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Ultrafine particle air pollution inside diesel-propelled passenger trains☆

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ABSTRACT

Locomotives with diesel engines are used worldwide and are an important source of air pollution. Pollutant emissions by locomotive engines affect the air quality inside passenger trains. This study is aimed at investigating ultrafine particle (UFP) air pollution inside passenger trains and providing a basis for assessing passenger exposure to this pollutant.

The concentrations of UFPs inside the carriages of push-pull trains are dramatically higher when the train operates in pull mode. This clearly shows that locomotive engine emissions are a dominant factor in train passengers' exposure to UFPs. The highest levels of UFP air pollution are observed inside the carriages of pull trains close to the locomotive. In push mode, the UFP number concentrations were lower by factors of 2.6–43 (depending on the carriage type) compared to pull mode. The UFP concentrations are substantially lower in diesel multiple-unit trains than in trains operating in pull mode. A significant influence of the train movement regime on the UFP NC inside a carriage is observed.

1. Introduction

Epidemiological studies have demonstrated that human exposure to air polluted by particles is associated with various adverse health effects, including respiratory and cardiovascular disease (Vallero, 2008; Chuang et al., 2007). The published research results suggest that ultrafine particles are more harmful to human health than larger ones because smaller particles can penetrate cell membranes and are transported within the blood stream to the human brain, liver, among other organs (Slezakova et al., 2013; Knibbs et al., 2011; Hoet et al., 2004).

Previous studies have mainly focused on investigating passengers' exposure to particulate air pollution (PM10, PM2.5, PM1 and UFPs) inside cars, buses, and bicycles; near highways; and at bus stations (Farrell et al., 2016; Gramotnev and Gramotnev, 2005; Kingham et al., 2013; Tartakovsky et al., 2013; Whitlow et al., 2011; Zhang and Zhu, 2010; Zuurbier et al., 2010; Joodatnia et al., 2013). A comprehensive review of passengers' exposure to particulate air pollution while commuting in various transportation modes was performed by Karanasiou et al. (2014). Recently, trains have attracted the attention of researchers, and the main focus has been on train emission factors and subway systems (Yan et al., 2015; Jaffe et al., 2014; Burchill et al., 2011; Abbasi et al., 2013; Salma et al., 2007; Braniš, 2006; Aarnio et al., 2005; Johansson and Johansson, 2003).

The worldwide railway passenger transport activity is constantly growing and was increased by more than 50% from 2003, reaching a level above 3.1 trillion passenger-km in 2012 (UIC–International Union of Railways, 2015). In China, the railway passenger turnover in 2015 was 1.3 trillion passenger-km (Xu et al., 2011). In Russia, passenger turnover by rail in 2010 was 28.7% of the total passenger transportation and almost the same as that by buses (28.9%) (Alexeyev, 2011). At the same time, it is important to note that in 2010 each passenger travelled an average of 146.1 km by railway compared with only 10.4 km by bus (Alexeyev, 2011). Considering the similar speeds of these transport modes, it is clear from the provided example that railway passengers spend much more time in trains than in buses. In the European Union (EU), the relative importance of passenger transport by train is increasing steadily at the expense of using buses and trolley buses (Eurostat, 2016).

Only approximately 1/3 of the total railway line length is electrified worldwide (UIC–International Union of Railways, 2015). Diesel-powered trains are widely used around the globe as a standard technological solution for train propulsion on non-

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electrified rail lines. In some regions, such as North America, almost all railway transportation is based on diesel propulsion (UIC–International Union of Railways, 2015). Railway lines sometimes pass through densely populated areas. The region of Tel Aviv is a good example (Tel-Aviv). Commuters actively use the railway, even for short journeys. The passenger traffic for Israel (the country of 8 million inhabitants) is 4 million people per month (Sela, 2014). On average, commuters spend two and a half hours per day travelling to and from work and waiting for trains at train stations. In countries with long travel distances, passengers are exposed to significant levels of air pollution, including the dangerous particulate matter (PM) produced by diesel engines, for long periods of time. Morawska et al. (2013) showed that indoor sources contribute up to 76% of the integrated daily residential exposure to ultrafine particles, which further stresses the importance of assessing train passengers' exposure to UFPs.

