Simulation model for predicting ecological condition of urban areas at traffic intersections

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Abstract. This article substantiates the relevance of the development and use of digital tools that allow modeling objects and processes of transport systems to determine the environmental consequences of changes in their quantities and states. The use of methods of structural analysis, systematization, observation, statistical analysis of data allowed to establish all key objects of the system and their qualitative and quantitative indicators necessary to create a digital twin. The use of simulation modeling methods allowed to formalize the obtained results into models involved in the digital twin of the transport system. Using the graphical method, state diagrams were developed to demonstrate the transition of states of each object of the process depending on changes in environmental conditions. On the basis of the statistical analysis of pollutant emissions in the study area, a parametric model was developed for each pollutant factor.

1 Introduction

The development of urban areas is accompanied by the modernization and scaling up of transport systems, which have a significant impact on air, soil, water and ecosystem functioning. For example, most of the vehicles that are the objects of such systems generate exhaust fumes and noise, which significantly increase the load on the environment and affect human health and life processes.

Modern research in the field of ecology related to transportation is aimed at reducing the amount of pollution and other negative effects of transportation [1]. The key aspects are the development and implementation of energy-saving solutions, the possibility of using alternative fuels, and the use of expert systems in the organization of traffic flows and the design of road infrastructure [2, 3].

The ecology of urban areas is a complex system consisting of many subsystems, which include social, technical, informational and administrative [4, 5]. The development of such territories should include the creation of such conditions that ensure the ecological balance of the natural and urbanized environment. The use of modern software tools makes it possible to analyze a large array of data obtained in real time from sensors or other devices that characterize the state of environmental objects [6-8]. Based on the obtained results and comparing them with archive data, it is possible to obtain scenarios of changes in objects and processes over a given time interval with a certain accuracy. For this purpose, specialized

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expert systems are used, based on the results of which control actions on the necessary environment parameters are developed [9, 10]. Creation of digital doubles of real objects of urban environment, including its objects and processes with a detailed description of quantitative and qualitative characteristics, is an important component of the process of functioning of expert systems in order to predict changes with a given accuracy [9, 11, 12].

Thus, the purpose of the study is to create a digital twin of the urban environment section of a megalopolis for predicting changes in its ecological state. For this purpose it is necessary to obtain a list of objects and processes that influence the state of the urban environment, to establish their qualitative and quantitative characteristics, to determine the relations and connections arising between objects and processes, to develop formal models suitable for use in simulation modeling on the basis of the obtained lists and relations.

The theoretical significance of the research is the obtaining of a formal model of the transportation system of a section of the urban area, combining the key aspects affecting its ecological state. On the basis of the obtained model it is possible to create scenarios of changes in environmental parameters in order to predict short-term and long-term consequences of these changes for the corresponding ecosystem. The results obtained are the basis for the creation of plans for the integrated development of territories. This is the practical significance of the study.

2 Materials and Methods

The object of the study is the transport flows occurring in the area bounded by the 2nd Pekhotny Proezd, Pekhotnaya Street and Volokolamskoye Shosse in the Shchukino district of the Northwestern Administrative District of Moscow. Fig. 1 shows the corresponding section on the map with a line.

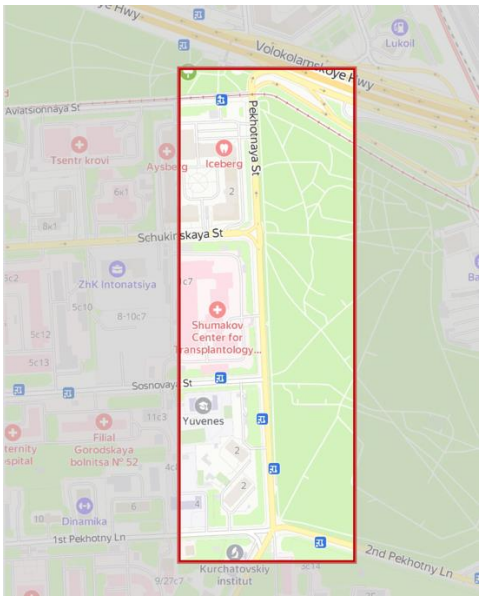

Fig. 1. Boundaries of the studied transportation facilities on the map of Shchukino district (source: Yandex-maps https://yandex.ru/maps/-/CDuwmJYW)

