N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 6, Number 438 (2019), 268 – 275 **https://doi.org/10.32014/2019.2518-170X.178**

UDC 656.13.078.1

V. V. Yavorsky, I. T. Utepbergenov, O. Zh. Mamyrbayev, A. T. Akhmediyarova

Institute of Information and Computational Technology, Almaty, Kazakhstan.
E-mail: yavorskiy-v-v@mail.ru, i.utepbergenov@gmail.com, morkenj@mail.ru, aat.78@mail.ru

MODELS OF ANALYSIS OF DISTRIBUTION OF PASSENGER TRAFFICS IN ROUTED TRANSPORT SYSTEMS

Abstract. The article considers the mathematical models for describing the processes of movement in cities, which are necessary for describing the processes of servicing on the routed urban passenger transport and making decisions to improve the management of traffics. It is proposed to create a database of all permissible movement paths in the city. There are many competing routes between any pair of city districts. An algorithm for the formation of paths is proposed, its essence is construction of typical multigraphs of transport links. The developed approach allows dividing the modelling of the processes of passenger traffic servicing on routes. This, along with the developed queuing models on the route, allows to obtain more detailed characteristics of the movement processes in the transport system in comparison with the known methods.

Keywords: urban passenger transport, transport network, route network, route link, movement paths multigraph, traffic correspondence, route selection strategy.

Introduction. The purpose of the urban passenger transport system (UPT) is to provide services to the city habitants by passenger transportation on the basis of efficient and coordinated use of available transport resources and in accordance with public interests.

Considering the application algorithms characteristic for transport systems, it is possible to single out a number of characteristic control tasks and corresponding subsystems of automated information resources [1, 2]. At the first stage of development of such systems, it is important to provide a single formalized description of the routed transport system [2].

The following formalized description of the transport system can be used for various types of routed transport. Indeed, in such transport systems there are a number of common basic elements: the transport network, the route network, the correspondence between the points on the transport network (TN), the traffic flow on the route network (RN), the routes between the TNs, the paths of servicing the traffic flows in the RN, etc. A universal formalized description of routed transport systems is especially relevant in link with the development of geoinformation systems [3].

The authors previously developed an algorithm for determining the maximum flow during distribution in the network [4] and examined the problem of placing the minimum number of cameras in a given transport network [5]. This scientific work is a logical continuation of the work performed on the research topic.

Description of the transport network in the form of a graph. The transport network means the set of points, characterized by a certain location and mutual relations between each other. The TN can be represented as a graph S (Z, W), where Z is a finite non-empty set of points $i \in Z$, $|Z|=n$; W is a set of links (arcs or edges) - $(i, j) \in W$, whose length corresponds to the distance between points i and j, $|W|=d$; $i \neq j$; $i,j = \overline{1,n}$. Here n, d are, respectively, the number of points and links on the graph S (Z, W).

The RN is specified by the set of transport routes (TR) - $\{M^k\}$, where $k \in I^M$; $|I^M| = m$; I^M is a set of indices of all TR-k operating on the RN; m is a number of TRin theRN.

Each TR-$k \in I^M$ is described by the sequence of passing the points i^k_ξ, $\xi = \overline{1,n_k}$, that make up the trajectory of its movement:

$$M^k = \{ i_1^k, i_2^k, ..., i_{n_k}^k \}, \tag{1}$$

where n_k is a number of points in TR-k, we should note that in the considered TR - k, the initial and final points in the trajectory M^k are the same, i.e. $i^k_1 = i^k_{n_k}$.

Link(i^k_ξ, i^k_η) is a route link of k-th TR. The set of all route links (i^k_ξ, i^k_η), $k \in I^M$, $k=\overline{1,m}$, $\xi \neq \eta$; ξ, $\eta \in \overline{1,n_k}$ on the route network can be represented as an oriented graph $M(Z_1, W_1)$. Z_1 is a set of points $i \in Z_1$, $|Z_1| = n_1$, $Z_1 \subseteq Z$; W_1- is a set of route links $(i^k_\xi, i^k_\eta) \in W_1$, As the arcs we can consider the time spent when following from point i^k_ξ to point i^k_η on TM - k, or distance between i^k_ξ and i^k_η on graph $S(Z, W)$ etc. The number of route links $|W_1| = d_1$ is such that their number - d_1, as a rule, is much larger than d, besides, it is obvious that $n_1 \leq n$.

