This study considers the aerodynamic characteristics of airflows on highways with protective roadside barriers. The task to optimize roadside barriers was addressed by analyzing airflow aerodynamic patterns using physical modeling and computational simulation. A flow structure visual diagnostics method (FSVD) was employed to analyze the kinematic features of airflow formation in the roadside barrier zone. It was established that the use of discrete-type barriers leads to the formation of stable air structures that enhance active flow mixing and dilution through external air entrainment. Each discrete element consists of a diffuser shield, expanding at an angle of 4° to the roadway axis, with a length equal to three lane widths. Additional elements in the form of parallel screens (confusors) are positioned between shields at an angle of 60° to the roadway axis. The combined approach, integrating FSVD and computational simulation in SOLIDWORKS Flow Simulation, provided a detailed representation of airflow behavior. It was determined that confusors between discrete shields generate an ejection effect, promoting external air entrainment and dilution within the roadway zone. This ensures unidirectional clean airflow and prevents exhaust gases from entering near-ground layers of residential areas. The applied computational model demonstrated the consistency and unidirectionality of dilution processes through ejection and dispersion via vertical flows. This enables better air circulation compared to conventional analogs, prevents stagnant zones, and reduces the impact of crosswinds and adverse atmospheric stability conditions. The devised structural solutions could be applied to design and optimize roadside barriers, particularly in residential areas

Keywords: vehicle emissions, protective roadside barriers, visual diagnostics method, computational simulation

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DETERMINATION OF THE DESIGN FEATURES OF ROADSIDE AIR PROTECTION BARRIERS OF URBAN MOTORWAYS USING VISUAL DIAGNOSTICS AND COMPUTATIONAL MODELLING

Kateryna Vasiutynska
Corresponding author
PhD, Head of Department
Department of Environmental Safety and Hydraulics*
E-mail: e.a.vasutinskaya@op.edu.ua

Vasyl Arsirii
Doctor of Technical Sciences, Professor
Department of Heat Supply and Ventilation**

Sergiy Smyk
PhD, Associate Professor
Department of Information Systems*

Olena Makovetska
Senior Lecturer
Department of Chemistry and Ecology**

*Odesa Polytechnic National University
Shevchenka ave., 1, Odesa, Ukraine, 65044

**Odessa State Academy of Civil Engineering and Architecture
Didrikson str., 4, Odesa, Ukraine, 65029

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1. Introduction

The acceleration of urbanization and the improvement of life of the urban population are inextricably linked to the development of transport infrastructure, a significant increase in roadways and transport flows. As of 2024, there were about 1.475 billion vehicles in the world [1]. The rapid development of cities has led to a change in the priority of contribution of mobile sources of pollution over stationary ones.

Transport emissions are often more dangerous than emissions from industrial and energy facilities, as they affect densely populated urban areas and spread over considerable distances. Studies of air quality near highways by the authors of work [2] showed that maximum concentrations of pollutants are observed within 100÷150 m, but excess concentrations are recorded at distances of up to 500 m from the road. Dense multi-story buildings change the direction and speed of wind flows, which seriously impedes the dispersion of pollutants and increases the danger of urban air.

Traffic-related air pollution (TRAP) includes volatile organic compounds (VOCs), nitrogen oxides (NO^x), carbon monoxide (CO), lead compounds, benzo(a)pyrene, particulate matter (PM), and others. This complex cocktail of substances pollutes urban air, which is especially dangerous during traffic jams. Adverse health effects include both short-term effects on changes in blood pressure, heart rate, and heart rate variability, and long-term effects on the increased risk of cardiovascular disease [3]. Available data [4, 5] indicate a link between TRAP and exacerbation of asthma and non-asthmatic respiratory symptoms, impaired lung function, and other diseases.

In Ukraine, the problem of automobile emissions is also extremely relevant. Only in five oblasts (Vinnytsia, Dnipropetrovsk, Donetsk, Zaporizhia, Ivano-Frankivsk) there was a predominance of stationary emissions over transport emissions at the beginning of 2022. The specific share of transport pollution per capita increased by 1.13 times over a 25-year period (1995–2020) against the background of a 1.8-fold reduction in specific emissions from stationary sources [6]. Transport emissions are dangerous not only for atmospheric air but also for other components of the environment. Studies [7] have established the maximum value of the pollution index of urban soils of roadside strips, which is close to the value of the index for soils near industrial enterprises.

Therefore, control of emissions from mobile sources, urban planning of highways, and organization of traffic flows in cities and beyond are necessary measures for sustainable development of the city. Studies [8, 9] report measures that make urban traffic more environmentally friendly and sustainable. Thus, control over the total number of vehicles, implementation of high emission standards, promotion of non-gasoline vehicles, optimization of traffic flow, and promotion of non-motorized transport systems are proposed.

An important addition is the installation of roadside protective barriers, which can provide an instant protective effect in places with high levels of pollution and significantly reduce the concentration of harmful substances near residential areas, schools, hospitals, etc. At the same time, it is protective barriers that can minimize the spread of secondary pollution, which is caused by wear of tires, brakes, and road surface.

However, in Ukraine there is practically no practice of using barriers to protect against noise and pollution both on major highways and within cities. Instead, the problem of installing roadside barriers made of artificial materials or vegetation is an important component of the fight against the spread of transport pollution in different countries of the world. Air protection structures provide local protection of public health and minimize the impact of transport activities on air quality. The key tasks for achieving maximum effect are to determine the optimal barrier design, type of material, pollutant dispersion efficiency, optimization of locations, etc. Such a multifactorial task requires a comprehensive analysis based on various methods of physical modeling and numerical simulation.

