Features of transport flow modeling in projects of sustainable development in urban areas

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Abstract. The paper highlights the problems of modern Russian cities that significantly affect their socio-economic development. Most of the problems are related to the transport and logistics system due to the historical design of urban neighborhoods, chaotic and point development, and the increasing importance of road transport. All this supports the need to develop comprehensive projects for the development of urban areas. It is impossible without the use of specialized software tools, which are based on all aspects of the territory being modernized. The use of a set of methods, based on structural analysis and simulation modeling, allowed us to obtain formal models of transport processes associated with Yeniseyskaya Street in the city of Moscow. Based on the obtained models, examples of created scenarios for forecasting changes in the processes of the object of study over time during the modernization of its individual elements are presented.

1 Introduction

The main factors constraining the economic and social development of Russian cities, domestic researchers refer to the results obtained after the socialist era and the time after it [1]. Domestic cities are not designed for high throughput capacity of highways and streets due to the peculiarities of historical design of urban neighborhoods, associated with the lack of accounting for the sharp increase in urban population density and its pendulum migrations, a significant increase in the share of personal motor transport [2, 3]. In addition, most cities are characterized by the centralization of infrastructure facilities, when the majority of workplaces, cultural and social infrastructure facilities are concentrated in the city center. Additional load on the transport system of the central part is caused by chaotic and point development of housing and economic complex objects [1, 4].

To create projects of sustainable development of urban areas in domestic and foreign urban planning policy use intelligent transport systems that allow to organize and evaluate the interaction of elements of transport and logistics infrastructure in terms of socio-economic, technological and transport aspects [1, 5, 6]. Such systems are based on digital models, which are a set of data obtained by objective control or monitoring systems by specialized specialists in real time [7]. Storage and processing of such data allows obtaining statistical reports to communicate the results to the subjects using them in their professional activities.

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It is possible to perform such tasks quickly and accurately only with the use of specialized software tools [8]. Their functioning is based on digital models of objects, processes or systems [5, 6]. Such models are built on the basis of dynamic data that need to be kept up-to-date. Each digital model is specific and requires the use of certain resources for its creation. Compliance with all the requirements of design and development methodologies provides a software tool capable of conducting experiments on the object of study in order to predict changes from control actions.

Based on this, the purpose of the research is to create a digital twin of the transportation system of a metropolitan area. The theoretical significance of the obtained results lies in the systematization of the elements of the urban environment, the establishment of links between the objects and processes of the transport system, the formalization of the obtained results for their use in studies related to the development of the urban area (socio-economic, environmental, transport, etc.). The practical significance of the study lies in the use of the obtained results for the creation of projects of integrated development of transport infrastructure and organization of traffic of transport (both private and public).

2 Materials and Methods

The object of the study is the transportation and pedestrian processes formed on the territory of Yeniseyskaya Street in the North-Eastern Administrative District of Moscow. The street is located in Babushkinsky District and is its longest street (about 4.5 km). For most of its length it has two lanes of motor transport in each direction, while moving towards Moscow region it is widened to three lanes.

Creation of a digital model of the processes of the research object can be conditionally represented in the form of the following stages:

1. Object survey. In the course of the stage, all key elements that have a significant impact on the implementation of the transport system processes were identified. In the research related to the decomposition of the system and formal description of the obtained elements complexly used methods of structural analysis, observation, synthesis and statistical analysis [3, 8, 9]. Such a set of methods was used in the current study to obtain the input parameters of the digital model of the research object.

2. Creation of formal models. At this stage, modeling of the subject area was carried out in accordance with the research objective. As noted in the works of researchers, such modeling allows establishing the regular structure of the object of research with the help of formal languages [10, 11]. For this purpose, the intensional (a set of rules and description of relations between elements) and extensional (a set of factors) of the study area were created. For this purpose, the methods of information modeling and graphical method were used.

3. Modeling. This stage is the final stage and combines the results obtained in the previous stages to create a digital twin. For this purpose, the method of simulation modeling is used, which allows using specialized software to combine and "revive" models of processes and objects. As researchers note in their works, it is required to adjust the behavior of each process object (agent) depending on its template behavior under the established external influences [3, 12, 13]. In this case, an agent is a homogeneous group of elements with similar behavior (e.g., a stream of cars moving along a lane in one direction).

3 Results

As a result of using the stated methods, all necessary qualitative and quantitative characteristics of the research object for creating its digital twin are established. We will consider the key indicators.
Yeniseyskaya Street has a clear vertical location. It connects traffic flows between the North-Eastern Chord (Moscow Central Diameter of regional significance of the first class with continuous and traffic-free traffic) and the Moscow Ring Road. Throughout the traffic flows along Yeniseyskaya Street there are conflicting traffic flows formed by the traffic flowing along the intra-district streets. Conflicting flows can be either intersecting or merging. The vast majority of these intersections are regulated. In addition, there are intersecting pedestrian flows that are also regulated. Creation of parametric models of all flows at intersections allowed to establish rules of interaction of objects for the use of methods of information and simulation modeling.

