A STUDY OF HORIZONTAL DISTRIBUTION PATTERN OF PARTICULATE POLLUTANTS NEAR A HIGHWAY

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ABSTRACT. Understanding vehicle-generated emissions, their dispersion near roads and their potential impact on the near-roadway populations is an area of growing environmental interest. This article presents the horizontal dispersion of coarse and fine particulate matter pollutants in places located near a busy highway (such as the Trakia highway) at the exit of the city of Sofia, over flat terrain, where the predominant dispersion mechanisms are atmospheric turbulence and the turbulence created by traffic. Four sites (at distances of 25, 50, 100 and 200 m from the highway) were selected to study the concentration profiles of pollutants. Under conditions of low wind speed, particles from the highway are established even in areas located far away upwind from the highway. Experimental results show that two dimensional modelling of particle flows produced by highway traffic is needed, and it is important to take into account the turbulence caused by traffic in order to accurately predict the dispersion of particulate pollutants near roads.

Keywords: vehicle-generated particulate matter emissions, particulate matter dispersion, concentration profiles, pollution near highway, dispersion mechanism

ИЗУЧАВАНЕ НА МОДЕЛ НА ХОРИЗОНТАЛНО РАЗПРЕДЕЛЕНИЕ НА ПРАХОВИТЕ ЗАМЪРСИТЕЛИ БЛИЗО ДО МАГИСТРАЛА

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РЕЗЮМЕ. Стремежът към по-добро разбиране на процесите на дисперсия на генерираните от превозни средства емисии, в близост до пътищата и потенциалното им въздействие върху населението, живеещо близо до тях, е област с нарастващ екологичен интерес. Настоящата статия представя хоризонталната дисперсия на едри и фини прахови замърсители на места, разположени в близост до натоварена магистрала (като магистрала Тракия) на изхода на град София, над равен терен, където преобладаващите механизми на дисперсия са атмосферната турбулентност и тази, създадена от трафика. Четири площадки (на разстояния 25, 50, 100 и 200 м от магистралата) бяха избрани за измерване на концентрацията на замърсителите. Когато скоростта на вятъра е ниска, частици от магистралата се установяват дори и на места, разположени сравнително далеч откъм подветрената страна на магистралата. Експерименталните резултати показват, че е необходимо при двумерно моделиране на потоците от прахови частици, генерирани от трафика по магистралите, да се вземе предвид турбулентността, причинена от трафика, за да се предвиди по-точно дисперсията на праховите частици в близост до пътищата.

Ключови думи: прахови частици от автомоболини емисии, дисперсия на прахови частици, концентрационен профил, замърсяване до пътища, дисперсионни механизми

Introduction

Road transport is globally recognized as a significant and constantly increasing source of air pollution.

The increased traffic has resulted in more pollutant emissions and the deterioration of environmental quality and human health in cities.

Vehicles in major cities are estimated to account for 70% of the respective total pollution loads there.

Particulate matter (PM) pollution in these cities near major roads was often found to be more severe than that in urban areas.

Motor vehicle emissions, however, usually constitute a significant source of coarse and fine particles, such as PM10 and PM2.5. (Batterman et al., 2010; Dallmann et al., 2012 and Gerardin et al., 2016)

It is necessary to quantify the emission levels of the gaseous pollutants and particles with different size fraction (PM10, PM2.5) near heavy traffic road and also to determine their behavior after emission as they are transported away from the road.

Thus the present study is designed to measure the horizontal concentrations of particulate pollutants PM10, PM2.5 and CO_2 levels aside the highway with the effect of meteorological parameters on them.
This study will help the authority boards in most cities to know about the status of pollutants concentration adjacent to highways (Halonen et al., 2016; He et al., 2012).

Particulate matter is the name used for a complex mixture of liquid droplets and solid particles suspended in the atmosphere such as dust, soot, black smoke and volcanic ash.

