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Modeling of the Car Traffic Air Pollution on the Territories Neighboring Multi-level Interchanges

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Ensuring the proper quality of the environment is a foreground and important task for achieving sustainable development goals in contemporary urban societies. Therefore, the aim of the research is to study the air pollution on the territories neighboring multi-level interchanges and assess the additional load on the lower levels based on the analysis of physico-chemical properties of harmful substances, which are exhausts components. The scientific novelty of the paper and the authors' contribution is in determining the level of ecological danger of territories neighboring multi-level interchanges as a result of the summation effect from emissions of vehicle flows, physical and chemical properties of pollutants, and processes of their sedimentation. To predict the pollution level of the roadside air, the model of torch approximation based on the K-theory and the equations of turbulent diffusion was used. Both mathematical modeling and visualization were performed by the Mathcad software package. Particular attention was paid to the analysis of the environmental situation neighboring multi-level interchanges and urban objects in terms of their pollution with nitrogen oxides and particulate matter PM_{10}. Research has shown that due to the sedimentation processes a significant increase of the technogenic load on the interchange first level road will be observed. It was found that, compared to the upper road, the technogenic load in the center of the lower road increases on average by 1.4–1.6 times in terms of nitrogen oxides and by 1.5–1.6 times in terms of PM_{10}. The territory with the harmful substances maximum permissible concentration excess is significantly increased. So, taking into account that multi-level interchanges are much more environmentally acceptable than surface sections of roads with traffic lights and pedestrian crossings, they still pose danger to the health of people who stay for a long time at the transport stops, move on the sidewalks and underground crossings, as well as for vehicle drivers and passengers. Thus, it is recommended not to place on the territories neighboring multi-level interchanges public transport stops, cafes, shops, and other city infrastructure objects, as well as to remove the existing ones.

Keywords: multi-level interchange, air pollution, engine exhausts, traffic flows, ecological danger.

Introduction

Monitoring of the air pollution in large cities and suburbs caused by the operation of the motor transport network is an important component of the national system of environmental monitoring of air quality. It is well known that emissions of harmful substances from the exhaust gases of vehicles significantly increase the pollution levels of territories along highways, which often leads to the appearance of geochemical anomalies in these areas. Besides, due to the developed motor transport network of the modern urban environments, these emissions affect the air quality in all parts of the city (Vallero, 2008; Wawer et al., 2015).

Crossroads and transport interchanges (single and multilevel, regulated and unregulated) are among the main elements of the road network. The ‘Crossroads’ sign was included in the first four international signs approved by the International Convention on the Movement of Automobiles in Paris, 1909. Today it is obvious that interchanges of all types are much more ecologically acceptable than road sections with traffic lights, pedestrian crossings, and other barriers (Sharifi et al., 2021).

In the twenties-fifties of the 20th century, the design and widespread implementation of multi-level, mostly two-level, transport interchanges began. In particular, the most popular interchanges were the ones designed as a ‘clover leaf’, ‘incomplete clover leaf’ or as a distribution ring with two or five overpasses. However, these schemes had many drawbacks. In particular, the main problem with the cloverleaf interchange type is a left turn, which has led to many collisions and traffic jams. Therefore, over time, the evolution of the cloverleaf interchange has led to the design of the so-called ‘differentiated cloverleaf’, which provides separate ramps for each of the transport flows. Schemes that take into account the purpose of the interchange – rural, suburban, urban, etc. – as well as the intensity of traffic flows on each of the roads have also appeared.

Among the contemporary schemes of transport infrastructure, experts note the double crossover diamond / diverging diamond interchange, roundabout interchanges, traffic light-tunnel, and hybrid interchanges. Modern road design develops under the concept of an intelligent transport system and not only aims to increase the capacity of intersections but also takes into account the convenience and accessibility of traffic rules for drivers, their psychology, traffic safety, etc. (Martinez and Cheu, 2012; Khan and Anderson, 2016; Bared et al., 2017).

Balanced and well-thought-out planning of urban infrastructure, including transport hubs and interchanges, is essential for smart city concept implementation which is aimed at the development of more mobile, sustainable and ergonomic cities (Heddebaut and Di Ciommo, 2018; Laufs et al., 2020; Fakhimi, 2021). During the last decade, many scientists in Europe and worldwide have proposed innovative and effective decisions for urban planning improvement in terms of the smart city concept, namely, Hernandez et al. (2016), Monzón and Di Ciommo (2016), Solecka et al. (2021).

However, at the present stage of development of the road network, in addition to the difficulties of designing transport interchanges and organizing traffic on them, there are also ecological problems, in particular, when the harmful effects of one part of the interchange are greatly enhanced by another. This causes the appearance of the areas of the local extreme air pollution by certain toxicants and, as a result, contributes to secondary pollution of areas located nearby highways. In addition, almost all road crossings have crosswalks (underground, surface, bridge-type) and objects of the urban underground infrastructure (cafes, shops, car parks), which are also highly affected by technogenic pressure from harmful components of exhaust emissions. Cyclists, drivers of scooters, motorcycles, mopeds, and other vehicles, pedestrians, people at public transport stops, etc. are also under the influence of a very strong toxic effect.

Statement of the problem and analysis of literary sources

It is well known that the geo-ecological state of the environment has both direct and indirect effects on the health and vital activity of people living in highly urbanized territories. According to the World Health Organization (WHO, 2018), air pollution is one of the factors that can directly worsen people's health and also affect their well-being. Air pollution is one of the greatest environmental hazards to human health, a factor of the occurrence of serious disorders in the health of people sensitive to toxicants, and can even lead to their premature death. And of particular concern to experts is the pollution of the surface layer of air with ozone and particulate matter (PM) with an effective diameter of up to 2.5 μm ($PM_{2.5}$).

Other toxicants emitted with the vehicle exhaust gases include carbon oxides (CO and CO_2), sulfur oxides (in particular, SO_2), and nitrogen oxides (N_2O, NO, N_2O_3, NO_2, N_2O_5), as well as aldehydes RC(O)H, polycyclic aromatic hydrocarbons, particulate matter (except $PM_{2.5}$, there is also an effective diameter from 2.5 μm to 10 μm – PM_{10}, including so-called 'black carbon' – soot, and also particles of metals, their oxides, sulfates, other inorganic salts, materials originated from tire wear, brake pads and roadway covering). At the same time, the volumes of emissions of toxicants with vehicle exhaust gases highly depend on the quality and type of motor fuel used, technical conditions and vehicle brand or model, traffic conditions, traffic flow intensity, type and conditions of the roadway covering, meteorological and weather conditions, other factors, etc. The problem of emissions can be partially solved by improving the quality of the fuel with special additives or transitioning to fuels of biological origin (Vasylkevych et al., 2016; Vasylkevych et al., 2017; Matani and Mali, 2021). However, even the use of the most modern and effective additives cannot reduce the engine exhaust toxicity to a safe level.

The harmful effects of toxicants are very diverse. Some of the pollutants (including benzo(a)pyrene, aldehydes, SO_2, as well as nitrogen and carbon oxides) can cause difficulties with breathing, asthma effects, bronchitis, and pneumonia, an increase in the incidences of cancer, and other adverse effects (*Table 1*). Other, for example, fine particles of soot, oils, the products of the roadway covering, engines, and other equipment wearing due to a well-developed surface can adsorb other harmful substances, in particular, heavy metal compounds, polycyclic aromatic hydrocarbons, including carcinogenic benzene(a)pyrene and then bring all these pollutants into the body of humans, animals, etc. (Kofanov et al. 2020).

In particular, PM_{10} is represented by thoracic particles that can penetrate the bronchioles and accumulate in the pulmonary airways, while the extreme danger of $PM_{2.5}$ is that they are respirable particles that inhale and can penetrate the alveoli and pulmonary capillaries involved in gas exchange between the lungs and blood vessels. Particles of this size also penetrate the bloodstream, organs, tissues, harming body cells. $PM_{2.5}$ can spread over long distances from the source of pollution and create secondary geochemical anomalies, and, consequently, cause a very high risk to human health (Resitoglu et al., 2014). The impossibility of their rapid excretion from the body due to the formation of strong organomineral compounds leads to their excessive accumulation in human tissues and organs.

Heavy metal compounds, penetrating the body through the respiratory tract, inhibit the activity of enzymes, impede the processes of respiration, phosphorylation, and transport, causing pathological changes in mitochondria, slowing down the synthesis of hemoglobin and, consequently, leading to metabolic disorders. They usually have a cumulative effect due to the formation of strong organometallic complexes.

Aldehydes, in particular formaldehyde HCHO and acrolein C_2H_3CHO, are products of incomplete combustion of hydrocarbons of fuel and are formed, as a rule, in the early stages of its combustion. Acetaldehyde CH_3CHO, tolualdehyde $CH_3C_6H_4CHO$, benzaldehyde C_6H_5CHO, furfural $C_5H_4O_2$, etc. are also present in small amounts in engine exhaust gases.

