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Ultrafine particle emissions by in-use diesel buses of various generations at low-load regimes

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HIGHLIGHTS

- No substantial reduction in UFP formation for newer bus generations.
- UFP number concentrations decrease with the power rise at a constant engine speed.
- Strong correlation between PNC under steady-state and free acceleration regimes.
- Filtration efficiency values of the retrofit DPF were found to be above 99.8%.

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ABSTRACT

Ultrafine particles (UFP) are major contributors to air pollution due to their easy gas-like penetration into the human organism, causing adverse health effects. This study analyzes UFP emissions by buses of different technologies (from Euro II till Euro V EEV – Enhanced Environmentally-friendly Vehicle) at low-load regimes. Additionally, the emission-reduction potential of retrofitting with a diesel particle filter (DPF) is demonstrated. A comparison of the measured, engine-out, particle number concentrations (PNC) for buses of different technological generations shows that no substantial reduction of engine-out emissions at low-load operating modes is observed for newer bus generations. Retrofitting the in-use urban and interurban buses of Euro II till Euro IV technologies by the VERT-certified DPF confirmed its high efficiency in reduction of UFP emissions. Particle-count filtration efficiency values of the retrofit DPF were found to be extremely high – greater than 99.8%, similar to that of the OEM filter in the Euro V bus.

1. Introduction

The problem of abatement of particle emissions by road transport is considered one of the main challenges in the quest for better air quality. Studies released in the last decades have indicated that particles produced by diesel engines present the serious urban air-pollution problem (Boffetta and Silverman, 2001; Pope and Dockery, 2006). The main particulate fraction of diesel exhaust consists of ultrafine particles (UFP). In 2012, diesel particulates were classified as carcinogenic (group 1) to humans (IARC, 2012). A strong correlation between exposure to diesel particulate matter and increasing rates of respiratory and cardiovascular diseases has been found (Chio et al., 2007; Pope and Dockery, 2006; Sullivan et al., 2005). Study performed by Oberdörster et al. (2004) showed that UFP can translocate to interstitial sites in the respiratory tract as well as to extrapulmonary organs, such as the liver and brain. A systematic analysis of all major global health risks performed in the fundamental Global Burden Decease Study (Lim et al., 2012) showed that air pollution by fine particles is a much more significant health risk than previously known. A comprehensive review and analysis of available data performed by the Health Effects Institute (HEI, 2013) concerning generation, composition, aftertreatment and health effects of diesel exhaust UFP confirms adverse health impacts of ultrafine particles. However, the mass fraction of UFP in the total diesel PM emissions mass is negligible in comparison with larger size fractions (AQMP, 2012). Therefore, a number concentration rather than a mass is used for

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assessing UFP emission intensity and health impact. Today, there is no consensus on whether the solid or volatile constituent of engine exhaust UFP is more dangerous to human health (Giechaskiel et al., 2012). Lovik et al. (1997) stated that the solid fraction of the UFPs stimulates the most adverse health reactions, while other studies (Stone et al., 2003) showed that volatiles and semi-volatiles might cause more adverse health impact than solids.

While modern legislation worldwide requires that newly manufactured heavy-duty diesel engines meet stringent emission standards, there have been limited major regulatory actions to similarly clean up diesels that are in use today. Because of the long service life of heavy-duty diesels (approximately 15 years for buses), there is a large number of older-technology vehicles on the road. Thus, cleaning up exhaust gases from these older vehicles presents an opportunity to gain quick improvements in air quality. Clean Air directives/laws available today in many industrial countries might provide a legal basis for retrofitting of in-use vehicles with emission-reduction technologies, while the conflict with vehicle-tampering prohibitions is still to be resolved (Mayer, 2008).

