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Buses retrofitting with diesel particle filters: Real-world fuel economy and roadworthiness test considerations

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ABSTRACT

Retrofitting older vehicles with diesel particulate filter (DPF) is a cost-effective measure to quickly and efficiently reduce particulate matter emissions. This study experimentally analyzes real-world performance of buses retrofitted with CRT DPFs. 18 in-use Euro III technology urban and intercity buses were investigated for a period of 12 months. The influence of the DPF and of the vehicle natural aging on buses fuel economy are analyzed and discussed. While the effect of natural deterioration is about 1.2%–1.3%, DPF contribution to fuel economy penalty is found to be 0.6% to 1.8%, depending on the bus type. DPF filtration efficiency is analyzed throughout the study and found to be in average 96% in the size range of 23–560 nm. Four different load and non-load engine operating modes are investigated on their appropriateness for roadworthiness tests. High idle is found to be the most suitable regime for PN diagnostics considering particle number filtration efficiency.

Introduction

Millions of premature deaths occur annually worldwide due to poor air quality. Several studies have established a relation between inhalation of particulate matter (PM) and adverse health effects (Dellinger et al., 2008; Dockery et al., 1993; Lelieveld et al., 2015; Pope and Dockery, 2006; Ware et al., 1981; B. Wang et al., 2016). (Kumar et al., 2010) summarizing the recent advances concerning the impact of atmospheric nanoparticles on human health. Pagotto et al. (2001) have found metals and other elements responsible for toxicological effects in PM sample associated with vehicle activities. Morawska et al. (2008) reviewed the existing knowledge on ultrafine particles and the consequences of human exposure.

In the effort to mitigate PM emission from the transportation sector, several aftertreatment technologies have been proposed and developed, while the most efficient of them has been shown to be the diesel particle filter (DPF) (Mayer et al., 1998). Due to the relative installation simplicity of this device on in-use vehicles, a massive DPF retrofitting is being performed worldwide, especially in heavy-duty trucks and buses, which can be kept in service for more than 15 years (Boudart and Figliozzi, 2012). DPF retrofit has reportedly led to great particle emissions reduction, usually above 99% (Mayer, 2008; Tartakovsky et al., 2015).

Despite the cleaner exhaust gases, worsening in the fuel economy have been reported when a DPF is used (Alleman et al., 2004; Lapuerta et al., 2012; Lin, 2002; Liu et al., 2011), due

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to the increased backpressure caused by the filter. Climate change and fossil oil availability challenges call for continuous efforts to improve vehicle efficiency (Tartakovsky et al., 2012). Hence, increase in fuel consumption due to DPF could be a serious obstacle. Mikulic et al. (2010)) used a MY2003 Volvo D12 turbocharged diesel engine and an empty DPF can (to overcome increasing backpressure due to PM accumulation in the DPF) operating in the ESC test cycle to investigate the influence of DPF generated backpressure on the engine fuel consumption. A linear correlation between backpressure increase and fuel consumption was observed. For the B50 mode it was found that an increase of one mbar in the backpressure corresponds to 5.61 g/hr increase in the fuel consumption, and for the C75 mode, this value is 7.64 g/hr. In mid-1990s, Stamatelos (1997)) has performed a review of the effect of DPF on the efficiency of vehicle diesel engines. He has focused on investigating the combined influence of backpressure imposed by DPF on the engine and additional energy required for filter regeneration on the overall efficiency of the diesel power plant. Quite a number of studies reported on change in a vehicle fuel economy after DPF retrofitting in real-world usage conditions (LeTavec et al., 2002; Richards et al., 2003). However, a reliable assessment of fuel economy penalty in real-world usage conditions caused by DPF adding into the engine exhaust system remains to be a challenging task due to a need to separate the effects of vehicle aging, changes in driving and ambient conditions, driving style, single vehicle peculiarities, *etc.* This information is very important in light of the massive usage of PDFs in Euro VI vehicles, as well as in DPF-retrofitted older generation heavy-duty diesel vehicles.

Since state-of-the-art engine and exhaust gas after treatment technologies have allowed a drastic decrease in PM emissions, conventional particle mass measurement methods have reached their limits and can't ensure accurate measurement of today's low PM emission levels (Burtscher et al., 2016). Particle number (PN) measuring is found to be a solution, since it is superior to particle mass assessment in terms of resolution, speed and precision, especially for the ultrafine particle fraction, the range where most of the PN concentration (PNC) lies (Kittelson, 1998).

PN as an additional PM measurement parameter is being introduced in vehicles emission legislation. In 1998 the VERT Association has published a list of DPFs that reached 95% PN filtration efficiency in the range from 20 to 500 nm (Mayer et al., 1998). In 2001 the Particulate Measurement Program (PMP) was formed and resulted in development of the UNECE regulation No. 83 revision 4, which led to the implementation of the first PN legislation by the European Union, the Euro 5B standard, with a limit of particles/km for light-duty diesel vehicles, based on standard cycles (Bischof, 2015). A program for heavy-duty diesel vehicles was developed later on. It followed the PMP procedures, and was published in the UNECE Regulation No. 49, introduced in 2011. It stablished Euro-VI emission standards of particles/kWh for the World Harmonized Stationary Cycle (WHSC) and of particles/kWh for the World Harmonized Transient Cycle (WHTC).

Despite the great advance that has been made in regulating vehicle PN emissions, the existing legislation is limited to the type approval of new engines. There is no international legislation that controls PN emission levels of in-use vehicles. The only national legislation prescribing PN measurement for periodic inspection of DPF-equipped engines is applied in Switzerland for off-road and construction machinery (Stäubli and Kropf, 2016). Bischof (2015) reports that transmission smoke meters and opacimeters also reach their limits and are not suitable for tests of diesel engines meeting Euro V or Euro VI standards. Giechaskiel et al. (2014) further confirmed in their comprehensive review that measurement of exhaust gas opacity is not suitable for modern diesel engines because PM emissions are far below the detection limit of conventional smoke meters. They overviewed recent programs dealing with a search for measurement principles that can be suitable for the roadworthiness tests. There was no discussion on suitable engine operating mode/s for particle diagnostics. In a more recent study of Kadijk et al. (2016), total 213 in-use diesel light-duty vehicles with DPF were investigated. The study confirmed the inappropriateness of the smoke measurement for roadworthiness tests of vehicles with DPF. PN measurements at low idle regime were performed and found to be beneficial compared to the smoke measurement. In their latest study Kadijk et al. (2017) tested 14 light-duty vehicles of Euro 3, 4, 5 and 6 generations with a purpose to propose a new roadworthiness emission test procedure aimed at identifying vehicles with a malfunctioning or removed DPF. The vehicles were tested at low and high idle, as well as at free acceleration regimes. Opacity measurements were performed at the free acceleration and high idle modes. PN measurements were carried out at low idle and chassis dyno (NEDC) tests. No attempt was made to separate the influence of engine and DPF. No assessment of particle number filtration efficiency (PNFE) was performed. While most of authors agree on a need to apply PN measurements in the roadworthiness tests, various attempts are still made to develop the improved methods of opacimetry (Kadijk et al., 2016; Axmann et al., 2017). For example, Axmann et al. (2017) suggested a novel multi-wavelength opacimeter for measurement of both NO_x and soot concentrations in the exhaust gas of diesel engines during the periodical inspection tests.

