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FINE PARTICLES SPREADING INTO THE ROADSIDE MODEL AND TYPICAL OF ITS DISTRIBUTION

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Abstract. Model of fine particles dispersion when crosswind is blowing is created on the ground of immediate observations of a whirl of dust formed behind a driven car. When the wind is absent, the cylindrical shape whirl of dust immediately changes into the cylindrical shape with a cut-off by the ground dust cloud. The properties of the distribution of particles concentrations model were studied on the basis of regression equation of probability density function. By variation of α_0, efforts were made to find the best congruence of normalised probability density and experimental data. For a practical implementation of the model it is important that the influence of the wind speed change in the distribution of the particles concentrations. A good congruence of regression equation and experimental data in the distances of more than 90 m from the road shows that, when the wind speed is low, the particles distribution scheme described in the model fits very well.

Keywords: fine particles, distribution, freeway.

1. Introduction

"Particulate matter" is the general term for a complex mixture of solid and liquid particles in the air. Its size in the air ranges from approx 0,005 to 100 µm in diameter. Fine particles are airborne particles with diameters of 2,5 microns or less. They can be directly released when coal, gasoline, diesel, other fossil fuels and wood are burned. Many particles are also formed in the atmosphere by chemical reactions of nitrogen oxides, sulphur oxides, some volatile organic compounds and ammonia. Major sources of fine particles are cars, trucks, buses, diesel construction equipment, coal-fired power plants, biomass (wood, vegetation etc) burning and agriculture.

Hyperfine particles, less than 0,1 µm of diameter, which occurr during the petroleum combustion in a motor engine, are associated with the main reasons of all combustion products emitted to the environment and destructive to health. Although they constitute only 1–8 % of the particulate matter emitted to the ambient air from engines, a lot of research works are dedicated to the concentration and distribution of all combustion products in the environment and especially in the industrial one. Just some works among them are dedicated to the distribution of these products hyperfine particles along the freeways [1–3].

The main attention is paid to the quality of measurements, including selection of measuring methods, instrumental peculiarities of measurements technologies and usable means in the research works mentioned above. In the latest one, 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 in 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 m/sec [1].

A good description with an appropriate exponential regression equation was got for a relative distribution of all particles of every type, in regard to its concentration in the roadside 30 m from the centre of the freeway. Thus the distribution of particles is defined near the freeway.

Including plenty of measurements in selected points and reliability of data, further purpose can be defined – to explain the processes determining the dispersion of particles defined by measurements. This problem could be solved by the application of physical model for particles dispersion in the freeway environment, and on the basis of it to compose particles dispersion descriptive distribution. The simulation and a match with experiment data makes easier the factor that all particles deposit to 300 m from the freeway centre.

2. Model of the fine particles from transport emissions dispersial to the roadside

Model of fine particles dispersial when a crosswind was blowing we created on the ground of immediate observations of a whirl of dust formed behind the driven car (Fig 1).

When the wind is absent, the cylindrical shape 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 2. Let's say that fine particles in the cloud formed on the road are spread constantly; the wind blows perpendicularly to the centre of the freeway in velocity v_x.

The centre of the cylinder clouds *O* moves at the velocity v parallel to 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*. It's shift downwards

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

As it was mentioned above, $x_{\max} = 300$ m. The mass of the settled particles is a value equal to the mass in cut-off alteration in volume limited by the height Δh.

