signalized intersection; saturation flow; intersection passing speed

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DENSITY OF THE TRANSPORTATION NETWORK AS A FUNCTION OF THE CORRELATION OF THE LENGTH OF ONE SIDE OF A RESIDENTIAL BLOCK

Summary. Methods of evaluating planning schemes of the street network were examined and it was determined that the main drawback of these schemes utilizing averages. It is therefore proposed to use the correlation of the length of the side of a residential block as a parameter which influences the density of the transportation network; relevant studies were conducted. It was determined that the density of the transportation network depends on the correlation of the length of one side of a residential quarter and not on the linear measurement.

ПЛОТНОСТЬ ТРАНСПОРТНОЙ СЕТИ КАК ФУНКЦИЯ СООТНОШЕНИЯ ДЛИН СТОРОН ЖИЛОГО КВАРТАЛА

Аннотация. Рассмотрены методы оценки планировочных схем улично-дорожной сети и установлено, что главным недостатком является использование их усредненных значений. Исходя из этого, предложено использовать соотношение длин сторон жилого квартала как параметр, влияющий на плотность транспортной сети, для чего проведены соответствующие исследования. Установлено, что плотность транспортной сети зависит от соотношения длин сторон жилого квартала нелинейно.

1. INTRODUCTION

Providing transport services to an urban population requires transport planning which considers social, economic and environmental factors [1].

An important phase of transport planning is correctly planning the components of the road network; this includes defining their parameters (length, width, slope and radius of the roadway). The parameters of all types of movement along the street network will point to the form and structure it should have. This is important because reconstructing any component of the street network is costly and inconvenient. For this reason, when planning the various elements of a street network, it is imperative to accommodate anticipated changes in the territory to prevent the need to reconstruct.

2. LITERATURE REVIEW

Modern requirements for moving vehicular and pedestrian flow demand that the main focus of creating or developing a rational road network structure should minimize the expenditures for such movement without diminishing its social value.

Creating a rational road network structure can be achieved by developing a comprehensive approach which includes consideration of transport, construction, planning and environmental issues. This will allow the best resolution to be found for transportation service problems [1].

Functionality and road network configuration formed alongside the historic development of cities; this in turn, influenced the geometric planning scheme of cities [2, 3].

Kosytskyi and Blahovydova believe [4] that the most effective cities were Grid Street planned. The main advantage of this plan is that traffic flow in all directions is duplicated and the city centre does not get overloaded.

2.1. Analysis of how Road Network Planning is evaluated

Fyshelson [5] concluded that the structure of the road network in any given city influences the speed of vehicular traffic, the time spent in transit, flexibility, safety, and the cost efficiency of transporting passengers and cargo.

There are criteria which assess how effectively a road network was planned or built. [1, 5–9].

The first indicator is the degree of the directness of links (the coefficient of the directness of links). This is the ratio of the length between two points as measured on the ground (in real life conditions) to the distance between the same two points in the air:

$$k_{dl} = \frac{l_{ij}^{road}}{l_{ij}^{air}}, \tag{1}$$

where $k_{непр}$ is the coefficient of directness of transport links; $l_{ij}^{дор}$ is the distance on the street between two points, in kilometres and l_{ij}^{air} is the distance between the same two points in the air, in kilometres.

Lobanov and Fyshelson [1, 5] note that the coefficient of directness depends on the planning scheme of the specific road network but generally ranges from 1.05-1.5.

The second indicator is the road network density. This is the relationship between the length of the transport network and the overall territory, expressed as:

$$\delta = \frac{L_C}{S_C}, \tag{2}$$

where δ is the street network density, in km/km ^{2}; L_C is the length of the transport network, in km and S_C is the territory, in km ^{2}.

As Bezlyubchenko noted [8] this indicator usually wavers around 0.7-4 km/km^2 and depends on how the city and neighbourhood (central, peripheral, industrial) are categorized.

Standards in planning roadways have changed over the years. The greatest changes have been to the width of the vehicular roadbed. This causes variations in the density indicator which is defined as the ratio between the area of the transportation network and the area of the city [10]:

$$\delta' = \frac{S_S}{S_C}, \tag{3}$$

where S_S is the area of the street network, in km^2.

The main disadvantage of these indicators is using their mean values. They are however useful for making decisions on a macro-level concerning the development of general city plans, complex transport schemes, etc. On a micro level other indicators are used to organize traffic flow such as: roadway volume (level of service) and intersection complexity.

Roadway volume can be evaluated by using the relationship of actual speed or traffic density to their maximum values [11]

$$c = \frac{V_z}{V_{max}}, \quad (4)$$

$$\rho = \frac{q_z}{q_{max}}, \quad (5)$$

where V_z, V_{max} are the actual speed of traffic and the speed of unhindered movement in km/hr. and q_z, q_{max} is the actual traffic density and maximal traffic density, in cars/km.

