ISSUES OF SUSTAINABLE URBAN MOBILITY SIMULATION

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Received: May 13, 2018
Received revised: July 6, 2018
Accepted for publishing: July 6, 2018

Abstract

To achieve the high level of sustainability according to the triple bottom-line criteria – economic, ecological and social factors, it is important to look at organization of urban habitat and transportation systems. In the XXI century the transport issue of a modern city has changed: instead of having maximum vehicles' throughput capacity, it is essential to reach the top figures in passengers' pass-through operating flow. At the same time, the transport systems should be user- and environmentally friendly, involve the principles of livability and multimodalism. This work examines experience of European cities in creating sustainable transport environment and suggests some measures for implementation of sustainable development in Russia, based on this expertise, regarding regional specifics of Russian cities. The important role of transportation hubs (TH) is shown. In this connection, the goal of the work is the creation and software implementation of the generalized mathematical model of TH, and its identification for the TH of Ekaterinburg. The BMAP model is used to describe the traffic in passenger transport hubs (PTH). The stochastic model of PTH operation is represented in the form of a multiphase non-Markov queuing system. In addition to mathematical simulating, the article discusses the issues of PTH interior space design modeling based on futuristic principles, using technologies of the future, but aimed at mass consumer. These ideas are not intended for immediate implementation, but give further prospects for the development of sustainable environment and transport systems in a modern city.

Key words: mobility-friendly environment, multi-modal passenger transportation, passenger transport hub, mathematic simulation, queuing systems.

1. INTRODUCTION

Currently, transport infrastructure, transport environment is the basis for sustainable development of a modern city. Transport environment forms the mobility of citizens, which in its turn forms the quality of life of a population. It is important to note that in the XXI century a focus is made on mobility-friendly environment in a city. That is why the goal of this research is to develop the creation principles of mobility-friendly multimodal transport space. A key role here is played by the objects of transport and logistics infrastructure, in particular, transport and transfer hubs. Their operation potential directly affects the speed of passenger traffic In this article, the authors propose a technique for modeling a transport-transfer hub, taking into account its significance, spatial organization both at the macro level (location in the city) and at the micro level (organization of the internal space). On its basis, a generalized mathematical and simulation model of TH functioning is built, their parametric identification for the planned TH in Ekaterinburg is carried out. Scenario calculations have been performed, allowing estimating the efficiency of the TH operation at the current loading level, and also taking into account the possible increase in passenger traffic.

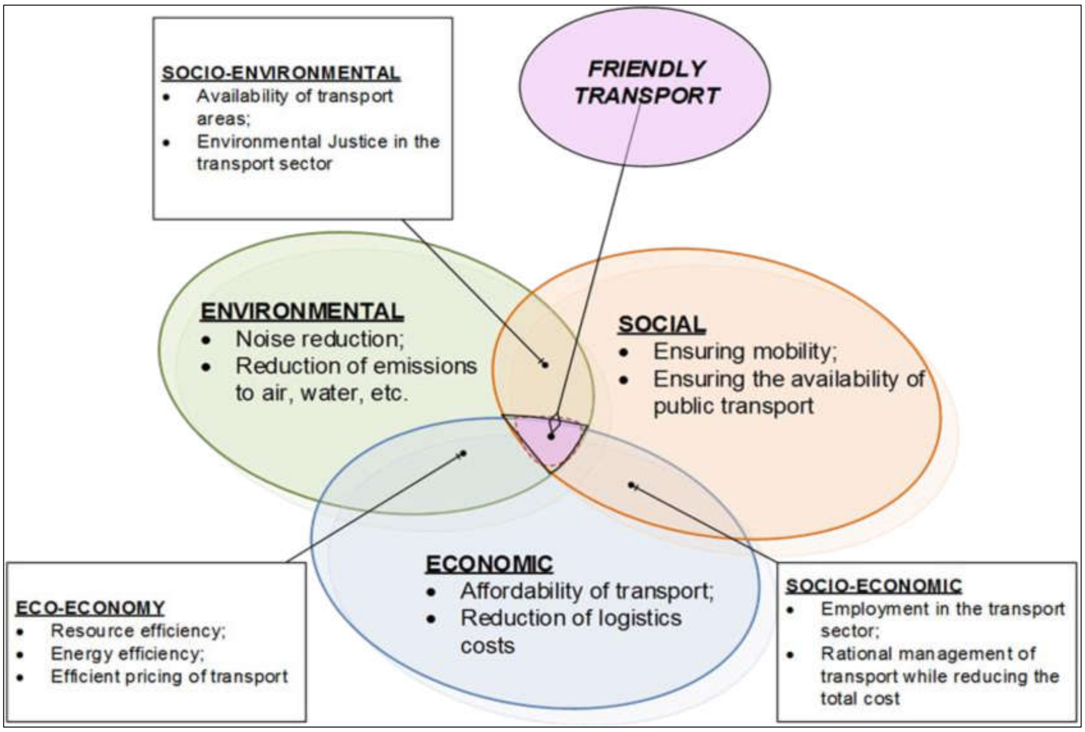
To achieve this goal, the authors have identified a number of objectives. First, investigation of the use of the term "friendly" in scientific works in different countries and the possibility of its implementation in the Russian environment. The next objective was to study foreign and Russian experience in the modeling of transport and logistics infrastructure. Finally, the development of a methodology for modeling the transport interchange hub, taking into account its importance, spatial organization both at the macro level (location in the city) and at the micro level (organization of internal space), as well as the technology of work.

