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Zdzisław CHŁOPEK

TESTING OF HAZARDS TO THE ENVIRONMENT CAUSED BY PARTICULATE MATTER DURING USE OF VEHICLES

BADANIA ZAGROŻENIA ŚRODOWISKA CZĄSTKAMI STAŁYMI PODCZAS EKSPLOATACJI POJAZDÓW SAMOCHODOWYCH*

The study presents results of tests on emissions of fractions of PM10, PM2.5 and PM1 dusts. For modeling of emissions of fractions of PM2.5 and PM1 particles, results of empirical tests were used as carried out in air quality supervision stations located in the agglomeration of the city of Brno. The results of modeling of emissions of fractions of PM2.5 and PM1 particles did not make it possible to make unequivocal conclusions, which proves that the discussed problem has to be treated statistically. However, a significant relation between models of emissions of fractions of particulate matter and sources of emissions of dusts and conditions for distribution of the same were observed.

Keywords: *dusts, particulate matter, PM10, PM2.5, PM1, vehicles.*

W pracy przedstawiono wyniki badań imisji frakcji pyłów PM10, PM2.5 i PM1. Do modelowania imisji frakcji cząstek stałych PM2.5 i PM1 wykorzystano wyniki badań empirycznych, przeprowadzonych na stacjach nadzorowania jakości powietrza w aglomeracji czeskiego miasta Brna. Wyniki modelowania imisji frakcji cząstek stałych PM2.5 i PM1 nie umożliwiły sformułowania jednoznacznych wniosków, co dowodzi konieczności statystycznego potraktowania badanego problemu. Stwierdzono jednak istotną zależność modeli imisji frakcji cząstek stałych od źródeł emisji pyłów i warunków ich rozprzestrzenia.

Słowa kluczowe: *pyły, cząstki stałe, PM10, PM2.5, PM1, pojazdy samochodowe.*

1. Introduction

Hazards posed by dusts to the environment are commonly known. The harmful character of dusts for human health has been discussed in a lot of studies relating both to health aspects [1, 10, 16, 18, 28, 31, 34, 35] as well as evaluation of factors affecting emissions of dusts [2, 3, 5–9, 11–15, 17, 19, 21, 22, 24, 27, 29]. Sources of emissions of dusts include natural phenomena and civilization activities. Most significant natural sources of emissions of dusts include volcanic eruptions, deposits, marine aerosols, animal and plant sources as well as forest fires. On a global scale, the natural sources of emissions of dusts are dominant, however, in the areas characterized by particularly intense human activities, anthropogenic sources of dusts have strongest impacts upon contamination of the environment. The anthropogenic sources of dusts include all production processes and fuel combustion processes. Automobile industry plays a significant role in contamination of the environment with dusts, especially in large centers of urban agglomerations.

The harmful character of dusts for human health depends on chemical and mineral composition and physical structure of dusts as well as sizes of dust particles [2, 3, 6, 7, 17, 21, 22, 35]. Depending on conventional sizes of dust particles, the following particles may be distinguished [2, 3, 6, 7, 17, 21, 22, 35]:

- TSP (total suspended particles) – a mixture of small particles of conventional sizes not exceeding 300 μm and suspended in the air (a dispersed phase of the solid body–gas two–phase system),
- PM10 suspended dust – of conventional sizes not exceeding 10 μm,
- PM2.5 fine dust – of conventional sizes not exceeding 2,5 μm,
- PM1 nanoparticles – of conventional sizes not exceeding 1 μm, constituting practically invisible dust [24, 29].

Particulate matter with conventional diameters exceeding 10 μm is mainly arrested in upper respiratory tract, where most of them are exhaled, PM10 particles (with exclusion of PM2.5 particles) even penetrate lungs and, although they do not accumulate in the lungs, they accumulate in the upper respiratory tract. PM2.5 particulate matter penetrates the deepest paths of lungs, where they accumulate. PM1 particulate matter even penetrates the circulatory system. Particularly toxic particulate matter includes dusts containing heavy metal compounds and polycyclic organic compounds, most of which are characterized by carcinogenic properties [31, 35]

Apart from the negative impact of dusts upon human and animal health, dusts also affect plants, soil and water. Combined with sulfur dioxide, carbon oxide and other compounds, dusts contribute to the formation of the London fog. [2, 11]. Dusts also impair the greenhouse effect in the atmosphere [2, 11]. It should also be noted that dusts limit visibility, which affects road traffic safety.

The hazardous character of air pollution is evaluated on the basis of imission of pollution – concentration of pollution dispersed in the air and measured at the height of 1.5 m above the ground level [26]. Exceeded admissible imissions of PM10 par-

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** ticulate matter in economically developed countries are most common reasons for authorities to undertake repair activities relating to the environment quality. Since 2009 a reduction of imissions of PM2.5 particulate matter in the European Union has been observed. It is planned to control imissions of PM1 particulate matter in the future.

The evaluation of particular sources of dust emissions as regards their negative impacts upon the environment is very difficult, as tests on the air quality in particular places include influence of all existing sources. Moreover, the quality of air is also affected by conditions of distribution of pollution. Therefore, it is purposeful to conduct comparative tests in places characterized by various shares of sources of pollution emissions and distribution of the same. On the basis of analyses of results of such tests it is possible to draw conclusions concerning impacts of particular sources of pollution emissions upon the air quality. The basic difficulty of such tests involves a relatively scarce network of air quality monitoring stations, which conduct constant measurements of imissions of complete fractions of particulate matter, i.e. PM10, PM2.5 and PM1 according to the present condition. In order to evaluate impacts of particular sources of emissions of dusts upon imission of fractions of particulate matter it is additionally necessary to perform measurements with the frequency enabling identification of dynamic properties of processes, which describe the phenomena causing emission of dusts, e.g. vehicle traffic. It has also been evaluated that, for such purposes, it is necessary to perform measurements with time intervals not exceeding 1 hour. Requirements are also posed to testing time, as it is purposeful to consider variability of the processes determining the anthropogenic emission of dusts connected with a weekly cycle as well as the variability resulting from seasons of the year. Additionally, long–term testing may also contribute effectively to decrease impacts of interferences upon testing results as connected with accidental factors such as weather conditions. As it is known, fluctuations of weather factors have a normal character in a given area and, therefore, their expected values reach zero with lengthening of the observation period. Therefore, it is purposeful that measurements should be conducted for at least one year.