On the transport routes $k \in I^M$, in accordance with its trajectory M^k, transport units (TU) move, which provide transportation to the TR.

The operation of each transport route k is characterized by the set of parameters $\{\Psi^k\} = \{\psi^k_1, \psi^k_2, ..., \psi^k_l\}$, where ψ^k_i – is i-th parameter of TM $k \in I^M$; $i = \overline{1,l}$, l is a number of parameters $\psi^k_i \in \Psi^k$.

Note that the type of transport route - k is determined by the type of transport units (TU) - φ_k, functioning on this TR.

Between points i and j, $i \neq j$; $i,j \in Z$, there are certain movement flows. If these flows can be considered as stationary, the potential flows between points i and j are determined by correspondence that can be represented as a matrix

$$\Lambda = || \lambda_{ij} ||, \tag{2}$$

where λ_{ij} is intensity of the flow from i to j, $i \neq j$; $i,j \in Z$, $i,j \in \overline{1,n}$.

The correspondences λ_{ij} are distributed on the route network in the form of flows on routes that can be represented using flow matrices:

$$X^k = || x^k_{\xi\eta} ||, \tag{3}$$

where $x^k_{\xi\eta}$ is intensity of flow from point ξ to point η on the transport route $k \in I^M$, $k = \overline{1,m}$; $\xi, \eta = \overline{1,n_k}$, n_k is a number of points on TR k.

Correspondence λ_{ij} consists of individual needs for movement, which we will call correspondence elements. The implementation of correspondence elements can occur in different paths. For example, individual movement of each element is possible, while restrictions on such movement are superimposed in the form of its duration over time. Along with individual movement, the correspondence elements can make movements using one or more transport routes of types φ_k, $k \in I^M$.

In the movement process using TR-k, it is possible to switch from one type of TU - φ_s to another type of TU- φ_t, $s \neq t$, , or from one TU to another TU of the same type φ_k, which is carried out using individual movement . Necessity of performing the switch is due to the fact that route links (i^k_ξ, i^k_η) do not exist between all pairs of points i and j on the TN. In addition, for different links, certain modes of transport can have different priorities.

Finding the shortest path. The implementation of movements by correspondence elements, as a rule, is carried out by several competing (alternative) paths of movement. Most preferable in this case is the shortest path and near-to-shortest ones. Movement paths consist of a sequence of alternating individual and route links, and the movement path shall begin and end with individual link. We introduce a more precise concept of the path of movement between the corresponding points on the transport network.

Path h^p_{kij} is k-th path of movement between points i and j on RN of order p, if a number of route links (i^l_ξ, i^l_η) on the given path is equal to p, and a number of switches is less on one. Here l is a route number: $l \in I^M$. Number of route links in the route (number of switches) can be limited by $p = \overline{1,S}$, S is the given allowable number of route links$(i^l_\xi,\ i^l_\eta)$in path h^p_{kij}. As deviation from the shortest path can be considered only in the allowable limits, then the number of paths between point s i *and* j; $i \neq j$; $i,j \in Z$, is limited as well: $k = \overline{1,N}$.

Path h^p_{kij} between points i *and* $j$on RN can be described in the following way:

$$h^p_{kij} = \{i,j;\ t(h^p_{kij});\ p;\ k_1, \xi_1, \eta_1;\ k_2, \xi_2, \eta_2; \dots\ k_l, \xi_l, \eta_l,\ \dots,\ k_p, \xi_p, \eta_p\} \tag{4}$$

where $t(h^p_{kij})$ is time spent to move on path h^p_{kij}; p is path order; k_l is TR index, implementing l-throute link$(\xi_l,\ \eta_l)$; ξ_l и η_l are initial and final points in route link$(\xi_l,\ \eta_l)$, $l = \overline{1,p}$.

Further, in terms of abbreviating, instead ofh^p_{kij} we shall write h_{kij}.

Usually, in order to determine sensible and reasonable limitations on a number of competing paths h_{kij} between points i *and* j on TN, the parties use the specified behavior strategy. Such a strategy is set by probability function of priority $p(h_{kij})$of movement paths h_{kij}, connecting corresponding points i and j:

$$p(h_{kij}) = f(\nu^k_1,\ \nu^k_2, \dots, \nu^k_l), \tag{5}$$

where ν^k_ρ is a value of ρ-th parameter, which specifies the path h_{kij}; $\rho = \overline{1,l}$, l is a number of parameters.

