

Traffic-related particle emissions and exposure on an urban road

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Keywords: vehicle emissions, mobile monitoring, particle concentration, commuters, deposition dose.

Abstract: Extensive aerosol particle concentrations are one of the factors contributing to poor air quality in cities. The aim of this study is to assess particle number and mass concentrations on a road in Lublin, Poland, in peak and off-peak traffic hours and its impact on the particle exposure for commuters and pedestrians. Mobile monitoring and fixed-site measurements on the sidewalk along the established 2.1 km long route were conducted with the use of Mobile Air Pollution Analytic Laboratory equipped, among other things, with instruments measuring the real-time number and mass concentrations of particles with size range from 10 nm to 32 μm . The highest average concentrations of ultrafine particle number $\text{PN}_{0.1}$ ($25.4 \pm 11 \times 10^3 \text{ pt/cm}^3$; mean \pm standard deviation), total particle number PN ($29.2 \pm 12 \times 10^3 \text{ pt/cm}^3$) as well as mass concentrations of $\text{PM}_{2.5}$ ($29.1 \pm 7.6 \mu\text{g/m}^3$) and PM_{10} ($45.4 \pm 10.3 \mu\text{g/m}^3$) were obtained in peak traffic hours for the part of the route with the most intensive traffic. The average particle number concentrations for the entire route and the part of route with the most intensive traffic in peak times were found to be about 3 to 4 times higher than in off-peak times. The average particle mass concentrations were about twice as high. Furthermore, the average values of the examined particle number and mass concentrations were higher for the on-road measurements than for fixed-site measurements. Moreover, a greater percentage of ultrafine particles was observed during mobile monitoring than in the fixed-site measurement points. It was established that a greater number and mass of particles, irrespectively of their size range, is deposited in the respiratory tract of commuters and pedestrians in peak hours than in off-peak hours. In peak times the average particle doses received by commuters and pedestrians equaled $4.8 \pm 2.4 \times 10^9 \text{ pt/h}$ or $29.6 \pm 10.7 \mu\text{g/h}$ (PM_{10}) and $4.2 \pm 2.3 \times 10^9 \text{ pt/h}$ or $29.6 \pm 8.6 \mu\text{g/h}$ (PM_{10}), respectively. Additionally, in both peak and off-peak hours greater particle doses were determined in the considered part of the route with the most intensive traffic; however, in off-peak traffic times pedestrians are more exposed to traffic-related pollutants than commuters. Overall, the obtained results reflect the importance of traffic-related particle emission measurements for exposure evaluations and the need of taking the actions aimed at decreasing it.

Introduction

Concentration of particles suspended in ambient air is one of the most important parameters determining air quality in cities. Such suspended particles may contain toxic substances which include polycyclic aromatic hydrocarbons such as benzo(a) pyrene, heavy metals as well as dioxins and furans (Klejnowski 2010, Olszowski and Bożym 2014). Mass concentrations of PM_{10} and $\text{PM}_{2.5}$ particles (with an aerodynamic diameter smaller than 10 μm and 2.5 μm , respectively) are most frequently monitored in urban areas. The legal standards for both PM_{10} and $\text{PM}_{2.5}$ are set by the Air Quality Guidelines (CAFE 2008).

At present more attention is drawn to the concentrations of ultrafine particles (UFP) with a diameter of less than 100 nm, which pose a significant health risk (Kumar et al. 2014). Therefore, while monitoring urban air quality, the share of UFP in the total particle concentration should be considered. The monitoring of the UFP levels is hindered by the fact that such particles undergo constant changes, both chemical and physical

(Sabaliauskas et al. 2012). Numerous other factors also affect the time and spatial variability of such particle levels. They include, among other things, wind direction and strength, temperature inversion and type of urban sprawl (Kozawa et al. 2012, Sartini et al. 2013). The latter may limit air exchange and create an urban canopy layer (UCL), the thickness of which depends on the height of the buildings. In deep street canyons aerosol particle concentrations may be many times higher than in other parts of the city. UFP concentrations, due to the lack of established permissible levels, are not monitored on an ongoing basis in the majority of urban areas.

Epidemiological studies have found an association between concentrations of airborne aerosol particles in ambient air and adverse health effects such as respiratory and cardiovascular diseases (Valavanidis et al. 2008). In 2013 respectively about 61% and 87% of the urban population in the European Union was exposed to PM_{10} and $\text{PM}_{2.5}$ concentrations which exceeded the daily limit imposed by the WHO for outdoor air pollution (EEA 2017). This study also linked $\text{PM}_{2.5}$ exposure to 403,000

premature deaths in 2012 in the EU. Studies in London have shown that commuters' exposure to particle concentrations in urban areas can be approximately 1.5 times higher while travelling by car and bus as compared to walking along roadsides (Kaur et al. 2005). In turn, according to Fruin et al. (2008) approximately 6% of the total commuting time spent in a car in the American road environment can contribute to about 36% of the daily average exposure to particle number concentrations. Dons et al. (2012) showed that about 3.6% of the daily time spent while commuting by car in Belgium contributed to approximately 14.5% of the average daily exposure to particle number concentrations. Similar results can be expected for individuals living in other EU member states (Knibbs et al. 2011). As travelling time has increased over the years, there is a growing need for an accurate exposure assessment. Despite numerous commuting exposure assessment studies that have been carried out in urban areas in recent years, the provision of accurate estimates for human exposure to aerosol particles is still challenging. This is due to the fact that each route has different characteristics related to, e.g., the traffic intensity, the number of trucks and passenger cars or the type of fuel used (Drozdziel et al. 2017a). Also the topography and the built-up area around the route differ. Even for the same route there are constant changes in the traffic characteristics related to the time of the day, the change of the weather conditions or other factors. Traffic intersections (TIs) are usually characterized by higher particle concentrations. Such locations are generally considered as pollution hotspots (Goel and Kumar 2015).

Mobile on-road and fixed-site measurements of particle concentrations provide different information. The former are used to assess the commuters' (drivers' and car passengers') exposure to particles, while the latter may constitute a basis for evaluating particle exposure of pedestrians. Both measurement methods may also be a source of information on particle transformation processes (e.g., nucleation, coagulation, condensation and deposition) on-road as well as on the sidewalk.

This work presents the variability of aerosol particle number and mass concentrations on a selected road in Lublin, Poland, which is one of the most congested cities in Europe, in peak and off-peak traffic times, and its impact on the particle exposure for commuters and pedestrians.

Characteristics of particle emissions

The research was conducted in the center of Lublin, the largest city in eastern Poland with the population of 340,230 (June 2017) and the area of 147 km². According to the ranking of the Dutch company TomTom, Lublin is the 12th most congested city in Europe and is ranked higher than Paris or Brussels (14th and 15th position, respectively). Lublin residents on average spend 37 minutes per day in a traffic jam, which is 140 hours per year. The morning rush hours are from 7:00 to 8:00 and the evening from 15:00 to 16:00 (TomTom 2017).