As regards numerous air quality monitoring stations found in Europe, there are such urban agglomerations that include several stations located in places with diversified character of emission sources and distribution of pollution. Additionally, the stations test complete fractions of particulate matter and pollutions such as nitric oxides and carbon oxide, the imission of which is argued as connected with imission of fractions of particulate matter [5–9, 12]. The similar collection of air quality monitoring stations may be found, among others in, the agglomeration of the city of Brno. For the purposes of analysis of imissions of fractions of particulate matter, this study has used results of tests made by three air quality monitoring stations located in Brno.

Brno is a city located in Moravia, the Czech republic. It is located in the south–east flat part of the country at the confluence of the Svratka and Svitava Rivers. Brno has over 400000 inhabitants (2008) and it occupies the area of 230 km^2.

The air quality monitoring stations are owned by the Division of Environmental Protection of the Municipality of Brno. The tests used results of measurements made by the stations located in Svatoplukova, Zvonařka and Lány. The stations differ in the character of the area, in which they are located. Svatoplukova and Zvonařka stations are located at large main roads and Zvonařka station is located directly at the road. Lány station is located far from busy roads. The stations measure imissions of PM10, PM2.5 and PM1 particulate matter as well as nitric oxides and carbon oxide every hour. This study does not use results of tests on imissions of nitric oxides and carbon oxides used for development of behaviorist [4] models of imissions of PM10 particulate matter [6–9], as these could not be contained in this study. However, the selections of stations considered deliberately the possibility of recording of imissions of nitric oxides and carbon oxide, which could facilitate obtaining of complete materials for modeling of imissions of particular fractions of particulate matter.

2. Modeling of imissions of PM2.5 and PM1 particles

Hazards to the environment may be evaluated on the basis of direct measurements of imissions of pollution, however this evaluation only relates to the place and time of measurements and generalization of the test results is not always qualified sufficiently. However, results of long–term tests in places with typical conditions of emission of pollution and distribution of pollution qualify for generalization of conclusions. In such cases, results of tests and modeling of imissions of pollution constitute a basis for evaluation of pollution of the environment. In other cases, hazards to the environment are evaluated on the basis of knowledge of emission of pollution and modeling of distribution of pollution. The knowledge of emission of pollution is possible owing to results of measurements and, in this case, there are the same restrictions as in the case of measurements of imissions. It is completely different in the case of mobile sources of emission such as, for example, vehicles. In this case, it is possible to model pollution only. As modeling of emission of pollution constitutes a basic tool for evaluation of hazards to the environment in most affected places, i.e. in city centers. Traditionally, all types of modeling connected with emission of pollution are referred to as modeling of emission of pollution, although in many cases the modeling applied formally to imissions. This simplification is justified in the possibility of concise formulation of opinions, although, formally it is inaccurate.

Modeling of emissions of PM10 particulate matter does not constitute the subject of this study, however, it is inherently connected with modeling of imission of PM2.5 and PM1 particles. Modeling of emission of PM10 particles has been described extensively in literature [6–9, 12–15, 21, 22, 27]. The following two testing methods are used:

- modeling of emission of PM10 particles on the basis of knowledge of traffic and properties of vehicles and roads – models created on the basis of structural similarity [4],
- modeling of imission of PM10 particles on the basis of imission of nitric oxides and carbon oxide – models created on the basis of functional similarity (behaviorist models) [4].
- models created on the basis of structural similarity consider the following sources of emission of PM10 particulate matter [6, 7, 13–15, 27]:
- vehicles,
- surface of the road,

- solid contamination found on roads – in the form of excitation of dusts.
- sources of dusts emitted by vehicles include [2, 3, 5–9, 13–15, 27]:
- a combustion engine – particulate matter contained in the exhaust gas[11, 23, 29],
- friction pairs – found mostly in the braking system [2, 3] and coupling,
- tires,
- other parts of vehicles that are subject to wear and tear.

Behaviorist models do not openly consider sources of emission of particulate matter, including those connected with automobiles and other particles. The behaviorist models use a significant statistical relation of imission of particulate matter and imission of other pollution and the theory and practice of automobile technology at least partly justifies such a relation, e.g. simultaneous increase of emission of particulate matter from combustion engines and other vehicle sources and emission of carbon oxide and nitric oxides with an increase of the vehicle velocity and, consequently, engine load.

The behaviorist models usually argue for a linear relation between imission of particulate matter and other contamination.

Generally, results of the analysis of models constructed on the basis of structural similarity cannot be compared to results of the analysis of models constructed on the basis of functional similarity, as structural models do not openly consider dust emission sources other than those connected with vehicle traffic. In reality, a wide scale of discretion of adoption of structural model coefficients, which are usually difficult to identify, causes it to become a significant reason for incomparability of results of the analysis of structural and functional models.

