Valeriia Lohvinenko, Master's student
O.M. Beketov National University of Urban Economy in Kharkiv
Kharkiv, str. Bazhanova,17
e-mail: lerocklogvinenko.vl@gmail.com

dr Alexander Rossolov, Associate Professor
O.M. Beketov National University of Urban Economy in Kharkiv
Kharkiv, str. Bazhanova,17
e-mail: rossolovalex@gmail.com

Evaluation of transport accessibility of the public transport network on the basis of stop points parametrization

Summary:

Every passenger trip by public transit is a part of the overall activity of any resident in the modern city. In spite of different type movements, they all have the same aim. Each passenger seeks to minimize the costs within every journey, that is why the public transit accessibility plays a major role in this problem solve.

The purpose of the study is to develop the models for assess the transport accessibility of the public transport route network based on the spatial characteristics of the transport interchanges and the stop points. Besides that, the formation of a set of actions for improvement of the transport services efficiency by public transport has been proposed. The models for estimation the rational number of stop points and their density at the transport network are proposed. The formalization of the walk distance to the nearest stop points is made on the basis of the possible location of the origin of movement relative to the stop points of the route network. The character of the distribution of stop points on the bus network of Uzhorod is determined and the influence of this parameter on the level of transport accessibility of the route network is determined. It was determined the regularity of the average trip time change considering the variability of bus stop density.

Key words:

transport accessibility, stop point density, distance between stops

1. Study of the current state of transport accessibility's estimation on the road network

1.1The meaning of transport accessibility and the form of its evaluation

The paper [1] means that accessibility is one of the key issues of transport and land use planning. It reflects the ease of reaching needed/desired activities and thus reflects characteristics of both the land use system and the transportation system [2].

Accessibility is strongly affected by the design of infrastructure such as PT routes and stops, road network, and the availability of various LUDs in a close proximity. It is also influenced by problems such as the legibility of a timetable and the perception of safety [3]. According to [4] accessibility can be directly related to both the qualities of the transport system (e.g. travel speed), and the qualities of the land use system (e.g. densities and mixes). At the same time, it can also be directly related to economic goals (access to workers, customers, suppliers), social goals (access to employment, goods, services, social contacts), and environmental goals (resource-efficiency of activity/mobility patterns).

«Destination-based accessibility» [5] focuses on accessibility of services such as shops, workplaces or schools, and 'origin-based accessibility' focuses on the accessibility of households to these services. This is based on the core concept that accessibility is considered as a function of opportunity and deterrence. Origin-based [5] accessibility analysis requires methods to measure the distances from origins to services through the transport network and also mathematical functions that define accessibility in terms of opportunity and deterrence.

For example, in [6] accessibility of «destination-based accessibility» was defined to quantify the performance of transportation systems which access a distinct destination. The access cost was determined to reflect the utility of the transportation system including the fatigue and inconvenience in the total cost.

1.2 Modern approaches to assessing transport accessibility

In [6] we can see the developing of a GIS-based method to analyse public transport accessibility of elderly people to support policies and planning strategies. To test this method, they propose an application to the city of Naples in Italy. They selected this study case because it represents an example of high population density, complex urban structure and low level of quality of life, especially for the elderly. The application to the city of Naples showed that the urban accessibility changes dramatically for different age segments. Results also reveal patterns of public transport coverage that are significantly low particularly in suburban settings.

LUPTAI accessibility measures [1] were also developed to consider and allow for diverse choice options in personal trip-making, especially in terms of walking to a PT stop. This approach extends upon the standard walking distances to PT, which are often conceived as maximum trip-lengths of 400m (5min walk) to bus stops and 800m (10min walk) to train stations. Accessibility measures within LUPTAI expand on the strict boundary limitations applied to walking in previous studies. This expansion improves accessibility measures in the index by allowing a degree of choice, between walking a short distance to PT for a long trip, and walking a longer distance to PT for a shorter trip. Walking distances to PT have been categorised into four distance-based categories: 'High, Medium, Low and Poor'. 1,200 metres (15min walk) is the maximum distance (limit to walking) applied within the health, shopping, financial and postal, and education accessibility measures. 1,600 metres (20min walk) is applied as the maximum walking distance for the employment accessibility measure.

