Simulation modeling as a means of forecasting passenger traffic at the Moscow Central Ring station

Yulia Altunina1,* and Vladimir Simonov2

1Moscow Polytechnic University, Moscow, Russia
2Moscow Aviation Institute (National Research University), Moscow, Russia

Abstract. The article presents the results of creating a digital twin of the Moscow Central Ring station “Izmailovo” using simulation modeling methods. The study’s main goal is to create a formal model demonstrating, at given time intervals, the changes in the objects and processes that make up the model when certain input parameters are changed. The results obtained during the simulation of the system behavior allow for evaluating the effectiveness of the concepts for the modernization of the transport system facility in terms of passenger traffic. The conducted structural analysis of the research object allowed to establish all elements and their corresponding characteristics to create models of the behavior of key objects. Additionally, a 3D graphical model has been developed to demonstrate the behavior of all objects and their corresponding processes.

1 Introduction

Moscow Metropolitan is the main city transportation system, with more than 10 thousand trains and about 7 million passengers passing through its lines daily [1].

In 2016, the Moscow Metro scheme was supplemented with a 14th line called the Moscow Central Ring. The length of the MCR is 54 kilometers and consists of 31 stations. From this point on, the development of an urban surface railroad began in the city. According to Moscow Mayor Sergei Sobyanin, 945 million trips have been made along the Moscow Central Ring during seven years of operation [Moscow City Planning Policy and Construction Complex: https://stroi.mos.ru/news/945-mln-poiezdok-soviersheno-za-siemi-riet-raboty-ntsk]. Most stations have interchanges to other metro stations or Moscow Central Diameter stations. As a result, passenger traffic has changed, reducing the load on the capital’s subway lines and railway stations.

In connection with the development of the capital’s transport system (construction of new metro lines, development of central diameters connecting suburbs with the central districts of Moscow, improvement of the ground public transport system, popularity of individual means of transportation), not only the nature and directions of passenger movement are changing, but also the density of the corresponding flows. Adjustment of traffic intervals is required to organize a comfortable movement of passengers, as well as the profitability of
transportation modernization of existing infrastructure. Addressing such problems requires the creation of a detailed development concept that forecasts the consequences of its implementation over a long period.

Digital twins of the real object simulating all its processes should be used to create such a concept [2]. This can be realized with the help of specialized software and the use of simulation methods [3, 4]. Simulation modeling allows obtaining an exact computer copy of an object in its shape and behavior [5].

Thus, the study aims to create a simulation model of a subway station to analyze the changes in passenger traffic.

The main tasks of the study are to identify all objects related to the problem domain, identify their structure, and set key parameters, properties, rules of interaction to create formal models used in simulation modeling and create a simulation model and its corresponding 3D visualization.

The theoretical significance of the study lies in the formal description of processes and objects of the transport infrastructure necessary for the creation of concepts of sustainable development, process research, and the creation of a set of methods of effective operational management.

The study’s practical significance lies in creating a safe tool for the analysis and design of concepts for the development of transport systems and the modernization of infrastructure facilities.

2 Materials and methods

The object of the study is the MCR station “Izmailovo”, located on the border of the Izmailovo and Sokolinaya Gora districts of the Eastern Administrative District of Moscow. The station is a ground station with a ground crossing to Partizanskaya metro station of the Arbatsko-Pokrovskaya line of the Moscow Metro.

From the point of view of the process approach, the station is a complex system including traffic and pedestrian flows, infrastructure, and other objects and processes affecting their states. Forecasting any change requires the development of an object model that accurately represents all qualitative and quantitative characteristics of the studied object. For this purpose, a set of methods was used, among which the main one was the method of structural analysis.

Application of the method of structural analysis to the object of research allowed us to obtain its primary description with different levels of detail. This approach is used at the formalization stage of the problem domain in the works of researchers associated with creating simulation models of objects of transport systems [4, 6, 7], systems that automate the processes of areas of national economy [8], etc. Observation, stepwise detailing, grouping, and synthesis methods were used to obtain accurate data in the structural analysis phase. Through this, the data obtained was processed and clustered to create appropriate models.