Let us present fragments of the description of such rules:

1. Intersection with Letchik Babushkin Street (Fig. 1):
   1.1. Two lanes in each direction are crossed by a regulated pedestrian flow. The phases of the traffic lights are synchronized in such a way that the pedestrian traffic is carried out simultaneously with the traffic on Letchik Babushkin Street.
   1.2. Distribution of traffic flows between the two streets regulated by the traffic light. Left turn on Letchik Babushkin Street is prohibited.
   1.3. The right turn from Letchik Babushkin Street is allowed on two lanes. There is no traffic light to regulate traffic.
   1.4. The exit p. 1.3 crosses an unregulated pedestrian stream.

Fig. 1. Map of the intersection of Yeniseyskaya Street and Letchik Babushkin Street (source: Yandex-maps https://yandex.ru/maps/-/CDudrKLA)

1. Merge with Urzhumskaya Street (Fig. 2):
   1.1. A right turn is permitted when traveling southbound.
   1.2. Exit from Urzhumskaya Street to Yeniseyskaya Street in southbound direction is permitted.
1. **Intersection with Beringov proezd (Fig. 3):**
   1.1 Left turn to Beringov Proezd (no traffic lights) is permitted when traveling northbound.
   1.2 Exit from Beringov Proezd to Yeniseyskaya Street in the south direction is permitted (no traffic light).
   1.3 Turning onto Beringov Proezd from Yeniseyskaya Street in southbound direction is permitted (no traffic light).
   1.4 There is an unregulated crosswalk in front of Yeniseyskaya Street on Beringov Proezd.
   1.5 When traveling northbound, a right-hand exit is permitted into the common area. Accordingly, it is permitted to exit from it and then proceed northbound.

2. **Intersection with Novy Beringov Proyezd and merge with Verkhoyanskaya Street (Fig. 4):**
   1.1 Regulated crosswalk over Yeniseyskaya Street.
   1.2 Regulated crosswalk over Novy Beringov Proyezd.
   1.3 Permitted right turn from Novy Beringov Proyezd when traveling southbound (traffic light).
   1.4 Left turns are permitted from Novy Beringov Proyezd when traveling northbound (traffic signal).
1.5. Right turns are permitted onto Novy Beringov Proyezd when traveling northbound (traffic signal).
1.6. Intersection of Novy Beringov Proyezd with streetcar tracks near Yeniseyskaya Street (traffic light).
1.7. Crossing of pedestrian flow with streetcar flow (traffic light).
1.8. Turning onto Novy Beringov Proyezd from Yeniseyskaya Street when traveling northbound (traffic signal).
1.9. Three lanes of traffic in two directions on Yeniseyskaya Street.
1.10. Permitted to exit onto Verkhoyanskaya Street when traveling southbound (no traffic light).
1.11. Exit from Verkhoyanskaya Street in northbound traffic (no traffic light).
1.12. Crossing of Verkhoyanskaya Street by pedestrian traffic near Yeniseyskaya Street (no traffic light).

**Fig. 4.** Map of the intersection of Yeniseyskaya Street and Novy Beringov Proyezd (source: Yandex-maps https://yandex.ru/maps/-/CDudrKMj)

1. Intersections and merges with Raduzhnaya Street, Pechorskaya Street, Lenskaya Street, Menzhinskogo Street, Starovatutinsky Proyezd (the rules are the same, the number of lanes of the mentioned streets is different):
1.1. Right turns are allowed when traveling northbound (traffic lights).
1.2. Right turns are permitted when traveling southbound (traffic light).
1.3. Left turns are permitted when traveling northbound (traffic light).
1.4. Left turns are permitted when traveling southbound (traffic light).
1.5. Through movements across Yeniseyskaya Street are permitted (traffic light).
1.6. Right turns are permitted from said streets onto Yeniseyskaya Street (traffic signal).
1.7. Right exits from Yeniseyskaya Street when traveling southbound (traffic light) are permitted.
1.8. Exits to Yeniseyskaya Street are permitted for southbound traffic (traffic light).
1.9. Left turns are permitted from said streets onto Yeniseyskaya Street when traveling southbound (traffic signal).
1.10. Left turns are permitted from said streets onto Yeniseyskaya Street when traveling northbound (traffic signal).
1.11. Regulated crosswalk across Yeniseyskaya Street (traffic signal) to coincide with crossing traffic flow.
1.12. Regulated pedestrian crosswalks crossing all specified streets in the vicinity of Yeniseyskaya Street.
1.13. Widening of Yeniseyskaya Street at intersection locations to four lanes.
1.14. Crossing of the above streets with streetcar tracks from the west side near Yeniseyskaya Street (except for Menzhinskogo Street and Starovatutinsky proezd).

**Fig. 5.** Map of the intersection of Yeniseyskaya and Raduzhnaya Streets (source: Yandex-maps https://yandex.ru/maps/-/CDudrGkK)

It should be noted that there is no public transportation bus service along the entire Yeniseyskaya Street. Certain routes enter the street at certain sections to ensure neighborhood connectivity and infrastructure accessibility. This is due to the fact that along most of Yeniseyskaya Street there is streetcar traffic on separate tracks from the roadway in a clock schedule mode.