The next paper [7] explores the use of accessibility performance measures, both to assess the extent of current public transport accessibility and as a potential metric for future planning and investment. This paper [7] is based on the researches that have been developed earlier [8-11]. The Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) tool is employed for analysis of accessibility. A sample of 21 international cities is assessed, representing a range of transport and land-use policy contexts from best to ordinary practice, including those held up as exemples in public transport infrastructure, service planning, and delivery in Europe and North America. The findings show that the incidence of successful metropolitan public transport systems, as measured by patronage, can be linked to accessibility performance measures of network and service configurations.

The next authors in their work [12] proposed to increase transport accessibility through implementation Demand-Responsive Transport (DRT), that firstly was recommended for future urban transportation in the 1960's [13]. Thise method helps to estimate the required capacity for a needed level of service and the resulting operating costs [14] or achieve whether DRT should sub-stitute fixed transit for a given scenario [15,16]. Exactly this study presents an assessment framework for possibility to evaluate the performance of DRT and related changes in transport accessibility. Research is hold with helping an empirical analysis for DRT service in the Netherlands.

This work has also estimated throughout simulation the impact that DRT services would have in real urban networks such as in Hino(Japan) [17], Lisbon (Portugal) [18], and New York City (United States) [19].

Transport accessibility can be increased through reducing public transport fares [20]. Author said that fare elasticity depends on the magnitude, sign and time-span of a fare change. Elasticity reduces with age, increase with income and is mostly higher for off-peak and non-commuting trips [23, 24]. The elasticity of public transport demand with respect to level of service variables was found systematically higher when compared with fare elasticity [21, 22, 24].

The author of the work [25] expressed transport accessibility through the developing of an endogenous price model including different urban agents (residents and firms), who have a heterogeneous behavior not only with respect to the willingness-to-pay for renting or buying a house, as in [26], but also in the typology of the dwelling unit needed.

2. Theoretical basis of transport accessibility's assessment of routine network based on stop points location

2.1 Setting the task of determining the rational number of stopping points

Parametrization of stop points based on spatial characteristics in order to develop models for estimation the transport accessibility of the route network on public transport in case of city Uzhorod (Ukraine). The main parameter for assess the transport accessibility of the city was chosen density of placement of stop points in the city area and its impact on travel time.

2.2 Development of the model for determining the rational number of stop points

To conduct research in software PTV Visum, a model of the city's transport network was built with the placement of existing stop points. Since stop points are formed on the basis of passenger gravity, it can be argued that the position of the stop point is random. In this case, the location of stop points was determined on the basis of the binary coordinate system. Each of the located stop points after insertion into the model has location coordinates. On the basis of these coordinates the database was formed, which was later used to construct a matrix of distances between stop points.

Since the position of the stop point is a random variable, then the distance between them is also random variables. To calculate this value, it was used the following formula:

$$l = \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \tag{1}$$

where: x_i, x_{i+1}- accordingly, *x* coordinates of the *i* and *i*+1 bus stop, y_i, y_{i+1} - accordingly, *y* coordinates of the *i* and *i*+1 bus stop.

The longer the distance between the stop points, the denser they are placed with each other. It was assumed that the change of the mathematical expectation of the distance between the stop points will lead the shift of the travel time (transport accessibility). That is why it is very important to take into account pedestrian transport accessibility and its impact on the efficiency of the transport process.

The criterion of efficiency is the average travel time of passengers on the network:

$$\bar{d} = \frac{\sum_{i=1}^{Z}\sum_{j=1}^{Z} d_{ij} \cdot t_{ij}}{\sum_{i=1}^{Z}\sum_{j=1}^{Z} t_{ij}} \rightarrow \min \tag{2}$$

where: d_{ij} - travel time between *i* and *j* transport zones, t_{ij} - number of trips between *i* and *j* transport zones, *Z* – number of the transport zones.