To obtain the list of key elements relevant to the transport flows of the research object, the methods of structural analysis, systematization, and observation were used. These methods are general scientific methods and are used by researchers in their works when

modeling objects and processes of the subject area [3, 5, 12]. With their help, not only the elements themselves, but also their properties and relations arising during the realization of processes are established.

To obtain quantitative characteristics obtained in the course of the structural analysis method, the methods of observation of relevant elements in the territory of the object of study, analysis of information from open sources and filtering, grouping and statistical analysis of data are used. As researchers note in their works, when creating a digital twin of any ecosystem object, a set of data is required to be used as input parameters [13, 14]. To this end, the stated methods of data acquisition and processing are used.

The digital twin of the research object is obtained by using simulation modeling techniques. In studies on similar topics, qualitative and quantitative characteristics of significant objects of the subject area, the rules of their interaction, which are characteristic of all instances of the corresponding objects [7, 9, 12], are used as a basis for the application of the stated method. Changing individual parameters allowed to create modeling scenarios corresponding to any situation, characteristic of the object of study.

Graphical methods were used to visualize the results of individual stages of the research. In research, such methods are used to demonstrate the relationships of objects or their parameters, allowing to visualize the results of individual stages of the work done [1, 6, 7].

3 Results

Using the stated research methods to identify the key objects of the subject area, it was possible to establish:

1. Pekhotnaya Street can be conditionally divided into two parts:

1.1. With one-way traffic in two lanes (from Shchukinskaya Street to Volokolamskoye Highway).

1.2. With two-way traffic with one lane in each direction (from 2nd Pekhotny Lane to Shchukinskaya Street).

2. There are traffic flows formed by the movement of personal and public motor transport. 3.

3. There are intersections of traffic flows:

3.1. Regulated T-junction (Shchukinskaya and Pekhotnaya Streets).

3.2. Regulated offset cross intersection (Pekhotnaya Street and 2nd Pekhotnaya Lane).

3.3. Non-regulated T-intersection (Pine Street and Piechotna Street).

3.4. Regulated crosswalk (Aviation and Infantry Streets). In the vicinity of the intersection, only public transportation is permitted along Aviation Street.

4. Availability of parking pockets along Infantry Street.

5. Availability of bus stops without a bus stop pocket.

6. Availability of four exits from the adjacent property.

7. Presence of one unregulated crosswalk across Pechotnaya Street. The presence of pedestrian crosswalks at each intersection.

All of the above characteristics affect the traffic density of the study site. In addition, the number of vehicles is found to be dependent on time of day, days of the week, and seasonality. The study area exhibits a peak time pattern of increased traffic load on the transportation network, during the morning (08:00 to 10:00) and evening (17:00 to 21:00) hours. This is true on weekdays, as the working day begins and ends for most residents of the neighborhood. At the rest of the time, the density of traffic flow is significantly reduced, despite the presence of social infrastructure facilities. On weekends and holidays, the traffic density is comparable to that during off-peak hours. At night time, regardless of the day of the week and season, there is practically no traffic flow.

Based on the results obtained, the elements (agents) affecting the traffic flows of the problem area were identified. These agents include personal motor vehicles, public transportation (road and rail), pedestrians and traffic lights. The use of agent-based modeling methodology (which is a type of simulation modeling) allowed us to develop state change diagrams for each of the agents. Figures 2-4 show fragments of the corresponding diagrams.

