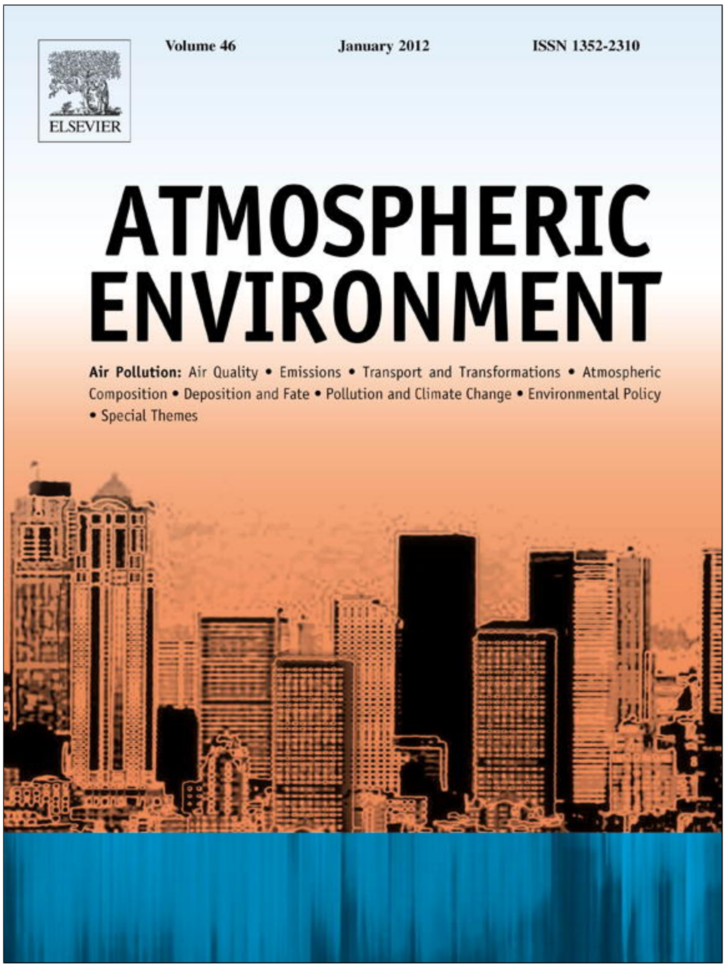

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In-vehicle particle air pollution and its mitigation

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HIGHLIGHTS

► In-cabin air purifier provided reduction of particle number concentrations up to 99%.
► With in-cabin air purifier CO_2 concentrations were kept below limits of the standard.
► Great differences in PM10 concentrations were found between the cars and the buses.
► Smoking inside a car leads to increase of PM2.5 concentrations by a factor of 90.

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ABSTRACT

This work presents results of particle mass, number and size measurements inside passenger cars (PCs), vans and urban buses. Effects of the in-cabin air purifier on particle concentrations and average size inside a vehicle are studied. Use of the air purifier leads to a dramatic reduction, by 95–99%, in the measured ultrafine particles number concentration inside a vehicle compared with outside readings. Extremely low particle concentrations may be reached without a danger of vehicle occupants' exposure to elevated CO_2 levels. The lowest values of particle concentrations inside a PC without air purifier are registered under the recirculation ventilation mode, but the issue of CO_2 accumulation limits the use of this mode to very short driving events. Lower PM concentrations are found inside newer cars, if this ventilation mode is used. Great differences by a factor of 2.5–3 in PM10 concentrations are found between the PCs and the buses. Smoking inside a car leads to a dramatic increase, by approximately 90 times, in PM2.5 concentrations.

1. Introduction

Epidemiological studies worldwide demonstrate a strong correlation between exposure to particulate matter (PM) and increasing rates of respiratory and cardiovascular diseases and other adverse health effects (Chio et al., 2007; Pope and Dockery, 2006; Sram et al., 2011; Sullivan et al., 2005; Zhu et al., 2007).

A review of the literature suggests that air pollution by combustion-related PM may result in increased lung cancer risk, despite the substantial gaps in knowledge that still remain (Pope and Dockery, 2006). The latest studies of health effects conclude that black carbon is a better indicator of harmful particulate substances from combustion sources (especially traffic) than undifferentiated particulate matter mass (Janssen et al., 2012).

Ultrafine particles (UFPs) are able to easily penetrate the lung tissue, enter the circulatory systems and be deposited in the brain (Oberdörster et al., 2004; Sullivan et al., 2005; Xu and Zhu, 2009). UFPs are a greater threat to human health compared with larger particles (Gong et al., 2009; Sullivan et al., 2005), especially for children (Zhang and Zhu, 2011). UFPs and nano-particles ($d_p < 50$ nm) from vehicle exhaust are very toxic because of their high organic carbon content, including polycyclic aromatic hydrocarbons and quinines (Kaminsky et al., 2009). According to Zhu et al. (2007), UFPs are the main components (up to 90% on a number basis) of the particles emitted by engines, especially by diesel engines, which are the major source of the on-road UFPs.

According to Taylor and Fergusson (1998), road users in the center of the roadway are likely to be traveling through a tunnel of the most polluted air, and this is the principal reason for their higher relative exposure to pollutants. This issue was broadly studied over recent decades. A large body of literature has dealt with investigation of road users exposure to gaseous pollutants

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inside vehicles (Chan and Chung, 2003; Esber et al., 2007; Taylor and Fergusson, 1998; and others). In the last few years, research has focused on the study of exposure to particle concentrations (Chan et al., 2002a,b; Fruin et al., 2004, 2008; Kaminsky et al., 2009; Knibbs et al., 2009, 2010; Knibbs and DeDear, 2010; Pui et al., 2008; Qi et al., 2008; Tang and Wang, 2006; Zhang and Zhu, 2010, 2011). Knibbs et al. (2011) published a comprehensive review of research on the measurement of UFPs inside vehicles. Chan et al. (2002a) examined commuter exposure to respirable suspended particulates (PM10 and PM2.5) in public transportation modes. They found that the effect of driving time has a minor impact on the in-vehicle air pollution level. Zhu et al. (2007) found that for an hour-long daily commute exposure, the in-vehicle microenvironment contributes approximately 10–50% of people's daily exposure to UFPs from traffic.