Progress on the investigation of particle emissions from rail vehicles is reviewed in the work by Abbasi et al. (2013). Both exhaust and non-exhaust particle emissions were considered in this review. While exhaust-generated particles are mainly attributed to locomotive engine and diesel-generator emissions, non-exhaust particles normally originate from wheel-rail contact, brakes wear, outdoor particles re-suspended by train motion and particles in passenger compartments that are re-suspended due to carriage vibrations and passenger movement (Tartakovsky et al., 2013; Abbasi et al., 2012, 2013). The authors of a previous study (Abbasi et al., 2013) discussed PM10 and PM2.5 emissions, particle size, morphology, composition, and adverse health effects with various solutions for reducing these emissions. Air pollution by particulates of PM10 and PM2.5 size fractions, as well as the particle number concentrations, have been measured inside electricity-powered trains and on the platforms of subway stations in various cities worldwide, e.g., Budapest (Salma et al., 2007), Prague (Braniš, 2006), Helsinki (Aarnio et al., 2005), Stockholm (Johansson and Johansson, 2003), Gothenburg (Boman et al., 2009), Seoul (Park and Ha, 2008), Taipei (Cheng et al., 2012), and Barcelona (Martins et al., 2016). The authors of these studies found that air pollution by particles inside electricity-powered train carriages was usually higher than in outdoor air. Aarnio et al. (2005) measured the particle number (size < 500 nm) concentrations and size distributions at an underground subway station and found them to be similar to those measured in the outdoor air, concluding that the source of particles of this size was road traffic. However, other researchers (Salma et al., 2007; Martins et al., 2016) reported that the composition of particles measured in subway stations differed from the average outdoor composition, attributing the PM found in the underground stations and inside subway trains to the wear of rails, train wheels and brake pads. Seshagiri (2003) studied the exposure of personnel in the cabs of leading and trailing locomotives of freight trains to gaseous and particle emissions during winter and summer. Negligible levels of elemental carbon (EC) were measured in the leading locomotive. In the trailing one, the measured in winter mean EC levels were 2.9 μg/m3, which is close to the detection limit of 2.0 μg/m3 (Seshagiri, 2003; Pronk et al., 2009). In summer, when windows were open from both sides of the locomotive, mean EC concentrations of 17.1 μg/m3 were measured. Liukonen et al. (2002) studied exposure of the locomotive's crew to diesel exhaust. They investigated the influence of the locomotive orientation ("long-hood" or "short-hood" forward), which affects the exhaust tailpipe position relative the crew cabin, on the air pollution levels inside the cabin. Liukonen and co-workers showed that open windows and an exhaust tailpipe position in front of the locomotive cabin had a substantial influence on the EC levels inside the cabin. Seshagiri and Liukonen, with their co-authors, did not study the UFP levels in passenger train carriages. Abadie et al. (2004) investigated passenger exposure to particulate air pollution in French high-speed train (TGV) smoker cars. Knibbs and de Dear (Knibbs and de Dear, 2010) measured the indoor concentrations of UFP and PM2.5 at the time of commuting along a similar route by train, bus, ferry and car in Sydney, Australia. The average concentration of UFPs in trains was found to be 2.8×10^4 cm^{-3}. The trains were powered by electricity delivered by overhead lines. Knibbs et al. (2011) reviewed 'in-transit' UFP exposure of commuters for six different transport modes: car, bus, bicycle, walking, ferry and train. They pointed out that a majority of train UFP exposure studies were performed on electricity-powered trains rather than the diesel-propelled ones. The limited available data overviewed in Knibbs et al. (2011) suggest that diesel trains may cause a much higher UFP exposure level compared with electricity-powered trains. Despite the data gained on train emissions and particle air pollution in subway systems, information related to the UFP levels in the indoor environment of diesel-propelled passenger trains, dependence of the UFP concentrations inside a carriage on the location relative to the locomotive and diesel-generator, spatial variation of the UFP concentrations inside a carriage, influence of the train operating mode, among other factors is fragmentary and not well documented.

This study aims to assess the UFP concentrations in the indoor environment of different passenger train types as well as to identify the main factors that affect the UFP concentrations in train passenger carriages and railcars. The concentrations of UFPs were analyzed with respect to various parameters, such as the carriage age, type, carriage location in the train, train operating mode (push or pull) and more.

2. Methodology

2.1. Instrumentation

The ultrafine particle number concentrations inside passenger train carriages were measured by a diffusion size classifier (DiSC, Matter Engineering AG, Switzerland). This device is a small, easily portable, battery operated instrument and is therefore well suited for field measurements. The main specification parameters of the DiSC are shown in Table 1. Although DiSC is somewhat less accurate (±30%) and sensitive than other frequently used laboratory devices, such as Condensation Particle Counter – CPC (accuracy ±10%) and Scanning Mobility Particle Sizer – SMPS, the DiSC is highly applicable for field measurements due to its compactness, portability and self-contained power supply.

Previously reported detailed tests with this instrument (Fierz et al., 2008) revealed that the measured UFP number concentrations agree well with those obtained by using CPC. The time resolution of this device allows for measurement of transient engine operation.

The instrument requires recalibration after 500 h of operation (Fierz et al., 2008). Moreover, cleaning the instrument's diffusion stage and replacing the filter in the filter stage are required when the differential pressure through an instrument with an open inlet connection reaches 10 mbar. The Pressure Error LED on the front panel of the device provides a signal when the critical pressure is reached. To ensure the quality of the data collection, both the instrument operation time and Pressure Error LED signal were carefully monitored. When completing the measurement program reported in this paper, no instrument recalibration was required. There was no need to clean and replace the filter during the period of experiments reported in this work. To ensure the best possible accuracy of the measurements, the zero reading of the instrument was checked daily before the start of measurements.

In the reported experiments, we did not use an evaporation

Table 1
Main specification parameters of the DiSC instrument used in experiments (from the user manual and Fierz et al., 2008).

Detectable particle concentrations (depend on particle size and averaging time) – typical values, cm^{-3}	20 nm: 3000–1,000,000 100 nm: 1000–500,000
Particle size range, nm	20–200[a]
Time resolution, sec	1
Accuracy	±30% in size and number
Flow rate, L/min	1.5 ± 0.1
Weight, kg	5.5
Maintenance interval (for calibrations, cleaning, etc.), hours of instrument operation	Minimum 500
Time of operation on one battery charge, hours	10 (typical)

[a] The instrument measures UFPs in the range 10–400 nm. However, for particles <20 nm, the DiSC will generally underestimate the particle number. For particles larger than 200 nm, overestimation of the particle diameter is possible.

tube. In all experiments, the sampling inlet was at the height of the breathing zone area of a sitting passenger. The sampling flowrate of the instrument was 1.5 ± 0.1 L/min – Table 1. A short Teflon tube of ~0.5 m in length and approximately 5 mm in internal diameter was connected to the sampling inlet of the instrument. The tube length was chosen to minimize particle loss (residence time ~0.4 s), while enabling sampling at the height of the passengers' breathing zone. We used a single DiSC instrument in the measurements. Unlike the commonly used definition, the 'ultrafine' particles measured in this work are defined as particles with a size cut of 10–400 nm.