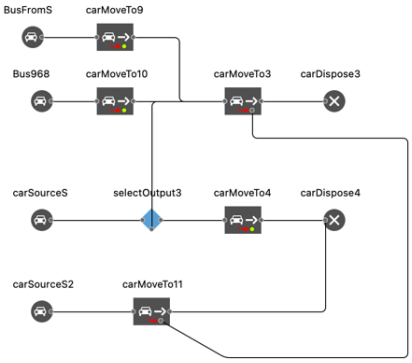

Fig. 2. Fragment of the diagram of state change of the road public transportation agents

Fig. 3. Fragment of the diagram of state change of rail public transportation agents

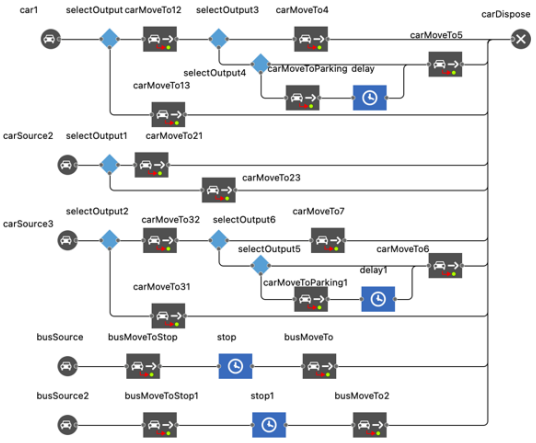

Fig. 4. Fragment of the diagram of state change of personal automobile transportation agents

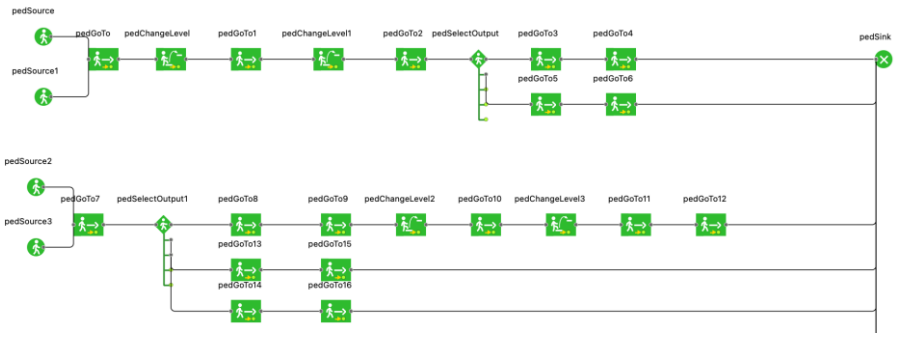

Fig. 5. Fragment of the diagram of state change of pedestrian agents

It should be noted that the study site is characterized by two types of pedestrian agents:

1. Pedestrians who move around the research object without using public transportation. Such pedestrians, for example, may include residents of apartment buildings who walk from home to social infrastructure facilities, to public transportation stops located outside the research object.

2. Pedestrians using public transportation. They are characterized by:

2.1. Moving to the stop and waiting at the stop location, creating an environment of several pedestrians.

2.2. Moving from the stop to different infrastructure of the study site or beyond. Appear at stop locations at intervals typical of the public transit schedule.

Pedestrian densities affect traffic flows around the unregulated crosswalk and passenger boarding/disembarking points from public transportation.

To determine the parameters affecting the environment and to develop a parametric model corresponding to the variants of their change, a mathematical analysis of the data of the station located on the territory of the research object and collecting the indicators of pollutants in real time was carried out. In order to visualize the obtained values using a graphical method, a diagram of changes in the indicators for the period from November 2022 to December 2023 was developed (Fig. 6).