Simulation modeling techniques were used to obtain the final model. Such methods allowed us to establish all objects involved in transport and pedestrian processes at the station, determine the rules of their interaction, and establish the peculiarities of behavior under external influences. If we analyze the works that used the simulation method, we can establish that researchers created models of the behavior of each system object by developing a parametric model [2, 9, 10]. Such a parametric model was essentially a set of rules established in a real system between objects or processes that received certain data as input. This approach was implemented in the conducted study.
3 Result

Izmailovo station was opened in 2016 as part of the Moscow Central Ring, an above-ground branch of the Moscow Metro. The station has a coastal platform layout and is located on an embankment. Exit from them is via a single ground terminal. Its exit provides access to the residential development and social infrastructure of Sokolinaya Gora district and an elevated crosswalk connecting the Izmailovo district, where the metro station, commuter bus stop area, a large hotel center, a park, and other cultural facilities are located.

Figure 1 shows the statistics of visits to the studied station.

![Fig. 1. Passenger traffic at Izmailovo station of the Moscow Central Ring in 2021-2023 (compiled from the Moscow City Government’s open data portal: https://data.mos.ru).](image)

Passenger density is influenced by traffic schedule and technical characteristics of rolling stock.

The first train leaves the station at 05:43 (05:45 in the opposite direction), and the last train leaves at 01:03 (00:41 in the opposite direction) [https://transport.mos.ru/metro/about]. It should be noted, however, that on weekends, the first and last train schedules differ slightly from the daytime schedule. Train interval depends on peak loads: during rush hour – 4 minutes (on weekdays from 07:30 to 11:30 and from 16:00 to 21:00, on weekends from 12:30 to 18:00), off-peak time – 8 minutes [https://mosmetro.ru/passengers/development/mcc/about]. Thus, 242 pairs of trains run along the Moscow Central Ring on weekdays and 211 pairs on weekends. The route is served only by five-car “Lastochka” trains (Figure 2) with a capacity of 1.5 thousand passengers.

![Fig. 2. Moscow Central Ring rolling stock (TVC image source: https://www.tvc.ru/news/show/id/220265).](image)
Pedestrian flows at the station are formed in the following ways:

1. **Arriving passengers at the station.** Each of the five cars has two doors; hence, one train initiates the occurrence of up to ten pedestrian flows. It should be noted that two entrances to the car (in the first and last car) are equipped for people with personal mobility aids and persons with disabilities. This means commuters in the two streams are slowing down the pedestrian flow.

2. **Passengers waiting to board a train.** This can be either people moving chaotically around the platform waiting for the train or waiting for the train at a designated carriage door stop. It should be noted that the presence of one entrance (exit) from the platform means the accumulation of more passengers in the first carriages for clockwise trains and the last carriages for counterclockwise trains.

3. **Passengers using the platform infrastructure.** This includes people occupying benches while waiting for a train and passengers using vending machines. Such passengers can be characterized as deviating from the main pedestrian flow when entering the platform.

4. **Passengers arriving at the station.** When disembarking, they merge into a single stream heading towards the platform exit. Occasional deviations from the standard flow when heading to vending machines are possible.

5. **Threads in the terminal.** Two options for passenger movement are possible, regardless of exit or entrance to the platform: stairs without separation of flows into descent or ascent, elevator. Flow separation at the entrance to the terminal is carried out behind the turnstiles after fare payment, unification of flows – before the turnstiles to the exit. Turnstiles are an object slowing down pedestrian flows. Separately, it should be noted that slowing down traffic at the entrance is the transport security service’s selective inspection of passengers and their hand luggage. A single deviation from the standard terminal flows is the flow of passengers stopping to choose a platform and buying a travel ticket.

Based on the findings, models of passenger behavior at the station were developed. Figure 3 shows a fragment of the diagram of state characteristics for passengers staying at the station and going to the terminal.

![Fig. 3. Status diagram of passengers arriving by train.](image)

Figure 4 shows a fragment of the state diagram for passengers arriving from the street to the terminal of Izmailovo station.
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Based on the findings, models of passenger behavior at the station were developed. Figure 3 shows a fragment of the diagram of state characteristics for passengers staying at the station and going to the terminal.

