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THE PECULARITIES OF FINE PARTICLES DISPERSION OVER THE ROADSIDE

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Abstract. On the ground of physical model mathematical distribution was written down for determining the pollutant dispersion peculiarities in the freeway. The correlation of Lithuanian and foreign studies of ultrafine particles and transition-metal measurements data was used for the reasoning of model. It was defined that the deposition rate of fine particles and aerosols, which are transporting metals is the same approx 2 cm/sec in the distance of more than 60 m from the road. It means that ultrafine particles due to the moisture, precipitation, wind and coagulation in the natural geographic environment has about 100 times higher deposition rate, than it should be according to its diameter. Considering the peculiarities of the model applied, pollutant concentration above the ground surface in the mentioned above distance from the road could be decreased by the same means as in the vicinity of the freeway: planting high impervious belts of trees and bushes.

Keywords: fine particles, distribution, freeway.

1. Introduction

High traffic flow creates a negative impact on the environment due to the generated dust spread into the environment. The composition of dust is very different. The main mass of dust is composed of carbon monoxide, particles of organic origin and nitrogen oxide. Also, dust is composed of particulate matter, mostly of black carbon, and particles generated by the roadway structure are dispersed into the atmosphere.

Pollutants emitted from a motor deposite into the environment, effects it and usually no proportional to their relative mass. Not mentioning the hazardous for human health and environment toxic substances, which are present in the dust, and the other ones which are less toxic or non toxic, but being ultrafine (less than 0,1 µm of diameter), have been regarded as a possible agent increasing the negative impact on humans health of all pollutants [1, 2]. Therein lays the importance of the study of ultrafine particles spreading into the freeway environment.

Major attention in the research literature is dedicated to the distribution of the particulates into the roadside at the distance of 50–60 m on both sides, where the main part of the particulates is deposited [3, 4].

The quantitative measurements of pollutant emitted from the vehicle engines shows that the major concentration of aerosols is 1 m away from the driving part and in the distance of 2 m decreases by 25 % due to the larger than 0,4 to 10,0 µm diameter particles [5].

The major part of fine and ultrafine particles is deposited also in the zone mentioned above, but relatively large part of them is spread far away into the environment at the distance of 300 m [4, 6]. The problems arise from the measurements of the particulate matter are related to the precision of the low mass measurements, including relief peculiarities and weather conditions. The results and methodology of similar measurements performed in France are described in [4]. In both studies the quantity of pollutant was measured in the air. But fine particles were measured in work [4] and ultrafine particles – in [6].

In work [4] the dispersion of transition-metals into the roadside was measured as particles of diameter more than 100 µm and associated with aerosols of diameter less than 100 µm are dispersed. These “dusts” produced by vehicles are dispersed into the atmosphere and (90 %) being spread by airborne dispersal and the rest (10 %) remains on pavement. Graphical charts of lead flux and zinc flux evolution deposits with respect to the distance from the roadway are similar to the results presented in [6] by the character and the proportions of the pollutant in the points dependent on the distance to the roadway. For the ground of model data of the work [6] was chosen, for the reason that the several measurements were performed in the same point. Therefore the errors of the measurements are statistical (not instrumental). The errors are larger, but they show the conditions of the measurements.

Including plenty of measurements in selected points and reliability of data, the processes determining the dispersion of particles defined by measurements are tried to explain in this work. This problem is solved by the application of physical model for particles dispersion in the freeway environment, and on the basis of it is composed the descriptive distribution of particles dispersion.

2. Objectives

The purpose of this work is to study the peculiarities of fine particles dispersion over the roadside by a mathematical statistical model and to make practical conclusions.

3. Methods

As it was mentioned above, the model was created on the basis of data [6] and the results of the topsoil pollution along the motorway Vilnius–Panevėžys (in Lithuania) study performed by the author of this work was used to compensate the inaccuracy and laxity of the data.

