# Seasonal Variability of Resuspension

*Jakub* Linda[1,*], *Klaudia* Köbölová[1], *Ondřej* Uhlík[2], *Jiří* Pospíšil[1], and *Tomáš* Apeltauer[2]

[1]Energetický ústav, Fakulta strojního inženýrství, VUT v Brně, Technická 2896, 616 69 Brno, ČR
[2]Ústav automatizace inženýrských úloh a informatiky, Fakulta stavební, VUT v Brně, Veveří 331/95, 602 00 Brno, ČR

**Abstract.** Particulate air pollution in cities is caused by a variety of sources. One of the less-studied contributors is wind-induced particle resuspension. As the wind speed increases, particles are removed from surfaces. These particles cause an increase in the total concentration in the air. It is known that particles of 10-2.5 µm in size can be resuspended ($PM_{10-2,5)}$. Modern emission monitoring in cities also allows the monitoring of fine particles of 10, 2.5 and 1 µm in size. The size fractions can then be sorted into $PM_{10-2,5}$, $PM_{2,5-1}$ and $PM_1$. When breathed in, particles of different sizes cause various serious health risks. This paper focuses on the identification of the resuspension process of different particle size fractions by a data processing method. Data measured by automatic emission monitoring are used. It is confirmed that the concentration increase can be dominated by the fraction $PM_{10-2,5}$. However, a concentration increase of fractions $PM_{2,5-1}$ and $PM_1$ is also evident with increasing wind speed. Although the increase in the $PM_1$ fraction is smaller than $PM_{10-2,5}$, it is more severe due to the respiratory deposition dose. The resuspension of particles of different fractions has different behaviours during the year. $PM_{10-2,5}$ particles are dominantly resuspended in the summer months. In winter, on the other hand, the proportion of $PM_{2.5-1}$ and $PM_1$ particles increases, which may be related to the heating season

**Keywords:** *health risk assessment, RDD, PM, particulate matter, road dust*

## 1 Introduction

$PM_{10}$ air pollution is still a problem in most of the world's metropolises. $PM_{10}$ is the term for the size of particles with an aerodynamic diameter of less than 10 micrometres. There are many sources of particles in the urban environment. Transport is one of the most emissions-intensive activities. Specifically, it accounts for 25 % of particle pollution in cities on a global scale [1]. As the rise of electric vehicles progresses, the focus is shifting from exhaust emissions to non-exhaust emissions [2]. Their amount may already exceed the exhaust particulate emissions [3]. This trend will only increase in the future. Other sources of urban particulate matter include industry, domestic fire burning, natural resources [1]. Study [1]

* Corresponding author: Jakub.Linda@vutbr.cz

points to a high degree of uncertainty in the determination of the source of the particles. The number of particles that cannot be classified as the aforementioned sources are then referred to as "unspecified sources of human origin". Wind-induced particle resuspension is indirectly related to human activity. In this process, already deposited particles are released from surfaces into the air by the wind, as already pointed out by [4]. There are several studies showing the characteristics of the wind-induced resuspension process [4–8]. However, the quantification is different each time, as the studies are based on different assumptions.

Wind-induced resuspension depends on many parameters. Among the main ones are time aspects. The initial number of resuspended particles is significantly greater than the number of particles after a period of higher wind speeds. This is caused by the weakly attached particles being lifted at the beginning of the process [9]. Resuspension is a process that occurs in a matter of seconds. Other factor affecting the resuspension is the humidity of the air. The humidity of the air can substantially affect the detachment of particles from the surface if it exceeds a value of about 60 % [10]. Availability of resuspendable particles varies throughout the year [11]. The total concentration of particles in the city is influenced by background concentrations. However, with respect to health risks, we are interested in the overall increase in particle concentration due to wind. It is known that background concentration is also strongly correlated with wind speed [1]. These factors should be taken into account when identifying wind-induced resuspension in the data.