Particle concentrations in the air in Lublin are determined by seasonal and daily variations (Polednik 2013a). Such particles originate from different sources. Lublin, in terms of the climatic and meteorological conditions as well as the lay of land and transportation structure, is a typical town of the Central and Eastern Europe (Drozdziel et al. 2017b). In accordance with the data supplied by Karagulian et al. (2015) the share of PM_{2.5} particles in the total particle emissions is

as follows: domestic furnaces 32%, road traffic 19%, industry 17%, natural sources 16% and other anthropogenic sources 16%. In the case of PM₁₀ particles, the share of domestic furnaces can be even higher and amounts to 45%. Then come other undefined anthropogenic sources 26%, industry 18%, road traffic 8% and natural sources 3%.

The concentrations of traffic-related particles are strictly connected with the number of vehicles. In 2016 there was a total of 217,311 registered vehicles in Lublin which were broken down as follows: 76.9% passenger cars, 13.3% trucks, 5.1% motorcycles, 0.7% municipal transportation vehicles and 4% of other vehicles, e.g., tractors, ambulances, special purpose vehicles (BIP 2017).

As regards the amount of the emitted particles (PM₁₀), according to a report published by the Voivodeship Environmental Protection Inspectorate in Lublin (WIOŚ 2016), between 2013–2015 the annual emission of traffic-related particles amounted to 2474.7 Mg/year which constituted approximately 10% of the total emission of particles originating from all other sources.

In Lublin, similarly to many other urban areas worldwide, only particle mass concentrations are measured. PM₁₀ concentrations have been measured since 2006 and PM_{2.5} concentrations since 2009. UFP concentrations are not monitored on a standard basis. Average hourly measurement values are made available online (WIOP 2017). In the case of PM_{2.5} concentrations, the mean hourly value for the entire measurement period amounts to 30.0 µg/m³ with a standard deviation of 30.5 µg/m³. For 42.7% of the measurement time the concentrations exceeded the amount of 25 µg/m³, while for 0.5% of the measurement time, values exceeding 200 µg/m³ were reported. The maximum reached value was 574.9 µg/m³ and it was reported in the winter season on 6 December 2012 at 22:00. In the case of PM₁₀ concentrations, the mean hourly value for the entire measurement period amounts to 31.3 µg/m³ with a standard deviation of 28.9 µg/m³. For 13.72% of the measurement time the concentrations exceeded the amount of 50 µg/m³, while for 0.43% of the measurement time the values exceeded 200 µg/m³. The highest reported concentration amounted to 551.1 µg/m³ and it was obtained in the winter season on 9 January 2016 at 23:00. Throughout the many years of conducting measurements, no increase or decrease trend has been observed both for PM_{2.5} and PM₁₀ concentrations. Despite a significant increase in the number of vehicles registered in the Municipality of Lublin, the values remain at a similar level. This however, does not exclude the material impact of motor vehicles on the concentration of suspended particles. Old passenger cars are regularly withdrawn while new ones are introduced with better engines which meet the European emission standards, including hybrid and electric cars (Caban et al. 2016).

For the period in which mobile and fixed-site measurements were performed as part of this study, the regularly monitored mean hourly concentrations of PM_{2.5} and PM₁₀ amounted to 13.1 µg/m³ and 26.8 µg/m³ with standard deviations of 7.4 µg/m³ and 10.4 µg/m³, respectively. However, it needs to be clearly underlined that the above results refer to measurements performed in a monitoring station which is not located in the direct proximity of traffic-intense streets.

Methodology

Route characteristics

Aerosol particle concentration monitoring was carried out on a 2.1 km long route which is part of one of the busiest streets in Lublin, eastern Poland (Fig. 1). This route was chosen with an intention to pass through three 4-way TIs and three 3-way TIs with different traffic, driving and surrounding built-up conditions. The 4-way TIs had double carriageways. The route is built of bituminous pavement. The fixed-site measurements were performed in 12 evenly distributed points on the sidewalk along the route. Three of such points were located in the vicinity of 4-way TIs and three in the vicinity of 3-way TIs.

Measurement procedure

Measurements were conducted with the use of a Mobile Air Pollution Analytic Laboratory (MAPAL) installed in a Renault Kangoo (2008 registration; 1461 cc) that was driven on the fixed route. Stops were made in 12 measurement points along the route during which 5-minute fixed-site measurements were performed. While carrying out the fixed-site measurements, MAPAL was parked on the sidewalk, at the curbstone.

Test runs were made in both directions (from point 0 to point 11 and back). While driving it was not always possible to park MAPAL at each of the stop due to the lack of parking space, therefore on the way back attempts were made (which were not always successful) to perform the measurements in the omitted points. Six runs a day were made which included morning and evening peak hours, light traffic at night and mid-day less intense traffic. Measurements were performed at the end of March and beginning of April 2017. This paper presents only the results of 6 consecutive test runs during which fixed-site measurements were carried out at almost all measurement points. The duration of the runs depended, among other things, on the period of the day and the related traffic intensity. For

the peak and night hours it was 103 ± 12 min and 92 ± 8 min, respectively.

The adopted measurement criteria with a relatively short fixed-site measurement time allowed MAPAL to perform measurements at each point during one run (there and back) at comparatively similar traffic conditions. The average values of the measurement results obtained in different days were not taken into consideration. Averaging results from runs performed at the same time but in diverse days was connected with a risk of combining results obtained in different measurement conditions. In the considered spring season the weather conditions underwent significant changes (wind, rain events, relatively cold days followed by relatively warm days).

Instrumentation

MAPAL was equipped, inter alia, with the Grimm Aerosol Spectrometer 1.109 with Nano Sizer 1.321 (Grimm Aerosol, Germany) – a complete system that removes humidity from samples and is able to perform real time measurements of number concentrations of particles within the size range from 10 nm up to 32 μm in different size channels and inhalable, thoracic and alveoli particle mass fractions according to EN 481 standard. The number concentrations of particles with the size ranging from 0.02 to about 1 μm (PN_1) were determined with the use of ultrafine particle counter P-Trak model 8525 (TSI Inc., USA). The number concentrations and size distribution of particles greater than 0.3 μm ($\text{PN}_{0.3-0.5}$, $\text{PN}_{0.5-1}$, PN_{1-2} , PN_{2-5} , PN_{5-10} and $\text{PN}_{>10}$) were measured using optical spectrometer OPS 3330 (TSI Inc., USA). Particle mass concentrations were measured using aerosol monitor DustTrak DRX model 8533 (TSI Inc., USA) which determined the approximations of mass concentrations of PM_{10} , $\text{PM}_{2.5}$, PM_{1} , $\text{PM}_{0.5}$, $\text{PM}_{0.1}$ and TSP (particles with an aerodynamic diameter equal or less than 1, 2.5, 4, 10 μm and total suspended particles, respectively). DustTrak monitor was subjected to the standard