Formaldehyde is generally included in the list of potentially carcinogenic substances; its harmful effects

Table 1. *The relative density of exhaust gas components by the air and their impact on the environment*

Component of vehicle exhaust gases	The molar mass of the compound, g/mol	Relative density by the air	Conclusion on the behavior in the air environment	Peculiarities of harmful effects on the human body and the environment
Carbon oxides: CO	28.01	0.967	Lighter than air, rises up.	Toxic effect; disrupts the transport of oxygen by hemoglobin; negatively affects the central nervous and cardiovascular systems; in high concentrations may cause death due to inhibition of the respiratory center.
CO_2	44.01	1.519	Heavier than air, can concentrate in the lower layers.	Does not support breathing; is a greenhouse gas.
Sulfur oxide SO_2	64.07	2.211	Much heavier than air, accumulates in the lower layers.	It is irritating to mucous membranes of the eyes, respiratory tract, provokes chronic lung diseases, promotes the formation of acid rain due to the oxidation to SO_3 and interaction with water drops.
Nitrogen oxides: N_2O	44.01	1.519	Heavier than air, can concentrate in the lower layers.	It is contained in small quantities in the vehicle exhaust gases; is a greenhouse gas.
NO	30.01	1.039	Close to air in molar mass.	Penetrates the blood during respiration and causes disorders of the central nervous system; disrupts the transport function of hemoglobin; under the influence of enzymes of the microflora of the stomach and intestines are converted into nitrates and nitrites.
NO_2	46.01	1.588	Heavier than air, can concentrate in the lower layers.	Very toxic, irritates the mucous membranes of the eyes, respiratory tract, disrupts the transport function of hemoglobin, promotes the formation of acid rain due to the oxidation and interaction with water drops.
N_2O_5	108.01	3.727	Much heavier than air, accumulates in the lower layers.	It is contained in small quantities in the vehicle exhaust gases; can cause acid rains due to interaction with water drops.
Formaldehyde HCHO	30.03	1.046	Close to air by molar mass.	Irritating to mucous membranes of eyes and respiratory tract; harmfully affects the central nervous system; inhibits the synthesis of nucleic acids; sensitizes the skin and has mutagenic properties; harmfully affects the reproductive function of the body.
Polyaromatic hydrocarbons, in particular benzo(a) pyrene $C_{20}H_{12}$	252.31	8.706	Much heavier than air, accumulates in the lower layers.	Have a carcinogenic effect, can accumulate in the body.

Component of vehicle exhaust gases	The molar mass of the compound, g/mol	Relative density by the air	Conclusion on the behavior in the air environment	Peculiarities of harmful effects on the human body and the environment
Particulate matter (aerosols)* PM_{10}	A complex mixture of substances	Heavier than air	Can stay in the air for a long time in a suspended state; they can settle near the road, on sidewalks, etc.	Affects the cardiovascular system and respiratory tract (in particular, provokes asthma attacks); has primary (capable of causing lung cancer) and secondary (due to adsorption on the surface of other toxicants) carcinogenic effects; cause allergopathology.
$PM_{2.5}$			Can stay in the air for a long time in a suspended state; almost do not settle; easily penetrate through biological barriers.	
Unburned hydrocarbons C_xH_y	A complex mixture	Heavier than air	Starting with C_3, they are heavier than air; as a rule, they can concentrate in the lower layers.	They affect the liver, central nervous, and cardiovascular systems, disrupt metabolic processes in the body, harm the environment.

Note: Particularly dangerous is the mutual influence of high concentrations of PM and sulfur dioxide

are described in *Table. 1*. There are also data on the combined effect of formaldehyde and phenol on human health, which leads to the formation of cellular and humoral immunodeficiency, suppression of nonspecific cellular resistance, and allergic sensitization of the body (Ki-Hyun et al., 2011).

The danger of increased concentrations of carbon monoxide CO in the air is caused by its ability to bind hemoglobin in the body of humans and higher animals with the formation of carboxyhemoglobin (HbCO). This causes a decrease in blood oxygen absorption, oxygen starvation, and, as a consequence, general poisoning of the body (*Table 1*).

The main part of nitrogen oxide emissions is formed from nitrogen monoxide NO and nitrogen dioxide NO_2 (Pournazeri et al., 2014), and in the atmosphere, NO under the influence of oxidants is quickly converted to NO_2 (after 0.5–100 hours depending on the concentration in the air). After 3.5 hours almost 80% of NO is converted to NO_2. The content of other nitrogen oxides (N_2O, N_2O_3, N_2O_4, N_2O_5) in the exhaust gases of engines is insignificant.

Both NO and NO_2 are involved in photochemical transformations that occur under the action of solar radiation in the troposphere and stratosphere and cause an undesirable phenomenon – photochemical smog.

Together with processes (1) and (2a, 2b), photolysis (photochemical decomposition) of NO_2 takes place in the atmosphere under the influence of solar radiation with the formation of NO:

$$NO + O_3 \rightarrow NO_2 + O_2, \tag{1}$$

$$NO + HO_2\bullet \rightarrow NO_2 + OH\bullet, \tag{2a}$$

$$NO + RO_2\bullet \rightarrow NO_2 + OR\bullet. \tag{2b}$$

$$2NO_2 \xrightarrow{h\nu} 2NO + O_2, \tag{3}$$

which is the main regulator of physiological activity of plants, and therefore its excess can cause its interruption (Pournazeri et al., 2014).

As shown in *Table 1*, nitrogen oxides and, especially NO_2, have a negative effect on the bronchi, myocardium, and mucous membranes of the nose, eyes, and stomach, and affect the state of the human central nervous system, the photosynthetic apparatus of plants. The presence of hydrocarbons in the air significantly increases the toxicity of nitrogen oxides due to their combined synergistic effect under the influence of solar radiation. One of the products of the photochemical interaction of nitrogen oxides and hydrocarbons is surface ozone, which, unlike the tropospheric one, has a detrimental effect on the environment and human health.

The danger of nitrogen oxide emissions is exacerbated by the fact that during the interaction with water vapor in the air, fine aerosols of HNO_2 (weak) and HNO_3 (strong) acids are formed, which leads to acid rain. Simplified process schemes are as follows:

$$NO + O_2 \rightarrow NO_2,$$
$$2NO_2 + H_2O \rightarrow HNO_3 + HNO_2,$$
$$4NO_2 + 2H_2O + O_2 \rightarrow 4HNO_3,$$
$$N_2O_3 + H_2O \rightarrow 2HNO_2.$$

Similar processes occur during the NO_2 contact with the wet surfaces of the respiratory tract of humans and higher animals; NO does not react with water, but because of this it can penetrate human blood during respiration and cause disorders of the central nervous system (*Table 1*). In addition, entering the blood, both nitrogen oxides disrupt the transport function of hemoglobin, and under the influence of enzymes of the microflora of the stomach and intestines, they are converted into nitrates and nitrites. The anion NO_2^-, in addition to the general toxic effect, oxidizes Fe^{2+} of the hemoglobin to Fe^{3+}, which leads to the formation of its oxidized form – metaglobin, and, as a consequence, slows down oxygen transport through the blood, leads to difficulties in breathing, hypoxia, destabilization of the cardiovascular system, etc. (Pournazeri et al., 2014).

Biogenic amines, which are components of the human body and higher animals, can also interact with nitric acid to form dangerous carcinogenic and mutagenic substances – N-nitrosamines ($R_1R_2N{-}N{=}O$, where R_1, R_2 are alkyl- or aryl- radicals) (Jain et al., 2020):

$$\underset{\text{amine}}{HNO_2 + R_1R_2NH} \rightarrow \underset{\text{N-nitrosamine}}{R_1R_2N{-}N{=}O} + H_2O.$$

The SO_2 is formed in the presence of sulfur compounds in the fuel. It can catalytically oxidize to SO_3 in the air under the action of other pollutants (trace metals, in particular, manganese, ozone, hydrogen peroxide, etc.), while aerosols of sulfate H_2SO_4 (strong) and sulfite H_2SO_3 (weak) acids are formed upon interaction with water vapor. So, conditions for acid rains, eutrophication of reservoirs, increasing the acidity of soil and groundwater, the formation of sulfates and sulfites, etc. are created (*Table 1*):

$$SO_2 + H_2O \rightarrow H_2SO_3,$$
$$SO_2 + O_2 \xrightarrow{h\nu} SO_3,$$
$$SO_3 + H_2O \rightarrow H_2SO_4,$$
$$2H_2SO_3 + O_2 \rightarrow 2H_2SO_4.$$

The SO_2 usually exists in the atmosphere for several hours or even days, depending on humidity and environmental conditions. It irritates the mucous membranes of the eyes and respiratory tract and is extremely dangerous for plants. In particular, during respiration, SO_2, getting into the leaves, inhibits cell activity. As a result, the leaves are covered with brown spots and dry up.

