Influence of Diesel Particle Filter on Ultrafine Particle Emissions from In-Use Buses of Different Generations

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Introduction

Current legislation prescribes that new heavy-duty diesel engines should meet severe emission standards aimed at substantial reduction of harmful ultrafine particle (UFP) emissions. However, there have been only limited regulatory actions to similarly reduce emissions of diesel vehicles that are in use today. Switzerland is a wonderful example of the country where governmental regulation is widely used to mitigate particle emissions of in-use road and off-road vehicles with diesel engines. Numerous laws starting in 1983 prescribe particle emissions reduction (Staubli and Kropf, 2004). Because of the long service life of heavy-duty diesels (approximately 15 years for buses), there are high numbers of older-technology vehicles on the road. Thus, cleaning up exhaust gases of these older vehicles is a possibility to gain improvements in the air quality in the short term. Clean Air acts/directives/laws available today in many industrial countries can afford a legal basis for in-use vehicles' retrofit with emission reduction technologies, while the conflict with vehicle tampering ban is still to be resolved (Mayer, 2008).

Retrofit exhaust aftertreatment technologies have emerged in start of 1990s and are increasingly being utilized (Mayer, 2008). Such systems need to be carefully matched to the individual vehicle and usually require very low sulphur fuel and low-ash lubricants. When optimized, they may provide very significant reductions of UFP and to a lesser extent NO_x emissions. It is proved already that the combination of in-use vehicles retrofit, recent engine designs, low-sulphur fuels and advanced lubricants may be an efficient tool in mitigation of urban air pollution by diesel powered transportation, while providing durability and efficiency required from heavy-duty vehicles (Mayer, 2008). There is a big body of literature available dealing with effects of diesel bus retrofits by various aftertreatment technologies on particle matter (PM) and particle number (PN) emissions (Biancotto et al., 2004; Richards et al., 2004; Liu et al., 2012; Biswas et al., 2009). However, information on a comparison between particle number emissions of buses of different generations is fragmental and still limited.

A main goal of this study was demonstrating a potential of ultrafine particle emissions mitigation from in-use heavy duty diesel buses of different generations by retrofit of advanced diesel particle filter (DPF). Additional goal was assessment of UFP emission levels from in-use buses of different technologies – from Euro II till Euro V EEV.

Methodology

A silicon carbide (SiC) VERT-certified wall-flow catalyst coated DPF was tested on five in-use buses representing all technology generations presented nowadays in the Israeli bus fleet – from EURO II to EURO V EEV. The tested EURO IV and EURO V EEV buses were equipped by the OEM-provided exhaust aftertreatment systems: PM-KAT and CRTec, respectively. The experiments were carried out on a chassis dynamometer under three steady-state (low idle, high idle and partial load) and one transient (free acceleration) engine operating modes. Bus operating regimes where measurements have been performed are presented in Table 1. It should be noted that in the case of the Euro II Mercedes O-405 bus the engine high idle speed 1300 rpm was much lower than the rated speed 2200 rpm. This is a result of the control system peculiarities of the OM447-hLA engine. All the measurements at low and high idle, free acceleration and partial load were repeated twice for each vehicle: without and with the retrofitted DPF. The obtained results allowed calculation of the DPF filtration efficiency *FE* as follows:

$$FE = (C_{w/o} - C_f)*100/C_{w.o.} \quad (1)$$

where: $C_{w/o}$ and C_f – UFP number concentrations without and with the DPF, correspondingly.

Table 1: Operation regimes of the tested buses

Bus type	Regime of operation	Engine speed, rpm	Bus Velocity, km/h	Power on the wheels, HP
Euro II MAN 18350	Low idle	600	-	-
	High idle	1900	-	-
	Free acc.	600-1900	-	-
	Load	1900	45	25
Euro II Mercedes O-405	Low idle	650	-	-
	High idle	1300	-	-
	Free acc.	650-1300	-	-
	Load	2500	43	19
Euro III MAN NL313F	Low idle	600	-	-
	High idle	2000	-	-
	Free acc.	600-2000	-	-
	Load	2000	54	17
Euro IV MAN NL 313F	Low idle	650	-	-
	High idle	2700	-	-
	Free acc.	650-2500	-	-
	Load	2500	54	18
Euro V EEV MAN NL 323F	Low idle	610	-	-
	High idle	2500	-	-
	Free acc.	610-2550	-	-
	Load	2550	55	18

In addition to UFP parameters, the following measurements were carried out: smoke level, gas temperature and pressure at the DPF inlet. Measurements of the engine speed and the vehicle velocity were carried out using the bus control panel gauges. A power on the bus wheels was measured using the Schenk chassis dynamometer.