Therefore, it is a relevant task to carry out studies on effective modeling and analysis of the impact of roadside barriers on the aerodynamic characteristics of air flow polluted by motor vehicles. This would make it possible to devise scientific and practical recommendations for their design and location and could also contribute to reducing the impact of transport emissions on the environment and human health, in particular in densely populated residential areas.

2. Literature review and problem statement

Vegetated roadside barriers are an effective tool for reducing air pollution, but the feasibility of their use depends on many factors, such as the type of plants, location, and climatic conditions. In [10] it is shown that tall vegetation (trees) in street canyon conditions lead to a deterioration in air quality, while low-growing green fences (hedges) improve air quality conditions. On the contrary, in open roads, wide and tall vegetation leads to a reduction in the concentration of pollutants on the windward side. However, the issue of a comprehensive analysis of the effectiveness of vegetative barriers under conditions of high traffic intensity has remained unresolved. In contrast, high solid barriers (usually higher than 4–5 m) provide the maximum effect of improving the quality of the urban environment [11].

Devising principles for the design of protective structures based on air flow modeling methods makes it possible to understand the possibilities of such barriers for combating traffic pollution in roadside areas. The main methods include field measurements, wind tunnel experiments, and computational simulation.

Field methods involve continuous monitoring of pollutant concentrations under real-world conditions along with building height, street width, wind speed, azimuth angle, etc., as shown in [12]. Although measurement data provide accurate values, the method itself is expensive, time-consuming, and has certain limitations. Therefore, it is mainly used to verify the results of dispersion models.

The wind tunnel experiment is a physical modeling method that makes it possible to empirically assess the characteristics of turbulent transport of pollutants under different flow conditions and barrier configurations. In [13], it was determined that barriers on both sides of the highway lead to a greater reduction in concentration than a single barrier on the leeward or windward side. The most effective factor for a 78 % reduction in concentration is the length of the recirculation zone. However, the applied models are limited by atmospheric stability conditions and the wind direction perpendicular to the road. As shown in [14], the wind tunnel method is convenient for repeated field tests and can provide modeling accuracy. Therefore, it can be used to verify other dispersion models. However, the complexity of the experimental conditions and the significant cost limit its application to typical dispersion scenarios.

Modern modeling methods are able to overcome the difficulties of physical modeling and make it possible to estimate a complex set of pollutants with high spatial and temporal resolution. This is the approach used in [15]. The micro modeling method used in the study allows for a temporal resolution of one second and a spatial resolution of up to ten meters. Such detail is necessary because the chemical composition of emissions changes rapidly in time and space. Therefore, mathematical modeling methods are more flexible, accessible, and able to overcome the shortcomings of field measurements and wind tunnel experiments.

The most common for modeling the impact of roadside barriers on air quality and assessing the impact of such key variables as barrier height and wind direction is the computational fluid dynamics (CFD) model. In [16], a 3-dimensional model of a 6-lane road was built. CFD simulations showed a decrease in the concentration of gaseous substance depending on the height of the barrier vertically (up to approximately half the height of the barrier) and at all horizontal distances from the road. Barriers with a height of 3 to 18 m reduce the maximum concentrations by 15÷61 % at a distance of 20 m from the road, but pollution on the road increases by a factor of 1.1÷2.3. The wind direction plays an important role since the spread of accumulated emissions from the windward side of the barrier significantly increases the concentration of emissions near the road. However, a drawback of the study is the lack of consideration of the features of the built environment and actual data on the profile of buildings.

The authors of [17], utilised a computational road-scale fluid dynamics (NR-CFD) model to analyse pollutant dispersion in a small roadside domain (height<250 m, length<1 km) and to determined the optimal geometry of solid barriers. It takes into account the relationship between the efficiency of reducing air pollution near the road and the cost of the barrier. The effectiveness of the model was verified based on the consistency of the modeling data and specific observations of SF_6 concentrations, with a correlation coefficient of R^2>0.86. The main factors determining the barrier effectiveness included the size of the barrier, which is more than 15 % of the width of the road, and proximity to its edge. The most cost-effective configuration was a quarter-ellipse-shaped barrier aligned parallel to the road axis. The study was limited by the conditions of a open flat terrain and the lack of consideration of weak winds. The disadvantages include the small scale of the modeling, which does not make it possible to assess the spread of transport pollutants across the urban area.

In [18], semi-empirical mixed-trail dispersion models were used to study aerosol transport pollution. The models are based on data from controlled experiments in a wind tunnel and using ultra-fine particles as tracers. The dependence of the reduction in concentrations of fine particles at several distances from the barrier on its height is shown. Model validation was assessed based on field research data on the leeward side of a kilometer-long barrier next to a real urban highway in the area of the University of California, Riverside campus. According to the modeling data, at a distance of 40 m, a 4-m-high barrier reduces the concentration by up to 35 %, and a barrier twice as high reduces it by up to 55 %. The results of the study are limited by the lack of consideration of the influence of street buildings, stable atmospheric conditions, and wind directions not perpendicular to the road.

The mixed-wake algorithm incorporated into a steady-state dispersion model was refined in [19] based on wind tunnel experiments. The simulation demonstrated that the vertical concentration profile varies with barrier height and the distance between the emission source and the barrier. This study showed, for the first time, that the barrier height and the distance from the source to the barrier affect the concentration on the windward side, and these effects decrease with distance from the barrier on this side. However, the analyzed models do not sufficiently represent the specificity of turbulent processes caused by traffic.