The fraction of PM2.5 particles may be treated as a subset of PM10 fractions. Therefore, a linear relation between imission of PM2,5 particles– $I_{PM2,5}$ and imission of PM10 particles– I_{PM10} is postulated:

$$I_{PM2,5} = k_{PM2.5-10} \cdot I_{PM10} \tag{1}$$

where: $k_{PM2.5-10}$ – coefficient of the model of emission of PM2.5 particulate matter; $k_{PM2.5-10} \in \langle 0;1 \rangle$

Similarly to the modeling of imission of PM2.5 particles, PM1 particles may be treated as a subset of PM10 particles and PM2.5 particles. Thus, imission of PM1 particles – IPM1 may be modeled in a linear relation to imission of PM10 particles:

$$I_{PM1} = k_{PM1-10} \cdot I_{PM10} \tag{2}$$

where: k_{PM1-10} – coefficient of the model of emission of PM1 particulate matter; $k_{PM1-10} \in \langle 0;1 \rangle$

and in a linear relation to imission of PM2.5 particulate matter:

$$I_{PM1} = k_{PM1-2.5} \cdot I_{PM2.5} \tag{3}$$

where: $k_{PM1-2.5}$ – coefficient of the model of emission of PM1 particulate matter; $k_{PM1-2.5} \in \langle 0;1 \rangle$.

Identification of models of imission of PM2.5 particles (1) and imission of PM1 particles (2 and 3) involves determination of coefficients of $k_{PM2.5-10}$, k_{PM1-10} and $k_{PM1-2.5}$ models on the basis of results of empirical tests on imission of fraction of PM10, PM2.5 and PM1 particles. Identification results generally depend on conditions of emission of pollution and distribution of pollution as well as the period of measurements.

3. Testing of imission of PM10, PM2.5 and PM1 particles in selected air quality monitoring stations

As used in this study, testing in air quality monitoring stations in Brno was conducted in the period from 1 January to 31 December 2010 with a sampling interval of 1 h. Fig. 1–3 present courses of imission of fraction of particulate matter for averaged values within the period of 1 week for time t as marked with day numbers – d and month numbers – m.

The course of imission of fraction of particulate matter indicates a strong relation between the imission and seasons of the year: imission increases considerably in winter months. One may also observe a relation between imission of fractions and weekdays, which indicated a strong influence of civilization factors upon the imission. The mutual relationship between imissions of particular fractions is especially visible, which justifies adoption of linear models (1–3).

Fig. 4–6 present statistical characteristics of the testes sets of imission of fractions of particulate matter[1] : minimum value, maximum value, average value, standard deviation and span.

There are considerable differences in extreme values of imission of particular fractions of particulate matter. The least values: maximum, minimum and average values of imission of particular fractions were recorded for Lány station (apart from the average value of imission of PM1 particles and minimum value of imission of PM10 particles that are very similar to the values recorded for Zvonařka station). It is interesting that the greatest maximum and average values of imission of all fractions were recorded in Svatoplukowa station located in the area with less intense road traffic than in the case of Zvonařka station.

A strong correlation between imission of fraction of particulate matter results from the same. This is confirmed in the analysis of the correlations. The analysis was carried out with the use of Pearson's theory of linear correlation [30] and non–parametrical methods [33]: Spearmann rang correlation [32], Kendall tau correlation [20] and Kruskal gamma correlation [25]. Fig. 7–9 present coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between the tested sets.

The probability that the hypothesis assuming absence of correlation between the tested sets will not be rejected does not exceed 1·10–6 in all cases. Results of the analysis of correlation of sets of imission of size fractions of particulate matter fully qualify for formulation of an opinion on a strong correlation between the tested sets. The values of Pearson correlation coefficient for particular sets and the probability that the hypothesis assuming absence of Pearson correlation between the tested sets

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[1] In statistics and, in particular, in commercial applications, barely formal nomenclature is used, which does not always comply with the formalized mathematics. Therefore, terms such as "maximum value" should be treated as "the greatest value" and "minimum value" as "the least value", as there are not extreme values within the meaning of terms applied in a mathematical analysis. However, due to the fact that such terms are common and make it possible to provide concise statements, this study uses them in descriptions.

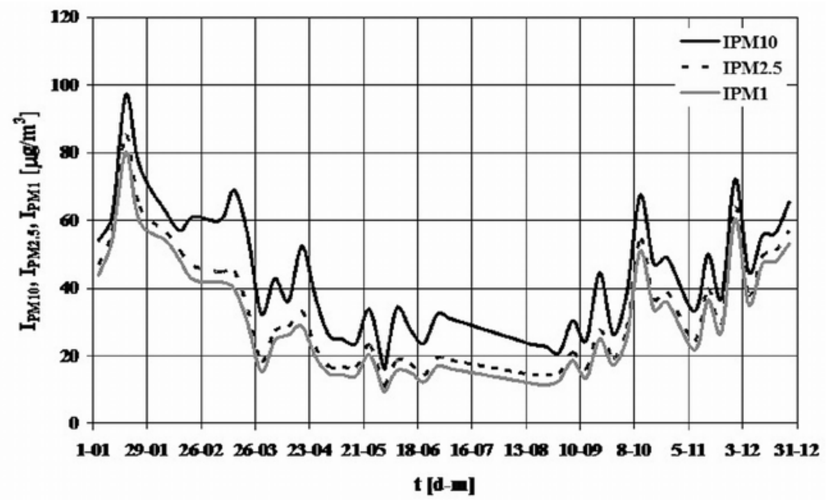

Fig. 1. The process of imission I of PM10, PM2.5 and PM1 particles in Brno–Svatoplukova air quality monitoring station