Such simplified model is required because the modelling of the mathematical expression on the ground of the differential equations, assuming that gas is ideal and particles are spherical, does not give positive results, though the results obtained this way are usually published. The data of particle deposition rate sometimes differ in several deep from theoretical one, which was obtained by the direct measurements in USA and Sweden [7]. It happens because of the complicated connection of the processes occurring in the nature and it indicates the sensitive interdependence of differential equations parameters. It is particularly well-defined for the particles of low density material, when the alteration of even insignificant equation parameter changes the result in series and modelling becomes impossible.

Whereas the ground of all further conclusions is a probability model [8], we will present it and shortly explain it once more (again).

Particles less than 0,1 μm of diameter, which compose only (1–8) % of pollutants, were measured in [6] and the main attention was paid to the quality of measurements, including selection of measuring methods, instrumental peculiarities of measurements technologies. Using even several parallel measuring methods, after summarising measurement results, concentrations of ultra fine particles were defined – carbon monoxide (CO), black carbon (BC) and all emitted particles mass concentration (MC) in selected points at the distance from the road centre 30 (15 m from the roadside), 60, 90, 150 and 300 m downwind, when the wind velocity is 1 and 2,5 m/sec. At both wind velocities when the distance from the road x_{max} = 300 m, the pollution is not noticeable and it is an important point of this model.

Model of fine particles dispersal when a crosswind was blowing was created by immediate observations of a dust whirl formed behind the driven car.

When the wind is absent, the cylindrical whirl of dust immediately changes into a cylindrical shape with cut-off by the ground dust cloud. When the small wind is blowing perpendicularly to the freeway, the cloud moves downwind and dust settles on the ground surface. The model described above is shown in Fig 1. Let's say that fine particles in the cloud formed on the road are spread constantly and the wind blows perpendicularly to the freeway at velocity v_x .

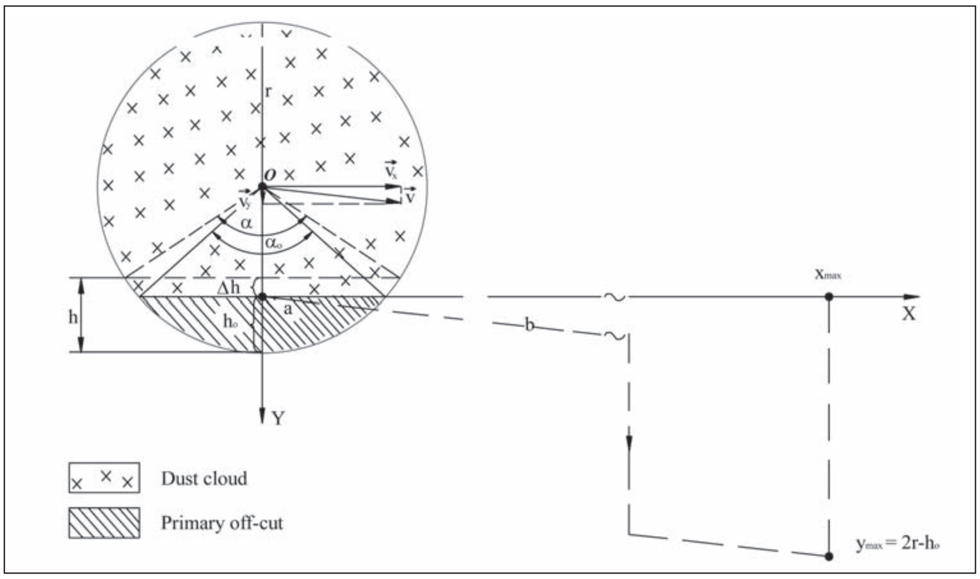

Fig 1. Cylindrical shape whirl of dust with cut-off model

The centre of the cylinder clouds *O* moves at the velocity v parallel to the movement direction of the point *a* equally falling at the velocity v_y. The height of the cut-off rises while the cloud is spreading and the point *a*, which describes the height of the primary cut-off, moves by the dotted line b parallel to the cloud centre point *O*. Its shift downwards

$$\Delta h = \frac{v_y}{v_x} \cdot x \text{ and } \frac{v_y}{v_x} = \frac{2r - h_0}{x_{\max}}. \quad (1)$$

The mass of the settled particles is a value equal to the mass in cut-off alteration in volume limited by the height Δh.