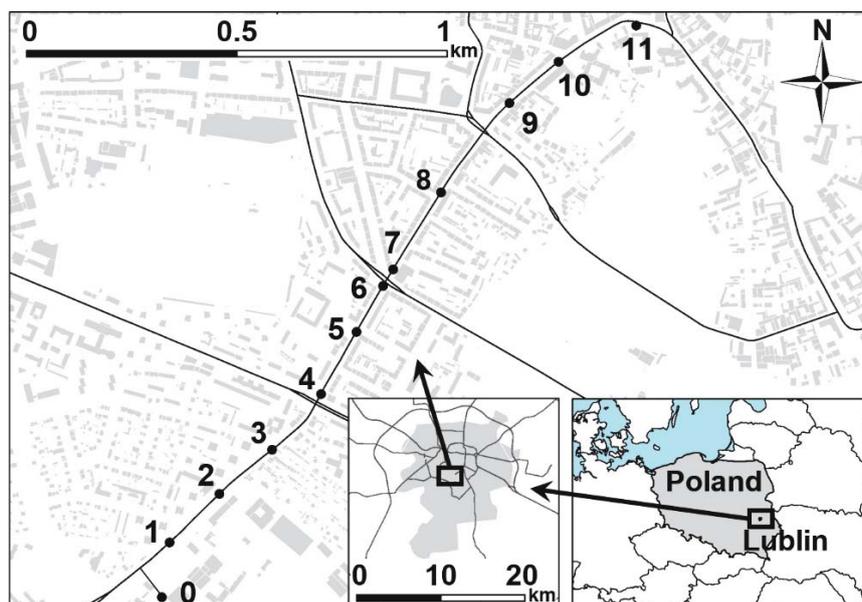


Fig. 1. Map of Lublin with the location of the route for mobile monitoring and the location of the fixed-site measurement points on the sidewalk along the route

real-time size correction factor calibration. The obtained approximations of the particle mass concentration values are not actual gravimetric values. For simplification purpose, all the DustTrak results presented in this paper omit the term “approximation”. Air was supplied to MAPAL instruments through tubes whose endpoints were jointly located in the middle of the vehicle, on the left side, at the height of approximately 1.7 m. All instruments were calibrated by their manufacturer at the beginning of the measurement campaign. The logging interval for the instruments was 6 seconds. The position and speed of MAPAL vehicle was continuously recorded using a Global Positioning System (GPS; Garmin Nuvi 2460LMT). HD 1080P Wide angle 170° camera located on the dashboard of the car was used to collect the traffic flow data at the time of measurements. Air temperature and relative humidity were measured outside the car cabin. Only the data of particle number and mass concentrations is used for further analysis. Timestamps of all the instruments were matched at the beginning of the experiment.

Estimation of exposure

Exposure to particles was quantified in terms of the respiratory deposition rate (DR) by using the methodology presented in Joodatnia et al. (2013). The total particle dose received by the car drivers and passengers (commuters) on the road and pedestrians on the sidewalk is directly related to the difference between the number or mass of particles inhaled and exhaled during each breath, the breathing rate and the period of exposure. In this study the average deposition rate of the inhaled particles in the respiratory tract was estimated by using the following equation (1):

$$DR = V_T \times f \times DF \times PC \tag{1}$$

where V_T is the tidal volume, f is the frequency of breathing, DF is deposition fraction and PC is the particle number or mass concentration.

Tidal volume and breathing rate which depend on the age, gender and the level of activity were assumed respectively as 800 cm³ per breath and as 18 per minute for a male adult car driver and passenger on the road and as 21 per minute for a male adult pedestrian on the sidewalk. In many exposure studies constant DF values are used which can provide an adequate approximation of the dose inhaled by commuters. However, an underestimation of the dose can be seen for cases in which the vast majority of inhaled particles are of sizes within the nanometer range. In this study DF values of 0.25 and 0.65, respectively, were assumed for the purpose of estimating the deposition rate of the number of inhaled ultrafine particles and large fraction particles (Joodatnia et al. 2013, Sturm 2016). DF values for the mass of the inhaled particles were adopted from Kumar and Goel (2016) i.e. for on-road exposure to $PM_{2.5}$ and PM_{10} DF values of 0.23 and 0.88, respectively, were assumed and for sidewalk exposure values of 0.14 and 0.88, respectively. An unlimited exposure to traffic-related pollutants was assumed for both commuters and pedestrians. For commuters, such exposure takes place when their car windows are fully open. The on-road measurements described in this paper may be considered as equivalent to the above mentioned situation.

All calculations and data analyses were performed with the use of software package Statistica 13.1 (StatSoft).

Results and discussion

The performed measurements allowed for tracking the changes of number and mass concentrations of particles in different size ranges along the route and in the given measurement points on the sidewalk in different times of the day. Figures 2, 3 and 4 present the time series of respectively the number concentrations of particles within the 20–1000 nm size range (PN_1), ultrafine particle number concentrations ($PN_{0.1}$), and mass concentrations of particles $\leq 10 \mu m$ (PM_{10}) during mobile and fixed-site measurements in 6 consecutive measurement periods, i.e., 0:00, 4:00, 8:00, 12:00, 16:00 and 20:00. The data in Figure 2 was obtained by P-Trak, in Figure 3 by Grimm and in Figure 4 by DustTrak instrument.

Figures 2, 3 and 4 indicate the part of the route with the most intensive traffic where the fixed-site measurement points 4, 5 and 6 were located. Measurement points 4 and 6 were near 4-way TJs. The obtained values changed considerably in the individual measurement periods. The greatest changes both in terms of the number and mass particle concentrations were observed during the rush hours, and specifically in the part of the route near 4-way TJs. Increased PM_{10} concentrations were observed along the entire route during the evening run (20:00). A similar trend was reported by Kumar and Goel (2016). In general, their studies confirmed that coarse particles are usually

