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Experimental and theoretical study of pollutant dispersion along a highway

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A model of particle dispersion when there is a crosswind was created on the grounds of the Gaussian distribution of particles over a road. When the wind is absent, a cylindrical cut-shaped whirl of dust immediately changes into a cylindrical one with a cut-off of the ground dust cloud. Later, when the wind blows perpendicular to the road, the particles are carried to the roadside. The source of particles is not only the emissions from automobiles, but also sources related to the automobiles (tyres, brakes, etc.). The particles and aerosols are grouped into two groups with average diameters. A good congruence of the regression equation obtained by the theoretical expression and the experimental data shows that the particle distribution scheme described in the model fits very well.

Key words: pollution, automobiles, Gaussian distribution, modelling

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INTRODUCTION

Particulate matter is the general term for a complex mixture of solid and liquid particles in the air. Particles of the average diameter of 10–120 nm dominate in the automobile emission. Many particles are also formed in the atmosphere from chemical reactions of nitrogen oxides, sulphur oxides, some volatile organic compounds and ammonia. The major sources of fine particles are cars, trucks, buses, diesel construction equipment, coal-fired power plants, biomass (wood, vegetation, etc.) burning and agriculture.

A lot of research works are dedicated to the concentration and distribution of all combustion products in the environment and especially industrial environment. Only some works among them are dedicated to the distribution of hyperfine particles of these products along freeways (Zhu et al., 2002; Shi et al., 1999; Hitchins et al., 2000).

It has been concluded that the tire dust consists of assimilated heavy metal particles emitted from road traffic materials, such as brake lining and road paint. It was determined that most of the mass (52%) was contained in the submicron range (< 0.8 μm) and an additional minor mode (20%) in the coarse size fraction (> 6.7 μm). The mean mass median aerodynamic diameter (MMAD) of PM was found at 0.85 ± 0.71 μm, while the mean MMADs of heavy metals followed the order Pb (0.96 ± 0.71 μm) < Cd (1.14 ± 0.82 μm)) < V (1.38 ± 0.63 μm) < Fe (3.82 ± 0.88 μm) (Samara and Vousta, 2005). This shows that the road dust is a very important heavy metal source. It is very likely that the coarse particles are enriched with heavy metals due to the surface adsorption or coagulation of fine and ultra fine particles emitted during the fuel combustion.

The main attention is paid to the quality of measurements, including the selection of measuring methods and instrumental peculiarities of the measurement technologies and unstable means in the above-mentioned research works. The concentration of modelling pollutant dispersion above and near the road should be known. The Engine Exhaust Particle Siser (EEPS) allows studying the particle size distribution data rapidly with a frequency of one second (Ning et al., 2005). In the work (Ning et al., 2005), the authors experimentally and numerically presented the dispersion characteristics of vehicular exhaust plume under the idle condition in an idealized and simplified environment, which gave that in the exhaust plume near the tailpipe of a diesel vehicle the particulate size distribution was nearly log-normal with mean diameters ranging from 60 to 120 nm, and the measurements performed with the exhausted pollutant from the standing vehicle showed that the pollutant was distributed above the road by the Gaussian law. We used the vehicular particle number size distribution averaged of a long scan – time.

In one source (Eskridge and Rao, 1986), a theory was educed and validated for the velocity deficit and turbulent energy fluctuations in the wake of a moving vehicle in still air (it was considered that the vehicle flow under real conditions created a whirlwind above the road), the dispersion was incorporated into an equation for pollutant conservation (Eskridge and Rao, 1986). The work (Baker, 2001) considers the flow velocities and dispersion of pollutants in the wake of a number of different types of ground vehicles, a number of experimental, numerical and analytical investigations show the structure of wake and its influence on the pollutant dispersion.

Mathematical models are widely used to evaluate the air quality near the roadways. The models vary in complexity, namely from a simple Gaussian line source approach to numerical solutions of liquid dynamics equations. Considering the numerous measurements at the selected points and the reliability of the data, the following purpose can be put forward – to explain the processes determining the dispersion of particles defined by the measurements.

