. The current regulatory method does not capture the non-volatile particles smaller than 23 nm, semi-volatile or secondary particles at all. Since September 2018, all new vehicles in the EU are certified according to the new Worldwide harmonized Light vehicles Test Cycle (WLTC) chassis dynamometer procedure, which has replaced the previous New European Driving Cycle (NEDC) test protocol (Dieselnet, 2020).

In order to meet the strict emission limits, modern diesel cars are equipped with diesel oxidation catalysts (DOCs) to reduce the emissions of hydrocarbons and carbon monoxide. They are also equipped with diesel particle filters (DPFs), especially due to PN regulation, to reduce nonvolatile soot particle emissions down to allowed levels. Moreover, in several vehicle models, selective catalytic reduction (SCR) systems are applied to reduce nitrogen oxides. The DOC having an open backpressure for the engine as with the original ATS.

The objectives of this paper are (i) to characterize particle number emission from a modern diesel passenger car (Euro 5b standard) exhaust under the valid regulated test cycles as well as during various transient and steady driving conditions, (ii) to study the role of lubricating oil in particle formation. Thus, the engine-out particulate emissions were measured using three different manufacturer-approved lubricating oils. Emissions were measured for all lubricant oils when the DPF was by-passed. In order to evaluate the performance of the ATS, for one lubricant oil, the measurements were also carried out when the engine was equipped with the DPF. Objective (iii) is to compare real driving emissions with chassis dynamometer emissions. Therefore, all transient test cycles were conducted under laboratory conditions with instruments connected to partial flow sampling system, and under on-road conditions with a chase vehicle. Objective (iv) is to put a special emphasis on the events where particulate emissions occurred even though the diesel engine was not simultaneously fueled, and on how these emissions were affected by the choice of lubricant oil. According to our knowledge, nanoparticle formation during engine motoring under real-driving conditions on-road has not been reported for diesel passenger cars before.

2. Experimental methods

2.1. Test vehicle, fuel and lubricants

The test vehicle was a Euro 5b emission level compliant TDI passenger car Audi A4 Sedan (displacement 2.0 dm³, model year 2012, odometer reading ~30,000 km). The car was front wheel driven and equipped with a manual gearbox. Engine was a modern common rail turbo diesel engine with maximum power output of 105 kW. The engine was equipped with an ATS including a diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF) along with an exhaust gas recirculation system (EGR).

As mentioned in Introduction, the purpose of these measurements was to determine whether diesel passenger cars emit particles during engine motoring and furthermore, if lubricants influence particle formation and emissions. DPFs have been observed to act very efficiently in removing particles from the engine exhaust. There were no means to control the timing and extent of regeneration events, therefore, the exhaust sample was taken upstream of the DPF in order to measure the particulate emissions originating from the engine. This was realized by removing the DPF and replacing it by a ball valve and muffler that caused the same backpressure for the engine as with the original ATS.

The engine was run on low sulfur (<10 ppm) commercial EN590 specified diesel fuel. Three commercial SAE 5W-30 lubricants from well-known brands were used. All of them were fully synthetic high-performance motor oils designed for extended oil drain intervals. The largest differences between the lubricants were in the fractions of the evaporation losses of the lubricants (Noack wt-%) and in the additive contents, particularly, in calcium, zinc and...
chlorine concentrations (Table S1).

2.2. Laboratory experiments

2.2.1. Driving modes

The measurements were conducted over the NEDC (duration 1180 s, mileage 10.9 km) and the US06 (596 s, 12.8 km) cycles. The NEDC comprises an urban driving cycle (UDC) with a total duration of 780 s, followed by a 400-s-long extra-urban driving cycle (EUDC). The UDC is driven at low engine load causing low exhaust gas temperature, and the average speed is only 18.4 km/h, whereas the EUDC part simulates highway driving with an average speed of 62.6 km/h and reaching 120 km/h at maximum. The US06 cycle during the first 500 s describes aggressive, high speed and high acceleration driving behavior up to 129 km/h, followed by steady speed indicated by the thermodenuder were possible. The EEPS measured always size distributions in real time. The UCPCs were organized so that the sampling system, and for the particle losses within the PSM and evaporated components were removed by activated charcoal. As mentioned above, these non-volatile particles are called primary particles whereas the particles monitored without the TD are called fresh particles.