Intersection complexity is assessed by determining how many accidents occur on them, traffic safety (according to the appropriate safety coefficient) and their ability to accommodate traffic flow.

Safety at intersections is determined by the accident indicator proposed by Lobanov [1]:

$$K_a = \frac{G \cdot K_p \cdot 10^7}{25(M_\Sigma + N_\Sigma)}, \quad (6)$$

where G is the sum of danger of all problem areas; K_p is the coefficient of annual variations in traffic flow and M_Σ, N_Σ are the total amount of traffic on the roads which intersect, in cars/day.

2.2. Analysis of studies that determine the length of the road network

Currently there are different ways to define a section of the road network; definitions are based on transport, pedestrian and passenger flows. Accordingly, the length requirements are different.

It is noted in *Mistobuduvanny: dovidnyk proektuvannya* [12] that the distance between arterial streets should be 600-800 meters. The distance between other streets should be as follows: motorways 800-1200 meters (in central parts of a city a minimum of 600 meters), regulated flow streets (in residential areas) 500-1500 meters and between intersections on one level 300-800 meters.

Bezlyubchenko [8] stated that the distance between arterial streets should not exceed 700-1000 meters (figures can change depending on the land relief at the location).

Comfortable walking distance should be the main criteria for determining the distance between streets; it should not however exceed 500 meters (according to Ukraine's building norms 360-92** [13]).

This approach is based on the interests of the family unit where protecting children from having to cross a street with vehicular traffic is of tantamount importance [14]. This approach puts schools at the centre of neighbourhoods; neighbourhoods are defined as the 800 meter radius around a school.

Today the concept of pedestrian access radius is largely connected to public transportation stops which, in turn, defines the distance between stops on public transportation routes. Ukraine's building norms [13] state that the distance between bus, trolley and tram stops should be 400-600 meters; between stops on express bus and tram routes 800-1200 meters; between subway stops 1000-1500 meters and between commuter train stops 1500-2000 meters.

An analysis of distances between bus stops in the USA [15-18] shows a wide variation of 300 to 2640 feet (90-800 meters).

Such large variations prevent us from determining the length of the road network or the length of a roadway section which influences the density of the transport network.

3. REVIEW OF PREVIOUSLY OBTAINED RESULTS

The authors previously completed studies on how the structure of a road network affects its efficiency [19]. The following criteria were used to evaluate the efficiency of a transport network:

$$\sum_{i=1}^{n} T_i \to min; \quad (7)$$

$$\sum_{i=1}^{n} L_i \to min; \quad (8)$$

$$\sum_{i=1}^{n} C_{mpi} \to min; \quad (9)$$

where T_i is the time a vehicle is moving along a specific portion of the transport network (*i*), in hours;; L_i – the length of the specific portion of the transport network (*i*) , in km and C_{mpi} are the expenses associated with using public transportation on the specific portion of the transport network (*i*), in UAH.

In order to determine how the structure of the road network influences efficiency, we examined two ways of breaking up a 200 hectare plot measuring 1x2km into residential blocks (fig. 1).