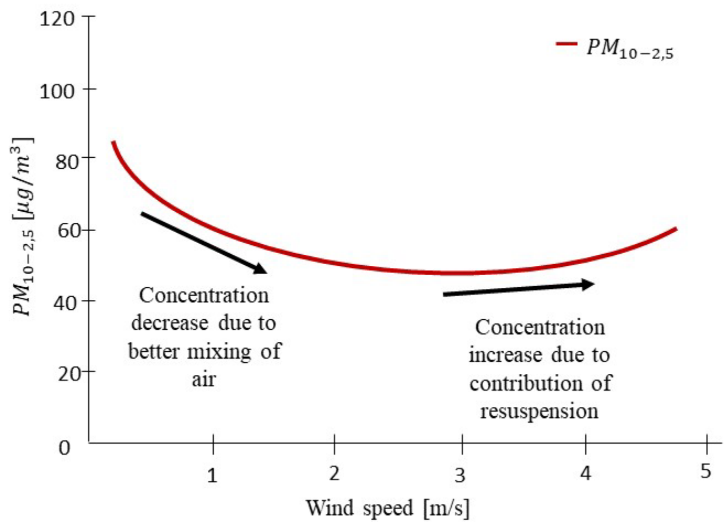


**Fig. 1.** Dependence of airborne particle concentration on wind speed.

The $PM_{10\text{-}2,5}$ concentration can be divided into two components depending on the wind speed. The first component dilutes with increasing wind speed. The second component increases with increasing wind speed [4]. The authors of the study assume that the $PM_{10\text{-}2,5}$ fraction can be resuspended by the wind and the $PM_{2.5}$ fraction is diluted by the wind. The $PM_{10\text{-}2,5}$ component is diluted by increasing wind speed at the same rate as the $PM_{2.5}$ fraction. Plotting the dependence of $PM_{10\text{-}2,5}$ on wind speed then results in a characteristic U-shape function.

Other studies [6–8], that have dealt with wind-induced resuspension have focused on the $PM_{10\text{-}2,5}$ and $PM_{2.5}$ fractions. Their assumption is that only $PM_{10\text{-}2,5}$particles are capable of resuspension and the concentration of $PM_{2.5}$ particles decreases with increasing wind speed. Many cities, however, are now offering monitoring of $PM_1$. In Brno, these particles have been monitored since 2016. The question is what results we get if we sort $PM_{10}$ particles into size fractions $PM_{10\text{-}2,5}$, $PM_{2.5\text{-}1}$ and $PM_1$. Evaluating the dependence of the concentration of each fraction on the wind speed will show how they are able to resuspend. There is a fundamental difference if the wind in a city is lifting larger or smaller particles, especially in terms of health risks.

Due to their size, $PM_1$ particles enter the human respiratory system very easily and deeply, which has a non-negligible impact on health. Compared to larger particles at the same mass, these fractions have a much higher concentration, active surface area, high deposition efficiency and a greater potential for harmful biological interactions with respiratory tissues [12–14].

Millions of people walk or run daily on streets and in parks as part of their daily routine, either on their way to work or recreationally. During these activities, large amounts of pollutants are inhaled into the respiratory system. Epidemiological studies [15–19] show a link between respiratory diseases and atmospheric PM. Most of those studies look at total deposition, with deposition of different parts of the respiratory system being important for assessing the potential hazard of PM [20]. Inhaled particles may be deposited in different regions of the respiratory system by the complex action of different deposition mechanisms or may be exhaled. The most important mechanisms are impaction, deposition and diffusion [21]. Particles that encounter the walls of the respiratory tract settle there and are not reabsorbed. The extent and location of particle deposition depends on the size, density and shape of the particles, the geometry of the airways and the mode of respiration. Many mathematical models exist to predict total and regional particle deposition. One possibility is to calculate the respiratory deposition dose (RDD), which expresses the entrainment between regional deposition and mass concentration. The aim of this work is to find a link between resuspension and RDD. The possibility of monitoring PM1 particles raises the question of whether these particles are also capable of resuspension and what health risks arise from this.

## 2 Materials and methods

### 2.1 Data measurement

The data were obtained from automatic emission monitoring (AIM) in Brno. The AIM in Brno includes five measuring stations:

- Svatoplukova – located in a populated part of the city. The measuring equipment is located at the four-lane road.
- Výstaviště – a location characterised by the presence of a major traffic junction. The measuring equipment is located on a less frequented four-lane road.
- Zvonařka – a site characterised by the presence of significant construction activity in 2019. The measuring device is located along a four-lane road.
- Arboretum – the measuring device is located directly in the center of the city park.
- Lány – a site characterised by the presence of residential development. The measuring equipment is located between houses.

Data were measured throughout 2019. The frequency of recording was 1 second. However, the data is reprocessed into 10-minute averages by default. Measured variables included: temperature, humidity, wind direction, wind speed, pressure and $PM_{10}$, $PM_{2.5}$ and $PM_1$ concentrations.

### 2.2 Data processing

Resuspension is a process that does not occur under all conditions. There are times of the year when, despite increased wind speeds, there is no increase in concentration. In order for the resuspension process to be recognized from the data, the data must be prepared according to predetermined conditions.