So, the term "friendly" is increasingly common in the world scientific literature: "age-friendly city" (Jackisch et al., 2015; Manchester & Facer, 2015), "walking-friendly cities" (Perić et al, 2015), "friendly administration" (Kisielnicki, 2010), "individuals' adoption of environmentally friendly behaviors" (Untaru et al, 2015), "friendly urban space" (Damingo, 2015), "friendly transport system" (Olivková, 2008), "public transport friendly" (Olszewski & Krukowski, 2015), etc.

What does the term "friendly" mean in general and in relation to urban public transport in particular? The analysis of the above-mentioned scientific works has shown that the term is usually used when talking about the sustainable development of systems, where together with economic and social spheres of human life, an important role is given to the environmental issues. According to Kisielnicki (2010) knowledge of the importance of taking care about the environment can be a good contribution to education. Great significance to the environmental component of the modern transport systems is paid by Canadian scientist T. Litman. He summarized the work of more than 150 studies and has developed a matrix of sustainable development (Litman, 2015). Thus, the friendly transport environment of the modern city should be based on universal integration: the degree of maintenance of economy, social sphere, and the environment.

The second meaning of the term "friendly" is defined in the scientific literature as a convenient, accessible environment for life and work of different sectors of society. Untaru et al (2015) maintains that city space is considered to be friendly if it is equally suitable for work and leisure, calm and favourable life. It is obvious that the global goal of creating a friendly environment is precisely the combination of these two meanings of the term: a convenient and environmentally safe transport environment. The authors of the article support this term, defining it as a convenient and environmentally safe form of mobility in the urban environment (Zhuravskaya et al, 2016; Anashkina, 2016, 2018) (Fig. 1).

Figure 1. Theory of sustainable development as a conceptual basis for a mobility-friendly environment



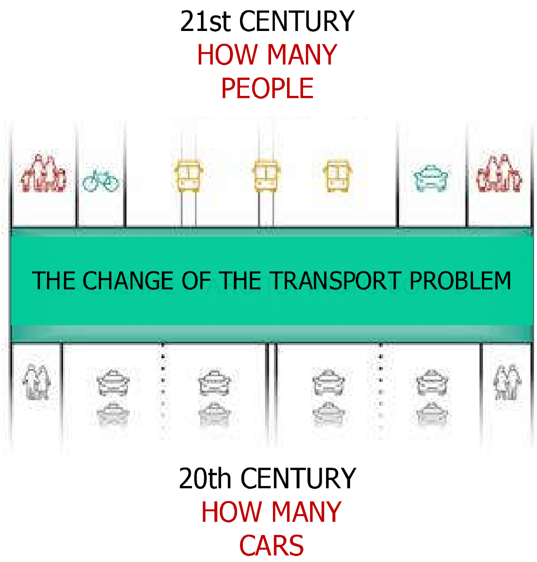
Source: Zhuravskaya (2017)