2.2. *UFP measurement procedure*

All experiments were performed inside different carriage types over a three-month period on various weekdays (Sunday to Friday) from 07:00 to 19:00 (Sunday is a weekday in this area). No special investigation on influence of rush hours on UFP levels inside the train carriages was performed. The ambient air temperatures during the measurements were in the range of 6–25 °C and the wind speeds varied between 1 and 9 m/s. In most experiments, the wind directions were as follows: north - 41%, south - 24%, west - 6%, and east - 29% (in our study, the train direction of motion was almost strictly from north to south and back). In total, 100 measurements were performed inside the carriages of passenger trains; 92 had valid results and were included in the analysis. Forty-six tests were performed in double-deck carriages, 13 in old single-deck ones, 17 in new single-deck carriages and 16 in diesel multiple-unit trains. Unfortunately, the total number of valid measurements is not sufficiently large to allow for reliable analysis of the day-to-day variance of the obtained results.

The experiments were performed on the railway route between Haifa Merkaz HaShmona station and Tel Aviv HaShalom station (the main railway route in Israel). The route length is approximately 95 km and includes up to 6 stops (depending on the train type and schedule). The duration of a one-way trip was 66–70 min. Each PN measurement lasted 15 min. Therefore, the authors completed the measurements in four carriages (#1, 3, 5 and 7), one-by-one, in a single one-way journey. The sampling frequency was 1 Hz. The results of the measurements were directly saved on a SD/MMC memory card and further processed offline. The average results and standard deviations presented in Figs. 2, 4–7 were calculated by processing all of the 1-Hz resolution data gained for each considered case.

2.3. *Carriage types*

Because all studied passenger trains are smoke-free, the issue of smoking was not investigated in our study. Measurements of the PN concentrations were performed in carriages of the following types:

2.3.1. *New single-deck passenger carriages*

These carriages, hereafter called 'new', were manufactured in 2009–2011. There are three types of new single-deck carriages, a power car with two diesel generators (each one is powered by a 4-stroke 339 kW engine), a trailer passenger car, and a handicap-accessible passenger car with wheelchair equipment (Siemens Transportation Systems, 2008). Information on the carriage dimensions and capacity is taken from Siemens Transportation Systems (2008). The length of the power and trailer cars is approximately 26 m. The width and height of all new single-deck carriages are 2.8 m and 4.4 m, respectively. The passenger capacities of the power and trailer cars are 27 (23 fixed seats) and 82 (78 fixed and four folding seats) passengers, respectively. The doors are 1.2 m in width and 1.9 m in height. Each push-pull train contained 8 or 9 cars. When the locomotive was at the tail of the train (push mode), the power car with a diesel generator that produces electricity for the train was at the nose of the train. Measurements were performed in various carriages of the train that were located at different distances from the locomotive and diesel generator according to the scheme shown in Fig. 1. In these experiments, in each carriage, UFP sampling was performed at the next-to-door seats.

2.3.2. *Old single-deck carriages*

The years of production of the single-deck carriages, hereafter called 'old' ones, are 1996–1997. Measurements in the old single-deck passenger carriages were performed on the same route during round trips. There are two types of carriages, a power car with two diesel generators (each one is powered by a 4-stroke 313 kW engine) and a trailer car. The information on the carriage dimensions and capacity is taken from Melling. The length of the power car is 27 m, and the trailer car is 26 m long. Each push-pull train of old single-deck carriages contained up to eight trailer cars and one power car. The passenger capacity of the latter is 38 passengers and is 86 passengers for the trailer car. The locomotive and carriage with diesel generators (power car) and measurement points were located as shown in Fig. 1. As for the new single-deck carriages, in old single-deck carriages UFP sampling was performed at the next-to-door seats.

2.3.3. *Multiple-unit trains*

The multiple-unit train is a medium/long distance diesel railcar. It is a three-unit train set that contains two power units and one middle unit (Melling). There are two 294-kW KHD diesel engines in each power unit, whereas the middle unit has no engines. In total, the propulsion power of the railcar train is 1176 kW (four 294-kW engines). The passenger capacity of power units varies from 50 to 56 passengers, which depends on the set and unit (Melling). The passenger capacity of a middle unit is 64 or 68 passengers (depending on the set). The lengths of a power unit and middle unit are 21 m and 18 m, respectively. The overall length of the railcar train is 59 m (Melling). Measurements of the PN concentrations in

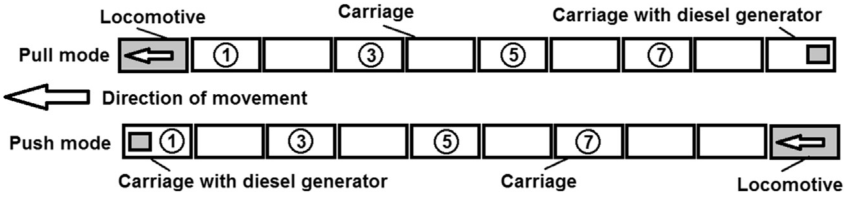

Fig. 1. Scheme of measurements in single-deck passenger carriages. A digit inside a circle indicates the carriage number where measurements were performed. Carriage #1 is always located in the nose of the moving train.

these railcars were limited to the short route segment of 8 km because these trains only run on this railway segment. For this reason, in these experiments, each measurement lasted 10 min. In the power units, sampling was performed at seats located in the center of a carriage and at the next-to-door seats. In the middle units, sampling was performed in the center of a carriage (there are no doors in this type of carriage).

