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Performance of in-use buses retrofitted with diesel particle filters

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Abstract

Inhalation of combustion generated nanoparticles leads to major adverse health effects. Public road transportation heavily depends on diesel fueled vehicles, which greatly contribute to air pollution in urban centers. Retrofitting polluting older buses with diesel particulate filter (DPF) is a cost-effective measure to quickly reduce particulate emissions. This study experimentally analyses the impact of DPF retrofitting on particulate emissions and engine performance aspects of in-use diesel buses. DPFs from three different major manufacturers were installed in 18 urban and intercity Euro III buses of a major Israeli bus company. Particulate number (PN) concentration and size distribution were measured both before and after DPF at different engine operating regimes. The average increase in fuel consumption due to DPF retrofitting was measured to be less than 2.5%, and backpressure increase is about one third of the acceptable limit. No deterioration of buses engine, as well as vehicle drivability were detected. The average reduction in total PN emissions was found to be higher than 97%, with no substantial difference between the different DPF manufacturers.

Keywords: diesel particulate filter, Road transport, buses engine.

1 Introduction

The link between inhalation of particulate matter and adverse health effects has been extensively studied and is well documented (Dockery et al. (1993), Pope III and Dockery, (2006), Lelieveld et al. (2015) and Ware and Thibodeau (1981)).

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Boffetta and Silverman (2001) and Vermeulen et al. (2014) have related the exposure to diesel engine exhaust with cancer incidence. Nonetheless, only relatively recent studies have established the connection with particulate size, suggesting that the smaller the particles, the greater the toxicity, as indicated by Dellinger et al. (2008).

Road transport represent a great challenge in attempts to achieve better air quality levels. It is the main source of air pollution in Israel’s cities and population centers, while public transportation in the country, both urban and intercity, is based almost entirely on diesel engines.

Exhaust emission regulations have progressively became more constrict in the last years, especially since the advent of the European emission standards. However, heavy-duty diesel engine vehicles may be kept in service for periods as long as 15 years or more. For example, approximately a half of Israeli buses fleet is composed of Euro III or older technology vehicles. As a result, their emission control technologies become obsolete and they turn into a major source of particulate emissions. Retrofitting older in-use buses with recently developed technologies, such as DPF, is a cost-effective measure to reduce particulate matter emissions, Mayer (2008), Tartakovsky et al. (2004).

The main goals of this study were to evaluate the reduction in nanoparticle emissions of in-use diesel buses retrofitted with DPF and to assess the impact of retrofitting on the buses performance in real-world usage conditions.

2 Methodology

Vehicles used

For the purpose of the study, a pilot group composed of 18 in-use buses from a major Israeli bus company were selected for DPF retrofitting. 9 of them were urban buses and 9 intercity coaches. Popular models from leading European bus manufacturers were chosen for retrofitting. All the vehicles were produced under the Euro III emission standards, and had travelled a distance compatible with its age. Every vehicle had an original engine and had been submitted to appropriate maintenance. The main engine parameters of the tested buses are shown in Table 1.

A control group composed of 18 identical vehicles was also defined. Data on fuel consumption, engine performance, maintenance and bus drivability aspects of both groups were compared. By means of that, it was possible to isolate the effect of the DPF retrofitting from the natural aging of the vehicles. All the considered buses, both the pilot and the control group were appropriately checked before the test and found to be in a well-tuned condition.

The content of maintenance operations, as well as their frequency, were monitored, for vehicles in both the pilot and the control group. The obtained results were compared, and abnormalities in maintenance activities were searched.

After driving the DPF-retrofitted buses, experienced bus drivers were asked to fill a simple questionnaire about their impressions on the bus performance and engine behavior.

Table 1: Main parameters of bus engines

Parameter	**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
Number of cylinders	6	6
Bore × Stroke, Displacement	128 × 155 mm, 11967 cm^3	128 × 155 mm, 11967 cm^3
Compression ratio	18.5:1	18:1
Rated power [kW]	260	228

In-use buses from three regions were chosen: Tel Aviv area, Jerusalem area and North area. These regions have different topographies, and might be characterized as flat, hilly and mixed, respectively. The vehicles were evenly divided in each area (three urban buses and three intercity coaches in each of them). After DPF installation, the vehicles were returned to service at their usual routes, at their original sites.

Ultra-low-sulfur diesel fuel, with sulfur content not exceeding 10 ppm, was used in the buses, in accordance to the EU practice. High quality low-ash lubricant oil, recommended for heavy-duty diesel vehicles with DPF was used in the bus engines.