2. SCOPE OF THE TERM “MOBILITY-FRIENDLY”

It is important to note that scientists from a number of countries were involved in the redesign or modeling of transport infrastructure that meets the principles of a friendly network (Spillar, 1997; Rotoli et al., 2016; Orengo & Livarda, 2016). The authors of this article widely studied the optimization of the transport network (Petrov et al., 2013, Zhuravskaya & Tarasyan, 2014). But a distinctive feature of this work is the emphasis on the formation of a friendly network of urban public transport in terms of compliance with economic, social and environmental requirements.

The phenomenon of friendliness arises at the intersection of the values of economic, environmental and social subsystems of transport and its friendly environment, meets the criteria of these subsystems. Thus, the evaluation measures concerned with user-friendliness of the environment are multi-criteria. Improving transport efficiency without losing social and environmental factors is in line with the general objective of improving the quality of life. For urban transport, the impact on quality of life can and should be seen as a direct development goal. At the same time, it should be noted that in the 21st century the transport issue has changed dramatically: the global task of transport modeling in the 20th century was to organize the maximum pass of cars around the city, but today it is important to organize comfortable, fast, safe, convenient movement around the city as well.

Figure 2. Changing transport paradigm in the 21st century



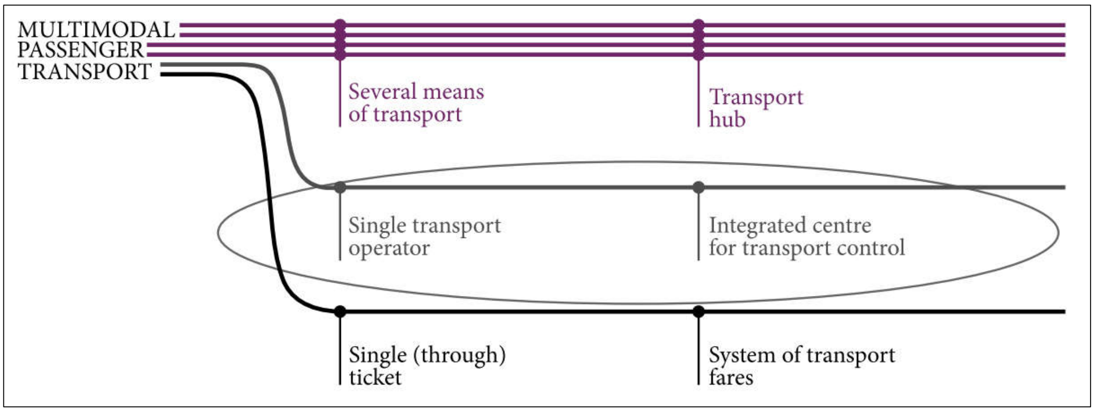
Source: own elaboration

In the new Millennium, people and urban public transport (UPT) have come to the first position. A number of authors have conducted studies on the development of public transport priority in urban agglomerations (McNaughton, 2014; Skibińska, 2013). The efficiency of public transport operation in the city of Vienna is demonstrated in the work of Vassilakou (2014): the share of private transport use is halved, and the use of public transport is characterized by a noticeable growth. However, these positive trends go together with a number of problems, which, due to the population growth forecast will increase in the coming years. In order to solve these problems, the city authorities of Vienna developed a "Public transport package", which will allow developing the right strategy and tactics for the management of passenger transport in this metropolis.

It is essential to note, that not just a separate type of urban transport (unimodal transport) becomes important in the life of the city, but multimodal transport, which is a combination of different types of urban public transport, is particularly relevant. In Milan, the work of urban public transport is coordinated by the company ATM-group (Bianco, 2014), which integrates in one system metro, tram, bus and trolleybus lines, the functioning of parking, car and bike sharing, as well as the funicular.