Due to the availability of particles at different times of the year, the resuspension process has seasonal variability. Thus, the data were sorted into four seasons. Hourly averages of the measured data are mostly used to indicate the resuspension history [4,5]. Resuspension occurs within seconds [9], the shortest available measured time intervals, 10 minutes, were thus used. Air humidity above 60 % can significantly affect the removal of particles from the surface [10]. Therefore, only data with humidity below 60 % were used. Subsequently, the particle concentrations were sorted into three size fractions:

1) $PM_{10\text{-}2,5}=PM_{10}\text{-}PM_{2,5}$,
2) $PM_{2,5\text{-}1}=PM_{2,5}\text{-}PM_1$,
3) $PM_1$.

The function of concentration on wind speed for particle size fractions, the sorted data were fit with a polynomial. The degree of the polynomial was determined by the k-Fold cross-validation method [22], where the dataset is split into training and test subsets. Subsequently, the root mean square error (RMSE) determining the deviation of the test subset of the real data from the polynomial curve is determined. This process was carried out k times and after its completion, the average of k RMSE values was calculated for a given polynomial degree. Subsequently, the polynomial with the lowest resulting RMSE was selected. The degree of the polynomial can therefore vary for each data filtering condition (season, location and fraction) just based on the RMSE results. Within this paper, the value of k was set to 10, which is the value standardly used in this method across disciplines. Local extremes were then determined on the curves for subsequent analysis of resuspension rates.

### 2.3 Evaluation of the data

The original methodology for evaluating resuspension characteristics is based on the procedure [4]. The component of particles that can resuspend from the $PM_{10\text{-}2,5}$ fraction is obtained by subtracting two functions. The first function is the rate at which particles of the $PM_{10\text{-}2,5}$ fraction are diluted with increasing wind speed. This rate is the same as the rate at which $PM_{2.5}$ particles are diluted. The second function is the dependence of the $PM_{10\text{-}2,5}$ concentration on wind speed itself. Thus, the wind speed is identifiable when the resuspension event is visible. At the same time, the rate of increase in particle concentration due to resuspension is determined. However, based on the known concentration of $PM_1$, the behaviour of other size fraction of $PM_{2.5\text{-}1}$ and $PM_1$ can be determined. These classes may have different behaviour depending on the wind speed.

Since the aim of this work is to evaluate how the concentrations of different particle size fractions behave as a function of wind speed, this approach is not applicable. Thus, the presented method of data processing and evaluation provides an indication of which particle size fraction concentration varies the most due to wind in the specified seasons. The increment of the concentration of the size fractions to the total increase in $PM_{10}$ concentration is known. The method itself consists of the following steps:

1. Identifying the best-fit of the relationship between particle concentration and wind speed.
2. Locating the extremes of given functions.
3. Determining the wind speed interval where the $PM_{10}$ increase occurs.
4. Deriving the concentration increase or decrease from the extremes of the functions for each particle size fraction in the specified wind speed interval.
5. Determination of the concentration increment of the individual particle size fractions to the total particle concentration increment.

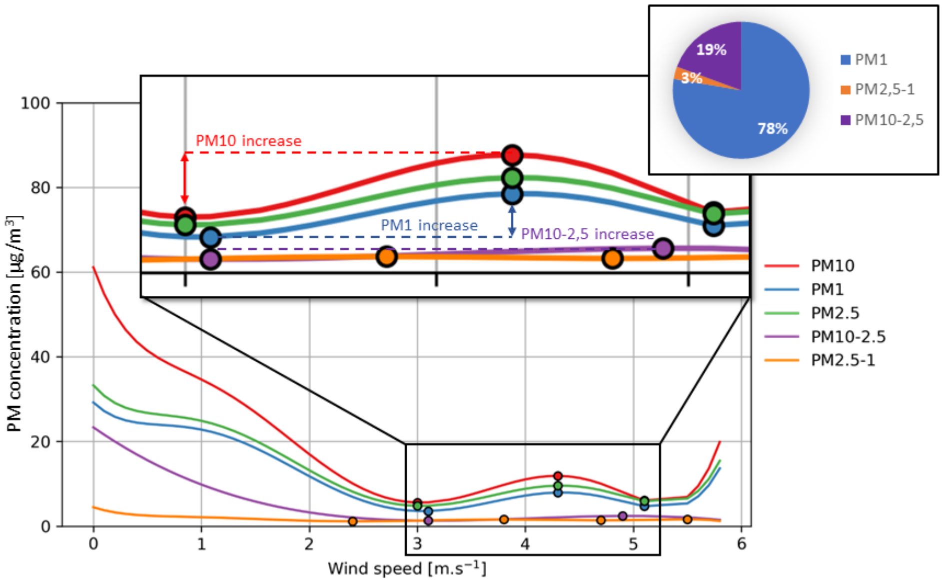


**Fig. 2.** Dependence of PM concentration on wind speed.

Furthermore, health risks from wind-induced particle resuspension may be identified. At different seasons, particles of different size fractions are resuspended. Regarding health risks, it then makes a difference which size fraction caused the increase in $PM_{10}$ concentration due to increasing wind speed.