A number of wide-scale bus retrofit projects were performed worldwide. Between others the projects in Berlin, Switzerland, Santiago de Chile, Bogota, Teheran can be mentioned (Lutz, 2013; Mayer et al., 2004; Reinoso, 2011; Cortes et al., 2016). PN measurements were carried out in these projects at different engine operating modes (various loads, low idle, high idle, *etc.*), but information on PN measurement procedure most suitable for roadworthiness tests is still lacking.

The main goals of the present study were to evaluate the impact of DPF-retrofitting on fuel economy of in-use diesel buses during real-world usage conditions and to propose a measurement procedure suitable for PN diagnostics in roadworthiness tests. DPF filtration efficiency in real-world usage, as well as the influence of different parameters on fuel economy are also addressed.

1. Methodology

1.1. Vehicles studied

A pilot group composed of 18 in-use buses of popular models from leading European bus manufacturers were selected for

DPF retrofitting. Nine vehicles were urban buses of MAN NL313F model and the other 9 vehicles — intercity coaches of Mercedes-Benz OC500 model. All the vehicles were produced under the Euro III emission standards, and had traveled a distance typical to their age (1.2–1.6 million km for intercity coaches and 450–580 thousand km for urban buses) at the moment of DPF retrofit. Every vehicle had an original engine and had been appropriately maintained before and during the experiments by the bus operator. The main engine parameters of the studied buses are shown in Table 1.

In-use buses operating in three geographical regions were chosen: Tel Aviv area, Jerusalem area and Haifa area. These regions have different topographies, and might be characterized as flat (averaged road gradient <2%), hilly (averaged road gradient >6%) and mixed (averaged road gradient ~4%), respectively. The vehicles were evenly divided in each area (three urban buses and three intercity coaches in each of them) (Table 2). After the DPF installation, the vehicles were returned to service at their usual routes, at their original sites.

A control group composed of 18 identical vehicles of the same age, type and model as in the pilot group was also defined. The buses of the control group were also divided between the same three areas, in a way equivalent to the pilot group. All the considered buses, both the pilot and the control group were appropriately checked before the experiment start and found to be in a well-tuned condition.

1.2. *DPFs selected for retrofit*

There is a large variety of DPF types and technologies available on the market, which could be more or less appropriate for installation on the selected buses. To choose the most suitable DPF technology for retrofitting in the studied buses, exhaust gas temperatures profile was measured during real-world operating conditions of intercity and urban buses in each of three selected areas. For this purpose, thermocouples were installed in the exhaust manifold, before the bus silencer, of the pilot group buses. The temperature was monitored for a couple of months prior the installation of the DPF.

Considering the measured temperature profiles, a Continuous Regeneration Trap (CRT) technology based on NO_2 soot oxidation (Cooper et al., 1990; Allansson et al., 2002) was selected as the most suitable. CRT DPFs from three leading manufacturers were selected. All of them are VERT-certified DPFs, present the best available technology and appear in the VERT-Filter List (Mayer et al., 2016). Main filter specification data is shown in Table 3.

Table 1 – Main parameters of bus engines.

Bus type	Intercity coach	Urban bus
Bus model	Mercedes-Benz OC500	MAN NL313F
Engine model	OM457	D2866 (LUH 28)
Combustion system	Four-stroke diesel direct injection	Four-stroke diesel direct injection
Air supply system	Turbocharging, intercooling	Turbocharging, intercooling
Emission control strategy	EGR	EGR
Number of cylinders	6	6
Bore × stroke, displacement	128 × 155 mm, 11,967 cm^3	128 × 155 mm, 11,967 cm^3
Compression ratio	18.5:1	19:1
Rated power [kW]	260	228

Table 2 – Selected buses.

Bus code	Topography	Bus type	Bus manufacturer	Distance traveled at DPF installation date (km)
I1	Mixed	Intercity	Mercedes OC500	1,521,700
I2	Flat	Intercity	Mercedes OC500	1,161,895
I3	Hilly	Intercity	Mercedes OC500	1,319,521
I4	Mixed	Intercity	Mercedes OC500	1,451,936
I5	Flat	Intercity	Mercedes OC500	1,441,011
I6	Hilly	Intercity	Mercedes OC500	1,406,971
I7	Mixed	Intercity	Mercedes OC500	1,297,858
I8	Flat	Intercity	Mercedes OC500	1,404,728
I9	Hilly	Intercity	Mercedes OC500	1,581,330
U1	Mixed	Urban	Man NL313F	463,398
U2	Flat	Urban	Man NL313F	451,465
U3	Hilly	Urban	Man NL313F	560,386
U4	Mixed	Urban	Man NL313F	539,626
U5	Flat	Urban	Man NL313F	474,150
U6	Hilly	Urban	Man NL313F	534,047
U7	Mixed	Urban	Man NL313F	568,681
U8	Flat	Urban	Man NL313F	462,893
U9	Hilly	Urban	Man NL313F	577,739

DPF: diesel particulate filter.

1.3. *Experimental setup and particles measurement procedure*

Three measuring campaigns were conducted through the year of the experiments. The first one was performed shortly after DPF installation, the second and the third - approximately 5 and 10 months later, respectively. This approach allowed the assessment of DPF performance over the long period of real-world operating after the retrofitting event together with analysis of different testing procedures over a large amount of measurements.

Four different operating regimes were selected for particle emission measurements. As mentioned in previous studies (Tartakovsky et al., 2015), these regimes reflect in some way real conditions of buses usage. For example, Brown and Rideout (1996) and later on Lanni (2003) showed that a cycle with 65% idling time, sharp accelerations and no cruising was found to be more representative of the actual operation of the buses. Three steady-state regimes (low idle, high idle and full load at 85% of rated speed) and one transient (free acceleration) operating mode were selected for particle measurements. Idling regimes were chosen because of their great contribution to particle emissions, especially in the events of passengers' collection. These regimes allow reducing the time of the measurement and diminishing the uncertainties caused by (Tartakovsky et al., 2015):

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

Table 3 – Main specification data of DPFs.

Bus type	DPF manufacturer 1	DPF manufacturer 2	DPF manufacturer 3
Regeneration technology	CRT	CRT	CRT
FBC supported	No	No	No
Pre catalyst	Stainless steel metal substrate	Platinum oxidation catalyst	Ceramic substrate
Pre catalyst cell density [cpsi]	300	n/a	400
Pre catalyst coating	PGM	Platinum	Platinum
Filter substrate	Cordierite	Cordierite	Sintered Metal Filter
Filter cell density [cpsi]	200	200	Pocket design
Filter coating	PGM	No	Yes (urban) No (intercity)

DPF: diesel particulate filter; CRT: Continuous Regeneration Trap; PGM: platinum group metals; FBC: Fuel borne catalyst.

Free acceleration was selected as a currently used testing regime in smoke roadworthiness tests. Full load regime was chosen because it is one of the most widespread engine operating modes in the bus driving pattern (Tartakovsky et al., 2003).

Full-load measurements were performed with aid of Schenck chassis dynamometer. Measurements duration was limited to approximately 45 sec to reduce tires wear. As mentioned above, in this test the bus was run at 85% of the rated maximum speed at full load.

