TRANSPORT PROBLEMS 2021 Volume 16 Issue 1
PROBLEMY TRANSPORTU DOI: 10.21307/tp-2021-008

Keywords: urban public passenger transport; walking distance; questionnaire; public transport stop; a priori ranking of factors; Kendall coefficient of concordance; dimensional theory; dimensional analysis

Baurzhan ZHAMANBAYEV*, Adilkhan RAIMBAYEV, Elmira ALMAKHANOVA, Saule RAIMBAYEVA
Taraz Regional University named after M.KH. Dulati
7 Suleimenova, 080012, Taraz, Kazakhstan
Waldemar WÓJCIK
Lublin University of Technology
38D Nadbystrzycka, 20-618 Lublin, Poland
**Corresponding author.* e-mail: zhaman78@mail.ru

TWO-STAGE SUBSTANTIATION OF PLACEMENT OF PUBLIC TRANSPORT STOPS

Summary. Designation of places for public transport stops is a key component of research on their accessibility. However, further research is needed to solve the problem with organization of public transport stops. This paper provides the results of an priori ranking analysis aimed at defining the most significant factors affecting the accessibility of stops and their scope. The proposed mathematical model, which uses dimensional theory, consists of two stages: pedestrians' movement to a stop and passengers' trip to a transit stop. It is a theoretical premise that allows to determination of placement of public transport stops considering the main indicators, which are the distance covered by pedestrians and the speed of public transport.

1. INTRODUCTION

Public transport plays an important role in providing service accessibility, including cost of services, physical accessibility, information and attitude. All these factors motivate citizens to use public transport.

Understanding of accessibility for improvement of social integration in the Republic of Kazakhstan is aimed at improving the efficiency of public transport usage [1, 2]. The development of public transport in Kazakhstan follows the trend of Eastern European countries. As a result, private transport is one of the dominant means of transportation, leading to a decline in the number of people using public transport. Taraz city, which is located in the south of the Republic of Kazakhstan, was chosen for the current research. According to the Statistics Committee of the Republic of Kazakhstan [3], the population of Taraz is 450000 people. It is important to mention that for the last 20 years, this number has not changed; however, the number of cars increased by 328%. In 2003, there were 102 cars per 1000 people, and in 2019, this number reached 437 cars. Table 1 shows the main information about urban public transport in Taraz.

In accordance with "Building Regulation 3.01-01-2008 of Republic of Kazakhstan", the distance between stopping points in the city area varies from 400 to 800 meters. [4]. At the same time, it should be noted that the maximum permissible distance, which is 800 meters, is inconvenient for passengers, especially for those with limited mobility.

Public transport plays a key role in the accessibility of services, such as work, education, healthcare, shopping and social and recreational activities. With continuous population growth, contemporary cities are overwhelmed by the growing number of individual vehicles, leading to some adverse effects such as congestion, increased noise and carbon dioxide emissions, which adversely affect drivers and pedestrians. Needless to say, with an increase in the number of vehicles, there is a growing demand for optimizing transport infrastructure, with the need to build new roads, forks and parking lots and increasing the capacity of existing roads [5-7]. However, the experiments shows that measures intended to improve transport infrastructure have only temporary impact on these adverse consequences. The measures can result to a crisis in the functioning of an urban environment. Reduction in congestion can be achieved by the improvement of public transport systems [8-10], for which the main factor is the availability of the route network, namely, stops for public transport [11]. The aim of this article is to study the locations of bus stops, i.e., finding intersection points of pedestrian movements and the factors influencing them.

Table 1

Characteristics of urban public transport in Taraz for 2019

The metrics of the route network	Units	Values
Population	Number of people	447981
Number of cars	units	195682
Area of the city	km^2	188
Total length of the streets for public transport movement	km	282,7
Total length of the network routes	km	828,2
Total length of all city streets	km	996
Number of routes	units	41

The stop, which provides temporary shelter for a person in various weather conditions (-45 …+50^0C), must comply with modern requirements. Considering that a warmly dressed pedestrian can withstand the maximum temperature no longer than 8-10 min, the rest of the waiting time depends on the endurance of the passengers (adults, children) [12]. Consequently, the forthcoming of the passenger vehicle during this period is one of the actual problems that need to be resolved.