During the last decades, substantial progress in diesel-combustion optimization was achieved, but only aftertreatment technologies could ensure a substantial reduction of UFP emitted into the atmosphere (Kittelson, 1998). Retrofit exhaust-aftertreatment technologies have emerged in the early 1990s and are increasingly being utilized. Mayer et al. (2000) were among the first, who have reported on the excellent efficiency of DPF (>99%) in mitigation of UFP emissions by urban buses. Other studies confirmed the high efficiency of DPFs (usually higher than 90%) in reduction of UFP emissions (Liu et al., 2012; Van Poppel and Lenaers, 2005; Biswas et al., 2009). It has been proven already that the combination of in-use vehicle retrofitting, recent engine designs, low-sulfur fuels and advanced lubricants is an efficient tool in the mitigation of urban air pollution by diesel exhaust, while providing the durability and efficiency required from heavy-duty vehicles. There is a substantial body of literature dealing with the effects of diesel-bus retrofits with various aftertreatment technologies on PM and PN emissions. Biancotto et al. (2004) reported on the retrofitting of Euro I and Euro II urban bus fleet in La Rochelle (France), using the ceria-based fuel-borne catalyst for diesel particulate filter (DPF) regeneration. They studied the regeneration behavior of a silicon carbide DPF with the ceria-based fuel-borne catalysts. Richards et al. (2004) studied influence of urban bus retrofitting by various types of DPF on PM and NO_2 emissions. This work presented the investigation of a base metal-coated DPF that enhanced the reduction of NO_2 tailpipe emissions. A number of other studies focused on the influence of diesel school bus retrofitting on in-vehicle particle number concentrations (Behrentz et al., 2004; Sabin et al., 2005). An important source of passenger exposure to pollutants during bus commutes is penetration of bus exhaust into the passenger compartment during idling. Prolonged bus idling is typical for school buses or general-purpose buses in regions with a hot climate, where drivers frequently switch-on engines to ensure comfort conditions (air conditioning) during breaks or passenger collection events (Rahman et al., 2013; Zhang et al., 2013). Hammond et al. (2007) investigated the effects of school bus retrofitting with a diesel oxidation catalyst (DOC) on PN concentrations inside a vehicle. A reduction of in-vehicle PN concentrations by 15–26% was achieved compared with non-retrofitted buses.

In sum, extensive knowledge has been gained regarding efficiency and performance of various particle-reduction technologies (Liu et al., 2012), characterization of particle emissions (Biswas et al., 2009), assessment of their toxicity (Mayer et al., 2003) and health effects (Lim et al., 2012), evaluation of fuel effects on UFP emissions (Stepien et al., 2011), development of efficient procedures of PN measurement (Thompson et al., 2004) and DPF verification (Mayer et al., 2002). However, information on a comparison of UFP emissions from vehicles of different technological generations is still limited. Only Euro VI legislation prescribes limitation of particle number concentrations. Thus, question remains about the necessity of DPF retrofit in heavy-duty vehicles of pre-Euro VI generations. Mayer et al. (2014) performed a comparison of UFP emissions between typical heavy-duty truck engines of Euro V (with SCR), Euro IV (with PM-Kat) and Euro III (with and without retrofit DPF) technologies. Their key conclusion was that only a moderate reduction of UFP emissions, compared to EURO III engine without DPF, was observed for the majority of operating modes of EURO IV with PM-Kat and EURO V with SCR engines. Moreover, at full load the EURO V engine emitted higher PN concentrations than a EURO III engine without DPF. These results, therefore, lead to uncertainty regarding the validity of the widespread interpretation that reducing particle mass automatically leads to reduction of particle number.

The main goal of the present study was a comparative analysis of UFP emissions at low-load regimes by buses of different technologies – from Euro II to Euro V EEV. In addition, we aimed at demonstrating a potential of mitigating UFP emissions from in-use heavy-duty diesel vehicles of different technologies via diesel particle filter retrofitting.

2. Methodology

2.1. Buses tested

Six in-use buses (one coach and five urban buses) of different technologies from Euro II until Euro V EEV were experimentally studied. Most popular models of the leading European bus manufacturers (UITP, 2012) were selected for this research. The buses with an average mileage for their technology generation were chosen. Emission control technology of each selected bus was typical for the relevant technology generation. The main parameters of the buses that were tested are collected in Table 1.

All of the tested buses had an original engine and were appropriately maintained & inspected. Buses 1–5 were tested at the same test site and day. Bus 6 – Euro V (2) was tested separately in another test site.

2.2. Experimental setup and measurement procedures

Each vehicle was tested under four operating regimes, three steady-state and one transient (Table 2): low and high idle, free acceleration and partial load. The latter approximately corresponds to the representative regime in urban driving conditions (Tartakovsky et al., 2013). Idling regimes were selected because of their proven contribution to exposure of bus passengers to pollutants, as explained in Section 1.

Zheng et al. (2013) noted that it is uncertain whether laboratory test cycles reflect on-road driving conditions for the particle-number emissions. Taking this into account, the well-reproducible steady-state regimes were chosen in this study for comparison of UFP number emissions by vehicles of different technologies with and without the DPF. This approach also allows shortening the test time and diminishing or excluding the uncertainties caused by the following issues:

- The DPF loading and spontaneous regeneration events where the DPF efficiency may change substantially;
- The effects of differences in transient response of various engine models due to variations in turbocharger design, fuel-feeding control and inertial masses.

Table 1
Buses tested in the study.