Currently, a clear majority of vehicles are equipped with air conditioning (AC) systems. A driver usually makes a decision about the desired method of in-cabin air ventilation. The driver's decision affects the concentrations of air pollutants inside the vehicle's cabin (Chan and Chung, 2003; Esber et al., 2007; Knibbs et al., 2010). The influence of vehicle ventilation/AC modes on PM concentrations inside a cabin has been investigated by Zhu et al. (2007), Zhang and Zhu (2011), Knibbs et al. (2010) and other researchers. Ott et al. (2008) studied the influence of the air change rate and second-hand smoke on the particle concentrations inside a car. Most of the previous research has focused on particle measurements inside passenger cars. Air pollution by particles in other vehicle types (e.g. buses and vans) has been studied to a lesser extent. Knibbs et al. (2011) analyzed the published results on particle measurements inside vehicles of different types.

Knowledge on ways to mitigate in-vehicle particle air pollution is still limited. Zhang and Zhu (2011) studied the influence of air purifiers (HAP 8650, Sunbeam Products, Inc., Boca Raton, FL) installed in school buses as an alternative method to protect children from particle exposure. The air purifier used was designed for large rooms (up to 40 m^2). It had a built-in fan with four speeds and drew air through a carbon odor filter followed by HEPA filters (MacNaughton, 2008). During the measurements, the air purifier was placed in the rear of the cabin, and the fan speed was set to maximum. The use of an air purifier was found to remove up to 50% of the in-cabin particles, and the use of air purifiers might be a short-to-medium-term strategy to protect children's health. These results indicate the great, untapped potential of in-cabin air cleaning of UFPs by the application of advanced air purifying technologies. None of the previous studies addressed the variability of the air purifier efficiency as a function of trip duration or its influence on the in-cabin CO_2 concentrations and noise levels.

To address these knowledge gaps, this study was mainly focused on the assessment of the influence of a novel in-cabin air purifier on the number concentrations and average size of UFPs for different vehicle types. To supplement the existing data on particle air pollution inside a vehicle, the effects of the vehicle type (car and bus), cabin ventilation mode, vehicle age, traffic conditions and second-hand smoke on the PM concentrations inside the vehicle were studied as well.

2. Experimental methods

2.1. Instrumentation

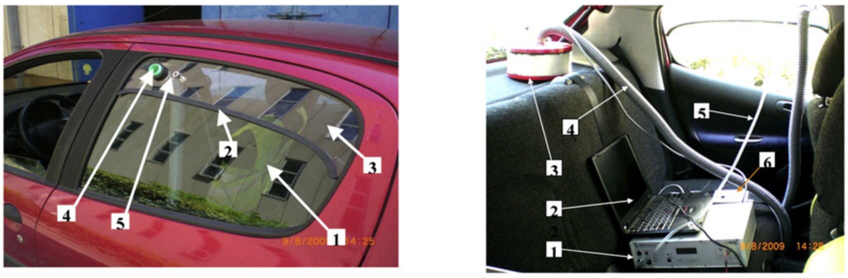
PM10, PM2.5 and PM1 mass concentrations were measured by the Grimm 1.107 PM-meter. The device was used with the factory calibration. No additional calibrations for a specific aerosol were carried out. In experiments with the in-cabin air purifier, the ultrafine particle number concentration (PNC) and their average size were measured by a diffusion size classifier – Matter Aerosol AG DiSC (Fierz et al., 2008). This instrument measured the number concentrations of UFPs with a detection limit of 300 cm^{-3} and an average size in the range of 10–400 nm. Its accuracy and sensitivity is somewhat worse than those of the commonly used CPC (which measures only PNC) and SMPC laboratory devices. Nevertheless, due to its compactness, portability and self-contained power supply, the DiSC is highly applicable for field measurements. Sampling collection was performed in the driver's breathing zone. Measured data were logged at a frequency of 1 Hz and were subsequently analyzed after downloading to a computer.

An in-cabin air purifier was placed in the rear part of a vehicle's cabin - Fig. 1, right. It was equipped with a pressure sensor to monitor filter clogging. The purifier's blower drew outdoor air through the filter and released it into the rear part of the vehicle's cabin. One of rear windows of the vehicle was equipped with a plexiglass insertion with two nipples for the Grimm 1.107/DiSC sampling and air purifier intake tube attachments – Fig. 1, left. There was a possibility of connecting the Grimm/DiSC sampling tube to this insertion nipple (outdoor sampling) or to the nipple at the driver's breathing zone.

CO_2 concentrations at the driver's breathing area were measured using a Li-COR Li-840 CO_2 analyzer. Noise measurements during experiments with the cabin air purifier were performed using a sound level meter, IEC 651 type D, Luton SL 4022.

2.2. PM measurements

All experiments were carried out during working days of the week, from 07:00 to 19:00. Ambient temperatures during the experiments were in the range of 20–30 °C.



1-vehicle original window; 2- seal; 3- insertion window; 4- air inlet to in-cabin purifier; 5- sample inlet to DiSC/Grimm

1-DiSC; 2- laptop with DiSC software; 3- in-cabin air purifier; 4- air purifier inlet line; 5 – DiSC sample line; 6 – air purifier control unit

Fig. 1. Installation of the air purifier in a test vehicle.

2.2.1. Passenger cars

The cars used in the experiments are listed in Table 1. They were divided into two groups according to the mileage accumulated: 'new' (25,000 km or less) and 'old' (150,000 km or more). All the vehicles were checked and found to be in a proper working order.