The places with large concentration of people reflect spatial allocation and they are also considered as indicators of the service level of public transport [13]. The studies of places with large concentration of people, i.e., public transport stops, helps developers to consider user convenience when assigning public transport stops and increase the number of passengers on the route [14]. The methods of measurement of the places concentration of people were usually based on the estimation of distances to public transport points [15]. Existing methods model how transit passengers gain access to transit points. They are mainly based on three types of geographical data [16]: arrangement of transit access points (bus stops, trolleybus stops, etc.); information on available pedestrian routes; and coordinates of measurable places.

Data collection is highly dependent on traditional methods [17, 18]; however, data collection is expensive and time-consuming, including frequent changes in transit services and environments. Measurement methods of places concentration of people to transit systems should become more efficient [19]. This article proposes a new method for studying the places concentration of people based on the creation of a two-stage theoretical and experimental model of the relationship between pedestrians and public transport.

2. SCIENTIFIC APPROACHES OF PREVIOUS RESEARCHERS

Studies of numerous previous researchers have focused on the issue of access to places public transport. This paragraph will focus on the views of scientists in the context of the goal of this article.

Access to public transport stops [11] is examined on the basis of evaluation of the distances passed by a pedestrian and influencing factors on the basis of socio-demographic and urban conditions (Ostrava and Ologoum).

S.S. Wibowo and P. Olszewski suggest an isolated route model that drops passengers at the right time to the right place taking into account the costs. The authors examined in detail the economic aspects of passenger transportation in the interval between stops [20].

$$I = \frac{T_r \times N}{N - \frac{C \times P_y}{k}} \quad (1)$$

where N is the number of transport units moving along the route; I is the traffic interval between transport units, hour; T_r is the travel time along the route, hour; P_y is the hourly passenger flow, person; and C is the time of embarkation and disembarkation, person/hour.

When moving to one end of the city, the maximum time spent by most people (80-90%) should not exceed 40 minutes in big cities and 30 minutes in other cities and urban-type settlements. On the basis of this statement, I.S. Efrimov and V.M. Kobozev suggested the concept of reduced transport time [21]:

$$t_{red} = 2t_{ped}\varepsilon_{ped} + t_w\varepsilon_w + t_{tr}\varepsilon_{tr} \quad (2)$$

where $2t_{ped} = t'_{ped} + t''_{ped}$, t'_{ped} is the time spent by a pedestrian traveling from the door to the stopping point; t''_{ped} is the time spent by a pedestrian traveling from a stopping point to the door; t_w is the time spent waiting for transport at the stopping point; t_{tr} is movement by transport; and $\varepsilon_{ped}, \varepsilon_w, \varepsilon_{tr}$ the coefficients taking into account the time of a pedestrian spent for movement and waiting and the movement of a passenger in transport, respectively. For example, $\varepsilon_{tr} = 1$, then $\varepsilon_{ped} = 1{,}5$ и $\varepsilon_w = 2$.

The pedestrian approach to public transport stops is considered one of the four main categories of indicators for the assessment of public transport accessibility [22, 23]. In addition, these studies include the duration of travel by public transport (in terms of time, distance or price), the accessibility of destinations by public transport and the number of transport hubs.

When analyzing the distance to stops, first, pedestrians seek to minimize the distance and the time of travel [24, 25]. Then, pedestrian distances may be affected by individual traits, characteristics of stops and areas, route features and temperature. Individual characteristics are the most important impact factors at walking, but in the case of walking to a stop, distance is preferred. [26].

Owning individual vehicles negatively affects the likelihood of walking [27]. Characteristics of the area that favor pedestrian access include the absence of barriers [28, 29] and a street network that provides more pedestrian joints or connections [26, 27, 29]. Reducing the number of routes at a stop increases the willingness to walk while waiting. The number of transfers during the trip reduces the distance required for walking [30].

In winter, a pedestrian spends more time to overcome the path than in summer due to the outdoor temperature [31]. At the same time, hot or cold weather prevents the use of public transport as it requires more walking and waiting outdoors [32].

3. A PRIORI RANKING OF FACTORS

Extensive research and scientific views of previous researchers show that the main positive factors influencing the willingness of passengers to go to public transport stops are the short (minimum) distance and the time taken to reach the stop. In addition, the factors include individual characteristics and location of pedestrians, characteristics of the stops of a specific transport line and weather. Using examples of scientific papers, consultations with specialists and brainstorming with authors, the following conclusions can be drawn:

1. The next main factors given in table 2 affect the movement of pedestrians moving to a public transport stop

2. The dependence of the combination of passengers accumulated at stops and arriving public transport is expressed by the influence of factors of the second stage

Based on the above data, a list of factors affecting the studied parameter is compiled, and the scope of each of the factors is established. All factors are included in the questionnaire. It is assumed that these factors influence places with large concentration of passengers for urban public transport. To highlight the most significant features according to the degree of influence, the method of a priori ranking was used (assessment of the importance of the factors) [33, 34].