Bus no.	Technology	Maker, Model	Traveled distance, km	Engine type	Power, kW/Speed, rpm	Number of cylinders/Displacement, cm^3	EGR system, Yes/No	Exhaust gas aftertreatment
1	EURO II, interurban	MAN HOCL 1835	1,227,503	D2066LOH12	257/2200	6/10,518	NO	NO
2	EURO II, urban	Mercedes O-405	994,600	OM447-hLA	176/2200	6/11,967	NO	NO
3	EURO III, urban	MAN NL 313F	595,560	D2866LUH24	228/1900	6/11,967	YES	NO
4	EURO IV, urban	MAN NL 313F	328,990	D2066LUH12	228/1700	6/10,518	YES	PM-KAT®[a]
5	EURO V (1) EEV, urban	MAN NL 323F	283,162	D2066LUH47	235/1900	6/10,518	YES	CRTec®[b]
6	EURO V (2) EEV, urban	MAN NL 323F	262,760	D2066LUH47	235/1900	6/10,518	YES	CRTec®[b]

[a] PM-KAT is a trade name of the Emitec partial-flow filter with an upstream diesel oxidation catalyst (DOC).

[b] CRTec is a trade name of the HJS-made continuously regenerating trap based on the wall-flow sintered metal filter with electronically controlled thermal management.

Table 2
Operating regimes of the buses tested.

Bus no.	Low idle, rpm	High idle, rpm	Free acceleration, rpm	Load		
				Engine speed, rpm	Bus velocity, km/h	Power on wheels, kW
1	600	1900	600–1900	1900	54	13
2	650	1300	650–1300	2500	55	14
3	600	2000	600–2000	2000	54	13
4	650	2700	650–2500	2500	54	13
5	610	2500	610–2550	2550	55	13
6	550	2140	550–2140	1000	50	20
				1000	50	40
				1000	50	60
				1300	75	40
				1600	90	40

It should be noted that in the case of bus 2 (Euro II Mercedes O-405) the engine high-idle speed of 1300 rpm was much lower than the rated speed of 2200 rpm and resulted from the control-system specificities of the OM447-hLA engine. All of the measurements with Euro II – Euro IV buses were repeated twice for each vehicle: with and without a retrofit DPF. The measurements with EURO V (1) and (2) buses were carried out only in OEM configuration that included a VERT-certified wall-flow DPF in their exhaust tract. Bus 6, Euro V (2), underwent more detailed measurements as presented in Table 2. Engine-out and tailpipe particle number concentrations (PNC) were measured for this bus in each operating regime.

A warm-up period was allowed prior to taking measurements until the coolant temperature reached a value of approximately 80 °C. In each operating mode, UFP number concentrations were measured with a NANOMET-3 portable solid particle counter from Matter Aerosol AG. It was equipped with a sampling line heated to 300 °C to prevent condensation of volatile species. NANOMET-3 is based on a Diffusion Size Classifier (DiSC) to measure number concentration and average diameter of solid particles in the range of 10–300 nm. It is proven to provide 90–99% correlation with Particle Measurement Program (PMP) systems. PMP prescribes measurement of solid particle number concentrations (SPNC) and is currently implemented within the European legislation. SPNC measurement method was selected for this study as it allows an efficient evaluation of different engine and aftertreatment technologies due to the very low limits of detection and high repeatability (Giechaskiel et al., 2012). Volatile fractions were not measured in this study. Particles referred to in this paper as 'solid' might also include semi-volatile material not evaporating at temperatures of 300 °C or below, e.g., heavy molecular hydrocarbons. Thus, some researchers use the term "nonvolatile material" instead (Giechaskiel et al., 2012).

Under low/high idle and partial load an average of 60 readings collected at a 1 Hz frequency was assumed to adequately characterize the given regime. Under the free-acceleration operating mode, six consecutive free accelerations were performed, and an average of maximal PNC values registered in each free-acceleration test was assumed to be a result of the measurement that was used in the filter-efficiency calculations.

The particle count filtration efficiency *PCFE* of the DPF was calculated as follows:

$$PCFE = \left(C_{w/o} - C_f\right)\cdot 100 \Big/ C_{w/o} \quad (1)$$

where $C_{w/o}$ and C_f – PNC without and with the DPF, respectively.

Size-specific filtration measurements were not performed in the framework of this study taking into account that properly designed DPFs allow high levels of particle interception by both impaction and diffusion mechanisms (Hinds, 1999).

In buses of Euro II – Euro IV generations, where a potential of UFP emission mitigation by DPF retrofitting was demonstrated, the concentrations of NO_x and CO in the bus exhaust gases were measured in addition to UFP parameters. Measurements of engine speed and vehicle velocity were carried out using the bus control panel gauges. The power on the wheels was measured using the Schenk chassis dynamometer. Measurements of the gaseous pollutant concentrations in the exhaust gas were not performed during free acceleration because the sampling response time was much longer than the time of the free-acceleration procedure. Concentrations of NO_x and CO in the exhaust gases were measured with a HORIBA gas analyzer, model PG-250A. A sampling line of the analyzer was equipped with a sample conditioning system that provided sample cooling, dehumidification and soot filtration. The conditioned gas was sampled in a special bag. The latter was consequently disconnected from the sampling line and connected to the gas analyzer inlet. Under each steady-state operating regime the sampling line was scavenged before filling the bag with the exhaust gas for 1–1.5 min. This procedure ensured a scavenging factor of 5–7.

