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FORECASTING THE MOBILITY PARAMETERS OF THE INHABITANTS OF SUBURBAN AREAS

Summary. *Potential mobility that meets the requirements of population displacement is determined following the biological and social needs, socio-economic characteristics, production necessity, and cultural needs. Because of the multifactor character and complexity of relationships, it is impossible to determine the potential mobility by a calculation method. The feasibility of different target movements, depending on their distance, is regarded by rural populations differently. Each rural settlement is located among many other rural and urban settlements with an individual quantitative and qualitative set of social, cultural, and industrial potential. With the developed road network and public transport system, the population selects the center of gravity with the limitations imposed by this transport system and is based on subjective considerations about the quality of service. The distribution of urban residents' movements to the rural areas is affected by the size of the city, movement distance, movement purpose, i.e. the same factors as rural residents' movement to cities. The difference is that the radius of urban residents' movements distribution is much smaller. Thus, the zone of intensive and regular movements in the working day cycle covers only nearest to cities rural area with a radius of 15 km. On weekends, due to guest visits and holiday trips, the radius of this zone extends approximately 1,5–2 times. Based on the links distribution, the scatter band of the initial and final points of movement can be obtained. Since the density of scattering varies with respect to settlements, then we can allocate the territorial units that will make service zone on their sets. Research results can be an integral part of comprehensive studies of determining the transport links density, hubs of passenger flows' origin, and suppression to construct mathematical models of the most efficient passenger transport system operation.*
Key words: *reliability, sustainability, transport systems, Delaunay triangulation, power function.*

1. INTRODUCTION

The problem of the efficient functioning of passenger road transport is an important part of a comprehensive social development program. Its successful solution depends on the degree of perfection and validity of the transport system. Comprehensive studies of the patterns of formation of the transport services market are based on studies of processes of resettlement and spatial self-organization of the population, determination of the density of transport links, nodes of origin and elimination of passenger flows.

The volume of transportation is measured by the number of planned or actual passengers. The background is the transport mobility of the population. Determination based on transport work for any period allows designing, planning, and choosing a rational relationship between settlement and transport infrastructure, calculating the required number and type of rolling stock, making the rational route network, and optimally distributing the rolling stock on the network.

Transport modeling is a mathematical representation of transport demand and resulting trips, based upon economic, municipal, household, and transport data and projections, and using formalized behaviour hypotheses and assumptions. Traffic models are used to analyze and forecast the traffic situation and to predict the outcomes of transport strategies. Sustainability is often used as a short form for sustainable development, for which the most commonly cited definition is: development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. A very widely established attempt to operationalize this term stipulates that sustainability requires a careful balance between social, economic, and environmental goals. The EU Transport Council [1, 2] define a sustainable systems as: allowed basic access and development needs of society to be met safely; balancing in human and ecosystem health; equity promotion within and between successive generations; fair and efficient choice of transport mode, support of competitive economy, considering balanced regional development.

2. LITERATURE REVIEW

The criteria for evaluating the performance of transportation systems are described in detail in the many research studies [3, 4, 15–17]. Methods of transport systems design were reflected in the works for static models and dynamic models [3, 5, 7–13]. The disadvantage of static models is that they optimize the transport system relative to random resettlement, resulting in estimated transport loads that can be significantly different from the actual ones.

There are known approaches, in which the authors [8, 9] consider the distribution of trips by Poisson's law, and note the multifactorial model of the formation of passenger correspondence, and therefore the mobility of the population, and propose to use the principle of maximizing entropy [12].

To build an efficient public passenger transport network, taking into account the travel demand, the authors [15] use the analysis of alternative Pareto-optimality trips.

In [11], it is possible to apply the methods of computational geometry [14, 18] for the transformation of geodata on spatial and other characteristics (population density, size of households, level of motorization) of settlements into generating trips, mobility of the population.

As an alternative approach, researchers [15, 17] have developed statistical models to predict external trips. These models generally follow a three-step approach. In the first step, external trips entering the study area are predicted at each external station (external trip generation). In the next step, external–external trips are distributed amongst external stations (external trip distribution). In the third step, external–internal trips are distributed within the study area.

The analysis of known methods of transport systems synthesis [3–14] indicates the need for their improvement, the development of new methods, algorithms for designing and evaluation of the efficiency and reliability functioning [3, 6] of existing transport systems and route networks, including suburban passenger transportation. The hierarchical significance of the city in the settlement system has a clear impact on the population's assessment of the appropriateness of the spatial choice of location to meet the purpose of the trip [3, 4, 13]. The higher it is, the more time in the daily balance of the rural and suburban population is allocated for resettlement. The interconnection of settlements is limited mainly by neighboring settlements (with some exceptions to business and guest travel).