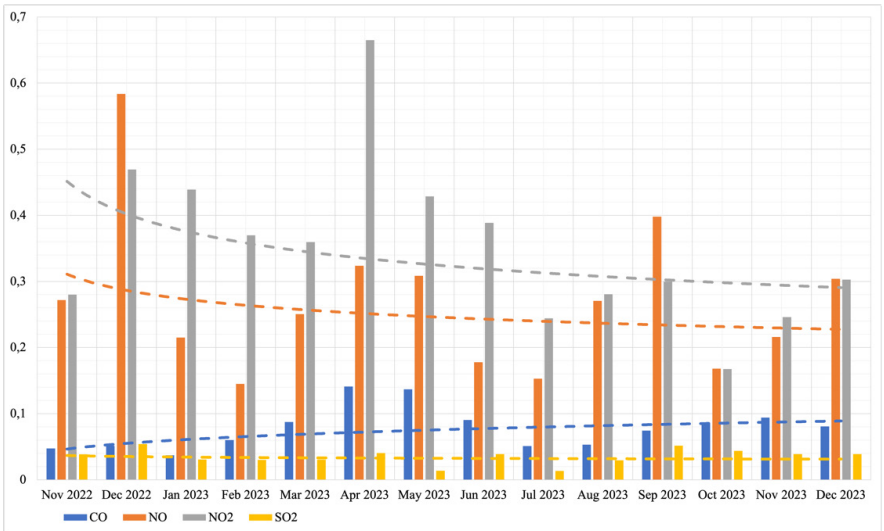

Fig. 6. Diagram of changes in indicators polluting the environment in the area of the study object (source: MOSECOMONITORING https://mosecom.mos.ru/svetlyj-proezd)

The approximating function for each of the indicators is plotted by dashed lines in Fig. 6 with dashed lines for each of the indicators is constructed approximating function, the form of which is presented in Table 1.

Table 1. Equations of approximating functions of changes in environmental pollution indicators

no	Polluting agent	Equation	Validity of approximation R^2
1	NO2	$y_{NO2} = 0.4514x^{-0.167}$	0.0834
2	NO	$y_{NO} = 0.3109x^{-0.118}$	0.0808
3	CO	$y_{CO} = 0.0465x^{0.2459}$	0.1328
4	SO2	$y_{SO2} = 0.0367x^{-0.062}$	0.0126

The obtained parametric model of changes in environmental pollution indicators, models of agents' behavior became the basis for input parameters and rules of the simulation model capable of implementing scenarios of changes in environmental conditions. To increase the accuracy of the forecast results, it is required to periodically update the data related to the density and nature of traffic and pedestrian flows, indicators of environmental pollutants.

4 Discussion

The analysis of the results obtained in the study showed that they correspond in their form to the results of other studies related to the development of simulation models in the field of transportation systems [3, 11, 14], agriculture [6, 7, 12] and the creation of projects for sustainable development of territories of settlements [2, 5, 13].This is achieved due to the similar use of the stated methods in the research. The thus obtained digital twin of the transportation system corresponds to the key characteristics of the research object and reflects all the changes in its structural elements when any parameters are transformed.

The developed model, in addition to being used in the development of territorial development projects, can be involved in the educational process in the training of specialized specialists related to state and municipal management, urbanism or ecologists. This is confirmed by the results obtained in studies related to the organization of the educational process [15]. Thus, the developers of educational methods recommend the active use of practice-oriented technologies capable of real-time modeling of educational tasks that require a large amount of consumables or other resources (including temporary) when conducting experiments on real objects. The model obtained in the course of the research is capable of implementing long-term scenarios of behavior of the system objects, which corresponds to the conclusions of these studies.

5 Conclusions

Simulation modeling of processes is a means for a deeper understanding of the nature of their implementation in order to obtain reliable information about the behavior of objects of the real world. This is necessary to stimulate the development of methods for solving scientific problems and to create a basis for making adequate and accurate decisions in the implementation of specific projects.In the system of sustainable environmental development of any territories, an integral stage between the analysis of initial data and forecast data, characterized by different spatial and temporal scales and multiple interrelated processes, is the modeling of the impacts of biotic and abiotic processes occurring under the influence of natural and anthropogenic factors.

The use of digital twins by specialists in such processes allows them to get a detailed idea of the impact of the transportation system on the ecological situation and the possibility to change the parameters in order to reduce the negative consequences. The concept of using digital twins allows not only to predict changes in the behavior of the system with a given accuracy, but also to reduce resource costs due to the absence of tests on real objects, during which irreversible damage may be caused to them.

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