2.3. Procedure for retrofit DPF selection

The retrofit DPF tested in this work was selected from the filters certified in accordance with the VERT procedure. The developed VERT procedure of DPF testing and certification is described in detail in the Swiss Norm SN 277206 and reported in (Mayer et al., 2002). The main features of this procedure are:

- Test 1: testing filtration quality, regeneration system, auxiliary, and control systems on engine dynamometer;
- Test 2: testing durability of the DPF-system in 2000-h field application, with data logger control and VERT inspections;
- Test 3: testing the DPF-system on the engine dynamometer after the field test, with similar objectives, as test 1.

Validation of filtration efficiency of a DPF by means of particle mass PM (regulated parameter up to date) is not sufficient and sometimes misleading. In several cases, particularly with the presence of some catalytic substances in the DPF, sulfates can be produced (only the sulfur from lube oil is sufficient for that purpose), passing the DPF as a vapor and condensing afterwards on the PM-measuring filter. The filtration efficiency of a DPF can be properly judged only for the solid particles when uncertainties of volatiles measurement are eliminated (Giechaskiel et al., 2012). Thus, the solid nanoparticles are considered in VERT as the most representative criterion of DPF filtration-efficiency (Mayer et al., 2003, 2004).

2.4. The tested retrofit DPF

The DiSiC catalyzed retrofit DPF, used in the tests described herein belongs to a “filter family”, which passed the entire VERT quality procedure briefly described above. In the VERT experiments the DPF was tested with the Mercedes Benz OM 926 LA heavy-duty diesel engine (meeting the 97/68/EG step IIIA emission standard) at the Horiba-Schenck engine test bench Titan D-600. In these tests particle mass PM was measured gravimetrically using the Horiba Micro-Dilution Sampling System MDT-905 and the diesel particulate-mass monitor – Tapered Element Oscillating Microbalance (TEOM) Series 1105 (Rupprecht & Patashnick Co., Inc.). Particle count and size distributions were measured with the TSI Scanning Mobility Particle Sizer (SMPS) system that included the model 3081 Long Differential Mobility Analyzer (DMA) and the model 3010 Condensation Particle Counter (CPC). Sampling dilution ratio after DPF was between 80:1 and 100:1, depending on the engine operating mode. A diluted sample was heated in the thermoconditioner to 300 °C, in order to prevent condensation of volatile species. The up-scan and down-scan time was 120 s and 30 s, respectively. The sample and the sheath flow rates were controlled to 0.6 and 6.0 l/min, respectively. The particle size distribution was recorded using TSI Aerosol Instrument Manager Software (version 8.1.0).

The DPF has a Silicon Carbide (SiC) wall-flow structure with catalytic coating. The main parameters of the tested retrofit DPF are listed in Table 3.

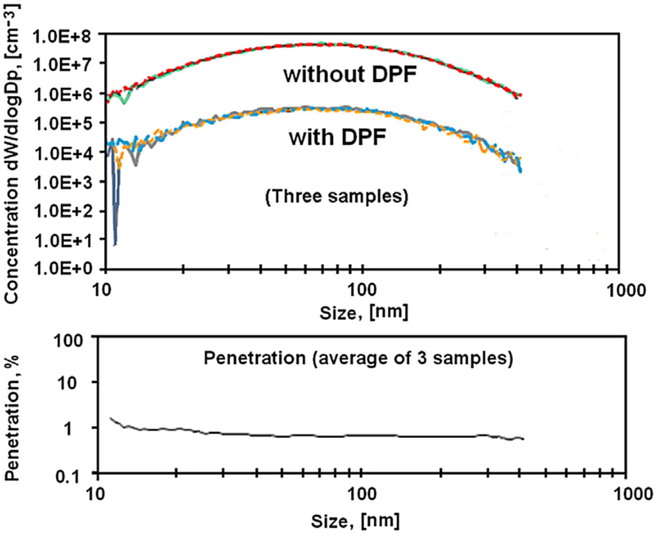

Fig. 1. SMPS size distribution with/without DiSiC catalyzed DPF (top); Average percentage of penetration (bottom): MB OM 926 LA engine, 1480 rpm/650 Nm, fuel sulfur < 10 ppm.

The non-degreened DPF was tested with the in-use buses because its degreening under the full engine load was not possible in this work. Diesel particulate filters are manufactured in such a way that following the application of the catalytic coating, a burn-off of the excess residue is required. The process of burning off the residue is called degreening (Detroit Diesel Corporation, 2003). The degreening process ensures that the DPF performance has stabilized. Therefore, the PNC measured downstream of the non-degreened filter were somewhat higher than might be expected with the degreened DPF.