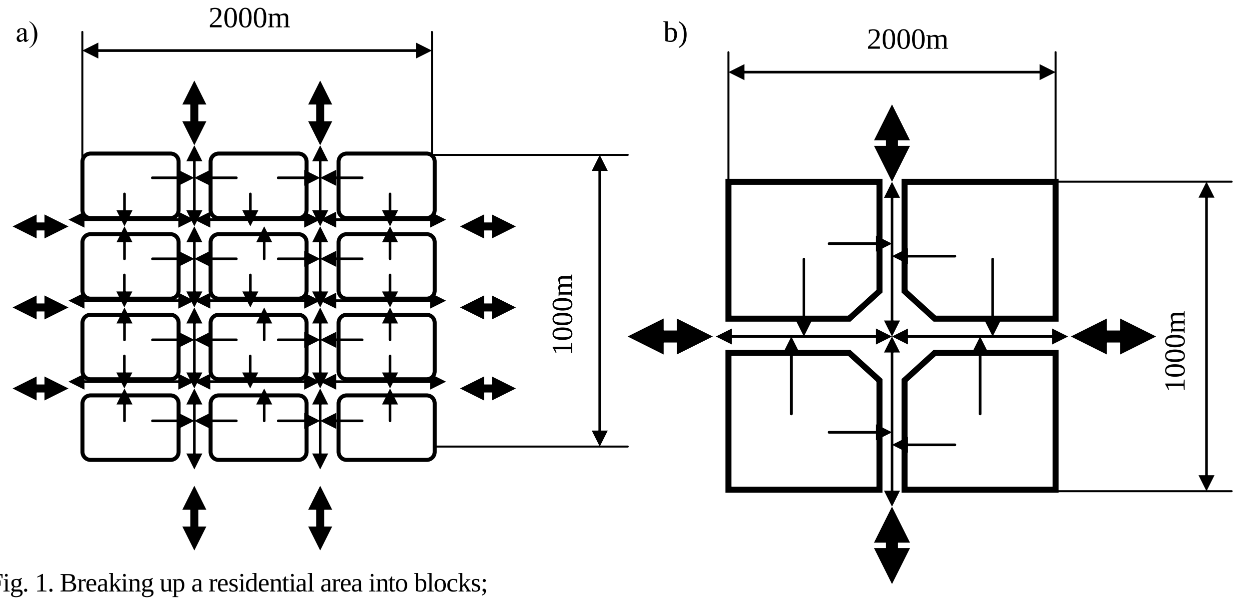

Fig. 1. Breaking up a residential area into blocks;
Рис. 1. Разбивка селитебной территории на жилые кварталы

- through streets
- транзитные транспортные потоки
- local access streets
- транспортные потоки местного формирования

The first version (fig. 1a) divides the area into 12 residential blocks, each up to 20 hectares and measuring up to 0.65x0.25km.

The second version (fig. 1b) divides the area into four residential blocks, each 50 hectares measuring 1.0x0.5km.

According to the layout of the residential blocks (fig. 1) and based on the characteristics of the area partitioned for development, we can calculate the maximum number of individuals that can live in this area.

Minimum density is calculated assuming 50 hectares for every 1000 individuals. This would mean that 4,000 people can live in this area. Maximum density would assume 7 hectares for every 1,000 individuals or 28,570 individuals. If we consider the characteristics of transportation flows on the criteria (7)-(9), we can create a comparative table (Tab. 1). Calculating the characteristics of the transportation flows on the basis of criteria (7) – (9), we can create a comparative table (tab. 1).

Tab. 1

Evaluating the efficiency of the transport network

Name of the parameter or indicator	Form of measurement	Values	
		Version One	Version Two
Area	ha (km^2)	200 (2)	200 (2)
Area for each 1000 residents	ha	16.25	50
Length of the transportation network	km	12	6
Transportation network density	km/km^2	6	3
Area of the transportation network: – 7.5 meter wide roadway – 15 meter wide roadway	km^2	0.09 0.18	0.045 0.09
Transport network density: – 7.5 meter wide roadway – 15 meter wide roadway	km^2/km^2	0.045 0.09	0.0225 0.045
Volume of arrivals and departures: -of them, transit flows	unit	8,000 2,000	8,000 2,000
Total length of the network: – if roadway width is 7.5 meters – if roadway width is15 meters	km	15,411.6 15,411.6	14,020 14,020
Overall time of movement: – 7.5 meter wide roadway – 15 meter wide roadway	hrs.	466.4 305.3	820 590.2
Overall transport expenses: – 7.5 meter wide roadway – 15 meter wide roadway	UAH	2,432.2 2,260.1	5,171.2 3,400

The obtained comparative data (tab. 1) show that there is no optimal way to divide the area into different sized residential blocks. The table supports the hypothesis that an optimal roadway section length exists, which abuts one side of the residential block and promises minimal time in transit, turning lanes and financial expense.

Royko [20] illustrates the dependence of the optimal roadway section length, which abuts one side of the residential block and would provide minimal expenses to ensure the functioning of transport system of movement passengers and cargo looks like this:

$$l_{\text{діл}}^{\text{опт}} = \sqrt{\frac{2\cdot V_p\cdot V_T\times}{2\cdot V_p\cdot(K_1\cdot HO\cdot S_T+HO\cdot S_T+N_t\cdot S_T+}}$$

$$\frac{\times(t_\Delta\cdot\left(HO+N_t\right)\cdot N_f\cdot C_f\cdot K_2\cdot l_v+}{+\left(HO+N_t\right)\cdot N_f\cdot C_f+B_c\cdot F)+2\cdot V_p\cdot V_T\cdot(B_{rb}\cdot C_a+} \qquad (10)$$

$$\frac{+t_\Delta\cdot\left(HO+N_t\right)\cdot S_T\cdot K_3\cdot l_v)}{+K_1\cdot B_{rb}\cdot C_r)+V_T\cdot(k_a\cdot k_b\cdot k_c\cdot B_p\cdot N_p)}.$$