2.3.4. Double-deck carriages

As for single-deck passenger carriages, the double-deck push-pull train consists of trailer cars and one power car. The latter contains two diesel generators (each one is powered by a 4-stroke 313-kW engine) as in the old single-deck trains. The information on the carriage dimensions and capacity is taken from Melling. The power and trailer cars have almost the same length of 27 m. The car width is 2.8 m. The height of both the lower and upper passenger compartments is the same - 2.0 m. The passenger capacities of the power and trailer cars are 79 and 142 passengers, respectively. The doors are 1.9 m wide. Unlike single-deck trains with 9 cars, double-deck trains running on a 95-km route with 4–5 stops consisted of seven carriages. As for single-deck carriages, UFP NC measurements were performed in coaches 1, 3, 5, and 7. The locomotive and power car in these trains were similarly located as for single-deck carriages - Fig. 1.

In addition to the measurements performed on the 95-km route, as described in section 2.2, an additional series of experiments was performed on double-deck carriages on the shorter segment of this route between Binjamina and Tel Aviv. The length of this segment is approximately 64 km. Trains running on this shorter route consisted of six carriages and made more stops (9 stops in a one-way journey). In these trains, measurements were performed in the same carriage in both the pull and push modes (in the 4th coach when a train operated in the push mode, and in the 3rd coach on the return trip). The measurements were performed at the next-to-door seats. The main goal of the experiments performed on the 64-km segment was to assess the possible influence of frequent carriage door opening on the UFP levels inside the passenger compartment. For this reason, the line with the maximum available number of train stops was selected. The sampling duration at each deck was 30 min.

2.3.5. Diesel locomotives and railcars

The types of locomotives, railcars and their engines are shown in Table 2.

3. Results and discussion

3.1. Effect of the train operating mode and distance from the emission source

Fig. 2 shows influence of the train's operating mode (push or pull) and distance from the emission source on the UFP number concentrations inside the train carriages. The data presented in Fig. 2 are average values of multiple measurements performed on the same route for the same carriage type. As we mentioned earlier, there are two major emission sources in the studied train configurations, diesel locomotive engine and diesel generators. The former has a much higher power than the latter and obviously produces substantially higher pollutant emission levels. As seen from Fig. 2, for all tested carriage types, when the locomotive operated in pull mode, very high UFP concentrations were measured in all train carriages. The minimal average UFP NC value, as measured in an old single-deck carriage that was most distant from the locomotive, was 10^5 cm^{-3}. This value is factors of 2.2 and 2.4 higher than the trip-weighted mean UFP NC values reported for car cabins ($4.5 \cdot 10^4$ cm^{-3}) and buses ($4.2 \cdot 10^4$ cm^{-3}), respectively (Knibbs et al., 2011). For comparison, the average UFP concentrations in the electricity-powered trains, as measured by Knibbs and de Dear (Knibbs and de Dear, 2010), were $2.8 \cdot 10^4$ cm^{-3}. It is important to note here that this comparison does not consider possible bias caused by different measurement and data processing methods.

Measurements performed by the authors in intercity buses using the same instrument and the same data processing method as in this study, reveal the average UFP NC value of $1.5 \cdot 10^4$ cm^{-3}, which is lower by a factor of 6.7 than the lowest average UFP NC measured in a passenger carriage of a train operated in pull mode. Tartakovsky et al. (2013) studied the UFP NC inside a car cabin using the same device as in this study. They found that in a car that was not equipped with an OEM-made cabin air filter, after switching on the recirculation ventilation mode, the measured UFP NC monotonously decreased and reached a level of $3 \cdot 10^3$ cm^{-3} in approximately 16 min. This value is lower by a factor of 30 than the lowest average UFP NC measured in a passenger carriage when a train operated in pull mode. We should remind here an important remark of Knibbs et al. (2011). They mentioned that while the comparison of mean UFP exposure level would reveal the general trend, it is not truly meaningful to rank the UFP exposure level of different transport modes, since the determinants of exposure (meteorology, cabin ventilation, aftertreatment technology, etc.) are highly variable and mode-dependent.

The highest levels of the average UFP number concentrations in the pull operating mode were observed in carriages adjacent to the locomotive, whereas the average UFP NC in these wagons reached values of $3–4.4 \cdot 10^5$ cm^{-3} (up to an order of magnitude higher than in averaged car cabins). Of course, when more information under various conditions is available for passenger trains, as is currently available for cars and buses, a more accurate comparison of commuters' exposure to UFPs in different transportation modes is possible.

The obtained results somewhat contradict a study by Seshagiri (2003) in which measurements of elemental carbon (EC) were performed in the cabs of leading and trailing diesel locomotives that were operated in tandem. According to Seshagiri (2003), negligible EC concentrations that were close to the detection limit (mean value of 2.9 $\mu g/m^3$) were measured in the cab of the trailing

Table 2
Diesel locomotives and railcars in the study.