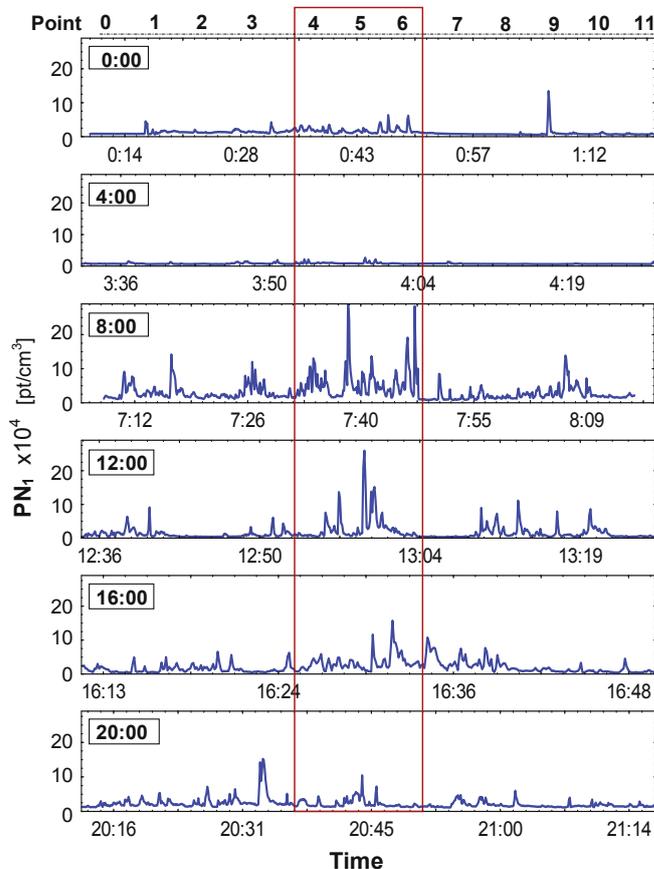


Fig. 2. Variations of submicron particle number concentrations PN_1 during mobile monitoring with an indication of the part of the route with the most intensive traffic and fixed-site measurement points in 6 consecutive measurement periods (0:00, 4:00, 8:00, 12:00, 16:00, 20:00), (data from P-Trak instrument)

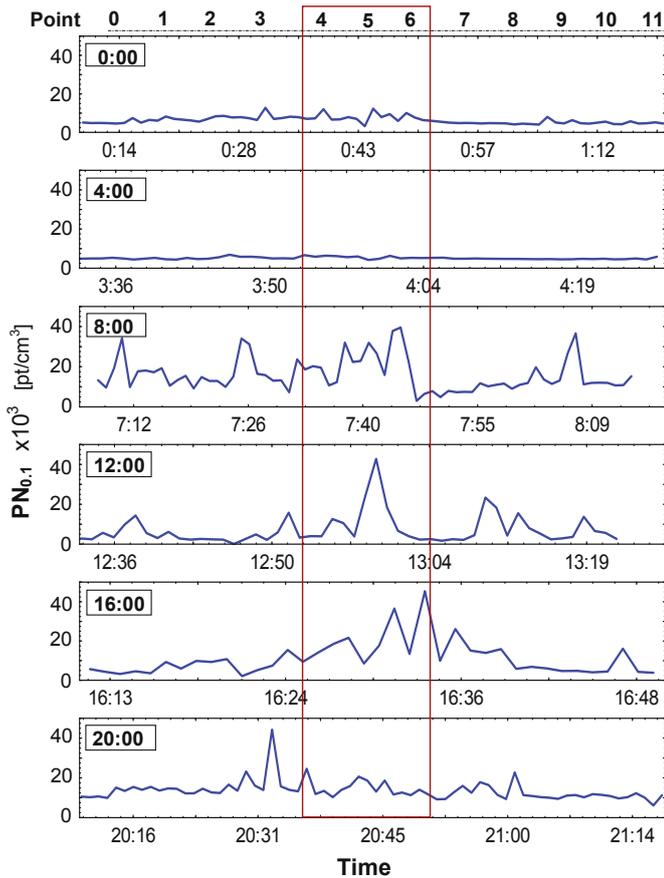


Fig. 3. Variations of ultrafine particle number concentrations $PN_{0.1}$ during mobile monitoring with an indication of the part of the route with the most intensive traffic and fixed-site measurement points in 6 consecutive measurement periods (0:00, 4:00, 8:00, 12:00, 16:00, 20:00), (data from Grimm instrument)

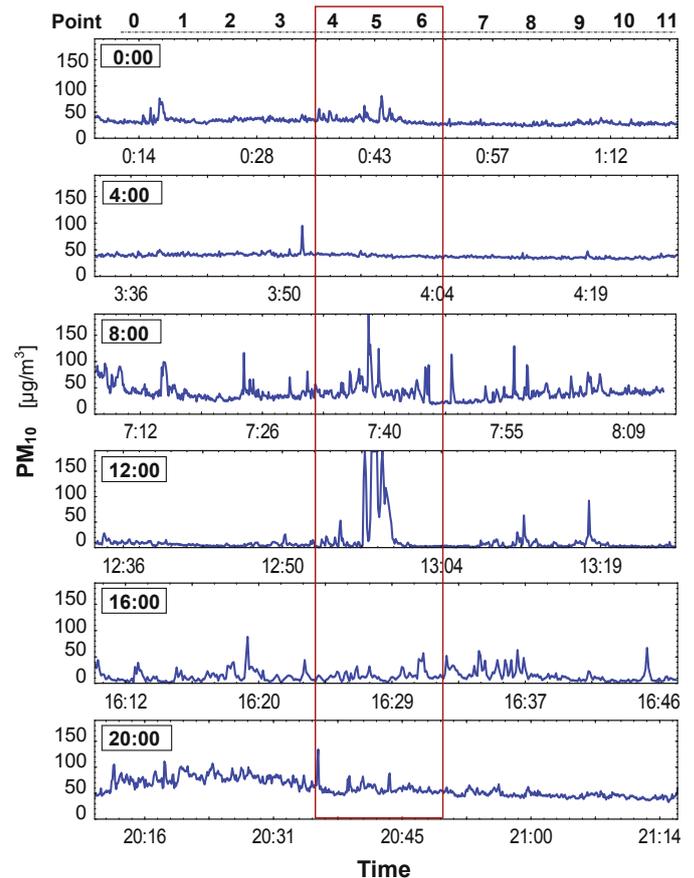


Fig. 4. Variations of mass concentrations of particles PM_{10} during mobile monitoring with an indication of the part of the route with the most intensive traffic and fixed-site measurement points in 6 consecutive measurement periods (0:00, 4:00, 8:00, 12:00, 16:00, 20:00), (data from DustTrak instrument)

dominated by the non-exhaust sources such as road abrasion, brake and tire wear while fine particles are mainly due to fuel combustion in engines. They have also observed that the on-road concentration of fine particles ($PM_{2.5}$) in the evenings ($33 \pm 9 \mu\text{g}/\text{m}^3$) was about twice that during the mornings ($16 \pm 4 \mu\text{g}/\text{m}^3$); no such differences were observed for fine particles. According to the study carried out by Kuhlbusch et al. (1998), this can be explained by higher fugitive dust emissions in the evening. These higher fugitive dust emissions can be expected during the evening hours as compared with those during the morning hours due to a higher surface temperature of the road and a lower surface moisture content. This would confirm that on-road coarse particles are principally affected by non-exhaust emissions during different hours of the day. While considering the above, one cannot ignore such important factors as daily changes in the meteorological conditions, including changes of wind speed and mixing-layer height (Oleniacz et al. 2016, Zhao et al. 2017) or changes in the traffic intensity (Amato et al. 2013).