From the viewpoint of an engineer, it is necessary to be able to calculate the dispersion of exhaust pollutants away from a roadway, and a number of methods exist for performing it. Generally, in roadway dispersion models, the roadway is considered a line source (Khare and Sharma, 1999) in which thermal and mechanical turbulences induced by moving vehicles contribute to the mixing of the vehicle exhaust (Hatano et al., 1989). CALINE4 model is among the most commonly used models, which is a Gaussian-based dispersion model (Hatano et al., 1989). Some researchers have shown a significant increase in the turbulent kinetic energy (TKE) due to the movement of vehicles on the road (Rao et al., 2002). It was then incorporated into the ROADWAY and ROADWAY-2 models in order to predict the pollutant concentration near the roadway. A typical Gaussian model is HIWAY (Zimmerman and Thompson, 1975) and its updated version HIWAY-2 (Petersen, 1980).

Although the Gaussian model can be used easily, the diffusion coefficients have to be correlated empirically in terms of various local atmospheric conditions, and their determination makes a lot of problems. For example, in a work (Macdonald, 2003) an expression $\sigma = ax^b$ is suggested for the dispersion coefficients, where coefficient a varies in the range from 0.40 to 0.31 and coefficient b – in 0.91–0.71 range. Various model approaches such as Monte Carlo simulation (Liu et al., 1994), stochastic method (Karim et al., 1998) and regression technique (Fomunung et al., 1999) have been used to describe the pollutant fluctuating properties during the dispersion process.

The Reynolds' averaged Navier-Stokes (RANS) equations were applied to simulate the turbulence structure, energy conservation and species transport for complex fluid flow (Richards et al., 2000). A three-dimensional vehicular pollutant dispersion numerical model was developed (Wang et al., 2006), at it was based on RANS coupled with a k–ε turbulence model to simulate the initial pollutant dispersion process.

Pollutant dispersion in the near-wake region of a light-duty diesel vehicle for both high and low idling conditions within urban road microenvironments was performed using the effects of turbulence diffusion, vortex recirculation, heat transfer and species transport, etc. (Dong and Chan, 2006). No matter how complicated the models considering all dispersion factors are, none of them is easy to use or their results differ from the real ones. The suggested model uses simple primary parameters, which are averaged regarding the time subject. This problem could be solved by an application of a physical model for the particle dispersion in the freeway environment and on this basis composing the particle dispersion descriptive distribution. The simulation and conformity with the experimental data proves the fact that all particles deposit up to 300 m from the centre of the freeway.

PRINCIPLE OF THE MODEL OF SEDIMENTATION OF THE PARTICLES FROM HIGHWAY TO THE ROADSIDE

The vehicular exhaust jet plume rises due to the thermally induced upward motion, which further enhances the pollutant dispersion process. In the far-wake region of a vehicle, there is a gradual decay of the vehicle induced velocity and turbulence, and this model can be used to describe the pollutant behaviour in the atmosphere. Let us assume that the wind blows perpendicularly to the centre of the freeway at a velocity of v_x. If the wind does not blow, the cloud stays above the road for a long time (Fig. 1).

The deposition velocity can be treated as a statistical parameter, which links the measured deposition fluxes with the concentration measured in the air. The sedimentation velocity v_y of these particles, which could be calculated by formula (1) below, is very low and make only hundreds or thousands parts of cm/s:

$$v_y = \frac{d^2 \rho g}{18\eta}, \tag{1}$$

where d – diameter of the particles, ρ – density of the particles, g – free falling acceleration, η – coefficient of air viscosity.