Particulate matter varies greatly in composition, and for this reason it is usually classified by size. The most common way to refer to particles is by classifying them into ultra-fine, fine and coarse particles, or by attaching the number in the subscript of the abbreviation, PM, that refers to the upper limit of the particle size taken into account. For example, PM10 encompasses all particles up to the size of 10 micrometers (μm).

Coarse particulate matter includes particles sized 2.5–10 μm in aerodynamic diameter or, as they are commonly referred to, PM2.5 – PM10. Fine particles are those with aerodynamic diameter smaller than 2.5 μm (PM2.5) and ultra-fine – less than 100 nm.

Depending on their origin, different sources result in different types of particulate matter with regards to their chemical composition. It should also be noted that while transported in the atmosphere, their chemical and physical characteristics may change as they encounter and react with other particles.

Generally speaking, especially in urban environments, coarse particles are most often of natural origin, while fine particles seem predominantly to have anthropogenic origin.

Primary PM emissions from road traffic come from vehicle exhaust, brake linings, tire wear, as well as road wear and resuspension of road dust. Resuspension, which is the renewed suspension of particles after their deposition, is affected by factors such as the road surface and traffic intensity, and weather conditions like humidity, wind speed and precipitation (Huertas et al., 2017; Ignacio et al., 2017; Savov et al., 2016; Wua Ye et al., 2002).

In the present study, the relationship between concentration of air pollutants and distance from a busy highway was observed. Relation was found between distance and concentrations of PM10 and PM2.5.

The horizontal gradients at the highway suggested that pollutants concentrations were affected significantly by re-suspended road dust and tailpipe exhaust from motor vehicles.

The present study is aimed at assessing the parameters that affect PM number and mass concentration and horizontal dispersion in places located near a busy highway (such as the "Trakia" highway) at the exit of the city of Sofia, Bulgaria.

Experiment

Instruments

The number and mass concentrations were measured by a portable laser particle counters BQ20 (TROTEC, Germany) laser particle counter (LPC) capable of measuring in two-channel: channel 1 (0 - 2.5 μm) and channel 2 (2.5 - 10 μm) denoted further in the paper as PM2.5 and PM10, respectively. The concentrations were measured instantly with time step 10 minutes. The sampling rate was 0.9 l/min. The accuracy of the devices is in the range of 15-20%.

The meteorological data were obtained from the multi-functional weather station with five sensors (temperature, precipitation, relative humidity, air pressure, wind direction and speed).

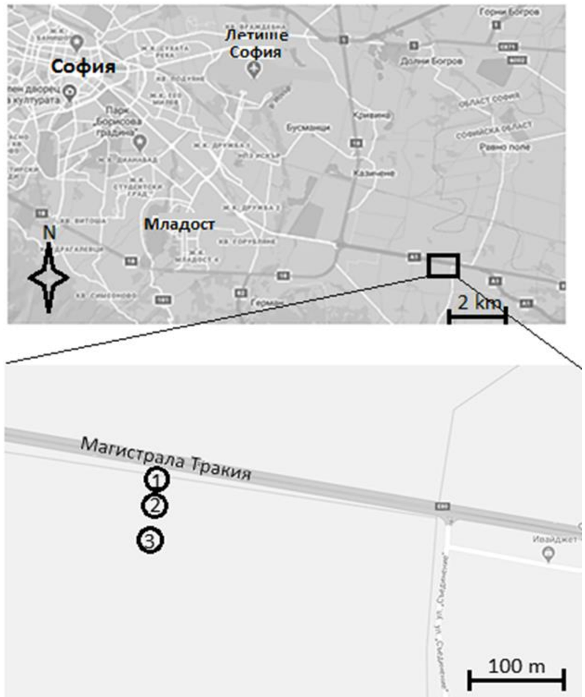

Fig. 1. Measurement sites 1, 2 and 3 near by Trakia highway

Site description

The site selected for the present study was conducted in the vicinity of "Trakia" highway about 4 km from Sofia (Fig. 1). The location selected is ideal both for the absence of residential areas and of local traffic. The highway has four lines and is approximately 20 m wide. Orientation is W–E direction. Measurements were made at three sampling sites, at distances of 25, 50, and 100 m to the highway, hereafter referred to as site 1, site 2, and site 3, respectively.