where V_p is the pedestrian speed, in km/hr.; V_T is the traffic speed, in km/hr.; K_1 is the coefficient of the directness of transport links; HO is the number of departures from the area, in units/day; S_T is the cost of moving vehicles within the territory, in UAH/hr.; N_t is the number of vehicles which pass through the road network without entering it, in units/day N_f is the amount of fuel consumed by the vehicles driving around the road network in kg/hr.; C_f are the standard fees charged for emission of pollutants when moving about the territory, in UAH/kg; K_2 is the coefficient which takes into account the difference in expense of fuel consumption when vehicles are moving and stopped at an intersection; l_v is the length of the vehicle queue at intersections, in km; t_Δ is the wait each vehicle has at intersection, in seconds; K_3 is the coefficient which includes the difference between the cost of movement and the cost of being stopped at an intersection; C_a, C_r is the value of maintaining 1 km^2 of main through and local access streets, respectively, in UAH/km2; B_{rb} is the width of the roadbed in km; B_c is the value of the time a passenger spends in transit, in UAH/hr.; F is passenger flow in passengers/day; k_b, k_a, k_c are the coefficients of choosing a stop location, directness of pedestrian flows and the relief of the locality respectively; N_p is the number of passengers who approach a public transportation stop, in passengers/day and B_p is the value of pedestrian movement, in UAH/hr.

4. DESCRIPTION OF MATHEMATICAL RESIDENTIAL NEIGHBOURHOOD TRANSPORT NETWORK DENSITY MODELS

As stated in Fyshelson's work [5], one of the components which determine transport network density (2) is the total length of the road network which is made up of individual sections. In order to increase the road network density, it is necessary to lengthen the road network if the area of the territory remains constant. This can be done by dividing a settled area into neighbourhoods and then into residential blocks. The excessive number of intersections leads to an increase in travel time. Additionally, branching out the street network requires significant capital investment and funds for maintenance. For these reasons it is necessary to define the pattern of influence that the correlation of the side of the residential block has on the density of the transportation network.

To this end we have illustrated a residential area (fig. 2) where the length of one border is designated as l_s and the other—the result of this length on the coefficient, which includes the correlation of sides in a rectangle k_r.

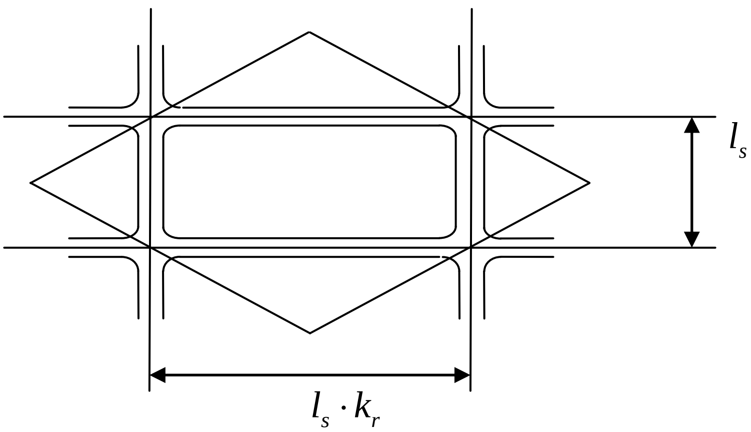

Fig. 2. Layout of residential area
Рис. 2. Схема жилого квартала

Using the dependency (2), we make substitutions for the length of the transportation network in the territory with the following formula:

$$L_C = 2(l_s + l_s \cdot k_r), \tag{11}$$

and the area of the territory served by this network:

$$S_C = 2 \cdot l_s \cdot l_s \cdot k_r. \tag{12}$$

The result of this dependency (2) for individual structural element of the residential territory, particularly the residential block, will be:

$$\delta_r = \frac{2(l_s + l_s \cdot k_r)}{2 \cdot l_s \cdot l_s \cdot k_r} = \frac{1 + k_r}{l_s \cdot k_r}. \tag{13}$$

5. RESULTS OF MODELING TRANSPORTATION NETWORK DENSITY IN RESIDENTIAL BLOCKS

In order to identify what kind of influence the relationship between the lengths of the borders of the residential district has we used the data in Tab. 2, to build a graph that will show how transport network density is affected by these changes (fig. 3).

Tab. 2

Results of modelling the transport network density of an area

Length of the area, l_s, in km	Coefficient of the relationship between sides of a rectangle, k_r						
	0.5	1	1.5	2	2.5	3	3.5
0.2	15	10	8.33	7.5	7	6.67	6.43
0.3	10	6.67	5.56	5	4.67	4.44	4.29
0.4	7.5	5	4.17	3.75	3.5	3.33	3.21
0.5	6	4	3.33	3	2.8	2.67	2.57
0.6	5	3.33	2.78	2.5	2.33	2.22	2.14
0.7	4.29	2.86	2.38	2.14	2	1.9	1.84
0.8	3.75	2.5	2.08	1.88	1.75	1.67	1.61

These patterns show that the transportation network density of the block will decrease when the length of its sides increases. If we follow the rule that a residential block's area should be between 20 and 50 hectares, then for the variables: l_s = 0.3–0.8 km and k_r = 2–0.5 the transport network density will be between 3.0-5.0 km/km^2 respectively.