Probability function of priority (5) allows to make distribution of correspondencesλ_{ij} in paths h_{kij} proportionally to probabilities:

$$x(h_{kij}) = \lambda_{ij} \cdot p(h_{kij}), \tag{6}$$

where $x(h_{kij})$is a flow in path h_{kij}, $k = \overline{1,N}$, $N$is a number of paths between points I and j.

As distribution of correspondences λ_{ij} may be fulfilled only in paths h_{kij}, connecting points I and j, so the following equalities are fulfilled:

$$\sum_{h_{kij} \in H_{ij}} p(h_{kij}) = 1, \tag{7}$$

$$\sum_{h_{kij} \in H_{ij}} x(h_{kij}) = \lambda_{ij}, \tag{8}$$

where H_{ij} is aset of all paths, connecting points i *and* j.

Let's consider the proposed approach for the formation of a formalized description of the transport system with respect to the UPT system.

The transport network for the UPT is a street-road network (SRN) other city which is represented by the SRN-S (Z, W) graph, where Z is a finite non-empty set of districts (zones) of the city $i \in Z$, $|Z| = n$; $W$is a set of arcs (often it is possible to consider edges) (i, j) $\in$ W, the weight (length) of which corresponds to the distance between i and j zones of the city on the SRN graph; | $|W| = d$, $i, j = \overline{1,n}$; n, d - are, respectively, the number of zones and edges on the graph of the SRN of S (Z, W).

The route network of the UPT consists of a number of routes. Routes in the city are of different types. The type of the route is determined, as a rule, by the type of transport units carrying out the transportation on the route.

Each k-th route of the UPT is described by the sequence of passing the zones i^k_ξ, $\xi = \overline{1,n_k}$ in the forward direction before returning to the parking point $M^k = \{i^k_1, i^k_2, \dots, i^k_{n_k}\}$. Note that $i^k_1 = i^k_{n_k}$, that is, the initial and final zones in the description of route k coincide, since the path of any route M^k is a route round trip. Route numbers form a set: $k \in I^M$, m is a number of routes in the UPT network.

Each route of urban passenger transport $k \in I^M$ is characterized by a certain set of parameters. These include, first of all, general parameters: this is a number of transport units carrying out transportation on the route - a_k; the time interval between transport units - τ_k;; the length of the route - L_k (sometimes, in the case of routes with a complex configuration, it is more convenient to consider the length of the round trip). The second group is formed by the parameters characterizing the means of transport that carry out the transportation on the route - this is primarily the type of transport - φ_k; the operational speed of transport on the route -V^k (except for the operational one, more detailed parameters of the speed of movement can be considered); capacity of transport units - $\aleph_k$.

The transport interlink of districts of the city is characterized by potential flows of inhabitants moving between zones i and j of the city, such flows are usually called potential correspondence. The intensity of correspondence is given in the form of a matrix:

$\Lambda = || \lambda_{ij} ||$ where λ_{ij} is the intensity of movement from zone i to zone j, $i, j = \overline{1,n}$, $i, j \in Z$.

The intensity of passenger flows on the transport route is also specified in the form of matrices. Elements of these matrices are real passenger traffic on each of the UPT routes - k: $X^k = || x^k_{\xi\eta} ||$, where $x^k_{\xi\eta}$ is the intensity of the passenger traffic from zone i to zone j on the route k; ξ, $\eta = \overline{1,n_k}$; n_k is a number of zones in the trajectory of the route $k \in I^M$

Elements of correspondence in the city are separate movements. Passengers when traveling between areas of the city use walking (individual) movement, as well as movement using the routes of the UPT.

Route links on the UPT network will be denoted by $h^M_{k\xi\eta}=(i^k_\xi, i^k_\eta)$, $k \in I^M$, $\xi\neq\eta$; $\xi,\eta = \overline{1,n_k}$. If we consider the route links of all routes cumulatively, then they form a multigraph of non-circular route links $M(Z_1, W_1)$, where Z_1 is a set of city zones $i \in Z_1$, $|Z_1| = n_1$, $Z_1 \subseteq Z$; W_1 is a set of direct route links $(i^k_\xi, i^k_\eta) \in W_1$. The arcs of graph $M(Z_1, W_1)$ can be associated with weight values that express certain characteristics of the corresponding route link. The main characteristic is the time of travel. The total number of route links in the city will be denoted by $|W_1| = d_1$.