Variables for inclusion in the land use and demographic dataset is given in Table 1, it is based on anticipated model structures. Variables are set in two categories: used for models and simulation, ready for forecasting and used for models calibration. For the last ones, actual dataset is completed by one-year data collection. This table shows the candidate variables, as well as they need to be forecasted or are calibration basis. There is also shown, which variables are anticipated to be used in trip generation. Another for the household micromodels, in the production and attraction models, in the Truck model, and in the creation of the mode split model and submodels [7].

Table 1

Proposed forecast variables and their use

Variable	Trip Generation					
	Household Submodel	Production	Attraction	Truck Model	Mode Choice	Need to be forecast?
Population (Residents)	+	+	+		+	Yes
Employed Residents		+			+	Yes
Average Income	+					Yes
Household Size	+	+				No
Income Level	+	+				No
Motorization Level	+	+			+	No
Total Employment			+	+	+	Yes
Zonal Area		+	+		+	Yes
Recreational Space			+			Yes

Even though there is a large family of distribution models, the most commonly used is the gravity model. This model was originally generated from an analogy with Newton's gravitational law. Interestingly, the gravity model has been criticized for its rather loose derivation: why should human behaviour necessarily comply on earth with the same principles as gravitational bodies? Fortunately, Wilson [9] and later on several other scientists [3, 4, 10, 19, 20], developed a sound statistical theory underlying gravity models.

The gravity model states that the number of trips between start and destination pair is directly proportional to the number of productions at the origin and the number of attractions at the destination and inversely proportional to the spatial separation between zones. The formulation of the gravity model is as follows:

$$T_{ij} = A_i \cdot O_i \cdot B_j \cdot D_j \cdot f(c_{ij}), \tag{1}$$

where T_{ij} – number of trips originating at zone i and terminating at zone j; O_i – number of trips originating at zone i; D_j – number of trips terminating at zone j; f – separation function; c_{ij} – separation function argument defining separation between zones i and j; A_i and B_j – balancing factors for origin and destination zones, respectively.

Balancing factors A_i and B_j, required to ensure the row and columns total constraints, are calculated as follows:

$$A_i = \frac{1}{\sum_j B_j \cdot D_j \cdot f(c_{ij})}, \tag{2}$$

$$B_i = \frac{1}{\sum_i A_i \cdot O_i \cdot f(c_{ij})}. \tag{3}$$

The balancing factors A_i and B_j are, therefore, interdependent; this means that the calculation of one set requires the values of the other set. This suggests an iterative process, which works well in practice: given set of values for the separation/deterrence function $f(c_{ij})$, start with all B_j=1, solve for A_i and then use these values to re-estimate al B_j; repeat until conve rgence is achieved.

Popular versions of the deterrence function, which represents the distribution of travel are exponential (4), power (5), and combined (6) functions given below:

$$f\left(c_{ij}\right)=e^{-\beta\cdot c_{ij}}, \tag{4}$$

$$f\left(c_{ij}\right)=c_{ij}^{n}, \tag{5}$$

$$f\left(c_{ij}\right)=c_{ij}^{n}\cdot e^{-\beta\cdot c_{ij}}, \tag{6}$$

where c_{ij} – separation measure, defined by e.g. travel time between zones i and j; β, n – calibration parameters.

As we have seen, the parameters A_i and B_j are estimated as part of the iterative balancing algorithm. The parameters of the deterrence function must be calibrated to make sure that the observed trip lengths are reproduced as closely as possible. A naive approach to this task is simply to 'guess' or to 'borrow' a value for parameters, run the gravity model and then extract the modelled trip lengths. This should be compared with the observed trip lengths. If they are not sufficiently close, a new guess for parameters can be used and the process repeated until a satisfactory fit is achieved (Fig. 1).