The experiments were carried out in the Haifa region on two pre-selected routes that had a flat topography (road gradients of less than 2%) and represented different traffic conditions. The first route was a segment of an urban collector type road (Andre et al., 2006), 3.6 km in length, representing downtown driving conditions. It was characterized by a traffic volume of 39,600 vehicles per day (13.6% of them were diesels – 3.8% buses, 6.1% trucks and 3.7% taxis) and low average speed measured at slightly above 19 km h^{-1}. The second route was a segment of a rural trunk road (Andre et al., 2006), 11.6 km in length, at the northern entrance to Haifa. It was characterized by a high traffic volume – 96,400 vehicles per day. Diesels were 12.4% of the traffic – 2.2% buses, 4.3% trucks and 5.9% taxis. The average speed was significantly higher, above 44 km h^{-1}.

A total traveled distance of more than 4000 km was accumulated during the measurements to ensure collection of sufficient experimental data. The following vehicle ventilation modes were studied:

- AC switched on, windows closed and introduction of the outdoor air into the car ('out')
- AC switched on, windows closed and internal recirculation of the cabin air ('rec')
- AC and ventilation fan switched off and driver's window completely opened ('win').

Approximately 170–185 trips were performed using each ventilation mode.

2.2.2. Buses

The measurements of PM concentrations inside urban buses were performed at 3 different routes, as shown in Table 2. The traffic volume for each route was calculated as the mean weighted value for all streets of the given route. Approximately 100 trips have been undertaken during the measurements with a total traveled distance of more than 1200 km. The sampling probe was fixed on the third line of seats, at the height of a seated passenger head.

2.2.3. Effects of in-vehicle smoking

This series of experiments was performed with Peugeot 307 and Renault Clio cars. The vehicles were driven at the Technion campus on a road with no traffic to ensure outdoor air quality conditions were as constant as possible. Average driving speed was approximately 30 km h^{-1}. The experiments were performed with the 'win' ventilation mode. Mass concentrations of PM10 and PM2.5 were measured for the following experimental conditions:

Table 1
Vehicles used in the study.

Vehicle model	Engine volume, cm^3	Mileage, km	Doors, no.	Body style	Test group
Toyota-Yaris[a]	1300	6000	5	Hatchback	New
Peugeot-206[a,b]	1400	23,000	5	Hatchback	New
Peugeot-307[a]	1600	25,000	5	Hatchback	New
Suzuki-Baleno[a]	1600	150,000	4	Sedan	Old
Renault-Express[a]	1400	190,000	3	Multi-purpose	Old
Renault-Clio[a]	1400	260,000	5	Hatchback	Old
Subaru EA71[a]	1600	338,000	5	Station wagon	Old
Renault Megane[b]	1600	130,000	4	Sedan	Old
Citroen C4[b]	1600	10,000	5	Hatchback	New
Volkswagen Transporter T5[b]	2500	130,000	4	Van	

[a] PM measurement.
[b] In-cabin air purifier tests.

Table 2
Description of the bus routes.

Route no.	Area description	Length of the route (km)	Average traffic speed (km h^{-1})	No. of bus stops/relative stop time (%)	Mean weighted traffic volume (vehicles day^{-1})
1	Rural, plain topography	21.8	23.7	51/25	64,400
2	Urban, plain topography	26.9	15.5	70/22	18,000
3	Urban, hilly topography	24.5	17.7	72/28	21,300

- The driver's hand carrying the cigarette was outside the vehicle – "outside smoking"
- The driver's hand carrying the cigarette was inside the vehicle – "inside smoking".

2.3. In-cabin air purifier tests

UFP size and number concentrations were measured in this study. The experiments were carried out at the 'rec' ventilation mode with 3 passenger cars and a shuttle taxi (VW Transporter) – Table 1. The in-cabin air purifier of the quartz fiber filter type (Burtscher et al., 2008) was used in these tests. It is a compact (of approximately shoebox size) stand-alone filtration unit, which removes sub-micron particles from the ambient air. It is designed for retrofit in vehicle and truck cabins and includes a blower and a coarse and a fine particle filter. According to the air purifier's specification, the unit removes particles in the size range of 20–500 nm at a rate of 95–99% and operates at a flow rate of 500 l min^{-1}. The passenger interior volume of the cars tested with the air purifier was between 2000 and 2500 l. Thus, the average air exchange rate may be estimated as approximately 0.2–0.25 min^{-1}. In all experiments with the air purifier, there were three occupants in a car.

For the experiments with the passenger cars, the following two city center routes were chosen:

- Haifa line route, with an average road gradient of 6% and a total length of 4.1 km.
- Tel Aviv circle route, with a plains topography (road gradients are less than 2%) and total length of 15 km.

The experiments were carried out at various time periods of the day: 08:00–09:00, 12:00–13:00 and 16:00–17:00. The testing program included measurements outside and inside a vehicle with the air purifier switched on and off. CO_2 concentration and noise measurements inside the vehicles were performed as well.

The experiments with the shuttle taxi were performed on a real service route in Haifa. This route had a mixed topography – mainly plains with two short road segments with 4% and 11% gradients. The total length of the round-trip drive was approximately 15 km. In these experiments, taxi stops for passengers boarding and disembarking were simulated. Two in-cabin air purifiers were used simultaneously. This provided an average air exchange rate of approximately 0.17 min^{-1} for the VW Transporter with an interior volume of 6000 l.

3. Results and discussion

3.1. PM measurements

3.1.1. Passenger cars – effects of daytime and road type

The average speeds (calculated as a route length divided by the total required driving time) were more than two-times higher for the rural driving route, based on the trunk road, compared with the urban downtown route, based on the collector type road, over all the daytime periods as a result of a different road type and higher speed limit.