The traffic on the main road was estimated by counting the numbers of cars, light trucks, and heavy trucks passing by in random 15 min periods during the measurements. The average traffic densities per hour during the measurements were: cars 2452, and heavy trucks 630, total vehicles 3082.

Methodology

For the purposes of the present study, the dependence of the mass concentration of PM on the class of atmospheric stability was determined by

$$C(x,0,0) = \frac{Q}{\pi \sigma_z u} e^{\frac{-H^2}{2\sigma_z^2}} . \qquad (1)$$

The power of the source (traffic) Q = 7 μg/m.s is determined by the measured number of vehicles and the ratio of cars to heavy trucks. For the base values we accepted 5 μg/m.s for cars and 20 μg/m.s for trucks. H = 0.5 m, which is the predominant height of the sources of pollutants above the ground (the exhaust system of vehicles); u - the wind component perpendicular to the roadway, and σ_z - coefficient depending on the stability class of the atmosphere and the distance x from the linear source. The values of σ_z are determined as follows (Colls, 2002):

$$\begin{aligned} &\text{class A} \quad \sigma_z = 0.20x \\ &\text{class C} \quad \sigma_z = 0.08x(1+0.0002x)^{-0.5} \\ &\text{class D} \quad \sigma_z = 0.06x(1+0.0015x)^{-0.5} \end{aligned} \tag{2}$$

Results and discussions

The results of the measurement of solar radiation show that its values vary between 720 and 880 W m2 (Fig. 2). Based on these data, as well as the magnitude of the wind speed (Fig. 3), we determined the atmospheric stability as corresponding to class A.

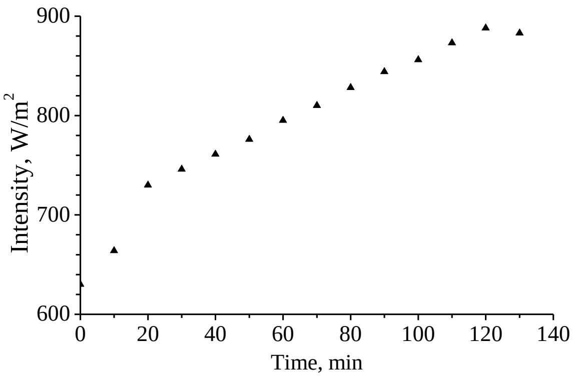

Fig. 2. Solar radiation

Wind speed and direction play an important role in pollution distribution and should be considered as key factors in most measurements (Fig. 3).