Figure 4 shows a fragment of the state diagram for passengers arriving from the street to the terminal of Izmailovo station.

Figure 5 shows a fragment of the diagram of the states of passengers waiting for the train’s arrival for departure from the station.

It should be noted that the states of waiting and arriving passengers depend on the availability of trains. Accordingly, object-train states are related to object-passenger states.

In essence, state diagrams are the rules of interaction of process objects and are the basis of a simulation model created with the help of specialized software tools. Appropriate 3D models have been developed to visualize the pedestrian processes of the simulation model. They illustrate the events of train waiting (Figure 6), boarding completion (Figures 7-9), passenger movement to the platform (Figure 10), and terminal processes (Figure 11).

Fig. 3. Status diagram of passengers arriving by train.

Fig. 4. Status diagram of passengers arriving from the street to the terminal.

Fig. 5. Status diagram of passengers departing from the station.

Fig. 6. Simulating the process of passengers waiting for trains.
Fig. 7. Simulation of the boarding completion process (movement of arriving passengers towards the exit from the platform).

Fig. 8. Simulation of the train departure process (deviation of passengers from standard flows when increasing the travel distance from/to distant cars).

Fig. 9. Simulation of the boarding completion process (combining all arriving pedestrian flows to exit the platform with partial mixing of upbound passengers from the terminal).

Fig. 10. Simulation of the process of passenger access to the platform.

Fig. 11. Simulation of processes in the station terminal.

The simulation model of the object display is simplified to increase the computing power. This does not affect the parametric model underlying the simulation model. A passenger density map is created to determine the pedestrian flows in different scenarios, as shown in Figure 12.

Fig. 12. Pedestrian traffic density map.

The resulting map shows the distribution of passengers across platforms while waiting for a train at a particular time, as well as in the terminal. With its help, it is possible to estimate the busiest or freest sections of the route. The right side of the platforms is free. The observation results prove this, as this part is far from the exit, so the main concentration of passengers is observed in the place close to the terminal. The density distribution allows for identifying locations where advertising counters or vending machines (e.g., ticketing, ATMs, etc.) can be placed so as not to interfere with passenger movement. In addition, it is possible to separate flows traveling in opposite directions in congested areas.
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4 Discussion

If we compare the methods of creating a simulation model presented in the studies of domestic and foreign scientists with the method we implemented, we can establish certain similarities [2, 4, 6, 10, 11].

At the beginning of the study, the boundaries of the problem domain are defined, and all objects and their details affecting the relevant processes are established [3, 5, 7, 12-14]. This is carried out by abstracting insignificant elements using strict formal rules of recording and detail. In this way, the method of structural analysis is realized. All processes and their characteristics related to transportation systems are established for simulation models related to pedestrians and the vehicles used [5, 10, 15]. This approach is realized in the conducted study, and a set of input parameters and interaction rules of the established objects is obtained.

After obtaining all the necessary data, researchers make formal models of the behavior of each object and set up a simulation model of the research object [4, 6, 8]. In the conducted study, behavior models of each object involved in the processes of the transportation system of the studied object have been created. Based on the results obtained, a simulation model was created, which reflects all qualitative and quantitative characteristics of the real object. Thus, the developed model is ready to implement different scenarios changing the behavior of objects to predict the system change over time and evaluate the corresponding consequences.

5 Conclusion

In the city of Moscow, to create comfortable living conditions for the population, projects are being implemented to develop a sustainably functioning, safe, attractive, and convenient for all population groups transportation system, which is part of the Moscow transportation hub.

The process of development of the transport system of any city is a complex process that requires detailed analysis and forecasting of consequences. This is due to the many factors affecting the final result and, more often than not, having a random character. Using simulation models as digital twins when testing the concept of modernization of transport infrastructure facilities or organization of processes at existing facilities is an effective means of evaluating the proposed provisions for implementation.

The developed simulation model during the research fully corresponds to the real object of the subject area, reflecting all its quantitative and qualitative characteristics. This is supported by the generally accepted use and application of research methods and the concordance of results with those in related studies. The obtained model can be used for educational purposes in business process management, urban planning, and urbanism, as well as by specialists in planning the sustainable development of urban areas and transportation.

References

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4. References