The measured in-cabin values of PM10, PM2.5 and PM1 for the 'win' ventilation mode over all daytime periods were higher at the rural trunk road with much higher traffic volumes than at the urban collector type road. This result supports the findings of Zhu et al. (2007), Thai et al. (2008), and Zuurbier et al. (2010). The measurements showed no statistically significant relationship between the daytime average speed fluctuations and the PM concentrations inside a vehicle. Additionally, no statistically significant correlation was observed between the in-cabin PM concentrations and daytime fluctuations of both total and heavy-duty diesel traffic volumes. This fact can be explained by the considerable influence of a random movement in a traffic flow behind a big polluter. In this work, the big polluters were identified by the visible tail smoke plume. In addition, information about vehicle age was always available because the license plate number in Israel indicates the vehicle's production year. It was observed many times during the experiments that the highest instantaneous values of PM and gaseous pollutant concentrations inside a vehicle were registered when the vehicle was driven behind a big polluter. We believe that this fact plays a major role in the shading the influence of vehicle traffic PM emissions. This consideration is supported by conclusions of Knibbs et al. (2011) that "short-term traffic patterns not represented in hourly or daily average data, such as the impact of passing traffic, may be important (Fruin et al., 2008; Boogaard et al., 2009)".

3.1.2. Passenger cars – effects of ventilation mode

Fig. 2 presents results of the comparison between average PM mass concentrations inside 'new' and 'old' cars under different ventilation modes. The data in Fig. 2 were calculated as weighted average values for both tested routes together. PM concentrations in the driver's breathing zone at the 'win' ventilation mode with vent/AC switched off and the driver window completely opened were similar to outside values (Fig. 3) and taken as 100%. As shown, the lowest in-cabin PM mass concentrations for all measured PM size ranges were observed with the 'rec' ventilation mode. A similar trend was found for both 'new' and 'old' car groups. The differences between the 'rec' and 'win' ventilation modes were statistically significant (at a 5% level of significance). The 'rec' ventilation mode reduced the in-vehicle particle air pollution by a factor of 1.4…1.7 for the 'old' cars and 1.8…1.9 for the 'new' cars, dependent on the PM size range.

It is important to note that the 'rec' ventilation mode leads to much slower changes in the in-vehicle PM concentrations compared with other ventilation modes and outside values. Fig. 3 shows a typical example of the outside and in-vehicle instantaneous PM10 mass concentrations for different ventilation modes as measured in one of the tested vehicles (Peugeot-307). A trend of a smooth decrease of the measured PM values was observed with the 'rec' ventilation mode. These results correspond to previous findings of Zhu et al. (2007) and Pui et al. (2008) for ultrafine particles. If use of the 'rec' ventilation mode is considered, the issue of CO_2 accumulation inside a vehicle's cabin should be taken into account – Fig. 4. As seen, the measured CO_2 concentration in the driver's breathing area was consistently increasing, and after 38 min of driving, it reached a level of 2600 ppm and continued to rise. Thus, during the short trip, CO_2 concentration reached half of the ACGIH (2005) threshold limit value – 5000 ppm. The ASHRAE standard 62-2001 prescribes that indoor CO_2 concentration should be kept to no more than 700 ppm above the outdoor air concentration. Therefore, in the considered case, the in-cabin CO_2 concentration should not exceed 1200–1300 ppm. The results of our measurements suggest that this limit is exceeded in case of 'rec' ventilation mode after 6 min of driving. The latter result limits the use of this ventilation mode to very short driving events.

Fig. 5 (left) presents results of the distribution analysis for the measured PM10 levels inside cars of the 'old' group. The measured data are compared with the limit value of the European Directive 2008/50/EC (2008) – 50 μg m^{-3} for 24 h exposure. Taking into account this limit value and much lower typical exposure times of vehicle users, one-hour and two-hour estimated threshold values were calculated by using the empiric equation $x_s = x_k\ (t_k/t_s)^{0.18}$ (Turner, 1970) and the Directive 2008/50/EC limit. Here, x_s is the desired concentration estimate for the exposure time, t_s, and x_k is

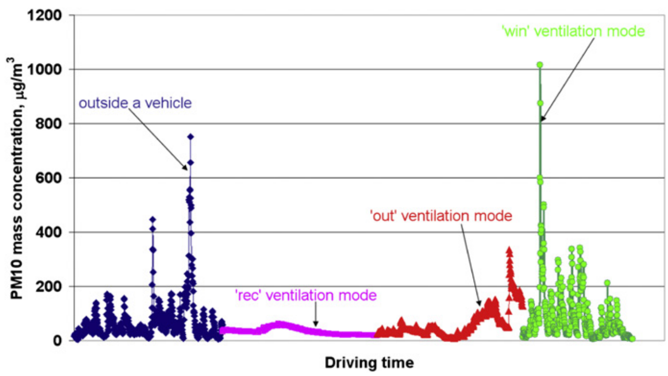


Fig. 3. Example of typical instantaneous values of PM mass concentration under different ventilation modes.

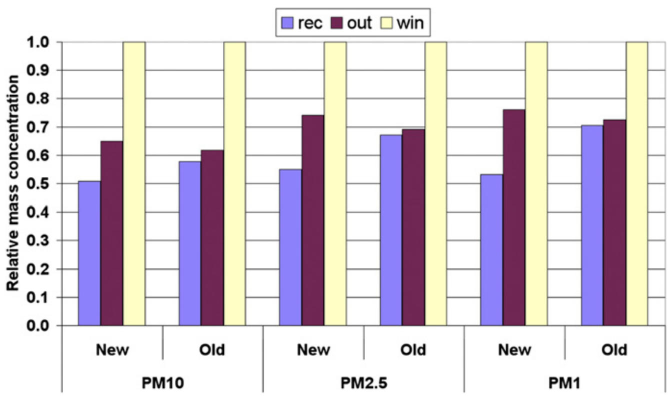


Fig. 2. Relative PM mass concentrations for 'new' and 'old' vehicles under different ventilation modes.