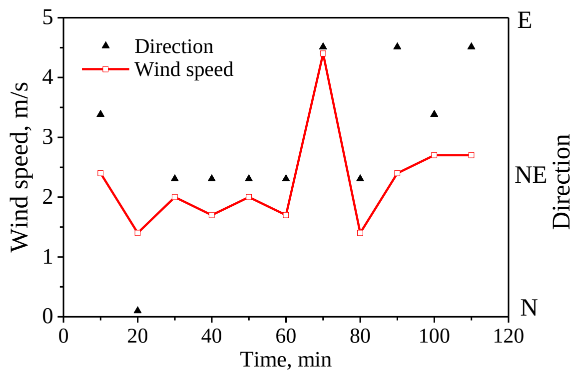

Fig. 3. Wind speed and direction

The numerical concentration of PM10 is low, between 1 and 2 m^{-3}, and decreases to 1 m^{-3} with increasing distance to 100 m (Fig. 4). Concentration fluctuations over time are more related to wind orientation - when the wind orientation is perpendicular to the road, the PM10 concentration values are higher. This is more pronounced in PM10 and very weak in PM2.5. After the first 30 minutes, the wind becomes mostly northeast (NE), and at the end of the measurement - east, parallel to the road. At a distance of 100 m from the highway, the wind orientation has no effect on the PM10 concentration.
When the wind blows directly from the source towards the receptor, the concentration gradient is more pronounced and extends further away than when the wind blows parallel to the road, or away from it. According to some research, the concentration of fine and ultra-fine particles drops by half at a distance of 100-150 m from the source when measurements are taken downwind. The reduction to half the concentration happens 50-100 m from the road when the wind is blowing parallel to the line source (Batterman et al., 2010; Dallmann et al., 2012 and Gerardin et al., 2016).

Different behavior in particle distribution is observed in the present study.

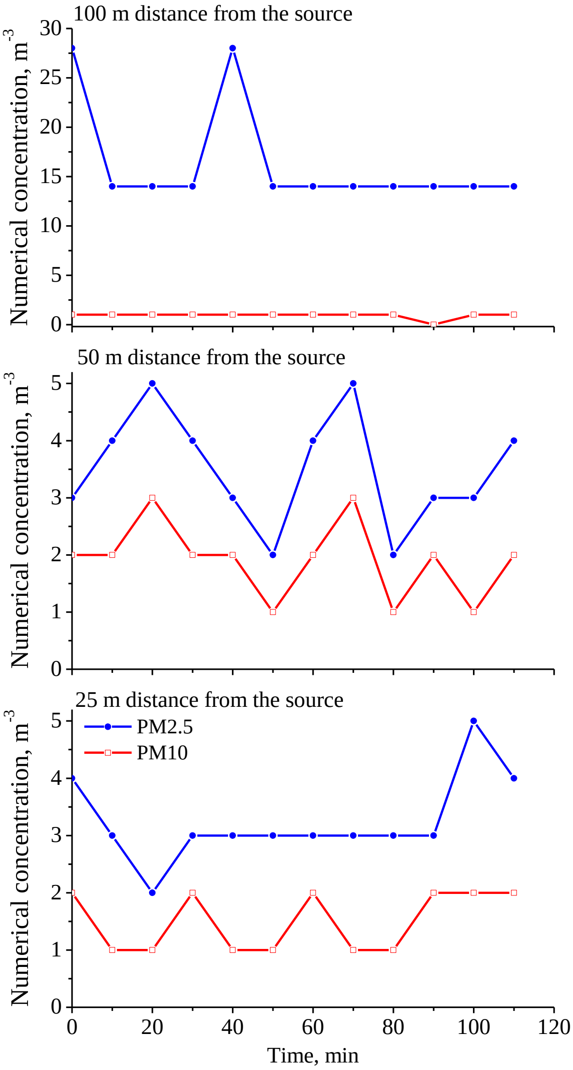

Fig. 4. Numerical concentration of PM 2.5 and PM 10 at different distances from the source

Fig. 6 presents the evolution of the mass concentration of aerosols as a function of distance and time. Although after about 60 minutes the wind direction changes from northeast to east, no significant change in concentrations is observed. The average values of the concentration as a function of the distance are given in fig. 8, as bars. It can be seen that even 100 m from the source the mass concentration is still high. This could be due to wind erosion of the soil from the open field and/or from the bioaerosol, which is inevitably emitted by the plantings (sunflower). This background effect is added to the residual aerosol from the highway and maintains high levels of pollution.

The CO_2 concentration is close to the background value, being slightly above it (410 ppm) near the road and decreasing to 380 ppm (Fig. 6). When the wind turns from the northeast and east (30th and 70th minute) the concentration at both distances decreases. This result shows that the main source of CO_2 above the background are vehicles.