Based on the established rules, two-dimensional models of traffic flows have been developed. Fig. 6 shows a fragment of such a model illustrating the fourth set of rules.

**Fig. 6.** Model of traffic flows at the intersection of Novy Beringov Proyezd and Yeniseyskaya Street

Based on this, models of state changes of agents were developed. Fig. 7 shows a fragment of the state change model for personal and public road transport on the section of Yeniseyskaya Street from Novy Beringov Proyezd to Verkhoyanskaya Street.
To determine the input parameters related to environmental pollution, data from the measuring station located in the vicinity of the study site were processed. Figs. 8-10 show the changes in values relative to their maximum permissible concentration (TLV) from January to December 2023.

**Fig. 7.** Diagram of traffic flow agent states on Yeniseyskaya Street from Novy Beringov Proyezd to Verkhoyanskaya Street

**Fig. 8.** Level of environmental pollution by carbon oxide (compiled from data of the Polar station, source: Mosecomonitoring https://mosecom.mos.ru/polyarnaya)

**Fig. 9.** Level of environmental pollution by nitrogen oxide (compiled from data of the Polar station, source: Mosecomonitoring https://mosecom.mos.ru/polyarnaya)
A three-dimensional model is created to visualize the simulation model that reflects all aspects of the subject area using a graphical method. By changing individual settings of parameters related to quantitative characteristics of transport processes and parameters of the ecological state of the environment, simulation scenarios are created. With their help the consequences of such changes are evaluated and on their basis the rules of operational control of processes are developed. Fig. 11-12 shows fragments of such a three-dimensional model for one of the modeling scenarios.

Fig. 11. Fragment of a three-dimensional model of the traffic flow density simulation scenario in the area of the intersection of Yeniseyskaya Street and Novy Beringov Proyezd

Fig. 12. Fragment of a three-dimensional model of the traffic density simulation scenario in the area of Novy Beringov Proyezd

The three-dimensional model reflects the main aspects of the object of study affecting directly the state of transportation processes, so infrastructure elements are not shown. This does not affect the implementation rules of the transportation processes and allows to increase the performance of the digital twin.

Figs. 11-12 show a scenario related to the modeling of traffic flows during the morning off-peak load on the transportation network. This time is characterized by a gradual increase in traffic density. The purpose of the scenario in this case is to obtain ambient air pollution
indicators when changing the traffic lights operation mode. The main feature of the traffic light operation mode is to increase the phase of traffic on Yeniseyskaya Street.

The main result of this scenario is a large accumulation of traffic waiting for turns to Yeniseyskaya Street from Novy Beringov Proyezd. At the same time, the traffic does not have time to pass through the driveway in one cycle and increases. Waiting for pedestrian flows crossing Yeniseyskaya Street.

4 Discussion

Analysis of the results obtained from the study with those related to process and system modeling showed the following features:

1. The key stage of any model creation is the establishment of structural features of the research object. Regardless of the nature of the research (transportation systems [2, 3, 5, 7], environmental monitoring systems [14-16] or resource management [10, 17]), agents (objects that are subjected to some impact or objects that are the initiator of such impact) and their quantitative and qualitative characteristics are distinguished. In the conducted study, exactly such results characteristic of the highlighted object of study are obtained.

2. Formalization of the obtained results in the course of structuring the object of research. Such results must necessarily be presented in a form that is suitable for design and development of a software product, digital processing or presentation for specialists who use them for experiments [2, 3]. As noted by researchers, the form must be consistent with the methodologies for unambiguous understanding of the content by all participants in the process of working on the research (or project) [5, 8, 9]. The use of the stated methods in the study allowed us to obtain such results (e.g., diagrams of agents' states or characteristics of their positioning relative to the elements of the research object), which are necessary for the simulation model (digital twin).

3. Possibility to change the quantitative characteristics of the research object. The creation of a digital twin implies virtual experiments that make it possible to forecast changes in the state of the research object as a whole or its individual parts [6, 7, 9]. In studies related to the creation of such scenarios, it is noted that such changes are carried out with the help of expert systems that are integrated with the digital twin, or are made by a specialized specialist engaged in keeping the digital twin up to date [10, 11, 17]. The resulting model can be used to conduct such experiments both using expert systems and in manual mode. For this purpose, access points of software products using Java technologies have been created.

4. Possibility of using the model for training of profile specialists in the field of urbanism. In studies related to educational technologies, it is noted that such models are a visualized electronic educational resource or digital simulator, allowing to form professional competencies in students of professional institutions [18]. The use of a graphical method to visualize the results of the stages of digital twin development meet the requirements of an electronic educational resource.

5 Conclusion

The transportation system of any city is its backbone, so it must meet all the challenges facing the economy, ecology and population. It is a complex system consisting of many interrelated processes, the change of which can not only negatively affect all objects inside and outside the system, but also have irreversible consequences (e.g., destruction of natural objects). Thus, planning for any changes is an important aspect in the design and implementation of projects to modernize infrastructure facilities or add new ones.
The use of software tools for predicting changes in any transportation system is an important and priority area. The created digital twin meets all modern requirements for data processing and generation of valid control actions on any element of the transportation system.

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