Type of locomotives or railcars	Number of engines	Year of production	Engine type	Engine displaced volume, L	Engine power, kW	Emissions control
Alstom JT42BW	1	2002	EMD, 2-stroke, 12-cylinders	139	2353	EU97/68 Stage IIIA No exhaust gas aftertreatment
Vossloh EURO 4000	1	2011	EMD, 2-stroke, 16-cylinders	185	2954	EU97/68 Stage IIIA No exhaust gas aftertreatment
Vossloh EURO 3200	1	2013	EMD, 2-stroke, 12-cylinders	139	2250	EU97/68 Stage IIIA No exhaust gas aftertreatment
Railcars	4	1990–1994	KHD, 4-stroke, 8-cylinders	12.8	294	N/A No exhaust gas aftertreatment

locomotive with closed windows. Negligible EC levels were also found in the leading locomotive's cab. Of course, direct comparison of the results obtained in this work with those mentioned in Seshagiri (2003) is impossible because of the different measuring methods that were used. As seen from the standard deviation bars in Fig. 2, a wide variation in the measured UFP concentrations was observed during the measurement period. For example, in the carriage adjacent to the locomotive, the measured values of the UFP concentrations varied from 10^5 to $6.7 \cdot 10^5$ cm^{-3}. This variation is a result of changes in the wind speed and direction, and using locomotives with engines that have different volumes (and subsequently different excess air factors at the same power, which is normally reflected in the different particle formation) - Table 2 in trains with the same type of carriages.

As seen from the results presented in Fig. 2, the UFP NC levels in all of the studied types of carriages were substantially lower when the train operated in push mode compared to pull-mode. This clearly shows that the locomotive engine emissions are a dominant factor in train passenger exposure to UFPs. In push mode, the UFP number concentrations were lower by factors of 2.6–43 (depending on the carriage type) compared to pull mode. Over the entire range of studied carriage types and for all carriages for which the measurements were performed, the average UFP NC values in push mode did not exceed $1.2 \cdot 10^5$ cm^{-3}. In most carriages, the measured average UFP number concentrations in push mode remained lower than in an average car cabin ($4.5 \cdot 10^4$ cm^{-3}) and average bus ($4.2 \cdot 10^4$ cm^{-3}).

For all carriage types, the lowest average UFP NC values were measured in the middle of a train between the 3rd and 5th carriage (in a train of 9 carriages), where the joint influence of emissions from both the diesel generators and locomotive engine, together with the effects of airborne non-exhaust particles, was minimal. The UFP NC values in the middle of a train were lower by a factor of 1.5–7.8 than in the most polluted carriages that were adjacent to the main emission source. In pull mode, the highest UFP levels were always observed in the 1st carriage adjacent to a locomotive. In push mode, this was no longer the case. The first carriage in the latter case is a power car with diesel generators, which produces much lower emission levels than the locomotive engine. Therefore, in push mode, the influence of the airborne non-exhaust particles is sensible. It is known from multiple observations that the level of re-suspended airborne particles increases from the train nose to tail, which results from longitudinal trailing vortices along the train (Baker, 2014). These particles penetrate the indoor compartment of a carriage through its HVAC system. A schematic layout of the fresh air grilles in the studied carriage types is shown in Fig. 3.

As seen from Fig. 3, the fresh air inlet in old single-deck carriages is located almost on the roof, which is much closer to the exhaust stacks and more distant from the re-suspended airborne particles. The situation is the opposite for double-deck carriages (Fig. 3). Naturally, the relative contribution of the engine exhaust decreases and that of re-suspended airborne particles increases from the train nose to tail. When the train operates in push mode and the levels of exhaust particles from the diesel-generator are much lower compared to emissions from the locomotive engine, the contribution of the re-suspended airborne particles that infiltrated through the carriage HVAC system becomes sensible. Towards rear carriages, the level of exhaust particles in the air around the carriage decreases and that of the re-suspended airborne particles increases. As a result, higher UFP levels were measured in the push mode in carriage 7 compared to carriage 5 for all of the studied carriage types (Fig. 4). In double-deck carriages, in push mode, carriage 7 was found to be the most polluted carriage. It had a UFP NC that was 1.7–1.8 higher than that in carriage 1 (Fig. 2). This is the result of the low-height location of the fresh air grilles in this type of carriage (Fig. 3). This led to enhanced infiltration of the re-suspended airborne particles into the carriage, whereas the relative influence of the engine exhaust (more distant from the grille) was weaker.

A comparison of the measured UFP NC values in new and old single-deck carriages (data for both carriage types were only available for the push operating mode) is shown in Fig. 5.

Analysis of the UFP levels measured in the new and old single-deck carriages confirms the similar findings for road vehicles (Tartakovsky et al., 2013; Hudda and Fruin, 2013) in terms of the vehicle age influence. As seen from Fig. 5, the average UFP NC levels were higher in old single-deck carriages throughout the train compared to new ones by a factor of 2–6. As previously demonstrated for road vehicles, more UFPs penetrate the passenger compartment of older carriages through less efficient air filters, less tight doors and window sealing and leaks in the carriage structure. The adjacency of carriage 1 to the emission source with the above-mentioned less tight sealing of old carriages resulted in a much higher UFP NC that was measured in 1st carriage of the old single-deck compared to the new counterpart (Fig. 5).

It should be noted that in one of experiments with double-deck carriages, when the train operated in pull mode, an extremely high UFP NC was measured in the third carriage, and the DiSC instrument readings reached scale saturation (not shown in Fig. 2). An immediately performed investigation revealed that in the center of the carriage on the top floor, one of windows was not tightly closed. This resulted in very high observed values of air pollution in the carriage. This finding allows us to conclude that the tightness of windows and other openings is a very important parameter that substantially affects the UFP NC levels in the carriages of moving trains. For clear reasons, this effect is most severe when a train is operating in pull mode. The significant influence of window opening on the particle concentrations inside locomotives was also mentioned in previous studies (Seshagiri, 2003; Pronk et al., 2009).