We consider, that the pollutants above the road distributed according to the two-dimension Gaussian function is the distri-

Fig. 1. A whirl of dust formed behind a running car

1 pav. Dulkių sūkurys, susiformavęs už važiuojančio automobilio bution function for uncorrelated varieties x and y having equal standard deviation σ (2):

$$E(x,y)=\frac{E_0}{2\cdot\pi\cdot\sigma^2}e^{-\frac{(x-\mu_x)^2+(y-\mu_y)^2}{2\sigma^2}}, \quad (2)$$

where $E(x, y)$ is the emission for the road length unit (g/ms) in any point of the cloud, E_0 is the total emission from the road for the road length unit, a theoretical evaluation of which is impossible. Horizontal velocity v_x is a lot higher, and the average in Lithuania is 3.5–4 m/s. We consider that the particles emitted from automobiles due to various turbulence currents formed by a moving automobile along the highway form a cylinder, which is cut in axle (Fig. 1). The wind starts to drive in the horizontal direction the cloud of particles formed in the initial stage by velocity v_x. At the same time the particles are settled at velocity v_y. Let us assume that all the particles are the same, that is, if we consider the average diameter $\bar{d}$

$$\bar{d}=\int_{d_{\min}}^{d_{\max}}\frac{d}{\sqrt{2\pi}\log_{10}\sigma_g}e^{\left\{-\frac{(\log_{10}d-\log_{10}d_c)^2}{2(\log_{10}\sigma_g)^2}\right\}}, \quad (3)$$

where σ_g is the geometric standard deviation, d_c – count median diameter and its density, then such moving particles will make the same angle with horizon α, the tangent of which is:

$$tg\alpha=\frac{v_y}{v_x}=m \quad (4)$$

Then in point x_0, the particles being on the plane (table), with connect points (x_1, y_1) and (x_2, y_2) will settle down.

EVALUATION OF THE DISTRIBUTION OF PARTICULATE MATTER FROM THE HIGHWAY IN THE PROPOSED MODEL

In point x_0, the pollutant will accumulate from the cut-off cylinder, and this point will be reached by those particles, which are in the line $y = -mx + n$, crossing the cut-off cylinder from point (x_1, y_1) to point (x_2, y_2) by the angle $tg\alpha = m$. It means that function (2) describes the distribution of the pollutant above the road and should be integrated by this line.

Taking into account that the centre of the cloud is coincident with the beginning of the coordinate ($\mu_x = 0, \mu_y = 0$) and having the linear equation, we get such expression of integral (5):

$$c(x_0)=\int_{x_1}^{x_2}\frac{E_0}{2\cdot\pi\cdot\sigma^2}e^{-\frac{(1+m^2)x^2-2mnx+n^2}{2\sigma^2}}dx \quad (5)$$

Having changed the variables:

$$a=\frac{1+m^2}{2\sigma^2};b=\frac{2mn}{2\sigma^2};c=-\frac{n^2}{2\sigma^2}, \quad (6)$$

we get such integral:

$$c(x_0)=\frac{E_0}{2\cdot\pi\cdot\sigma^2}\int_{x_1}^{x_2}e^{-ax^2+bx+c}dx, \quad (7)$$

which assumes such form:

$$c(x_0)=\frac{E_0}{2\cdot\pi\cdot\sigma^2}e^{\frac{b^2+4ac}{4a}}\int_{x_1}^{x_2}e^{-a\left(x-\frac{b}{2a}\right)^2}dx, \quad (8)$$

and after one more change of the variables $\sqrt{a}\left(x-\frac{b}{2a}\right)=z$, the integral from formula (8) is transformed into the integral:

$$\int_{z_1}^{z_2}e^{-z^2}dz=\int_{z_1}^{0}e^{-z^2}dz+\int_{0}^{z_2}e^{-z^2}dz, \quad (9)$$

and the last mentioned integral is an error function:

$$erf(z)=\frac{2}{\sqrt{\pi}}\int_0^z e^{-z^2}dz. \quad (10)$$

It is necessary to use this feature of the error function:

$$\int_{z_1}^{z_2}e^{-z^2}dz=\frac{\sqrt{\pi}}{2}\left(\frac{2}{\sqrt{\pi}}\int_0^{z_2}e^{-z^2}dz-\frac{2}{\sqrt{\pi}}\int_0^{z_1}e^{-z^2}dz\right). \quad (11)$$