3. Results and discussion

3.1. VERT tests of the retrofit DPF

Fig. 1 (top) shows an example of particle-size distributions with and without DPF at one of the tested operating modes of the OM 926 LA engine after more than 2000 h of field operation. Fig. 1 (bottom) demonstrates the percentage of UFP penetration (ratio of particle counts passing through the DPF). The resulting average penetration is lower than 1% for particles larger than 20 nm.

Table 4 summarizes the results of PCFE and PMFE measurements of the DPF used in this work at several investigated operating modes (PMFE – particle mass filtration efficiency was calculated in a similar way as described in Eq. (1)). Measurements at the 1480 rpm/1310 Nm regime were repeated to confirm a lower efficiency of the DPF compared with other operating modes.

The slightly lower PCFE value measured at the full-load regime of 1480 rpm/1310 Nm (with the highest exhaust temperature causing maximal heating-up of the DPF-substrate) was caused most likely by bundle substances, such as sulfates and heavy hydrocarbons that were stored in the trap after a field test. The substances evaporated during the high-heating of the filter and became precursors of spontaneous nanoscopic condensates after

Table 3
DPF characteristic parameters.

Filter medium	Cells per square inch	Porosity, %	Wall thickness, mm	Cell size, mm	Filter surface, m^2/l	Soot load capacity, g/l
SiC	150	41–43	0.5	1.6 × 1.6	0.71	12

Table 4
Comparison of PMFE and PCFE (20–300 nm) of the DiSiC catalyzed DPF: MB OM 926 LA engine, fuel sulfur < 10 ppm.

Engine speed, rpm	Torque, Nm	PMFE, [%]	Average PMFE of all regimes, [%]	PCFE, [%]	Average PCFE of all regimes, [%]
1480	1310	91.21	92.19	98.75	99.15
1480	650	94.78		99.32	
2250	490	94.26		99.42	
2250	1010	93.97		99.19	
1480	1310	86.74		99.08	

the filter.

As seen in Table 4, under all operating modes, the PMFE values were lower than those of the PCFE. This outcome was most likely due to condensation artifacts after the trap. The difference between the PMFE and PCFE values was moderate because of the ultra-low sulfur content in the fuel consumed during the test. With higher sulfur content and strong catalytic activity of the DPF, the PMFE is expected to be much lower in spite of very high filtration efficiency of solids (PCFE).

3.2. Comparison of UFP emissions for different bus technologies

Average values of UFP number concentrations as measured without DPF retrofit are presented in Fig. 2. In this Figure, the tailpipe PNC of Euro II – Euro IV buses without any aftertreatment or with a PM-KAT (Euro IV) are compared with the engine-out UFP number concentrations of the Euro V bus (No. 6 in Table 1). Because engine-out emissions of the bus No. 5 (Table 1) were not measured, they were assessed based on the measured tailpipe values and the assumed CRTec PCFE of 99%. Following comparison of the measured engine-out PNC data for buses of different technology generations from Euro II to Euro V, we conclude that no substantial reduction in solid UFP number concentration at low-load operating modes was observed for newer bus generations. It seems contradictory to the known fact of much lower particle-mass emissions by modern engines but confirms recent findings about the absence of direct correlation between PM mass and UFP number, especially at lower PM mass emissions (Giechaskiel et al., 2012; AQMP, 2012). The reason for this observation is the fact that newer engines produce less primary particles, resulting in less agglomeration, reduction in the average particle size and stability of the non-agglomerated population of small particles (Hinds, 1999). Very high engine-out particle number emissions of the EURO V buses most probably are the result of high EGR ratios applied in their engine. This finding emphasizes the danger of extremely high UFP emissions (similar to those of the Euro II technology) by the EURO V buses that could arise in case of a DPF malfunction. Surely, proper operation of the Euro V aftertreatment system that contains a highly efficient, VERT-certified, wall-flow sintered metal filter ensures very low tailpipe UFP emissions (Fig. 3), substantially lower than those of the older buses (Fig. 2). PCFE values, as measured for the Euro V (2) bus, are between 99.4 and 99.9% for all studied operating modes.