Analysis of the specialized literature devoted to the research topic has shown that most of the contemporary studies on the interchanges are primarily focused on the evaluation of their convenience and safety, rather than environmental impact. In particular, in the study on the application of diverging diamond interchange (DDI), Alabama, Khan and Anderson (2016) studied the possibility of replacing the existing conventional diamond interchange (CDI) with a diverging diamond interchange placed at the same location. They have found that DDI can not be a good measure for traffic improvement compared with CDI for the studied area because only in four investigated cases it performed better than CDI. Besides, they have found that DDI cannot be an effective traffic calming measure when it is associated with the upstream/downstream intersections.

Bared et al. (2017) have determined that DDI construction will deliver more safety benefits than CDI and that speed reduction on DDI will also reduce the severity of crashes due to drivers' mistakes in comparison with CDI. Besides, due to the speed reduction, positive environmental effect will be achieved that is in full agreement with the United Kingdom National Traffic Operations Centre data (www.nationalhighways.co.uk), according to which lowering the traffic flow speed to approximately 95 km/h is the most effective from the ecological point of view.

The problem of environmental pollution caused by operating traffic lights to regulate urban car flows was studied by Drew (1968). It was found that the problem is exacerbated by the presence of discharged traffic flows when the driver must brake in front of the traffic light and accelerate after it, even if he was the only one on the road or in the absence of pedestrians at the crossing. According to Drew, intersections (or one-level interchanges) determine the capacity of the entire transport network, as well as affect the mode of vehicle movement, their average speed, etc.

Moon et al. (2014) have proposed the unique intersections geometric designs that optimize traffic flows and minimize environmental pressure from the vehicle exhausts. Sharifi et al. (2021) have paid particular attention to the road infrastructure improvements and CO_2 emissions reduction. The authors modeled the effects of different roadway infrastructure configurations on the vehicle carbon dioxide emissions using the U.S. Environmental Protection Agency Motor Vehicle Emission Simulator model.

The aim of the research is to study the air pollution on the territories neighboring multi-level interchanges and assess the additional load on the lower levels based on the analysis of physico-chemical properties of harmful substances, which are exhausts components.

Methods

It is well known that the main cause of air pollution from vehicles due to congestion and uneven urban traffic is represented by regulated one-level intersections, as well as the lack of traffic lanes on the roads. At an average vehicle speed of 60 km/h with a traffic flow density of ≈ 30 cars/km at a red traffic light before the intersection, a long queue of dozens of vehicles can be formed (Wu et al., 2010; Mandal et al., 2020).

In recent years, the evolution of intersections has led to the predominant design and construction of complex multi-level (often two-level) interchanges instead of traditional traffic light-regulated or unregulated intersections. Undoubtedly, multi-level interchanges are much safer and environmentally smarter, as they provide a certain balance of traffic flows, minimize the formation of congestion and promote a steadier movement of vehicles. But under the unfavorable meteorological and weather conditions, as well as because of the physico-chemical characteristics of different exhaust components, even on the most modern interchanges, significant air pollution can be seen. So, it is important to study how the total contamination by certain toxicants from the interchange levels impact the neighboring territories.

The level of air pollution is determined by comparing the mass concentrations of a particular impurity with the corresponding values of its maximum permissible concentration (MPC). There are two key types of MPC – the average daily $MPC_{a.d.}$ and the maximum single $MPC_{m.s.}$. The air quality of urban areas is most often assessed by a complex, integrated indicator – the index of air pollution (IAP (or 'ISA') or IAP_5 (or 'ISA_5')), which is calculated based on the average annual (average monthly) concentrations of harmful substances by formula (1) and takes into account the level of harmful effects of particular impurities on the living organisms. The index of air pollution is determined by the five most important impurities for a particular city (or district) according to the formula (1) below:

$$IAP = \sum \left[\frac{C(X_i)}{MPC_{a.d.}(X_i)} \right]^{a_i}, \text{ standard units} \quad (1)$$

Where: $C(X_i)$ – the average mass concentration of the particular toxicant in the air, mg/m^3; $MPC_{a.d.}(X_i)$ – the average daily maximum permissible concentration of the particular toxicant; X – the particular toxicant; a_i – a coefficient that takes into account the harmfulness level of the toxicant compared with the harmfulness of the substance of the 3rd class of hazard, in particular, SO_2.

According to the United States Environmental Protection Agency (EPA, 2014), the Clean Air Act identifies 187 hazardous air pollutants which have to be controlled to protect human health. In particular, in urban areas, 30 air toxicants represent the greatest threat to human health. At the same time, Borys Sreznevsky Central Geophysical Observatory of Ukraine identifies four hazard classes of the dangerous substances, for which the coefficient a_i in formula (1) is set to 1.7 for the 1st hazard class; 1.3 for the 2nd class; 1.0 for the 3rd class; and 0.9 for substances of the 4th class.

To characterize air pollution by individual pollutants, partial IAP(X_i) is used. When the value of $IAP_5 < 5$, the level of pollution is considered low, 5–7 is quite high, 7–14 is high, and above 14 is considered very high. Another indicator of air quality is the standard pollution index (SPI) – the highest established single concentration of a certain harmful substance, divided by the value of its MPC. As a rule, this indicator is estimated by the number of observation posts, where the MPC exceeding for a certain impurity is determined. Therefore, at $SPI < 5$, that is SPI = 1–4, there is an increased level of air pollution; $5 \leq SPI < 10$ means a high level; and $SPI \geq 10$ means a very high level of air pollution (Wu and Lin, 2019; Borys Sreznevsky Central Geophysical Observatory).

Meteorological conditions are very important for the assessment of the air quality in cities because they greatly affect the patterns of transfer and dispersion of harmful substances in the atmosphere. In particular, the strongest influence is exerted by the wind regime (its direction and speed), as well as temperature stratification, the presence and type of precipitation, fog, solar radiation, temperature inversions, etc. It is known that the higher the average wind speed, the more intense is the dispersion of impurities and the larger is the area that is ‘covered’ by the pollutant.

The main types of pollutants penetrating the air with vehicle emissions have been considered in terms of their aerodynamic characteristics and the possibility of local concentration in certain layers of the air (or at a certain distance from the road). *Table 1* shows chemical formulas of toxicants, which are components of the vehicle exhausts, as well as their relative density in the air, calculated by the formula (2):

$$D_{air}(X) = \frac{M(X)}{M_{air}}, \qquad (2)$$

Where: $D_{air}(X)$ – the relative density of the gaseous compound X by the air; $M(X)$ – the molar mass of the compound, g/mol; M_{air} – the molar mass of the air that is equal to 28.98 g/mol; the conclusions on the behavior of pollutants in the air environment of the roadside space have been made.

According to the values of the relative density of toxicants by the air, it was established that some pollutants (components of the exhaust gases) are lighter than air and are likely to rise with upward air currents, while pollutants-gases and solid particles, which are heavier than air, in particular PM_{10}, will be mainly concentrated and accumulated in the lower layers of the atmosphere. This allows us to conclude that from an environmental point of view, transport interchanges in two or more levels can contribute to uneven, additional local pollution of the lower road section environment, while pedestrians and participants of the upper-level traffic will breathe in high concentrations, for example, CO and HCHO (*Table 1*).

Motorways (roads) in the models for calculating the pollutants dispersion, as a rule, are presented as a set of linear and point pollution sources (Kholodnov et al., 2007). There are many scientific and scientific-practical approaches, models, formulas, etc. in the world to establish surface concentrations of toxicants (Berlyand, 1975; Berkowicz et al., 1997; Dorokhov et al., 2014; Reggente et al., 2015; Vafa-Arani et al., 2014; Voloshkina et al., 2018; EPA), but not all of them have been tested and can be used in practice.

For example, the American Meteorological Society (AMS), EPA, and Regulatory Model Improvement Committee AERMOD use Gaussian models that take into account possible chemical transformations, as well as dry and wet deposition of toxicants in the surface air layer, and their concentrations are described by the three-dimensional Gaussian function (EPA).

The European Environment Agency offers the COPERT 4 software package for the calculation and inventory of vehicle emissions, based on the empirical data on specific emissions as well as the fuel consumption of certain vehicle types, fleet size, its structure and age, length of roads of different categories, types of fuels used, ecological class and mileage of vehicles, traffic flow characteristics, etc. COPERT 4 software is primarily used to give the international organizations official data of the particular country on emissions of pollutants (including greenhouse gases) by transport, modeling the state and quality of air in cities and suburbs, to calculate local pollution of the territories, and so on.