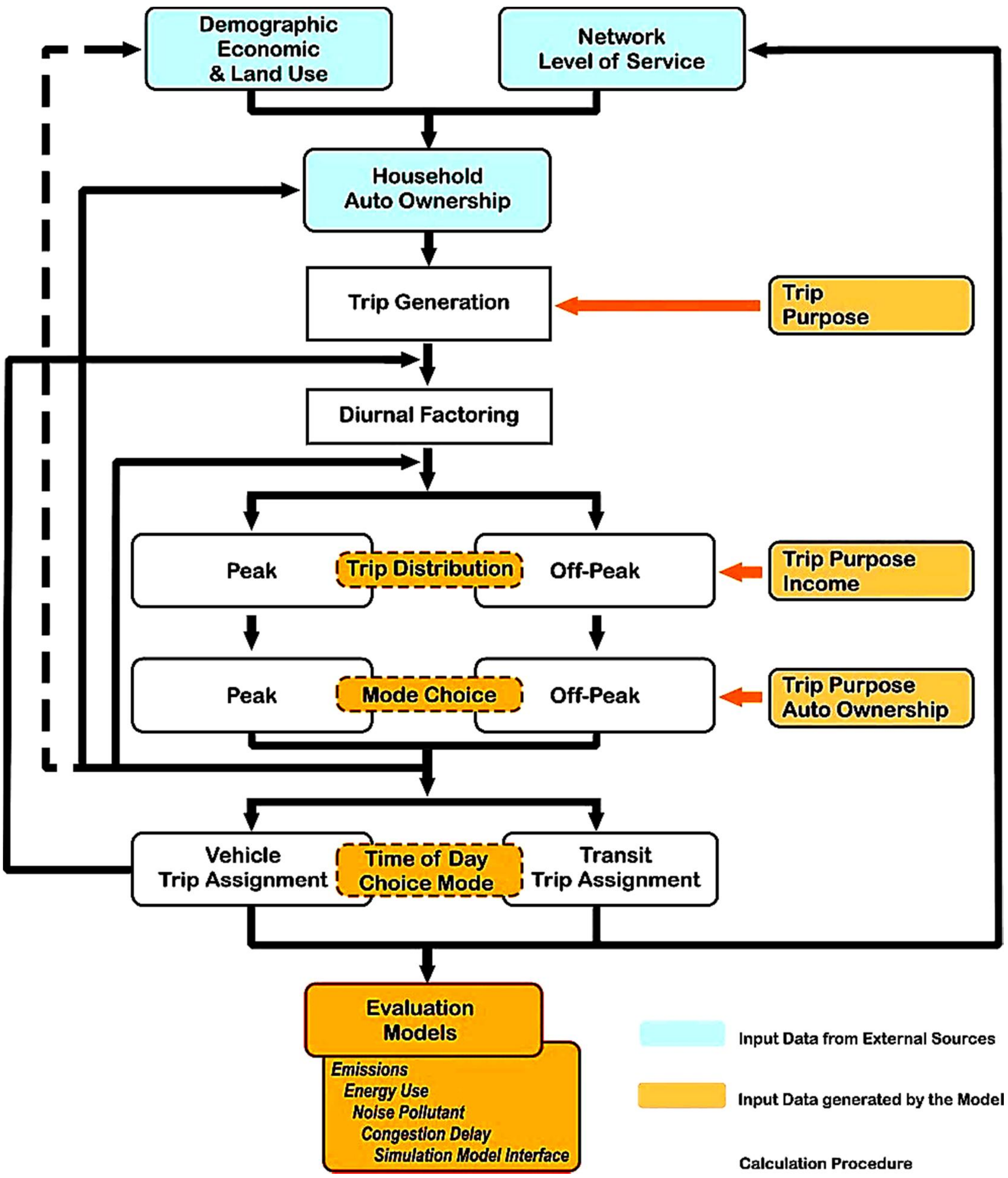

Fig. 1. Schematic representation of the regional travel forecasting model system

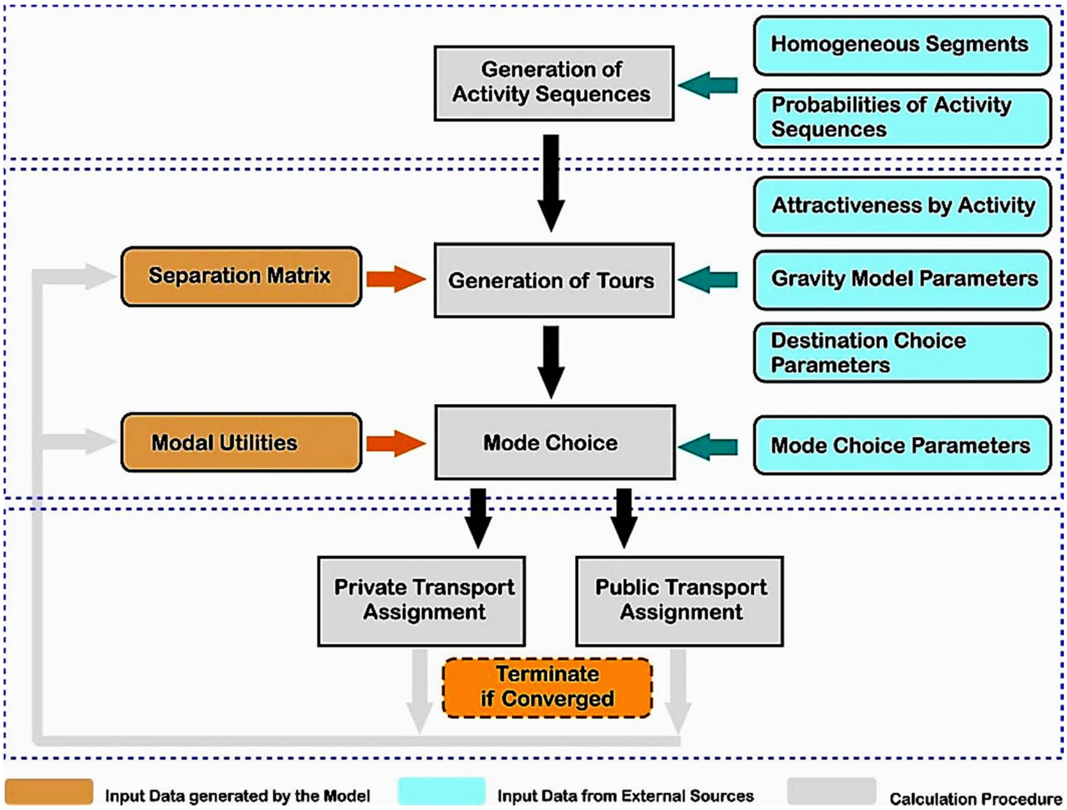

Fig. 2. Conceptual representation of tour-based travel demand modeling procedure

Proposition of recommended transportation model system structure is displayed in Fig. 1-2. Application of the model begins with two input keys: demographic, economic, and land use information (construction of city zoning, urban street network and their performance), and the multimodal transportation network level-of-service data. The trip generation model is composed of two basic models – a production and an attraction. It also can be complited by more micromodels or submodels. The trip generation model estimates the overall magnitude of trip making on a specific geographic basis (transport zones, points of attraction). Various submodels are used to support and describe the disaggregation of households (and/or workers) by selected independent variables.

3. PROBLEM SETUP AND RESEARCH METHODOLOGY

Mathematical models of transport mobility of the population are of practical importance [8 – 13]. Their main purpose is prediction. Determination based on transport work for any period allows designing, planning, choosing a rational relationship between settlement and transport infrastructure, calculating the required number and type of rolling stock, making the route network rational, and optimally distributing the rolling stock on the network. The law of settlement is a consequence of the law of spatial self-organization in time expenditures for movement.

The volume of transportation is measured by the number of planned or actual passengers. The background is the transport mobility of the population. It can be defined for a country, region, or city as the total number of people travelling during the year covered by the entire number of residents. Mobility of people related to their livelihoods. In the specific socio-historical and economic circumstances demand for movements (deliveries) determines the level of the productive forces development, social production, the social structure of society. The intensity of the movement is expressed quantitatively by the indicator of the population mobility. The distinction is made between the concepts of potential, realized, absolute, total, pedestrian, and transport mobility. In general, mobility is understood as the number of movements per person from the considered group for a particular estimated period.

The study area can be represented by a set of point objects (settlements) with a set of parameters that characterize them. To simplify the calculations, we restricted the survey area (area of interest) to a rectangular section. The construction of a graph model is based on the assumptions [5, 14, 18]:

- vertices of the graph – settlements (represented as point objects), with coordinates and characteristic parameters determined by the processing of mapping data (population, correspondence of passengers between settlements, number of routes passing through the settlement, etc.);
- edges of the graph – transport routes connecting the settlements;
- proximity zones (zones of mutual influence) are constructed without taking into account the weight of vertices or edges of the graph.
- This technique involves three stages of work:
- determination of the survey region and preparation of baseline data;
- construction of irregular model;
- building a regular model.

In the first stage, we restricted the study area to a rectangular section adjacent to the center of gravity (regional or district center). At this stage, we prepared the initial data on the spatial location (determination of coordinates) of the set of point objects (settlements) and their parameters to be investigated.

The second stage is the construction of an irregular model – to build a graph model of transport links (settlements are vertices, transport routes are edges). The main parameters of the problem are the coordinates of settlements and the values of the parameter under the study for the vertices of the graph.

In the third stage, we built a regular model. For the transition from the irregular to the regular model of the parameter under investigation, we performed the Delaunay triangulation [14, 18] and applied the method of inverse weighted distances [14].

4. RESEARCH RESULTS

4.1. Testing the hypothesis of the exponential population density distribution

Potential mobility that meets the requirements of population displacement is determined following the biological and social needs, socio-economic characteristics, production necessity, and cultural needs. Because of the multifactor character and complexity of relationships, it is impossible to determine the potential mobility by the calculation method [3, 4, 9].

Based on routes survey we obtained data of dispatching passengers from the regional centre to the periphery. Dispatching and moving of passengers in suburbs subordinate laws, similar to patterns of settlement, so let us assume that the number of passengers' deliveries from the centre to the settlements located at the periphery can be determined by the functional connection:

$$\lambda = a_1 e^{-b_1 l}, \tag{7}$$

where a_1 – passengers' deliveries from the centre of gravity; b_1 – the degree exponential decrease in deliveries of passengers with increasing distance from the peripheral settlement to the centre of gravity.