Typically, modeling approaches have not been applied to vegetated barriers due to the complexity of the deposition and mixing process within the vegetated barrier and on the leeward side. The use of field-validated CFD model parameters allowed the authors of [20] to propose a new multi-mode Gaussian model to describe the physical mechanisms of particle deposition, dispersion, and sedimentation. These mechanisms are key factors in reducing the concentration of pollutants due to the influence of plant barriers. The issues related to a comprehensive model that takes into account physical, chemical, and biological processes remain unresolved. This is due to the complexity of modeling the processes of pollutant transport through a plant barrier, the large number of input parameters, and the difficulty of measuring them.

In [21], a numerical model was built to calculate pollution zones along the road, not only using the parameters of the vehicle geometry, meteorological conditions, and the barrier height. The model takes into account the chemical transformation of nitrogen oxides in the atmospheric air based on the mass transfer equation. Based on the constructed NO_x concentration fields, subzones of more intense pollution were identified and changes in the barrier height were recommended. The places of formation of stagnant zones with locally high concentrations of chemical pollution were also determined. The reason for this is the location of the barrier on the side of the road, where the air flow velocity is low. However, the installation of local suctions proposed in the work is technically complex and economically impractical. In [22], a mathematical model of pollutant transport was built under the condition of the location of the highway and buildings in the type of street canyon based on the equations of separation flows of an inviscid fluid. It has been established that the use of barriers of different heights reduces the level of pollution behind the road by approximately 20÷50 %. L-shaped barriers with an additional element “along the flow” have been proposed based on a combination of numerical simulation (Navier-Stokes aerodynamics equation) and physical modeling. However, the impact of barriers of different designs on air pollution on large spatial scales has not been studied. Also, possible negative effects from secondary accumulation of pollution have not been taken into account, although stagnation zones are established in the models. All this indicates the need to further consider dynamic changes in flow turbulence with air monitoring under different conditions of operation of barriers.

In general, numerical models do not take into account the variability of weather conditions and possible interactions between air flows over large areas. The analyzed models extremely simplify the complex aerodynamic situations on city streets. This reduces their predictive ability and leaves unresolved the issue of assessing changes in the effectiveness of barriers under real road conditions with high traffic density.

The reasons for this are that the problem of modelling roadside airflows containing transport pollution faces a number of technical and methodological challenges. First, it is difficult to take into account the turbulence of the flows, which is caused by the movement of vehicles, the geometry of the road, and urban development objects. Similarly, the variability in time and space of such microclimatic parameters as wind direction and speed, temperature, humidity, etc. requires the use of complex numerical models. Roadside barriers change air flows, creating turbulent zones and stagnation zones. Therefore (As a result), the concentration of pollutants may either increase or decrease at different locations around the barriers depending on wind direction, which requires additional analysis. The use of modern numerical methods, in particular CFD (Computational Fluid Dynamics), requires significant computational resources to accurately describe the three-dimensional distribution of pollutants in time and space.

Therefore, despite a large number of research, our review of the literature reveals that many critical aspects of the functioning of protective barriers remain insufficiently studied. Thus, the issues of inadequate adaptability of models to the complex development of urban areas and limited consideration of turbulence from traffic remain unresolved. There is a lack of coordinated approaches to assessing the effectiveness of barriers under different operating scenarios and different weather conditions. At the same time, most existing models do not make it possible to take into account the spatial and temporal variability of polluted air flows. Solving these problems requires an integrated approach, which involves combining the results of physical modeling and numerical simulation with the use of new ideas about the laws of aerodynamics of air flows. This will provide a clearer understanding of airflow behavior near barriers and support scientifically grounded principles for designing protective structures under real-world conditions.

3. The aim and objectives of the study

The aim of our study is to determine the influence of roadside barriers with specific design parameters on the kinematics of the air flow and aerodynamic characteristics in the context of a roadway system with moving vehicles, using physical modeling and computational simulation methods. This will make it possible to increase the efficiency of both designing new and modernizing existing protective roadside structures using new ideas about the laws of aerodynamics of air flows in the area of moving vehicles. The proposed solutions can be applied to both highways and urban roads, especially in densely populated areas, where rapid and effective improvement of air quality is necessary.

To achieve the goal, the following objectives were set:

– to model the kinematic scheme of air flow formation by a moving vehicle based on the data of jet parameters in the flooded space obtained by the method of flow structure visual diagnostics;

– to design the structure of air-protective roadside barriers according to the results of visual studies of the flow structure;

– to conduct computational simulation of the aerodynamic structure of the air flow created in the system of a roadway with barriers of a certain design using the "SOLIDWORKS Flow Simulation" module.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the aerodynamic features of airflows formed on highways with protective roadside barriers.

The main hypothesis of the study assumes that the airflow polluted by vehicle exhaust is generated by a moving car on a roadway, with the exhaust jet spreading in a space confined by roadside barriers. The exhaust jet spreads in the space limited by roadside barriers, which makes it possible to apply an analogy with the movement of a jet in a flooded space.

The scheme of formation of the exhaust-polluted airflow from a moving vehicle within a barrier-defined roadway includes the following assumptions:

– the core of the jet is formed by a car moving at a speed V_a (15 m/s);

– by analogy with a piston, this causes a local increase in air velocity above the road surface;

– the formed air jet captures the vehicle's exhaust emissions;

– the width of the roadway corresponds to the width of the flooded channel.

The adopted simplifications concern the consideration of standard ambient atmospheric conditions, as well as the lack of consideration of atmospheric temperature stratification, stable atmospheric conditions, etc.