Under the steady-state regimes (low/high idle and partial load) an average of 60 readings of UFP parameters measured with the frequency of 1 Hz was assumed to be a result of the measurement at the given regime. Under the transient regime (free acceleration) six free accelerations were performed with each bus with and without DPF. An average of six pick values was assumed to be a result of the measurement that was used in the filter efficiency calculations.

UFP parameters (number concentrations, median diameter and summary active surface of the nanoparticles, SASN) were measured with NANOMET 3-PS device manufactured by Matter Aerosol AG. It was equipped by the sampling line heated to 300^{o}C to prevent condensation of volatile species in the exhaust gas. NANOMET 3-PS contains a Diffusion Size Classifier (DiSC) to measure number concentration and average diameter of nanometer sized particles in the range of 10 – 300 nm.

The DPF instrumentation is shown in Fig. 1. As can be seen, in the case of tests without the retrofit DPF, both upstream/downstream covers were connected directly one with another.

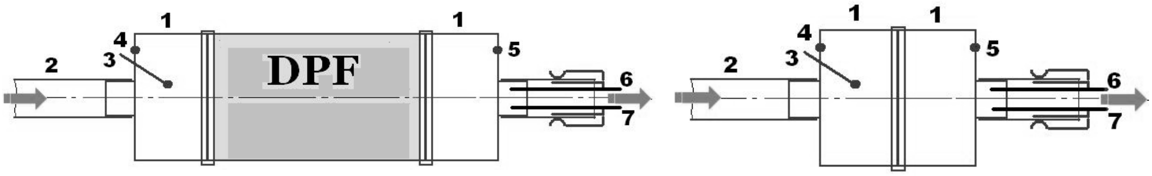

Figure 1: Scheme of the DPF instrumentation; left – with DPF; right – without DPF

1 – upstream/downstream covers; 2 -flexible connection with a bus tailpipe; 3 – upstream temperature; 4 – backpressure; 5 – UFP sampling point; 6 – exhaust gas sampling; 7 – smoke level sampling.

The processes of DPF regeneration were not studied in this work. The unloaded (not-degreened) DPF was tested since it degreening under the engine's full load was not possible in this study. This means that the data measured downstream the filter were somewhat higher than may be expected when DPF's efficiency is stabilized.

Results and discussion

Fig. 2 shows an example of UFP instantaneous number concentrations as were measured at various regimes of bus engine's operation. These data for each bus type and operation mode were used as a base for the following processing and analysis.

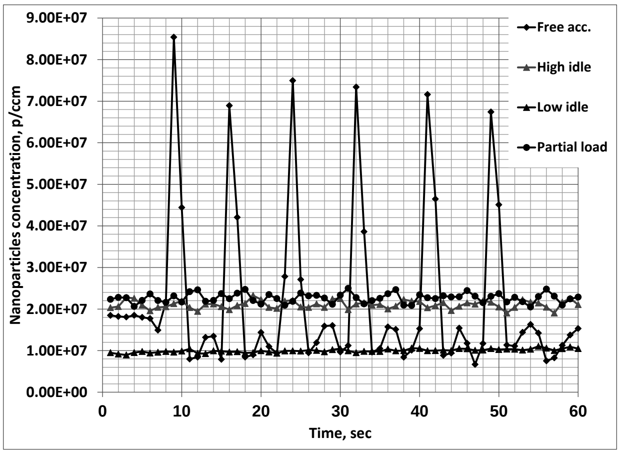

Figure 2: Example of instantaneous PN number concentrations as were measured at various operation modes of the MAN EURO II bus engine

Average values of particle number (PN) concentrations for both tested cases (without and with DPF) under steady state regimes (low/high idle and partial load) are presented in Fig. 3. It should be noted that without DPF the PN emissions of the interurban bus MAN EURO II were lower in comparison with not only Mercedes EURO II, but also MAN EURO III and IV buses. In contrast to this, in the case of DPF retrofitting, exhaust gases of the bus MAN EURO II contained much higher PN concentrations in comparison with those of other buses. This most probably is explained by the fact that measurements of UFP emissions by the MAN EURO II bus were performed with the unloaded DPF when the not-degreening effect was maximal.