The authors [3, 16, 18] proposed a method for determining patterns of settlement in the region around the centre of gravity (regional, district centres) and performed the construction of a regular model for the function of population density, depending on the distance relative to the centre of gravity, which in turn allows us to set quantitative indices of transport mobility of the population in the region based on patterns of spatial self-organization of the population.

Satisfactory results in determining patterns of settlement and population movements in suburbs allow the use of models with power dependences of population density and deliveries of passengers from a distance to the centre of gravity. These functional connections have the forms:

$$d_F = A \cdot l^{-B}, \tag{8}$$

and

$$\lambda = A_1 \cdot l_1^{-B}. \tag{9}$$

The calculation results of population density and deliveries of passengers depending on the settlements` remoteness from the centre of gravity using the exponential model are presented in Fig. 3, using the power function – in Fig. 4.

For exponential models, the corresponding coefficients are set. These coefficients vary in the range:

a = 720…1502; b = 0.0802…0.097; a_1 = 131…327; b_1 = 0.0818…0.1081.

For models with a power function, corresponding coefficients vary in the range:

A = 48427…178418; B = 2.01…2.34; A_1 = 9231…26554; B_1 = 1.83…2.32.

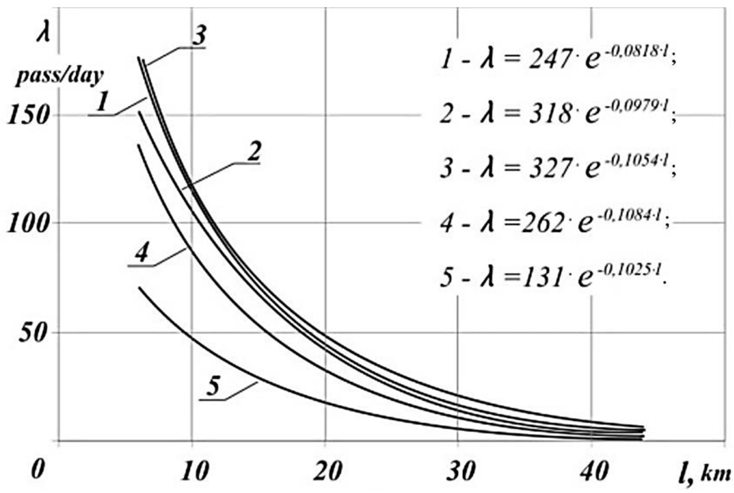

Fig. 3. Construction of population settlement patterns relative to the centre of gravity (regional centre) and deliveries of passengers λ from the regional centre to the periphery based on the exponential model

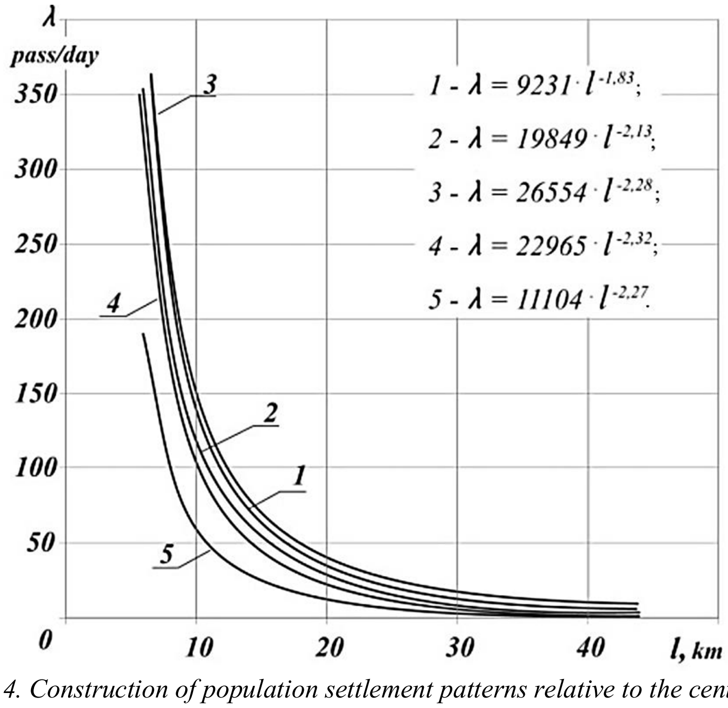

Fig. 4. Construction of population settlement patterns relative to the centre of gravity (regional centre) and deliveries of passengers λ from he regional centre to the periphery using a power function

Labour relationships can be divided into three zones in relation to cities – centres of rural residents' gravity. The first zone with Rn < 20 km is characterized by the stability of connections over a long period.

The probability of the existence of unstable relationships in this case $p \geq 0.8$. In this case, there is a constant process of labour relationship that almost defies the influence of random factors.