4. 2. Flow structure visualization method

To build a model of airflow formation after the exhaust pipe of a car moving along a highway with roadside barriers, an analogy with the kinematic behavior of a jet in a flooded space was used.

The work uses data on the kinematic structure of the jet (Fig. 1), obtained by the flow structure visual diagnostics (FSVD) method in specially designed physical modeling devices [23]. The method belongs to the class of polarization-optical methods for visualization of transparent working bodies using an optically active liquid.

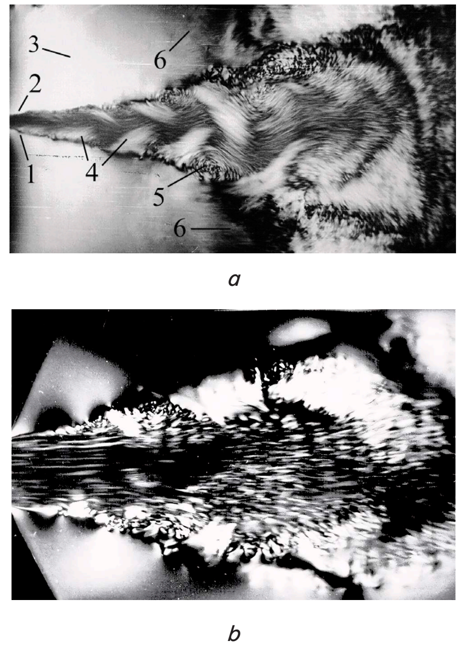

Fig. 1. Visual pattern of the jet structure at different Reynolds numbers: *a* – turbulent flow regime at Re>10^4; *b* – transition from laminar flow to turbulent flow at Re≈$5\cdot10^3$; 1 – jet; 2 – channel; 3 – flooded space; 4 – discrete structures; 5 – vortices; 6 – boundary of the zone of stable existence of discrete structures

Based on this method, the types of structure formation occurring in liquid and gas flows were shown [24, 25]. Analysis of more than 100 visual images of jet outflow into a flooded environment revealed regularities in the arrangement of longitudinal discrete structures in turbulent flow, indicating a process of self-organization. The studies were carried out on the jet section, where the distribution of longitudinal discrete structures at Reynolds numbers Re≥10^4 is statistically stable [24]. Visual images characterizing the instantaneous values of velocity gradients based on the optical density value demonstrate a regular distribution of light and gray areas. In the decoding of visual images, "light areas" characterize positive velocity gradients relative to the average values, "dark areas" correspond to negative ones.

The longitudinal flow structures in the turbulent regime (Re>10^4) include clearly defined light discrete and dark vortex regions (Fig. 1, *a*). The pattern of the flow structure at low Reynolds numbers (Re≈$5\cdot10^3$) corresponds to the transitional regime from laminar to turbulent (Fig. 1, *b*). This visualization not only allow to distinguish individual layers of the flow but also establish the formation of large-scale light discrete regions and vortex formations. They are a consequence of differences in the energetics of neighboring discrete structures. The initial jet region also has a layered structure, which is inherent in the laminar flow regime [25].

4. 3. Method of computational simulation of air flows using the "SOLIDWORKS Flow Simulation" module

To numerically simulate the dispersion of exhaust-polluted airflow near highways, the commercial software "SOLIDWORKS Flow Simulation" was used. This computational fluid dynamics (CFD) module, embedded in SOLID-

WORK [26]. The module uses the finite volume method (FVM) to solve stationary or unsteady Navier-Stokes equations that describe the motion of liquids and gases taking into account turbulence. The basis of the mathematical model is:

– mass conservation equation (continuity);

– momentum conservation equation (motion);

– energy conservation equation (for heat transfer problems);

– mass transfer equation (for modeling pollutant concentrations).

The key simulation features are as follows.

The Realizable k-ε model with Two-Layer Wall Treatment is used, which allows for accurate description of areas with high velocity and pressure gradients. For additional optimization in problems with flow separation, the SST k-ω model is used.

The iterative SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) method is used to link the values of the pressure and velocity fields, which ensures numerical stability.

Automatic mesh refinement is used in areas with elevated turbulence levels (for example, near protective screens or emission sources) to enhance the accuracy of visualization.

The simulation process in SOLIDWORKS included the following steps:

1. Preparation of 3D geometry:

– construction of a model of a highway section with protective screens (9×9 m) and pedestrian zones;

– setting the slope parameters of the screens to prevent flow separation.

2. Setting boundary conditions:

– input flows: vehicle-induced air flow velocities of 5, 10, 15, 20 m/s (corresponding to different traffic regimes);

– physical properties: air is considered as an ideal gas (density 1.225 kg/m^3, kinematic viscosity $1.5\cdot10^{-5}$ m^2/s);

– turbulent parameters: turbulence intensity 5 %.

3. Mesh generation: use of a hybrid mesh (tetrahedral and prismatic elements) with local compaction near the barriers.

4. Visualization of results:

– construction of particle trajectories for analysis of pollutant propagation paths;

– verification of the ejection effect (pulling in additional air masses) and vertical rise of the flow to a height of more than 30 m.

The simulation assumed standard atmospheric conditions: pressure – 101,325 Pa, isotherm, standard air density 1.2 kg/m^3. To simulate the speed of cars moving in opposite directions, oncoming air flows were set with speeds in the ranges of 5, 10, 15, 20 m/s. The width of the roadway is 2 lanes, the width of each lane is 3 m, between the lanes there is a neutral strip with a 1.2 m high bumper.

