IMPROVEMENT OF WORK OF URBAN PUBLIC TRANSPORT BASED ON PASSENGER TRAFFIC SIMULATION

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Abstract. The modern stage of socio-economic and demographic development of cities is characterized by the process of urbanization. Characteristics of indicators of transport activity of the metro of the city of Saint Petersburg are given in the paper. The maximum load in the morning and evening hours was statied based on a study of daily passenger traffic. The classification of metro stations was given based on the obtained models of passenger traffic. The model of the incoming passenger traffic of the N-station was built taking into account 4 passenger traffic intervals. The incoming passenger flow at each interval was described using a straight line equation. The values of the parameters of the line equations for each interval were obtained using the least squares method. A graphical representation of the model of the incoming passenger traffic of the N-th metro station is presented. The developed model allows you to manage the unevenness of passenger flows and is a real reserve for improving the work of the metro, facilitating the conditions for passengers to stay in the car, and rational use of the main means of transportation.

Key words: territory development, urbanization, megalopolis, metro stations, mathematical model.

1. Introduction

The modern stage of socio-economic and demographic development of the states all over the world is characterized by the process of urbanization (Graovac *et al.*, 2017; Pantić, 2019; Ognjenovic *et al.*, 2015a; Poku-Boansi and Cobbinah, 2018). Thus, according to UN experts, the number of urban residents will double by 2050 to reach 6.4 billion people. Hereby there is not only growth of the absolute number and share of urban population, but also formation of new types of settlements: agglomerations, conurbations (Proskuryakova, 2015; Ambarwati *et al.*, 2017), metropolises and megalopolises (Medina *et al.*, 2019; Muñoz *et al.*, 2016; Anciaes *et al.*, 2016). All these processes are characteristic of the Russian Federation (RF) as well.

The second largest urban agglomeration of the RF after Moscow is St. Petersburg. St. Petersburg is the center of the Northwestern Federal District. As of 01.01.2019, the population of St. Petersburg is 5,383.9 thousand people, the main satellite towns and surrounding industrial centers include: Kolpino, Kronstadt, Petrodvorets, Pushkin, Sestroretsk, Zelenogorsk, Pavlovsk.

Non-conformity of the transport system development level to the increasing needs of the society and economy is one of the most urgent problems associated with urbanization all over the world (Liang *et al.*, 2018; Sitharam and Kumari, 2017; Smirnova 2017a; 2017b). The urban transport system is a complex infrastructure consisting of subsystems of various transport modes (trunk, urban public and personal) which main function is mass transportation of goods and passengers.

The purpose of this study is to build a mathematical model of the incoming passenger flow of the N-th metro station to improve the performance of urban passenger transport. To achieve this goal, the following tasks must be completed:

- to analyze the main volume indicators of the metro (for example, Saint Petersburg);
- to study the temporary intra-day fluctuations in passenger traffic in the St. Petersburg metro;
- to get the values of the incoming passenger traffic using the regression equation and confidence interval boundaries.

2. Characteristics of St. Petersburg subway

Subway takes the leading position among urban modes of transport by transportation of passengers in large metropolises (Peng *et al.*, 2019; Ognjenović *et al.*, 2015b; Kharitonov *et al.*, 2016; Lediaev *et al.*, 2017). "St. Petersburg Metro" St. Petersburg State Unitary Enterprise (SUE) began operations on November 15, 1955. Today, the St. Petersburg Metro has 72 stations located on five lines, the operating length of the lines is 124.8 km. Passenger traffic volume exceeds 2 million people per day. The main volume indicators of operation of St. Petersburg Metro for the last 5 years are presented in Table 1.

Analysis of subway operation shows that the carrying capacity of the busiest lines in St. Petersburg, especially during peak hours, does not meet the population transportation needs. However, the construction of new metro lines is rather slow, due to difficult geological conditions. Useful experience in such conditions is presented in the works of foreign scientists (Pérez *et al.*, 2016; Sanz *et al.*, 2016; Sanz Perez *et al.*, 2017). The heavy load of subway not only worsens the passengers transportation conditions, but also reduces the service life of the rolling stock, adversely affects the reliability of its operation.