4.2. Regular model of the population density function

While determining the parameters, it is advisable to use an approach based on the study of patterns of interaction between the population, production with traffic flows. The main task is to establish the type of feedback of objects located in space, i.e., settlements, on mobility in transport services: planning the network, its capacity, studying the patterns of settlement, and spatial self-organization of the population. For comprehensive studies of the patterns of changes in the density of transport links in the passenger transport system, it is proposed to use an approach based on the application of GIS technologies, it allows to obtain tabulated functions of indicators:

- population density of the defined region;
- the carrying capacity of the itinerary network and its individual sections;
- transport mobility of the population etc.

To determine the patterns of resettlement in the region around the center of gravity (regional, district centers), a regular model for the population density function was constructed, depending on the distance to the center of gravity $h_F(x,y)$. Simultaneously, for the selected region, the survey was conducted:

1) Determining the survey region. We restrict the survey region to a rectangular section adjacent to the regional center. At this stage, we prepare the initial data on the spatial location (determining the coordinates x_i and y_i) of the set of point objects (settlements) and population H_{Fi}.

2) The construction of an irregular model is a graph model of transport links (settlements are vertices, transport paths are edges). The main parameters of the problem are the coordinates of settlements and the number of inhabitants.

The first step in constructing the population density function is to determine the population density for the major settlements in the region. Let us suppose that the population is concentrated in a settlement represented by a point object. To determine the zones of mutual influence of settlements (polygons), the Voronoi diagram was constructed. The fragment of the diagram for our task is given in Fig. 5.

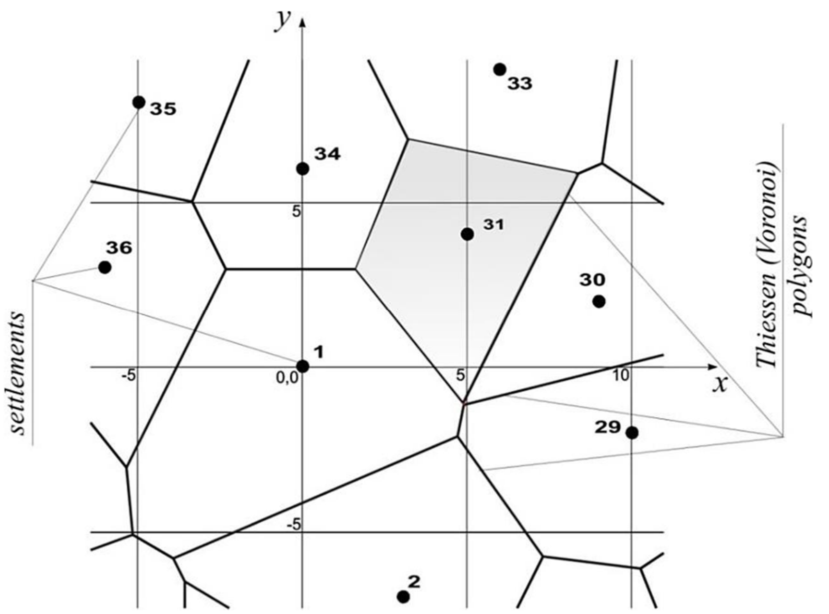

Fig. 5. A fragment of the Voronoi diagram for studying the population density of a region

Population density for the *i*-th polygon is determined by the formula:

$$h_{Fi} = {H_{Fi}}/{F_i}, \qquad (10)$$

where F_i – the area of the polygon to which the settlement belongs.

3) Building a regular model.

For the transition from the irregular to the regular population density model, we perform the Delaunay triangulation and apply the inverse distance weighting method. We define the population density in the i-th settlement as the average value for the i-th polygon by the formula (10). The population of settlements forms an irregular network. The problem of constructing a regular network for the population density function is solved by the inverse distance weighting method. Population density function of the region by the inverse distance weighting method looks as follows:

$$h_F(x, y) = \frac{h_{F1} \cdot w_1 + h_{F2} \cdot w_2 + h_{F3} \cdot w_3}{w_1 + w_2 + w_3}, \quad (11)$$

where h_{F1}, h_{F2}, h_{F3} – population density (determined at the previous stage) at points (vertices) of the triangle to which the running point belongs; w_1, w_2, w_3 – weights determined by the inverse distance weighting method.

As a result of the implementation of the mentioned steps of constructing a regular model of the population density function, we obtained a tabulated population density function for the considered Rivne region. A graphical representation of the function is shown in Fig. 6–7. In the calculations, the characteristics of the settlements were used according to the statistics of the census, the coordinates of the points were determined by the processing of cartographic objects.

The use of the STATISTICA 6.0 statistical processing package allows building a Voronoi diagram for multiple points based on the source data, which is the coordinates of the points. The results are processed and visualized using an Excel spreadsheet and SURFER 6.0.

The results of calculations of the population density along the routes of suburban passenger routes for a particular region in different directions by the regular resettlement model (RRM) and theoretical resettlement model (TRM) can be tabulated. Moreover, the calibration coefficient that determines the width of the impact of the i-th settlement w_i can be found as the ratio of the number of inhabitants in this settlement to the number of inhabitants of the average settlement (in our case, 500 inhabitants).