Since in general the routes cannot pass through all zones of the city $i \in Z$, then $n_1 \leq n$. The power of the set of direct links, in sufficiently developed networks of UPTs, considerably exceeds the power of the set of links on the SRN, that is, $d1 >> d$.

The passenger during his movement also makes possible switches, which is due to the lack of direct links between all pairs of zones i and j of the city on the SRN.

Basic parameters. Considering the movements picture in general, it can be said that the movement of passengers between the zones of the city is carried out along competing routes (4) in accordance with a specific strategy of behavior (5). It is possible to single out a number of basic parameters of the paths of movement, that affect son choosing them by the population during their travels. This is, first of all, the time of movement, which includes time for walking and departure from the beginning and end of the movement; time for switch, time of travelling on the TU, time of waiting for maintenance. The second most important parameter of the path of movement is a number of switches that has to be made during the movement. In addition to these two parameters, the size of the payment for travel, the comfort of the vehicle that carries out transportation, security, etc. are included in the characteristics of the travel path.

The procedure for the free distribution of correspondence λ_{ij} to the RNUPT is performed in accordance with (6).

Let us consider in more detail the representation of the elements which form the travel paths h_{kij}, $k=\overline{1,N}$, $N$is a number of paths between the zones of the city i, j. Let's give the definition of the basic elements of the movement path. The pedestrian link between zones i and j on the TN reflects the possibility of the corresponding type of movement, when the correspondence elements λ_{ij} are implemented. The main parameter of such a link is the time of movement. We will denote the pedestrian (individual) travel routes by

$$h^И_{ij} = \{i, j; t^И_{ij}\};\ i, j = \overline{1,n},\ i, j \in Z, \tag{9}$$

where $t^И_{ij}$is the time of individual movement from point $i$to point j; $t^И_{ij} = \infty$, if between points i and j there is no possibility of walking in the TN. One can limit the possibility of walking movement, first of all, by allowable distance between the corresponding zones.

Between the zones I and j on the TN, in the general case, there can be several individual links, so we will consider the set of individual links:

$$H^И_{ij}:\ h^И_{ij} \in H^И_{ij}. \tag{10}$$

The individual relationship $h^И_{ii} = \{i, i; t^И_{ii}\}$defines the possibilities of get the route stops in zone i; $t^И_{ii}$is the average time get the TN stop in zone i, $i=\overline{1,n}$, $i \in Z$.

The route link $h^{M}_{k\xi\eta} = (i^{k}_{\xi},\ i^{k}_{\eta})$corresponds to a trip made by correspondence elements on a certain transport route - k without a switch, we will denote it by

$$h^{M}_{k\xi\eta} = \{k,\ \xi,\ \eta;\ t^{M}_{k\xi\eta}\}, \tag{11}$$

whereξ *and* η are the numbers of the initial and final zones of the k-th route; $t^{M}_{k\xi\eta}$is the travel time on link$(\xi, \eta)_k$. Let's denote by H^{M}_{ij} the set of all route links between zones *I* and *j* with use of all possible routes: $h^{M}_{k\xi\eta} \in H^{M}_{ij}$.

The route-individual link between the zones of the city *I* and *j* is a link that is a combination of some route link $h^{M}_{k\xi\eta}$, $i = i^{k}_{\xi}$and then an individual link $h^{И}_{\eta j}$:

$$h^{MИ}_{k\xi j} = \{\xi,\ j;\ t^{MИ}_{k\xi j};\ k,\ \xi,\ \eta\}, \tag{12}$$

where $t^{MИ}_{kij}$ is time of movement on the route-individual link $h^{MИ}_{kij}$; ξ andη are initial and final indices of the points of direct route link$(\xi,\ \eta)_k$; k is a number of the TR that performs the link $(\xi,\ \eta)_k$. Walking movement is implemented between pointsη and *j*, information about the possibility of such movement is given by the element $h^{И}_{\eta j}$is an individual link between pointsη and *j*.

Let's denote by $H^{MИ}_{ij}$ the set of all route-individual links connecting the zones *I* and *j* of the city in TN, $i,j=\overline{1,n}$, $i \neq j;\ i,j \in Z$.