Table 2

First stage factors that affect pedestrian traffic

№	**Factor code**	**Factor description**
1	t_1	Approaching time to the stop (time for the pedestrian to reach the stop of transport from the door of the departure point), sec
2	l	Distance walked by the pedestrian to the public transport stopping point, м
3	v	Pedestrian speed, m/sec
4	θ	Ambient temperature, K
5	P	Ambient pressure, kg/m*sec^2
6	G	Pedestrian with hand luggage, H
7	H	Height of the pedestrian, m
8	Q	Transport stop capacity, people

Table 3

Factors of the second stage that affect use of public transport

№	**Factor code**	**Factor description**
1	t_2	Travel time in transport, sec
2	v_a	Speed of the transport, m/sec
3	a_a	Acceleration of transport when starting off, m/sec^2
4	a_t	Deceleration of the vehicle when braking (before the crossroads, stopping and turning), m/sec^2
5	l_a	Distance from the reference point to the transit stop, m
6	G_a	Weight of public transport, kg
7	J	Intensity of movement of public transport, sec

To filter out the above factors, we conducted an a priori study by distributing questionnaires to 50 respondents (professors and teachers, engineers, students, etc.) from the city of Taraz from the field of passenger transportation from September to November 2019. The respondents filled out the questionnaire by ranking factors in the specific row. Based on a priori information, a priori ranking of factors was performed, which allows to identify the most significant factors and exclude factors that have an insignificant effect.

A priori ranking of factors was carried out in the following sequence [33, 34]. Based on preliminary studies, a list of factors most affecting the studied parameter was compiled. Then, the respondents filled out a questionnaire, which indicated the studied factors. Each factor was evaluated by the rank-place assigned by the respondent to the studied factor when ranking the others, taking into account their expected impact. Respondents rated each factor on a scale from 1 to 8. The factor determining the best conditions was assigned a score of 1 and the rest were arranged in order of increasing degree of their influence on the selected parameter.

Further, according to the results from the questionnaires, a rank matrix was created, i.e., ranked rows were obtained for each target variable.

The survey data are processed as follows: for each factor, the sum of the ranks is determined as

$$S_r = \sum_{j=1}^{m} a_{ij} \quad (3)$$

where m is the number of respondents surveyed and a_{ij} is the rank of an i factor, which is assigned by the j respondent.

The average sum of ranks for all factors will have the value

$$\bar{\Delta} = \frac{1}{k}\sum_{i=1}^{k}\sum_{j=1}^{m} a_{ij} \quad (4)$$

where k is the number of factors.

Then, derivation Δ_i of the sum of ranks from the average sum of ranks for each of the factors is calculated as follows:

$$\Delta_i = S_r - \bar{\Delta} \quad (5)$$

The Kendall coefficient of concordance in the absence of related ranks is found by the formula

$$W = \frac{12S_\Delta}{m^2(k^3-k)} \quad , \quad (6)$$

where $S_\Delta = \sum_{i=1}^{k} \Delta_i^2$ is the sum of squared deviations.

The value of W lies in the range $0 \le W \le 1$. When $W = 1$, it means that the opinions of the respondents coincide completely. When $W = 0$, it means complete disagreement of opinions.

The results of the survey of respondents are presented in the form of a matrix of ranks (Tables 4 and 5).

Table 4

First-stage rank matrix

Respondents	Ranks by factors							
	l	***t_1***	***v***	**θ**	***P***	***G***	***H***	***Q***
1	2	1	4	3	5	6	8	7
2	1	3	2	7	5	4	8	6
3	3	2	1	4	6	5	7	8
4	1	2	4	3	5	8	6	7
5	2	1	3	5	4	6	7	8
6	2	3	1	4	5	8	6	7
…	…	…	…	…	…	…	…	…
50	1	3	6	5	2	8	7	4
Sum of ranks S_r	**83**	**103**	**143**	**202**	**257**	**326**	**343**	**343**
Average sum of ranks $\bar{\Delta}$	**225**							
Deviation of the sum of ranks from the average sum of ranks Δ_i	**-142**	**-122**	**-82**	**-23**	**32**	**101**	**118**	**118**
Deviation squares Δ_i^2	**20164**	**14884**	**6724**	**529**	**1024**	**10201**	**13924**	**13924**
Sum of squared deviations S_Δ	**81374**							
Kendall coefficient of concords W	**0,77**							

As a result of data processing, the Kendall coefficient of concordance of the first stage W = 0.77> 0.5 (for pedestrian traffic) and the second stage W = 0.72> 0.5 (for bus travel) indicates a good degree of consistency among respondents in the considered factors.