Fig 1. A whirl of dust behind a driven car

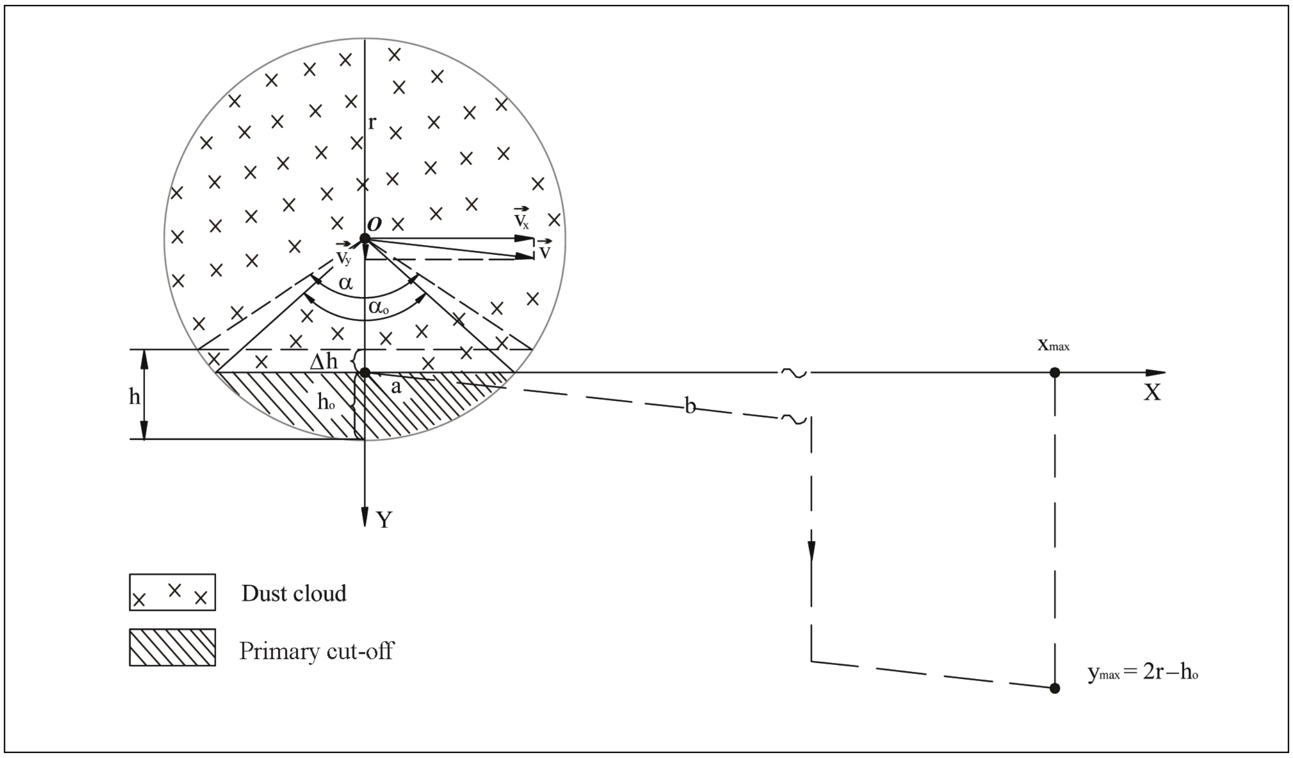

Fig 2. Cylindrical shape whirl of dust with cut-off model

3. Distribution of fine particles emitted from the transport engines

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 out 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

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

and

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

get relations between angle α and axis x and vice versa:

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

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

And including the result (1)

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

and

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

4. Evaluation of the model propriety

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 [1]), 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 the 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 90 m (Fig 3).

All measured pollutants of the normalised concentrations in [1] depend on the distance from the road; the correlation of data have been mentioned in this work, but a significant indeterminacy of mass concentration study remains, because of a large distribution of the measurements data in all points.

To evaluate the pollution caused by motor transport and the propriety of described above model, soil samples were collected along the motorway Vilnius-Panevėžys (in Lithuania) and the profile contained 17 samples [4]. 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 Department of Vilnius Gediminas Technical University. The soil sample analysis was performed following the standard procedure

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

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) ($\times 10^{-5}$/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)