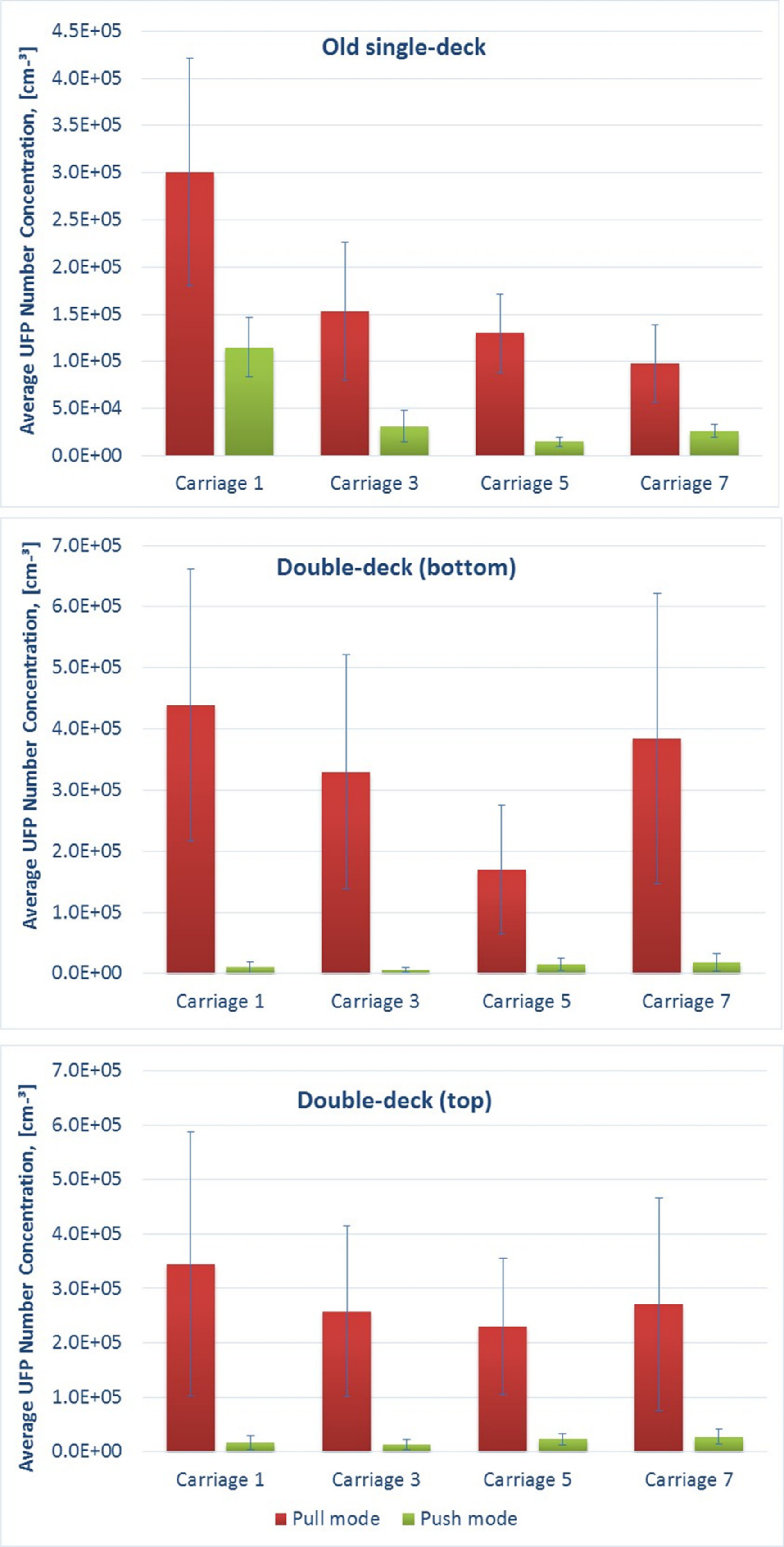

Fig. 2. Comparison of the average UFP number concentrations measured in single-deck and double-deck carriages in the pull and push operating modes. Error bars - standard deviation of the average UFP number concentrations.

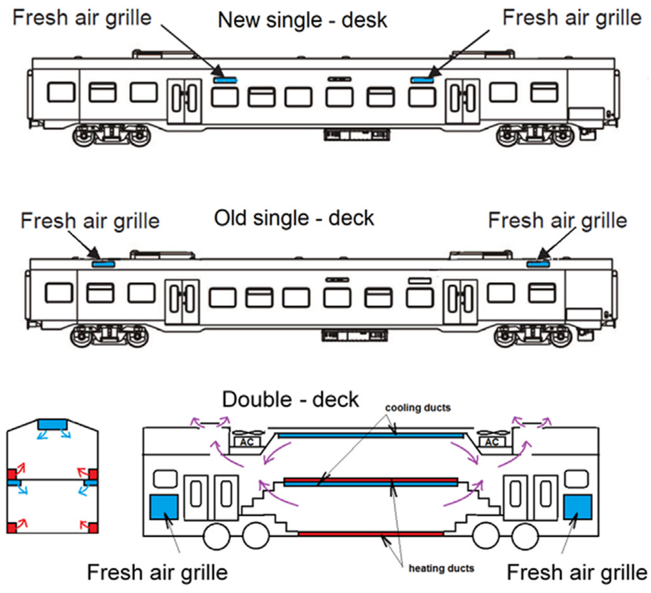

Fig. 3. Fresh air grille location in the studied carriage types.