5. Results of investigating the aerodynamic behavior of the airflow created in the system of a roadbed with barriers

5. 1. Model of air flow formation by a moving vehicle using flow structure visual diagnostics

The kinematic representation of the structure of a turbulent jet in a flooded space (Fig. 2) based on the FSVD method demonstrates the location of optically homogeneous "bright areas". They are discretely and asymmetrically located along the jet boundary and oriented at an angle β≈55–65° to the flow axis.

In Fig. 2, three areas can be distinguished:

A – Discrete section of the jet from the nozzle channel cut to the first darkened zone (8) in the flooded space, which has a clearly expressed transverse interface. The section is characterized by a deterministic structure of the boundary layer (7) in the form of large-scale structures – homogeneous light discrete structures (5). In this case, the vortex zones (4) are a consequence of only a discrete change in the distribution of the energy potential of the jet since each subsequent discrete region has a lower energy.

B – Quasi-discrete section is located between two darkened zones (8) and (9). In this case, the vortex zones arise exclusively as a result of a discrete change in the distribution of the energy potential of the jet. Each subsequent discrete region has a lower energy in the flooded space, which forms two implicitly expressed interfaces of the jet according to its kinematic characteristics. Thus, the regularity of the vortices is preserved, but their discreteness is destroyed.

C – A non-discrete section does not have a boundary between the jet and the flooded space. At a certain distance, residual phenomena of the regularity of the jet structure may persist, but the processes of interaction between the jet and the flooded space are not observed.

Therefore, in the structure of the flow, a cellular structure is distinguished both inside the jet and in light discrete areas (5), with stable cell sizes. Longitudinal discrete structures, "light areas", are responsible for the attraction, or ejection, of the external environment (flooded space). And cellular structures inside longitudinal discrete structures show the internal structuring of the attraction processes.

It is proposed to use the established kinematic laws to determine the air flow formation scheme taking into account the attraction of roadside air and its mixing with exhaust gases of moving cars (Fig. 3).

The model of the spread of polluted automobile exhaust in the environment is considered by analogy with a jet stream in a flooded space. In this case, visual images of the structure of a turbulent flow are taken into account at Reynolds numbers $Re\geq10^4$ (Fig. 1, *a*) and $Re\approx5\cdot10^3$ (Fig. 1, *b*) during the transition from laminar to turbulent regime.

The results of analysis of the field of instantaneous velocity values, obtained by the FSVD method, served as the basis for building the model and the nature of the location of roadside barriers, as shown in Fig. 3, taking into account the assumptions given in chapter 5. 1. 1. Fig. 3 shows the lane along which the car moves. The width of one lane B corresponds to the width of the jet channel in a flooded space according to the modeling scale. The structural dimensions of the barrier were determined relative to B, which is used in physical modeling methods [17]. The velocity distribution diagram in the initial section of the jet (2 in Fig. 3) differs from the velocity distribution diagram in the main section of the polluted air jet (4 in Fig. 3) and corresponds to the wave nature of the pulsating velocity components, as established in [23].

The flooded jet model with longitudinal discrete structures makes it possible to establish the places of maximum attraction (ejection) of unpolluted air from the roadside space into the main vehicle movement zone (item 6 in Fig. 3, which correspond to item 5 in Fig. 2 and item 4 in Fig. 1).

This is explained by the occurrence of rarefaction in the zones of gaps between the screens, as a result of which the attraction of clean air from the off-road space is created, which is confirmed by the velocity diagrams (Fig. 3).

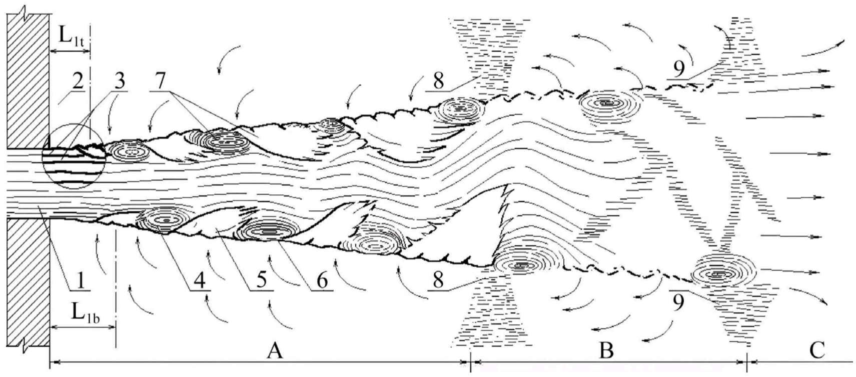

Fig. 2. Generalized kinematic scheme of a jet in a flooded space:
$L_{t,b}$ – distances from the nozzle cut to the center of individual longitudinal discrete structures; 1 – nozzle channel; 2 – flooded space area; 3 – layers, or transverse discrete structures; 4 – jet boundaries; 5 – light homogeneous areas (discrete longitudinal structures); 6 – vortex areas; 7 – combination of longitudinal discrete structures and vortex areas; 8, 9 – first and second darkened zones

Thus, the protective barrier consists of separate diffuser-positioned shields, between which it is necessary to provide a section of flow ejection from the roadside area with additional elements arranged in a confusor manner. In order to eliminate vortex zones (vortex zones 6 in Fig. 2), it is proposed to install parallel screens in the openings between the discrete shields, which play the role of confusors, which provide conditions for the ejection of cleaner air from outside the barrier space.