There is a large variety of DPF types and technologies, with different characteristics, which could be more or less appropriate for installation on the selected buses. In order to choose DPF type suitable for retrofitting in the tested buses, temperature profiles of exhaust gas before the bus silencer have been measured. For this purpose, thermocouples were installed in the exhaust manifold of the selected buses, and the temperature profile was monitored for a couple of months. As an example, Figure 1 shows the obtained temperature profile for bus I3 in the period from January to March 2015

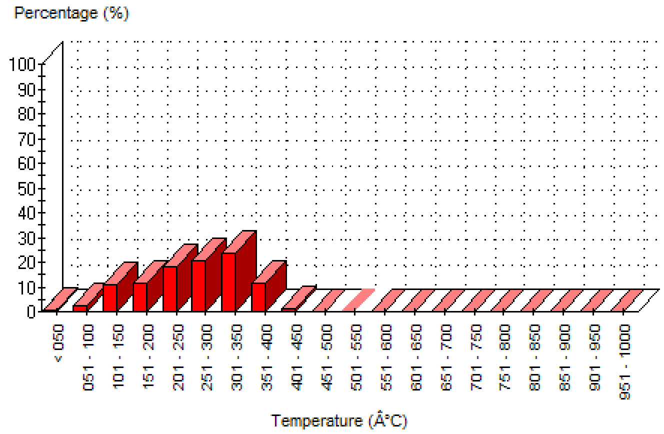

Figure 1: Exhaust gas temperature profile of bus I3

As can be seen from Figure 1, the temperature of the exhaust gas is higher than 100°C, 200°C, 300°C and 400°C during 97%, 75%, 36% and 1% of total usage time, respectively. Moreover, the mean temperature during engine operation was found to be 258°C.

DPFs selected for retrofit

Only VERT-certified DPFs, as published in the VERT-Filter List, were selected for the experiment. Filters from three leading manufacturers were selected. The different filters were evenly divided by area and bus type, as can be seen in Table 2.

The regeneration mechanism used by all of the chosen filters is based on the passive regeneration of Continuous Regeneration Trap (CRT) technology, developed by Johnson Matthey, Cooper et al. (1990) and Allansson et al. (2002). With this method, the accumulated soot is continuously oxidized using NO_2-oxidation mechanism.

Table 2: Selected Buses

Bus Code	**Area**	**Bus Type**	**Bus Manufacturer**	**DPF Manufacturer**	**Distance travelled at DPF installation date [km]**
I1	North	Intercity	Mercedes OC500	"A"	1,521,700
I2	South	Intercity	Mercedes OC500	"A"	1,161,895
I3	Jerusalem	Intercity	Mercedes OC500	"A"	1,319,521
I4	North	Intercity	Mercedes OC500	"B"	1,451,936
I5	South	Intercity	Mercedes OC500	"B"	1,441,011
I6	Jerusalem	Intercity	Mercedes OC500	"B"	1,406,971
I7	North	Intercity	Mercedes OC500	"C"	1,297,858
I8	South	Intercity	Mercedes OC500	"C"	1,404,728
I9	Jerusalem	Intercity	Mercedes OC500	"C"	1,581,330
U1	North	Urban	Man NL313F	"A"	463,398
U2	South	Urban	Man NL313F	"A"	451,465
U3	Jerusalem	Urban	Man NL313F	"A"	560,386
U4	North	Urban	Man NL313F	"B"	539,626
U5	South	Urban	Man NL313F	"B"	474,150
U6	Jerusalem	Urban	Man NL313F	"B"	534,047
U7	North	Urban	Man NL313F	"C"	568,681
U8	South	Urban	Man NL313F	"C"	462,893
U9	Jerusalem	Urban	Man NL313F	"C"	577,739

Measurement procedure

To assess how the influence of DPF retrofitting varies with time, three measuring rounds were planned. The first one shortly after DPF installation, and the second and the third about 4 and 9 months later, respectively. The data presented on this paper does not include the third measuring round. Different operating regimes were selected for particle emissions measurements. According to Tartakovsky et al. (2015), these regimes reflect in some way real conditions of buses usage. Three steady-state regimes (low idle, high idle and 85% of rated speed at engine’s full load) and one transient (free acceleration) operating mode were selected for measurements carrying out. Idling regimes were chosen because of their great contribution to particle emissions, especially in the events of passengers' collection. Table 3 presents the bus operating modes applied in the tests. For the load-regime measurements, experienced dyno-operators and bus drivers operated the vehicles over a chassis dynamometer, used to impose load on the wheels. Due to the difficulty to sustain steady-state operation, fluctuations on the engine speed, load imposed on the wheels and on bus velocity were perceived, even after the goal load was reached. Fluctuations, however, were usually small, as can be seen in Table 3.