Taking along the road the unit length of the dust cloud gets the distribution of fine particles correspondent to their model of spread. Then the volume of this part of the cloud is digitally equal to the area with cut-off of the circle (further we will use this consideration):

$$S_0 = \pi r^2 \left(1 - \frac{\alpha_0}{2\pi}\right) + \frac{r^2}{2} \sin \alpha_0. \quad (2)$$

It is a normalisation factor *A* in the probability distribution function:

$$F(\alpha) = \frac{1}{A} S(\alpha) \Big|_{\alpha_0}^{\alpha} = \frac{\alpha - \sin \alpha}{2\pi - \alpha_0 + \sin \alpha_0} \Big|_{\alpha_0}^{\alpha}, \quad (3)$$

where $S(\alpha)$ – area of the cut-off, which corresponds to the central angle $\alpha(rad)$. From (3) we find the probability density function:

$$f(\alpha) = \frac{dF(\alpha)}{d\alpha} = \frac{1 - \cos \alpha}{2\pi - \alpha_0 + \sin \alpha_0}. \quad (4)$$

In theses expressions $\alpha_0 \le \alpha \le 2\pi$.

From the figure we find out that

$$h = h_0 + \Delta h = h_0 + \frac{v_y}{v_x} \cdot x, \quad (5)$$

$$h = r\left(1 - \cos \frac{\alpha}{2}\right). \quad (6)$$

From these equations follows the relation between angle α and axis *x* and vice versa:

$$x = \frac{v_x}{v_y} \left[r\left(1 - \cos \tfrac{\alpha}{2}\right) - h_0 \right], \quad (7)$$

$$\cos \tfrac{\alpha}{2} = 1 - \frac{1}{r} \left(h_0 + \frac{v_y}{v_x} x \right). \quad (8)$$

Including the result (1),

$$x = \frac{x_{\max}}{1 + \cos \frac{\alpha_0}{2}} \left(\cos \tfrac{\alpha_0}{2} - \cos \tfrac{\alpha}{2} \right) \quad (9)$$

and

$$\cos \frac{\alpha}{2} = \cos \frac{\alpha_0}{2} - \frac{x}{x_{\max}} \left(1 + \cos \frac{\alpha_0}{2} \right). \quad (10)$$

4. Evaluation of the model

The propriety of the distribution of particles concentrations model was studied on the basis of regression equation of probability density function (4). By variation of α_0, it was tried to find the best congruence of normalised probability density and experimental data. The point of reference was taken the distance larger than 30 m from the freeway (as it is done in [6]), because of the exceptionally big dispersion of measurement data at the distance of 30 m (Table 1). We count that the reason of big dispersion of data is not only the wind, but also transport, especially the heavy one, causes airflows.

The good result was obtained by subtraction of background values and by normalising (equate to one) in point of concentration values at the distance of 90 m for CO, BC and MC in all points further than 60 m (Fig 2).

It is clearly seen that all measured pollutants of the decrease of normalised concentrations correlate depending on the distance from the road and it correlates to the data of the [4] as well. But a indeterminacy of mass concentration study remains, because of a large distribution of the measurements data in all points.

