EXAMINATION OF A PARTICULATE MATTER PM10 IMMISSION MODEL IN THE ENVIRONMENT AROUND ROAD TRANSPORT ROUTES

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Summary

Behaviouristic models of the immission of particulate matter PM10 have been analysed in this paper. One-dimensional models based on an assumption of linear dependence of the particulate matter PM10 immission on the nitrogen dioxide and carbon monoxide immissions have been examined. Results of an empirical survey of pollutant immissions, carried out at the "Warszawa-Komunikacyjna" air quality monitoring station in Warsaw at Al. Niepodległości, have been used to identify the model coefficients. The model coefficients have been identified for sets covering the measurement results taken for the whole year and individual months. As a result of the examination carried out, strong correlation between the sets examined as well as significant non-repeatability of both the coefficients of correlation of the sets examined and the model coefficients have been revealed. It has been ascertained that the identification of behaviouristic models of the particulate matter PM10 immission must be statistically treated for the categories describing the properties of pollutant emission sources and the pollutant dissemination conditions.

Keywords: motorisation, particulate matter, PM10, modelling, immission.

1. Introduction

If remedial actions are required due to negative air quality assessment, this is most frequently caused by excessive concentrations of particulate matter PM10, especially in the central parts of cities. The air quality is assessed on the grounds of pollutant immissions, i.e. concentrations of pollutants dispersed in to the air at a height of 1.5 m, averaged for periods as specified in the appropriate regulations [20]. There are only few cases where the PM10 immission, like the immission of other pollutants, may be empirically determined. In all the other situations, the PM10 immission must be assessed by modelling the pollutant emissions and dissemination.

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There are many dust emission sources [5–11, 13–16, 20, 23]. Natural emission sources are connected with e.g. processes taking place involving sedimentary materials, volcano eruptions, or fires. The anthropogenic causes include all the activities of civilisation, in particular industry, power generation, and transport. In cities, the particulate matter emissions are chiefly caused by motor transport.

The parameters employed at modelling the emission of particular matter from the sources related to motor transport include quantities describing the quality of road surface, vehicle mass, number of road wheels, and, in some cases, the number of days with precipitations. In other models, the average vehicle speed is also taken into account. The models listed here are built in accordance with the criterion of structural (morphological) similarity [4]. Such models have been developed, *inter alia*, at the US EPA (Environmental Protection Agency) [14÷16] and Ingenieurbüro Lohmeyer GmbH & Co. KG–Karlsruhe und Dresden [21]. The generalisation of the theory of models of the PM10 emission from motor traffic sources, for the models developed in accordance with the criterion of structural similarity, may be found in [5÷9, 23]. It is typical of the models of this type that they have a complicated structure and, in consequence, the identification of many parameters of such models is very difficult.

Another available method to assess the hazard of environmental pollution caused by particulate matter PM10 is the employment of the PM10 immission models built in accordance with the criterion of functional similarity (behaviouristic models) [4]. Although the pollutant immission is actually modelled in this case, these models are traditionally classified in the category of emission models. The behaviouristic models of the PM10 imission are built with employing a correlation dependence of the PM10 immission on the nitrogen oxides and carbon monoxide immissions, postulated as linear based on the results of empirical surveys [1÷3, 10, 12, 17, 18, 22, 23]. The parameters of behaviouristic models of particulate matter imission depend on the types of pollutant emission sources and on pollutant dissemination conditions [1÷3, 10, 12, 17, 18, 22, 23]; however, there is a possibility of effective assessment of the PM10 immission in conditions comparable with those of the empirical survey used for model identification [10].

In this study, behaviouristic models of the PM10 immission were analysed. For this purpose, results of an empirical survey carried out at the "Warszawa–Komunikacyjna" air quality monitoring station situated in Warsaw at Al. Niepodległości were used. The linear one–dimensional models of the PM10 immission were identified with taking as a basis the results of measurements carried out in 2009 for the whole year and for individual months of the year.