In all the experiments carried out at steady-state operating conditions, the average value of the measured PN concentration was assumed to adequately characterize the given regime. Each of low-idle and high-idle regime measurements lasted for 60 sec, while the latter was performed by completely pressing the gas pedal, when the vehicle clutch was disconnected (neutral gear shift).

For the transient free-acceleration regime, six consecutive accelerations were performed (as accepted in smoke measurement procedures), when vehicle was run at neutral gear shift. Intervals during free-accelerations allowed engine's speed return to low idle values (typically about 10 sec). A typical free-acceleration test lasted for approximately 100 sec.

The results of free-acceleration measurements were processed and further analyzed using two methods. The first one, referred to as "peaks", considers only the highest PN emissions of every free-acceleration event. Averaging was performed of the highest total PN emissions for every one of the six accelerations. The second one, referred to as "average", considers the average PNC value of the whole measurement. A summary of the operating modes applied in this study for PN measurement is provided in Table 4.

All buses of the pilot and control groups were fueled with ultra-low-sulfur diesel fuel meeting the current Israeli and EU legislation (EN590), with sulfur content below 10 ppm, over the whole experiment duration. A low-ash lubricant oil (sulfated ash content <1% m/m) recommended for heavy-duty diesel vehicles with DPF was used. A warm-up period was allowed prior each measurement. A bus was considered warmed-up when coolant temperature reached 80°C.

Table 4 – Operating regimes studied.

Operating regime	Characteristic	Duration
Low idle	Steady-state	~60 sec
High idle	Steady-state	~60 sec
Acceleration (peaks)	Transient	~100 sec
Acceleration (average)	Transient	~100 sec
Full load	Steady-state	~45 sec

For every bus at each testing operation mode, PNC and size were performed by sampling through the pressure sensor plug. Downstream-DPF measurements were performed by exhaust gas sampling from the bus tailpipe.

The reliability and reproducibility of PN measuring highly depends on the sample conditioning and dilution (Burtscher, 2005). TSI-made Rotating Disk Thermodiluter Thermal Conditioning device 379020A-30, based on the principle described by (Hueglin et al., 1997) was used for sampling, diluting, and conditioning exhaust gas sample prior PN measurement with TSI-made Engine Exhaust Particle Sizer (EEPS) Spectrometer. This allowed PN measurement in accordance with requirements of Particle Measurement Program – PMP (UNECE Regulation 83, Commission Regulation 692/2008). As prescribed in PMP protocol, the sample preconditioning included hot dilution at 150°C, followed by an evaporation tube at 300°C, to remove volatile particle fractions.

TSI-made EEPS Spectrometer 3090 model was used for measurement of particle number concentration and size distribution, after dilution. The EEPS is based on the electrical mobility principle (Johnson et al., 2004). The equipment measures particles from 5.6 to 560 nm with particle size resolution of 16 channels per decade (32 total) and time resolution of 10 Hz. In the reported study, following PMP, nonvolatile particles larger than 23 nm were analyzed to ensure repeatability of obtained results (Giechaskiel et al., 2012). The sample flow admitted into the EEPS-3090 was 10 L/min. The sheath air flow was 39.4 L/min. As showed by X. Wang et al. (2016), the new SOOT matrix recently developed by TSI to improve the EEPS PNC and size distribution measuring accuracy (which was used in our study) provides PN concentration readings in the range of 84% to 96% of those obtained with a scanning mobility particle sizer (SMPS) across a wide range of diesel engine operating conditions.

All the measurements were performed at the bus operator maintenance sites, equipped with a chassis dynamometer. A schematic layout of the experimental setup can be seen in Fig. 1.

DPF particle number filtration efficiency, PNFE, was calculated as follows:

$$\mathrm{PNFE}[\%] = \frac{(\mathrm{TPN_U} - \mathrm{TPN_D})}{\mathrm{TPN_U}} \cdot 100 \quad (1)$$

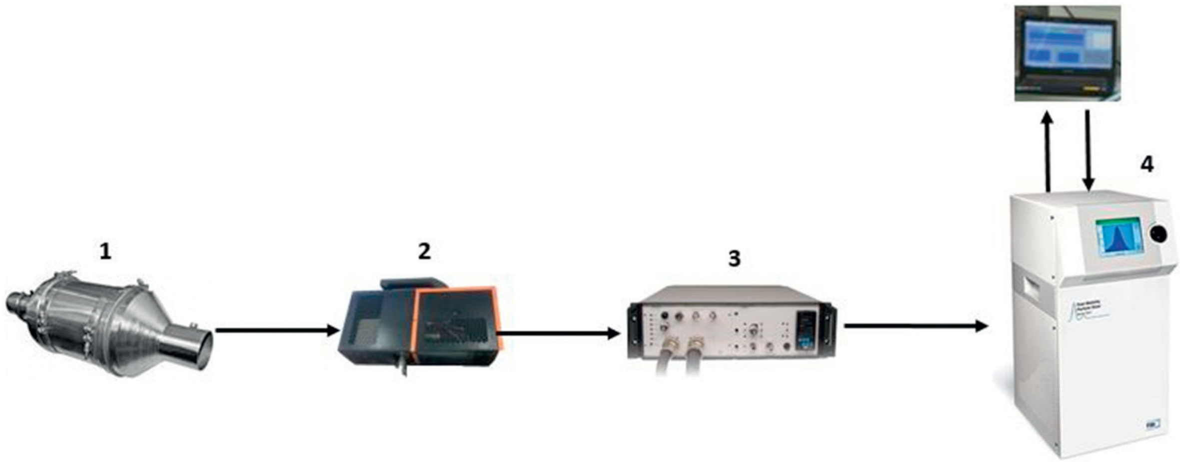

Fig. 1 – Experimental setup. 1: DPF; 2: 379020A-30 Thermodiluter Head; 3: 379020A-30 Thermal Conditioner Air Supply; 4: EEPS 3090. DPF: diesel particulate filter; EEPS: Engine Exhaust Particle Sizer.

where TPN stands for total particle number and the subscripts "U" and "D", for upstream and downstream the DPF, respectively.

1.4. *Fuel economy assessment*

Data on the distance traveled, as well as the amount of diesel fuel consumed by each vehicle in the pilot and the control groups was gained for the period from January 2014 until July 2016. This comprises a total of 31 months, 19 months before the installation of the DPF and 12 months after retrofitting. The average monthly fuel economy FE (in km/L) was calculated by dividing the monthly traveled distance by the amount of fuel consumed during the same period of time. In this way, the monthly-averaged fuel economy of 36 vehicles for 31 months was calculated, resulting in a total of 1116 values. It is known that fuel economy is significantly affected by various factors, like bus driving pattern, topography, ambient conditions, usage of air conditioning, *etc*. For this reason, as large as possible volume of FE data was collected and further processed to compensate for possible day-to-day changes in driving conditions, driving style, single vehicle peculiarities, *etc.* We assume in our further analysis that the joint effect of these factors on buses fuel economy is negligible.