The classical approach in the evaluation takes place on t_{ij}, but in this work we put unit matrix (table 1). In the work, this formula can be reduced to the following form:

$$\bar{d} = \frac{\sum_{i=1}^{Z}\sum_{j=1}^{Z} d_{ij}}{Z^2} \rightarrow \min \tag{3}$$

Tabela 1. O-D matrix

№ transport zone, z	1	2	3	4	…	21	22	23	24
1	1	1	1	1	…	1	1	1	1
2	1	1	1	1	…	1	1	1	1
3	1	1	1	1	…	1	1	1	1
4	1	1	1	1	…	1	1	1	1
…	…	…	…	…	…	…	…	…	…
21	1	1	1	1	…	1	1	1	1
22	1	1	1	1	…	1	1	1	1

23	1	1	1	1	…	1	1	1	1
24	1	1	1	1	…	1	1	1	1

Source: own researc

As we can see in table 1 the number of trips between each pair of the transport zones are equal 1. This value has been used in accordance to following assumption. If the number of trips is not equal to each other in the O-D matrix, the calculated value of the average trip time (using formula (2)) will be shifted to the bigger trips number (t_{ij}). So, in case of this research it is studied the "free" network state, mainly, not taking into account the trips distribution on the city territory. That is is why it was made the transformation of formula (2) to (3).

Travel time is considered as a neutral state of demand and can be represented schematically (fig. 1).

According to [27] the density of stop points affects transport accessibility, first of all, through hours indicators, which reflect two types of time formation: the transport process and time consumption on simple vehicles on the route and mathematically can be represented as follows:

$$d_d = d_v + d_l + d_p , \quad (4)$$

where d_d – the part of time trip as a function of stop points number at the city route, d_v – duration of the trip in the route vehicle, min., d_l – passenger walk time to reach the nearest stop point (station), min., d_p – the general idle time of the route vehicle during execution passenger trip between stop points q and w, depending on quantity of stop points at the route, min.

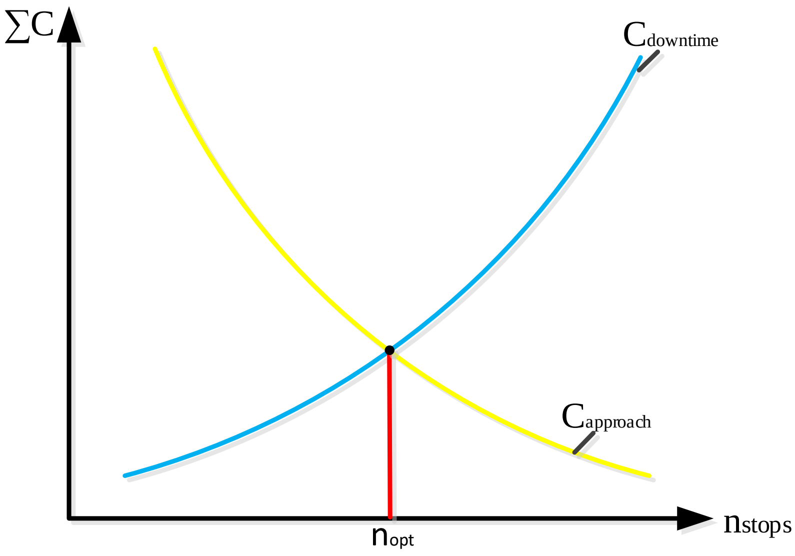


Figure 1. Dependence of total time costs on the number of stop points

Source: own research

Time trip d_v and general idle time of the route vehicle d_p are determined by well-known formulas so in the framework of the study question of mathematical formalization, these processes is not performed in contrast to the time of approach-departure d_l. The study proposes to determine the time of approach to the nearest stop point based on the following model (fig. 2).

The general form of the equation (4) does not show the functional interdependence of the elements, so it is rational to make the decomposition of the function (5). As a result of the decomposition function d_d takes the following form [27]:

$$d_d = \frac{l_t}{V_t} + \frac{\sqrt{\left(\frac{l_r}{2 \cdot n}\right)^2 + l_k^2}}{V_p} + k \cdot n \cdot \frac{l_t}{l_r}, \qquad (5)$$

where: l_t – trip distance executed on the one route of city public transport, km, V_t – road speed of route vehicle, km/h., *k*– the average idle time of route vehicle at one stop point, h.