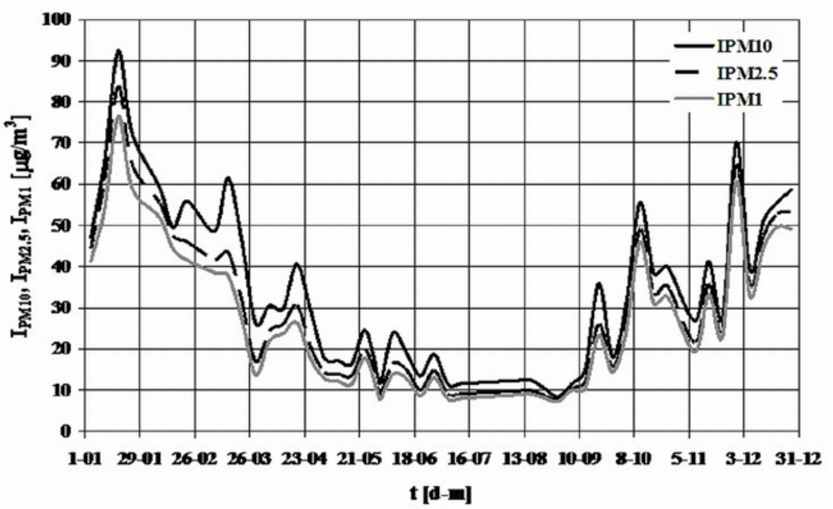

Fig. 2. The process of imission I of PM10, PM2.5 and PM1 particles in Brno–Zvonařka quality air monitoring station

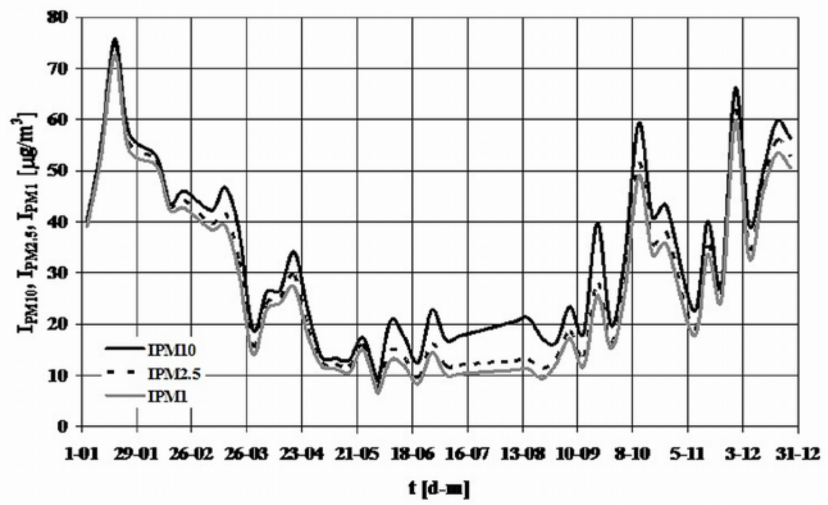

Fig. 3. The process of imission I of PM10, PM2.5 and PM1 particles in Brno–Lány air quality monitoring station

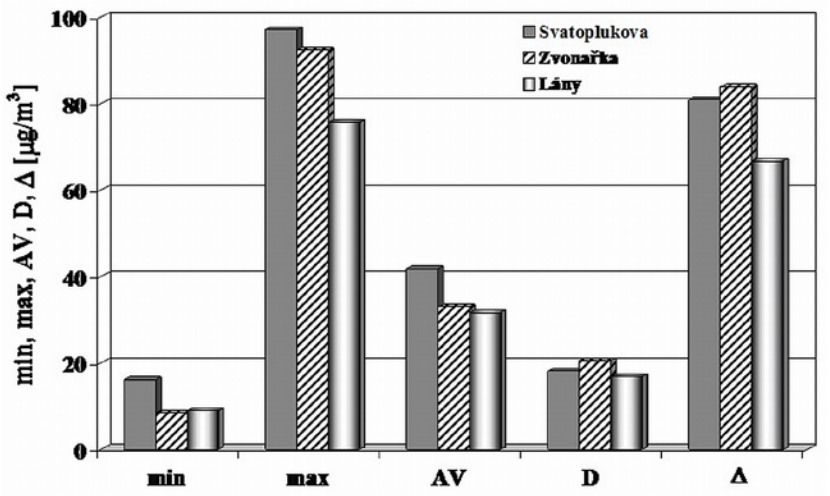

Fig. 4. Statistical characteristics of concentration of PM10: min – minimum value, max – maximum value, AV – average value; D – standard deviation, Δ – span

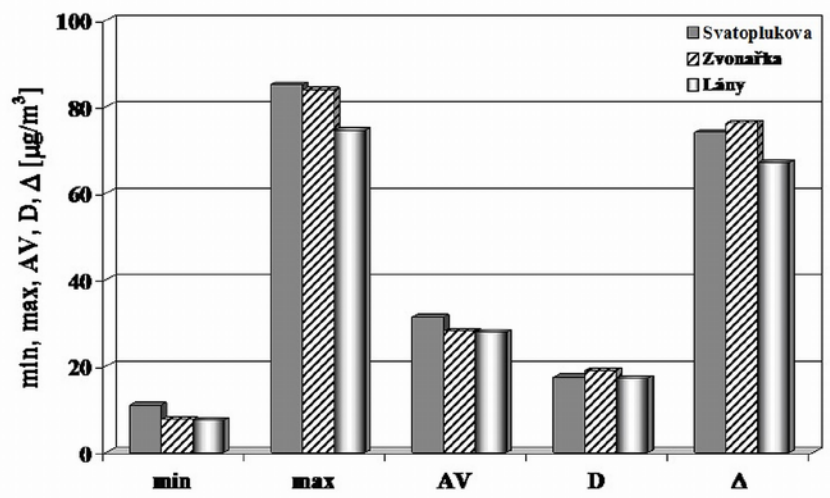

Fig. 5. Statistical characteristics of concentration of PM2.5 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, Δ – span