## 2.4 Estimation of the respiratory deposition doses

Atmospheric particles inhaled during breathing are deposited on the lining of the airways and are not exhaled, which can cause serious breathing disorders. A mathematical model based on calculations and data from the International Commission on Radiological Protection (ICRP) has been used to determine the extent of particle deposition in different regions of the respiratory tract. Respiratory deposition dose [23–25] is calculated according to the equation (1):

$$RDD = V_T \cdot f \cdot DF_i \cdot PM_i \quad (1)$$

where $V_T$ is the breathing rate (m³/inhale), $f$ is the frequency of breathing, $DF_i$ is the deposition fraction of the size fraction $i$, $PM_i$ is the mass concentration of size fraction $i$. Breathing volume and respiratory rate depend on physical activity, but also on gender and age. The different values are given in Table 1. People usually perform little activity, mostly walking, when exposed to particles from resuspension, and because of this, the values for light physical activity were chosen and the calculation was calculated for men as well as women and children.

**Table 1.** Respiratory volume and respiratory rate during light physical activity [20].

| | $V_t$ [m³.inhale⁻¹] | F [min⁻¹] |
|---|---|---|
| Man | $12.5 \cdot 10^{-4}$ | 20 |
| Woman | $9.92 \cdot 10^{-4}$ | 21 |
| Children | $5.83 \cdot 10^{-4}$ | 32 |

The deposition size fraction is calculated in three different regions of the respiratory system - the head airway (HD), the tracheobronchial region (TB) and the alveolar region (AL) according to Hinds [20]. They are calculated as follows:

$$DF_{HD} = IF\left(\frac{1}{1+\exp(6.84+1.183\ln d_p)} + \frac{1}{1+\exp(0.924+1.885\ln d_p)}\right) \quad (2)$$

$DF_{HD}$ is the deposition fraction for the head airways, $d_p$ is the particle size, $IF$ is the inhalable fraction, which is calculated as follows:

$$IF = 1 - 0{,}5\left(1 - \frac{1}{\left(1+0.00076 d_p^{2{,}8}\right)}\right) \quad (3)$$

$DF_{TB}$ denotes the deposition fractions in the tracheobronchial region and is given by the following equation:

$$DF_{TB} = \left(\frac{0.00352}{d_p}\right)\left[\exp\left(-0.234(\ln d_p + 3.40)^2\right) + 63.9\exp\left(-0.819(\ln d_p - 1.61)^2\right)\right] \quad (4)$$

Deposition fraction for the alveolar region $DF_{AL}$ is calculated using the equation:

$$DF_{AL} = \left(\frac{0.0155}{d_p}\right)\left[\exp\left(-0.416(\ln d_p + 2.84)^2\right) + 19.11\exp\left(-0.482(\ln d_p - 1.362)^2\right)\right] \quad (5)$$

The particle mass concentration was used for the calculation, which corresponds to the increase in particles due to wind-induced resuspension. Consequently, the calculated RDD value corresponds to the value that a person would breathe while walking in the city with wind blowing at the speed at which the increase in particle concentration was identified.

## 3 Results and discussion

Based on the explained methodology, the data were processed and evaluated. The data are divided into four seasons in five locations. For each location, the concentration of $PM_{10}$, $PM_{10-2,5}$, $PM_{2.5-1}$, $PM_1$ ($PM_{2.5}$ fraction is also evaluated for illustration) is evaluated depending on the wind speed. The data were fitted with a polynomial in a way that best fits the nature of the data. An example of the polynomial translation of the data is shown in the following figure.