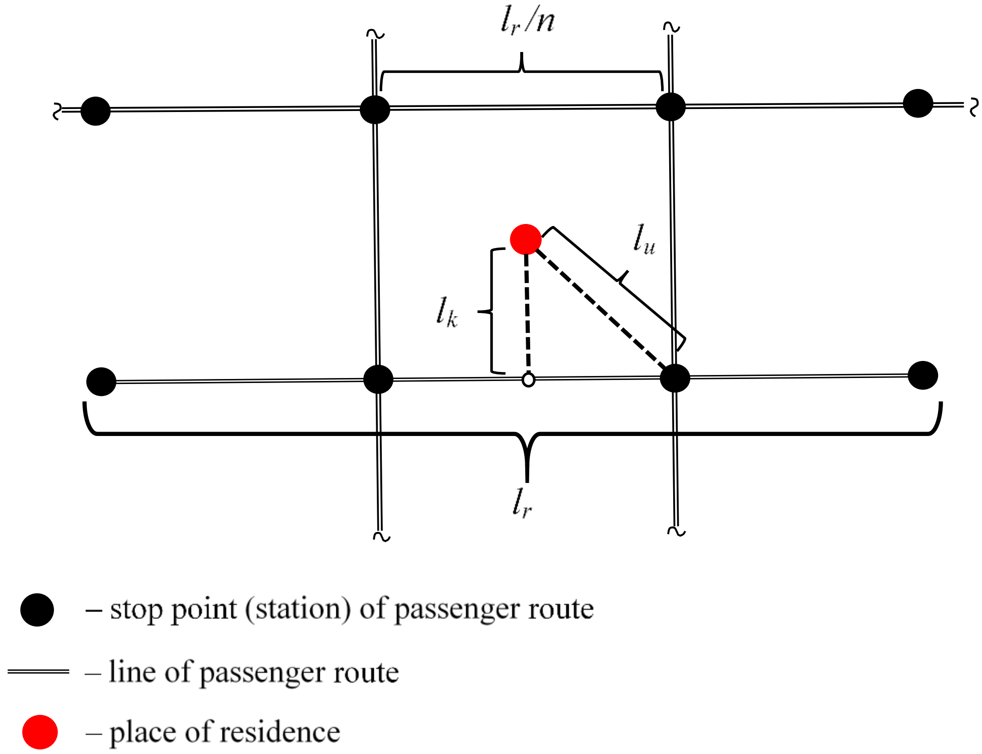


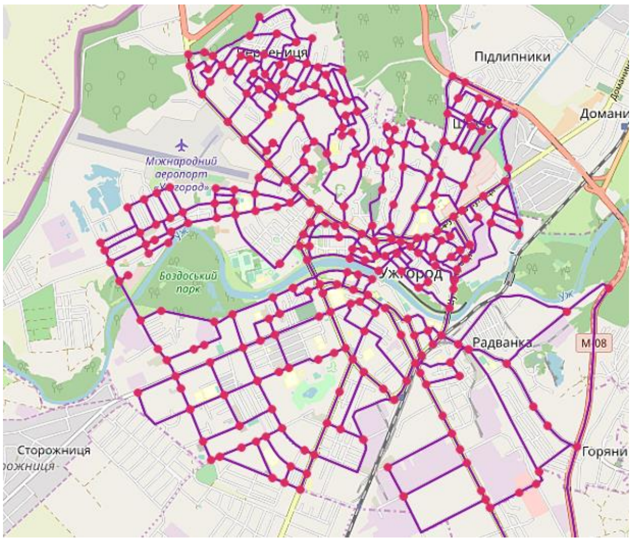
Figure 2. Scheme for determining the walking distance from the place of residence to the stop point

Source: [27]