2. Behaviouristic models of the immission of particulate matter PM10

For the modelling of the PM10 immission, the functional dependencies observed of the immission of various types of air pollutants may be used. In most cases, the functional dependencies of the PM10 immission on the immission of nitrogen oxides, reduced to nitrogen dioxide, and on the immission of carbon monoxide are used. Within the scope of the particulate matter emitted from motor traffic sources, such dependencies may be physically explained. An increase in the intensity of the emission of nitrogen oxides from internal combustion (IC) engines is a result of an increase in engine load and this occurs at higher vehicle speeds and load mass values. It is known from empirical surveys and from the examination of structural models of the PM10 emission that higher vehicle speeds and loads cause increased PM10 emissions not only from the IC engine but also from other motor traffic sources. Similarly, heavy loads of the IC engine are accompanied by high intensity of the emission of carbon monoxide. The immission of pollutants is operationally related to the intensity of emission of the pollutants involved; it may be assumed, however, that the averaged values of the immission and the intensity of emission may be treated as functionally depending on each other [10, 11].

In general, the model of the immission of particulate matter PM10 coming from road transport has been assumed to have the following form:

$$I_{PM10} = f(I_{NOx}, I_{CO}) \tag{1}$$

where:

I_{PM10} – immission of particulate matter PM10;
I_{NOx} – immission of nitrogen oxides NOx;
I_{CO} – immission of carbon monoxide CO.

This function meets conditions (2) within the range of the immission values that are consistent with the values obtained from the empirical survey and used for model identification purposes.

$$\frac{\partial I_{PM10}}{\partial I_{NOx}} > 0; \qquad \frac{\partial I_{PM10}}{\partial I_{CO}} > 0 \tag{2}$$

Predominantly, the PM10 immission models are assumed as linear in relation to the immissions of nitrogen oxides and carbon monoxide:

$$I_{PM10} = a_0 + a_1 \cdot I_{NOx} \tag{3}$$

$$I_{PM10} = a_0 + a_1 \cdot I_{CO} \tag{4}$$

It is also possible to assume non-linear models of the PM10 immission, in most cases in the form of a polynomial function of the second degree:

$$I_{PM10} = a_0 + a_1 \cdot I_{NOx} + a_2 \cdot I_{CO} + a_3 \cdot I_{NOx}^{2} + a_4 \cdot I_{CO}^{2} + a_5 \cdot I_{NOx} \cdot I_{CO} \tag{5}$$

The identification of behaviouristic models of the PM10 immission indicates a significant dependence of model parameters on the properties of pollutant emission sources and on the pollutant dissemination conditions [10]. It is common for the models may significantly differ from each other for areas of different vehicle traffic intensity [10].

According to most sources, the correlation between the PM10 and carbon monoxide immissions exceeds that observed between the PM10 and nitrogen oxides immissions [10, 24]. In spite of this, the nitrogen oxides immission is more commonly used for the construction of PM10 immission models [1÷3, 12, 13, 17, 18, 22].

3. Identification of behaviouristic models of the PM10 immission

To identify the linear models of the PM10 immission (3 and 4), the results of an empirical survey carried out at the "Warszawa–Komunikacyjna" air quality monitoring station in 2009 were used. The model according to formula (3) was modified in the survey by adopting nitrogen dioxide as a measure of nitrogen oxides. The reduction of nitrogen oxides to nitrogen dioxide is not a singular operation because the reactions of conversion of nitrogen oxides into nitrogen dioxide depend on many factors, including complex photochemical phenomena. In this connection, a decision was taken to identify the following model:

$$I_{PM10} = a_0 + a_1 \cdot I_{NO2} \tag{6}$$

The source results of the pollutant immission survey have the form of values averaged for a period of 1 hour. They were subjected to preliminary processing to search for gross errors and fill in any gaps in data. To complete the data results, a Savitzky–Golay filter [21] was used, with the approximation of five points by a quadratic function. The same filter was used to reduce the share of high-frequency noise in the signal.

The the process of the PM10, nitrogen dioxide, and carbon monoxide immissions have been shown in Figs. 1÷3.