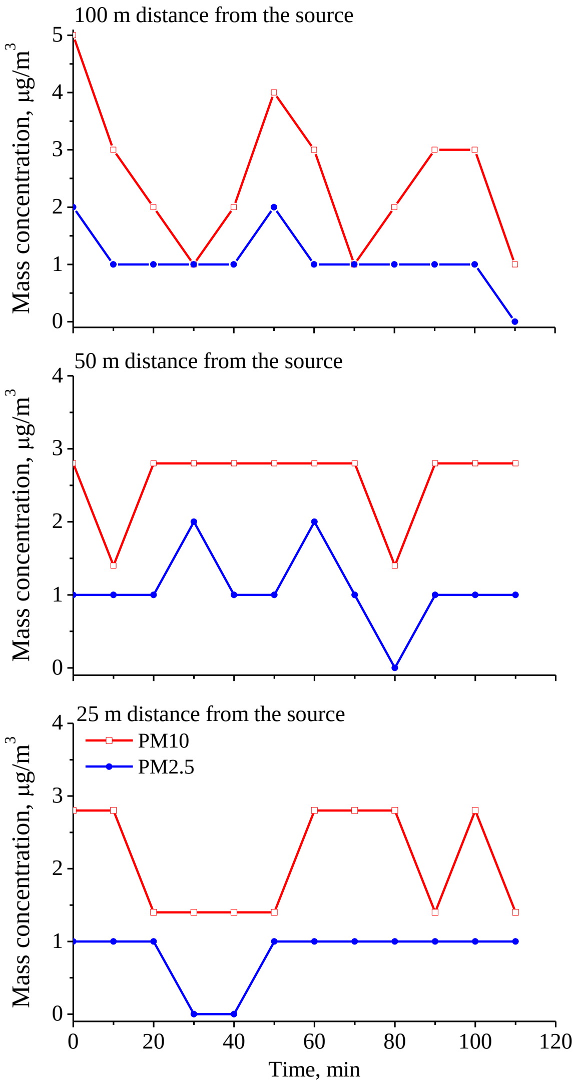

Fig. 5. Mass concentration of PM 2.5 and PM 10 at different distances from the source

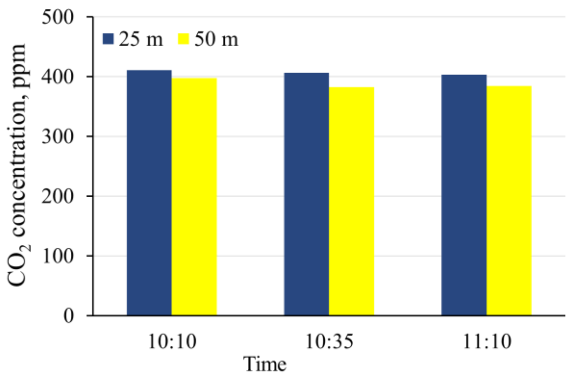

Fig. 6. CO_2 concentration at different distances from the source

In Fig. 7 the dependence of the mass concentration on the wind speed for stability class A, as observed during our measurements, is presented.

The same figure shows the measured concentration for PM10 at 25, 50 and 100 m of the highway. The values are averaged over a time interval in which the wind has a relatively constant speed and direction - between the 30th and 60th minute (Fig. 3). It was taken into account that the wind blows at an angle of 45° to the road during this period. In this sense a comparison should be made with the graph for u = 1 m/s.