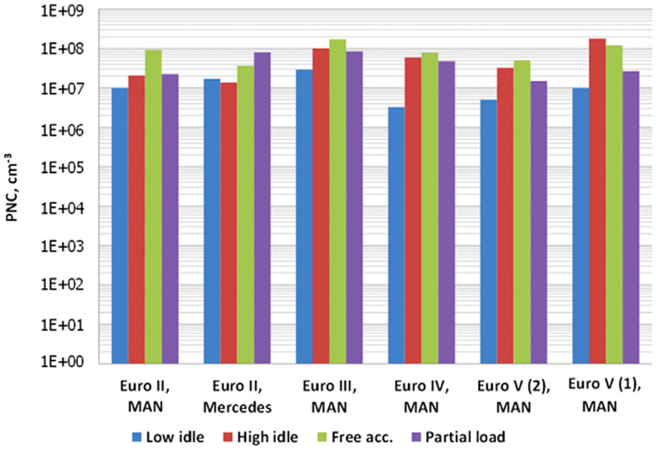

Fig. 2. Average values of UFP number concentrations for buses of different technologies (engine-out PNC for the Euro V buses).

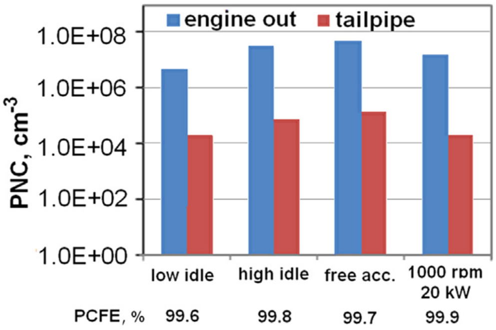

Fig. 3. Comparison of engine-out and tailpipe PNC of the MAN Euro V (2) bus.

3.3. Operating mode effects

The results presented in Fig. 2 showed no clear dependence of engine-out UFP number concentrations on the load at steady-state, low-load operating modes. The PNC values measured on loaded regimes were usually found to be somewhat lower than those at similar engine speeds without load (high idling). Similar PNC behavior was observed in buses irrespective of the presence of an OEM aftertreatment system (Euro III, IV and V buses). The MAN Euro II bus showed similar PNC values at high idle and partial load regimes. Particle number concentrations in the high-idle regime of the Mercedes Euro II bus (No. 2 in Table 2) were found to be substantially lower than in the partial load regime due to the strong limitation of the high idle speed (1300 rpm). To provide more information on the dependence of PNC values on engine load and speed at low-load regimes, more detailed measurements were performed with the Euro V (2) bus (No. 6 in Table 2). Results of these measurements are shown in Fig. 4.

As seen in Fig. 4 left, UFP number concentrations decrease as the power increases at constant engine speed. This confirms the observations made for buses of other technological generations. The obtained data were cross-checked to eliminate any possible measurement mistakes. It should be noted that at higher engine loads, direct proportionality of UFP number concentrations to engine load has been previously reported (Mayer et al., 2014). The latter fact corresponds to known data of PM dependence on engine load (Cheung et al., 2008; Kittelson and Kraft, 2014) where particle mass normally increases with load increase in the whole load range, mainly due to reduction of the air-excess factor. A possible reason of the effect observed in our tests at low loads might be a deterioration of fuel spray atomization and penetration due to low nozzle flow rates. This fact might lead to an increase in a number of particle nucleation sites. This assumption is indirectly supported by the results of PNC dependence on the engine speed at low constant power of 40 kW (Fig. 4 right). It is clear that the speed increase under constant engine power corresponds to the lowering of the engine torque, subsequent reduction of the fuel injection rate and, hence, the reduction of nozzle flow rates.

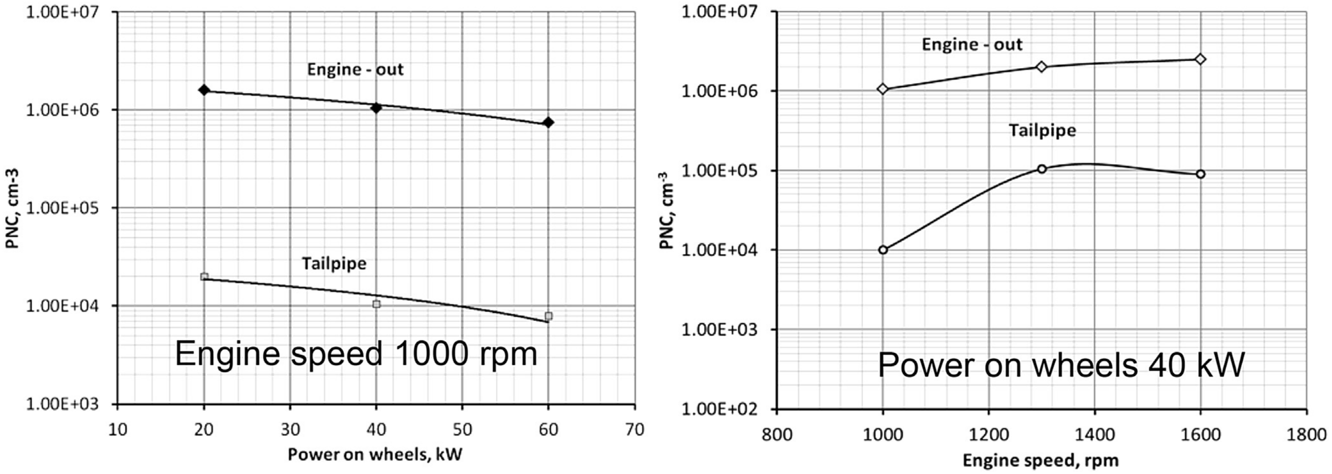

Fig. 4. Influence of load (left) and engine speed (right) on UFP number concentrations, Euro V bus.