Table 3: Operating regimes of the buses tested

	Low Idle	**High Idle**	**Free Acceleration**	**Load**		
Bus Number	**Engine speed [rpm]**	**Engine speed [rpm]**	**Engine speed [rpm]**	**Engine speed [rpm]**	**Power on wheels [kW]**	**Minimum Bus velocity [km/h]**
I1	550	1700	550-1700	1600-1200	155-149	79-77
I2	550	1700	550-1700	1950-1900	186-185	70-71
I3	580	1700	580-1700	1950-1900	157-145	70-71
I4	550	1700	550-1700	1400-1250	179-141	80-78
I5	550	1700	550-1700	1920-1900	179-180	70-71
I6	550	1700	550-1700	1970-1950	179-172	70-71
I7	680	1800	680-1800	1400-1300	154-151	83-80
I8	550	1700	550-1700	1900-1600	157-149	70-71
I9	560	1700	560-1700	1920-1900	169-168	70-71
U1	650	2400	650-2400	1650-1600	130-129	68-65
U2	650	2450	650-2450	1700-1680	150-149	68-69
U3	680	2680	680-2680	1950-1920	123-122	68-69
U4	720	2600	720-2600	1900-1700	140-134	70-69
U5	700	2450	700-2450	1700-1720	153-154	69-68
U6	700	2700	700-2700	1820-1800	122-121	68-69
U7	650	2450	650-2450	1800-1650	129-127	74-68
U8	700	2700	700-2700	2020-2000	145-140	68-69
U9	700	2650	700-2650	1920-1900	124-123	69-70

For every bus at each operating regime, PN concentrations and size distributions in the bus exhaust gases were measured both upstream and downstream the DPF.

The PN weighted concentration per channel, n_i was used to estimate particle mass (PM) weighted concentration per channel, m_i and is described by the equation:

$$m_i = \rho \frac{\pi d_i^3}{6} n_i$$

Here the subscript i indicates the measuring channel, ρ is the particle density (assumed to be 1 g/cc) and d_i is the particle mobility size. Due to the fact that this study devotes more concern to PN, the simplification assumption that all particles are spheres was made. A more sophisticated method for calculating particle mass was developed by Maricq and Xu (2004) and takes into account effective density and fractal dimension.

Total PN and PM concentrations were calculated, respectively, by:

$$TPN = \sum_{i=l}^{u} n_i$$

$$TPM = \sum_{i=l}^{u} m_i$$

DPFs filtering efficiencies in terms of number and mass, PNFE and PMFE, respectively, were calculated by the following equations, where the subscripts “B” and “A” stand for before and after the DPF, respectively:

$$PNFE = \frac{\left(TPN_B - TPN_A\right)}{TPN_B} \cdot 100$$

$$PMFE = \frac{\left(TPM_B - TPM_A\right)}{TPM_B} \cdot 100$$

Particle emissions measurement

All the measurements were performed at the bus company garages. The garages were equipped with a chassis dynamometer. Figure 2 shows the experimental setup.

TSI-made Engine Exhaust Particle Sizer (EEPS) Spectrometer 3090 model was used for particles size distribution measurements. Particles pass through an electrical diffusion charger where they get a predictable charge level based on their size. An electric field drags the particles in the sizing region where 22 sensing electrometers are installed. Particles, which land on the sensing electrodes transfer their charge. 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 readings per second.

TSI-made Rotating Disk Thermodiluter Thermal conditioning device 379020A-30 was used for diluting the sample. The equipment is composed of two separate parts, the Thermodiluter Head and Thermal Conditioner Air Supply. It is suited for sampling, diluting, and conditioning exhaust particles prior their measurement in dedicated equipment. A small quantity of the raw exhaust is captured by a cavity of the rotating disk and transported to the measurement channel where it is mixed with HEPA-filtered, particle-free dilution air. It performs a two-stage dilution and can heat the sample up to 400°C.

Figure 2: Experimental setup*:* 1: DPF; 2: 379020A-30 Thermodiluter Head; 3: 379020A-30 Thermal Conditioner Air Supply; 4: EEPS 3090

A warm-up period was allowed prior each measurement. A two-stage dilution and heating to 300°C were performed to prevent condensation of the volatile particles, in accordance with the ECE-PMP-Protocol as described in UN ECE (2010, 2013a, 2013b).

The average value of the PN measurements was assumed to adequately characterize the given regime under steady-state measurements. 60 seconds measuring duration was used for idling regimes and about 45 seconds for measurement under load. Since the EEPS collects values at a frequency of 10 Hz, averages of 600 and about 450 readings were taken into account, respectively.

For the transient free-acceleration regime, six consecutive accelerations were performed, with intervals that allowed engine's speed returning to low idling values (typically about 5 to 10 seconds). The average of the higher PN concentration of each peak were considered in filter efficiency assessment.

Total PN concentration, as well as PN size distribution, were measured. Data collected from the measuring equipment includes particles with diameters from 5.6 nm up to 560 nm. Nonetheless, current Particle Measurement Program procedure prescribes PN measurement for particles with diameter greater than 23 nm. Thus, all data regarding smaller particles was not considered in the provided analysis results.