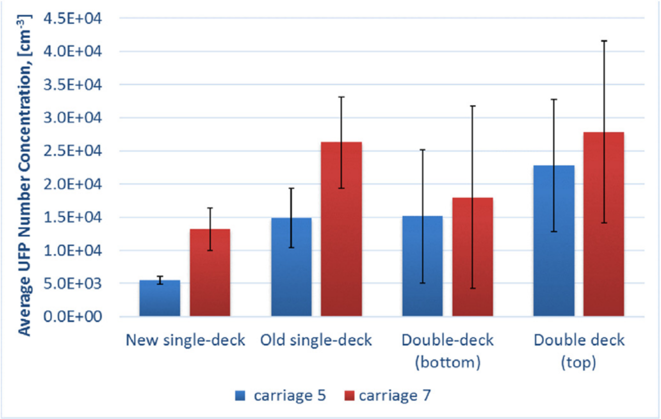

Fig. 4. The average UFP number concentrations in carriages 5 and 7 in push operating mode. Error bars – the standard deviation of the average UFP number concentrations.

3.2. *Effects of the emission source presence in a carriage*

Fig. 6a shows an example of the time - resolved UFP number concentrations in a diesel railcar (multiple - unit train) measured at different distances from the emissions source (railcar diesel engine). For the results shown in Fig. 6a, the measurements always started and finished at the same train stops. Fig. 6b presents the average values of the UFP NC measured at various locations inside the power and middle units.

The highest UFP NC values were measured in a power unit (carriage with engines) in the vicinity of seats located near doors (it should be noted that middle units without engines lack entrance doors). The main reason for this phenomenon is UFP penetration of the carriage through fresh air grilles that are located directly above the entrance door near the exhaust tailpipes of two diesel engines located in the carriage. As seen from Fig. 6a, the UFP NC measured in the power units in the vicinity of doors is very sensitive to the train operating regime and significantly increases during train accelerations reaching values above $3 \cdot 10^5$ cm^{-3}.

The short measurement duration did not allow us to obtain more complete information on UFP NC fluctuations inside a power

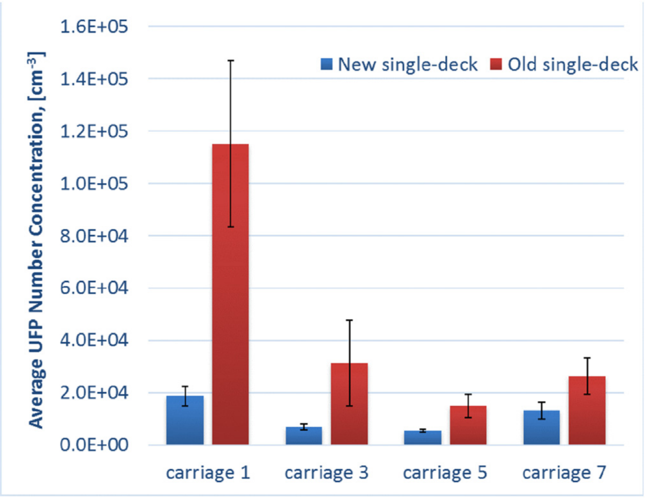

Fig. 5. Comparison of the average UFP number concentrations in new and old single-deck carriages. Push mode. Error bars – the standard deviation of the average UFP number concentrations.

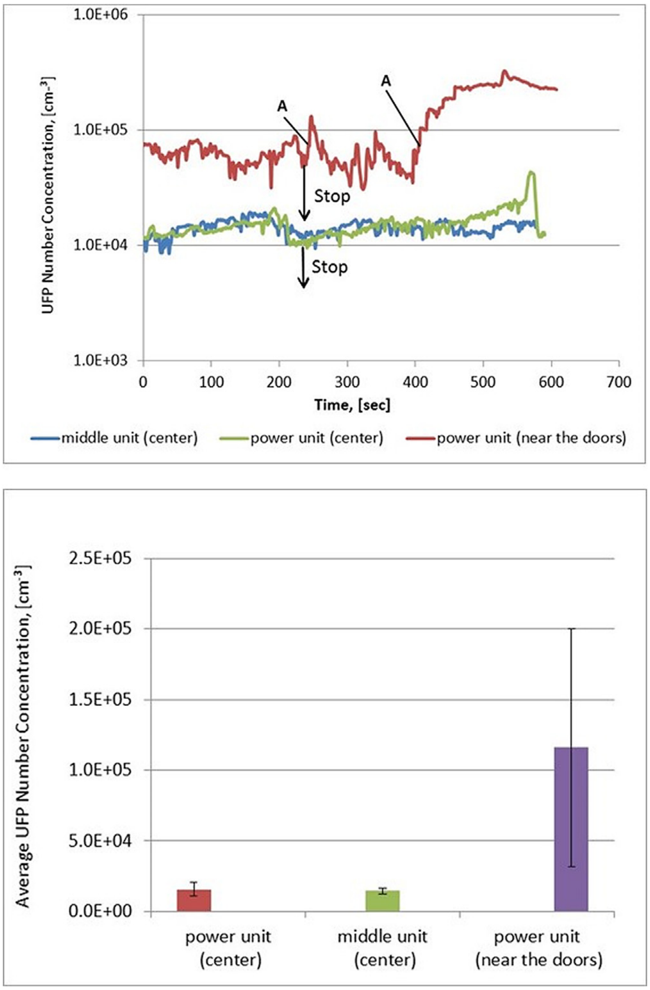

Fig. 6. UFP number concentrations in diesel railcars. Error bars – the standard deviation of the average UFP number concentrations.
6a) Example of the time-resolved UFP number concentrations; A - train acceleration.
6b) Average UFP number concentrations.

unit. However, based on the available data, we assume that the "puff" of particles produced during train acceleration arrives at the middle of the carriage approximately 5–6 min after penetrating the carriage in the vicinity of doors (Fig. 6a).