A complex of multi-modal UPT technologies is a unique tool for transition to new scenarios of public transport services. The structure of multimodal passenger transportation is presented in the form of a scheme (Figure 3), which clearly defines three parts: participation in the transportation of several modes of transport, responsibility for the organization of transportation of a single operator, and the availability of a single (for all modes of transport) ticket.

Figure 3. Diagram of the multimodal transportation



Source: Zueva et al. (2018)

To implement the mentioned scheme, it is necessary to create conditions, so the interaction of different modes of transport is effectively carried out through transport interchange centers, for the organization of the work of a single multimodal transport operator; a single transportation management center and a single tariff system for a single travel document are required.

Logistic integration and coordination of forms of urban passenger transport in the cities worldwide with efficient UPT systems is implemented on the basis of the multimodality principles. Multimodal passenger transportation is transportation of passengers by two or more means of transport under the responsibility of one operator with a single ticket to satisfy inhabitants' demand for transportation (Zueva et al., 2018). Switching to multimodal technologies is a complex and multi-stage process. The city has to take a complex of measures to integrate various forms of passenger transport into a single urban transport system in a way that it would be comfortable for passengers, as well as profitable and reliable for transport companies. The set of measures includes:

• creation of a network of transport hubs;

• organisation of a single dispatcher centre for management of the urban public transport;

• design of a single travel document for all means of transport – a single ticket with efficient system of fares.

If public transport in the cities of Western Europe is developing on the basis of multimodality, in Russian cities scattered urban public transport is not always ready to provide passengers with quality transport service. Despite this, the growing population of cities is increasingly making new requirements for the organization of transport services: compliance with reliable-high speed transport, ensuring road transport and environmental safety, providing up-to-date information about the location of vehicles, creating a comfortable and aesthetically attractive conditions of travel and transfer from one mode of transport to another, etc. These circumstances determined the relevance of the presented research and defined the main goal as the study of modeling of a friendly transport environment on the example of the largest city. The object of the study is the urban public transport of the city of Yekaterinburg, as well as the cities of the world with well-functioning transport systems. The subject of the study is the transport interchange hub. There are different approaches to the classification of transport hubs, the authors of this study it was important to explore the multilevel TH, which can be urban, regional and Federal.

The modeling of the friendly space of such TH should be performed both at internal level inside the node (micro-level) and at the external level (macro-level). The issue of location place of multilevel TH of federal importance in the urban environment has been elaborated (Zhuravskaya et al., 2017). There are four important points of placement of potential TH of Federal importance in Yekaterinburg:

- Prospekt Kosmonavtov metro station, where the introduction of inter-municipal high-speed tram, connecting Yekaterinburg with the city of Verkhnyaya Pyshma it is planned;
- city railway station, where passenger flow from the main railway merges with the motor transport flow;
- metro station "Botanicheskaya", where the integration of high-speed highway in the direction of Chelyabinsk-Ekaterinburg is planned by end 2026;
- Koltsovo Airport, which provides the acceptance and departure of passenger traffic from/to the main air transport.

And if public transport in the cities of Western Europe is being developed on the basis of multimodality, in Russian cities scattered urban public transport is not always ready to provide passengers with qualitative transport service because of multimodality absence. Despite this, the growing urban population is increasingly presenting new demands for transport services.

Modeling at the macro level was performed based on the gravity model and the developed method. Much attention was paid to the issues of building a friendly space inside the TH (at the micro level). The study of foreign analogues showed that the design of TH in most cases is limited to the organization of passenger traffic and the creation of a standard navigation system. We also wanted to make steps to the design of the internal environment and the principles of self-perception of the person in it, so the purpose of this part of the work is to offer an original style of interior design of a TH in Ekaterinburg. The main idea of navigation inside the center is to create some structures-partitions. They form a network of corridors, helping people choose the right option in choosing the way. The entrances to these tunnels are marked with the color assigned to this mode of transport (Fig. 4).