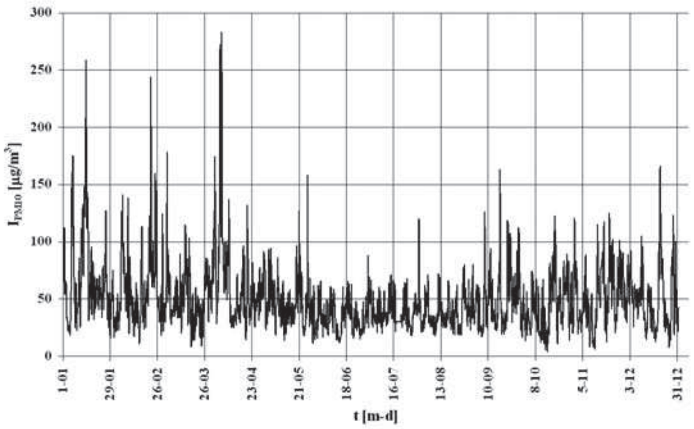

Fig. 1. The process of the particulate matter immission I_{PM10}.

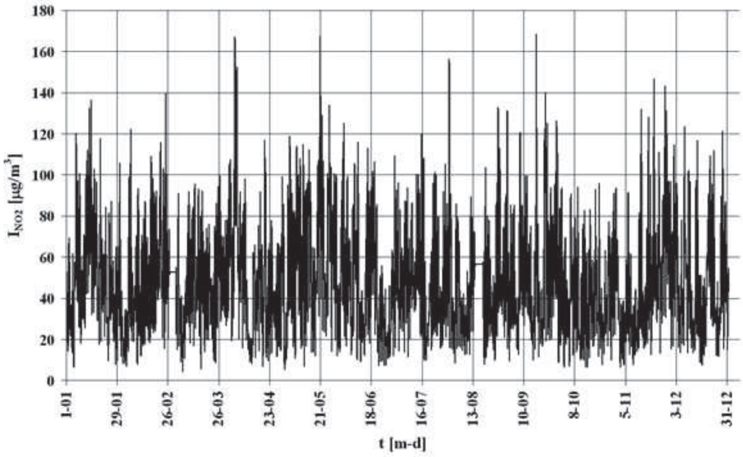

Fig. 2. The process of the nitrogen dioxide immission I_{NO2}.

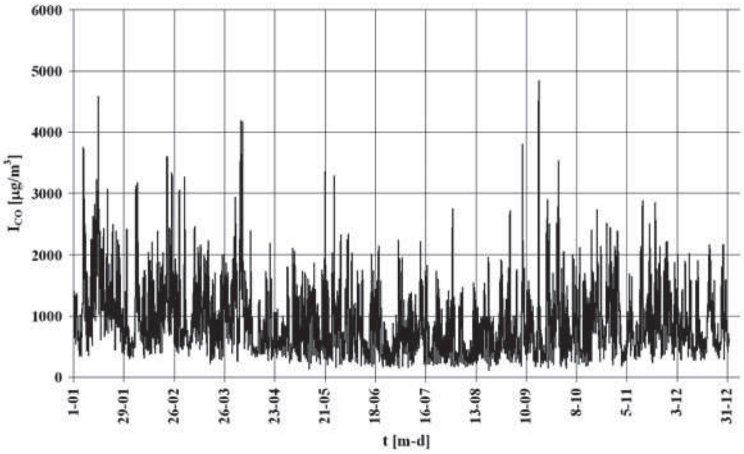

Fig. 3. The process of the carbon monoxide immission I_{CO}.

The correlation dependencies of the particulate matter immission on the nitrogen dioxide and carbon monoxide immissions have been shown in Figs. 4 and 5, respectively.

The sets under examination are strongly correlated with each other. For the set of the PM10 and nitrogen dioxide immissions and the set of the PM10 and carbon monoxide immissions, the Pearson correlation coefficient is equal to 0.5919 and 0.7918, respectively. For both cases, the probability that the hypothesis of absence of linear correlation will not be rejected is below 1×10^{-5}.

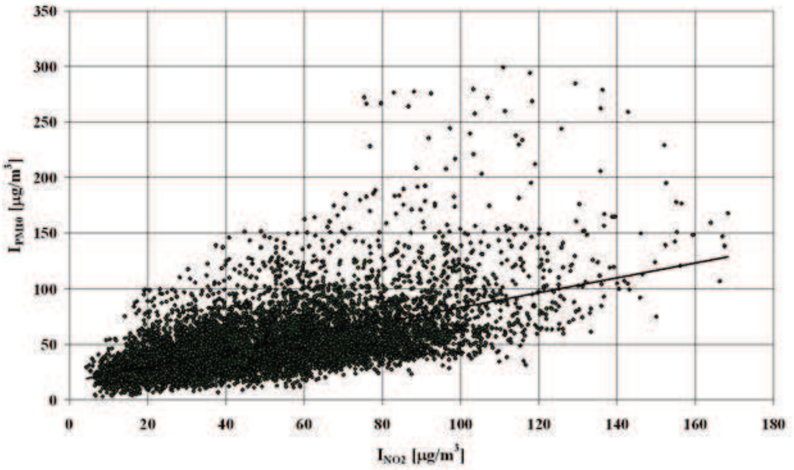

Fig. 4. Correlation dependence of the particulate matter immission I_{PM10} on the nitrogen dioxide immission I_{NO2}.