Fuel Consumption

The travelled distance and amount of diesel fuel refueled were used to calculate the vehicles monthly fuel consumption (in kilometers per liter). This analysis includes a period from 19 months prior DPF installation to 7 months after it. Monthly fuel consumption of the retrofitted buses was compared with that of the control group. Herewith, it's possible to know how DPF retrofitting affects fuel consumption.

The average value of fuel consumption of the period from January to July 2014 was compared to that of the same months of the year 2015 for vehicles in both the pilot and the control group. It was chosen to consider the average of all the 36 vehicles to increase sample size and minimize the effects caused by the fact that the buses don't always ride on the same routes and are not always conducted by the same driver. In both periods all the buses worked without DPF retrofitting. By means of that, the average natural deterioration of fuel efficiency of the buses due to vehicle aging was evaluated for urban and intercity vehicles.

Then, the fuel consumption of the vehicles in the pilot group for the period of 9/2014-3/2015 was compared to that for the period 9/2015-3/2016, i.e. exactly one year later. In the first period, buses worked without DPF retrofitting, and in the second period they had already had it. The difference in the results of fuel consumption is the gross fuel efficiency deterioration. By subtracting the fuel efficiency deterioration due to natural aging, the net fuel efficiency deterioration due to DPF retrofit was obtained.

Backpressure

Pressure sensors were installed in the exhaust manifold of the retrofitted buses, upstream the DPFs. The frequency of reading of the pressure sensors is 0.1 Hz. Pressure sensors worked only when the engine was operating.

Analysis of the obtained data allows evaluation of the increase in backpressure due to the DPF retrofitting and assessment of the backpressure built-up during the buses real-world operating.

3 Results and Discussion

Nanoparticle emissions

Figure 3 and Figure 4 show examples of typical obtained particle size distributions for intercity and urban buses, respectively. Results for the 4 analyzed operating regimes are presented, for both measurements performed upstream and downstream the DPF.