Figure 4. Organization of the internal space of TH

Source: Zhuravskaya et al. (2017)

Orientation towards the consumer of the future allowed the authors to offer storey-zoning, where each level is responsible for a certain type of transport. Passenger flows were analyzed and separated in right order within a TH, with supplementation of a scheme of directions inside an entrance hall, and elaboration of respective navigation: visual, audio, tactile. A special feature of the project is futuristic interior of the terminal of the transport interchange hub with cutting-edge technologies focused on the mass consumer. This design is not intended for immediate implementation, but outlines promising ideas and directions. Thus, unique images of solutions for a user-friendly transport and logistics environment of a city of the future are created.

3. MATHEMATICAL AND SIMULATION MODELS OF TRANSPORT HUB

To determine the incoming traffic flows, monitoring was carried out at the main entrances to Yekaterinburg. Large volume of researches were carried out daily for several weeks during different day hours – in the morning, lunch and evening. Measurements were made using full-scale counting and surveillance cameras. According to the results of monitoring the volumes of transport and passenger flows on arrival and departure in different directions are estimated. At each entrance to the city transport situation is studied, and the score of traffic jams according to application "Yandex. Probki" is determined. The coefficient of variation was calculated to assess the stability of the flow and the XYZ-analysis method was used.

Spillar (1997) maintains that in transport hubs repeated actions do take place: arrival of vehicles, disembarkation of passengers, their transition to another mode of transport, waiting. At the same time, random factors play a significant role at each stage. In this study, to describe the operation of the TH a queuing theory is applied. It is currently used for the simulation of transport processes, objects and systems. One of such systems is Markov Queuing systems (MQS) (Kerner, 2009). The flow of incoming service requests in such systems belongs to the simplest, i.e. has the properties of being stationery (flow parameters do not change over time), ordinary (simultaneous receipt of two or more applications is impossible), and having no aftereffect (prehistory does not affect the further course of the process). However, in practice we have to deal with situations when the flow of events is not the simplest (Zharkov, 2018). In the monograph (Kerner, 2009) the theory of three phases in a transport stream is developed and a stochastic three-phase model is constructed.

When building a mathematical model of TH, the authors distinguish the external and internal stages. The first is the stage of formation of the total incoming flow of requests; the second is the stage of service.

To describe the incoming flow of requests, the authors propose to use the BMAP-flow (Batch Markov Arrival Process) (Lucantoni, 1991). BMAP is a generalization of the simplest (Poisson) stream. Its features are the possibility of combining several separate flows into a single structure and taking into account the random character of the arriving group.

A BMAP flow has the following properties:

- intensity of receipt of request groups depends on the state number of the Markov control circuit (MCC) v_t with continuous time and finite state space {0,1,..., W};
- residence time of v_t in the state v has an exponential distribution with parameter λ_v, $v = \overline{0,W}$;
- after the chain's stay in state v is over, MCC moves to another state v', $v' = \overline{0,W}$ with the specified probability $p_k(v,v')$, and a size group k ≥ 0 is generated;
- transition probabilities $p_k(v,v')$ satisfy the condition $\sum_{k=0}^{\infty}\sum_{v'=0}^{W} p_k(v,v') = 1$ for $v = \overline{0,W}$.

D. M. Lucantoni suggested that the performance of BMAP-flow in the form of a set of matrices D_k,, k ≥ 0, of size (W+1)×(W+1), which are defined in the following way: $(D_k)_{v,v'} - (v,v')$ th element of the matrix D_k has the form

$$(D_0)_{v,v'} = \begin{cases} \lambda_v p_0(v,v'), & v \neq v', v,v' = \overline{0,W}, \\ -\lambda_v, & v = v', \ v = \overline{0,W}, \end{cases} \qquad (D_k)_{v,v'} = \lambda_v p_k(v,v'), v,v' = \overline{0,W}, k \geq 1.$$

In this paper, we consider systems with the following properties: the BMAP-flow enters the system; the size of the group of requirements is a random variable; the aftereffect is absent; the system has three phases of maintenance, each phase is a separate QS; queue maintenance is performed on the FIFO principle (first in — first out).

The maintenance stage consists of three phases. In the first phase, the transition from the vehicle to the terminal is simulated, in the second phase – buying tickets and passing through turnstiles, in the third phase, the work of the metro station is simulated.