The obtained concentration values of the same particle type depended on the instrument used for performing measurements. During mobile monitoring and in fixed-site measurement points the average mass concentrations of PM_{10} , $PM_{2.5}$ and PM_{10} particles obtained by the Grimm instrument were respectively 2.1, 1.7 and 1.3 times lower than the concentrations of

those particles measured with the use of DustTrak. Grimm also indicated lower particle number concentrations. In the case of PN_{10} , the measured concentrations were on average approximately 1.8 times lower than the results obtained by P-Trak. Previous studies also reported very similar differences. For example Cheng (2008) reported about 1.8-times lower concentrations of $PM_{2.5}$ by using the Grimm as compared to the TSI instrument. For simplification purposes, the further part of this study focuses on the results obtained with the use of the Grimm instrument.

Table 1 presents basic statistical information on particle number ($PN_{0.1}$, PN) and mass concentrations ($PM_{2.5}$, PM_{10}) for mobile monitoring for the entire and part of route with the most intensive traffic (between two 4-way TIs) in peak (8:00 and 16:00) and off-peak traffic hours (0:00 and 4:00). In turn, Table 2 presents such information for the individual fixed-site measurement points in peak and off-peak traffic times. The average particle number concentrations for entire route and part of road with the most intensive traffic in peak hours were, depending on particle size, about 3–4 times higher than in off-peak hours. The average particle mass concentrations were about 2 times higher. Furthermore, the average values of the considered particle number and mass concentrations were higher for on-road measurements than for fixed-site measurements.

Table 1. Descriptive statistics for ultrafine particle number $PN_{0.1}$ and total particle number PN concentrations and mass concentrations of particles $PM_{2.5}$ and PM_{10} for the entire and part of mobile monitoring route with the most intensive traffic in peak (8:00 and 16:00) and off-peak traffic periods (0:00 and 4:00)

Route	$PN_{0.1} \times 10^3$ [pt/cm ³]	$PN \times 10^3$ [pt/cm ³]	$PM_{2.5}$ [µg/m ³]	PM_{10} [µg/m ³]
	Peak periods			
Entire route	19.2 (10.0) 37.6	22.1 (11.0) 39.8	23.7 (7.9) 29.4	38.9 (14.1) 73.7
Part of route	25.4 (11.0) 34.6	29.2 (11.8) 36.5	29.1 (7.6) 24.1	45.4 (10.3) 34.3
Off-peak periods				
Entire route	6.3 (2.0) 9.5	7.8 (2.2) 9.8	12.5 (2.8) 15.3	16.6 (4.2) 16.9
Part of route	6.7 (2.1) 9.1	8.3 (2.3) 9.2	13.4 (2.7) 15.3	17.9 (4.2) 16.7

Arithmetic average (SD) range

Table 2. Ultrafine particle number $PN_{0.1}$ and total particle number PN concentrations and mass concentrations of $PM_{2.5}$ and PM_{10} particles in the individual fixed-site measurement points in peak (8:00 and 16:00) and off-peak traffic periods (0:00 and 4:00)

Points	$PN_{0.1} \times 10^3$ [pt/cm ³]	$PN \times 10^3$ [pt/cm ³]	$PM_{2.5}$ [µg/m ³]	PM_{10} [µg/m ³]
	Peak periods			
0	8.2 (1.3) 3.4	9.8 (1.2) 3.4	16.2 (0.9) 2.1	30.3 (3.3) 7.4
1	14.2 (3.5) 8.3	16.5 (3.8) 9.5	20.7 (1.4) 3.6	41.8 (6.4) 14.8
2	9.8 (1.8) 4.5	12.0 (2.4) 5.7	17.1 (2.5) 5.9	27.3 (3.9) 10.5
3	13.0 (5.8) 15.7	14.7 (6.0) 16.4	15.4 (3.0) 7.2	26.3 (3.6) 8.8
4	17.1 (8.1) 20.2	20.1 (8.7) 21.3	25.5 (8.8) 21.5	43.4 (12.1) 30.7
5	33.6 (12.4) 30.2	37.6 (12.8) 30.4	33.8 (5.7) 13.1	53.7 (5.6) 14.0
6	25.9 (9.1) 20.1	30.0 (11.0) 23.7	27.1 (8.4) 19.8	35.6 (5.7) 13.3
7	5.6 (1.4) 3.3	6.9 (1.3) 3.1	12.0 (1.8) 4.5	15.5 (2.6) 6.8
8	8.6 (1.0) 2.4	10.4 (1.1) 2.6	16.9 (1.3) 3.1	31.0 (2.0) 5.2
9	8.8 (0.9) 2.2	10.6 (1.0) 2.6	16.9 (2.9) 7.8	28.9 (8.6) 22.8
10	16.8 (10.0) 23.8	20.3 (11.0) 25.2	25.6 (8.4) 20.5	35.3 (8.8) 21.1
11	10.2 (1.6) 3.9	12.2 (1.8) 4.6	18.0 (1.7) 4.6	30.7 (2.0) 5.5
Off-peak periods				
0	5.2 (0.5) 1.2	6.5 (0.6) 1.4	11.7 (1.0) 3.1	17.4 (3.3) 10.2
1	5.9 (1.2) 3.8	7.3 (1.4) 4.5	12.1 (1.4) 3.8	16.8 (3.6) 12.1
2	6.5 (1.7) 4.2	7.8 (1.9) 4.5	12.4 (1.8) 5.7	17.2 (2.5) 8.0
3	6.5 (1.2) 3.2	8.0 (1.3) 3.7	12.7 (1.3) 4.0	16.8 (2.3) 6.2
4	6.3 (1.2) 4.7	8.0 (1.3) 4.5	13.8 (1.8) 5.2	18.3 (3.6) 11.6
5	5.7 (1.0) 2.6	7.1 (1.0) 2.6	13.0 (2.3) 6.6	17.5 (4.3) 13.6
6	7.1 (1.8) 5.6	9.1 (2.2) 7.1	15.0 (3.8) 12.0	18.8 (5.5) 14.7
7	5.1 (0.5) 1.7	6.3 (0.5) 1.9	10.4 (0.4) 1.3	13.2 (1.8) 6.1
8	8.2 (3.9) 12.5	9.5 (3.9) 12.6	12.8 (2.7) 8.5	17.0 (7.4) 23.7
9	5.0 (1.1) 4.0	6.2 (1.2) 4.5	10.0 (0.7) 2.4	13.5 (0.9) 2.7
10	4.7 (0.4) 1.3	5.8 (0.4) 1.4	10.2 (0.6) 1.7	13.2 (2.0) 6.2
11	4.8 (0.2) 0.7	5.8 (0.2) 0.7	9.7 (0.3) 0.8	12.3 (1.4) 4.8