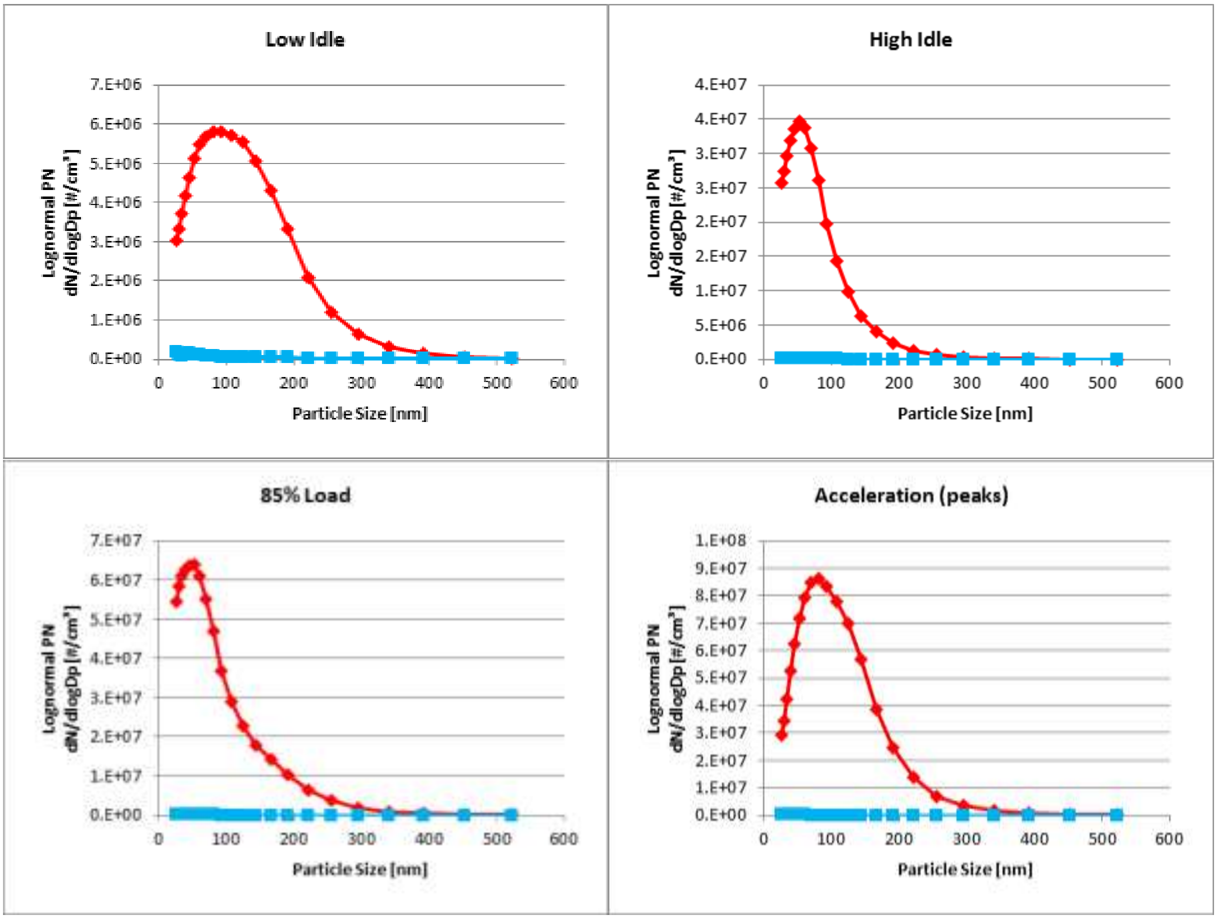

Figure 3: Particle Size Distribution of Bus I3. Red: Before DPF; Blue: After DPF

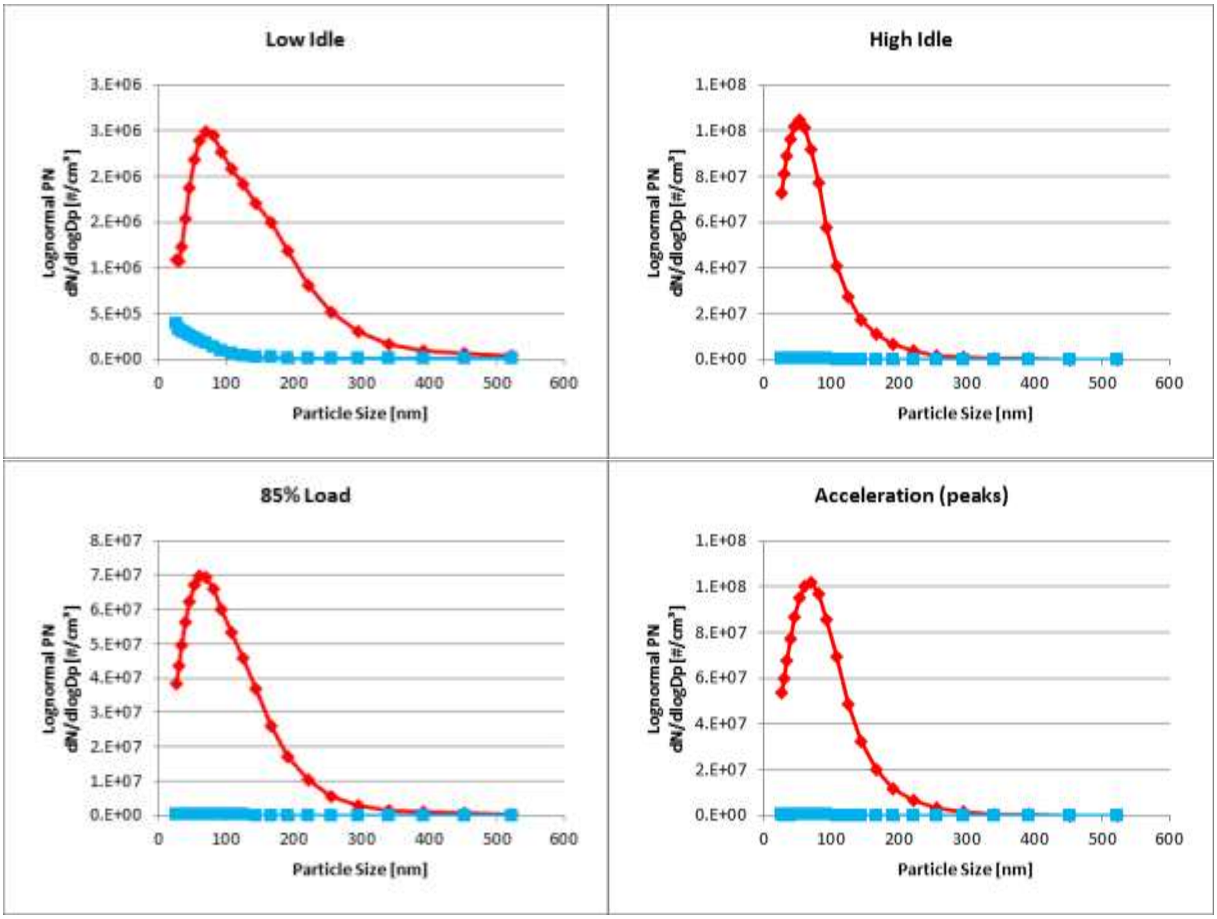

Figure 4: Particle Size Distribution of Bus U3. Red: Before DPF; Blue: After DPF

Table 4 and Table 5 summarize the Total PN concentration, Total PM concentration, PNFE and PMFE for the graphs presented in Figure 3 and Figure 4. DPF efficiency, for both PN and PM was found to be very high. The average PNFE for all the DPFs installed in the 18 analyzed vehicles was found to be higher than 97%.