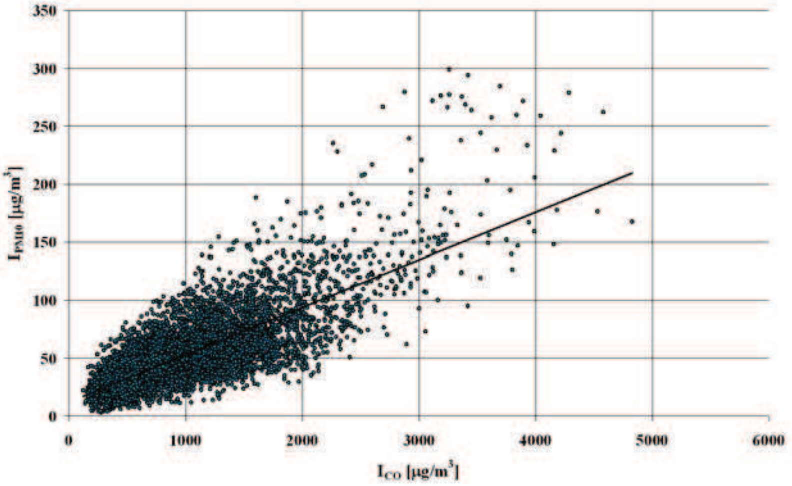

Fig. 5. Correlation dependence of the particulate matter immission I_{PM10} on the carbon monoxide immission I_{CO}.

The identified models for the period covering the year 2009 have the following form:

$$I_{PM10} = 16.43 + 0.668 \cdot I_{NO2} \tag{7}$$

$$I_{PM10} = 12.24 + 0.0401 \cdot I_{CO} \tag{8}$$

where: IPM10 [μg/m³], INO2 [μg/m³], and ICO [μg/m³].

The models were also identified for individual months. This study was carried out to assess the non-repeatability of model parameters and the impact of individual seasons on the models.

Examples of the process of the PM10, nitrogen dioxides, and carbon monoxide immissions and correlation dependencies of the sets under examination for January 2009 have been presented in Figs. 6÷10.

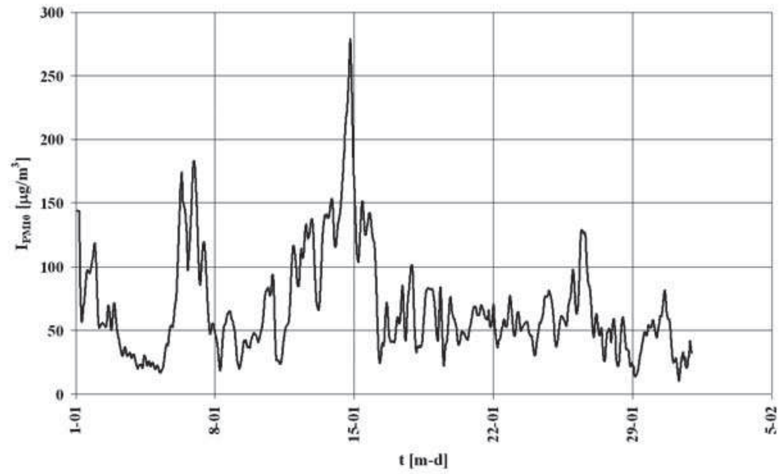

Fig. 6. The process of the particulate matter immission I_{PM10} in January.