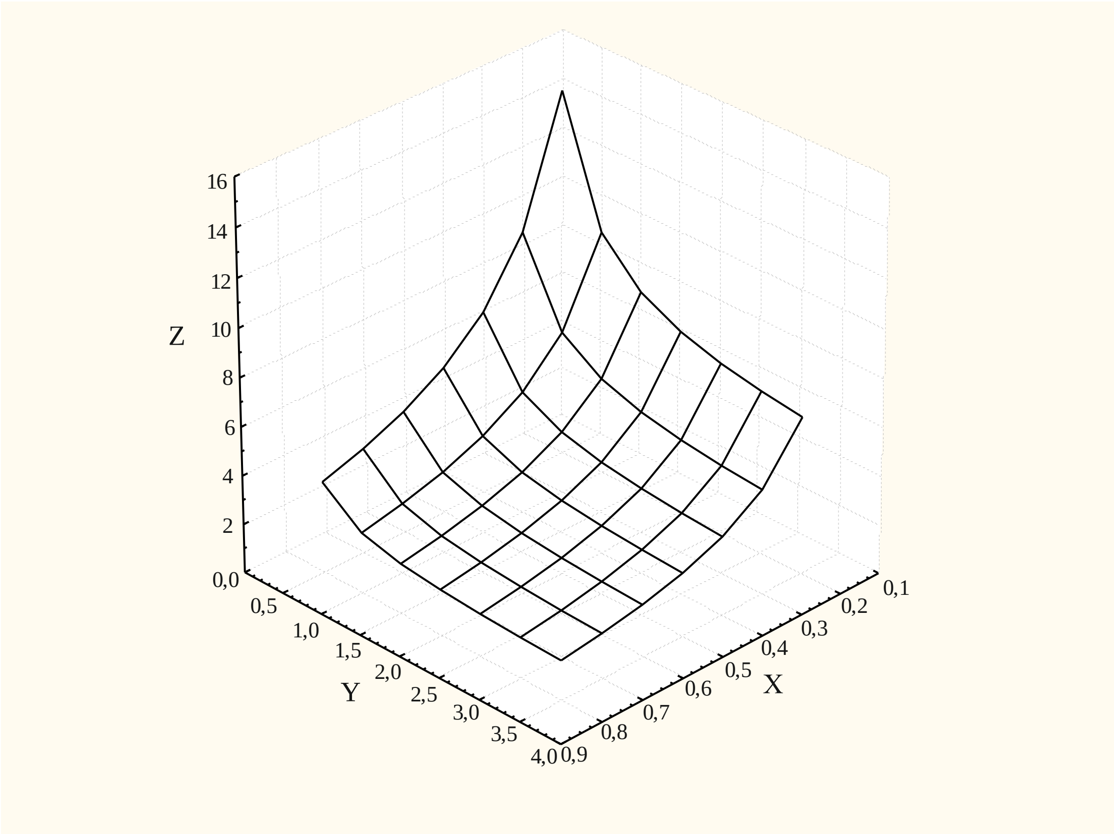

Fig. 3. Graph showing the dependency between an area's transport network density (Z), the length of one border of the residential block (X) and the coefficient of its relationship to the other border (Y)
Рис. 3. График зависимости плотности транспортной сети квартала (Z) от длины одной стороны жилого квартала (X) и коэффициента соотношения второй стороны (Y)

Defined patterns must be checked to ensure they comply with traffic conditions and passenger flows. For this purpose, using the equation (13) as the foundation, we will change the length of one border of the residential area according to the chosen parameters for various values of the coefficient of the relationship of the sides of a rectangle.

An important parameter of transportation flow is speed. Changing the speed of traffic due to certain traffic delays and queue lengths, we obtain the density of the transport network inside the area. To show the character of the influence these changes have on the density of the transport network under various ratios of length of the residential area we created a graph (fig. 4) which shows a delay of 45 seconds at traffic intersections and a 200 meter vehicle queue.

These patterns show that increasing the wait before an intersection or the length of the line reduces the density of the transport network. However, the result of higher density is reduced vehicle speed.

Characterizing the dependency of an area's transport network density on vehicle speed, it is important to consider the number of vehicles using the area's roadways. Therefore, the next step is to identify the impact of motorization and the number of residents served by the transport network, on the area's transportation network density. In order to show what kind of influence these changes have on the area's transportation network density when one border is of various lengths, we created a graph (fig. 5). The graph works on the premise that there are 200 vehicles for every 1,000 individuals.