In accordance with the structure and operation technology of TH, the first and second phases are multichannel QS, the third – a single-channel QS with group service. A queue of finite size is allowed in all phases. Feedback consists in blocking the channels of the first phase in the absence of available seats on the second and third. In terms of Queuing theory, the TH model looks like (Medhi, 2003), where S denotes the size of the serviced group, D is the deterministic distribution of maintenance time.

Here T_{in} is the time between successively received groups; X – size of the incoming group of requests; T_1,T_2,T_3 – time of service at the appropriate phase; S is the size of group requests, selected for service on the third phase; $N1,N2$ – the number of channels on the phase of the first and second phases; M_1, M_2, M_3 – queue length on the corresponding phase; P_1, P_2, P_3 the output stream of requests corresponding phase; $\bar{Y}$ - is a vector of output parameters of the system including the number of served requests and groups of requests; the average queue length l; the average number of busy channels k; the average time of a request stay in system T_s; the average number of handled requests per minute A; the average time in the queue w; the average time in phase t_{ph}; the average number of accepted requests on the corresponding phase x_{unload}. The distributions T_{in},T_1,T_2 are continuous and discrete.

Due to the complexity of the constructed model, the laws of distribution of random variables will be sought approximately with the help of simulation methods. A key role in this process is played by the procedure of finding the stationary probabilities of the system states, with the help of which the desired output parameters are determined.

The simulation model (Graham & Talay, 2013; Bychkov et al., 2016) is implemented as a software module that is designed to calculate stationary probabilities and determine the functional characteristics of the simulated system, as well as multi-variant scenario calculations. In addition, the software module allows to generate incoming request flows with specified characteristics.

Before starting the simulation, the user is given the opportunity to set the parameters of the system: the number of working phases, the number of channels and places in the queue at the appropriate phase, and the total simulation time. It is also possible to configure the following characteristics: firstly, time intervals between incoming multi-applications and time of service channels can be either a constant, or comprise a set of indicative, uniform, normal, gamma distributions; secondly, the number of requests in the group can be set or generated by uniform discrete, binomial or discrete exponential laws, as well as by the Poisson law. The distribution law parameters are set by the user.

Main functions of the program:

- generate the number of requests per group;
- generate the arrival times of groups of requests;
- system status check;
- display the application maintenance process graphically;
- display of process data to unload the tables;
- displaying the result of generation in tables and saving in MS Excel format.

Channels in the system are independent from each other and, generally speaking, can have different intensity of service. As soon as the channel is released, it receives a request from the queue (if any). If the queue is empty, the channel goes into standby mode.

4. COMPUTATIONAL EXPERIMENTS

Experiment № 1. The time interval from 7.00 to 9.00 is chosen, as it accounts for the highest peak of the arriving traffic flow going to Yekaterinburg. The purpose of the simulation is to evaluate the efficiency of passenger service, during the period of passengers' trip from the interception parking to the metro station.

The inbound flow - average number of cars entering the parking lot (as shown earlier) is 700 units per hour. Let's assume that the time interval between arriving cars is subject to exponential distribution with parameter $a_{\text{in}} = 12$. The number of passengers in the arriving car is subject to the geometric distribution law with the parameter $\lambda = 0.75$ and can take values from 1 to 4.

Phase 1 is modeled by the QS, which has 6 channels (doors) and an infinite queue. The operating time of each channel is subject to an exponential distribution with parameter $a_1 = 20$. Phase 2 has 10 service channels (cashiers), where operating time is exponentially distributed with parameter $a_2 = 20$ and a queue for 200 requests. Phase 3 is a QS that simulates the operation of a metro station.

Currently, Yekaterinburg metro operates trains, consisting of 4 cars with 81-717.5 M series head car and 81-714.5 M series intermediate car. The capacity of such cars at a density of 10 people/m2 is 308/330 people. For our model let's take the average density - 5 people / m2. Half of the train cars will be allocated to serve the needs of the population living in the area, not being motorists. Consequently, the serviced group in the second phase has a volume of 300-360 people.