Such models as HIWAY-2 (Highway air pollution model), CALINE-4 (California Line Source Model), GFLSM (General Finite Line Source Model), GM (General Line Model), and OMG (Osaka Municipal Government volume source model) are widely used. They are based on the normal Gaussian distribution law. Models ROADWAY (Roadway air pollution model) and MGO (Main Geophysical Observatory), which are based on the K-theory, are also widely used. In order to calculate the level of air pollution in street canyons, the OSPM (Operational Street Pollution Model) is used, which takes into account the characteristics of both street canyons and urban buildings, as well as meteorological conditions, street configuration, etc. (Berkowicz et al., 1997). The dispersion of impurities in the air is determined by a combination of ‘box’ and ‘plume’ models. There are also many methods of mathematical modeling of the air state based on GIS technologies.

The prediction of the ecological state of the airspace of a certain area requires, firstly, reliable information on the content of primary pollutants in the air, and, secondly, information on the conditions of their possible transformation into secondary pollutants, which can sometimes be even more dangerous, as well as the time of their ‘life’ in the atmosphere, the nature of dispersion (concentration), the conditions of sedimentation and coagulation in dry conditions and/or during precipitation (wet deposition), etc. Such tasks require a lot of time and powerful software, so they are usually implemented in research centers and institutes.

Thus, the processes of dispersion and concentration of harmful impurities in the air are influenced by the direction and speed of the average wind, meteorological and weather conditions, physical and chemical properties of the pollutant, possibilities, and conditions of its transformation in the environment, sedimentation and/or secondary mechanical transfer. The level of danger of atmospheric air pollution should be determined by the highest concentration of the pollutant, calculated under dangerous meteorological conditions (Berlyand, 1975; Wu and Lin, 2019; Borys Sreznevsky Central Geophysical Observatory), in particular, during the warmest month of the year and at dangerous wind speeds (up to 6 m/s).

The most common Kholmogorov’s equation in hydrodynamics, which allows modeling complex stochastic processes of transfer of harmful impurities without taking into account possible chemical and physicochemical transformations, has the following form:

$$\frac{\partial C}{\partial t} = -v_x \frac{\partial C}{\partial x} - v_y \frac{\partial C}{\partial y} - v_z \frac{\partial C}{\partial z} + D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right) \quad (3)$$

and characterizes the change in the concentration of the impurity in the flow along the axes x, y, and z in time t, which is due to the movement of the flow with the corresponding velocities v_x, v_y, v_z taking into account the diffusion coefficient of the impurity D_i.

In our investigation for the prediction of the roadside air pollution, in a surface layer with the height up to 2 m, a model of flare approximation by the method (Berland, 1975; Kholodnov et al., 2007) was used. This model is based on the K-theory and the turbulent diffusion equations (Berland, 1975; Berlyand and Bezugla, 1983; Voloshkina et al., 2018).

The study uses a torch approximation model in the Mathcad software to solve the semi-empirical equation of turbulent diffusion for a linear source as a set of point emission sources based on the principle of superposition of concentration fields of a certain harmful impurity. The model allows potentially taking into account the density of urban development, terrain, qualitative characteristics of the underlying surface, photochemical and various chemical transformations, meteorological conditions (normally unfavorable, abnormally unfavorable), the presence and type of precipitation and more.

The idea of the method, the calculation algorithm, and the peculiarities of visualization of the obtained fields of concentrations of the studied toxicants are presented in detail in (Kofanov et al., 2020). The result of the calculation of surface concentrations of a certain impurity is given in the multiplicity of its $MPC_{m.s}$, the mathematical model of impurity dispersion is obtained in the form of a system of differential equations in partial derivatives, the solution of which is possible only under certain boundary conditions. The model was based on the equation (Kholodnov et al., 2007; www.uazakon.com):

$$Q = \frac{M}{(1+n) \cdot k_1 \cdot \varphi_0 \cdot x^2 \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{u_1 \cdot H^{1+n}}{k_1 \cdot (1+n)^2 \cdot x} - \frac{y^2}{2 \cdot \varphi_0^2 \cdot x^2}} \qquad (4)$$

Where: M – the power of the emission source (mass of the substance emitted by the pollutionsource per unit of time); n – the coefficient characterizing the atmosphere stability; u_1 – the parameter characterizing the wind speed; k_1 – the coefficient for the turbulent diffusion profile of the impurity in the atmosphere; φ_0 – the standard deviation for a pulsation of wind direction; H – the height of the emission source above the surface of the ground.

In the obtained concentration fields, the coordinate system is oriented so that the OX axis coincides with the average wind direction; the OY axis coincides with the traffic flow direction and the OZ axis is perpendicular to the traffic flow. The concentration from a linear source is considered equal to the superposition from point sources according to the equation:

$$Qp = \int_{L_1}^{L_2} Q \cdot \left(a - L \cdot \sin(\beta), b - L \cdot \cos(\beta)\right) dL \qquad (5)$$

Where: a and b – new coordinates in the redirected by the average wind direction system of coordinates that are related to the original coordinates by Eq. (6); L – the length of the studied road section.

$$\begin{aligned} a &= x \cdot \cos\beta + y \cdot \sin\beta; \\ b &= -x \cdot \sin\beta + y \cdot \cos\beta \end{aligned} \qquad (6)$$

Where: β – the angle between the direction of the average wind and the direction of the traffic flow on the motorway.

The concentration fields showing the dependency of the multiplicity of the $MPC_{m.s}$ excess from the distance from the road were created using the formula:

$$Q' = \frac{Q_p}{MPC_{m.s.}} \qquad (7)$$

The reliability of the used methodology can be proved, first of all, by its affirmation at the state level in Ukraine (www.uazakon.com) and using similar methods in other European countries. In particular, the proposed methodology correlates with the European standard BS EN 16258:2012 'Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)' established by the British Standards Institution. An analogical method was used by Jereb et al. (2021) for the aim of assessment of fuel consumption and CO_2 emissions caused by urban traffic flows in Celje city (Slovenia), as well as in the paper of Alobaidi et al. (2019) for the aim of estimation of carbon monoxide, carbon dioxide, nitrogen oxides, and hydrocarbons emissions.

Results and Discussion

Under favorable meteorological conditions, harmful impurities disperse quickly in the air. But under conditions of temperature inversions, calms, fogs, strong air heating, dense urban development, the formation of zones of local emergency concentration of certain impurities is possible. These zones can be located both near sources of emissions of harmful substances, and near apartment houses, public transport stops, in yards, especially of a 'well type', etc.

Dispersion of harmful impurities in the air is due to atmospheric turbulence, which occurs, firstly, due to molecular diffusion (minor role) and, secondly, due to turbulent (major role) diffusion of gaseous substances. Turbulent diffusion, in turn, consists of two components – thermal and dynamic. Thermal diffusion provides convective turbulence and is associated with a vertical temperature gradient of the air, while dynamic diffusion provides mechanical turbulence and occurs during the movement of air masses under the action of wind. In the lower atmosphere layers, it is enhanced by the orography of the area, in particular under the influence of macro-unevenness of the relief, and is not associated with the air temperature gradient (Vallero, 2008). So, the surface layer of the atmosphere is formed due to the interaction of airflow with the elements of the underlying surface; it is called the roughness layer.

The main dynamic characteristic of the surface is its roughness z_0 – zero level, from which the logarithmic wind profile is counted. Below the level of roughness, the average progressive motion of the airflow is absent, because the flow is exposed to pressure forces that occur near the elements of roughness. Above this 'zero' layer of roughness, there are usually so-called layers of 'permeable roughness', which have different heights and contain various obstacles that resist the airflow. In such layers, there is (*Table 2*) a decrease in the average wind speed compared with the layers that do not contain these obstacles (Berland, 1975; Berlyand and Bezugla, 1983; Afiq et al., 2012).

So, the task of modeling the movement of air masses and forecasting the conditions of dispersion of harmful impurities in the atmosphere is complicated by both the proximity and heterogeneity of urban development and the peculiarities of the terrain.

Therefore, atmospheric turbulence is usually represented by a combination of two processes – convective turbulence (these are natural convective flows that appear as the result of heating the layers of atmospheric air) and mechanical turbulence as a result of wind displacement of air flows (Berlyand and Bezugla, 1983; Vallero, 2008). Therefore, the main processes that ensure the mixing of air masses in the lower atmosphere layers are the temperature gradient and mechanical turbulence (as has been noted, it is closely related to the interaction of wind currents with the underlying surface). At the same time, the degree of atmosphere stability largely determines its ability to disperse harmful impurities. It is determined, for example, by the absence of significant vertical movements and mixing of air masses.

Vegetation also significantly affects the characteristics of wind flows and the peculiarities of the dispersion of toxic impurities in the surface layer of the air. Firstly, the partial absorption of toxicants by vegetation can be observed and, as a result, the effect of air purification, and secondly, due to mechanical inhibition of the spread of toxicants, conditions for the formation of so-called geochemical barriers are created. Water bodies near the highways not only affect the climatic and meteorological conditions of the city but also partially absorb harmful impurities, concentrating them, for example, in bottom sediments and aquatic organisms.