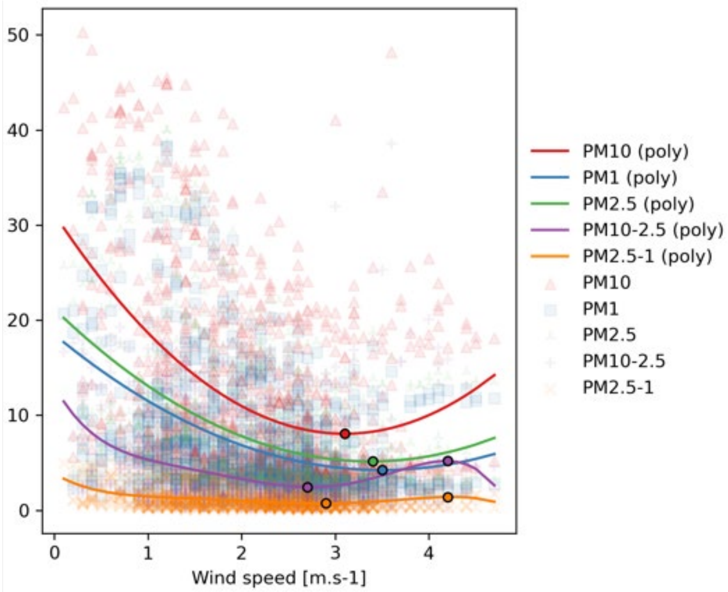


**Fig. 3.** Best fit polynomial to the evaluated data for location Výstaviště in winter period.

For each season and location, it was determined at which wind speeds $PM_{10}$ particles increase. Within a specified range of wind speeds, the contribution of each size fraction to the increase in $PM_{10}$ was determined. The concentration increase was calculated as the difference in the concentration maxima and minima of the polynomials for each particle size fraction over the observed wind speed range. The particle size fraction dominantly responsible for the increase in $PM_{10}$ concentration due to wind is summarized in the following table.

**Table 2.** Fraction of particles dominantly responsible for the increase in total concentration due to particle resuspension.

| Location | Arboretum | Lány | Výstaviště | Svatoplukova | Zvonařka |
|---|---|---|---|---|---|
| Spring | - | $PM_{10-2,5}$ | $PM_{10-2,5}$ | $PM_1$ | $PM_{10-2,5}$ |
| Summer | $PM_{10-2,5}$ | $PM_{10-2,5}$ | $PM_{10-2,5}$ | $PM_{2,5-1}$ | $PM_{10-2,5}$ |
| Autumn | $PM_{10-2,5}$ | $PM_{10-2,5}$ | $PM_1$ | $PM_{10-2,5}$ | $PM_{10-2,5}$ |
| Winter | - | - | $PM_{10-2,5}$ | $PM_1$ | $PM_{10-2,5}$ |

The table shows that $PM_{10-2,5}$ is a fraction, which is predominantly resuspended by wind, confirming the assumption of the studies [4,8]. However, a further assumption of a decrease in $PM_{2.5}$ concentrations with increasing wind speeds could not be confirmed. In the vast majority of cases, there were increasing concentrations of both $PM_{2.5-1}$ and $PM_1$ fractions due to wind. This phenomenon can be caused by fitting the data with a polynomial. Previous studies used a second-degree polynomial, which could suppress small changes in concentration with a wind speed. The behaviour of the size fractions on the wind speed interval where the increase in $PM_{10}$ occurred is evident in Tab. 2. The locations where there was an increase in concentration, a decrease in concentration, or the concentration was constant are marked.

**Table 3.** Concentration behaviour of the particle fraction due to an increase in wind speed.

| Season | Fraction | Arboretum | Lány | Výstaviště | Svatoplukova | Zvonařka |
|---|---|---|---|---|---|---|
| Spring | $PM_{10-2,5}$ | - | Increase | Increase | Decrease | Increase |
| | $PM_{2,5-1}$ | - | In | Increase | Constant | Increase |
| | $PM_1$ | - | Increase | Increase | Increase | Increase |
| Summer | $PM_{10-2,5}$ | Increase | Increase | Increase | Increase | Increase |
| | $PM_{2,5-1}$ | Increase | Increase | Increase | Increase | Increase |
| | $PM_1$ | Increase | Increase | Increase | Increase | Increase |
| Autumn | $PM_{10-2,5}$ | Increase | Increase | Increase | Increase | Increase |
| | $PM_{2,5-1}$ | Constant | Constant | Constant | Increase | Constant |
| | $PM_1$ | Decrease | Increase | Increase | Decrease | Increase |
| Winter | $PM_{10-2,5}$ | - | - | Increase | Increase | Increase |
| | $PM_{2,5-1}$ | - | - | Increase | Constant | Increase |
| | $PM_1$ | - | - | Increase | Increase | Increase |

It can be seen from Tab. 3 that the increase in concentration was evident in almost every season and location. Based on Tab. 2, it is known that the $PM_{10-2,5}$ fraction is dominantly responsible for the increase in $PM_{10}$ due to wind. However, Tab. 3 shows that the concentration increase is also recorded for other fractions. From the point of view of health risks, it is important to know how concentrations increase for all fractions and seasons.