Arithmetic average (SD) range

Data presented in Table 1 indicates the exposure for commuters. The highest average concentrations of ultrafine particles $PN_{0.1}$ ($25.4 \pm 11 \times 10^3$ pt/cm³; mean \pm standard deviation), of PN ($29.2 \pm 12 \times 10^3$ pt/cm³) as well as of $PM_{2.5}$ (29.1 ± 7.6 µg/m³) and PM_{10} (45.4 ± 10.3 µg/m³) were obtained in peak traffic times for the part of route with the most intensive

traffic. The lowest average particle concentration levels with the least variations were observed at night (0:00 and 4:00). In terms of the fixed-site measurement points (Table 2), the highest average number and mass particle concentrations were observed in points near 4-way TIs. Both during peak and off-peak traffic hours the highest average number and mass particle

concentrations were reported in point 5 and 6, respectively. However, the reported concentrations were many times higher in peak hours as compared to off-peak hours. For example, the highest average ultrafine particle $PN_{0.1}$ and total PN particle concentrations in the peak hours were observed in point 5 and amounted to 33.6×10^3 pt/cm³ and 37.6×10^3 pt/cm³, respectively. In the off-peak hours, their average concentrations amounted to 5.7×10^3 pt/cm³ and 7.1×10^3 pt/cm³, respectively. Average $PM_{2.5}$ and PM_{10} mass concentrations in point 5 equaled respectively $33.8 \mu\text{g}/\text{m}^3$ and $53.7 \mu\text{g}/\text{m}^3$ for the peak hours and $13.0 \mu\text{g}/\text{m}^3$ and $17.5 \mu\text{g}/\text{m}^3$ for off-peak hours. The highest average $PM_{2.5}$ and PM_{10} mass concentrations were reported in point 6 in the off-peak hours and amounted to $15.0 \mu\text{g}/\text{m}^3$ and $18.8 \mu\text{g}/\text{m}^3$, respectively.

Particle concentration changes in the considered measurement points in the individual periods are presented in Figure 5. The bar charts show changes in the average number concentrations of ultrafine particles $PN_{0.1}$, total particles PN and mass concentrations of particles $PM_{2.5}$ and PM_{10} in the individual measurement points with respect to the given measurement periods. They confirm the observations presented earlier in which pedestrian exposure to particles depends on the time of the day and the location along the examined route. The results of previous studies carried out in Poland concerning the particle concentration changes related to the measurement points along main roads showed that the concentration of particles originating from vehicles decreased twice in the distance of over 150–200 meters from the roads (Wróbel et al. 2000). In other studies performed by Skubacz (2009) it was proven that a great number of submicron particles are produced

close to roads with the high traffic intensity. In turn, Rogula-Kozłowska et al. (2008) determined that the proximity of busy intersections also has a significant impact on the particle concentration levels. Similarly, increased concentrations of these particles are observed in street canyons (Grynkiewicz-Bylina et al. 2005).

Table 3 presents the percentage of ultrafine particle number $PN_{0.1}$ concentrations in the total particle number PN concentrations during mobile monitoring and in fixed-site measurement points of the entire and part of mobile monitoring route (between two 4-way TIs – points 4, 5 and 6).

The table demonstrates that a greater percentage of ultrafine particles was observed for mobile monitoring than in the fixed-site measurement points. The highest percentage fraction of ultrafine particles (89.1%) in the total particle number concentrations was reported in the part of the mobile monitoring route with the most intensive traffic (between two 4-way TIs) and it was higher than such fraction in the fixed measurement points on the sidewalk along that part of the route. The percentage fractions of such particles were also higher during the morning and afternoon rush hours than at night. As already presented in the literature (Joodatnia et al. 2013, Goel and Kumar 2015) this is obviously due to a greater number of vehicles and the related higher concentration of freshly emitted nucleation mode particles (size range 5–30 nm).

Table 4 presents the estimated doses of the considered particles deposited in the respiratory tract of commuters and pedestrians after spending one hour on the considered route in peak and off-peak traffic times. It should be emphasized that the obtained values are based on the measurement results

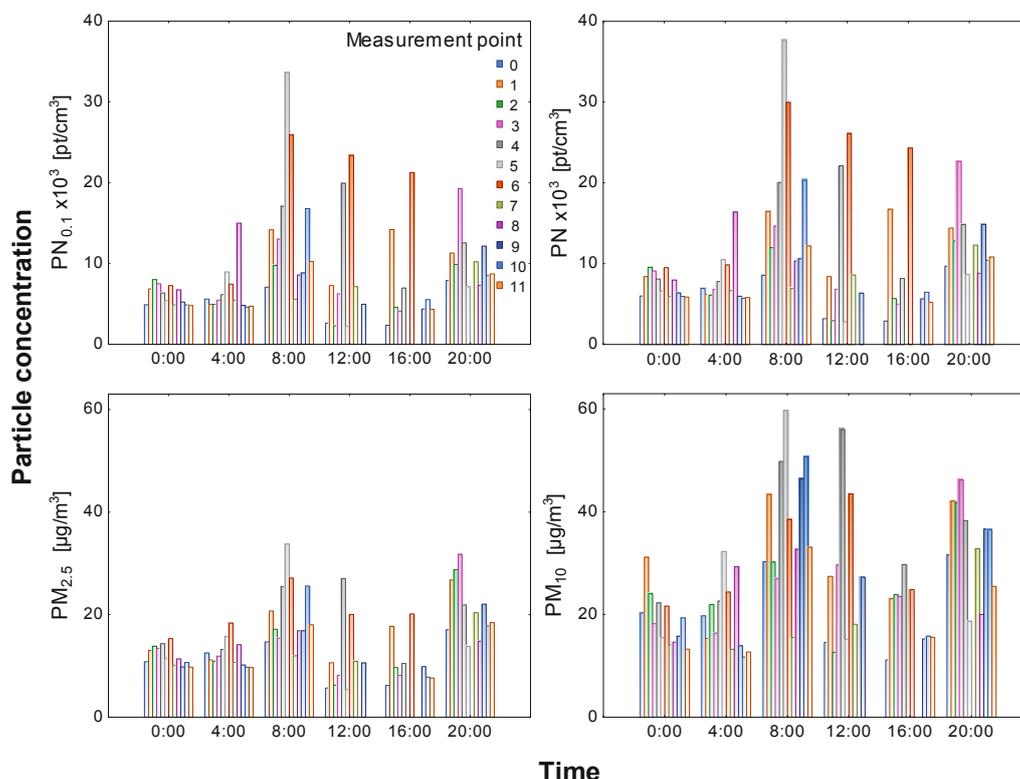


Fig. 5. Average values of ultrafine particle number concentrations $PN_{0.1}$, total particle number concentrations PN, mass concentrations of particles $PM_{2.5}$ and PM_{10} in the considered monitoring periods and in the individual fixed-site measurement points (based on Grimm instrument data)