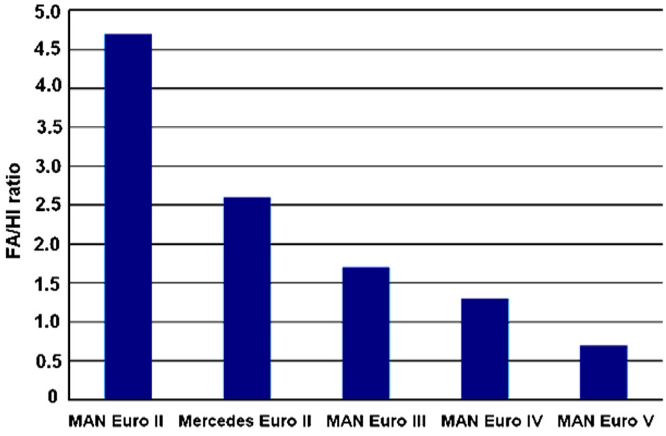

Fig. 5. Ratios of the pick values of PNC at free acceleration and at high idle.

Another important reason might be an increased participation of the lube oil from the cylinder wall in combustion at low loads and idling. Due to lower working pressures and relatively cooler cylinder wall surface, there is a thicker lube-oil layer and the function of the piston rings (their tension and oscillations) is usually less advantageous than at high-load operating (Stepien et al., 2011; Mayer et al., 2012). This usually increases emissions of metal-oxide nanoparticles, which mostly originate from the lube-oil additive packages. These nanoparticles are either of the nuclei mode (the lowest size range below approximately 30 nm) or, in certain conditions, can contribute to the spontaneous condensation of SOF, agglomeration and growth effects of nanoparticles (Hu et al., 2013; Mayer et al., , 2010). Further in-depth studies should be carried out to provide a better understanding of the observed phenomenon.

Fig. 5 compares the ratios of the pick values of PN concentrations at free acceleration and at high idling (FA/HI ratio). As anticipated, FA/HI ratios were substantially higher for the older buses of EURO II generation and decreased with the advancement of the engine technology. In the case of the Mercedes EURO II bus, the lower values of the FA/HI ratio compared with the MAN EURO II counterpart were obtained due to the severe limitation of the high idle speed of the engine.

Table 5
PCFE [%] of the tested retrofit DPF in comparison with the OEM filter of MAN Euro V bus.

Operating regime	MAN Euro II	Mercedes Euro II	MAN Euro III	MAN Euro IV	MAN Euro V (2)
Low idle	98.5	99.8	99.8	99.7	99.5
High idle	90.4	99.6	99.6	99.8	99.6
Partial load	93.6	99.9	99.9	99.9	99.8
Free acceleration	93.6	99.8	99.9	99.9	99.7

3.4. Effects of DPF retrofitting

As mentioned above, buses of the Euro II, Euro III and Euro IV technology generations were also tested with the VERT-certified DPF to demonstrate a potential of UFP emission mitigation by DPF retrofitting. The DPF efficiency values (PCFE) in reduction of UFP number concentrations under all tested operating modes are presented in Table 5. The PCFE values were calculated via Eq. (1) using data of the tailpipe PNC measurements with and without the retrofit DPF. The retrofit DPF's PCFE is compared in Table 5 with a filtration efficiency of an OEM filter of the Euro V (2) bus. As seen, in the cases of the Mercedes EURO II, MAN EURO III and IV buses, the PCFE values of the retrofit DPF were found to be extremely high

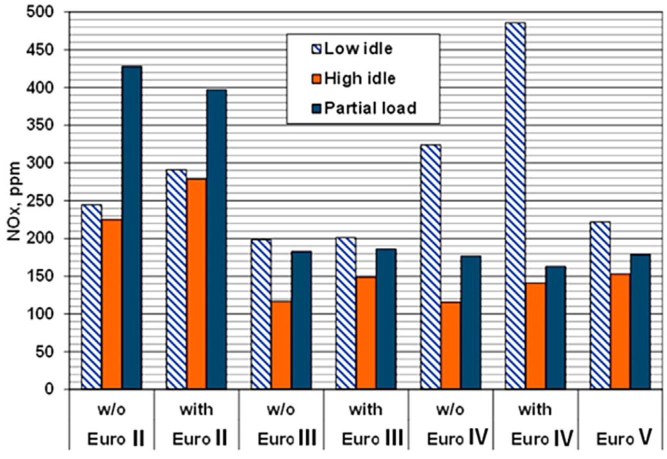

Fig. 6. NO_x concentrations in exhaust gas of the buses of different generations without/with the DPF.