It was expected that the vehicles' FE would be worsening as time passes. In case of a retrofitted bus, this phenomenon is a consequence of the combined effect of the DPF, as well as natural deterioration of the vehicle efficiency due to aging. In order to separate influence on fuel economy of DPF only, natural deterioration of FE due to aging was estimated. For this purpose, evaluation of the average yearly deterioration of fuel economy of all the buses of both the pilot and the control group during the period they worked without the DPF was performed. Monthly fuel economy of each vehicle was compared to the one at the same month, one year later. This yielded in 19 comparisons for each of the buses of the control group (from Jan/2014–Jan/2015 to Jul/2015–Jul/2016) and 7 comparisons for each of the buses in the pilot group (from Jan/2014–Jan/2015 to Jul/2014–Jul/2015). By means of that 468 comparisons for natural fuel economy deterioration (FED) due to aging were obtained.

Fuel economy deterioration was calculated according to the equation below:

$$\text{FED}\ [\%] = 100 \cdot \frac{\text{FE}_1 - \text{FE}_2}{\text{FE}_1} \tag{2}$$

where FE_1 expresses a monthly fuel economy value, and FE_2 expresses fuel economy of the same month, one year later.

After that, monthly-averaged results of fuel economy of the pilot group from August 2015 to July 2016 (after DPF retrofitting) were compared with those of the same months, one year earlier. As already noted, the obtained deterioration in fuel economy was assumed to be due to the combined effects of natural aging and impact of the DPF. By means of that, 216 comparisons for FED values due to aging + DPF were obtained, 108 comparisons for each bus type.

In order to assess FE penalty due to DPF, the mean value of FED due to aging (FED_{ag}) was calculated based on the previously generated 468 comparisons. The mean FED values were calculated separately for the urban and intercity buses (based on 234 results for each bus type). Similarly, the mean value of FED due to aging + DPF ($FED_{ag + DPF}$) was calculated using the appropriate set of 216 comparisons, 108 for each bus type. Finally, fuel economy deterioration due to DPF only (FED_{DPF}) was calculated as a difference between the respective values of $FED_{ag + DPF}$ and FED_{ag}:

$$\text{FED}_{\text{DPF}} = \text{FED}_{\text{ag+DPF}} - \text{FED}_{\text{ag}} \tag{3}$$

In addition to the influence of DPF on FE penalty, also effects of the vehicle type (urban or intercity), air conditioning switching-on and topography were assessed based on the gained real-world FE data.

2. Results and discussion

2.1. *Fuel economy*

The monthly-averaged fuel economy of the 36 buses in both the pilot and control group was calculated for a period of

31 months (19 months before DPF retrofit and 12 months after it), yielding a total of 1116 results. A series of analyses were performed to investigate the impact of various factors on buses fuel economy. Fig. 2 presents the monthly-averaged fuel economy of all the 36 buses in both the pilot and the control group categorized by vehicle type: urban or intercity.

As expected, intercity vehicles have a better fuel economy, compared to urban buses. In fact, the average value of intercity coaches' fuel economy for the analyzed period was found to be 2.35 km/L, compared to 1.68 km/L for urban buses. This is mainly due to the higher percentage of engine operating under more efficient regimes and subsequently lower share of idling in the driving pattern of intercity buses (Tartakovsky et al., 2003).

As can be seen from Fig. 2, a wavy cyclic variation in fuel economy of buses over year was observed. It can be noticed that fuel economy substantially improves from September, reaching a best (maximum) value at about January or February. Then it decreases, reaching worst (minimal) values during the summer months. This pattern is observed for the whole considered period (from Jan 2014 to Jul 2016) for the vehicles in both the pilot and the control group.

The reason of this phenomenon is the intensive usage of air conditioning during the hot summer months in Israel. Air conditioning systems are activated on day-to-day basis during this season. Compared to hot summer, winter in this area is usually featured by a mild weather, and buses usually operate without air conditioning and without heating. An and Stodolsky (1995) showed that air conditioning (AC) is the most energy-consuming auxiliary device on a vehicle, causing the highest penalty in fuel consumption. To investigate the impact of the AC system on fuel economy, (Lee et al., 2012) used a four-cylinder port injection gasoline engine controlled by an eddy-current dynamometer. They found that AC operation increased the fuel consumption by 90% maximum compared with the operation without air-conditioning during the idling. For loaded operation, the relative increase of fuel consumption due to air conditioning is naturally smaller because of its smaller share in a total power demand. In our study, the average bus fuel economy during the three hottest months of the year (June 2014 to August 2014) was compared with that of the three coldest months (December 2014 to February 2015). During this period, DPFs were not installed yet in any vehicles. All the 36 vehicles were considered for calculating the average values of fuel economy. We found that fuel economy raises from 2.34 in summer to 2.44 km/L in winter and from 1.63 to 1.77 km/L for intercity coaches and urban buses, respectively. Assuming that this difference is caused by air conditioning, AC impact on fuel economy worsening (ΔFE_{AC}) was calculated according to Eq. (4), and found to be 4.0% and 8.2% for intercity and urban buses, respectively. This result confirms similar findings of previous researches (Lee et al., 2012) that relative impact of AC on fuel economy increases with engine load reduction.

$$\Delta FE_{AC} = 100 \cdot \frac{FE_{win} - FE_{sum}}{FE_{win}} \% \tag{4}$$

Here FE_{win} is fuel economy in winter and FE_{sum} is fuel economy in summer.

Another finding obtained as a by-product of the performed study, is the influence of topography on bus fuel economy. As previously discussed, buses in the pilot group were evenly divided into the regions with flat, hilly and mixed topography. Vehicles of the control group followed the same topography and driving patterns.

The average fuel economy values of the 36 vehicles of both control and pilot groups were used for this analysis. Fig. 3 provides the monthly fuel economy averages for urban buses as a function of operating area. As expected, buses run in the region characterized by a flat terrain, presented the best fuel economy results followed by those for mixed and hilly topography. In fact, the average fuel economy over the period of 31 months provided values of 1.79, 1.67 and 1.60 km/L for the buses run in the flat, mixed and hilly area, respectively. The relative difference in FE was found to be higher than 10% between the hilly and the flat bus driving patterns.

As discussed in the Methodology section, two independent factors were assumed as contributing to deterioration in fuel

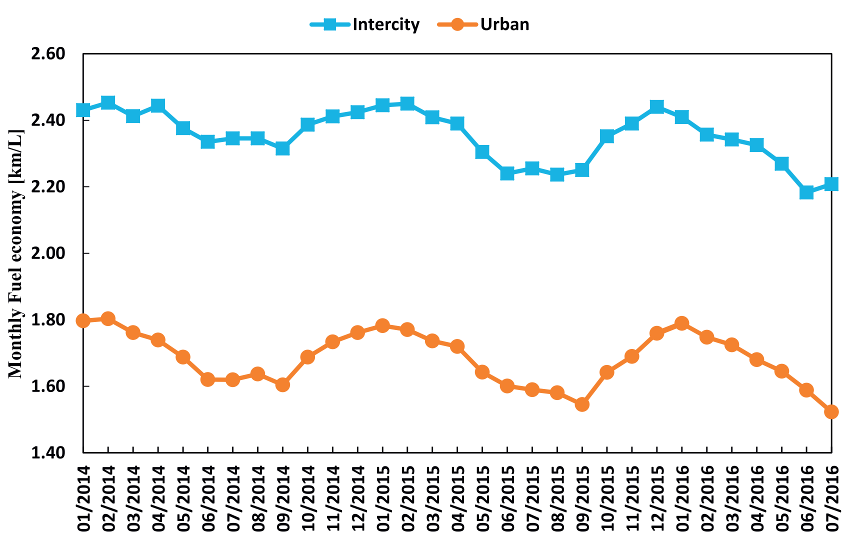

Fig. 2 – Monthly fuel economy of buses per vehicle type.