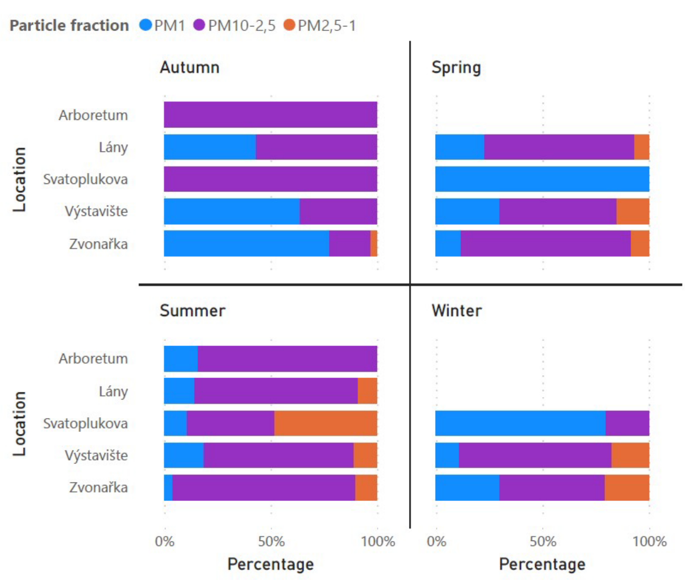


**Fig. 4.** The percentage increase for each fraction against the total increase.

Almost every location is dominated by an increase in the $PM_{10-2,5}$ fraction. Sites that showed similar behaviour across seasons were Výstaviště, Zvonařka and Lány. Here, the contribution of the fine fraction $PM_1$ to the overall concentration increase decreased during the spring and summer months. The increase in the $PM_{2.5-1}$ fraction remained approximately constant or did not change at all during the year. During the autumn and winter months, the increase in the $PM_1$ fraction increased.

However, the overall increase in the concentration of individual fractions does not indicate a problem related to health risks. Particle size is key with respect to health risks, as smaller particles settle deeper in the respiratory system. Although the increase in the $PM_{10-2.5}$ fraction is dominant, the increase in $PM_1$ concentration has a more negative impact on human health. The following graph shows the number of resuspended particles that can settle in different parts of the respiratory system.

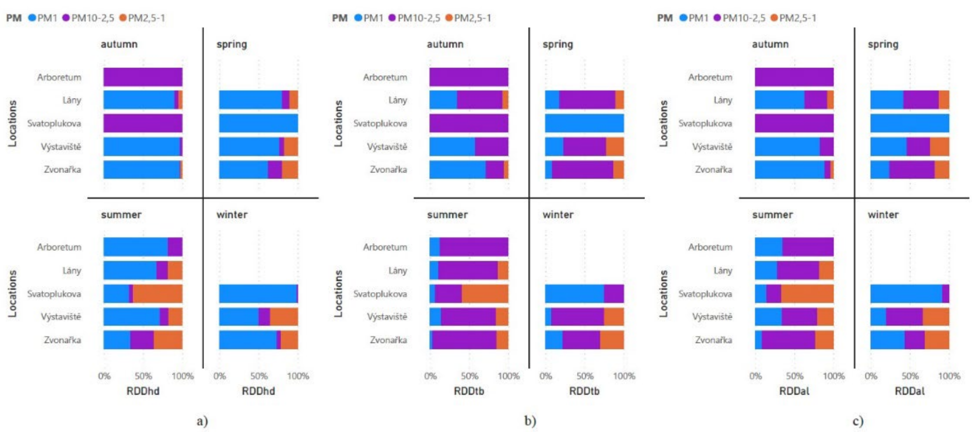


**Fig. 5.** The percentage of particle fraction deposided in respiratory sytem against topal deposited mass of particles. a) the head airway (HD), b) the tracheobronchial region (TB), c) the alveolar region (AL).

Comparing Fig. 4 and Fig. 5, it is evident that although the increase in concentration is dominated by the $PM_{10-2,5}$ fraction, more $PM_1$ particles are trapped in the human body. The $PM_1$ fraction is a minority fraction in the concentration increase in most cases. Considering the total amount of trapped particles in the human body, the fraction of $PM_1$ is not negligible, especially in head airways region. Similarly, the $PM_{2.5-1}$ fraction is too significant due to its concentration increase. However, due to health risks, the proportion of trapped particles has increased, especially in the alveolar region. In tracheobronchial region, the fraction of $PM_{10-2,5}$ particles captured is dominant, as in the overall concentration increase in Fig. 5. Thus, the results show that $PM_1$ particles are trapped in the head airways despite the low total concentration. $PM_{10-2,5}$ particles are predominantly trapped in the tracheobronchial region. The alveolar region is dominated by $PM_1$ capture, and it should be noted that $PM_{2.5-1}$ particles also make a non-negligible contribution in this region. Gender and age don't influence the results.