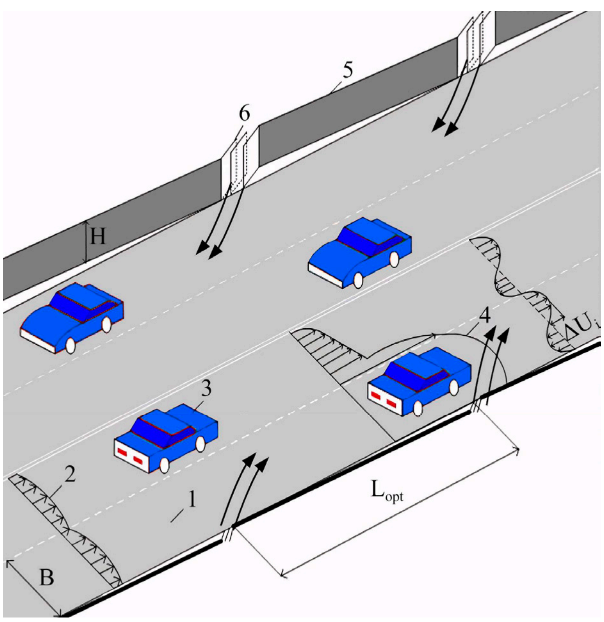

Fig. 3. Model of the location of discrete shields of a protective roadside barrier taking into account the data obtained by the flow visual diagnostics method:
1 – roadbed with width B; 2 – velocity distribution diagram in the initial section of the jet; 3 – moving car; 4 – velocity distribution diagram in the main section of the jet of polluted air; 5 – discrete roadside barrier with shields of length L_{opt}; 6 – additional parallel screens of the ejection sections

Such a diffuser-confusion barrier design helps eliminate vortices and ensure continuous flow of the flow. The [25] authors' experience has shown that vortices are a consequence of the separation of the flow from the barrier walls, which creates additional resistance to the movement of the vehicle.

The shields are located at an angle α relative to the axis of the transport belt. The approximate value of the angle at the level of $\alpha \sim 4°$ is determined by the generally accepted diffusivity angle (~8° for the jet, 4° on each side). This angle value ensures the continuity of the flow from the walls.

Thus, the analogy between the movement of the jet in a flooded space and the air flow polluted by exhaust gases makes it possible to apply the results of visual studies. The identified characteristics of longitudinal discrete structures were used to design the structural dimensions and discrete location of air-protective roadside barriers.

5. 2. Establishing the design parameters of protective roadside barriers

Simulation, based on the FSVD method, of air flows polluted by automobile emissions in the system of urban highways with protective structures makes it possible to optimize the location and geometry of protective barriers consisting of separate shields. Fig. 4 shows a diagram of a traffic lane with roadside barriers, the design features of which are set according to the parameters of discrete air flow structures in accordance with FSVD.

The proposed air protection structure consists of a system of discrete shields, the optimal length of each of which is a function of the distribution of longitudinal structures (Fig. 2). Therefore, the length L_1 in Fig. 4 corresponds to L_{opt} in Fig. 3, and is set accordingly to the distance $L_{t,b}$ in Fig. 2. This is the distance from the beginning of the flow expansion to the first, second, or next stable "light" discrete structure, where clean air from the external environment is attracted.

Based on the flow visualization data (Fig. 1), L_{opt} is a function of the road (channel) width:

$$L_{opt}=f(B)=k\cdot B, \quad (1)$$

where B is the width of one road lane.

The optimal value of k=3 is recommended based on optical measurement data [23, 24] since this is the minimum value of the coefficient at which a discrete flow structure is manifested.

Analysis of the kinematic characteristics of the flow based on the FSVD method make it possible to establish the design parameters of the barriers (Fig. 4). Thus, the length of the discrete barrier at the level of 3*B* (*B* is the width of one road lane) is justified by the distribution of longitudinal discrete structures, which is determined by optical measurements (Fig. 1, *a*) and the values of $L_{t,b}$ in the diagram of Fig. 2.

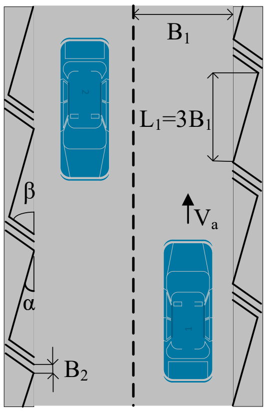

Fig. 4. Schematic of a traffic lane zone with discrete shields (top view): B_1 – width of one road lane; B_2 – width of gaps between the shields; L_1 – length of each shield; α – angle between the axes of the shield and the roadside strip; β – angle of inclination of the intermediate shields between the shields to the axis of the roadway; V_a – speed of a moving vehicle

Parallel screens between discrete shields are located at distances B_2, the width of which is determined by road safety requirements. Distances B_2 within 0.3÷0.5 m make the roadside barrier, as a whole, continuous for transport and make it impossible for pedestrians to cross the road.

The expediency of the angular arrangement of the shields is due to the fact that the jet expansion angle should be in the range of values that ensure the air flow is not detached from the barrier walls.

The angle of opening of the shield (angle α) in relation to the axis of the roadway, which prevents the flow from detaching from the road surface and the formation of vortices near the shield, as shown in Fig. 2, is 4°. The value of the angle of inclination of the intermediate screens between the shields to the axis of the roadway is β=60°. As established by visual experiments for the kinematic structure of the jet, with such a value of the angle β (at this value of the angle β) the flow will not return back to the zone behind the barriers, and stagnant zones will not form at the ends of discrete shields.