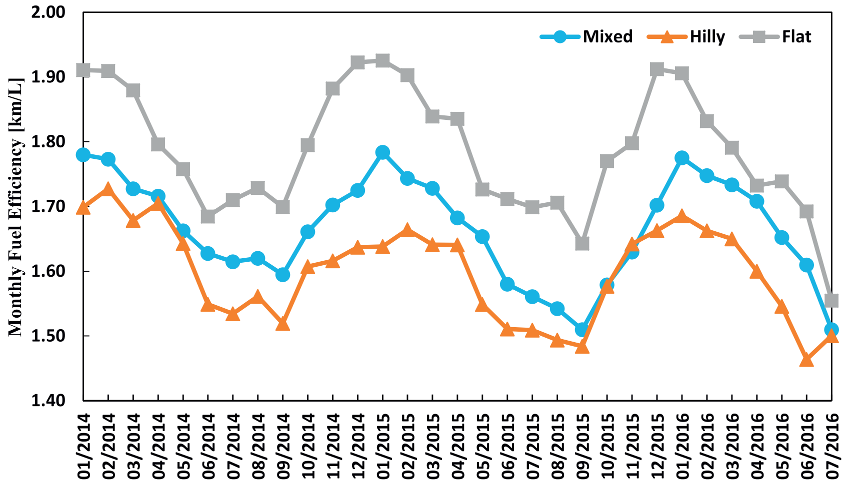

Fig. 3 – Monthly fuel economy of urban buses from both groups per topography: mixed, hilly, flat.

economy: the natural deterioration of the vehicles due to aging and the usage of DPF. To separate these two effects, a method of evaluating the annual deterioration in fuel economy due to aging was implemented for the period before DPF retrofitting. This was done by taking into account all the available data for both the pilot and the control groups of buses. Later on, the fuel economy deterioration of the pilot group referring to the period it worked with the filters (and thus both factors contributed to FE worsening) was assessed. The difference in the results was considered as the effect of the DPF installation solely (Eq. (3)).

The fuel economy deterioration of the pilot group referring to the period it worked with the filters (FED_{ag+DPF}) was found to be 3.1% and 2.0% for intercity and urban buses, respectively. These results match closely the ones obtained by (Lanni, 2003), who found that the fuel economy exhibited about 3% variation with DPF-equipped vehicles. The results of the average of the 468 comparisons where no DPF was used yet yielded the values of annual fuel economy deterioration due to natural aging only (FED_{ag}) of 1.2% and 1.3% for intercity and urban buses, respectively. Following Eq. (3), the effect of the DPF on fuel economy penalty was found to be 1.8% and 0.6% for intercity and urban buses, respectively. Fig. 4 presents the obtained FED results.

As can be seen, the net influence of DPF on FE penalty was found to be substantially lower than 3% in real-world usage conditions. As expected, the obtained fuel economy penalty due to DPF installation is lower in urban buses. The latter run at lower engine speeds and loads compared to intercity coaches, which leads to lower volumetric flow rates of exhaust gas through the filter and as a result to lower pressure losses in DPF. DPF: diesel particulate filter; FE: fuel economy.

2.2. *Filtration efficiency*

Eighteen buses of the pilot group were tested at four operating regimes in three measurement campaigns, both upstream and downstream the DPF. Two different analyses were performed out of the free acceleration regime (average and peaks). Unfortunately, due to technical problems, it was not possible to operate the chassis dynamometer in one site (with flat topography) during the first round of measurements. For this

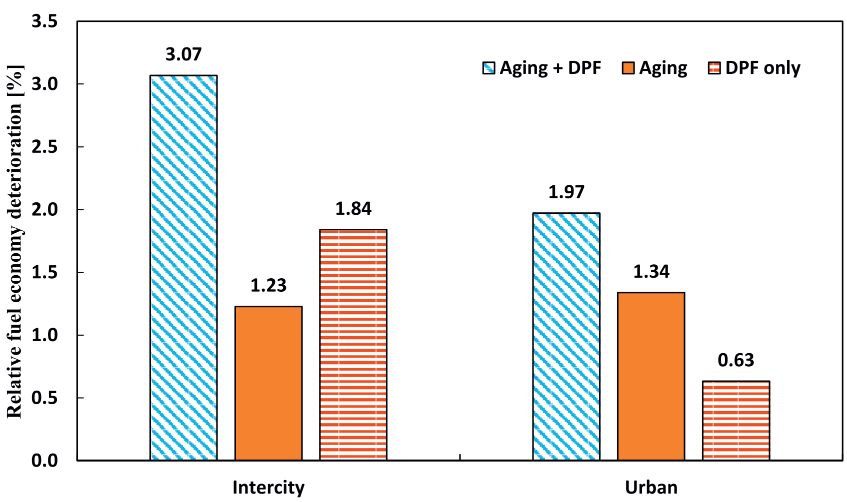

Fig. 4 – Impact of natural aging and DPF retrofit on fuel economy deterioration.

reason, no load measurements were performed for the six buses in the first measurement campaign. Therefore, the overall number of measurements performed was 528, instead of 540. The overall PN filtration efficiency was found to be 96%.

Particle matter emissions were also categorized according to the testing mode. 108 measurements were performed at the regimes of low idle, high idle and free acceleration (peaks and average). 96 measurements were performed at the load regime (due to the reasons explained above). Half of the measurements refer to PN sampling upstream the DPF and the other half - downstream it.

The averaged PN emissions of the vehicles in the pilot group systemized per testing mode are presented in Fig. 5. Analysis of the measured data before DPF reveals that free acceleration (peaks) regime is associated to the highest PN emissions, with an average value of approximately 5.88×10^7 cm^{-3}. This result is followed by load, high idle, acceleration (average) and low idle, with respective average PNC values of about 5.84×10^7, 5.39×10^7, 2.98×10^7 and 2.03×10^7 cm^{-3}. These results clearly show the impact of engine testing mode on the obtained *PN* concentration. In fact, the measured total PNC during free acceleration (peaks) can be almost three times as high as that during low-idle operating.

Total PN concentrations downstream the DPF are, as expected, significantly lower. It should be noted that total PNC measured after the DPF are organized from higher to lower as a function of the testing mode following the same order as were measured before the DPF. The obtained average total *PNC* are about 1.42×10^6, 1.39×10^6, 1.00×10^6, 9.19×10^6 and 8.03×10^6 cm^{-3} for the free acceleration (peaks), full load, high idle, free acceleration (average) and low idle testing modes, respectively. Note, that the mean PNC measured in the transient no-load free acceleration (peaks) testing mode were found to be very similar (in fact, somewhat higher) compared to the full-load testing mode. This finding further confirms a great contribution of transient operating modes to particles formation usually caused by instantaneous disruptions in air-fuel mixture preparation.