Table 1. Main volume indicators of St. Petersburg Metro according to http://www.metro.spb.ru

Indicator name	2015	2016	2017	2018	2019
Passenger transportation, million passengers.	741.7	740.4	726.5	743.2	762.5
Inventory car stock, pc.	1.680	1.711	1.805	1.895	1.929
Transport work, million cars-km	211.4	213.1	215.9	228.8	236.0

Organization of transportation by subway depends on the size and regularities of passenger traffic. It is passenger traffic that predetermines development of the subway network, technical equipment capacity, number of vehicles, repair time with the lowest economic losses, etc. According to passenger traffic the vehicles are distributed by lines, release of vehicles is regulated by hours of day, the working hours of stations and escalators are established, etc. Despite this, insufficient attention is paid to scientific and methodological issues of organization of transportation by underground railway, study of already established and future passenger traffic.

3. Simulation of passenger traffic of St. Petersburg Metro station

Study of passenger traffic for settlement of the most important tasks of subway is based on construction of its mathematical model (Proskuryakova, 2019). Passenger flow simulation results are used for:

- spreading of the opening hours of enterprises, organizations, institutions and educational institutions in the area of walking accessibility of stations;
- revelation of real peak hour, construction of a cartogram of passenger traffic and passenger turnover of stations, calculation of the need in rolling stock;
- determination of irregularity of pickup and drop off of passengers by train cars, utilization rate of station vestibules;
- establishment of interstation correspondence, transfer of passengers, average distance of passenger's trip in the network, significance of different stations in formation of transfer passengers and assessment of the need to organize new links of the existing subway lines;
- revelation of maximum loads of entrances and exits, escalators, staircases and crossings, as well as pedestrian traffic by 15 minutes intervals in morning and evening peak hours (Yu *et al.*, 2019; Khattak *et al.*, 2018; Feng *et al.*, 2017; Yang *et al.*, 2019; Belentsov and Smirnova, 2018; Smirnova *et al.*, 2019; Badland *et al.*, 2017).
- Study of the transportation pattern shows that real passenger traffic has a complex structure with certain regularities of change of its components in time and space as shown in Fig. 1. This article focuses on intraday fluctuations in passenger traffic.

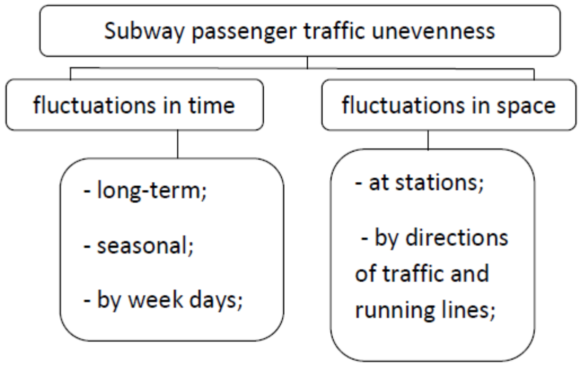


Fig. 1. Types of passenger traffic irregularities on the subway

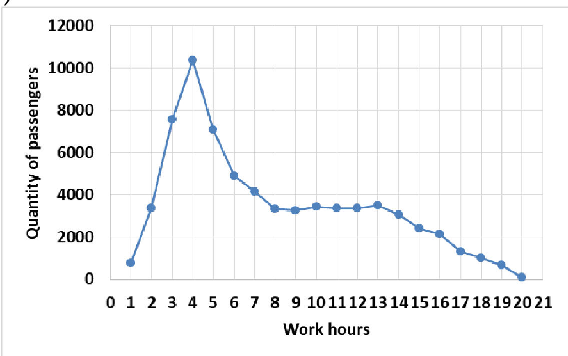
Analysis of incoming passenger traffic of St. Petersburg Metro lines showed that all stations can be divided into three groups:

- morning maximum;
- evening maximum;
- double-peak.