2.3. On-road experiments

The chase studies were conducted on the same diesel passenger car in a remote environment on an approximately 2 km strip of a straight road as in Pirjola et al. (2015) and Karjalainen et al. (2014a). The location was chosen to minimize the amount of interfering traffic and local sources of air pollution. A mobile emission laboratory, the “Sniffer” (Pirjola et al., 2004; Rönkkö et al., 2006; Pirjola et al., 2015), was used to chase the tested passenger car at a distance of ~10 m. The sample was taken from the front bumper of the Sniffer at a height of 0.7 m and transported in a sample line inside the car to the aerosol measurement devices. Two UCPCs and an EEPS were used to measure particle number concentrations and size distributions in real time. The UCPCs were organized so that simultaneous measurements both upstream and downstream of the thermodenuder were possible. The EEPS measured always upstream of the TD. Each of the transient cycles (Table S2) were repeated at least 15 times for each lubricant.

2.4. Data processing

All aerosol instrument data were corrected for the total DR of the sampling system, and for the particle losses within the PSM (Jarvinen et al., 2019) and the thermodenuder (Heikkila et al., 2009). The maximum penetration factor (minimum loss correction) based on Heikkila et al. (2009) was used for the thermodenuder loss correction for the UCPC data. All data from the different instruments were synchronized to the speed profiles obtained from the vehicle’s OBD data. Intake mass airflow was used to calculate the instantaneous emissions from the vehicle.

Emissions factors $EF$ in #/km for particle number were estimated by the following equation

$$EF = \frac{\sum_{i=1}^{n} N_{raw,i}M_{AF}}{P_{exh} \sum_{i=1}^{n} v}$$

where $n$ is the number of seconds of the cycle, $M_{AF}$ is the momentary mass flow of the exhaust, $P_{exh}$ is the exhaust density (assumed to be air density), $v$ is the vehicle speed, and $A$ is a conversion factor for the units. $N_{raw}$ is the raw particle number concentration, and it is calculated by Eq. (2)

$$N_{raw} = \frac{dN}{dC_{O_{2}}} \frac{dC_{O_{2},raw}}{dC_{O_{2}}} = \frac{(N - N_{bg})}{(C_{O_{2} - C_{O_{2},bg}})} (CO_{2}^{\text{sw}} - CO_{2}^{\text{bg}_{2}})$$

where $N$ and $C_{O_{2}}$ are the measured (diluted) particle number and carbon dioxide concentrations, and the subscript bg refers to the background concentrations.
3. Results

3.1. Particle number emissions during the NEDC and US06 cycles

Fig. 2 presents the time-series of the vehicle speed and number emissions of primary and fresh particles (>2.5 nm) during the NEDC and US06 cycles for different lubricants used. With all oils, driving conditions strongly affected exhaust emissions. The peak emissions occurred at vehicle accelerations and decelerations during engine braking. In the acceleration parts of the NEDC, the primary and fresh exhaust particle emissions were at a rather similar level, indicating that these particles were non-volatile in nature and already existed inside the tailpipe. However, under the engine braking conditions, especially when the car was braked from 120 km/h to 0 km/h, the primary particle emissions were clearly lower compared to the fresh particle emissions. Consequently, the majority of these particles were volatile. Overall, the highest emissions occurred with Oil 1; the emission factors (EFfresh) over the whole cycle were 1.30 × 10^{14}, 1.15 × 10^{14} and 1.18 × 10^{14} #/km for oils 1, 2 and 3, respectively (Table S3), and the average fraction of primary particles of these were 76%, 89% and 90% for Oil 1, Oil 2 and Oil 3, respectively. As a curiosity, with Oil 1 automatic regeneration started before the EUDC during one cycle, and a huge number of particles was released as shown in Fig. S1. Consequently, the EFfresh was higher, 1.58 × 10^{14} #/km.

The emissions of nanocluster aerosol (NCA) with particle diameters in the range of 1.3–2.5 nm were measured during all cycles. As seen from Fig. 1, the highest NCA emissions occurred at the accelerations and decelerations, as for the fresh exhaust particles. The lubricant oils affected NCA emissions. During the NEDC, the largest EFNCA = 3.23 × 10^{13} #/km was estimated for Oil 1 covering 20% of the fresh exhaust EFPSM. The EFNCA was 1.12 × 10^{13} #/km for Oil 2 and 4.5 × 10^{12} #/km for Oil 3 being about 10% and 4% of the corresponding EFPSM.