Table 5 presents the mean PNFE values and standard deviation numbers averaged for the whole pilot group over the whole test period and categorized per bus type, as well as per testing mode. As can be seen from Table 5, the overall mean PNFE was found to be close to 96% with the standard deviation of 8.6%. No reduction in particle number filtration efficiency over the pilot test period was detected. Moreover, a slight trend of mean PNFE improvement (from 95% to 97%) was observed. The mean PNFE and its standard deviation are almost the same for urban buses and intercity coaches. This picture changes when various testing modes are considered. Very high and quite similar PNFE values, above 96% were measured for all the tested operating modes, excluding low idle. For the latter PNFE of 90% only was obtained. In addition, the low idle PNFE standard deviation stands at 16.2%, while high idle PNFE results are far more stable, providing 3.6% standard deviation only. Higher standard deviation of *PN* concentrations at low idle is a result of a less stable engine operation at this regime with usually much higher cycle-to-cycle variability.

Typical examples of particle size distribution, as were measured for the urban buses and intercity coaches upstream and downstream the DPF are shown in Figs. 6 and 7.

Fig. 6 shows the typical PN size distribution at the five studied testing modes for the urban bus before (upstream) and after (downstream) the DPF. A peak in the nuclei mode emissions is more noticed for the low idle regime, with values of approximately 6.1×10^7 d*N*/dlog*Dp*. This is explained by emission of lubrication-originated metal oxide particles (Mayer et al., 2010, 2012) and is boosted by lower temperatures and longer residence time, typical for the low idle regime. Agglomeration mode particle emissions, however, are dominant at the high idle and acceleration (peaks) regimes, with values of approximately. 1.1×10^8 dN/dlog*Dp*. This can be explained by the agglomeration phenomenon of smaller particles, boosted by the very high total *PN* concentration associated with these regimes. Actually, *PN* size distribution at those two regimes is fairly similar, with a slight shift to larger particle sizes at the acceleration (peaks) regime. At load and acceleration (average) regimes, PN values of about 4.0×10^7 d*N*/dlog*Dp* were measured for the agglomeration mode. Even though high idle, acceleration (peaks), and load regimes are all associated with high engine speed, PN concentration peaks are higher for the former two.

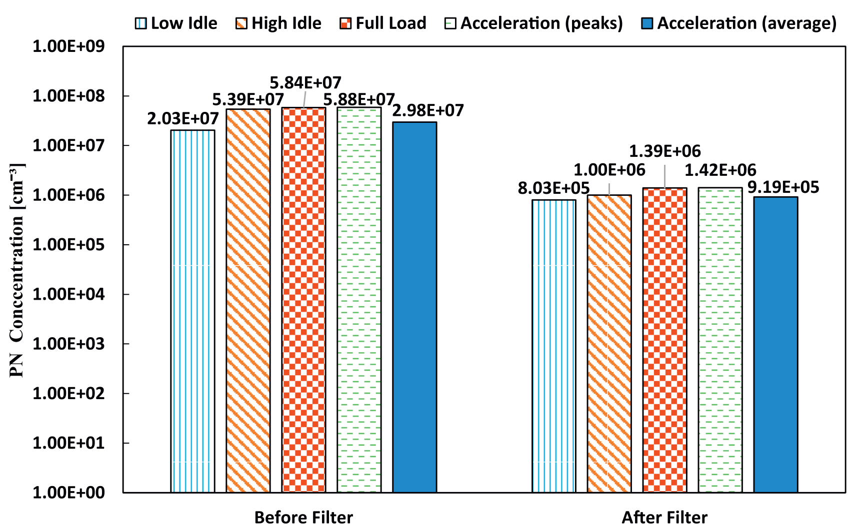

Fig. 5 – Average total PN concentration as a function of testing mode. PN: particle number.

Table 5 – DPF filtration efficiency and standard deviation per category.

	PNFE average (%)	PNFE standard deviation (%)
Overall	95.5	8.6
Intercity	95.8	8.6
Urban	95.3	8.5
Full load	97.2	4.1
Free acceleration (average)	96.4	3.7
Free acceleration (peaks)	96.6	4.4
High idle	97.5	3.6
Low idle	90.1	16.2

DPF: diesel particulate filter; PNFE: particle number filtration efficiency.

This is a consequence of different conditions influencing the intensity of nanoparticles growth and accumulation. These conditions are: different air excess and temperature of engine-out exhaust, different residence times of the nanoaerosol from engine-out to the sampling- and dilution point, but first of all - different composition of the nanoaerosol in different engine operating modes. According to the previous experience (Mayer et al., 2010, 2012; Czerwinski et al., 2006, 2009), the authors postulate that for low idle, high idle and acceleration there is a higher share of lube oil and metal oxides, while for load conditions there is a higher share of carbonaceous elements originating from the heterogeneous combustion process.

After-DPF PN concentrations are drastically lower, as compared with the PN values measured before the DPF. All the five studied testing modes presented low PN concentrations for all the measurement range, with an exception of a peak in the nuclei mode particle size. However, the obtained PN concentration peak values after DPF are still about one order of magnitude lower than those before the DPF. Moreover, it can be noticed that the high idle regime resulted in a slight peak in PN concentration in the accumulation mode particle size range. It should be noticed, however, that while