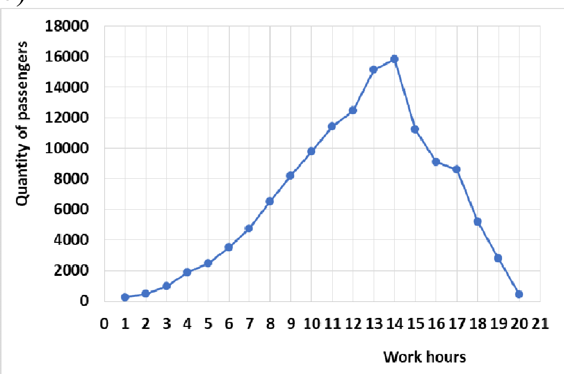
Examples of distribution of intra-day passenger traffic of such stations are shown in Fig. 2. The average number of passengers that entered the station within an hour on Wednesdays of the studied year is shown on the axis of ordinate; opening hours of stations: the 1st hour of work from 5.00 to 6.00, ... the 20th - from 0.00 to 1.00 - on the axis of abscissas. The model of passenger traffic of the N-th subway station with the morning maximum is presented in Fig. 2a.

The number of people that entered subway in a certain interval of time was considered as passenger traffic, from a physical point of view. From a mathematical point of view, incoming passenger traffic of subway is a time series which value is a random variable.

a)



b)



c)

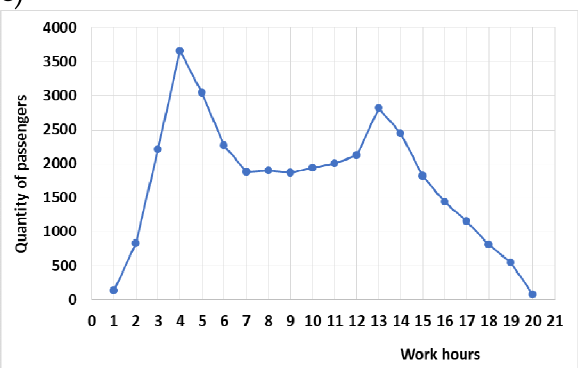


Fig. 2. Classification of subway stations:
a) morning maximum; b) evening maximum;
c) double-peak

4. Construction of mathematical model of incoming passenger traffic in St.Petersburg subway

Construction of a stochastic mathematical model of passenger traffic, having an analytical task, will allow assessing its accuracy, reliability, predicting the values of incoming passenger traffic with a preset probability level.

Various functional dependencies including splines can be used to model passenger traffic. A spline is a piecewise defined function, i.e. a collection of several functions, each of which is defined on a certain set of argument values and the sets of argument values are pairwise disjoint. Splines are widely used in solving various applied mathematical problems. However, the higher the degree of the spline (the degree of the polynomial used in the spline), the more complex and cumbersome the analytical task the model has. Thus, splines of the first degree are most widely used in practice. First degree splines are piecewise linear functions that are easier to calculate, construct and analyze.

Visually, incoming passenger traffic of the N-th station (Fig. 2a) can be divided into four intervals. At each interval, incoming passenger traffic can be described using the straight-line equation. The following values of parameters of the straight-line equation were obtained by the least square method for each interval:

$$\hat{y} = \begin{cases} 3789{,}4x - 3185{,}5;\ x \in [1;4] \\ -2715{,}5x + 22280;\ x \in [4;7] \\ -64{,}821x + 3995;\ x \in [7;13] \\ -489{,}91x + 9778{,}9;\ x \in [13;20] \end{cases}$$

All passenger traffic is approximated by piecewise linear function that one can see in Fig. 3.

Table 2. Main volume indicators of St. Petersburg Metro.

Area	Hour of work	y_i	$\hat{y}_i$	σ	Confidence interval	
					lower limit	upper limit
1-4	1	824.69	603.97	506.17	-403.36	1,616.30
	2	3,867.37	4,393.44		3,381.11	5,405.77
	3	8,591.98	8,182.91		7,170.58	9,195.24
	4	11,877.65	11,972.38		10,960.05	12,984.71
4-7	4	11,877.7	11,417	764.49	9,888.21	12,946.19
	5	8,366.3	8,701.5		7,172.51	10,230.49
	6	5,277.1	5,985.8		4,456.81	7,514.79
	7	3,855.1	3,270.1		1,741.11	4,799.09
7-13	7	3,855.10	3,541.25	354.16	2,832.94	4,249.57
	8	3,633.04	3,476.43		2,768.12	4,184.75
	9	3,164.76	3,411.61		2,703.30	4,119.93
	10	2,746.83	3,346.79		2,638.48	4,055.10
	11	3,304.14	3,281.97		2,573.65	3,990.28
	12	3,294.42	3,217.15		2,508.83	3,925.46
	13	3,429.38	3,152.33		2,444.01	3,860.64
13-20	13	3,429.38	3,410.07	266.60	2,876.77	3,943.37
	14	3,028.21	2,920.16		2,386.86	3,453.46
	15	2,347.02	2,430.25		1,896.95	2,963.55
	16	1,978.87	1,940.34		1,407.04	2,473.64
	17	1,278.77	1,450.43		917.13	1,983.73
	18	903.73	960.52		427.22	1,493.82
	19	576.21	470.61		-62.69	1,003.91
	20	20.42	-19,30		-552.60	514.00