It should be noted that in the case of the MAN EURO V bus, UFP concentrations without the DPF were substantially lower than those of other buses. This is a result of applying highly efficient VERT-certified CRTec aftertreatment device with the wall-flow sintered metal filter. At the same time, a comparison of the measured PN concentrations in exhaust gases of the MAN EURO V bus with those of the MAN Euro III bus retrofitted with DPF provides an indication on very high engine-out PN emissions of the EURO V bus. The latter most probably is a result of great EGR ratios applied in this engine. This finding emphasizes a danger of extremely high PN emission by the EURO V buses in the case of CRTec malfunction.

The results presented in Fig. 3 showed that there was no clear dependence of PN concentrations on engine load at steady-state low-load operating modes. UFP number concentrations measured at loaded regime were found to be sometimes higher and sometimes lower than PN values at the same engine speed without load (high idle). The similar PN behaviour was observed in buses with and without OEM aftertreatment system.

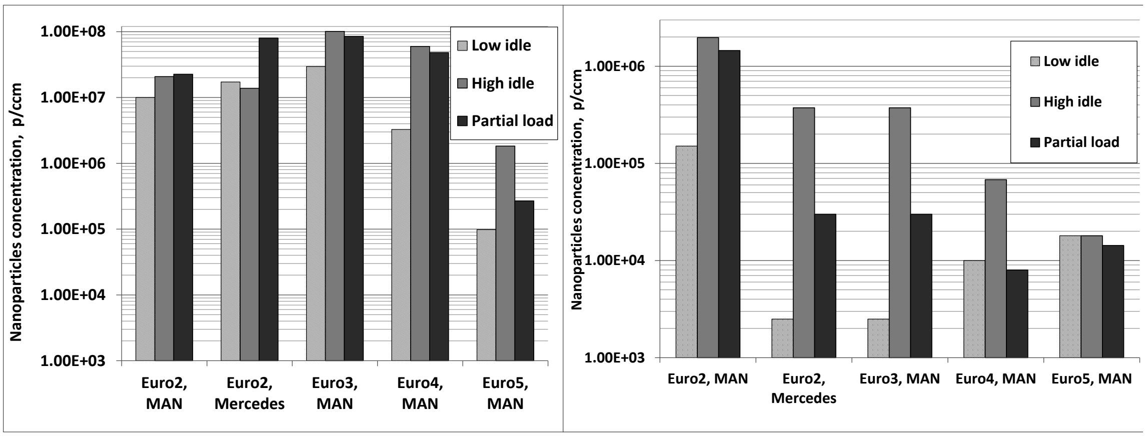

Figure 3: UFP number concentrations under steady-state regimes: left – as supplied (Euro IV MAN with PM-KAT, Euro V MAN with CRTec); right – with a retrofit DPF

DPF filtration efficiency values in reduction of UFP number concentration under steady-state regimes calculated with eq. (1) are presented in Fig. 4. As can be seen, in the cases of the Mercedes EURO II, MAN EURO III and IV buses the efficiency was found to be extremely high - above 99.8%. In the case of the MAN EURO II the DPF efficiency was slightly lower: 90 – 98%. The latter finding may be explained by the fact that namely on this bus the measurements were performed with the unloaded DPF when the not-degreening effect was maximal and its efficiency had not yet stabilized.

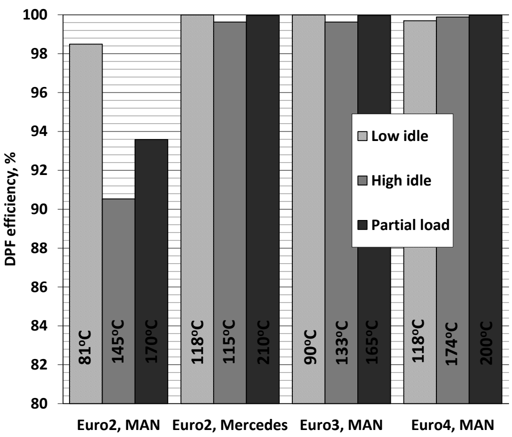

Figure 4: DPF efficiency under steady-state regimes

Pick values of PN concentrations under free acceleration regime without and with the DPF are shown in Fig. 5. As can be seen, in the case of the Mercedes EURO II without the DPF the concentrations were found to be relatively low. This may be explained by the fact that the engine high idle speed of this bus was strongly limited - see Table 1. Extremely low value of the PN concentrations was measured, as anticipated, at the free acceleration test of the MAN EURO V bus. Application of the two-stage turbocharging that allowed utilization of the lower-inertia turbochargers together with an advanced fuel supply control contribute to further limitation of the PN emission in addition to the CRTec effect.