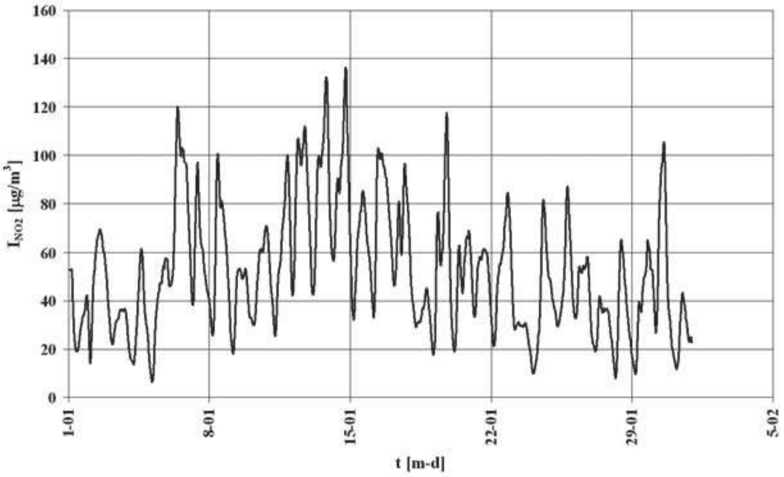

Fig. 7. The process of the nitrogen dioxide immission I_{NO2}. in January.

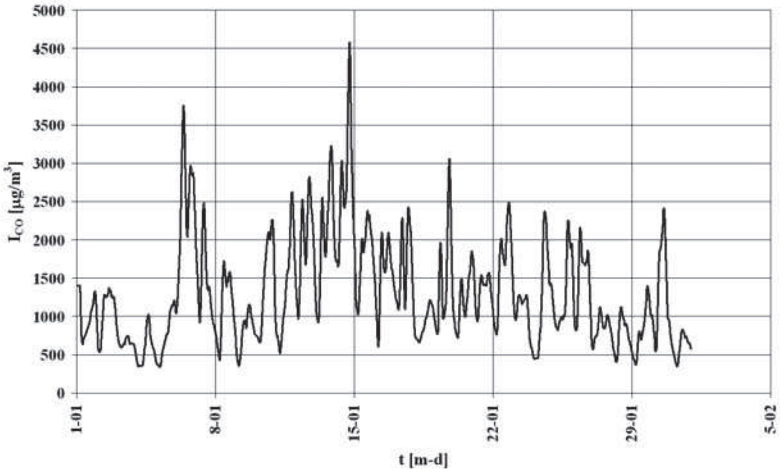

Fig. 8. The process of the carbon monoxide immission I_{CO} in January.

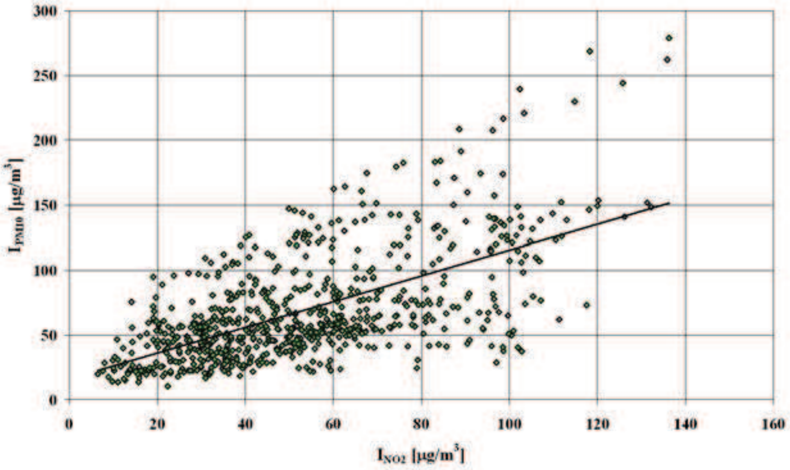

Fig. 9. Correlation dependence of the particulate matter immission I_{PM10} on the nitrogen dioxide immission I_{NO2}. in January.