## 4 Conclusion

The present study focuses on the identification of the wind-induced resuspension process in cities. Emission monitoring data are used. The data are divided into four annual periods. Times when the resuspension process is suppressed and humidity reaches values above 60 % are not evaluated [10]. The remaining data were separated into size fractions $PM_{10-2,5}$, $PM_{2.5-1}$ and $PM_1$ and expressed as a mathematical dependence on wind speed. From the resulting functions, it was determined which fraction was responsible for the increase in $PM_{10}$ concentration due to increasing wind speed. It was found that particles with the size fraction $PM_{10-2,5}$ resuspended at a dominant rate, which is in agreement with previous studies. The original assumption of a decrease in $PM_{2.5}$ concentration with increasing wind speed was not evident. This may be due to the fact that the $PM_{2.5}$ fraction has split into $PM_{2.5-1}$ and $PM_1$. The methodology used identified a concentration increase in the $PM_{2.5-1}$ and $PM_1$ fractions.

However, this increase cannot be attributed with certainty to resuspension alone. The source of these particles may be traffic or other sources [4–8], which the wind carries. A more detailed data analysis would be needed to confirm or disprove this. It would be necessary to link the particle concentration information to the $NO_x$ concentration.

With increasing wind speed, the concentration of all size fractions increases in each season. Whatever the source of the particles, this increase has an impact on human health. Although the increase in $PM_{10-2,5}$ fraction has been dominant, the increase in $PM_1$ concentration is more serious for health. These particles are inhaled more by humans compared to $PM_{10-2,5}$. Within the respiratory system, different fractions are trapped in different parts. The $PM_1$ fraction is trapped in the head airways. The $PM_{10-2,5}$ fraction in the tracheobronchial region and the $PM_{2.5-1}$ fraction in the alveolar region.

This paper has been supported by the EU project Computer Simulations for Effective Low-Emission Energy Engineering funded as project No. CZ.02.1.01/0.0/0.0/16_026/0008392 by Czech Republic Operational Programme Research, Development and Education, Priority 1: Strengthening capacity for high-quality research and the collaboration. This research was further funded by projects of Brno University of Technology: FSI-S-20-6280, FAST/FSI-J-22-7905.

## References

1. Karagulian, F.; Belis, C.A.; Dora, C.F.C.; Prüss-Ustün, A.M.; Bonjour, S.; Adair-Rohani, H.; Amann, M. Contributions to Cities' Ambient Particulate Matter (PM): A Systematic Review of Local Source Contributions at Global Level. *Atmos. Environ.* 2015, *120*.
2. Harrison, R.M.; Allan, J.; Carruthers, D.; Heal, M.R.; Lewis, A.C.; Marner, B.; Murrells, T.; Williams, A. Non-Exhaust Vehicle Emissions of Particulate Matter and VOC from Road Traffic: A Review. *Atmos. Environ.* 2021, *262*.
3. Casotti Rienda, I.; Alves, C.A. Road Dust Resuspension: A Review. *Atmos. Res.* 2021, *261*.
4. Harrison, R.M.; Yin, J.; Mark, D.; Stedman, J.; Appleby, R.S.; Booker, J.; Moorcroft, S. Studies of the Coarse Particle (2.5-10μm) Component in UK Urban Atmospheres. *Atmos. Environ.* **2001**, *35*, doi:10.1016/S1352-2310(00)00526-4.
5. Thorpe, A.J.; Harrison, R.M.; Boulter, P.G.; McCrae, I.S. Estimation of Particle Resuspension Source Strength on a Major London Road. *Atmos. Environ.* **2007**, *41*, 8007–8020, doi:10.1016/J.ATMOSENV.2007.07.006.
6. Pospíšil, J.; Jícha, M. Mezní Rychlost Resuspenze Částic PM10 v Prostředí Městské Zástavby.; Česká aerosolová společnost: Prague, 2007; pp. 33–34.
7. Grundström, M.; Hak, C.; Chen, D.; Hallquist, M.; Pleijel, H. Variation and Co-Variation of PM10, Particle Number Concentration, NOx and NO2 in the Urban Air - Relationships with Wind Speed, Vertical Temperature Gradient and Weather Type. *Atmos. Environ.* **2015**, *120*, doi:10.1016/j.atmosenv.2015.08.057.
8. Kassomenos, P.; Vardoulakis, S.; Chaloulakou, A.; Grivas, G.; Borge, R.; Lumbreras, J. Levels, Sources and Seasonality of Coarse Particles (PM 10-PM 2.5) in Three European Capitals - Implications for Particulate Pollution Control. *Atmos. Environ.* **2012**, *54*, doi:10.1016/j.atmosenv.2012.02.051.
9. Wang, Y.; Zhao, Y.; Yao, J. Large Eddy Simulation of Particle Deposition and Resuspension in Turbulent Duct Flows. *Adv. Powder Technol.* **2019**, *30*, 656–671, doi:10.1016/J.APT.2019.01.012.
10. Gotoh, K.; Takebe, S.; Masuda, H.; Banba, Y. The Effect of Humidity on the Removal of Fine Particles on a Solid Surface Using High-Speed Air Jet. *KONA Powder Part. J.* **1995**, *13*, doi:10.14356/kona.1995024.