Free acceleration tests of the MAN EURO II bus with the DPF showed substantially higher UFP concentrations (by about 15 times) in comparison with the same generation's Mercedes bus. It seems that the main reasons of this result are the Mercedes high idle speed limitation and use of the unloaded DPF with the MAN EURO II bus.

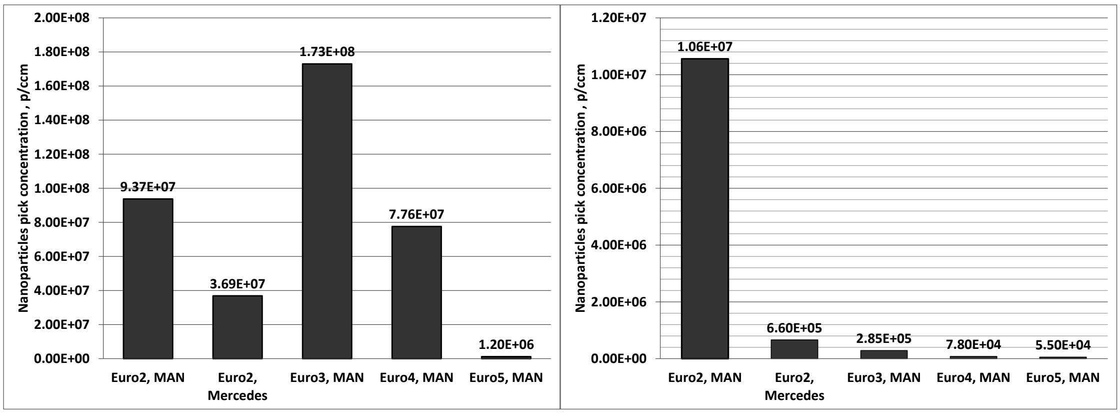

Figure 5: Pick values of NP number concentrations under free acceleration regime: left - without the DPF; right - with the DPF

Fig. 6 presents values of the DPF efficiency under free acceleration regime. As can be seen, the DPF efficiency of the tested buses at free acceleration corresponds with the trends found at steady-state operating modes. For Mercedes EURO II, MAN EURO III and IV buses the efficiency was 99.9 or higher. For the MAN EURO II bus it was in the vicinity of 94%.

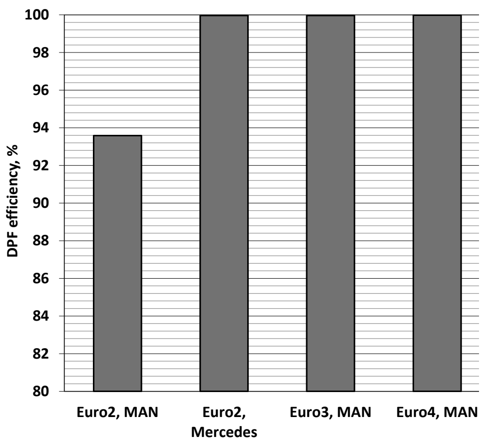

Figure 6: DPF efficiency under free acceleration

Smoke measurements confirmed the known data about a weak correlation between the particle number (PN) concentrations and smoke opacity. Thus, impossibility of using smoke measurements in inspection-maintenance procedures of modern buses was demonstrated once more.

Conclusions

Tests of the retrofit DPF on the in-use urban and interurban buses of different technology generations confirmed its high efficiency in reduction of UFP emissions. The DPF efficiency with all buses at almost all operation regimes was above 94% and in some cases reached near 99.9%.

A comparison of the measured PN concentrations in exhaust gases of the MAN EURO V bus with those of the MAN Euro III bus retrofitted with DPF provides an indication on very high engine-out PN concentrations of the EURO V bus. The latter most probably is a result of high EGR ratios applied in this engine. This finding emphasizes a danger of extremely high UFP emission by the EURO V buses in case of the particle filter malfunction.

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