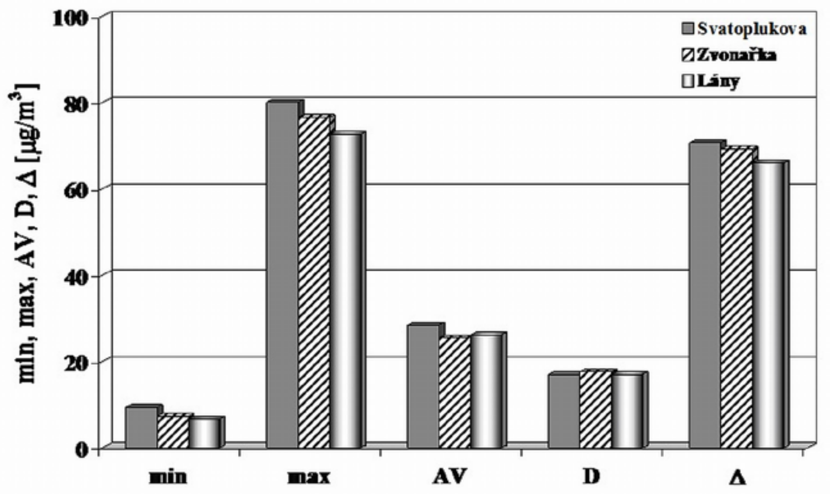

Fig. 6. Statistical characteristics of concentration of PM1 particulate matter: min – minimum value, max – maximum value, AV – average value; D – standard deviation, Δ – span

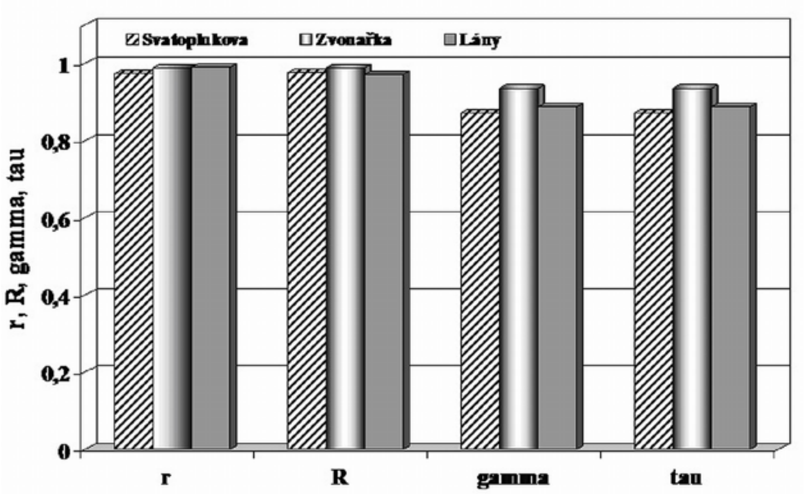

Fig. 7. Coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between sets of imission of PM10 and PM2.5 particles

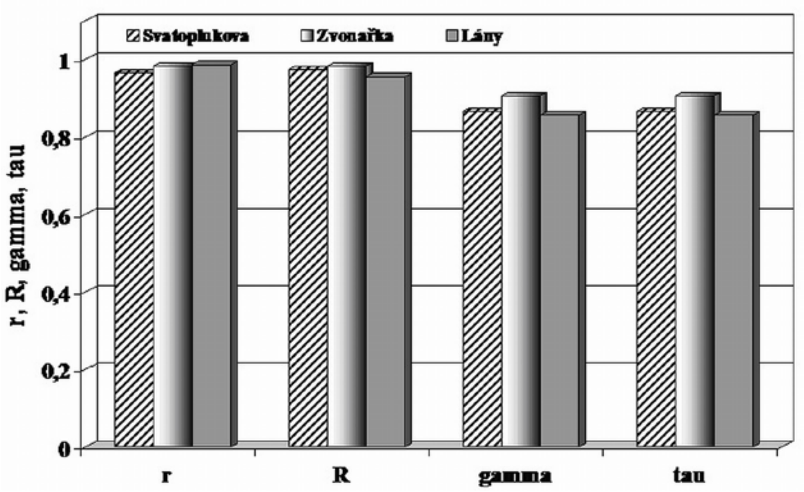

Fig. 8. Coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between sets of imission of PM10 and PM1 particles

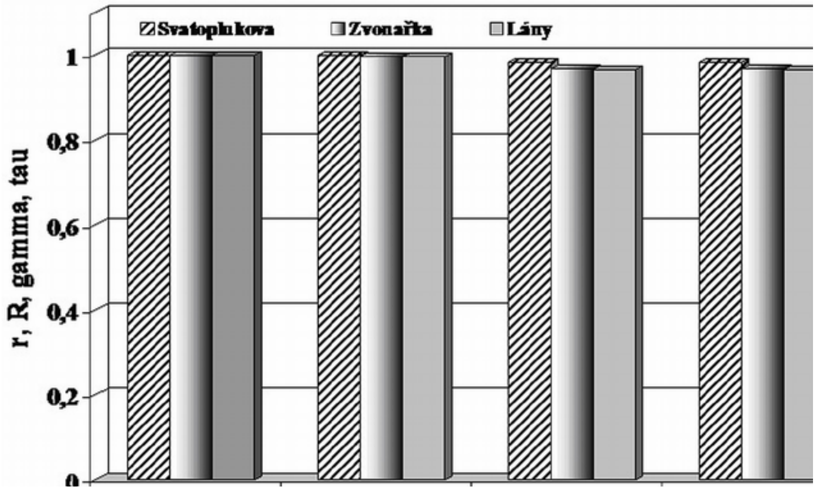

Fig. 9. Coefficients of Pearson r, Spearmann R, Kendall tau and Kruskal gamma correlations between sets of imission of PM1 and PM2.5 particles