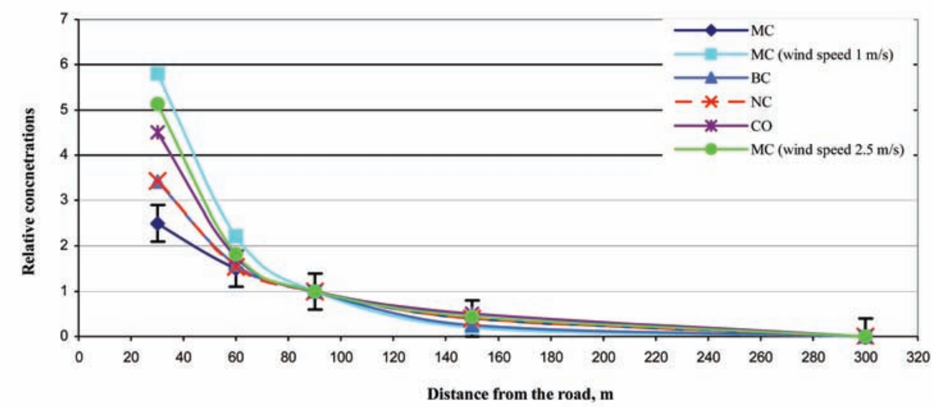

Fig 3. Pollutants dependency on the normalised concentrations on the distance from the road

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 [5].

The total contamination index Z_s was calculated by formula:

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

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

The concentration coefficients were calculated:

$$C_c = C_i / C_f, \qquad (12)$$

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 and concentration coefficients are presented in Table 2.

Concentration coefficients of heavy metals show that heavy metals are concentrated in the road-dividing zone or in the nearest zone of the road up to 10 m from the road centre. The average speed in this part of the road is 90 km/h and the average volume of the traffic is 4 500 cars per day of all types of vehicles. Expression for the approximation of the total index experimental data and pollutants dispersion near the road has been chosen the following equation:

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

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.

The approximated values for the total contamination index Z_s is presented in Table 3.

Total contamination index Z_s was normalised by subtraction of background values in the point of 90 m and

Table 2. Soil samples in 110 km of the motorway Vilnius–Panevėžys

Distance from the road centre		Concentration coefficients of heavy metals, C_c						Z_s index
		Cu	Cr	Zn	Mn	Ni	Pb	
	0 m	1,35	1,16	3,15	2,93	1,10	0,99	6,0
East	10 m	0,60	0,74	1,64	2,05	0,98	0,95	2,0
side	20 m	0,58	0,70	0,95	1,98	0,92	1,03	1,2
of	25 m	0,66	0,63	0,84	1,97	0,86	1,00	1,0
the	35 m	0,62	0,61	0,94	1,93	0,83	0,92	0,8
road	60 m	0,62	0,61	0,91	1,91	0,83	0,84	0,7
	85 m	0,66	0,60	0,85	1,80	0,82	0,79	0,5

Table 3. The approximated total contamination index Z_s values

Measurement	Downwind distance (m)				
	30	60	90	150	300
Total contamination index Z_s	2,5559	1,4974	1	0,4868	0

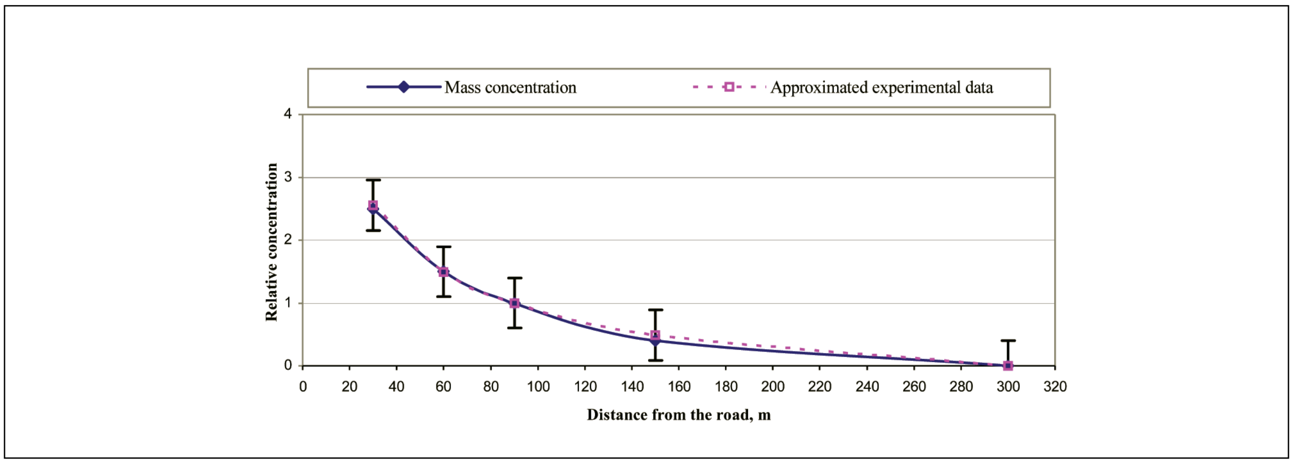

Fig 4. The approximation of total contamination index Z_s and measured concentrations MC dependence on the distance from the road