Thus, the structural dimensions and geometry of the location of individual shields in the protective structure have been proposed based on the flow structure. Discrete barriers will contribute to the formation of air flows directed in a certain way. As a result, unpolluted air from roadside areas will be attracted to the vehicle traffic area through separate entrance zones between the shields and enhance the dispersion of impurities.

5. 3. Computational simulation of air flows on a highway with discrete-type air barriers

To confirm the experimental data on the physical model of FSVD, computational simulation was additionally used for air flows created by moving vehicles within the roadway with discrete barriers of the above-proposed design.

The initial data of the model using the commercial SOLIDWORKS Flow Simulation module were selected taking into account the flow structure parameters determined by visual diagnostics and described in chapter 5. 2. In the model, each discrete shield of roadside barriers was modeled with a length of 3 widths of the roadway, or 9 m, a height of 9 m, the angles had the values α=4°, β=60°.

The simulation results are shown in Fig. 5.

Fig. 5 shows the opposing flows (marked in green and red in the figure), created by car exhaust gases when driving in oncoming lanes. When the flows collide, a vortex rises, and the combined airstream is deflected upward. Thus, the model demonstrates the dispersion of the polluted flow. The impact of discrete barriers is as follows. Through the gaps between the screens of the protective barriers, an ejection flow of cleaner air from outside the road space is sucked (blue lines in Fig. 5). Ejection occurs due to viscous friction forces. The flows formed due to the suction of clean air mix with the total polluted airstream and further affect the dispersion. Barriers in the form of discrete shields with transverse screens at experimentally determined angles initiate the ejection process, which enhances the suction of clean air and dilutes pollution inside the road. At the same time, air does not escape through the gap, but is sucked in, which is ensured by a certain inclination of the screens separating the shields. Thus, the simulated flows confirm the effectiveness of the barrier design proposed based on visual diagnostics.

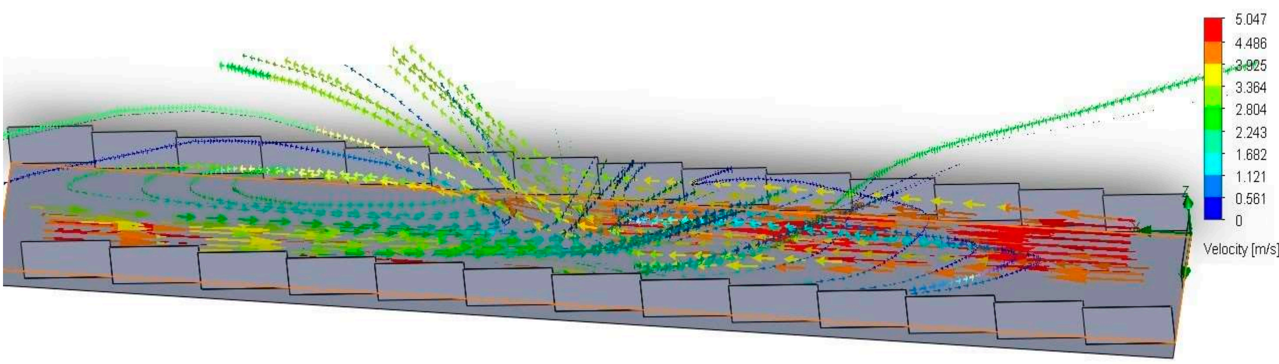

Fig. 5. Airflow model on a highway with discrete barriers using SOLIDWORKS Flow Simulation

6. Discussion of results based on studying the features of the formation of air flows in the zone of discrete-type roadside barriers

Vehicles generate local pollution, as well as air movement over the highway, which can be represented by a kinematic picture of a jet in a flooded space. The visual image (Fig. 2) provides the basis for a schematic representation of the model of air flow formation within the highway, which includes the attraction of roadside air and its mixing with exhaust gases in the presence of discrete-type barriers (Fig. 3).

Analysis of air flows in the zone of a highway with moving cars (Fig. 3) revealed that discrete barriers with parallel screens between them contribute to the creation of an ejection effect. The formation of stable aerodynamic structures in the roadside zone (discrete longitudinal structures 5 in Fig. 2) determines the places of ejection of unpolluted air from the roadside space. This ensures intensive mixing of polluted and clean flows and a decrease in the concentrations of pollutants. This is explained by the occurrence of rarefaction in the zones of gaps between the screens, as a result of which clean air is attracted from the off-road space, which is confirmed by velocity diagrams (Fig. 3).

The design of air protection barriers was based on the results of visual studies and analysis of aerodynamic characteristics of flows in the roadside zone (Fig. 4). Analysis of kinematic characteristics of the flow based on the FSVD method makes it possible to establish the design parameters of the barriers (Fig. 4). Thus, the length of a discrete barrier at the level of $3B$ (B is the width of one road lane) is justified by the distribution of longitudinal discrete structures, which is determined by optical measurements (Fig. 1, *a*) and the values of $L_{t,b}$ in the diagram of Fig. 2. The performance of the functions of a diffuser by discrete shields justifies the angular arrangement of the shields to the axis of the roadway. The angle value at the level of $\alpha \sim 4°$ ensures the continuity of the air flow from the walls of the barrier, which is proven by experimental studies [24]. The placement of discrete shields with a diffuser angle of $\alpha \sim 4°$ to the axis of the roadway forms an air flow in the direction of transport movement, reducing the likelihood of the formation of vortex areas (Fig. 2), and the angle of inclination of the intermediate screens $\beta=60°$ contributes to the ejection of air from the off-road space. Such a diffuser-confusor design of the barrier contributes to the continuity of the airflow and minimizes vortex formation. The experience of authors of [25] has shown that vortices are primarily caused by flow detachment from the walls of the barrier, which creates additional resistance to the movement of the vehicle.