Due to more aggressive driving conditions and higher speeds, the peak emissions during the US06 were much higher than during the NEDC (Fig. 1). The highest momentary emissions occurred during the fast accelerations with Oil 1 whereas the highest emissions during the engine braking were observed with Oil 2. Over the NEDC, the highest particle emissions occurred with Oil 1, 2.04 × 10^{14} #/km compared to 1.48 × 10^{14} #/km with Oil 2 and 1.08 × 10^{14} #/km with Oil 3 (Table S3). The average ratio of the primary and fresh particles were 63%, 66% and 96% for Oils 1, 2 and 3, respectively, indicating that with Oil 3 the particles were less volatile. The average NCA emission factors followed the order of the fresh exhaust emission magnitude (Table S3), and covered 22%, 20% and 17% of the fresh exhaust particle emissions factors (EFPSM) for Oils 1–3, respectively.

3.2. Particle number size distributions during the NEDC, US06 and steady speed cycles

As an example, the time evolution of particle number size distributions measured by the EEPS during the NEDC and US06 with Oil 1 is shown in Fig. 3a–d, and with the other oils in Figs. S2–S3. During accelerations and high-speed driving in the EUDC of the NEDC, the particle size distribution was typically dominated by the soot mode particles, the mode peaking at ~60 nm (Fig. 3a). Instead, during deceleration, the size distribution was shifted to smaller particle sizes and the role of sub-20 nm particles became much more significant. Plausibly the origin of these particles was from the lubricant oil (Rönkkö et al., 2014; Karjalainen et al., 2014a).

During the US06 cycle, a stronger soot mode peaking at 70 nm was observed and furthermore, larger particles >200 nm appeared in aggressive accelerations during the first 150 and last 100 s (Fig. 3b,f). The smaller particle modes peaking at ~10 nm and 20 nm can clearly be distinguished over the both cycles (Fig. 3e and f). A major part of these particles was volatile and evaporated during the TD treatment so that the sizes of the primary particles were close to 10 nm. Some differences in the average size distributions of the emitted particles (#/km) between the oils can be discovered (Fig. 3e and f). The soot mode particle emissions were highest with Oil 1 over the both cycles, whereas the emissions of the particles smaller than 30 nm were highest with Oil 2.

The steady state tests (Table S2) indicate that the lubricants used have minimal effect on particle number emissions when the wheel power was low, 5 kW and 10 kW. Instead, at 20 kW wheel power a large mode peaking at ~80 nm was emitted with Oil 3 (Fig. S4). These particles were larger than the ones with Oils 1 and 2, and ~40% of these particles in number were volatile. Altogether, the...
emissions of the soot particles decreased in increasing wheel power.

3.3. Particle number emissions during the transient cycles

Detailed investigations on the particle formation during different situations of diesel engine motoring were performed in the laboratory as well as on the road. The time evolution of the number size distributions measured by the EEPS of fresh exhaust particles emitted during the three transient cycles 30-70-30 with gear 3 (Table S2) are displayed in Fig. 4 for Oil 3 and in Fig. S5 for Oils 1 and 2. These measurements were performed on the chassis dynamometer with the ATS bypassed. As a general observation, the repeatability of the driving cycles was excellent. During accelerations, a wide soot mode peaking at ~60 nm dominated both the fresh and primary particle number size distributions, and these emissions were similar. Instead, during deceleration by engine braking when the engine load was 0% (black curve in Fig. 4a and b), the size distribution totally changed; the wide soot mode vanished and a bi-modal size distribution was formed. The smaller mode was located at 10–20 nm and the larger mode, with much lower emissions, at around 100 nm (Fig. 4f). The larger mode was not practically affected by the thermodenuder while the smaller mode shifted towards the smaller particle sizes, and simultaneously, the number emissions dramatically decreased (Fig. 4d and e). The behavior of the emissions were similar with the other oils (Figs. S5 and S6).

The emission factors between the oils did not deviate much but the highest emissions over the transient cycle were observed with Oil 2. The fresh exhaust particle emission factors were $1.43 \times 10^{14}$, $1.56 \times 10^{14}$, and $1.41 \times 10^{14}$ #/km for Oils 1–3, respectively, and the primary ones $1.18 \times 10^{14}$, $1.22 \times 10^{14}$, and $1.12 \times 10^{14}$ #/km, respectively (Table S3) based on the UCPC data. No notable differences across engine lubricants was seen in the particle emissions during accelerations and steady speed parts of the cycle (Fig. S7). However, some differences were seen in the average size distributions of the brake particle emissions (Fig. 5e). While the larger mode emissions were highest with Oil 3, the smaller mode emissions were highest with Oil 2, leading to the highest brake particle emissions factor of $1.82 \times 10^{14}$ #/km with Oil 2 over the braking distance and the lowest of $1.34 \times 10^{14}$ #/km with Oil 1 (Table S3). With all the oils the majority of the smaller mode particulate material was volatile and consequently, the fraction of the primary brake particle number emissions of fresh brake particle emissions were 38%, 41%, and 36% for Oils 1, 2, 3, respectively, whereas during the whole 30-70-30 cycle, the fraction of non-volatile particle number emissions of all particles were 83%, 78%, and 80%, respectively. Zn content was highest for Oil 2, 25% higher than for Oil 3, and sulfur content 7% higher than for Oils 1 and 3 (Table S1). These additives might have increased the particle emissions (Pirjola et al., 2015).