In general, the calculation of surface concentrations of toxicants from vehicle emissions requires data on the intensity of traffic flows on the city's highways, as well as data on the vehicle types and emission volumes for all pollutants. In this regard, the study performed space-time field video surveillance separately for linear highway sections, for regulated intersections and interchanges at different levels; traffic conditions were studied. Investigations were conducted on the workdays at several observation posts simultaneously in the morning 'peak' time (8^{00}–9^{00}), in the afternoon after 11 and 16 o'clock, as well as during the 'peak' time in the evening (18^{00}–19^{00}). The mathematical statistics methods were applied both at the stage of planning and organization of the road observations of

Table 2. *The value of the surface roughness parameter z_0 depending on the type of underlying surface (Berlyand and Bezugla, 1983; Afiq et al., 2012)*

Surface type	z_0, cm
Sand	0.01÷0.1
Snow cover	0.1÷0.6
Mown grass (~0.01 m)	0.1÷1
Low grass	1÷4
High grass	4÷10
Dwarf plants	10÷30
Suburbs with medium-sized buildings	20÷40
Cities with continuous urban development	80÷120
Centers of large cities	200÷300

vehicle flows in the studied areas, and at the stage of the research results processing. Monitoring of traffic flows (*Table 3*) was carried out 3 times for 20 minutes, which made it possible to calculate the value of the power of the emission source M in Eq. (4) with a probability of $p = 0.9$.

Table 3. *The intensity of traffic flows at the studied multi-level interchanges (Kyiv, Ukraine, summer season, the number of vehicles)*

Time	Industrial Multi-level Interchange		Akademika Palladina Ave. – Kiltseva doroha st. Interchange	
	Upper road	Lower road	Upper road	Lower road
8^{00}–9^{00}	2424	2982	4503	4791
11^{00}–12^{00}	1782	2052	3279	3486
16^{00}–17^{00}	1689	1944	3150	3396
18^{00}–19^{00}	2337	2685	3624	3906

Thus, at the first stage, statistical data on the traffic flows density and intensity at different interchange levels were accumulated; based on the empirical data, the amounts of motor vehicle emissions for the definite pollutants were calculated. For mathematical model development, data on the main meteorological parameters were recorded, in particular, the average wind direction and speed, the temperature and humidity of the atmospheric air. So, the synoptic-statistical method was applied.

Days with an air temperature of $0 < t_{air} < 25^{o}C$, wind speed of 1–5 m/s, and neutral or medium-unstable atmosphere stratification were chosen for road observations. Observations were made at different times of the year; precipitation and traffic jams on the roads were absent (Kofanov et al., 2020). During the simulation, it was assumed that the dispersion of both gaseous impurities and particulate matter (PM_{10} and $PM_{2.5}$) conform to the same laws since the latter ones have a low deposition rate in the air.

Statistical processing of the results of road observations was carried out by the sampling method which includes several stages. For task solving, the first stage is the calculation of the main statistical parameters of each of the statistical samples and checking the type of distribution law for all of them. However, the results obtained during the statistical processing can be considered reliable only if the investigated sample is homogeneous. In this regard, at first, the homogeneity of the empirical data samples was evaluated by the control criterion (Q-criterion), the values of which depend on the number of measurements (observations) n and the value of the probability p.

In order to check the homogeneity of the empirical data sample, the obtained observation results were grouped appropriately, the variation interval R and control criteria Q_{exp} were calculated for the first and last variation values of the studied sample with a probability $p = 0.9$. The statistical sample is considered heterogeneous if at least one of Q_{exp} is higher than the table value of Q_{tab}. So, before the statistical processing, homogeneous empirical data samples were formed and only they were used for the further analysis. Therefore, the checking of the homogeneity of investigated statistical samples at the selected time intervals (*Table 3*) has shown that all of them were homogeneous. At the next stage, the main statistical parameters of the investigated samples were calculated, namely: mode, median, the distributional mean at a certain time interval, the expectation (or the expected value), variance and standard deviation of the sample. Statistical analysis of the empirical data was conducted using Microsoft Office Excel and IBM SPSS Statistics software packages.

During studying the pollution of atmospheric air and territories neighboring multi-level interchanges with harmful substances, originating from the motor vehicle emissions, a particular attention was paid to the extreme values. This approach can be substantiated by the fact that in a case when a potential danger to human health is observed on a certain territory due to the possible exceeding of the impurities MPC, it is necessary to organize the monitoring in order to control the level of environmental safety. If there is no exceeding of the impurities MPC, then systematic monitoring of the state of atmospheric air in this area will be economically unjustified.

Due to the mentioned facts, the modeling of concentration fields of the main toxicants, which are the components of vehicle emissions (carbon monoxide, nitrogen oxides, and particulate matter), under adverse weather conditions, in particular, in summer, for dangerous wind direction and speed 1–5 m/s, was conducted according to the methodology equations (4–7). In *Fig. 1*, *Fig. 2a*, and *Fig. 3a*, the concentration fields of the most dangerous pollutants – nitrogen oxides (in terms of NO_2) and particulate matter PM_{10} – for the transport interchange in two levels (on the example of the Industrial Multi-level Interchange, Kyiv) are shown. The upper road has two traffic lanes in each direction; the lower road has three traffic lanes in each direction. The interchange is constructed in the form of an 'incomplete clover leaf'.

For further computational experiment and in order to prove the potential danger of extreme local concentration of certain impurities in the lower road (first level) and especially at public transport stops, located on the territories neighboring multi-level interchanges, due to the harmful effects of the upper road (second level), these pollutants were selected since their relative density in the air is $D_{air}(X) > 1$ (formula (2)).

Thus, in *Fig. 2b* and *Fig. 3b*, the concentration fields of the same pollutants on the first level road, taking into account the sedimentation processes of these impurities under the action of gravity were visualized. As an example, the modeling results are shown for the 50% of the additional load from nitrogen oxides (in terms of NO_2) and for the 70% of the additional load from PM_{10} on the lower road from the primary emissions of pollutants from the upper road of the investigated transport interchange.

As can be seen (*Fig. 2*b and *Fig. 3*b), under such conditions, there will be a significant increase in the concentration of harmful impurities in the center of the road, as well as an increase in the distance at which the safe concentration of pollutant $C(X) < MPC_{m.s.}(X)$ will be settled. This is especially noticeable for nitrogen oxides when due to the sedimentation processes the technogenic load in the center of the first level road will increase almost 1.6 times, while safe concentrations of the toxicants will be achieved at a distance of more than 17–18 m from the road center.

In addition to the primary pollution from traffic flows, secondary pollution of the areas adjacent to the highways is possible due to the mechanical transfer of pollutants, their interaction, including under the influence of the sunlight, precipitation, etc.

All this poses a serious danger to the health of people who stay for a long time at the transport stops, move on the sidewalks and underground crossings, as well as for vehicle drivers and passengers. This is quite relevant also for cafes and different retail outlets which are often placed on the territories neighboring multi-level interchanges.

The ecological situation can be significantly aggravated if after a long-term concentration of pollutants on the lower road there are harsh and powerful gusts of wind (with a speed above 7–10 m/s), which either lift the accumulated toxicants directly into the human respiratory zone or blow them into underground crossings. This is especially related to PM, which, as noted, can adsorb harmful, including carcinogenic, substances throughout their localized state.