The dispersion of a pollutant depends on the climatie conditions: temperature, air moisture, precipitation etc. Because the data of works [4] and [6] correlate, we measured heavy metal concentrations in soil samples for the purpose of modelling, which were collected along the motorway Vilnius–Panevėžys (in Lithuania) and the profile contained 17 samples [9]. The distances between the samples along the transect were 1 m, 2 m, 5 m, 10 m, 25 m, 50 m, 75 m and 100 m. The quantities of Zn, Cr, Ni, Cu, Pb, Mn were obtained using the atomic absorption spectroscopy (AAS Buck 210 VGP) method at the laboratory of Environmental Protection Dept of Vilnius Gediminas Technical University. The soil sample analysis was performed following the standard procedure for AAS method ISO 11047:1998. For the evaluation of model propriety the total contamination index Z_s was used. The index reflects the risk of the soil contamination [10].

The total contamination index Z_s was calculated by formula:

$$Z_s = \sum C_{ci} - (n - 1), \quad (11)$$

where *n* is the number of elements; C_c – the concentration coefficient of the element.

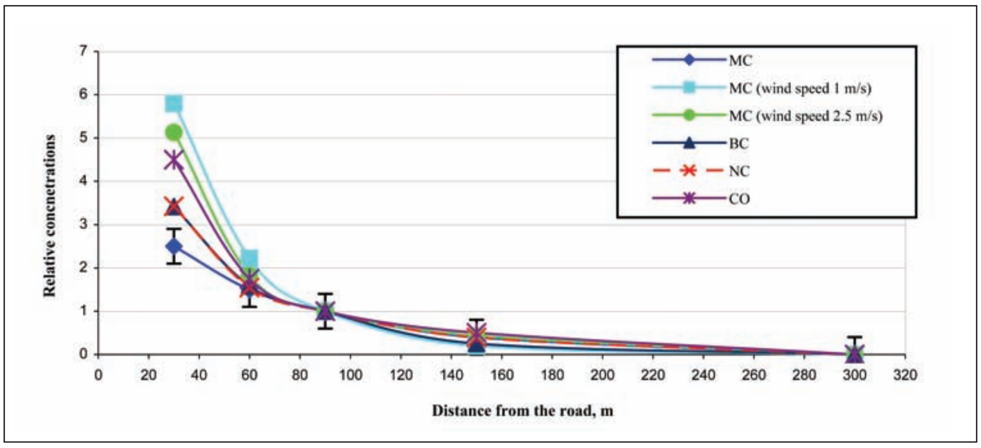

Fig 2. Pollutants dependency on the normalised concentration of the distance from the road, according to [6]

Table 1. Measured average concentrations at increasing distances from the freeway [6]

Measurement	Downwind Distance (m)				
	30	60	90	150	300
Carbon monoxide (CO) (ppm)	2,0 (1,7–2,2)	0,9 (0,7–1,0)	0,6 (0,5-0,7)	0,4 (0,3–0,5)	0,2 (0,1–0,3)
Black carbon (BC) (μg/m³)	5,4 (3,4–10,0)	3,2 (3,0–3,5)	2,5 (2,4-2,6)	1,6 (1,1–2,0)	1,3 (1,1–1,5)
Number concentration (NC) (x10⁻⁵/cm³)	1,5 (1,3–1,7)	0,88 (0,77–0,96)	0,7 (0,61-0,85)	0,5 (0,42–0,58)	0,37 (0,30–0,39)
Mass concentration (MC) (μg/m³)	49,0 (30,2–64,6)	48,0 (37,1–55,0)	47,5 (29,5-63,4)	46,9 (30,1–65,5)	46,5 (30,0–58,9)

The concentration coefficients were calculated:

$$C_c = C_i / C_f, \tag{12}$$

where C_i – the concentration of i element in a sample; C_f – the background value of i element.

The background value for the sandy loamy soil was taken from the Hygiene Norm HN 60:2004 "Maximum permitted and temporarily permitted concentration in soil". For heavy metals they are the following: Cu – 8,1; Cr – 30,0; Zn – 26,0; Mn – 427,0; Ni – 12,0, and Pb – 15,0 mg/kg.