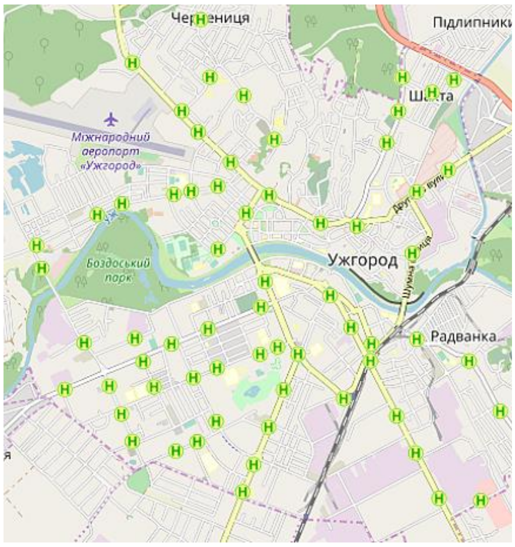
As we see from the form of equations (4) and (5), they have quadratic dependencies and subverb expression. These mathematical functional dependencies are substantiated by the following processes. Each passenger performs an approach to reach the nearest stop point (station) when it realizes its need to travel around the city. Distance approach depends on the density of stop points on urban routes and their spatial distribution. Obviously, the passenger seeks to minimize the total travel time by reducing the time spent on each element: the time of approach-departure, waiting time, travel time in the vehicle, and so on. In such conditions, pedestrian accessibility significantly influences the overall assessment of the functioning of the public network and acts as the basis for choosing the mode of transport and the route of travel.

3. Transport accessibility's experimental researches of the road network at example on uzhorod city

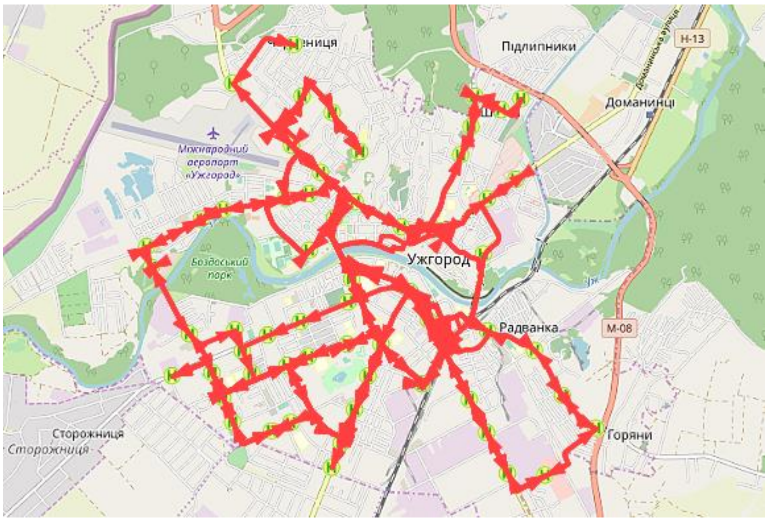
The first stage of the model's development was to built graph of the route network. At the next stage, the formation of transport areas was completed. This procedure is carried out in accordance with the following rules: the structure of the transport area should be homogeneous, its boundaries should not separate the buildings, industrial and recreational zones. Model is presented on the figure 3.



a) Graph of the route network



b) Displacement of stop points



c) Traces of the bus routes

Figure 3. Built model of the Uzhorod

Source: own research

Information about all built routes is shown in the table 2.

Table 2. Information about bus city routes

№ of route	Length of the route, km	Number of stop points	Average distance between neighboring stop points, km
1	2	3	4
1	2,43	6	0,48
	2,63	6	0,52
2	3,27	7	0,54
	3,23	7	0,53

3	6,25	13	0,52
	6,25	13	0,52
4	7,48	12	0,68
	7,48	12	0,68
5	4,02	10	0,44
	4,04	4	1,34
6	4,2	10	0,46
	4,2	10	0,46
7	8,38	17	0,52
	8,38	17	0,52
7D	6,21	11	0,62
	6,06	8	0,86
8	9,58	19	0,53
	9,58	19	0,53
9	8,21	18	0,48
	8,21	18	0,48
10	9,35	19	0,51
	9,35	19	0,51
11	5,67	13	0,47
	5,67	13	0,47
12K	4,21	8	0,6
	4,7	11	0,47
12P	3,52	9	0,44
	2,87	7	0,47
14	6,67	12	0,6
	6,67	12	0,6
15	1,29	4	0,43
	1,29	4	0,43
18	11,33	20	0,59
	12,79	20	0,67
20	7,45	14	0,57
	7,45	14	0,57
21	7,55	17	0,47
	7,55	17	0,47
22	5,26	10	0,58
	5,72	13	0,47
26	7,13	9	0,89
	7,13	9	0,89
27	8,36	18	0,49
	8,36	18	0,49
58	6,24	13	0,52
	6,24	13	0,52
156	8,39	17	0,52