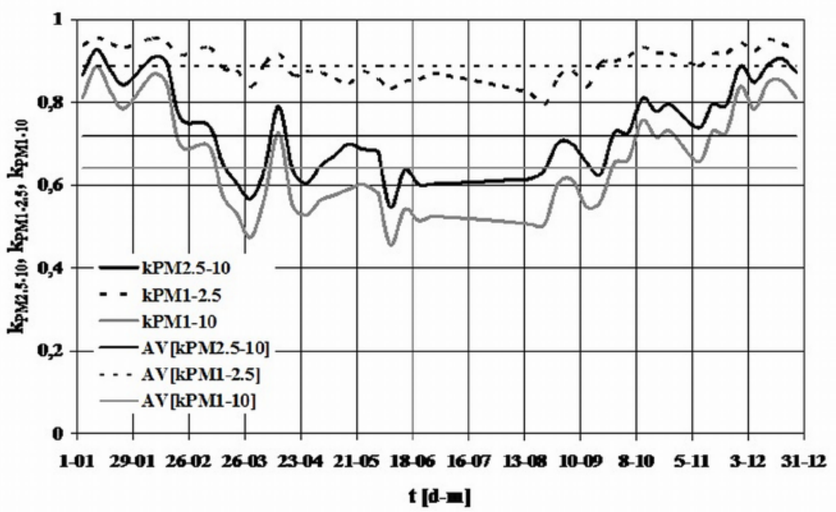

Fig. 10. The process and AV average value of k coefficients of imission models of PM2.5 and PM1 particles in Brno–Svatoplukova air quality monitoring station

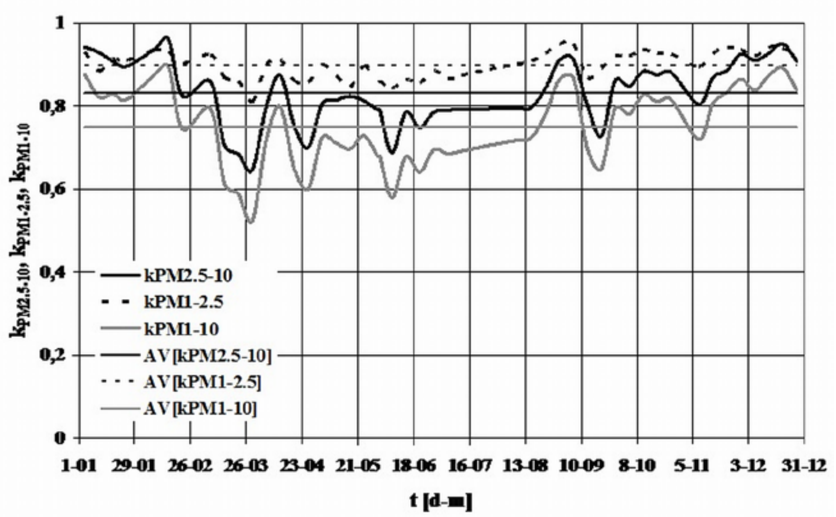

Fig. 11. The process and AV average value of k coefficients of imission models of PM2.5 and PM1 particles in Brno–Zvonařka air quality monitoring station

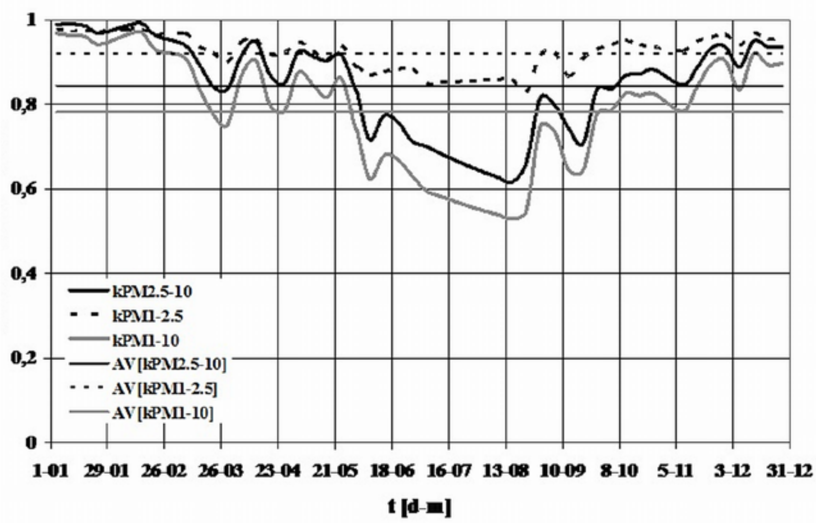

Fig. 12. The process and AV average value of k coefficients of imission models of PM2.5 and PM1 particles in Brno–Lány air quality monitoring station

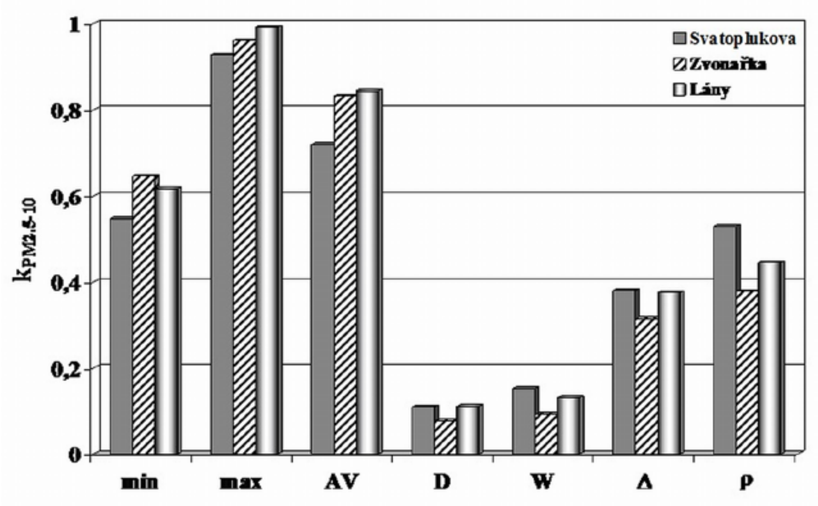

Fig. 13. Statistical characteristics of coefficients of imission model of PM2.5 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, W – variability coefficient; Δ – span; ρ – relation between the span and average value