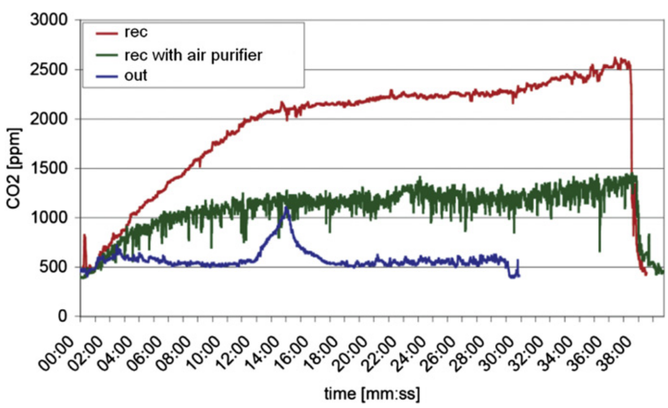


Fig. 4. CO_2 concentrations outside and inside the cabin for different ventilation modes.

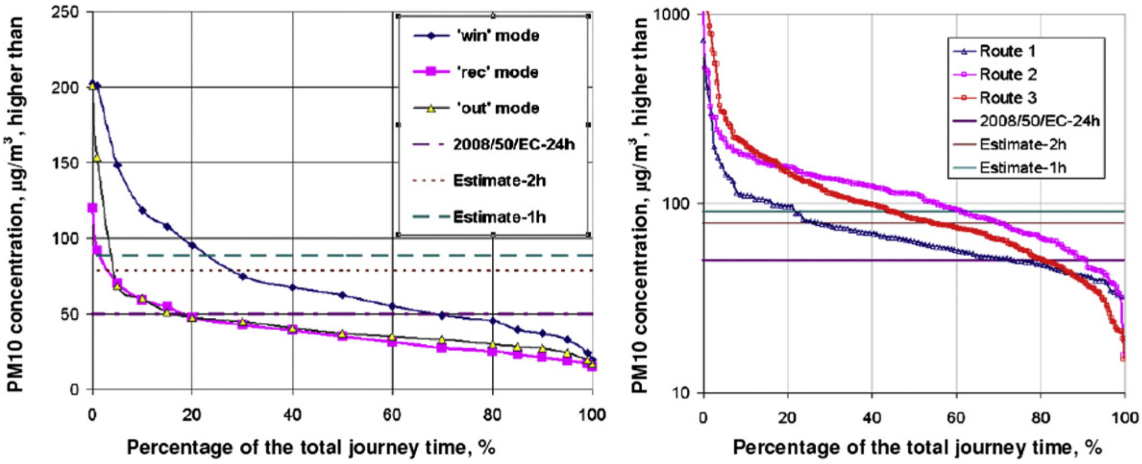


Fig. 5. Relative time of passenger exposure to PM10 air pollution in cars (left) and in buses (right).

the limit value of Directive 2008/50/EC for the exposure time $t_k = 24$ h.

As shown in Fig. 5 (left), in the case of using the 'win' ventilation mode, vehicle users are exposed to air pollution by PM10 that exceeds the one day limit of Directive 2008/50/EC during approximately 70% of the total driving time. In case of using the 'rec' ventilation mode, this number decreases to 18%. For the estimated one-hour threshold value (approximately 88 µg m^{-3}), the appropriate duration of vehicle user exposure while exceeding the threshold value are assessed to be approximately 23% and 2% for the 'win' and 'rec' ventilation modes, respectively.

3.1.3. *Passenger cars – effects of vehicle age*

Fig. 6 shows a comparison of PM10 mass concentrations for the 'new' and 'old' car groups. As seen, the average measured PM10 levels in the 'win' ventilation mode were higher by 17% for the 'new' cars group, which most likely followed from the higher average outside PM10 concentrations. Despite this fact, in the 'rec' mode for the 'new' car group, lower average PM10 concentrations by approximately 25% were measured. A possible reason for this could be better sealing of new cars and, most likely, higher efficiency of new air filtration systems. An analogous trend was also observed for the PM2.5 and PM1 concentrations. The changes observed are statistically significant (with a 5% level of significance). Our results are similar to those reported by Zhu et al. (2007), who considered in-cabin commuter exposure to UFPs; Qi et al. (2008), who studied cabin air filter effects; and Knibbs et al. (2010), who investigated cabin ventilation rate effects.

3.1.4. *Urban buses*

Similar to the results obtained with passenger cars, no statistically significant relationship was found between the daytime average speed fluctuations and the measured PM concentrations inside a bus. Comparison of the PM10 mass concentrations, as measured in the buses and PCs, is presented in Fig. 6. For PCs, the three different ventilation modes were taken into consideration in this comparison. For buses, different ventilation modes are irrelevant because of periodic opening and closing of the doors to allow boarding/disembarking of passengers. PM concentrations inside buses that appear in this Figure were calculated as average values for the three tested routes. Fig. 6 shows that considerably higher PM10 mass concentrations were observed inside the buses compared with the passenger cars. We believe that the major source of in-bus PM10 is the dust deposited on the bus inner surfaces (mainly on the bus seats) and on the passengers' clothes. This dust was re-suspending at the time of passenger movement. Values for the instantaneous PM10 and PM2.5 mass concentrations, as measured inside buses, prove this supposition – Fig. 7. Clearly recognized peaks (by a factor of 6…8) in PM10 concentrations were registered during movement of passengers inside the bus, mainly at the stops, while peaks of PM2.5 were found to be significantly lower. Overall, particulate matter measured inside buses are the