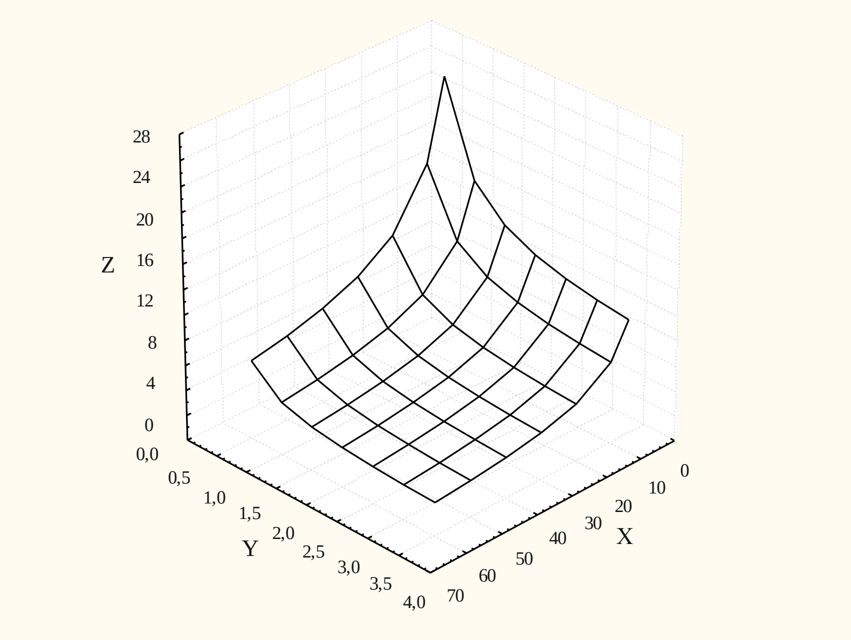

Fig. 4. Graph showing the dependency between an area's transport network density (Z), vehicle speed (X) and the coefficient of sides (Y) when the delay before the intersection is 45 seconds and the queue is 20 meters long
Рис. 4. График зависимости плотности транспортной сети квартала (Z) от скорости движения (X) и коэффициента соотношения (Y) при задержке перед перекрестком 45 с и длине очереди 200 метров

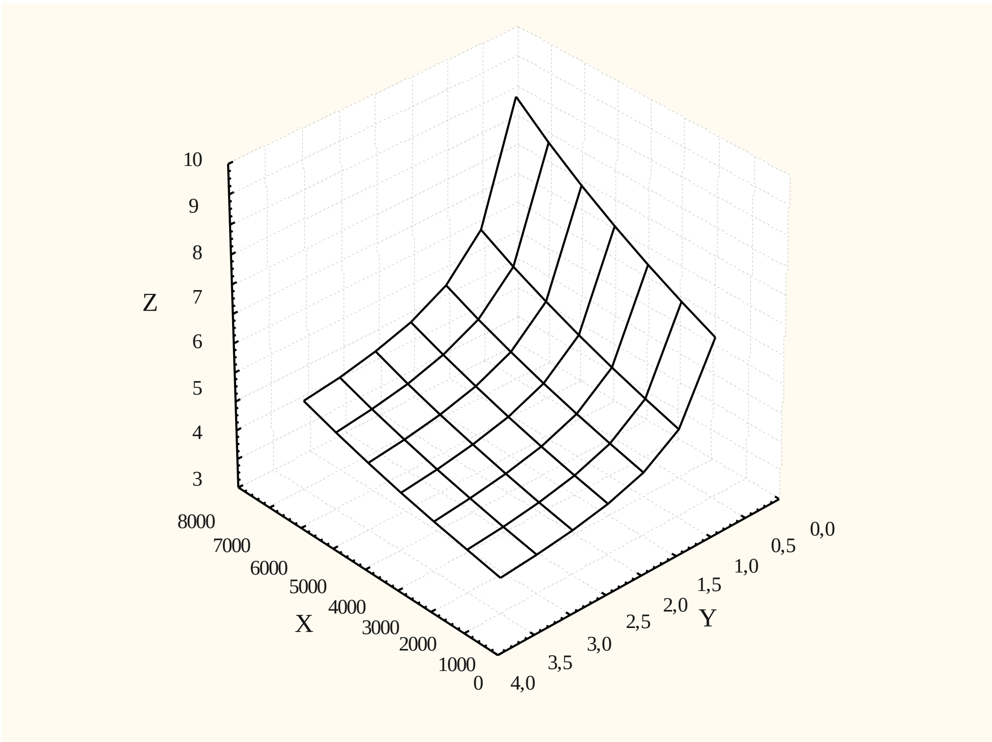

Fig. 5. Graph showing the dependency between an area's transport network density (Z), the number of residents (X) and the coefficient of sides (Y) and assuming 200 vehicles per 1000 inhabitants
Рис. 5. График зависимости плотности транспортной сети квартала (Z) от количества жителей (X) и коэффициента соотношения (Y) при уровне автомобилизации 200 авт. / 1000 человек

6. RESULTS OF MODELING A NEIGHBOURHOOD'S TRANSPORT NETWORK DENSITY

These patterns are related to a specific residential block. As these blocks are the structural elements of neighbourhoods, it is necessary to understand the effect that the ratio of the lengths of the borders have before partitioning the neighbourhood.