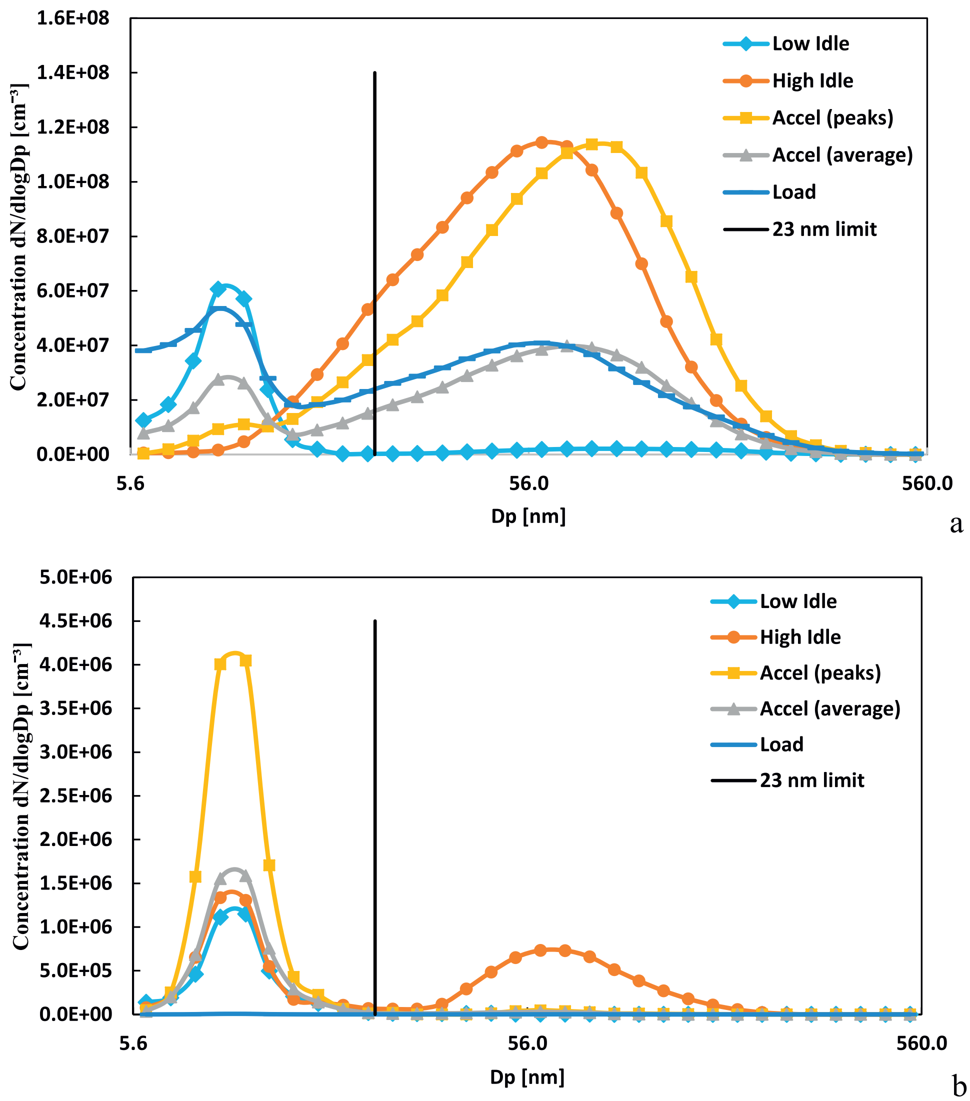

Fig. 6 – PN size distribution of an urban bus for different testing modes before (a) and after (b) DPF. In the reported study nonvolatile particles larger than 23 nm were analyzed to ensure repeatability of obtained results. PN: particle number; DPF: diesel particulate filter.

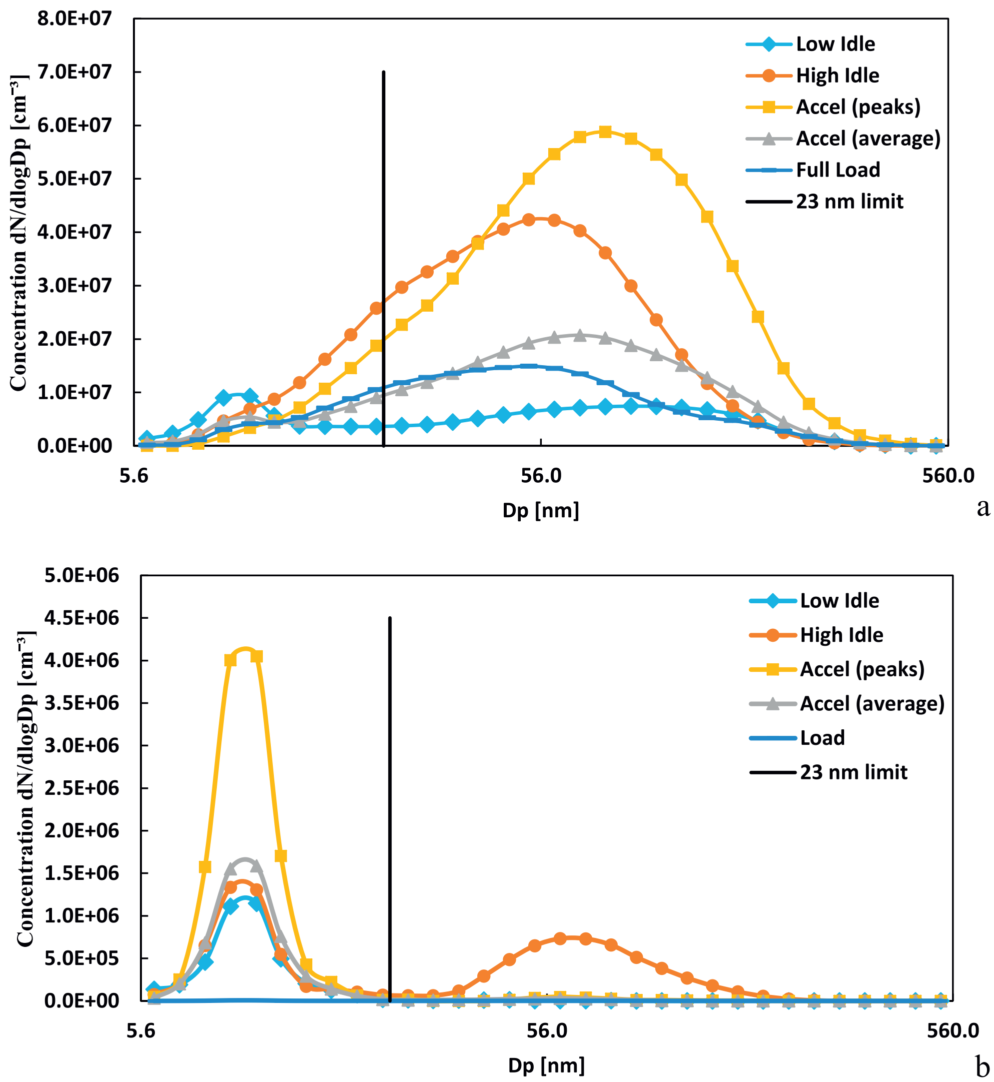

Fig. 7 – PN size distribution of an intercity bus for different testing modes before (a) and after (b) DPF. In the reported study nonvolatile particles larger than 23 nm were analyzed to ensure repeatability of obtained results. PN: particle number; DPF: diesel particulate filter.

every vehicle resulted in slightly different results, the accumulation mode peak in the high idle regime is not a universal trend.

A similar analysis can be performed for the intercity coach, as presented in Fig. 7. For this vehicle, the first thing that may be noticed is the reduced contribution of the nuclei mode particles before DPF, when compared with the urban bus. This is due to different engine geometry, different engine wear (including turbocharging system), operational parameters, like EGR, and processes of lubricating the cylinder wall and blow-by, resulting in a different PN size distribution profile. A small peak of only about 9.3×10^6 dN/dlogDp is observed for the low idle mode. However, peaks at the agglomeration mode are present for all other regimes. Acceleration (peaks) present the highest values, reaching 5.9×10^7 dN/dlogDp, followed by high idle, with emissions of about 4.2×10^7 dN/dlogDp. Acceleration (average) and load regimes follow.

After DPF, the similar effects, as for the city bus (Fig. 6) were observed. There are concentration peaks in nuclei mode in the size range of 10 nm indicating a lower filtration efficiency of the DPF in this domain. This result contradicts the filtration theory presuming very efficient diffusion deposition of small particles. More research is required to clarify a reason of this phenomenon. Of course, the question remains whether eventually some re-nucleation from the gaseous to the liquid or semisolid phase happens in the DPF, like it is known about the sulfates. In this context, even with low-sulfur fuels, the DPF stores some sulfates during the long operation and may release them in certain operating conditions.

As seen from Table 5, no sensible differences in the obtained values of particle filtration efficiency between the urban buses and intercity coaches were found. All the tested best available technology (BAT) DPF types showed the similarly high particles filtration efficiency. A valid assessment of topography effects on the filtration efficiency values was not possible due to the low number of buses of the same type run in the same area (only three buses of each type in each area).