The total contamination index is presented in Table 2. The average motor transport speed in this part of the road is 90 km/h and the average volume of the traffic is 4500 cars per day of all types of vehicles. For expression the approximation of the total index experimental data and pollutants dispersion near the road the following equation has been chosen:

$$Z_s(x) = a \cdot x^b \cdot e^{-c \cdot x} , \tag{13}$$

where a, b, c are coefficients deduced by solving regression equation using the DataFit – 6.1.10 application: a = 5,87, b = –0,54, c = 0,002.

Total contamination index Z_s was normalised in the point of 90 m from the road in all sampling points. The approximation of Z_s and MC showed the same tendency of concentrations dependence on the distance from the road (Fig 3). Applying the statistical model (4) with an experiment (Fig 3), the correlation of the curves becomes better by increasing the angle α_0 and at the α_0 = 4,80 rad a relatively good (R^2 = 0,69) congruence of mass concentration MC is obtained (Fig 4) in the points further than 60 m. This α_0 value is a good match for the dust cloud shape of immediate observations. Futhermore, normalising the data in the point of 60 m, the worse correlation (R^2 = 0,46) of experimental and model data was obtained.

The reason of it, as a clear difference between experimental and regression equations values in the distance less than 60 m is, that obviously not all particles float up into the described above cloud of particles. The marked part of particles is distributed into the vicinity road ambience not only under the influence of side-wind but also by the airflows caused by transport.

Table 2. Values of the total contamination index Z_s

	Downwind distance (m)							
Value	0	10	20	25	35	60	85	100
Total contamination index Z_s	6,0	2,0	1,2	1,0	0,8	0,7	0,5	0,4

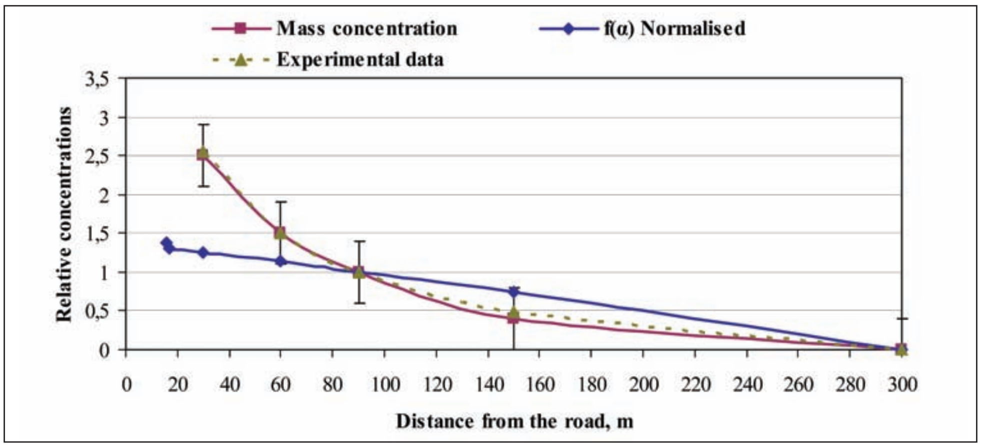

Fig 3. Mass concentration, normalised function and experimental model curves

The measurements data [6] presented for the comparison, when the wind speed is 1 m/s and 2,5 m/s shows that the distribution of the particles concentrations varies slightly and there is no change of concentration in the distance of 300 m and this fact was used in the model.

It means that the wind speed in our model changes by just α_0 value.

Let us assume that mass concentration and probability density function, which was normalized in the point of 90 m (Fig 3), correlates in the margins of the errors in the distance of 60 to 300 m from the road. The conclusion of the efficient dispersal of particles into the roadside follows.