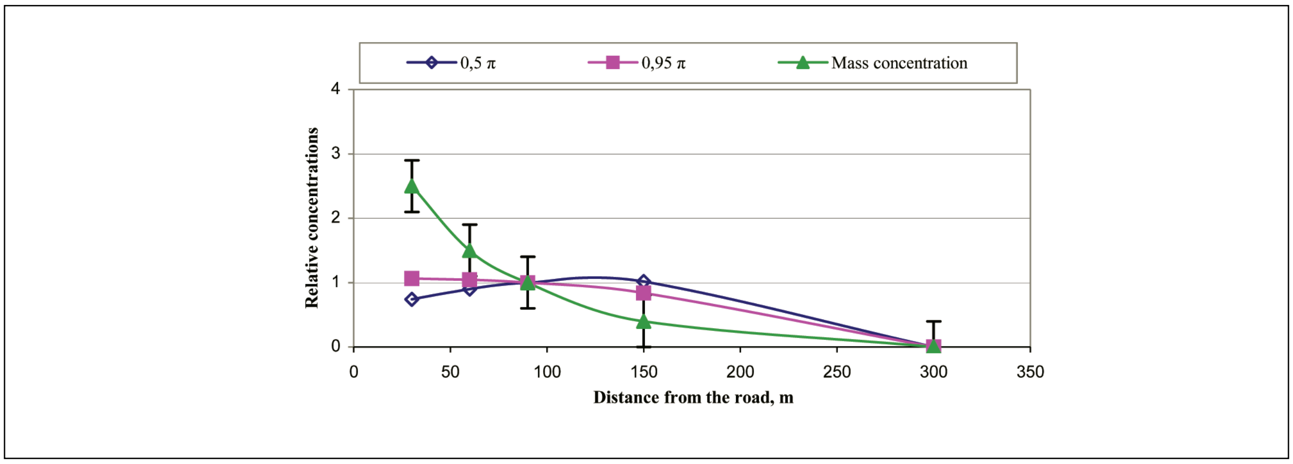

Fig 5. Mass concentration and experimental model curves, when $\alpha_0 = 0{,}5\pi$ and $\alpha_0 = 0{,}95\pi$

dependence on the distance from the road. Mass concentration MC was normalised in the point of 90 m from the road data [1]. They were measured in the air above the Earth's surface. The approximation of Z_s and MC showed the same tendency of concentrations dependence on the distance from the road (Fig 4). Applying the statistical model (4) with an experiment (Fig 4), the correlation of the curves becomes better by increasing the angle α_0 and at the α_0 = 0,95π a relatively good (R^2 = 75 %) congruence of mass concentration MC is obtained (Fig 5) in the points further than 90 m. This α_0 value is a good match for the dust cloud shape of immediate observations (Fig 1).

When evaluating particles concentrations in the distance of 30 m, a clear difference between experimental and regression equations values can be seen. The reason is that obviously not all particles float up into the described above cloud of particles. However, the marked part of them is distribute into the vicinity road ambience not only under the influence of side-wind but also by the airflows caused by transport.

For a practical implementation of the model it is important that the influence of the wind speed change the distribution of the particles concentrations. For this purpose in the work [1] measurements data are presented for the comparison, when the wind speed is 1 m/s and 2,5 m/s. The most interesting thing is that there is no change of concentrations in the distance of 300 m.

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

5. Conclusions

1. A good congruence of regression equation and experimental data in the distance of more than 90 m from the road shows that, when the wind speed is low, the particles distribution scheme described in the model fits very well.

2. In the distance of less than 90 m from the road, the particles distribution is more complicated and, for example, in the point x = 30 m about 50 % fixed concentration consist of particles from other sources.

3. This model could be a baseline for the complete physical modelling of the particles distribution, taking into account the atmosphere impact on particles falling down and coagulation.

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