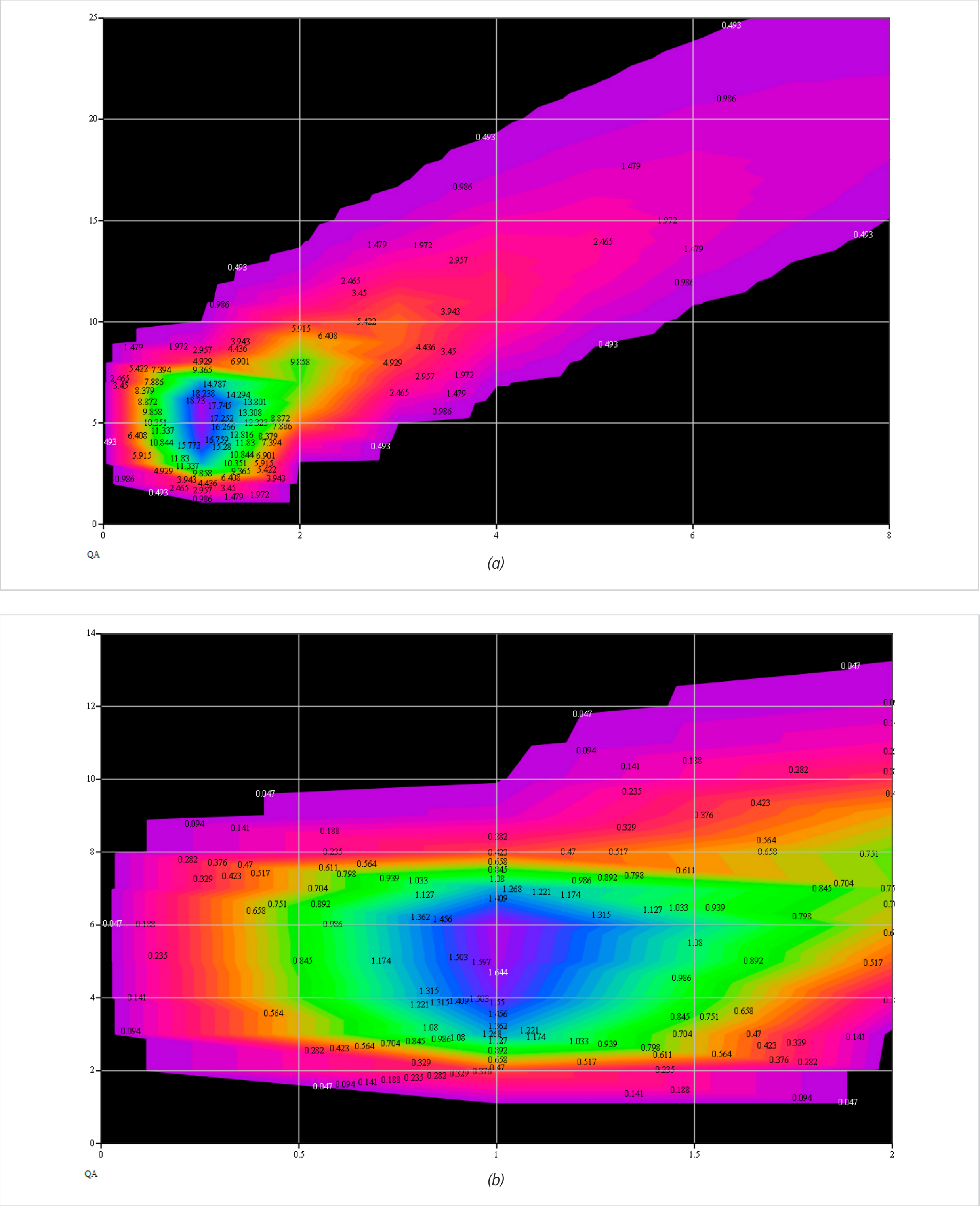
On the example of the transport interchange of Akademika Palladina Ave. – Kiltseva doroha st. (Kyiv), the concentration fields of nitrogen oxides (in terms of NO_2) and particulate matter PM_{10} are presented for the upper road (second level) (*Fig. 4*).

This interchange is constructed in the form of a big clover leaf and characterized by four traffic lanes in each direction both for the upper and lower roads. The concentration fields of the investigated pollutants for the lower road without the load from the upper road are shown in *Fig. 5a* and *Fig. 6a*.

Taking into account the sedimentation processes, in *Fig. 5b* and *Fig. 6b*, the concentration fields of these pollutants for the first level road, considering the deposition of 50% of the emissions of nitrogen oxides (in terms of NO_2) and 70% of PM_{10} emissions from the primary emissions of the second level road, are shown.

Thus, for nitrogen oxides due to sedimentation, the technogenic load in the center of the first level road will be ~ $48.6 \cdot MPC_{m.s.}$ (*Fig. 5b*). The particulate matter PM_{10} behaves similarly under the same meteorological conditions (in particular, wind direction and speed). Its dispersion conditions will be much more difficult; therefore, it will be concentrated at a distance of not more than 1–2 m from the road center. Thus, from *Fig. 5* and *Fig. 6*, it can be seen, that the technogenic load in the center of the first level road will be increased almost by 1.4 times in terms of nitrogen oxides and 1.6 times in terms of PM_{10}.

Fig. 1. *Concentration fields of a) nitrogen oxides (in terms of NO_2) and b) particulate matter within the investigated traffic interchange at south-east wind direction (average wind speed is 3 m/s) on the upper road*



(a)

(b)

Fig. 2. *Concentration fields of nitrogen oxides (in terms of NO_2) within the investigated traffic interchange at south-east wind direction with an average speed of 3 m/s: a) the lower road without taking into account additional load from the primary nitrogen oxides emissions from the upper road; b) the lower road taking into account 50% additional load from the primary nitrogen oxides emissions from the upper road*

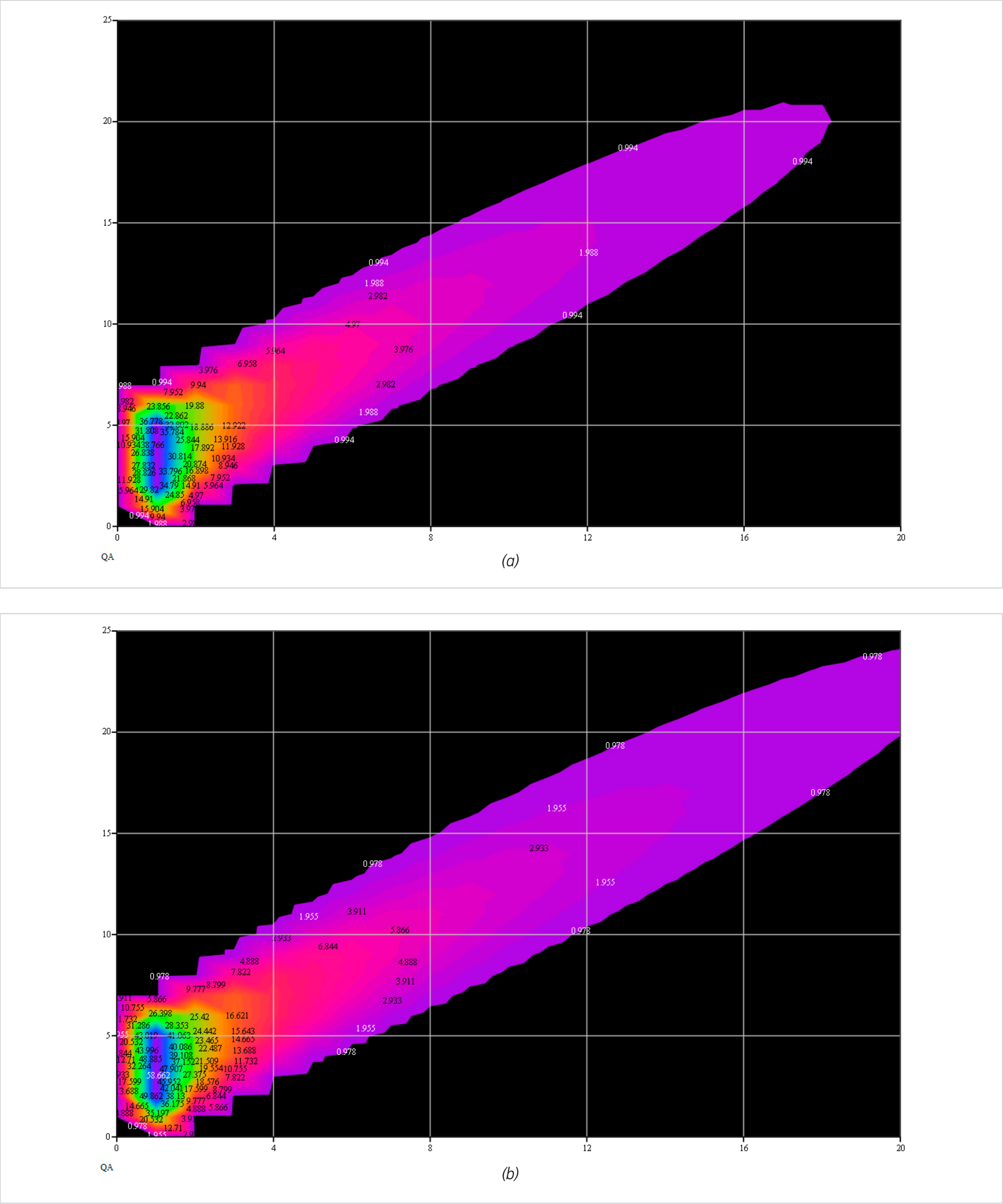
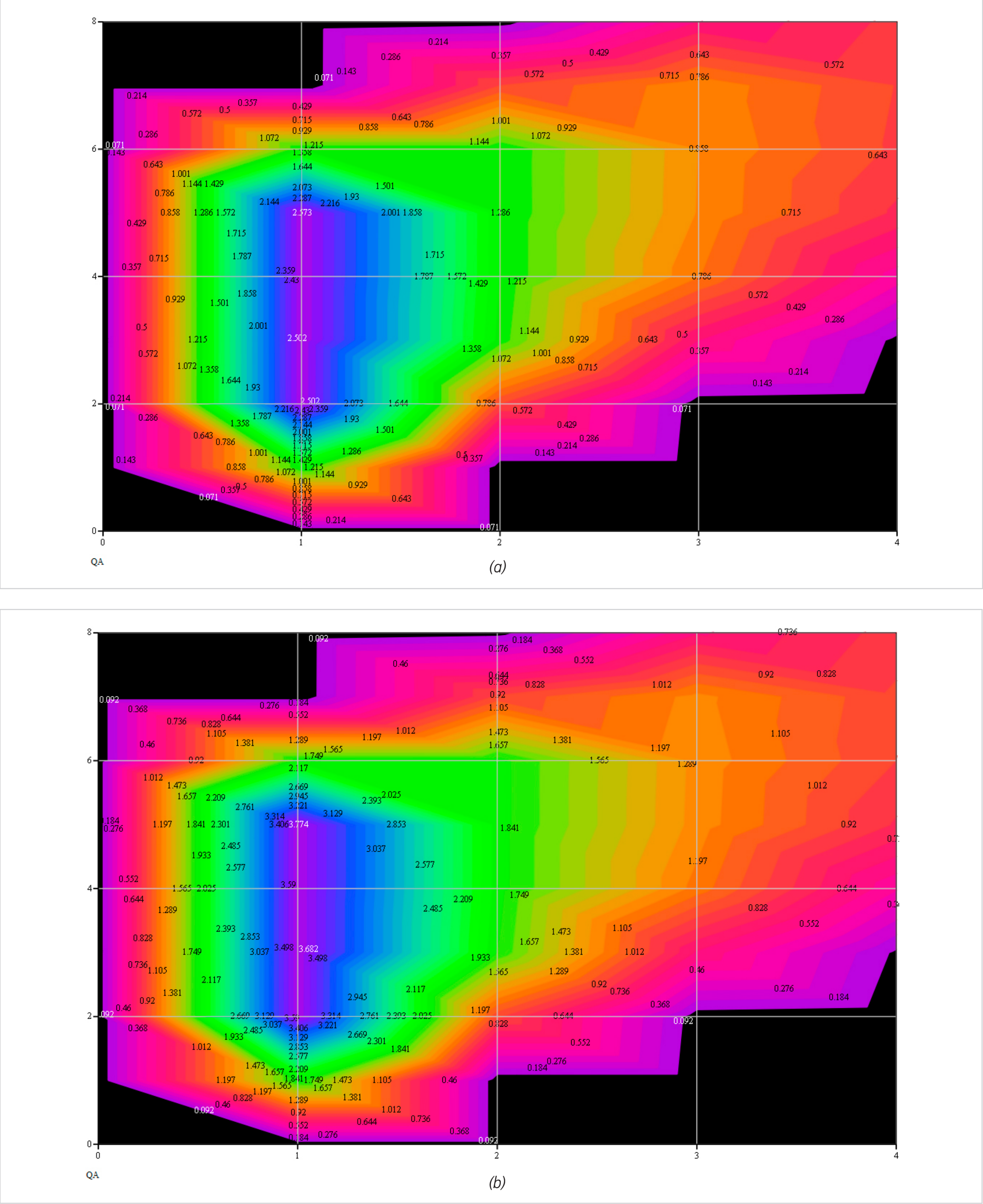