For this we use dependency (2), which looks like this:

$$\delta_p = \frac{\sum(l_s + l_s \cdot k_r)}{L_1 \cdot L_2}, \tag{14}$$

where L_1, L_2 are the lengths of the borders of a neighbourhood, in km.

To describe the sum of the length of the residential area's borders $l_{діл}$ we use the following equation:

$$\sum l_s = \left(\frac{L_1}{l_s} + 1\right) \cdot L_2. \tag{15}$$

To describe the sum of the length of the block's borders $l_{діл} \cdot k_{пр}$ we use the following formula:

$$\sum l_s \cdot k_r = \left(\frac{L_2}{l_s \cdot k_r} + 1\right) \cdot L_1. \tag{16}$$

Using formulas (15) – (16) dependent on (14), we get the following formula:

$$\delta_p = \frac{1}{l_s}\left(\frac{k_r(L_1 + l_s)}{L_1} + \frac{L_2 + l_s \cdot k_r}{L_2}\right). \tag{17}$$

As the area of the residential block is between 80-400 hectares [6], when examining the relationship between the length of the borders of the neighbourhood we use six variables $L_1 \times L_2 = 0{,}8 \times 1{,}0$ km, $L_1 \times L_2 = 1{,}0 \times 1{,}0$ km, $L_1 \times L_2 = 1{,}0 \times 1{,}5$ km, $L_1 \times L_2 = 1{,}5 \times 1{,}5$ km, $L_1 \times L_2 = 1{,}5 \times 2{,}0$ km and $L_1 \times L_2 = 2{,}0 \times 2{,}0$ km. The results are plotted on the graph shown in Table 3 and Fig. 6.

Tab.3

Results of modelling a Neighbourhood's transport network density

Length of the territory, l_s, km	Coefficient relationship of the sides of the rectangle, k_r						
	0.5	1	1.5	2	2.5	3	3.5
1	2	3	4	5	6	7	8
Relationship of the lengths of the neighbourhood's borders $L_1 \times L_2 = 0{,}8 \times 1{,}0$ km							
0.2	8.63	12.25	15.88	19.5	23.13	26.75	30.38
0.3	6.13	8.92	11.71	14.5	17.29	20.08	22.88
0.4	4.88	7.25	9.63	12	14.38	16.75	19.13
0.5	4.13	6.25	8.38	10.5	12.63	14.75	16.88
0.6	3.63	5.58	7.54	9.5	11.46	13.42	15.38
0.7	3.27	5.11	6.95	8.79	10.63	12.46	14.3
0.8	3	4.75	6.5	8.25	10	11.75	13.5
Relationship of the lengths of the neighbourhood's borders $L_1 \times L_2 = 1{,}0 \times 1{,}0$ km							
0.2	8.5	12	15.5	19	22.5	26	29.5
0.3	6	8.67	11.33	14	16.67	19.33	22

0.4	4.75	7	9.25	11.5	13.75	16	18.25
0.5	4	6	8	10	12	14	16
0.6	3.5	5.33	7.17	9	10.83	12.67	14.5
0.7	3.14	4.86	6.57	8.29	10	11.71	13.43
0.8	2.88	4.5	6.13	7.75	9.38	11	12.63
Relationship of the lengths of the neighbourhood's borders $L_1 \times L_2 = 1,0 \times 1,5$ km							
0.2	8.33	11.67	15	18.33	21.67	25	28.33
0.3	5.83	8.33	10.83	13.33	15.83	18.33	20.83
0.4	4.58	6.67	8.75	10.83	12.92	15	17.08
0.5	3.83	5.67	7.5	9.33	11.17	13	14.83
0.6	3.33	5	6.67	8.33	10	11.67	13.33
0.7	2.98	4.52	6.07	7.62	9.17	10.71	12.26
0.8	2.71	4.17	5.63	7.08	8.54	10	11.46
Relationship of the lengths of the neighbourhood's borders $L_1 \times L_2 = 1,5 \times 1,5$ km							
0.2	8.17	11.33	14.5	17.67	20.83	24	27.17