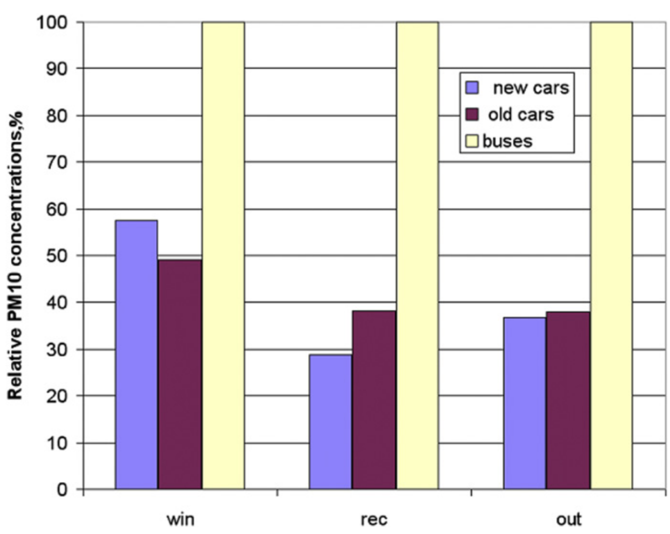


Fig. 6. Comparison of PM10 mass concentrations inside cars and buses.

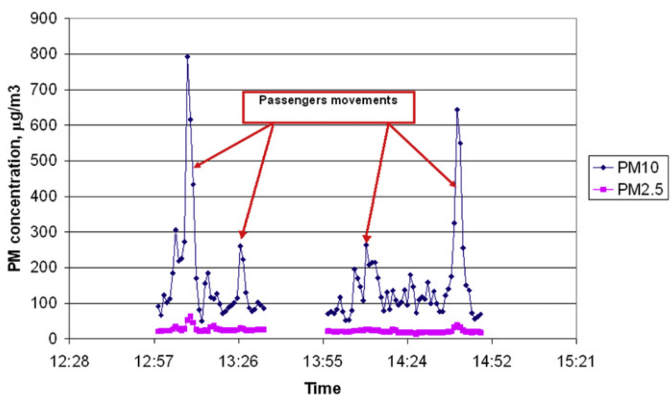


Fig. 7. Instantaneous values of in-bus PM mass concentration.

result of 1) PM penetrating to the bus interior through on-roof ventilation, 2) PM in the ambient air periodically coming in through the bus doors at stops, and 3) PM re-suspended from the bus seats and passengers' clothing during movements of the passengers. According to our findings, the latter source is the main reason for much higher average values for PM10 that were measured inside a bus in our study. Fig. 5, right, presents results of the distribution analysis for the measured PM10 levels inside buses. As in the case of passenger cars, the measured data are compared with the limit value (24 h) of the European Directive 2008/50/EC and the estimated threshold values for the 1 h and 2 h exposure times. As seen from Fig. 5, bus passengers were exposed to PM10 levels exceeding the estimated 1 h threshold value during 22–60% of the total journey time. These values are substantially higher than those found for the passenger cars (2% at the 'rec' ventilation mode). Possible ways to reduce passengers' exposure to air pollution by PM10 inside a bus include improving in-cabin air filtration and cleaning the bus interior.

3.1.5. *Effects of in-vehicle smoking*

Fig. 8 shows the variation of in-vehicle PM10 and PM2.5 mass concentrations (the driver's window was fully opened) for the 'outside' and 'inside' smoking cases. In the case of 'outside' smoking (a hand with the cigarette was outside the vehicle), the measured PM10 concentrations increased by a factor of 5 and PM2.5 – by a factor of 8, Fig. 8, left. It is noted that for this smoking mode, PM2.5 mass reached values above 90% of the PM10. Smoking inside the car (a hand with the cigarette was inside the vehicle) led to a dramatic increase in the in-vehicle PM concentrations. PM10 approached 2400 μg m^{-3} (Fig. 8, right) – higher by a factor of 27 than the 1 h threshold value, which was calculated based on the Directive 2008/50/EC requirements. The measured PM2.5 concentration increased by a factor of approximately 90 in this case and reached a value of 2300 μg m^{-3}, which accounts for approximately 98% of the PM10 mass. This result correlates well with the findings of Ott et al. (2008), who measured a value of 3200 μg m^{-3} with all the vehicle's windows closed.

3.2. *Effects of in-cabin air purifier*

At this stage of the study, PCs were equipped with the in-cabin air purifier, and measurements of the UFP number concentration and size were performed. Fig. 9 shows particle number (PN) concentrations and size, outside and inside a vehicle with the air purifier switched on and the vehicle's ventilation mode set to the 'rec' setting, as was measured during all the experiments with air purifiers. The results of the experiments show clearly that the application of the in-cabin air purifier allowed significant reductions of up to 95–99% in the PN concentrations inside the car compared with the outside readings. Fresh air was continuously supplied into the vehicle cabin through the air purifier, thus relieving the issue of CO_2 accumulation (Fig. 4). As seen from this Figure, CO_2 concentration inside the car with the air purifier and the 'rec' ventilation mode switched on was practically stabilized after approximately 10 min of air purifier operation at a level of approximately 1200–1300 ppm, which is lower by a factor of 4 than the appropriate threshold limit value of ACGIH (2005) and meets the requirements of the ASHRAE standard 62-2001. After approximately half an hour of driving, this value was lower by a factor of two than that measured in the 'rec' ventilation mode without the air purifier.