– in excess of 99.6%, similar to the filtration efficiency of the OEM filter in the Euro V (2) bus. In the case of the MAN EURO II bus (tested first) DPF efficiency was slightly lower: 90–98%. This occurred in the MAN Euro II bus because the measurements were taken with the unloaded DPF when the non-degreening effect was maximal and the filter efficiency had not yet stabilized.

Fig. 6 shows that at partial load test conditions, DPF retrofitting had no evident effect on NO_x concentrations in the exhaust gas. No detectable reduction of NO_x emissions at the tested operating modes was observed with bus technology advancement from Euro III to Euro V. However, it should be noted that the studied operating regimes are not representative of NO_x emissions assessment due to weak NO formation at low temperatures, which is typical for the non-load and low-load regimes. For the purpose of NO_x emissions comparison, driving-cycle measurements would be more representative.

As anticipated, DPF application led to the substantial reduction of CO concentrations due to oxidation effects of the filter's catalytic coating (Fig. 7). Reduction of CO concentrations was in the range of 35%–80% for MAN EURO II bus and exceeding 80% – for the EURO III, EURO IV buses. Measurements of pollutant concentrations with the Mercedes bus were not performed.

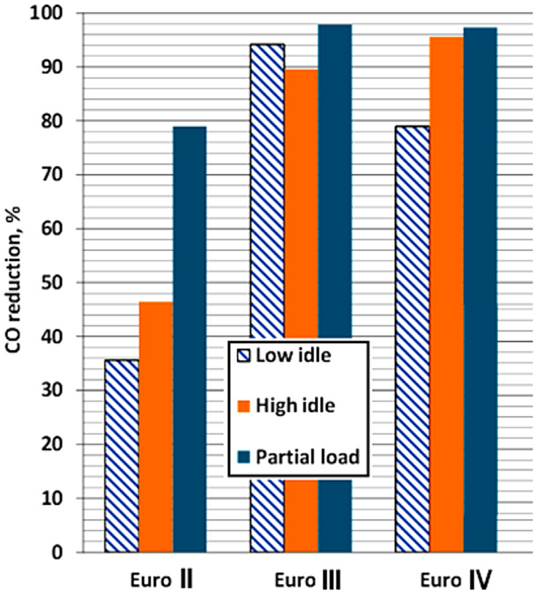

Fig. 7. Reduction of CO concentrations by the retrofit DPF.

4. Conclusions

Comparison of the measured engine-out PNC data for buses of different technological generations from Euro II to Euro V allows us to conclude that no substantial reduction in engine-out UFP emissions at low-load operating modes is observed for newer bus generations. Very high engine-out particle-number emissions of the EURO V buses are most likely the result of high EGR ratios applied in their engine.

UFP number concentrations at low-load operating modes decrease as the power increases at a constant engine speed. A possible reason of the observed effect at low loads may be a deterioration of fuel atomization and penetration quality at low nozzle flow rates, thus leading to an increase in the number of particle nucleation sites. Another reason is the increased part of lube oil and lube-oil additives interfering with combustion at engine idling and low-load operating modes. Further in-depth investigations could be useful for providing a better understanding of the observed phenomena.

A strong correlation between PNC levels under steady-state (especially, high idle) and free-acceleration operating regimes was observed. As anticipated, the ratios of the measured PN concentrations at free acceleration and high-idle operating modes were substantially higher for the older buses of EURO II generation and decreased with advancement of the engine technology.

Retrofitting the in-use urban and interurban buses of Euro II – Euro IV technologies with the VERT-certified diesel particle filter confirmed its high efficiency in reducing solid UFP emissions. The PCFE values of the retrofit DPF were found to be extremely high – in excess of 99.8% and very similar to PCFE values of the OEM filter of the Euro V bus.

At the operating modes studied, the retrofit DPF practically had no influence on NO_x content in the exhaust gases. As anticipated, DPF application led to a substantial reduction of CO concentrations due to the oxidation effects of the catalytic coating of the filter. Reduction of CO concentrations was in the range of 35%–80% for the EURO II bus and exceeding 80% – for the EURO III and EURO IV buses.

Investigation of retrofit DPF behavior in real-world driving conditions of in-use buses with a measurement of UFP number emissions during regeneration events, DPF loading, backpressure tendencies, etc. could be an interesting continuation of the reported study.

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