Table 3 continued

0.3	5.67	8	10.33	12.67	15	17.33	19.67
0.4	4.42	6.33	8.25	10.17	12.08	14	15.92
0.5	3.67	5.33	7	8.67	10.33	12	13.67
0.6	3.17	4.67	6.17	7.67	9.17	10.67	12.17
0.7	2.81	4.19	5.57	6.95	8.33	9.71	11.1
0.8	2.54	3.83	5.13	6.42	7.71	9	10.29
Relationship of the lengths of the neighbourhood's borders $L_1 \times L_2 = 1,5 \times 2,0$ km							
0.2	8.08	11.17	14.25	17.33	20.42	23.5	26.58
0.3	5.58	7.83	10.08	12.33	14.58	16.83	19.08
0.4	4.33	6.17	8	9.83	11.67	13.5	15.33
0.5	3.58	5.17	6.75	8.33	9.92	11.5	13.08
0.6	3.08	4.5	5.92	7.33	8.75	10.17	11.58
0.7	2.73	4.02	5.32	6.62	7.92	9.21	10.51
0.8	2.46	3.67	4.88	6.08	7.29	8.5	9.71
Relationship of the lengths of the neighbourhood's borders $L_1 \times L_2 = 2,0 \times 2,0$ km							
0.2	8	11	14	17	20	23	26
0.3	5.5	7.67	9.83	12	14.17	16.33	18.5
0.4	4.25	6	7.75	9.5	11.25	13	14.75
0.5	3.5	5	6.5	8	9.5	11	12.5
0.6	3	4.33	5.67	7	8.33	9.67	11
0.7	2.64	3.86	5.07	6.29	7.5	8.71	9.93
0.8	2.38	3.5	4.63	5.75	6.88	8	9.13

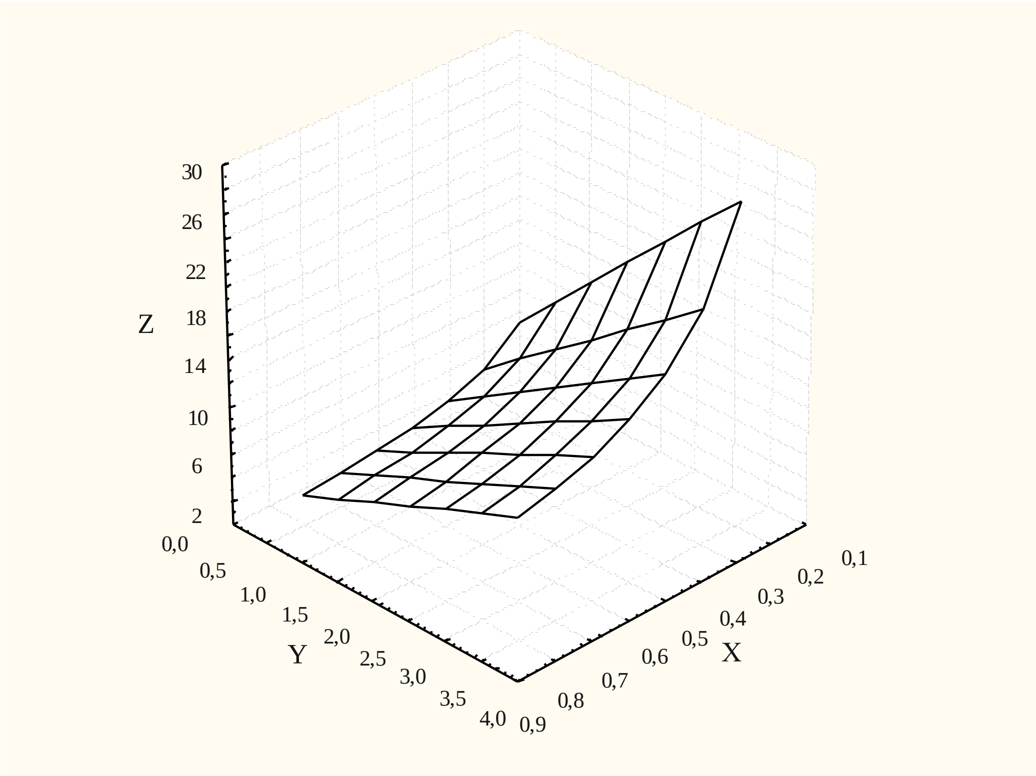

Fig. 6. Graph showing the dependency between a neighbourhood’s transport network density (Z), the length of one of the neighbourhood’s borders (X) and the coefficient of relationship to the other border (Y) assuming the relationship of the length of the neighbourhood’s borders is $L_1 \times L_2 = 1{,}5 \times 1{,}5$ km

Рис. 6. График зависимости плотности транспортной сети жилого района (Z) от длины одной стороны жилого квартала (X) и коэффициента соотношения другой стороны (Y) при соотношении длин сторон жилого района $L_1 \times L_2 = 1{,}5 \times 1{,}5$ км

7. CONCLUSIONS

Analysing research done on the transport planning of cities showed that when developing new sections of a city’s territory are being developed, project planners and researchers are focusing more attention on identifying a rational road network structure which would require minimal expense to move vehicular and pedestrian flows.

Perfecting a model for an area’s transport network density, which is based on including the correlation of the length of the borders of the residential space, allowed us to impose it (density) in indirect dependence on the parameters of transport and passenger flows.

The proposed mathematical model of the transport network density in a neighbourhood allowed us to use its indirect dependency on the transport network density in its residential blocks and neighbourhood size.

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