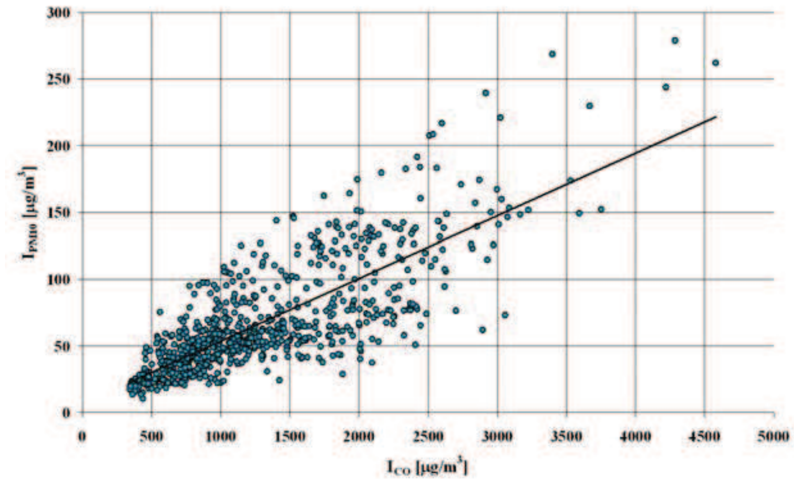

Fig. 10. Correlation dependence of the particulate matter immission I_{PM10} on the carbon monoxide immission I_{CO}. in January.

The Pearson correlation coefficient for the set of the PM10 and nitrogen dioxide immissions and the set of the PM10 and carbon monoxide immissions as determined for 2009 as a whole and for individual months of that year, together with the average value and standard deviation for the corresponding sets of the coefficient values in individual months have been presented in Figs. 11 and 12, respectively.

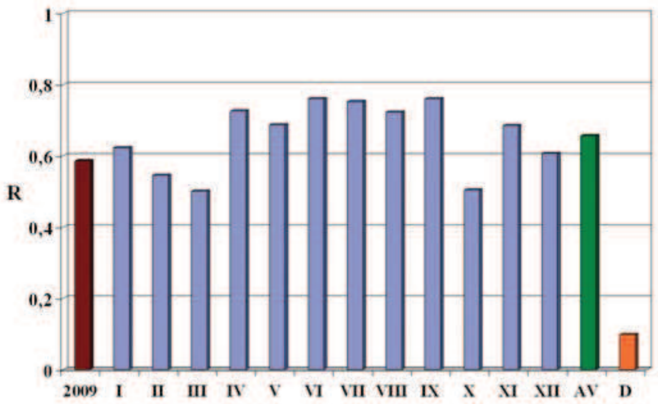

Fig. 11. Values of the Pearson correlation coefficient (R) for the set of the PM10 and nitrogen dioxide immissions in 2009 as a whole and in individual months of that year, together with the average value (AV) and standard deviation (D) for the set of the coefficient values in individual months.

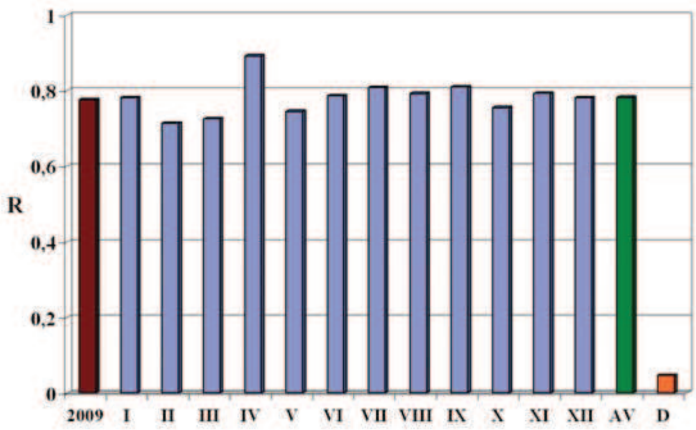

Fig. 12. Values of the Pearson correlation coefficient (R) for the set of the PM10 and carbon monoxide immissions in 2009 as a whole and in individual months of that year, together with the average value (AV) and standard deviation (D) for the set of the coefficient values in individual months.

For all the cases under consideration, the probability that the hypothesis of absence of linear correlation will not be rejected is below 1×10^{-5}.

The results of the correlation analysis for individual months have confirmed previous results, according to which the correlation between the PM10 and carbon monoxide immissions is stronger than that between the immissions of PM10 and nitrogen oxides (or nitrogen dioxide, as it is in this case). The non-repeatability of the correlation coefficient between the PM10 and carbon monoxide immissions is also significantly lower than that observed between the PM10 and nitrogen dioxide immissions.