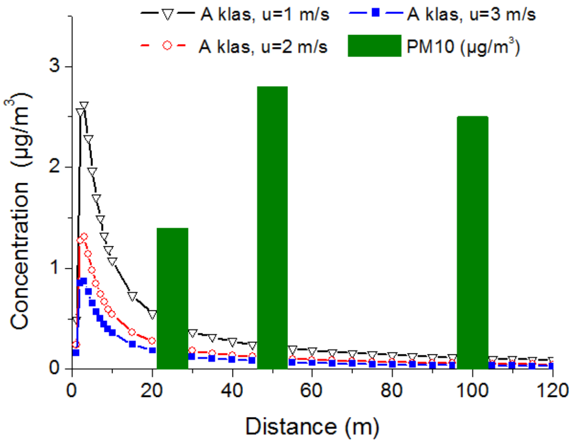

Fig. 7. Wind dependence of mass concentration for stability class A and comparison with the measured values of PM10

The experimental profiles of particle concentration close to the highway are significantly different from model calculated. This behaviour could be due to a combination of three processes. First, the effect of bushes and trees barrier in near-roadway neighborhoods reduce air flow, leading to increased pollutant concentrations behind the trees. Second, the plume is likely to ascend near the highway because of the thermal buoyancy associated with the temperature gradient between traffic exhaust and ambient air.. Three, the vortices by traffic-produced turbulence and ground surface friction can help to facilitate the mixing of particles in the air mass in the lower heights. The first process explains the lower particle concentration in site 1. The second process explain the peak plume displacement away from highway in comparison withcalculated one. The third process explains the relatively higher concentrations in experimental plume in comparison with calculated.

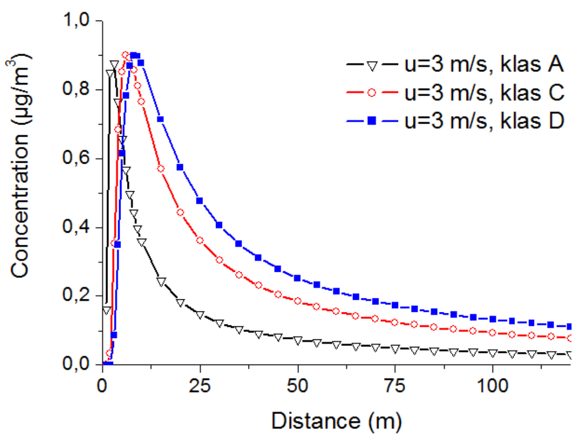

Fig. 8. Mass concentration dependence on atmospheric stability class A, C and D

In Fig. 8. the dependence of the mass concentration on the atmospheric stability class at wind speed 3 m/s, perpendicular to the highway, is presented. The calculations were made according to (1) and (2) under the mentioned conditions for *Q* and *H*.

There was no significant difference in the maximum concentration for the three classes.

In the comparison of Fig. 8 and Fig. 9 it is seen that the combination of weak wind and strong instability or strong wind and neutral stratification of the atmosphere contribute to the strongest dispersion of pollutions away from the source. In a situation with light wind (about 1 m/s) and strong instability, the pollution levels around the source are the highest.

Conclusion

The purpose of this study is the characterization of the "Trakia" highway in terms of evolution of particle mass and number concentration at different distances from the highway. Mass concentrations of large particles measured were significantly lower than the average values for the urban environment.

The discrepancy between experimental and calculated mass and number concentration is establish. This is do for three main reasons:

- the effect of bushes and trees barrier in near-roadway neighborhoods;
- thermal buoyancy associated with the temperature gradient between traffic exhaust and ambient air;
- the vortices by traffic-produced turbulence and ground surface friction.

All this factors cause displacement and stretch in particle dispersion profile from highway in comparison with Gauss's profile.

An additional result we got is that the main source of CO_2 above the background are vehicles.

The experimental results suggest the need for three-dimensional modelling of particle plumes from highways and the importance of considering enumerate phenomenon for accurate prediction of particle dispersion near roadways.

Acknowledgements. This work is supported by contract № GPF-231 /2020 University of Mining and Geology is "St. Ivan Rilski".

This work has been carried out in the framework of the National Science Program "Environmental Protection and Reduction of Risks of Adverse Events and Natural Disasters", approved by the Resolution of the Council of Ministers № 577/17.08.2018 and supported by the Ministry of Education and Science (MES) of Bulgaria (Agreement № Д01-322/18.12.2019).

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