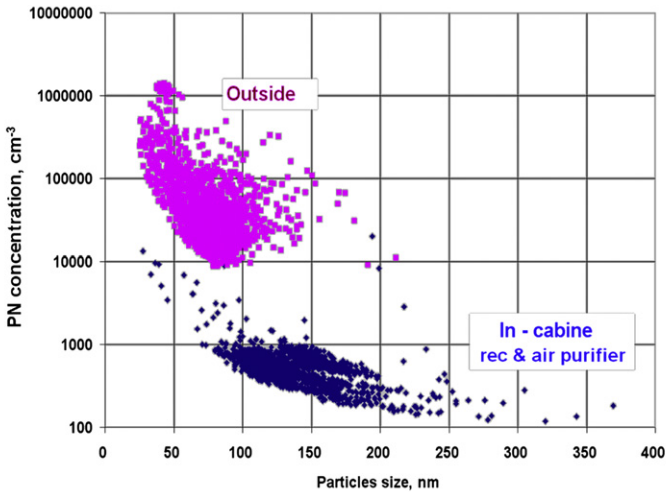


Fig. 9. UFP size and number concentration measured outside and inside the vehicle with the air purifier.

Fig. 10 shows a typical example of UFP number concentrations measured during one ride on the Tel-Aviv driving route outside and inside a car. The car was not equipped with an OEM-made cabin air filter. During these measurements, sequential switching-on of the 'rec' and 'rec. & air purifier' modes was performed. As was previously shown by Zhu et al. (2007) and Pui et al. (2008), switching-on the 'rec' ventilation mode leads to reduction of observed PNC to values typical for a clean office (approximately 3000–4000 cm^{-3}). Pui et al. (2008) reported that with air recirculation and an OEM-made cabin air filter,

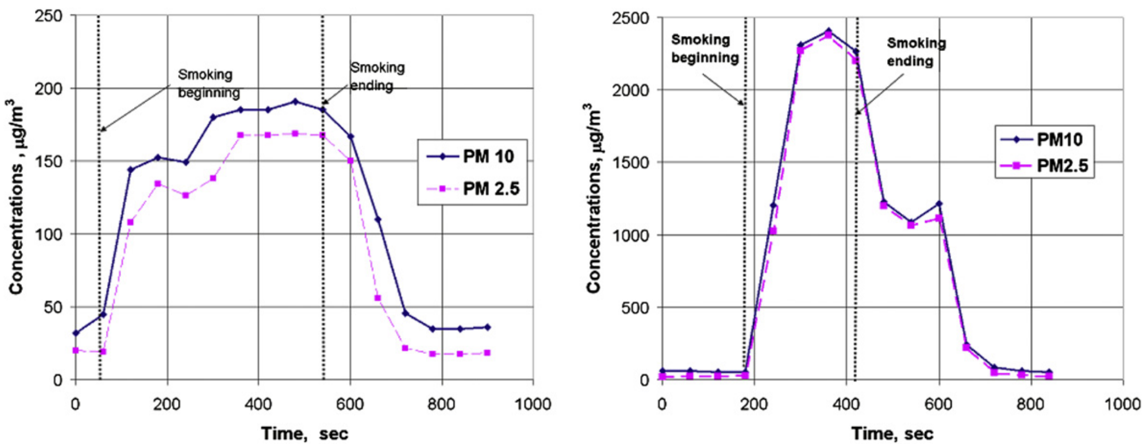


Fig. 8. The influence of in-vehicle smoking on PM mass concentration: left – hand with cigarette outside the vehicle; right – hand inside the vehicle.

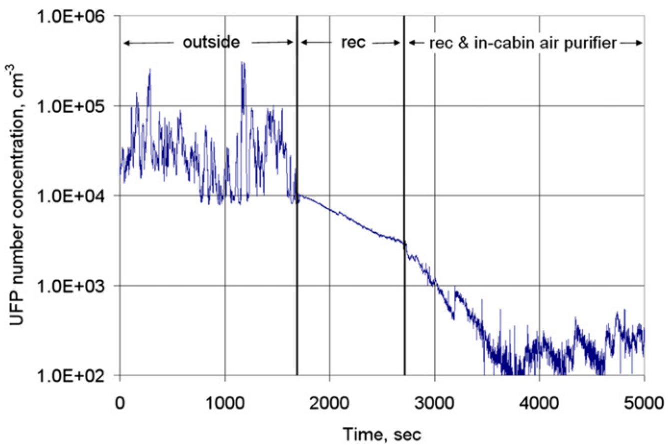


Fig. 10. UFP number concentrations outside and inside the car.

particle concentrations inside a car were reduced to below typical office air concentrations of 4000 particles cm^{-3} in approximately 3 min. Without the filter and with the 'rec' ventilation mode switched on, in-cabin particle concentrations still decreased and reached 4000 particles cm^{-3} in approximately 13 min. In our experiments with the car that was not equipped with an OEM-made cabin air filter, after switching-on the 'rec' ventilation mode, the in-vehicle PNC monotonously decreased and reached a level of 3000 particles cm^{-3} in approximately 16 min. This result agrees well with data obtained by Pui et al. (2008). Taking this outcome into account, it is important to mention again that using the 'rec' ventilation mode is strongly limited by the quick increase of in-cabin CO_2 concentrations (Fig. 4), which may be dangerous for vehicle occupants. Any switching to the 'out' or 'win' ventilation modes led to the immediate increase of in-vehicle particle concentrations. Use of the reported in-cabin air purifier allowed reaching very low UFP concentrations without the danger of exposing the vehicle occupants to elevated CO_2 levels. Application of the air purifier allowed a further reduction in the UFP number concentrations inside a car down to values below 500 cm^{-3}, which are really close to the detection limit of the DiSC device used (300 cm^{-3}) and are much lower than the PNC typical for a clean office. Along with this, some minimal time was required to achieve maximal cleaning effect. For example, the experiments on the long Tel-Aviv driving route (route length of 15 km) showed that minimal PN concentrations inside a car (lower than 500 cm^{-3}) were achieved after 17–20 min of filter operation, see Fig. 10. Thus, in shorter urban driving trips, it will be impossible to achieve a maximal cleaning effect. This was confirmed by the results of experiments on the short driving route in Haifa (route length of 4.1 km), where the duration of one driving run usually did not exceed 12–13 min. As a result, maximal reduction of PNC inside a car did not exceed 90% in this case compared with the outside readings. The relatively significant time (17–20 min) required to achieve the lowest possible PNC inside a car at the reported air exchange rate of 0.2–0.25 min^{-1} is most likely a result of a) unfiltered air penetration into the car through existing leaks and b) lower local air exchange rate in the driver's breathing area as a result of air purifier's location in rear part of the car, far from the sampling point. The validity of these suppositions should be confirmed in further research.