The intervals of trains in the Yekaterinburg metro at weekdays from time period 7.00 to 9.30 are 4 minutes. Thus, the service time intervals in the third phase are deterministic and are 4 minutes. In case of insufficient number of seats in the third phase, the channels of the first phase are temporarily blocked. The average transition time between phases is 5 minutes and is included in the average staying period in the system.

According to the description in terms of TMO model has the following form: $BMAP/M^X/6/\infty \to /M/10/200 \to /D^S/1/400$.

Two simulating experiments were carried out to determine the required level of service and characteristics of the system. In the first, the parameters of the TH at the current level of passenger traffic were determined. In the second, the incoming flow rate and the number of channels in phase 1 and 2 have been increased to determine the capacity of the metro (phase 3). The simulation results are presented in Table 1 and Table 2.

Table 1. Simulation results No. 1

	Arrived	Accepted	T_s (min.)	A	
Application groups	1345	1345	13,42	16,11	
Applications	2056	2056			
	k	l	w (сек.)	t_{ph} (сек.)	x_{unload}
Phase 1	5,64	–	–	30,72	1
Phase 2	8,38	4,21	24,26	55,11	1
Phase 3	1	33,87	119,32	119,32	73,55

Source: own elaboration

Next, several tests were carried out to determine the metro capacity, which is part of the TH (Phase 3).

Experiment № 2. In Table 2 results of modeling with twice the intensity of incoming flow (1400 groups of applications/hour) and the following characteristics are presented: 16 channels in the first phase; 20 channels in the second phase and service time equal to 4 minutes in the third phase.

Table 2. Results of simulation No. 2

	Arrived	Accepted	T_s (min.)	A	
Application groups	2885	2885	13,42	33,29	
Applications	4371	4371			
	k	l	w (сек.)	t_{ph} (сек.)	x_{unload}
Phase 1	11,2	–	–	30,8	1
Phase 2	17,55	9,55	25,75	54,94	1
Phase 3	1	71,42	119,55	119,55	143,45

Source: own elaboration

From the results of the simulation, it can be seen that the metro's capacity is sufficient to transport passengers during rush hours. With a more than twofold increase in passenger traffic, metro traffic does not reach the threshold value. The most dependent on the volume of passenger flow is cashiers' level in the TH. However, the simulation did not take into account the possibility of pass tickets for passengers. Taking this fact into account in the future it is useful to significantly reduce the number of necessary cash registers to ensure efficient service.

5. CONCLUSION

As a result of this study, the concept of "mobility-friendly environment" was primarily defined, and was shown that TH is an important element of the friendly transport and logistics space of the modern city. The article presents the structure of a TH and focuses on the spatial solutions of the organization of a TH at the macro-and micro-levels.

The authors worked out in detail the issue of the formation of a friendly multimodal space by the example of TH. Of course, for the comprehensive implementation of the program of the friendly multimodal space of the modern city it is necessary to solve at least two more tasks. This is the creation of a single traffic control center (Zueva, 2018) and the development of a tariff system for different scenarios of transport services (Zhuravskaya et al., 2017).

Both micro-and macro-space of TH should meet the concept of creating a friendly transport and logistics environment, for this purpose designed high-tech futuristic space, full of technologies of the future. The original recognizable style of the transport interchange hub is created, in which the interior, as a single operating system, promotes the rapid movement of passengers, sets the direction and dynamics of movement, providing users with all the necessary information. Mathematical and simulation models of a TH are suggested, and computational experiments are carried out.

The continuation of our research will be related to the development of the proposed model and algorithmic apparatus. In the future, it is proposed to build mathematical models of large transport interchanges in the form of multiphase queuing systems with an incoming BMAP-flow, which will allow performing scenario modeling of the movement of urban passenger transport along the highways of megacities. The end result of the research, in our view, should be the creation of a computer tool that allows modeling the operation of the entire urban transport system, taking into account random and control impacts, uneven transport flows, including tariffing, the possibility of emergency situations. The results of modeling, in turn, will be used as input data in the formation of a mobility-friendly logistics space in modern cities.

The work was carried out with partial financial support of RFBR, projects № 18-07-00604, 16-06-00464.

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