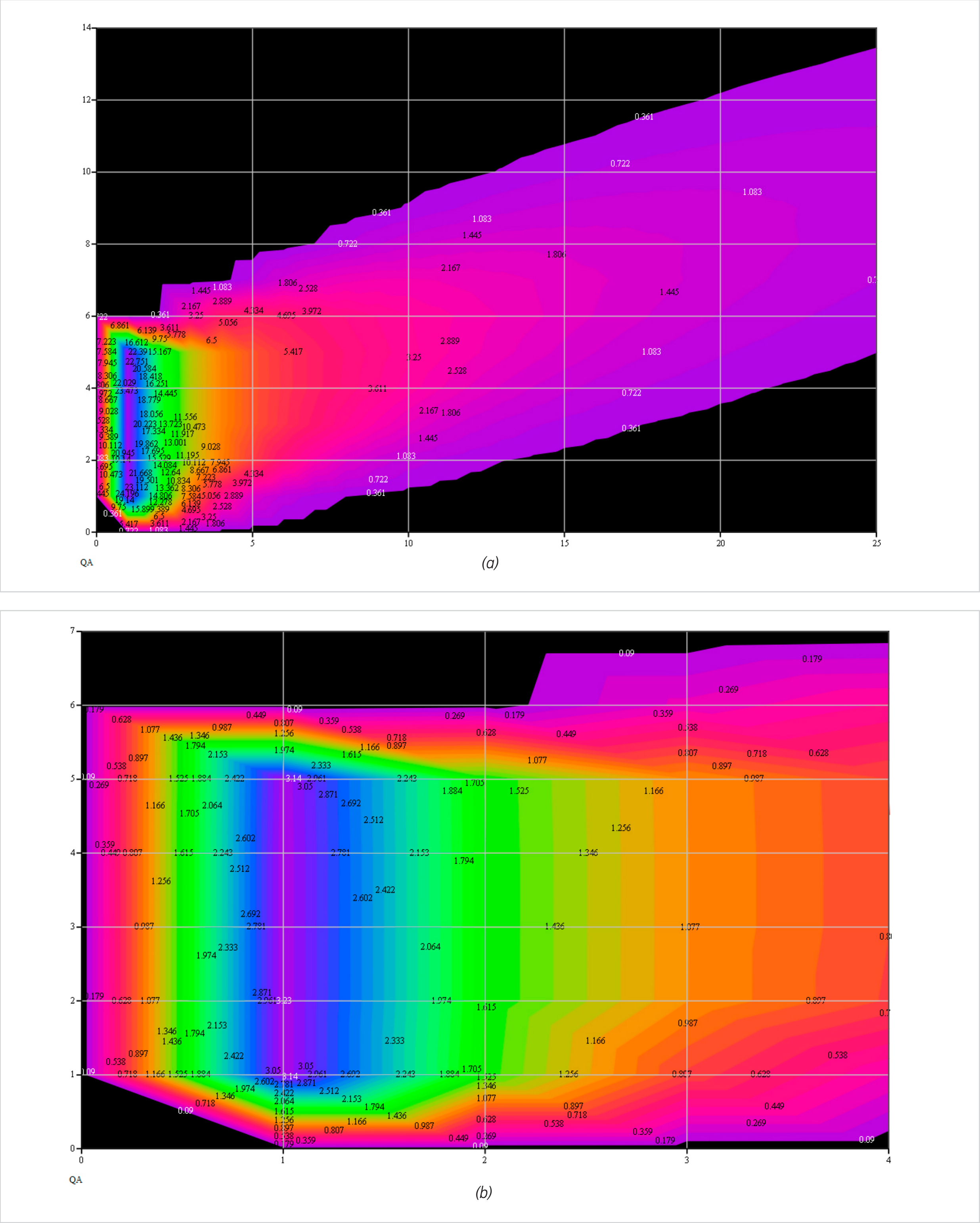
Fig. 3. *Concentration fields of PM$_{10}$ within the investigated traffic interchange at south-east wind direction with an average speed of 3 m/s: a) the lower road without taking into account additional load from the primary PM$_{10}$ emissions from the upper road; b) the lower road taking into account 70% additional load from the primary PM$_{10}$ emissions from the upper road*



(a)

(b)

Fig. 4. *Concentration fields of a) nitrogen oxides (in terms of NO_2) and b) particulate matter within the investigated traffic interchange at west wind direction (average wind speed is 3 m/s) on the upper road*



(a)

(b)

Fig. 5. *Concentration fields of nitrogen oxides (in terms of NO_2) within the investigated traffic interchange at west wind direction with an average speed of 3 m/s: a) the lower road without taking into account additional load from the primary nitrogen oxide emissions from the upper road; b) the lower road taking into account 50% additional load from the primary nitrogen oxide emissions from the upper road*