Fig. 11 presents the distribution of average particle size data measured during all of the experiments with the air purifier and shown in Fig. 9. These data demonstrate that the use of the air purifier leads to an increase in the size of particles measured inside a vehicle compared with outside air data. The average UFP size outside a vehicle was 70–80 nm compared with 120–130 nm inside a vehicle with the operating air purifier. This result may be explained by the increased contribution of the dust particles deposited on seats and other surfaces inside a vehicle, which are re-suspended due to a jolty ride and air movement, while the in-cabin air purifier cleaned only the air entering the vehicle from outside.

To assess the possible addition of noise by the air purifier's operation, some preliminary measurements were performed during the experiments with passenger cars. The measured noise levels with (68…73 dB) and without (66…71 dB) operation of the in-cabin air purifier indicated some noise intensification with the purifier switching-on. More detailed study of this issue with frequency analysis of the noise spectrum and development of appropriate noise mitigation measures may be recommended.

As mentioned above, in the experiments with the shuttle taxi, two in-cabin air purifiers were used and operated simultaneously. Taking into account the interior volume of the studied vehicle (approximately 6000 l) and the flow rate of the two air purifiers used in these experiments, the average air exchange rate of the filtered air was estimated as 0.17 min^{-1}. Frequent door openings at the taxi stops diminished the cleaning effect of the air purifiers.

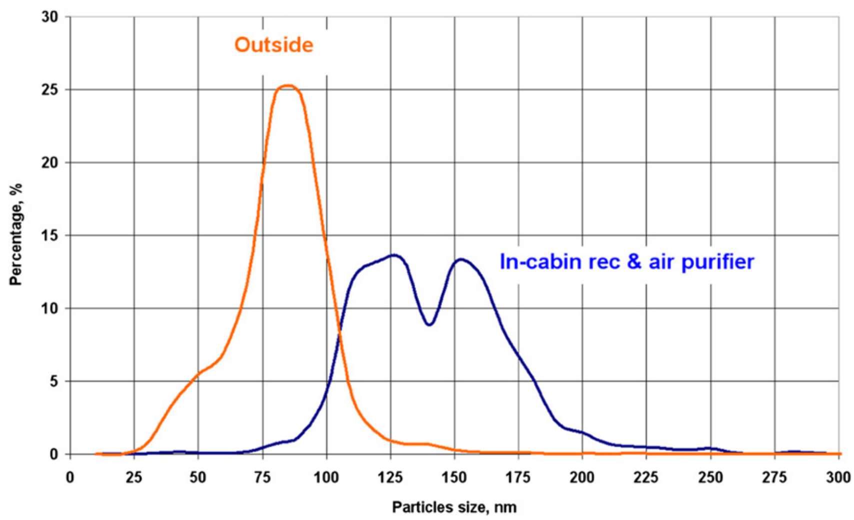


Fig. 11. Distribution of UFP size outside and inside the vehicle.

During the major part of the test, the PN concentrations did not fall under 8000 cm^{-3} with a rise back to near outside levels at the time of door openings. We suppose that the average PN concentration levels may be further reduced by an appropriate increase in the filtered air exchange rate. However, quantitative assessment of the required air exchange rate is needed.

4. Conclusions

The dedicated in-cabin air purifier achieved significant reductions of up to 99% in the in-vehicle UFP number concentration compared with the values for outside air. The application of the air purifier allowed a reduction in the in-vehicle particle concentrations down to values lower than 500 cm^{-3}, which are much lower than PNC typical for a clean office. This was accompanied by some increase in the average size of particles.

Minimal PNC in the driver's breathing zone were achieved after approximately 17–20 min of filter operation. The relatively significant time required to achieve the lowest possible PNC at the reported air exchange rate of 0.2–0.25 min^{-1} is most likely the result of a) unfiltered air penetration into the car through existing leaks and b) lower local air exchange rate in the driver's breathing area as a result of air purifier's location in rear part of the car, far from the sampling point. The validity of these suppositions should be confirmed in further research work.

In-cabin air purifier achieved extremely low UFP concentrations without dangerous exposure of occupants to elevated CO_2 levels. CO_2 concentrations inside a car with the air purifier were practically stabilized after approximately 10 min of air purifier operation at the level of approximately 1200–1300 ppm, which is lower by a factor of 4 than the threshold limit value of ACGIH and meets the requirements of the ASHRAE standard 62-2001. After approximately half an hour of driving, this value was lower by a factor of two than that measured in the 'rec' ventilation mode without the air purifier.

Study results confirmed that the lowest in-vehicle particle concentrations without an air purifier are observed at the 'rec' ventilation mode. The latter ensured decrease of the in-cabin air pollution by a factor of 1.4…1.7 for the 'old' cars and 1.8…1.9 for the 'new' cars, dependent on the PM size range. The issue of CO_2 accumulation limits the use of the 'rec' mode to very short driving events.

Considerably higher PM10 concentrations were measured inside buses compared with passenger cars. This phenomenon is a result of the re-suspension of particles deposited on the bus seats and passengers' clothes during passenger movements. Bus passengers are exposed to PM10 levels exceeding the estimated 1-h threshold value during 22–60% of the total journey time compared with 2% for the passenger cars in the 'rec' ventilation mode.

Smoking inside a car led to a dramatic increase of in-vehicle PM concentrations. PM2.5 levels increased by a factor of 90 and approached 2300 $\mu g\ m^{-3}$.

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