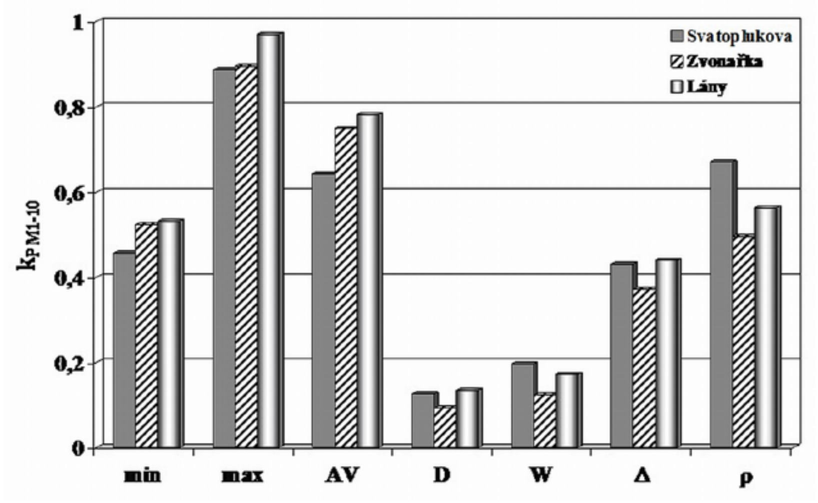

Fig. 14. Statistical characteristics of coefficients of imission model (2) of PM1 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, W – variability coefficient Δ – span; ρ – relation between the span and average value

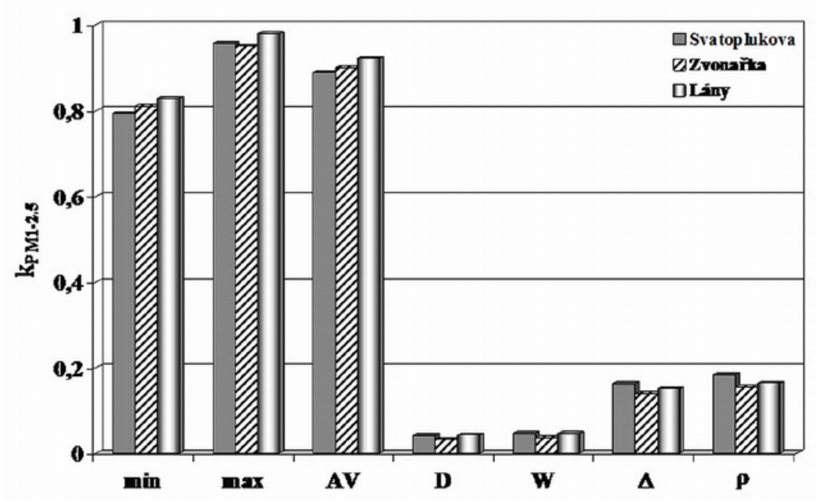

Fig. 15. Statistical characteristics of coefficients of imission model (3) of PM1 particles: min – minimum value, max – maximum value, AV – average value; D – standard deviation, W – variability coefficient Δ – span; ρ – relation between the span and average value

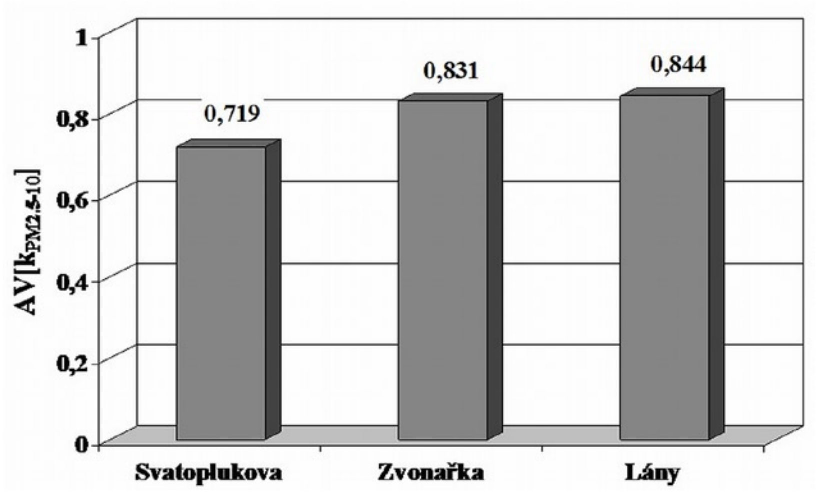

Fig. 16. AV average value of k coefficients of the model of emission of PM2.5 particles

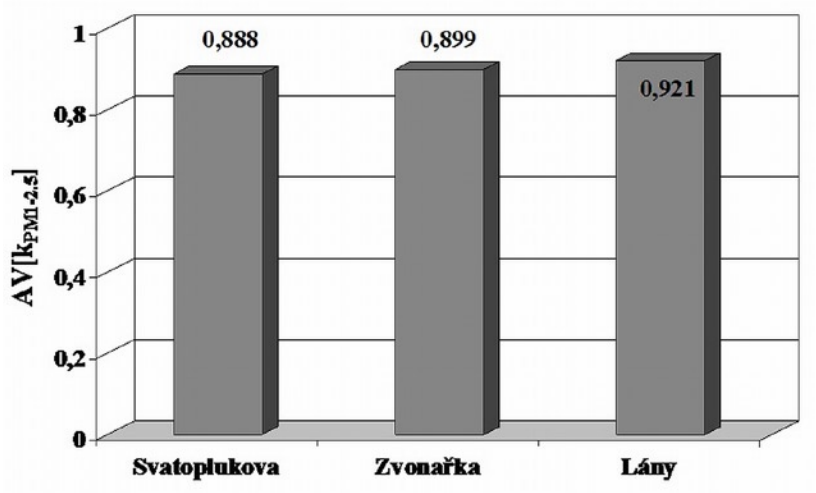

Fig. 17. AV average value of k coefficients of the model (2) of emission of PM1 particles