At the wind speed $v_x = 2$ m/sec cloud of particles during the time $t = 150$ sec reach the margin of $x_{max} = 300$ m. Assuming that the cloud of a cylindrical shape with cut-off formed on the road reaches the margins of the road r = 15 m [6], and the height (according to the various studies in the freeways) is less than 6 m, at the particles deposition rate of v_y = 2,6 cm/sec, we get $h_{01} = 3{,}9$ m and it coincides with $\alpha_{01} = 4{,}80$ radian. We will get the same results, when the wind speed $v_x = 1{,}0$ m/sec and v_y = 1,3 m/sec, $h_{02} = 3{,}9$ m and $\alpha_{02} = 4{,}80$ radian. In both cases the particle deposition rate coincides with the average pollutant particle size deposition rate. The fine particles deposition rate, which was measured by experiment, is presented in Table 3. Putting down the parameter h_0 and α_0 for a formula (3) and (5) we get the graphic view of the probability distribution F(α) and the height of dust cloud above the ground surface (Fig 4).

Due to the approximate regular intervariation receding from the road (Fig 2), the obtained results could be applied for the CO gas, BC, particle concentration and particles less than 0,1 μm of the total mass.

From the similarity of Fig 2 and Fig 3 the possibility

Table 3. The comparison of the particles deposition rate and the lifetime (dependent on the diameter of particles) [7]

Diameter of particle, μm	0,1–1	2	4	6	8	10	15	20
Deposition rate, cm/sec	0,026	0,1	0,38	0,88	1,6	2,7	6,0	10
Lifetime, days	220	58	15	6,6	3,6	2,1	0,96	0,58

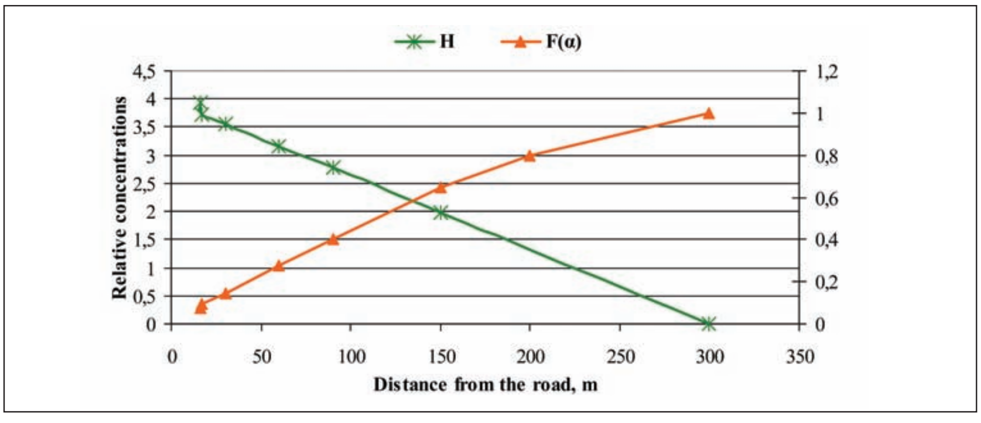

Fig 4. The graphical view of the alteration of the height of pollutant cloud ($H(x) = 2R - h$) receding from the freeway above the ground surface and the probability distribution function $F(x)$

to apply these consistent patterns for the dispersion of the aerosols, which transport metals, ie for transitions metals occurs.

5. Conclusions

1. A good congruence of measurements data, which express the correlation of fine particles and heavy metal concentrations with probability density function, normalised in the point of 90 m from the road, was obtained in the distance larger than 60 m from the road.

2. Such congruence was obtained for fine particles at the same as for the aerosols deposition rate of 1,3 – 2,6 cm/sec, which is adequate (correspondent) for the average pollutant particle size deposition rate (Table 3).

3. The description is valid just for the part of particles, so from the probability distribution function the relative particle deposition in the distance of more than 60 m from the road could be defined.

4. Pollutant dispersion in the distance more than 60 m from the freeways could be decreased by the means of shields (screens) like the belts of impervious to wind trees or bushes, of the height is more than H(x) value.

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