The average UFP NC values measured in the center of the power and middle (without engine) units were approximately a factor of 6 lower than the particle number concentrations near the doors (Fig. 6b). No significant difference was observed between the average UFP NC measured in the center of the power and middle units. The main reason for this finding is the absence of internal partitioning between the carriages, which equalizes the air quality in the power and middle units.

3.3. *Effect of the floor number in double-deck carriages*

Fig. 7 presents the average values of the UFP NC as measured in the bottom and top floors of double-deck carriages under both push and pull modes. The obtained differences between the UFP concentrations at the bottom and top floors are non-significant. However, some trends that can serve as a basis for future studies can be outlined. As previously mentioned, in push operating mode, the contribution of airborne particles that infiltrated the carriage through the HVAC system becomes sensible. A close look at the scheme of a double-deck carriage HVAC system (Fig. 3) shows that the length of the air ducts conveying air from the AC unit (can be operated in the AC, heating or ventilation modes) to the top and bottom floors in a double-deck carriage is substantially different. Fresh air travels a much longer distance on its way to the bottom passenger compartment of the double-deck carriage. The longer length of the air ducts inevitably leads to more particle loss due to particle coagulation and sedimentation. This probably results in a somewhat lower UFP NC measured in push mode at the bottom floor of all of the studied double-deck carriages (Fig. 7). In pull mode, as we previously showed, the influence of locomotive exhaust emissions is dominant. It seems that infiltration of the exhaust-originated particles through carriage leaks (a random factor when considering differences between the carriage decks) becomes sufficiently significant to lead, together with UFP infiltration through the HVAC system, to the results shown in Fig. 7.

The results of measurements performed on both floors of double-deck carriages further confirm the earlier discussed dependence of the UFP number concentration on the train motion regime (as shown in Fig. 6a) when the UFP number concentrations increase during train accelerations, while the opposite behavior is observed during deceleration. An additional series of experiments with frequent stops did not reveal any clear variation in the indoor UFP concentrations when the carriage doors were opened at stops. No substantial change in the UFP NC (≤10%) was observed during door opening.

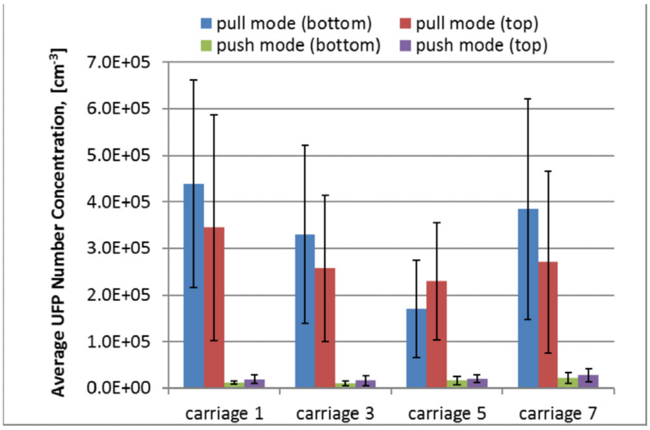

Fig. 7. Average UFP number concentrations at various floors of double - deck carriages. Error bars – the standard deviation of the average UFP number concentrations.

4. Conclusions

The UFP concentrations inside the carriages of push - pull trains are dramatically higher when the train operates in pull mode. This clearly shows that locomotive engine emissions are a dominant factor in train passengers' exposure to UFPs. In push mode, the UFP number concentrations were lower by factors of 2.6–43 (depending on the carriage type) compared to those in pull mode.

The highest levels of the average UFP number concentrations were observed for the pull operating mode in the carriages close to the locomotive, whereas the average UFP NC in these carriages reached values of $3–4.4 \cdot 10^5$ cm^{-3}. For all of the studied types of carriages, the lowest average UFP NC values were measured in the middle of a train between the 3rd and 5th carriages (in a train of 9 carriages). The UFP NC values in the middle of a train were a factor of 1.5–7.8 lower than in the most polluted carriages adjacent to the main emission source.

The average UFP NC was higher in old single-deck carriages throughout the train than in the new ones by a factor of 2–6. This finding confirms the known similar results that were previously obtained for road vehicles.

The average UFP NC values measured in the center of the power and middle (without engine) units of a railcar were lower by approximately a factor of six compared to the particle number concentrations near the doors of the power unit.

Effective measures can be undertaken at affordable costs and over a reasonable amount of time to substantially reduce passengers' exposure to air pollution inside trains (e.g., retrofitting locomotive engines with particle filters (Tartakovsky et al., 2015) or even with more effective combined NO_x-PN reduction systems, using HEPA filters in the carriage HVAC system (Tartakovsky et al., 2013), etc.). Further investigations in this field can significantly contribute to reducing train passengers' exposure to harmful ultrafine particles.

Main finding of the work

The concentrations of UFPs inside the carriages of push-pull trains are dramatically higher when the train operates in pull mode with the highest levels of UFP air pollution in the carriages adjacent to locomotive.

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