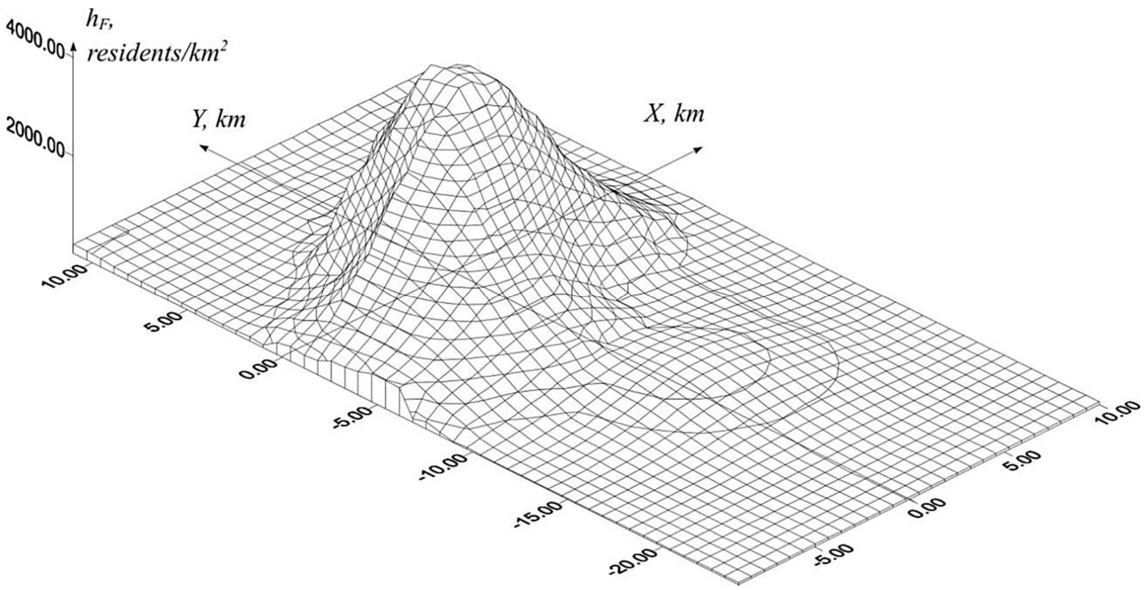

Fig. 6. Graphic representation of the population density function for the Rivne region in the immediate vicinity of the regional center

Table 2 shows the results of a comparative analysis of regular and theoretical models of resettlement. The correlation level is 0.959–0.976, which indicates a close connection between population density and distance from the center of gravity. Testing of the results by Fisher and Student's criteria showed that the probability of agreement of the results obtained by the regular and theoretical model of the resettlement described by function (11) is in the range 0.31–0.47.

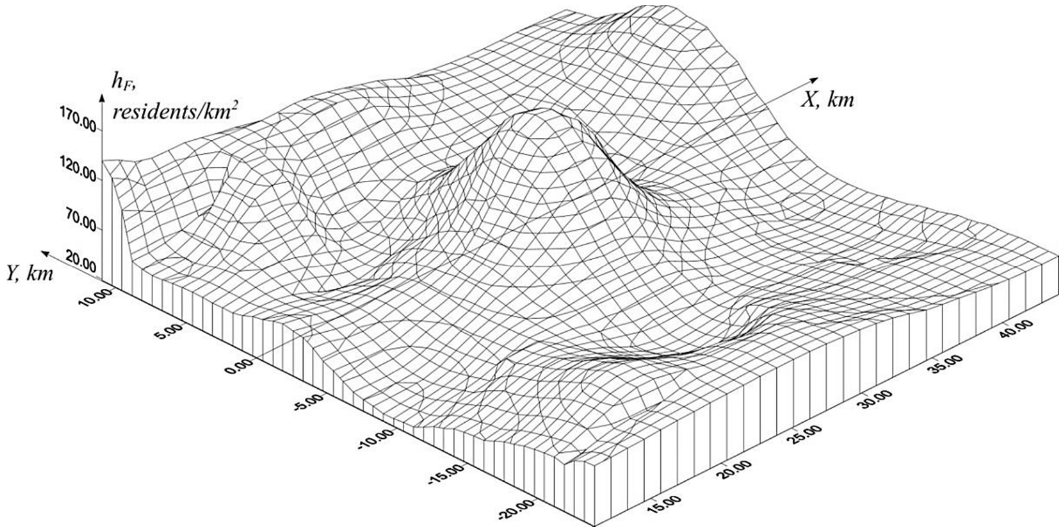

Fig. 7. Graphic representation of the population density function for the Rivne region at a distance of 10–45 km from the regional center