Table 3. Percentage of ultrafine particle number $PN_{0.1}$ concentrations in the total particle number PN concentrations during mobile monitoring and in fixed-site measurement points of the entire and part of mobile monitoring route with the most intensive traffic

Type of measurements	Measurement periods					
	00:00	04:00	08:00	12:00	16:00	20:00
Mobile monitoring of entire route	81.5	80.8	85.9	87.4	86.1	81.6
Points along the entire route	81.3	80.6	84.0	84.3	83.1	81.2
Mobile monitoring of a part of route	80.9	80.0	86.5	89.1	86.9	83.2
Points along the part of route	78.5	97.1	86.5	89.0	85.8	82.5

Table 4. Exposure to particles by commuters and pedestrians in peak and off-peak traffic periods

Traffic periods	$PN_{0.1} \times 10^9$ [pt/h]	$PN \times 10^9$ [pt/h]	$PM_{2.5}$ [μ g/h]	PM_{10} [μ g/h]
	Commuters			
Peak	4.2 (2.2) 8.1	4.8 (2.4) 8.6	4.7 (1.6) 5.8	29.6 (10.7) 56.0
Off-peak	1.4 (0.4) 2.1	1.7 (0.5) 2.2	2.5 (0.5) 3.0	12.6 (3.2) 13.1
Pedestrians				
Peak	3.6 (2.1) 7.1	4.2 (2.3) 7.8	2.9 (0.9) 3.1	29.6 (8.6) 34.2
Off-peak	1.5 (0.3) 0.9	1.8 (0.3) 0.9	1.7 (0.2) 0.7	14.2 (2.0) 6.1

Arithmetic average (SD) range

collected with the use of the Grimm instrument. Such results would be approximately 2 times higher if the TSI instruments were used. It follows from the presented data that commuters receive greater particle doses during peak times. In peak periods the average particle doses received by commuters equaled $4.8 \pm 2.4 \times 10^9$ pt/h or 29.6 ± 10.7 μ g/h (PM_{10}). For pedestrians, the doses amounted to $4.2 \pm 2.3 \times 10^9$ pt/h or 29.6 ± 8.6 μ g/h. In comparison to the amount estimated by Polednik (2013b), these doses were about 7 and 5 times higher, respectively, than the ones inhaled at a certain distance from busy streets (1.4×10^9 pt/h for PN and 12.5 μ g/h for PM_{10} , respectively, based on TSI instrument measurements). The average dose of PN inhaled by commuters as estimated by Joodatnia et al. (2013) in Guildford (UK) was somewhat higher (5.5×10^8 pt/min). It could come from the fact that the instrument employed in that study (DMS50) measured the particles in the 5–560 nm size range. Besides, taking into consideration all the factors that contribute to the dose estimation such differences are not surprising.

Figure 6 provides details on the particle exposure and shows the estimated doses of particles received by commuters and pedestrians after spending an hour on the monitored route and in the part of the monitored route with the most intensive traffic. Both in peak and off-peak traffic times, greater particle doses are received by them in the considered part of the route as compared to the entire route. It seems rather odd that pedestrians are exposed to greater particle doses (apart from $PM_{2.5}$) than commuters. This is affected by the differences in the adopted deposition factor values as well as in the breathing frequency of commuters and pedestrians. Contrary to the findings of Kaur et al. (2005), the obtained results clearly indicate that pedestrians are more exposed to traffic-related pollutants than commuters, all the more that commuters usually drive with closed windows and the air supplied to the vehicle is subjected to filtration.

Meteorological conditions could have a significant impact on the performed ambient air quality measurements and assessed particle exposure. During the measurement period the wind speed ranged from 1.1 to 4.7 m/s, with an average of about 2.1 m/s and the wind was blowing from the south-west for most of the time. Ambient temperature and relative humidity varied from 8 to 14°C and from 52 to 73%, respectively. Meteorological data together with the information on the source’s emission intensity is necessary to model the dispersion of pollutants in order to evaluate urban air quality (Szczygłowski and Mazur 2008, Holnicki et al. 2017). An in-depth analysis taking into account these parameters as well as traffic intensity data should be the subject of further, wide-ranging research.

To sum up, the obtained results indicate that changes of the aerosol particle number and mass concentrations and the particle size distributions on the monitored road and its vicinity that depend mostly on the traffic conditions may significantly contribute to the exposure and adverse health effects for commuters and pedestrians.

More detailed research is necessary to determine the relations between the daily and seasonal traffic intensity changes as well as vehicle and road characteristics in different parts of Lublin, the on-road and sidewalk particle concentration levels and the potential health effects related to the exposure to particles for commuters and pedestrians. Actions aiming at decreasing the particle exposure in Lublin are also of significance.

Conclusions

This preliminary study conducted in one of the busiest streets in Lublin which consisted in mobile monitoring and fixed-site measurements performed during peak and off-peak traffic hours has reported that the traffic-related particle emissions