Using all the above-mentioned integrals and returning to the initial functions we get:

$$c(x_0)=\frac{E_0}{2\sigma\sqrt{2\pi(1+m^2)}}e^{-\frac{m^2x_0^2}{2\sigma^2(1+m^2)}}\left[erf(z_2)-erf(z_1)\right], \quad (12)$$

where

$$z_1=\sqrt{\frac{(1+m^2)R^2-m^2x_0^2}{2(1+m^2)\sigma^2}}, \quad (13)$$

and

$$z_2=-\sqrt{\frac{(1+m^2)R^2-m^2x_0^2}{2(1+m^2)\sigma^2}} \quad (14)$$

Since $m << 1$, then z_1 and z_2 assume such expressions:

$$z_1=\frac{R}{\sqrt{2}\sigma},z_2=-\frac{R}{\sqrt{2}\sigma}, \quad (15)$$

and using the error function feature, that $erf(-x) = -erf(x)$, we get the final expression of concentration $c(x_0)$, which allows to calculate the quantity of the pollutant in the unit of the surface area, as well as considering $m << 1$:

$$c(x_0)=\frac{E_0}{\sigma\sqrt{2\pi}}e^{-\frac{m^2x_0^2}{2\sigma^2}}erf(z_2). \quad (16)$$

In point x_0, the particles of different diameter d, which moves by different angles, will settle down, and this corresponds to different m. Also, m depends on the particle diameter d, and this means that formula (16) has to be summed to m, whereas let us assume that all the particles are mixed equally through the turbulence, i. e. σ is equal for all the particles:

$$c(x_0)=\sum_{i=1}^{i=2}\frac{E_{0i}}{\sigma\sqrt{2\pi}}e^{-\frac{m_i^2x_0^2}{2\sigma^2}}erf(z_2). \quad (17)$$

EVALUATION OF THE MODEL PROPRIETY

The evaluation of our model propriety was based on a comparison of the dynamics of the concentrations got by the experiments and the calculation using formula (16).

In order to evaluate the pollution caused by motor transport vehicles and the propriety of the above-described model, soil samples were collected along the motorway Vilnius–Panevėžys in Lithuania, and the profile contained 17 samples (Baltrėnas and Kliaugienė (Brannvall, 2003). 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. Certain quantities of Zn, Cr, Ni, Cu, Pb and Mn were obtained using atomic absorption spectroscopy (AAS Buck 210 VGP) method at the laboratory of the Environmental Protection Department 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 the model propriety, the total contamination index Z_s was used. The total contamination index Z_s reflects the risk of the contamination in the soil (Kadūnas et al., 1999).

The total contamination index Z_s was calculated by formula:

$$Z_s = \Sigma C_{ci} - (n-1), \tag{18}$$

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

The concentration coefficients were calculated:

$$C_c = C_i / C_f, \tag{19}$$

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".

The total contamination index and concentration coefficients are presented in the work (Martinėnas et al., 2006).

The calculations show that there are enough particles to group into two groups, therefore, as an expression for the approximation of the total index experimental data and the pollutant dispersion near the road has been chosen the following equation:

$$Z_d(x) = a_1 \cdot e^{-b_1 \cdot x^2} + a_2 \cdot e^{-b_2 \cdot x^2}, \tag{20}$$

where a_i and b_i, are the coefficients deduced by solving a regression equation using DataFit-6.1.10 program. The parameter values of the function are the following: $a_1 = 4.7$, $b_1 = 0.013$, $a_2 = 1.2$, $b_2 = 0.00008$. The adjusted coefficient of multiple determination of this equation is $R^2 = 0.98$. If the adjusted coefficient of the multiple determination is close to 1, the functional dependence of the data is very high. As the coefficient is close to 1, it means that the conformity of modelling (theoretical) and experimental results is good.

Then the approximated total contamination index Zs expression is the following:

$$Z_s(x) = 4.7 \cdot e^{-0.013x^2} + 1.2 \cdot e^{-0.00008x^2}. \tag{21}$$

Total contamination index Z_s was normalized by subtraction of the value in the point of 90 m and dependence on the distance from the road.