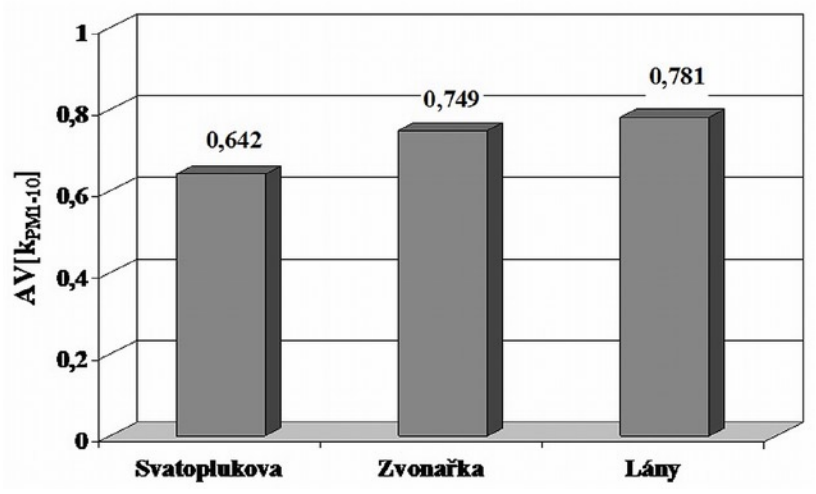

Fig. 18. AV average value of k coefficients of the model (3) of emission of PM1 particles

justify adoption of linear models of imission of PM2.5 and PM1 particles.

On the basis of empirical tests, parameters of imission models of PM2.5 and PM1 particles were identified.

Fig. 10–12 present courses of the coefficient of imission models of PM2.5 and PM1 particles and the average value of those coefficients during tests. There is a visible regularity involving that in cold months coefficients of imission models of fractions of PM2.5 and PM1 particles are greater than in warm months, which means a greater share of fine particles in cold months.

Fig. 13–15 present statistical characteristics of parameters of imission models of fractions of particulate matter. The variability coefficient and relation between the span and average value for coefficients of the models is considerably smaller than in the case of imission sets. The variability coefficient for coefficients of the models is (5 ÷ 20)%.

Average values of imission models of fractions of particulate matter were compared in Fig. 16–18. The determined average values of coefficients of imission models of PM2.5 and PM1 particles are within normal limits found in literature [21, 22]. The results of identification of imission models of PM2.5 and PM1 particles cannot be interpreted unambiguously and one may even say that they are puzzling. The values of coefficients of models for Zvonařka and Lány stations are similar, especially for models of imission of PM2.5 particles and model (3) of imission of PM1 particles. In the case of the model (2) of imission of PM1 particles, the difference of the model coefficient for Lány and Svatoplukova stations is even greater than for Zvonařka and Lány stations. One should expect similar values of model coefficients for Zvonařka and Svatoplukova stations or Svatoplukova and Lány stations, which results from conditions of location of the stations and, in particular, from traffic in the roads found in the vicinity of the stations.

4. Conclusions

Dusts constitute one of most severe hazards for the environment, especially in centers of large urban agglomerations. Evaluation of imission of particular fraction uses results of empirical tests carried out in air quality monitoring stations as well as results of modeling of imission of pollution. Testing of imission of particular fractions of dusts use emission models of PM10 particles that are constructed on the basis of structural similarity and models of distribution of pollution as well as imission models of PM2.5 and PM1 particles constructed on the basis of functional similarity.

Identification of functional imission models of PM2.5 and PM1 particles (as carried out on the basis of results of measurements of imissions of fractions of PM10, PM2.5 and PM1 particles in 2010 in three air quality monitoring stations in Brno as characterized by diversified sources of emission of pollution and distribution of pollution) made it possible to draw the following conclusions:

1. A strong correlation may be noticed between sets of imissions of particular fractions of particulate matter in all stations.
2. There is a strong relation between imission of fractions of particulate matter and seasons of the year: imission is much greater in cold seasons of the year.
3. There are also relations between imission of fractions of particulate matter and days of the week, which indicates a strong impact of civilization factors upon the imission.
4. There is a visible mutual relation between imission of particular fractions, which justifies adoption of linear models of imission of PM2.5 and PM1 particles.
5. There are great differences in extreme values of imissions of particular fractions, which is confirmed by great values of the variability coefficient and relation between the span and average value.
6. The determined average values of coefficients of imission models of PM2.5 and PM1 particles are within normal limits found in literature [21, 22].
7. There is a visible regularity involving that in cold months coefficients of imission models of fractions of PM2.5 and PM1 particles are greater than in warm months, which denotes a greater share of fine particles in cold months.
8. The results of identification of imission models of PM2.5 and PM1 particles cannot be interpreted unambiguously. No results were obtained indicating an impact of road traffic upon composition of size fractions of particulate matter.

The ambiguousness of results of identification of imission models of PM2.5 and PM1 particles indicates that it is necessary to treat this issue in a more comprehensive way. One may justify the expectation that on the basis of a larger set of result of empirical tests, which also include results from the stations located in other areas, it is possible to draw more unambiguous and general conclusions. Despite the partly critical evaluation of results of testing of imission models of PM2.5 and PM1 particles it may be stated that modeling of size fractions of particulate matter in accordance with the criterion of functional similarity is the only effective method of testing of hazards to the environment caused by dusts.

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Prof. Zdzisław CHŁOPEK
The Motor Transport Institute in Warsaw
ul. Jagiellońska 80, 03–301 Warsaw
E–mail: zdzislaw.chlopek@its.waw.pl