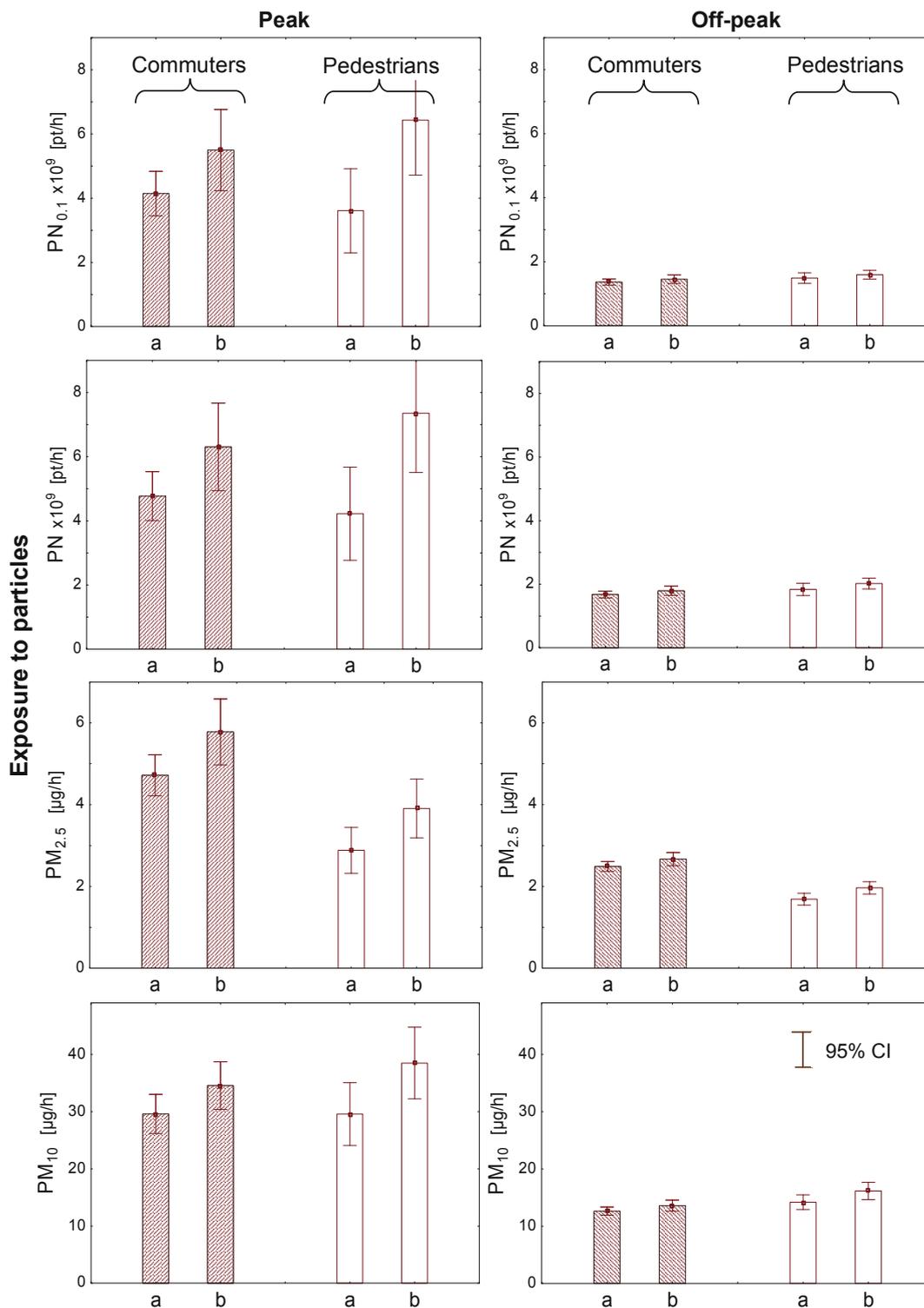


Fig. 6. Average particle doses received by commuters and pedestrians during one hour spent in the monitored route in peak and off-peak periods; a – entire route, b – part of the route with the most intensive traffic; CI – confidence interval (based on Grimm instrument data)

have a significant impact on the on-road and sidewalk particle concentration levels. The highest average concentrations of ultrafine particle number $PN_{0.1}$ ($25.4 \pm 11 \times 10^3$ pt/cm³), total particle number PN ($29.2 \pm 12 \times 10^3$ pt/cm³) as well as particle mass $PM_{2.5}$ (29.1 ± 7.6 µg/m³) and PM_{10} (45.4 ± 10.3 µg/m³) were obtained in peak traffic hours for the part of the route with the most intensive traffic. The average particle number concentrations for the entire route and the part of the route

with the most intensive traffic in peak times were found to be, depending on the particle size, about 3 to 4 times higher than in off-peak times. The average particle mass concentrations were about twice as high. Average values of the above-mentioned particle number and mass concentrations were higher for the on-road measurements than for fixed-site measurements. What is more, a greater percentage of ultrafine particles in the measured total particle number concentrations was observed

during the mobile monitoring than in fixed-site measurement points. A greater number and mass of particles is deposited in the respiratory tract of commuters and pedestrians in peak hours with the average particle doses of $4.8 \pm 2.4 \times 10^9$ pt/h or $29.6 \pm 10.7 \mu\text{g/h}$ (PM_{10}) and $4.2 \pm 2.3 \times 10^9$ pt/h or $29.6 \pm 8.6 \mu\text{g/h}$ (PM_{10}), respectively. It can be stated that regardless of the time of the day, higher particle doses are received in the part of the route with the most intensive traffic, and in off-peak traffic times pedestrians are more exposed to traffic-related pollutants than commuters. The further research should focus on the substantial impact of the changes of meteorological conditions and traffic intensity on the particle concentration levels. It should also concentrate on determining negative health impacts and the methods of their mitigation.

Acknowledgements

The work was financially supported by the Polish Ministry of Science and Higher Education under grant no. S-13/WIS/2017.

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Emisja cząstek ze źródeł komunikacyjnych w mieście

Streszczenie: Celem pracy było określenie stężenia liczbowego i masowego cząstek na wybranych ulicach Lublina w godzinach szczytu oraz poza szczytem, a także ocena narażenia kierowców i pieszych na ich oddziaływanie. W ramach badań przeprowadzono zarówno pomiary mobilne, jak i stacjonarne w określonych punktach pomiarowych na trasie o długości 2,1 km. Mierzono w czasie rzeczywistym między innymi stężenia liczbowe i masowe cząstek o rozmiarach w zakresie od 10 nm do 32 μm . Najwyższe średnie koncentracje ultradrobnych cząstek $\text{PN}_{0,1}$ ($25,4 \pm 11 \times 10^3 \text{ \#/cm}^3$) oraz koncentracje całkowitej liczby cząstek PN ($29,2 \pm 12 \times 10^3 \text{ \#/cm}^3$), a także stężenia masowe $\text{PM}_{2,5}$ ($29,1 \pm 7,6 \text{ \mu g/m}^3$) oraz PM_{10} ($45,4 \pm 10,3 \text{ \mu g/m}^3$) rejestrowano w godzinach szczytu na wydzielonym odcinku trasy o największej intensywności ruchu. Średnie koncentracje cząstek mierzone w godzinach szczytu dla całej trasy oraz dla wydzielonego odcinka były, w zależności od wielkości cząstek, ok. 3-4 razy większe w porównaniu do wyników pomiarów dla godzin pozaszczytowych. Z kolei średnie stężenia masowe cząstek były około dwa razy większe. Ponadto, większe średnie stężenia liczbowe i masowe cząstek odnotowano dla pomiarów mobilnych niż dla stacjonarnych. Wyznaczone dawki dotyczące liczby i masy cząstek deponowanych w drogach oddechowych kierowców w godzinach szczytu wynosiły odpowiednio $4,8 \pm 2,4 \times 10^9 \text{ \#/h}$ i $29,6 \pm 10,7 \text{ \mu g/h}$ (PM_{10}). Zarówno dla godzin szczytu, jak i poza szczytem, większe dawki deponowanych cząstek uzyskano dla wydzielonego odcinka trasy o największej intensywności ruchu. Podsumowując, otrzymane wyniki wskazują na istotność pomiarów cząstek emitowanych ze źródeł komunikacyjnych, szczególnie w kontekście narażenia uczestników ruchu drogowego na te cząstki.