Having compared formulas (17) and (21), it can be seen that when the distribution of the particle diameter is lognormal, the coefficients a_1 and a_2 in formula (20) could be considered a probability in the given distribution of particle diameters d_1

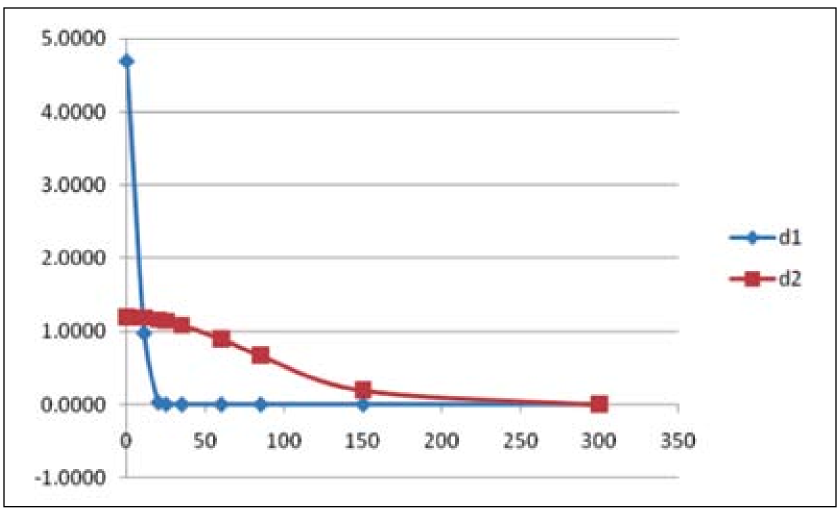

Fig 2. Distribution of concentration $c(x_0)$ of the particles with diameters d_1 and d_2 in the unit of the surface area in the distance of x_0 from the highway

2 pav. d_1 ir d_2 diametrų dalelių koncentracijų pasiskirstymas paviršiaus ploto vienete x_0 atstumu nuo greitkelio

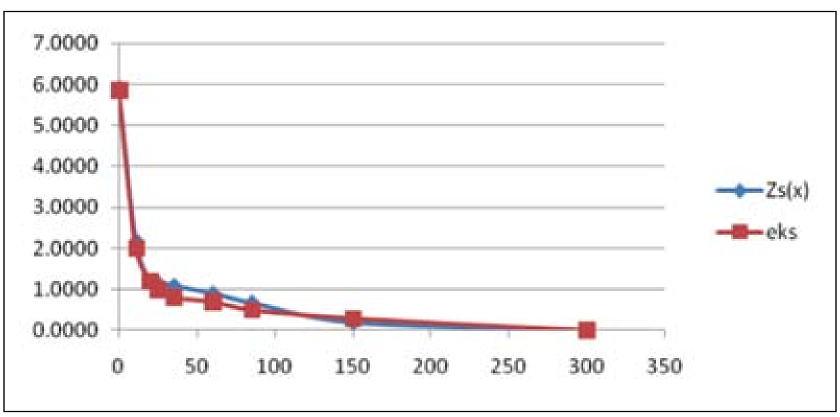

Fig 3. Distribution of experimental total contamination index Zs and approximated function $Zs(x)$

3 pav. Eksperimentinio suminio užterštumo rodiklio Zs ir aproksimuotos funkcijos $Zs(x)$ pasiskirstymas and d_2, therefore, the average density $\overline{d}$ of the particles and the proportion of d_1 and d_2 could be expressed as follows:

$$\overline{d} = \frac{a_1}{a_1 + a_2} d_1 + \frac{a_2}{a_1 + a_2} d_2, \frac{d_1}{d_2} = \sqrt[4]{\frac{b_1}{b_2}}. \quad (22)$$

From these formulas it follows that:

$$d_1 = \frac{a_1 + a_2}{a_1 + \sqrt[4]{\frac{b_2}{b_1}}} \overline{d}; \quad d_2 = \frac{a_1 + a_2}{\sqrt[4]{\frac{b_1}{b_2}} a_1 + a_2} \overline{d}. \quad (23)$$

It is possible to group the particles into small and big ones by means of formula (23) as well as to find the average diameter of these particles. This is an important analysis of the parameters of particles. Regarding formula (21), the concentration of the particles of larger diameter d_1 decrease suddenly and this is absolutely clear because these particles settle down faster than the smaller ones with average diameter d_2, which settle down further from the road (Fig. 2) If both average diameters d_1 and d_2 of the particles are summed, the total concentration expressed as curve $Zs(x)$ will be obtained (Fig. 3). This curve fits the experimental data very well, and this shows the propriety and efficiency of the chosen model.