Table 2

Results of the comparative analysis of the regular resettlement model (RRM) and the theoretical resettlement model (TRM)

Statistical parameter	East direction		West direction	
	RRM	TRM	RRM	TRM
Average value	90.36	90.46	82.37	81.15
Dispersion	1548	1422	4247	3666
The level of correlation	0.976		0.968	
Average approximation error, %	7.82		9.85	
F – Fisher's criterion, (F = 1.641)	1.088		1.158	
Probability of agreement, p	0.39		0.31	
Student's t-test, (t = 1.679)	-0.082		0.495	
Probability of agreement, p	0.47		0.31	

Determining the calibration coefficients of the mutual influence of settlements as a function of the theoretical model of resettlement in each case requires a study of resettlement in the territory for different regions.

With a clear identification of the center of gravity, as an administrative-territorial unit, which is decisive in the passenger flows generation from the surrounding territories and settlements, which are very different in size, area, size of the zone of mutual influence; construction of a regular model of resettlement allows to assess the potential of transport services at a designated area. The use of methods of computational geometry makes it possible to match the demand for transport services with the offer of such services more closely. In turn, it is possible to achieve efficient use of vehicles, transport infrastructure, taking into account the real needs of the population of a certain region.

5. CONCLUSIONS AND RESEARCH PERSPECTIVES

Known methods [3, 8, 11, 12] of establishing the potential of transport services and forming matrices of passenger correspondence are based on the use of gravity models and have been developed, mainly for the study of the interaction between transport areas of cities. However, with the use of gravity models, it is difficult to form correspondence in suburban communication, with the interaction of many settlements with different population densities and remoteness from the city center.

Unlike the existing methods of establishing the laws of settlement, the proposed method is easier to use in practice and gives fairly accurate results.

The type of theoretical function of population density and the calibration coefficients, determined by the ratio of the number of inhabitants in the settlement and the number of inhabitants of the average settlement equal to 500 inhabitants, are established. The theoretical function has made it possible to determine the potential of suburban transport services more accurately compared to the known models [8], which is due to the significant unevenness of population density along routes. Satisfactory results were obtained in the process of modeling of passenger traffic on the route network of suburban passenger traffic of Rivne region, which made it possible to adapt the offer of transport services to the real needs of the population.

The results obtained can be used in planning the transfer or at the organization of interchanges in the outlying territories of urban areas. This approach requires modification of the existing public passenger transport route network, which is associated with the redistribution of passenger traffic and the organization of powerful passenger areas. However, when selecting the locations of transport infrastructure objects that ensure the interaction of individual, public passenger transport traffic, and the redistribution of passenger correspondence at interchanges, complex models should be considered, with the possibility of optimizing some global criterion for the efficiency of the network.

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ПРОГНОЗУВАННЯ ПАРАМЕТРІВ МОБІЛЬНОСТІ ЖИТЕЛІВ ПРИМІСЬКИХ ЗОН

Анотація. *Потенційна мобільність, що відповідає вимогам населення щодо пересування, визначається відповідно до біологічних і соціальних потреб, соціально-економічних характеристик, виробничої необхідності та культурних потреб. Через багатофакторний характер і складність взаємозв'язків неможливо визначити потенційну мобільність методом простого розрахунку. Доцільність різних цільових переміщень, залежно від їх відстані, сільське населення оцінює по-різному. Кожне сільське поселення розташоване серед багатьох інших сільських та міських поселень з індивідуальним кількісним та якісним набором соціального, культурного і промислового потенціалу. Завдяки розвиненій дорожній мережі та системі громадського транспорту населення вибирає центр тяжіння з обмеженнями, накладеними цією транспортною системою, і ґрунтується на суб'єктивних оцінках щодо якості обслуговування. На розподіл пересувань жителів у приміських зонах впливає розмір поселення, відстань, мета пересування, тобто такі самі чинники, як і щодо переміщення сільських жителів до міст. Відмінність полягає у тому, що радіус розподілу міських жителів набагато менший. Отже, зона інтенсивних та регулярних рухів у циклі робочого дня охоплює лише найближчі до міст сільські райони радіусом 15 км. У вихідні дні через гостьові поїздки радіус цієї зони розширюється приблизно в 1,5–2 рази. На основі розподілу поїздок можна отримати зони розсіювання початкової та кінцевої точок пересувань. Оскільки щільність розсіювання варіює відносно до населених пунктів, то за їх множинами можна виділити територіальні одиниці, які становитимуть зону обслуговування. Результати досліджень можуть бути частиною комплексних досліджень із визначення щільності транспортних зв'язків, центрів зародження та погашення пасажирських потоків для побудови математичних моделей ефективної роботи системи пасажирського транспорту.*

Ключові слова: *надійність, стійкість, транспортні системи, тріангуляція Делоне, показникова функція.*