11. Amato, F.; Pandolfi, M.; Moreno, T.; Furger, M.; Pey, J.; Alastuey, A.; Bukowiecki, N.; Prevot, A.S.H.; Baltensperger, U.; Querol, X. Sources and Variability of Inhalable Road Dust Particles in Three European Cities. *Atmos. Environ.* **2011**, *45*, doi:10.1016/j.atmosenv.2011.06.003.
12. Mei, M.; Song, H.; Chen, L.; Hu, B.; Bai, R.; Xu, D.; Liu, Y.; Zhao, Y.; Chen, C. Early-Life Exposure to Three Size-Fractionated Ultrafine and Fine Atmospheric Particulates in Beijing Exacerbates Asthma Development in Mature Mice. *Part. Fibre Toxicol.* **2018**, *15*, doi:10.1186/s12989-018-0249-1.
13. Seaton, A.; Tran, L.; Aitken, R.; Donaldson, K. Nanoparticles, Human Health Hazard and Regulation. *J. R. Soc. Interface* 2010, *7*.
14. Yang, M.; Chu, C.; Bloom, M.S.; Li, S.; Chen, G.; Heinrich, J.; Markevych, I.; Knibbs, L.D.; Bowatte, G.; Dharmage, S.C.; et al. Is Smaller Worse? New Insights about Associations of PM1 and Respiratory Health in Children and Adolescents. *Environ. Int.* **2018**, *120*, doi:10.1016/j.envint.2018.08.027.
15. Pirsaheb, M.; Sharafi, K.; Hopke, P.K.; Hadei, M.; Shahsavani, A. Carcinogenic Risks of Particulate Matter during Middle Eastern Dust Events and Normal Days. *Atmos. Pollut. Res.* **2020**, *11*, doi:10.1016/j.apr.2020.06.012.
16. Ziou, M.; Tham, R.; Wheeler, A.J.; Zosky, G.R.; Stephens, N.; Johnston, F.H. Outdoor Particulate Matter Exposure and Upper Respiratory Tract Infections in Children and Adolescents: A Systematic Review and Meta-Analysis. *Environ. Res.* 2022, *210*.
17. Pope, C.A.; Dockery, D.W. Health Effects of Fine Particulate Air Pollution: Lines That Connect. *J. Air Waste Manag. Assoc.* **2006**, *56*, doi:10.1080/10473289.2006.10464485.
18. Yang, M.; Guo, Y.M.; Bloom, M.S.; Dharmagee, S.C.; Morawska, L.; Heinrich, J.; Jalaludin, B.; Markevychd, I.; Knibbsf, L.D.; Lin, S.; et al. Is PM1 Similar to PM2.5? A New Insight into the Association of PM1 and PM2.5 with Children's Lung Function. *Environ. Int.* **2020**, *145*, doi:10.1016/j.envint.2020.106092.
19. Mei, L.; Yan, S.; Li, Y.; Jin, X.; Sun, X.; Wu, Y.; Liang, Y.; Wei, Q.; Yi, W.; Pan, R.; et al. Association between Short-Term PM1 Exposure and Cardiorespiratory Diseases: Evidence from a Systematic Review and Meta-Analysis. *Atmos. Pollut. Res.* **2022**, *13*, doi:10.1016/j.apr.2021.101254.
20. 'William, C.H. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, 2nd Edition*; 2nd ed.; Wiley-Interscience Publication: Canada, 1999;
21. Darquenne, C. Deposition Mechanisms. *J. Aerosol Med. Pulm. Drug Deliv.* **2020**, *33*, 181–185, doi:10.1089/jamp.2020.29029.cd.
22. 'Trevor, H.; 'Robert, T.; 'Jerome, F. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*; 2nd ed.; Springer New York, NY: New York, 2009;
23. Azarmi, F.; Kumar, P. Ambient Exposure to Coarse and Fine Particle Emissions from Building Demolition. *Atmos. Environ.* **2016**, *137*, doi:10.1016/j.atmosenv.2016.04.029.
24. Prabhu, V.; Gupta, S.K.; Madhwal, S.; Shridhar, V. Exposure to Atmospheric Particulates and Associated Respirable Deposition Dose to Street Vendors at the Residential and Commercial Sites in Dehradun City. *Saf. Health Work* **2019**, *10*, doi:10.1016/j.shaw.2019.01.005.
25. Gupta, S.K.; Elumalai, S.P. Exposure to Traffic-Related Particulate Matter and Deposition Dose to Auto Rickshaw Driver in Dhanbad, India. *Atmos. Pollut. Res.* **2019**, *10*, doi:10.1016/j.apr.2019.01.018.