It can be noticed that PNFE values were always higher than PMFE. This is due to the relatively higher PN concentration of smaller sized particles, whose contribution to total PM is small. Nonetheless, at low idle regime, filtration efficiencies were found to be the smallest. At this regime, the residence time of the gases inside the cylinder and in the exhaust manifold is higher, thus allowing a greater agglomeration of the particles, resulting into less and larger particles.

It was found that the three DPFs from different manufacturers behave similarly and present the same PN distribution patterns. It was also found that PNFE tend to be slightly higher for interurban buses, most probably because of smaller contribution of low-load operating modes. Figure 5 presents a comparison of average PNFE values of intercity and urban buses for all the 18 vehicles in the pilot group.

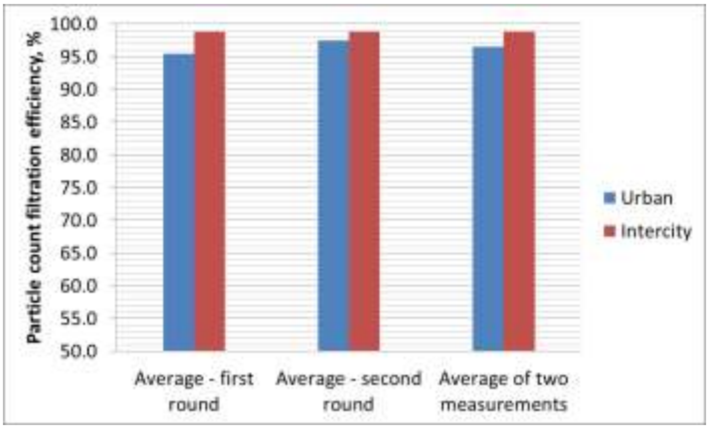

Figure 5: Comparison of PNFE values for intercity and urban buses

Table 4: PN and PM emissions, and Filtration Efficiencies of Bus I3

		Total PN Concentration [#/cm³]	Total PM [µg/m³]	PNFE [%]	PMFE [%]
Low Idle	Before Filter	4.70E+06	5.81E+03	98.14	96.27
	After Filter	8.76E+04	2.17E+02		
High Idle	Before Filter	2.08E+07	6.12E+03	99.73	98.96
	After Filter	5.71E+04	6.38E+01		
Full load, 85% rated speed	Before Filter	4.20E+07	2.22E+04	99.83	99.67
	After Filter	7.28E+04	7.25E+01		
Free acceleration (peaks)	Before Filter	5.76E+07	4.75E+04	99.83	99.80
	After Filter	9.74E+04	9.62E+01		

Table 5: PN and PM emissions, and Filtration Efficiencies of Bus U3

		Total PN Concentration [#/cm³]	Total PM [µg/m³]	PNFE [%]	PMFE [%]
Low Idle	Before Filter	1.81E+06	2.60E+03	90.9	95.11
	After Filter	1.65E+05	1.27E+02		
High Idle	Before Filter	6.13E+07	1.71E+04	99.82	99.16
	After Filter	1.12E+05	1.44E+02		
Full load, 85% rated speed	Before Filter	4.90E+07	3.65E+04	99.79	99.42
	After Filter	1.05E+05	2.11E+02		
Free acceleration (peaks)	Before Filter	6.36E+07	2.80E+04	99.88	99.61
	After Filter	7.39E+04	1.10E+02		

Fuel Consumption

As expected, it was found that compared to urban buses, intercity coaches achieve a better fuel efficiency. Figure 6 presents the averaged fuel consumption of all 9 urban buses and 9 intercity coaches of the pilot group.

Moreover, the seasonal variation in fuel consumption is made very clear. Due to the use of air conditioning during the hot Israeli summer, fuel consumption increases significantly, for both urban and intercity coaches. Average of the 36 vehicles of both the pilot and the control group indicate that fuel consumption increases by about 4 and 8 percent for intercity and urban buses, respectively, during summer, as can be seen in Figure 7. This is a result of higher relative influence of power demand for air conditioning at urban driving, due to lower engine loads at the latter operating mode.

Natural deterioration of the fuel efficiency due to vehicle aging was evaluated in this study. The result was used to isolate the effect of DPF on fuel consumption, which is shown in Figure 8. It was found that the average increase of fuel consumption due to DPF retrofitting is 2.5% and 2.1% for intercity and urban buses, respectively. The usage of DPFs had a higher impact on fuel consumption of intercity buses most probably due to the greater percentage of time they operate under higher load regimes with respectively higher values of backpressure due to bigger flow rate of exhaust gases.