	8,39	17	0,52
158	5,99	9	0,74
	5,99	9	0,74

Source: Own research

Average distance between stops was calculated by the next formula:

$$\bar{l} = \frac{\sum_{i=1}^{s} l_{i-(i+1)}}{s-1} \quad (6)$$

where: l_i- distance between stops *i* and *i*+1, *s* – number of the stop point in each bus route, units.

Current state of the object was determined with helping the model (1) and then we made 7 sample. Every sample was tested on the hypothesis about the normal distribution law. Result of these tests is presented on the figure 4.

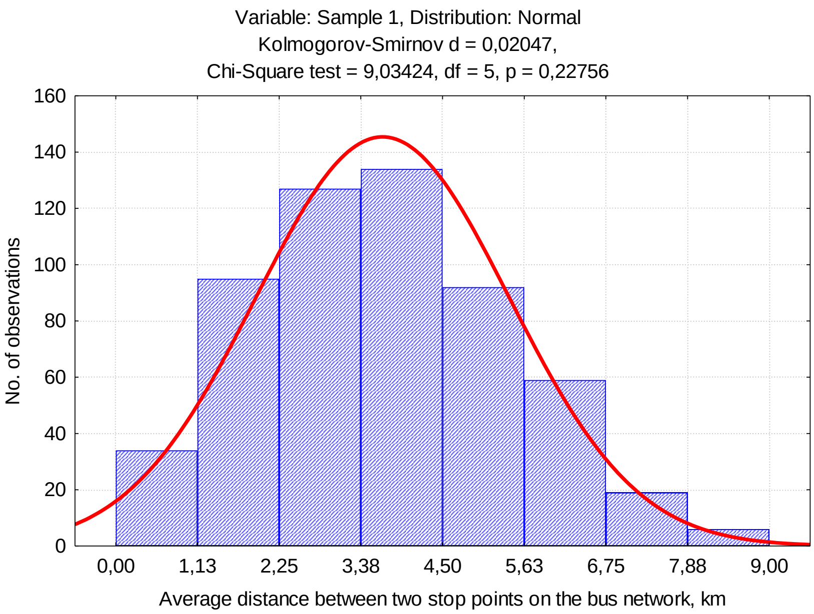


Figure 4. Sample test example on the hypothesis about the normal distribution

Source: Own research

Using the distribution law, the general dispersion and mathematical expectation of the distances between the stopping points of the considered model were determined (table 3).

Table 3. Indicators of the distribution law in existence model of stop point's dislocation

№ of sample	Mathematical expectation (distance between two bus stops), meters	Variance, meters^2	Goodness of fit probability	Degree of freedom
1	3543,06	3240092,5	0,22756	5
2	3613,65	3108698,5	0,06141	6
3	3466,27	3159806,4	0,17089	7
4	3688,57	2918126,7	0,48566	7
5	3689,93	2852524,8	0,06815	9
6	3635,77	3160204,1	0,37701	6
7	3614,44	3287205,6	0,09367	6
Weighted average	3619,54	3084957,94	-	-
Spread of values	31223,66	434680,8	-	-
Total variance	148596618,48	26442760973,31	-	-

Source: Own research

Total variance can be calculated by the next formula:

$$s^2 = \frac{\sum_{i=1}^{n} (\mu_i - \overline{\mu})^2}{n-1} \tag{6}$$

The general mathematical expectation can be calculated by the following formula:

$$\overline{\mu} = \frac{\sum_{i=1}^{n} (\mu_i \cdot P_i)}{\sum P_i} \tag{7}$$

Average journey time was calculated by the formula (2).

$$\bar{t} = \frac{9375}{576} = 22,5 \text{ m.}$$

Analysis of the stop points density influence on transport accessibility is executed according to two scenarios: exclusion stop points from the network and inclusion stop points to it. The analysis of distance distribution was carried out according to the algorithm was presented above. The results are presented in the tables 4-5.