The parallel measurements with the PSM and UCPC for all oils and the estimated NCA emissions (particle diameter 1.3–2.5 nm) are presented in Fig. S8. During the acceleration and steady driving, the NCA formation is low while during the engine braking the NCA emissions cover 10% for Oil 1, 17% for Oil 2 and 20% for Oil 3, of all engine braking particle emissions.

In addition, the transient cycle was carried out when the vehicle was equipped with the DPF. During this experiment, the particle number emissions were very low (Fig. 5c and d), however, weak variability, similar as without the DPF, can be seen. Based on the UCPC data, with the DPF the EF was $2.3 \times 10^{8}$ #/km, only 0.0016% of the case without the DPF. Thus, the filtration efficiency of the DPF was excellent (99.998%) during this cycle, and it was fairly independent of the altering driving conditions.

![Fig. 2. Time series of particle number emissions (#/s) (measured by the UCPC) over the NEDC (a–c) and over the US06 (d–f) for the three lubricants. Vehicle speed is shown by green color. Note different y-scales for the NEDC and US06. Also shown are the NCA emissions measured by the PSM.](image-url)
Fig. 5 shows the emissions of particle number measured by the UCPC and the number size distributions measured by the EEPS during one repetition of the 30-70-30/3 cycle on the road. The experiment was conducted without the DPF in the test vehicle. The average dilution ratio of the exhaust was estimated as a ratio of the average $\Delta CO_2$ concentration measured in the laboratory over the same cycle and the average atmospherically diluted $\Delta CO_2$ concentration measured on road. In this case DR was 636. During the engine braking (after 30 s from the beginning) the smaller particle mode can be observed as in the laboratory tests, however, the larger particle mode seen in the laboratory measurements can hardly be detected on the road. Due to the much higher atmospheric dilution ratio their concentration is small and close to the detection limit of the EEPS.

3.4. Emissions factors

Emission factors of all particles and engine brake particles for the three lubricant oils during the different cycles (Table S1) are shown in Fig. 6. The EFs were highly dependent on the test cycle. Over cycles 20-50-2/1, 30-70-30/2 and 30-90-30/2, the EFs were clearly higher compared to the NEDC and the US06 but it should be noted that the tests were driven by using a small gear. Altogether, the engine-out particle number emission factors varied from $1.0 \times 10^{14}$ to $1.3 \times 10^{15}$ #/km.

The emission factors calculated for different oils within a specific cycle did not vary much; however, the EFs with Oil 3 were the highest in the road environments compared to Oil 1 and Oil 2 whereas the laboratory conditions they were most frequently the lowest. In practice, the fraction of brake particle
emissions of the fresh particle emissions followed the same mutual order as the fresh particle emissions.

4. Discussion

The sampling system used in the laboratory experiments of this study has been designed to mimic the particle processes in atmospheric exhaust dilution but it should be kept in mind that ambient temperature, humidity, residence time and turbulence of the exhaust plume can vary and affect the exhaust's nanoparticle formation and growth (Keskinnen and Rönkkö, 2010). In this study, the results corrected for the dilution ratio from the laboratory and from the on-road tests agree very well in terms of particle number concentration (Fig. 6). This may be caused mostly by the dominating role of non-volatile primary particles; both the laboratory experiments and on-road experiments showed that the engine out exhaust, i.e., when the DPF was removed from the tailpipe system, contained soot mode particles. In addition, it seems that nanoparticle emissions during engine braking are not sensitive on measurement method, at least in terms of particle number emissions. However, the study underlines the importance to measure the diesel exhaust particle number concentrations over a large particle size range so that also the smallest particles are included in the particle number emission factors.