4. RESULTS OF THEORETICAL SUBSTANTIATION

After making sure that the opinions of the respondents were consistent, we obtained the results of ranking factors that affect the movement of pedestrians, presented in Figure 1, and travel by public transport, shown in Fig. 2.

Table 5

Second-stage rank matrix

Respondents	Ranks by factors						
	t_2	v_a	l_a	J	G_a	a_a	a_t
1	2	1	5	4	3	6	7
2	1	2	5	4	3	7	6
3	1	2	4	5	3	6	7
4	1	2	4	3	5	6	7
5	2	3	1	5	4	7	6
6	3	4	5	1	2	6	7
…	…	…	…	…	…	…	…
50	2	4	3	1	5	7	6
Sum of ranks S_r	**90**	**132**	**157**	**180**	**191**	**315**	**335**
Average sum of ranks $\overline{\Delta}$	**200**						
Deviation of the sum of ranks from the average sum of ranks Δ_i	**-110**	**-68**	**-43**	**-20**	**-9**	**115**	**135**
Deviation squares Δ_i^2	**12100**	**4624**	**1849**	**400**	**81**	**13225**	**18225**
Sum of squared deviations S_Δ	**50504**						
Kendall coefficient of concords W	**0,72**						

An a priori ranking chart allows pre-selection of the most important factors. These include those for which $S_r < \overline{\Delta}$.

According to the ranking chart (Fig. 1), the factors l, t_1 and v и θ, in the opinion of the respondents, affect the studied parameter more than others.

From the diagram (Fig. 2), it follows that the factors t_2, v_a and l_a и J have the greatest impact on the parameter, while the rest of the factors have a less significant effect. The factors that did not affect the studied parameters significantly were excluded from the research.

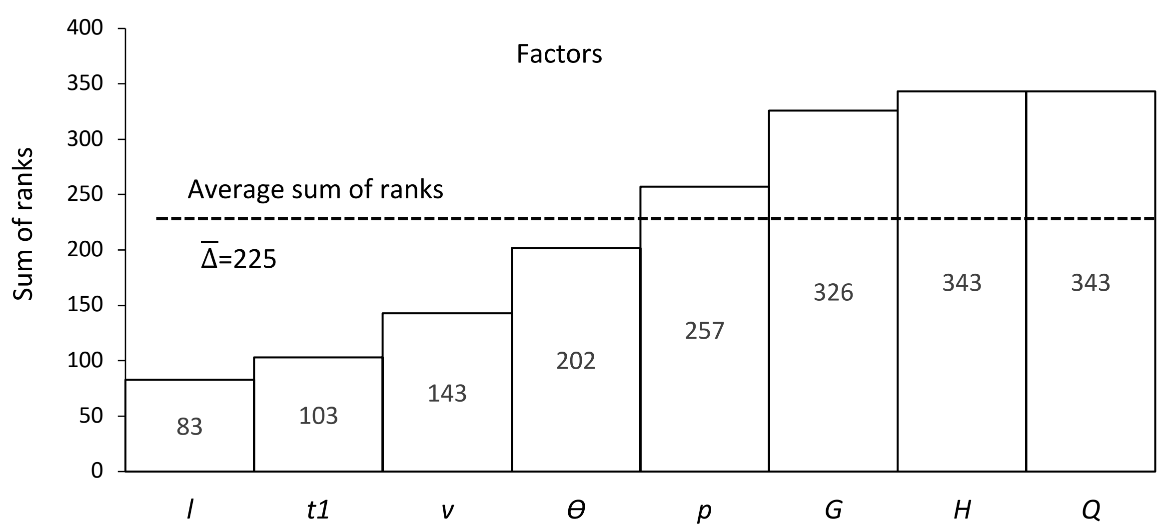

Fig. 1. Results of the ranking of factors, influencing the movement of pedestrians to the stopping point