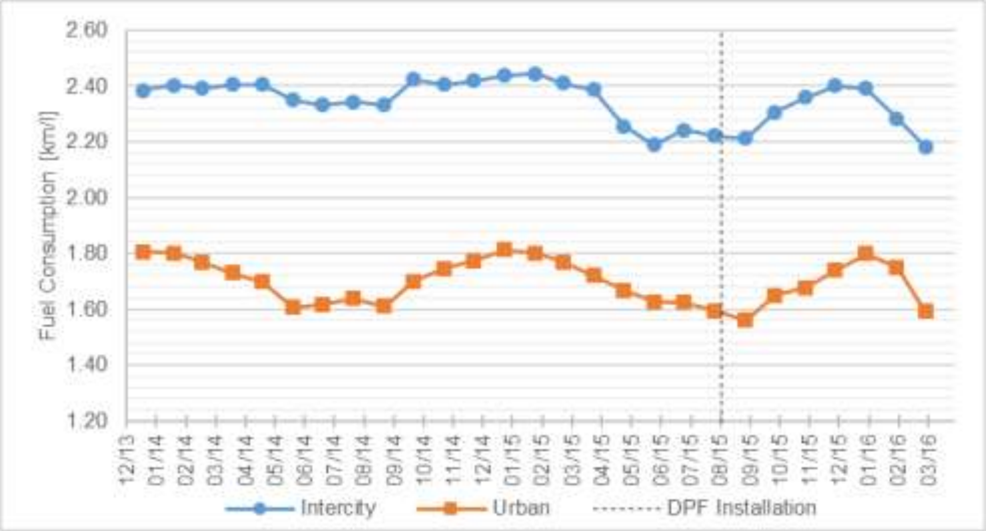

Figure 6: Fuel consumption of intercity and urban buses of the pilot group

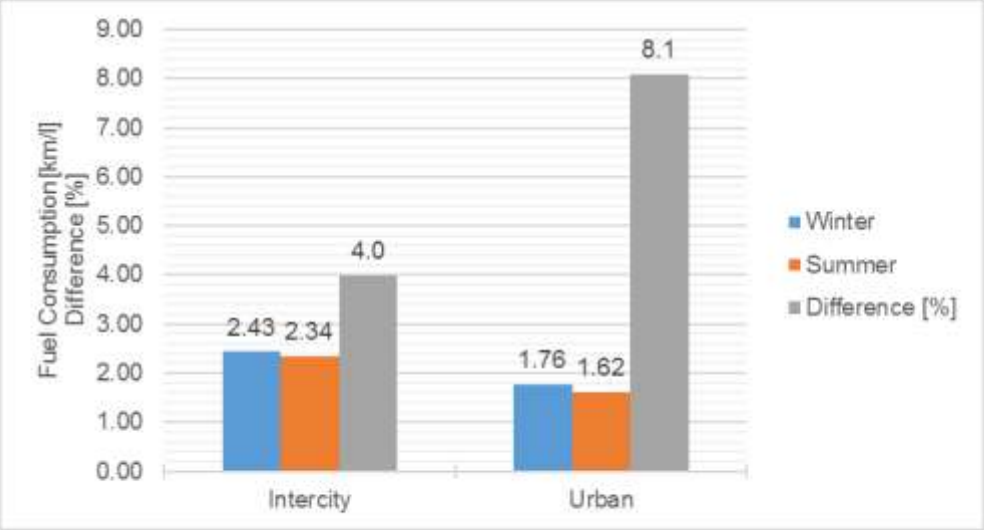

Figure 7: Seasonal variation in fuel consumption of buses of the pilot and control groups