The coefficient of variation of the correlation coefficient for the sets of immissions in individual months is:

- 0.1490 for the sets of immissions of PM10 and nitrogen dioxide;
- 0.0595 for the sets of immissions of PM10 and carbon monoxide.

For the sets of immissions of particulate matter PM10 and nitrogen dioxide, it can be observed that the higher values of the correlation coefficient occur in warmer months. However, this observation based on an analysis carried out for one year does not provide sufficient grounds for the generalisation of such a conclusion, all the more so because this trend has not been confirmed in the case of the sets of the PM10 and carbon monoxide immissions.

The model coefficient values for the models of the PM10 immission, determined for 2009 as a whole and for individual months of that year, together with the average value and standard deviation for the corresponding sets of the coefficient values in individual months have been presented in Figs. 13÷16.

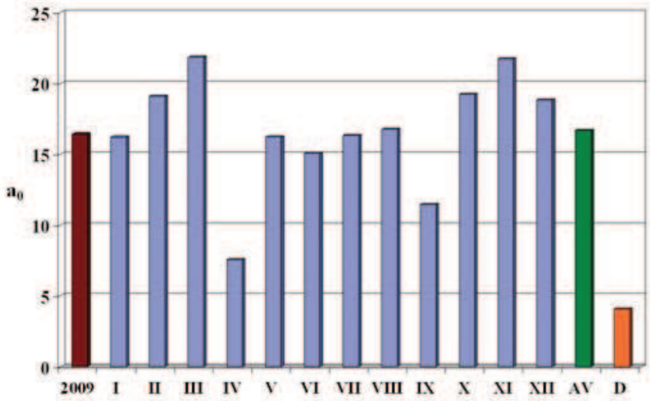

Fig. 13. Values of the coefficient a_0 of model (6) in 2009 as a whole and in individual months of that year, together with the average value (AV) and standard deviation (D) for the set of the coefficient values in individual months.

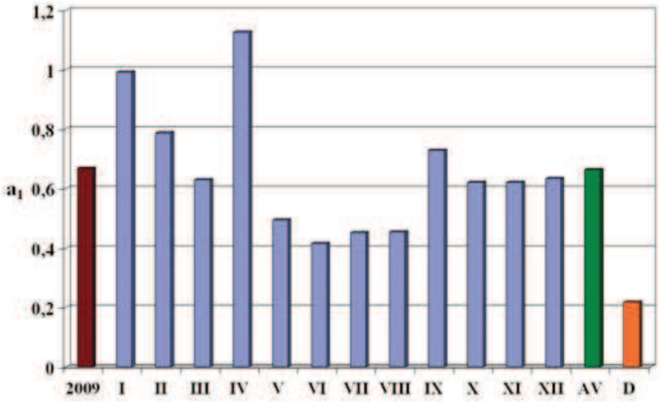

Fig. 14. Values of the coefficient a_1 of model (6) in 2009 as a whole and in individual months of that year, together with the average value (AV) and standard deviation (D) for the set of the coefficient values in individual months.

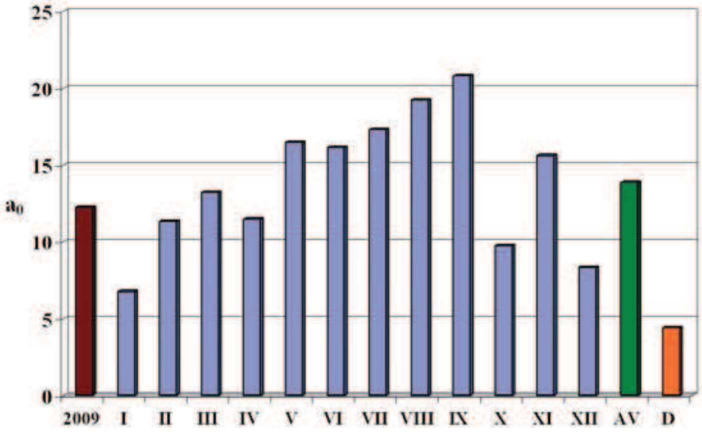

Fig. 15. Values of the coefficient a_0 of model (4) in 2009 as a whole and in individual months of that year, together with the average value (AV) and standard deviation (D) for the set of the coefficient values in individual months.