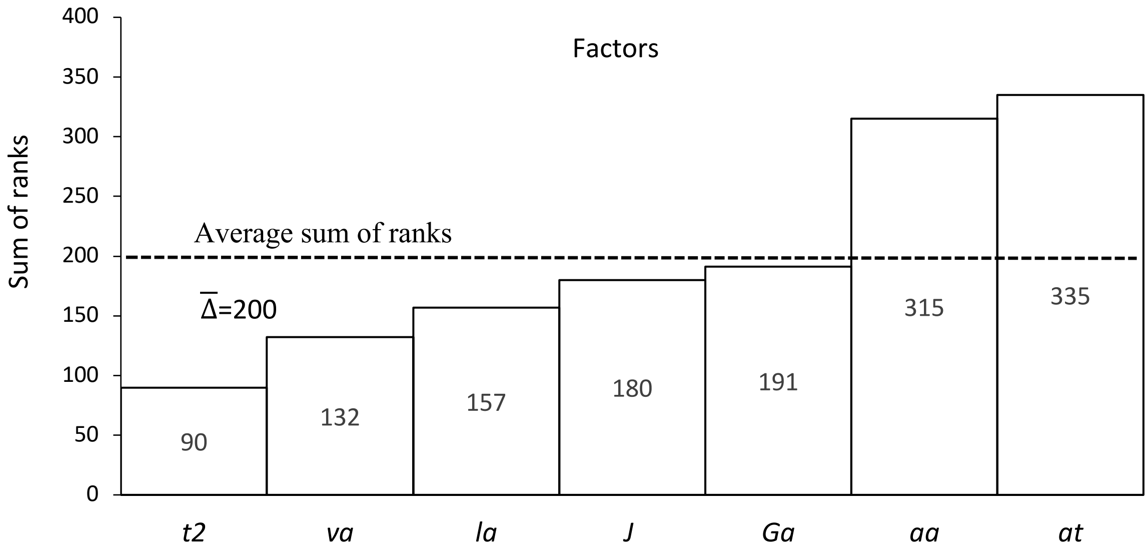

Fig. 2. Results of the ranking of factors, influencing the trip of a passenger to a transit stop

When designing a simulation in this case, it is appropriate to apply the theory of similarity and dimensions. The theory of similarity and dimensions is of interest and is the main focus of the study of such scientists as Szirtes, T. & Rózsa, P., Gibbings J.C., Delaplace and G. et al. [35-37].

The advantages of the dimensional method are that quick assessment of the extent of the phenomena studied is possible and high-quality and functional dependencies can be determined. To draw up a dimension formula, for each basic quantity, a unit of significant variables is introduced. It is needed for measuring the description of the movement of pedestrians to a stop and the passenger's trip to a transit stop, Table 6.

Table 6

Dimension of a physical quantity

№ п/п	Name of the variable	Designation	Dimension formula	Units
1	Approach time to the stop	t_1	T	sec
2	Pedestrian distance to a bus stop	l	L	m
3	Pedestrian speed	v	LT^{-1}	m/sec
4	Ambient temperature	θ	ML^2T^{-2}	К
5	Travel time in transport, sec	t_2	T	sec
6	Speed of the public transport	v_a	LT^{-1}	m/sec
7	Weight of the public transport	G_a	MLT^{-2}	kg*sec/sec^2
8	Intensity of the traffic of public transport	J	$N*T^{-1}$	un./sec

Stage 1. According to respondents, factors influencing the movement of pedestrians to the stopping points are L, t_1, v and θ. Thus, using the methodology of dimensional theory [38, 39], we obtain

$$t_1 = f(L, v, \theta, \mathrm{p}) \tag{7}$$

$$T = (L)^{\alpha} * (LT^{-1})^{\beta} * (ML^2T^{-2})^{\gamma} \tag{8}$$

For (T) $1 = -\beta - 2\gamma$

For (L) $0 = \alpha + \beta + 2\gamma$ (9)

For (M) $0 = \gamma$

Solving the system of equations, we obtain

$$\alpha = 1;\ \beta = -1; \gamma = 0. \tag{10}$$

Substituting the values that were found into the main identity (8) and interpreting the mathematical operation, as well as introducing a dimensionless relation $\frac{\theta}{p \cdot Q}$, we obtain

$$t_1 = \left(\frac{L}{v}\right) \cdot f\left(\frac{\theta}{p \cdot Q}\right) \tag{11}$$

Analyzing formula (11), it is possible to state that the pedestrian movement from the places concentration of people place is affected not only by the distance (considering the presence of stairs and the quality of the sidewalks) but also the weather (hot summer, cold winter).

Stage 2. Passenger ride to the transit stop.