2.3. *Testing regime for roadworthiness tests*

PN measurement has been shown to be of fundamental importance for control of particle matter emissions of modern vehicles equipped with state-of-the-art engine and after treatment technologies (Giechaskiel et al., 2014). For this reason, PN measurement has been made compulsory for type approval of new vehicles under the European Union standards. Moreover, future legislation requiring PN measuring is also in progress in other parts or the world and for other mobile sources, like construction machinery and aircrafts (Bischof, 2015). Considering wide and continuously expanding spread of diesel (and in the future, probably gasoline) particle filters in road- and off-road vehicles, PN control should be also included as an inherent part of roadworthiness tests to efficiently monitor a technical state of particle control systems of in-use vehicles (Giechaskiel et al., 2014).

As PN diagnostics is expected to be added to the roadworthiness tests of in-use diesel vehicles equipped with DPFs, the most suitable testing mode should be chosen together with suitable PN-measurement technique. The testing regime to be selected must represent in some way real driving conditions, be easy to perform and control, require minimum equipment, as minimum as possible requirements to manpower qualification and be highly reproducible. PNFE assessment in periodic technical inspection (PTI) tests is important because it allows separation of engine- and DPF-related effects on particle emission. A tailpipe PN measurement is always the product of a joint engine and DPF influence, and does not allow a proper diagnostics of reasons leading to elevated PN emissions. PNFE assessment in PTI tests can be relatively easily performed through standardization of size and location of the probe connection fitting upstream DPF. In our further analysis of most suitable regime for PTI PN test we will consider PNFE assessment.

The low idle testing mode is the easiest, less expensive and well-reproducible engine operation mode that does not require special operator skills, since no interaction with a driver is required at all. However, PNFE values obtained at low-idle conditions relatively poorly represent those at higher speed and load, as well as in transient conditions (Table 5). Moreover, less stable engine operation at this mode can result in higher variability of the obtained PNFE values, standard deviation of PNFE at low idle was found to be above 16% compared with approximately 4% at all other considered testing modes (Table 5).

High load testing mode is, in a certain way, a better representation of real driving conditions, considering the typical bus driving patterns (Tartakovsky et al., 2003). Nonetheless, it requires the usage of a complicate and expensive equipment, the chassis dynamometer. This test requires highly qualified operators to run the tested vehicle and to operate the dyno. Considering variations in operators' skills and the test complexity, it supposed to be less reproducible. Moreover, adding more instrumentation to the measuring procedure increases the uncertainties associated with the measuring, lowering the test robustness. Clearly, running a vehicle on the chassis dynamometer presumes higher costs, tire wear and test safety issues.

The free acceleration testing mode is widely used nowadays in roadworthiness procedures for smoke measurements. Thus, applying it for PN measurement that should replace the smoke control could be considered as a natural solution, because it will not require any change in the currently used vehicle testing procedure. An additional well-known benefit of this testing mode that it represents in some extent a transient event known as substantially affecting particle matter formation and emissions. This testing mode does not require any chassis dynamometer with an appropriate reduction of investment and maintenance costs. Both the considered analysis methods, free acceleration (average) and free acceleration (peaks), produce PNFE values very close to the full-load test results (Table 5). However, the obtained results, similarly to smoke test, heavily depend on operator's skills (a way and a rate the gas pedal is pressed) and thus the results reproducibility is compromised. This testing mode produces the most operator-dependent results compared to any other considered counterpart. In addition, the free acceleration mode is the most time-consuming one (Table 4).

The high idle testing mode is highly- reproducible, similarly to the low-idle test. No special skills of operator are needed, because the latter is required to simply keep the gas pedal fully pressed during all the test length. As compared to low-idle mode, high idle is a much more stable regime, standard deviation of PNFE at this mode was found to be 3.6% only compared with 16.2% for low idle (Table 5). There is no need in a chassis dynamometer or any other additional equipment. The test duration is equal to this one of the low-idle test. Furthermore, despite being a steady-state test, it showed PNFE values very similar to the load and the transient free acceleration testing modes (Table 5). The measured PN size distribution in this testing mode in most of the experiments was found to be closer to that one in the transient operation compared to the low-idle test (Figs. 6, 7).

Therefore, out of the studied testing modes, high idle proves to be the most suitable testing regime for roadworthiness tests of vehicles equipped with DPFs. PNFE assessment during such a test is worthy for an appropriate diagnostics.

2.4. *DPF effects on backpressure, vehicle performance and maintenance routine*

Due to the critical importance of backpressure monitoring, pressure sensors were installed in each of the retrofitted buses in the pilot group and placed just upstream the DPFs. Pressure was measured with a frequency of 0.1 Hz. Pressure sensors worked only when the engine was operating.

Readings from pressure sensors installed onboard the buses before DPF were continuously monitored and analyzed. The backpressure build-up, during 12 months of continuous operation, was far from reaching the alarm value (200 mbar), though a trend of slow backpressure rise was observed because of ash accumulation. After 12 months of real-world operation, the backpressure values in the studied 18 buses did not exceed 75 mbar. Note that periodic DPF service cleaning is to be performed to remove noncombustible ash and enable durable filter operation. Periodicity of DPF cleaning is defined by filter manufacturer (typically 1–1.5 year for buses).

The maintenance actions of the vehicles from the pilot group were carefully compared with those of the control group. Frequency of the maintenance operations was also compared.

No abnormalities were found in both the frequency and the content of maintenance operations performed with the vehicles of the pilot group, as compared to the ones in the control group. Moreover, the company's drivers didn't report any deterioration or worsening in engine performance or drivability.

These results further confirm those found by (Lanni, 2003), who also didn't notice any adverse effect of DPF on the operation, reliability or maintainability of the retrofitted vehicles after nine months of operation.

3. Conclusions

The effect of the DPF on fuel economy was separated from the fuel economy deterioration caused by natural aging of the vehicles. It was found that FE worsening due to aging solely is about 1.2% and 1.3% for intercity and urban buses, respectively. DPF was shown to result in the real-world fuel economy penalty of 1.8% and 0.6% for intercity coaches and urban buses, respectively. This *FE* penalty is much lower compared with air conditioning and topography effects. It was noticed that air conditioning usage leads to increase in fuel consumption by approximately 4% and 8% for intercity and urban buses, respectively. Urban buses operating in a hilly topography consume more fuel than those running in flat-terrain regions by 10%.

The results of this study further confirm high efficiency of DPF in particle emissions mitigation. The overall mean PNFE was found to be approximately 96%. No reduction in particle number filtration efficiency over the pilot test period was detected. No sensible differences in the particle filtration efficiency between the urban buses and intercity coaches were found. All the tested BAT DPF types showed the similarly high values of PNFE.

PNFE assessment in PTI tests is important because it allows separation of engine- and DPF-related effects on particle emission. PNFE assessment in PTI tests can be relatively easily performed through standardization of size and location of the probe connection fitting upstream DPF.

High-idle testing mode was found to be the most suitable for *PN* diagnostics in future roadworthiness tests of vehicles with DPF. As compared to low-idle mode, high idle is a much more stable regime, standard deviation of PNFE at this mode was found to be 3.6% only compared with 16.2% for low idle.

The backpressure build-up, during 12 months of continuous operation, was far from reaching the alarm value (200 mbar), though a trend of slow backpressure rise was observed due to ash accumulation. After 12 months of real-world operation, the backpressure values in the studied 18 buses did not exceed 75 mbar. No abnormalities were found in both the frequency and the content of maintenance operations performed with the vehicles of the pilot group, as compared to the ones in the control group. No reports on deterioration or worsening in engine performance or bus drivability were obtained.

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