This study shows that, in addition to the variation in particle number emissions, transient driving conditions affect the size distribution of particles emitted by diesel cars. This is important to note because the potential effect of particles depends on particle size. We observed that while the acceleration conditions are clearly linked with soot particles (mean size > 50 nm) in engine out exhaust, significantly smaller particles (in sizes < 20 nm) are emitted under deceleration conditions conducted by engine
braking. This was very clearly seen in our self-made transient cycle but also under acceleration and deceleration conditions during the official laboratory test cycles NEDC and US06. The nanoparticles emitted during deceleration were affected by the thermodenuder treatment, indicating that semi-volatile compounds participate in their formation and growth. However, it is possible that these particles contained non-volatile cores because a fraction of these particles did not evaporate in the thermodenuder treatment and, from the other hand, the results gathered from laboratory experiments are in line with the results from on-road experiments. Besides, the nucleation of new particles in the cooling dilution process of the exhaust typically requires high exhaust temperature, high oxidation capability of the exhaust after-treatment system, high fuel sulfur content and, based on some previous experiments (e.g. Karjalainen et al., 2014b), exhaust aftertreatment components that can store and release the nucleating compounds efficiently. In this study, the situations that led to the nanoparticle emission events (decelerations) do not fulfill these requirements.

Besides driving conditions, the effects of lubricant oil on particle emissions of the diesel passenger car were investigated. We did not see significant effects on soot mode particles and the effects on nanoparticles during deceleration were moderate, although the particle formation during deceleration can be considered as a lubricant oil driven process. The effect of lubricant oil was seen most clearly in the volatility properties of the particles; the fraction of non-volatile particles was 90–96% with Oil 3, 66–89% with Oil 2, and 63–76% with Oil 1 (Table S3).

Most importantly, this study demonstrates clearly how efficient the DPF is in reducing the real-world particle emissions of diesel passenger car. This effect is seen both in soot particles from fuel combustion (especially during accelerations) and in nanoparticles most likely originated from lubricant oil (emissions seen in this study especially during decelerations). Thus, this study encourages the implementation of efficient DPFs in new geographical and application areas of diesel-powered engines. Together with low sulfur fuels that decrease the nucleation mode particle emissions, DPFs may significantly decrease the particulate air pollutants and thus benefit both human health and climate.

Significant nanocluster aerosol (NCA) concentrations have been observed in urban areas from road traffic (Rönkkö et al., 2017), in natural gas engine exhaust under high temperature conditions (Alanen et al., 2015), and in exhaust of city busses in real traffic (Jarvinen et al., 2019). In the atmosphere, these NCA particles may act as nanosized condensation nuclei for the condensation of atmospheric low-volatile organic compounds, and thus influence human exposure in urban areas. This study indicates that also the non-filtered diesel passenger car exhaust may contain these particles, thus contributing to the atmospheric loading of smallest particles in urban areas.

5. Conclusions

In this study, the fresh and primary exhaust emissions from a Euro 5b diesel vehicle were measured under the NEDC, US06 and various transient cycles with three commercial engine lubricant oils on the chassis dynamometer. Furthermore, the real-world emissions during the transient cycles were measured by chasing the same vehicle. Driving conditions and lubricant oil properties strongly affected exhaust particles’ number emissions, size distributions and volatility properties. During accelerations and steady speeds, the observed soot mode was non-volatile. During decelerations by engine braking high particle number emissions were observed although the engine was not fueled. The size distribution of the particle emissions was bimodal. The particles in the larger particle mode were non-volatile, whereas the nanoparticles had non-volatile cores with volatile material condensed on them. The origin of these particles was from a lubricant oil driven process and their volatility properties also depended on the used lubricant oil. The results obtained in the laboratory and on-road nicely agreed. Overall, the emission factors varied from $1.0 \times 10^{14}$ to $1.3 \times 10^{15}$ $#/km$. Engine brake emissions contributed 12–65% of total emission, and for the first time this phenomenon was observed for a diesel passenger car. However, with a DPF practically all particles were filtered. This study indicates that in regulated markets where
DPFs are mandated, particles formed during deceleration or otherwise under engine motoring conditions is not a problem. However, the role of these particles in urban air quality can be significant in the countries where the renewal of vehicle fleet is slow (more than a decade) or in several developing countries where DPF enforcing regulations do not exist.

Declaration of competing interest

The authors declare that they have no competing interests.

CRediT authorship contribution statement

Hugo Wiheransaari: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization.
Liisa Pirjola: Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. Panu Karjalainen: Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration.

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Supplementary data

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