When choosing the factors, it was taken into account that «L_a» is included in «v_a », and the relation of «a_a» to «a_t» is a function; therefore

$$t_2 = \varphi(v_a, J, \sum G_a) \tag{12}$$

$$T = (LT^{-1})^{\alpha}, (N * T^{-1})^{\beta}, (MLT^{-2})^{\gamma} \tag{13}$$

For (T) $1 = -\alpha - \beta - 2\gamma$

For (L) $0 = \propto\ + \gamma$ (14)

For (M) $0 = \gamma$

When solving the system of equation, we obtain

$$\alpha = 0;\ \beta = -1; \gamma = 0 \tag{15}$$

Substituting the values that were found into the main identity (8) and interpreting the mathematical operation, as well as introducing a dimensionless relation $\frac{a_a}{a_t}$, we obtain

$$t_2 = const\left(\frac{1}{N * t^{-1}}\right) \cdot \varphi\left(\frac{a_a}{a_t}\right) \tag{16}$$

However, assuming that $\frac{a_a}{a_t} \approx 1$, which is when there is a coordination of actions on pedestrian and public transport, we obtain

$$t_2 = const\left(\frac{1}{N * t^{-1}}\right) \tag{17}$$

On expressing the time of public transport *t* as $\frac{L_a}{v_a}$, we obtain

$$t_2 = const\left(\frac{L_a}{N * v_a}\right) \tag{18}$$

5. GENERAL CONCEPT OF THE THEORETICAL AND EXPERIMENTAL BASES

Basing on logical understanding, it is possible to assume the following:

$$\frac{t_1}{t_2} = \frac{\frac{L}{v} \cdot f\left(\frac{\theta}{p \cdot Q}\right)}{\frac{1}{N * t^{-1}} \cdot \varphi\left(\frac{a_a}{a_t}\right)} \tag{19}$$

Consequently,

$$t_1 = \frac{\frac{L}{v} \cdot f\left(\frac{\theta}{p \cdot Q}\right)}{\frac{1}{N * t^{-1}} \cdot \varphi\left(\frac{a_a}{a_t}\right)} * t_2 \tag{20}$$

or on consideration of the speed of public transport

$$t_1 = \frac{\frac{L}{v} \cdot f\left(\frac{\theta}{p \cdot V}\right)}{\frac{L_a}{N * v_a} \cdot \varphi\left(\frac{a_a}{a_t}\right)} * t_2 \tag{21}$$

Thus, given that the speed of public transport in various countries is regulated, particularly in Kazakhstan, including Taraz $v_a = 50 \frac{km}{h}$, the pedestrian speed determined experimentally is $\cong$ 3 ...4

km/h, and taking into account the above factors during the movement of a pedestrian, as well as the decreased speed of public transport vehicles at intersections and turn:

$$L_a \cong L \cdot \frac{50}{4} \cong (8 \dots 12.5) \cdot L \, . \qquad (22)$$

The obtained dependence (11,21,22) can be used in the development and substantiation of locations of stops of public transport.

6. CONCLUSIONS

The solutions proposed by the authors are aimed at improving the efficiency and accessibility of public transport. This article analyzes and identifies factors affecting the movement of pedestrians and public transport to a stop.

The method of a priori ranking of indicators obtained on the basis of a survey of respondents, depending on the variation coefficient, will allow observation of a good degree of consistency among respondents' opinions and help determine the most influential factors.

On the basis of dimensional theory, a mathematical model of the justification of the location of stops is obtained, which has two stages: accounting for the nature of complex pedestrian movement and public transport speed. Compared with known parameters, the difference in the suggested dimensionless complexes is that they consider the weather, the characteristics of the pedestrian, route and public transport.

Two-stage theoretical and experimental considerations of the question on the interaction of pedestrian and public transport allowed to theoretically and physically substantiate the point of their intersection based on their travel time. An expression (11) that was obtained during this research allows to determine not only the time taken to reach the stop from the destination but also specifies number of pedestrians at public stops.

Scientific research was conducted with a combination of dimensional theory foundations and logical analysis of the mathematical interpretation of factors and optimization parameters. The authors, using the methodological recommendations of well-known theoretical combinations, proposed a two-stage theoretical and experimental substantiation for placement of public transport stops. It is mathematically expressed by formula (21), which takes into account specific coefficients, and allows to justify the economical movement of pedestrians and public transport regulated by speed limits in a particular city, district area, etc.

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Received 29.08.2019; accepted in revised form 23.02.2021