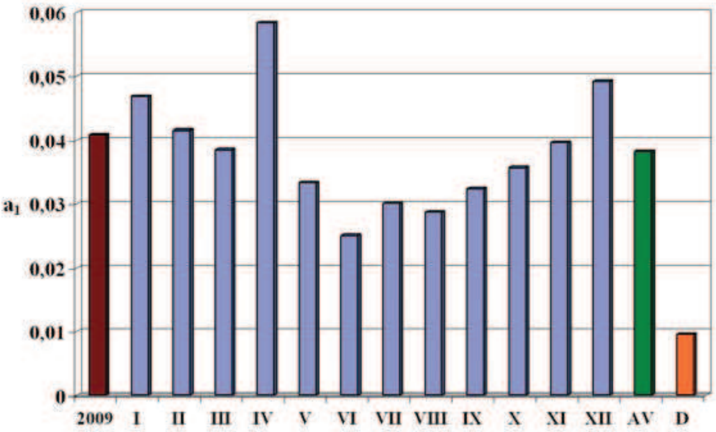

Fig. 16. Values of the coefficient a_1 of model (4) in 2009 as a whole and in individual months of that year, together with the average value (AV) and standard deviation (D) for the set of the coefficient values in individual months.

An analysis of the coefficients of the PM10 immission models has revealed that the coefficients show significant irregularity in the time domain.

The coefficient of variation of the model coefficients for the sets of immissions in individual months is:

- 0.2443 for a_0 and 0.3293 for a1, for the sets of immissions of PM10 and nitrogen dioxide;
- 0.3181 for a_0 and 0.2502 for a1, for the sets of immissions of PM10 and carbon monoxide.

The results of analysis of the behaviouristic models of the PM10 immission have confirmed the necessity ascertained, *inter alia*, in [10] for the identification of these models being treated statistically.

4. Recapitulation

The significant difficulties encountered at the identification of the particulate matter PM10 emission models based on structural similarity induce the searching for other possibilities to assess the environmental hazard caused by dust. Such a possibility is offered, *inter alia*, by the employment of models based on functional similarity. The models of this type describe the immission of particulate matter PM10. Alas, serious problems arise in this case as well, because the model parameters are highly sensitive to the properties of pollutant emission sources and to the pollutant dissemination conditions. In this study, an attempt was made to assess the sensibility of linear one-dimensional models of the PM10 immission to the properties of pollutant emission sources and to the pollutant dissemination conditions. Results of the identification of models in various periods, i.e. during a whole year and in individual months of the year, were used for this purpose.

The following conclusions may be formulated, based on the research carried out:

1. The correlation between the PM10 and carbon monoxide immissions and between the PM10 and nitrogen dioxide immissions is very strong. It has been ascertained that the probability that the hypothesis of absence of linear correlation will not be rejected is below 1×10^{-5} for all the pollutant immission sets under consideration.
2. The regularity observed previously that the correlation between the PM10 and carbon monoxide immissions is stronger than that between the PM10 and nitrogen dioxide immissions has been confirmed.
3. The correlation coefficient showed significant non-repeatability for the pollutant immission sets under consideration for various months of 2009. If we measure the non-repeatability by the coefficient of variation then we may state that the correlation coefficient showed much higher non-repeatability for the sets of the PM10 and nitrogen dioxide immissions.
4. The non-repeatability of coefficients of the models identified for various months of 2009 should be assessed as high. In this respect, no fundamental difference was found to exist between the models where the carbon monoxide or nitrogen dioxide immissions were employed.

The results obtained for the PM10 immission models based on functional similarity confirm high sensitivity of the model coefficients to the properties of pollutant emission sources and to the pollutant dissemination conditions. This justifies the advisability of statistical approach to the model identification task for arbitrarily assumed categories of the quantities that describe the properties of pollutant emission sources and the pollutant dissemination conditions. The choice of the number of these categories is a matter of compromise. The employment of a higher number of the categories makes it possible to achieve better conformity of the models with the phenomena modelled. Simultaneously, an increase in the number of categories requires more labour to be spent and sometimes causes problems with the classifying of an existing situation in a specific category and this in practice may become a serious difficulty.

Although the conclusion is partly critical of the method, the modelling of immission of particulate matter PM10 should be considered an effective method of assessment of the environmental hazard caused by dust, especially where mass surveys preventing the carrying out of empirical tests are involved.

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