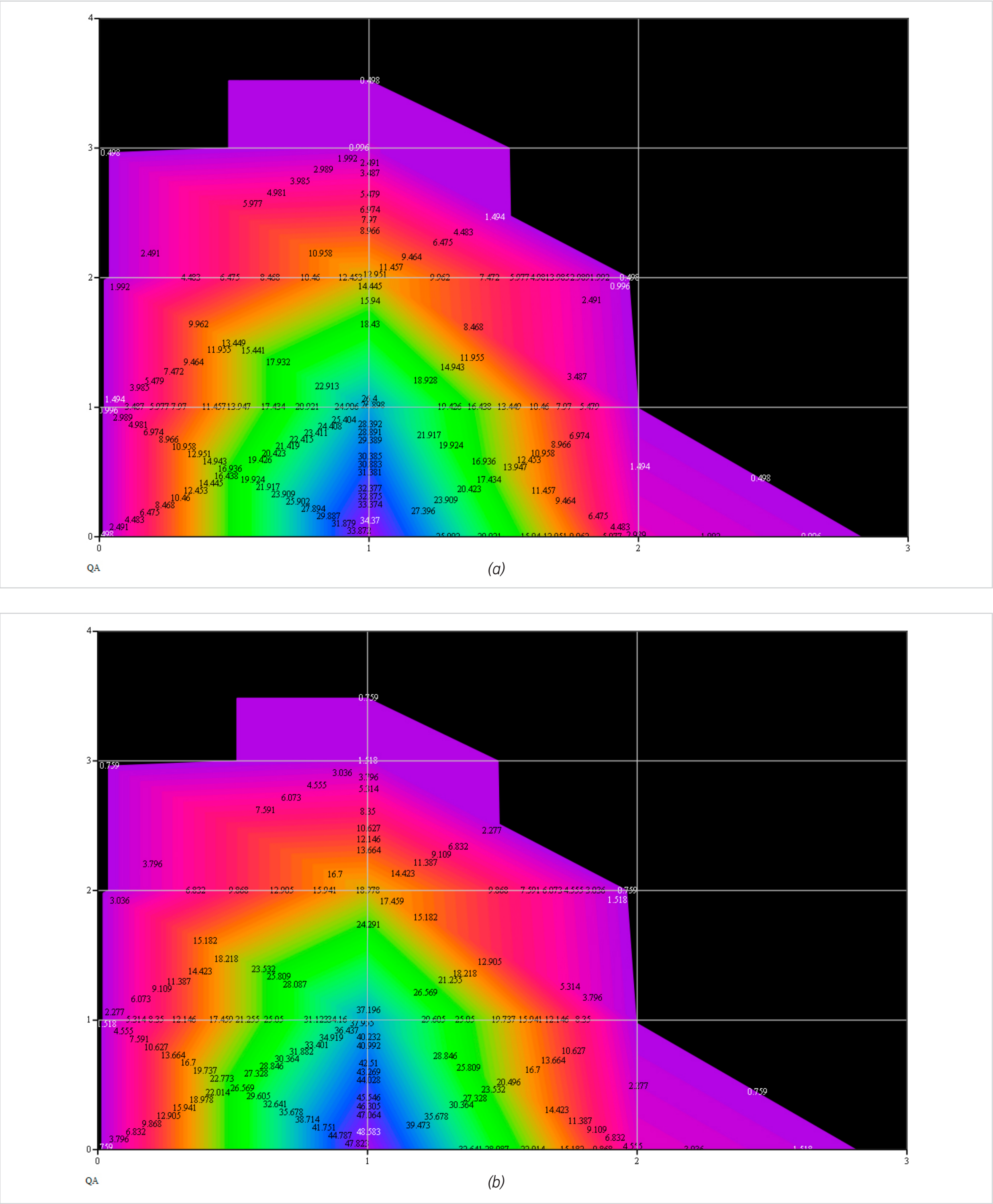
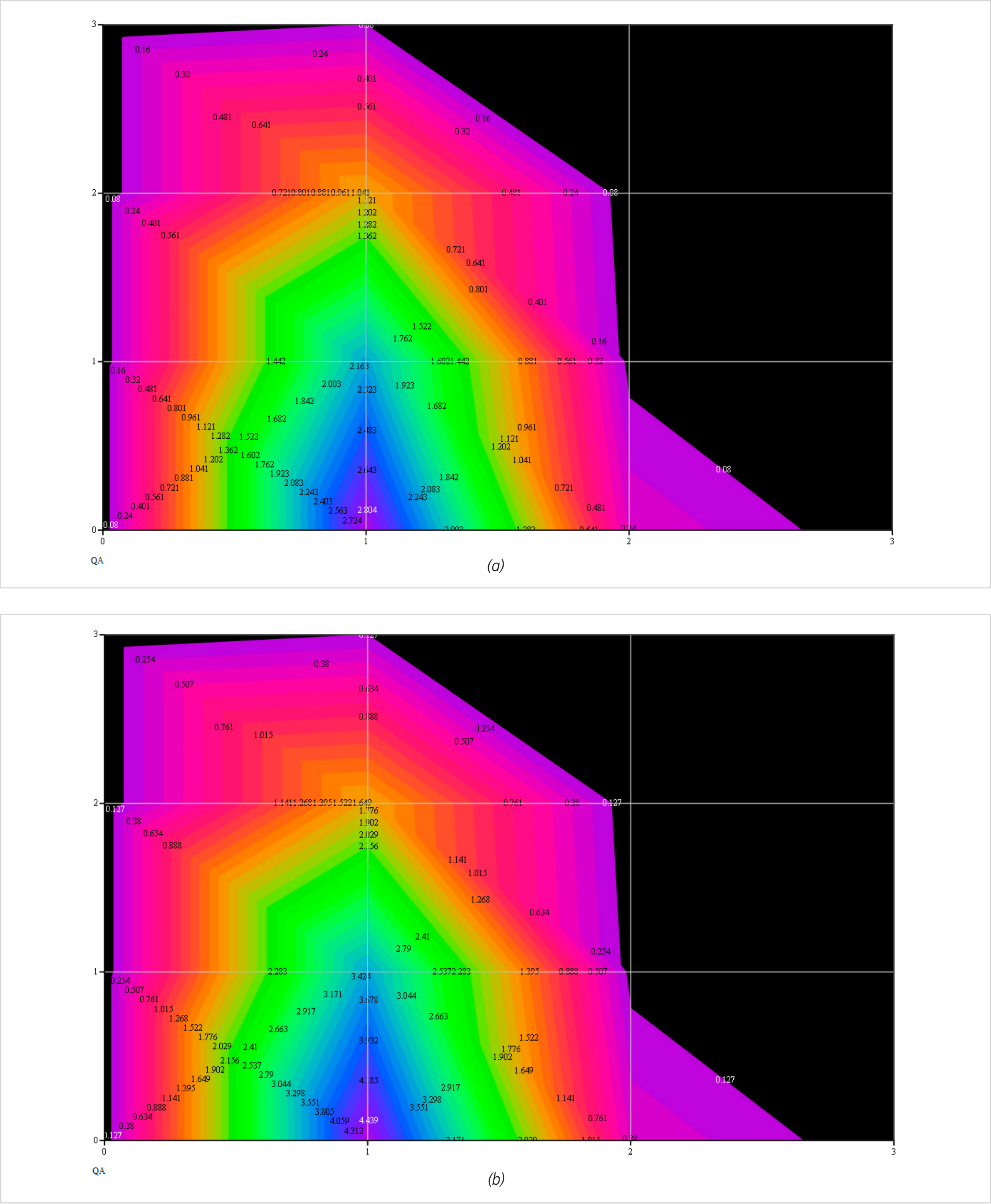


Fig. 6. *Concentration fields of PM_{10} within the investigated traffic interchange at west wind direction with an average speed of 3 m/s: a) the lower road without taking into account additional load from the primary PM_{10} emissions from the upper road; b) the lower road taking into account 70% additional load from the primary PM_{10} emissions from the upper road*



(a)

(b)

Conclusions

The air pollution on the territories neighboring multi-level interchanges was studied and the additional load on the interchanges lower levels was assessed based on the analysis of physico-chemical properties of harmful exhaust components and the mathematical modeling approach. A computational experiment for air pollution level prediction on different interchange levels was carried out with the help of Mathcad software package. To predict the pollution level of the territories neighboring multi-level interchanges, the model of torch approximation based on the K-theory and the equations of turbulent diffusion was used.

Research shows that due to the sedimentation processes a significant increase of the technogenic load on the interchanges first-level road will be observed. Such additional load is mainly caused by exhaust components heavier than air (with a relative density by the air greater than 1.0). It was found that, compared with the upper road, the technogenic load in the center of the lower road increases on average by 1.4–1.6 times in terms of nitrogen oxides and by 1.5–1.6 times in terms of PM_{10}. Moreover, the territory with the harmful substances maximum permissible concentration excess is significantly increased.

So, taking into account that multi-level interchanges are much more environmentally acceptable than surface sections of roads with traffic lights and pedestrian crossings, they still pose a serious danger to the health of people who stay for a long time at the transport stops, move on the sidewalks and underground crossings, as well as for vehicle drivers and passengers. This is quite relevant also for cafes and small shops which are often placed on the territories neighboring multi-level interchanges. Thus, for sustainable and smart urban planning it is recommended not to place public transport stops, cafes, shops and other city infrastructure objects on such territories, as well as to remove existing ones.

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