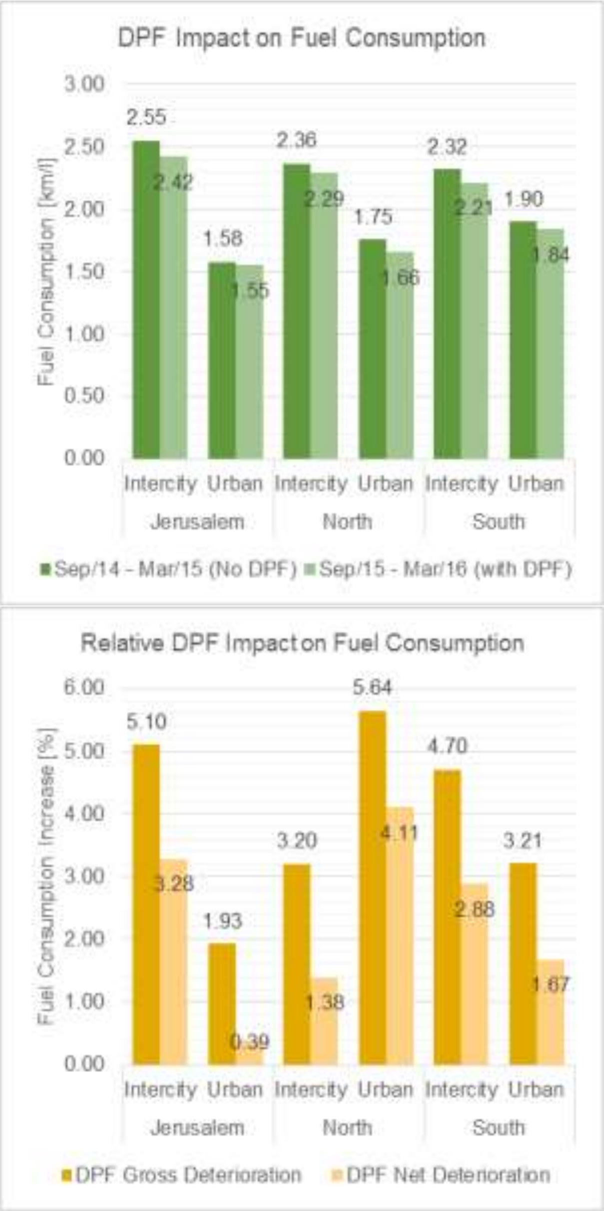

Figure 8: DPF effect on fuel consumption

Backpressure

Data from the pressure sensors installed in the exhaust manifold at the entrance to the DPF was logged and analyzed. The average daily backpressure increase due to the DPF was calculated and is presented in Figure 9. It can be seen that after half a year of real-world usage, DPF doesn't cause backpressure increase greater than 60 mbar, and is far from the maximal recommended value of 150 mbar.

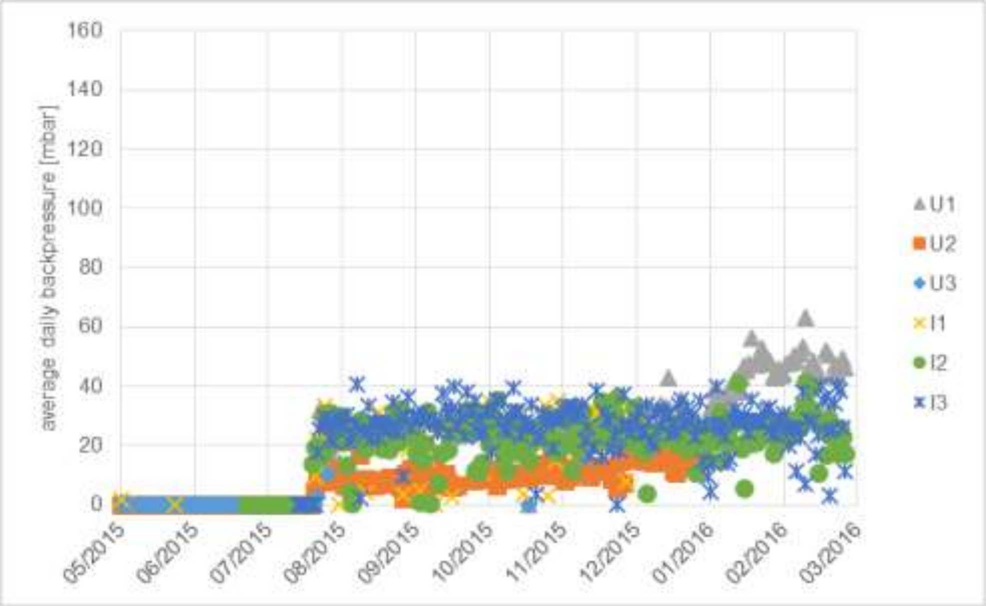

Figure 9: Backpressure increase due to DPF: buses U1, U2, U3, I1, I2 and I3

Moreover, it should be noticed that DPF was installed replacing the bus silencer, which also imposed some resistance to exhaust gases flow. In this manner, the actual backpressure increase due to DPF retrofitting is somewhat lower.

Maintenance and drivability

The maintenance actions of the vehicles of the pilot group were compared with that of the control group. No influence of DPF retrofitting on the maintenance operations, as well as their frequency was detected till now. Moreover, drivers didn’t report on any deterioration in buses drivability.

4 Conclusions

Comparison of the measured engine-out and tailpipe nanoparticle number concentrations clearly demonstrates the potential of nanoparticle emissions mitigation by DPF retrofitting. The average values of PNFE were found to be higher than 97% for all the measured bus operating regimes. Low idle regime presents slightly lower efficiencies, possibly because of the higher agglomeration values at this regime. It was also noticed that DPF’s PNFE values are somewhat higher for intercity coaches.

The increase of fuel consumption due to DPF retrofitting was found to be 2.5% and 2.1% for intercity and urban buses, respectively.

The backpressure values measured upstream a DPF after retrofitting lay below 60 mbar after half a year of buses operation with retrofitted DPFs and don’t approach the limit value of 150 mbar. No deterioration in vehicle drivability was reported, as well as unusual repairs or changes in maintenance volumes.

Acknowledgments

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