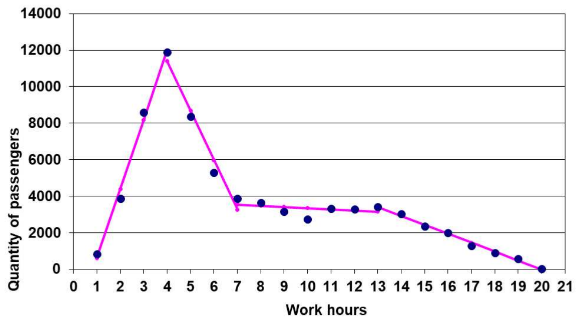


Fig. 3. Piecewise linear model of incoming passenger traffic of the N-th subway station

The width of the confidence interval on each area is determined by the formula:

$$\hat{y}_i - t_\alpha \sigma \le y \le \hat{y}_i + t_\alpha \sigma,$$

where $\hat{y}_i$ - theoretical values obtained by regression equation;
t_α - value t — the Student criterion, with probability P = 0.95, $t_\alpha \approx 2$;
σ – mean square deviation of the actual time series values from the theoretical ones obtained by regression equation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n - m}}$$

where n – number of series levels;
m — number of parameters of the studied function;
y_i- actual values.

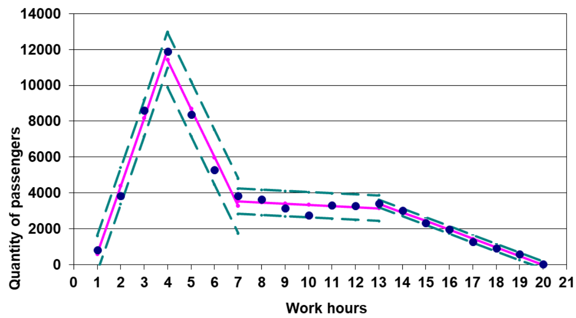


Fig. 4. Graphic representation of the model of incoming passenger traffic of the N-th subway station.

The results of calculation of confidence interval are presented in Table 2. Fig. 4

shows actual values of incoming passenger traffic.

The values of incoming passenger traffic obtained from by regression equation and confidence interval limits.

5. Conclusions

The model of incoming passenger traffic of the N-th subway station is constructed based on conducted studies. The nature of hourly irregularity is mainly predetermined by work and study trips, which give pronounced morning and evening peaks of traffic. Materials of all studies show that during morning and evening peak hours, cars are loaded above the permissible standard. The situation is exacerbated by the fact that as a rule year after year, the share of traffic during peak hours does not decrease, but increases.

All kinds of irregularities in distribution of passenger traffic in time and space affect the operation of subway lines, dictating strict requirements to organization of the transportation process. Traffic irregularity is an objective phenomenon, it cannot be "cancelled", but it can be controlled. Smoothing of irregularities is a real reserve for improvement of subway operation, facilitation of conditions of stay of passengers in the car, rational use of basic transportation means.

The following measures can be offered in order to improve subway efficiency:

- regulation of operation of escalators for descending and ascending;
- increase of the speed of escalators;
- increase of the frequency of trains; coordination of all modes of transport;
- sectioning of trains (change of the number of cars in the train);
- zone movement of trains (some trains go to the terminal stations and the rest turn at one of the intermediate ones);
- spreading of the opening and closing hours of enterprises and educational institutions.

Thus, in modern conditions of urbanization there is an increasing need for development of urban transport systems, the main mode of transport of which is subway. Specialists in all countries of the world work to solve the transport problem in the cities. It can be most fully settled with mutually agreed transport technology on all modes of passenger transport which lines and routes will represent a single transport system of the city.

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