Comparing equations (16) and (21) and Fig. 3, we see that in our model there are constants E_0, m, σ that cannot be defined theoretically. So, now we have expression (21), which describes the experimental results, and these parameters are defined by the complex experiments, which is very important for the modelling of traffic pollutant dispersion along the highways.

CONCLUSIONS

1. First of all, the concentration of the particles emitted by automobiles in the roadside air could be grouped into two groups with different average diameter d_1 and d_2, and then the distribution of the particle concentration in the roadside could be explained.
2. Good congruence of the modelling equation and the experimental data (Fig. 3) shows that the particle distribution scheme described in the model fits well. The adjusted coefficient of multiple determination of this equation $R^2 = 0.98$.
3. Using the curve constants obtained by approximation and comparing them with the model expression, we can define such important particle dispersion parameters as diameter, velocity of the particle settlement, the coefficient of dispersion or transport emission capacity.
4. Having the total road emission E_0 and using formula (17), the pollutant concentration could be forecasted in the topsoil after a certain period.

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Evelina Brannvall, Valdas Špakauskas

EKSPERIMENTINIAI IR TEORINIAI TERŠALŲ SKLAIDOS TYRIMAI ŠALIA GREITKELIO

Santrauka

Taršos dalelių plitimo, pučiant šoniniam vėjui, modelis sudarytas remiantis prielaida, kad dalelės virš kelio pasiskirsto pagal Gauso dėsnį. Kai vėjo nėra, už nuvažiuojančios mašinos susidaręs cilindro formos dulkių sūkurys greitai virsta cilindru su nuopjova, kurioje esančios dalelės nusėda šalikelėje pučiant šoniniam vėjui. Dalelių šaltinis yra ne tik tiesioginė automobilių emisija, bet ir automobilio dalys (padangos, stabdžiai ir kt.). Virš kelio taršos šaltinį sudarančios dalelės ir aerozoliai yra suskirstyti į dvi grupes, kurios apibūdinamos vidutiniu diametru. Aproksimacijos būdu gautas kreivės konstantas palyginę su modelio išraiška, galime nustatyti tokius svarbius dalelių sklaidos parametrus kaip skersmuo, dalelių nusėdimo greitis, sklaidos koeficientas ar transporto emisija. Žinodami bendrą emisijų kiekį E_0 ir naudodami (17) formulę galime prognozuoti teršalų koncentraciją paviršiniame dirvožemio sluoksnyje po tam tikro laiko.

Эвелина Браннвалл, Валдас Шпакаускас

ЭКСПЕРИМЕНТАЛЬНОЕ И ТЕОРЕТИЧЕСКОЕ ИССЛЕДОВАНИЕ ДИСПЕРСИИ ЗАГРЯЗНЕНИЯ ВОЗЛЕ ШОССЕ

Резюме

Модель дисперсии аэрозолей в условиях встречного ветра создана по причине Гауссовского распределения частиц по дороге. В отсутствии ветра цилиндрической формы водоворот пыли преобразуется с сокращением облака пыли основания. Позже, при ветре, перпендикулярном к направлению, частицы несутся к обочине. Источники частиц – не эмиссия от автомобилей, но с автомобилями связаны (шины, тормоза и т. д.). Частицы и аэрозоли объединены в две группы со средними диаметрами. Уравнение регресса, полученное по теоретическим расчетам и экспериментальным данным, показывает, что схема распространения частиц, описанная в модели, хорошо коррелирует. При полной дорожной эмиссии E0 с концентрацией загрязнителя формулы (17) загрязнение могло быть предсказано в верхнем слое почвы после определенного периода.