Table 4. Indicators of the distribution law for the scenario "Stop point density increase" (Scenario 1)

№ of sample	Mathematical expectation (distance between two bus stops), meters	Variance, meters^2	Goodness of fit probability	Degree of freedom
1	3451,4	2578423,9	0,06606	3
2	3375,2	2814922,3	0,08947	4
3	3357,2	2413409,4	0,12803	3
4	3581,1	2797672,7	0,71041	9
5	3517,3	3293402,4	0,0701	2
6	3550,3	2855289,9	0,23258	4
7	3297,02	2244837,3	0,19903	4
Weighted average	3498,31	2714755,86	-	-
Spread of values	284,08	1048565,1	-	-
Total variance	14616,97	116951616342,51	-	-

Source: Own research

Table 5. Indicators of the distribution law for the scenario "Stop point density decrease" (Scenario 2)

№ of sample	Mathematical expectation (distance between two bus stops), meters	Variance, meters^2	Goodness of fit probability	Degree of Freedom
1	2	3	4	5
1	3446,63	3110076,8	0,08616	5
2	3514,15	3096682,5	0,33832	9
3	3686,09	2860495,3	0,12743	7
4	3569,8	2747377,8	0,09216	8
5	3592,2	2901495,4	0,49865	8
6	3607,01	3415250,4	0,12262	5
7	3528,02	2947061,5	0,25022	6
Weighted average	3563,64	2993195,59	-	-
Spread of values	239,46	667872,6	-	-
Total variance	5856,32	48512342064,25	-	-

Source: Own research

Table 6. Resultive table of models' comparison

State of the system	Average distance between stops, meters	The percentage of distance between stops change, %	General mathematical expectation, meters	Total variance, meters^2	Average journey time, minutes	Δt, minutes
Current	0,572	-	3619,54	3084957,94	22,5	-
Scenario 1	0,510	+17,8	3498,31	2714755,86	24,6	+2,1
Scenario 2	0,674	-10,8	3563,64	2993195,59	22,3	-0,5

Source: Own research

4. Discussion of results

Experimental studies allowed to confirm the theoretically substantiated dependence of transport accessibility on the number of served stop points within the urban passenger transport routes. As a result of the evaluation of two alternative scenarios, it was found that pedestrian accessibility (the passenger's approach to the nearest stop point) is less significant for transport accessibility (as the assumption in the study is equal to the travel time in the vehicle). This result was obtained as a result of modeling the total travel time, provided that the vehicle's idle time at the stop point is one minute. Of course, in the framework of further research, it is necessary to conduct a statistical assessment of the indicator's variability influence on the total time of movement on the network. It will allow making a comprehensive assessment of the dependence of the total transport accessibility (travel time on the network) from the idle time of transport vehicles at stoppoints and, directly, the number of data stoppoints (dislocation density).

5. Conclusion

As a result of research, a close relationship has been revealed between the density of stop points and the time of movement of passengers through the network. Increasing pedestrian accessibility by increasing the density of stop points allows reducing the people's time for approaching to stop points. However, the implementation of this procedure can lead to negative consequences, namely, to decreasing of the active transport accessibility (increasing in travel time on the network). In the framework of the research, two alternative scenarios for serving the population of the city of Uzhgorod (Ukraine) by public passenger transport were evaluated. The first scenario assumed increasing of the stop point's dislocation density (by 17% compared with the current option). The second scenario, vice versa, suggested decreasing of the stop point's density (by 10% compared to the current network option). As a result, “Scenario 1” led to increasing of the average travel time on 2 minutes. While "Scenario 2" allowed reducing the average time of movement on 0,5 minutes. Thus, the nonlinear nature of the influence of flotation of the stop point's placement on the value of the average time of movement is revealed.

In the framework of further research, it is necessary to evaluate experimentally the impact of vehicle's idle time at stop points on transport accessibility (using the example of the city of Uzhgorod).

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