As shown by our review of the literature [10, 16, 21], conventional solid barriers create an obstacle to air circulation and contribute to the accumulation of pollution. In contrast to them, the proposed discrete type barriers, form an aerodynamic effect of dilution of impurities, flow rise, and reduction of the concentration of harmful substances.

The influence of the geometric parameters of the barrier on the aerodynamics of air flows was analyzed by computational simulation (Fig. 5). The results fully agree with the physical model (Fig. 3). According to both the physical and computer models, the improvement of dispersion conditions is achieved by diluting aerosol pollution from vehicles with a stream of clean air ejected through the gaps of roadside barriers. The ejected stream, after mixing with exhaust gases, will rise upwards, leading to intensive pollutant dispersion. The results of computational simulation confirmed that the design of shields – confusors and diffusers in the form of parallel screens direct the external flow towards the main traffic flow. This minimizes the formation of recirculation zones and enables more effective dispersion of pollutants.

The resulting numerical model reasonably demonstrates the dilution of the pollutant flow due to ejection and its dispersion due to vertical flows. The established processes prevent the spread of pollutants in the surface layer, and the discrete design of the barriers does not create stagnant zones. Thus, aerodynamic conditions are created that contribute to the dispersion of pollutants. It should be noted that the wind direction, which is considered in detail in other similar models [16–19] and significantly complicates them, in this case will play a secondary role, directing the emission plume. The design of the shields also makes it possible to mitigate the impact of adverse atmospheric stability conditions (for example, inversions), since the scattering flows will be created by the shields themselves and the movement of vehicles and will depend less on the temperature of the lower layer of the atmosphere.

In addition, when installing protective barriers of a discrete type, the gas-dynamic air resistance of a moving vehicle decreases due to a decrease in the coefficient of hydraulic friction in the boundary layer. Underlying the statement is the Nikuradze plot, which models the laws of friction for laminar and turbulent regimes [27]. This can provide additional advantages of using barriers of a discrete design by reducing fuel consumption and the corresponding levels of exhaust gas emissions.

The limitations of our results stem from the fact that both models considered only the aerodynamic behavior of flows, and did not include models for determining the concentration fields of pollutants. Extreme atmospheric factors (wind gusts, precipitation, abrupt temperature changes) that may affect the effectiveness of barriers under real operating conditions were also not taken into account. Computational simulation did not reflect changes in traffic and the nature of vehicles. The design of discrete barriers was investigated under relatively flat terrain conditions, which may require additional research for more complex urban landscapes and taking into account the impact of high-rise buildings.

Despite the positive results obtained, the study has certain shortcomings that may limit its practical application. These include the lack of experimental verification under actual conditions, modeling based on simplified assumptions, and the failure to consider the impact of noise pollution.

Further development of our research may involve building models of air flow with aerosol pollution. This area is promising since it will be able to solve the problem of a significant increase in fine particles in the structure of vehicle emissions due to tire and road surface wear. In the future, it is also planned to construct a numerical model that would make it possible to estimate the height of the air flow upward for cases of both solid and discrete barriers. To build models of pollutant dispersion in the surface layer, it is planned to take into account temperature changes, which can be associated with both external conditions and vehicle exhaust gases.

7. Conclusions

1. To build a model of the formation of the air flow after the exhaust pipe of a car moving along a highway with road-

side barriers, an analogy with the kinematic behavior of a jet in a flooded space has been used. It was shown that the model based on conventional ideas about the distribution of kinematic parameters has low informativeness. The applied method of flow structure visual diagnostics makes it possible to estimate the instantaneous values of the dynamic parameters of the exhaust flow jet under a turbulent flow regime. Using the method, data on the cellular structure of the flow were obtained and the conditions for the formation of homogeneous discrete structures in the longitudinal section of the flow near the vortex zones were determined. The presence of such structures makes the process of ejection of air from the external space relative to the highway and its mixing with exhaust gases more intense. The use of FSVD has made it possible to establish the places of maximum suction (ejection) of unpolluted air from the roadside space into the zone of the main movement of the car. The dimensions and location of longitudinal discrete structures determined as a result of visual studies justify the optimal design scheme of a discrete-type air barrier.

2. The proposed design of roadside barriers based on the FSVD method consists of a system of discrete elements and air ejection sections. Each discrete element consists of a diffusor shield, expanding at an angle of 4° (α) to the axis of the roadway, with a length of 3 traffic lane widths. The angle (α) ensures that the flow of the stream does not break away from the roadside barriers. Additional elements are placed between the shields in the form of parallel screens (confusors) located at an angle of 60° (β) to the axis of the roadway. They prevent the return of polluted air into the roadside environment.

3. To confirm the experimental data on the FSVD physical model, numerical modeling of air flows created by moving vehicles within the roadway with discrete barriers using the commercial SOLIDWORKS Flow Simulation module was additionally used. The applied computational model demonstrates the consistency and unidirectionality of the dilution processes due to ejection and dispersion due to the lifting of vertical flows and long-distance transport. Since the scattering flows will be created by the shields themselves and by the movement of vehicles, according to physical and computer models, discrete barriers have the following advantages. First, the discrete design of the barriers does not create stagnant zones. The alternating arrangement of diffusor and confusor sections forms aerodynamic conditions that contribute to the dispersion of transport emissions. The influence of wind speed and direction, adverse conditions of atmospheric stability (for example, inversions), etc. is reduced.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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