In general, between the zones *i* and *j* of the city there are several individual, route and route-individual links.

We denote the set of individual links between all pairs of points *i* and *j* by

$$H^{И} = \bigcup_{i,j} H^{И}_{ij} \tag{13}$$

a set of route (direct) links between all pairs of points $\xi$and $\eta$by

$$H^{M} = \bigcup_{\xi\eta} H^{M}_{\xi\eta} \tag{14}$$

a set of route-individual links between all pairs of points ξ and *j* by

$$H^{MИ} = \bigcup_{\xi,j} H^{MИ}_{\xi j} \tag{15}$$

Let's denote the set of admissible movement paths between zones *i* and *j* with a given number of switches (of order p) by H^{p}_{ij} . To determine such paths, we introduce a special operation for gluing together the paths -⊗ [10]. The non-transfer paths between zones i and j - H^{1}_{ij} (p = 1) will be determined by gluing together individual and route-individual links:

$$H^{1}_{ij} = H^{И}_{i\xi} \otimes H^{MИ}_{\xi j} \ . \tag{16}$$

In case if we form the movement paths of *s*-th order between all pairs of vertices $i,\xi \in Z$ - $\mathrm{H}^{s}_{i\xi}$, we can obtain movement paths of orders$s+1$by scheme:

$$H^{s+1}_{ij} = H^{s}_{i\xi} \otimes H^{MИ}_{\xi j} \ . \tag{17}$$

Thus, relations (16) and (17) define a recurrent scheme for obtaining movement paths between vertices $i,j \in Z$of any order. For real transport systems, the permissible travel routes are of limited order. For example, for the UPT system, it is practically possible to consider paths of traveling above the 4th order (having three switches). We denote the higher order of the considered paths q^{M}, then the whole set of movement paths connecting the vertices *i* and *j* is defined as

$$H_{ij} = H_{ij}^{\Pi} \bigcup \left[\bigcup_{S=1}^{q^M} H_{ij}^{S} \right], \tag{18}$$

but the whole set of paths is

$$H = \bigcup_{i,j} H_{ij} \tag{19}$$

We now define the gluing operation by ⊗, used to form the movement paths in the city. To generate a database of transportation routes, the street-road network graph and information on the routes of the UPT are used. At the preparatory stage, the graphs of pedestrian and route-pedestrian links in the city are formed.

Database of transportation routes. For the further formation of the database, a multigraph of route-pedestrian links is used, the arcs of which are "glued together" with pedestrian paths, and then with paths of the first and any other order. Thus, the arcs of the movement paths multigraph are formed between all pairs of vertices corresponding to the transport zones of the city. The set of these arcs can be significantly limited, taking into account the actual behavior of the population of the city when traveling. First of all, the path of movement can be considered permissible if the number of switches performed on it is not greater than a certain maximum value of q^M. In developed urban transport systems, q^M can be taken as equal to two for cities up to a million inhabitants and equal to three for large cities. It is a quite justified requirement that the travel time t_{kij} shall be different from the minimum possible travel time between zones *I* and *j* - $t^M_{ij}$by not more than α times: $t_{kij} \leq \alpha t^M_{ij}$. It is also necessary that the routes sequence used in the travel route is elementary (the UPT route numbers should not be repeated). The path shall also be elementary, however, pedestrian transitions within one zone are permissible. This means that the following equalities are possible:

$$i = \xi_1, \quad \eta_l = \xi_{l+1}, l = \overline{1, q-1}, \quad \eta_q = j$$

Obviously, for the sequence $i, \xi_1, \eta_1, ..., \xi_q, \eta_q, j$, we can formulate a number of other natural limitations that describe the processes of movement in a particular city and which are in fact constants of self-organization of the transport system of the city[4].

In order to obtain a set of arcs $\{h_{ij}^{q+1}\}$, aggregates are taken and route-pedestrian links from the collection are attached to them. The gluing operation ⊗ can be defined as follows:

$$(i,\xi;t_s;q;\ k_1,...,k_q;\ \xi_1,\eta_1,...,\xi_q,\eta_q) \otimes (\xi,j;\ t_v;\ k_v;\eta_v) =$$
$$= \begin{cases} (i,j;\ t_s + t_v;\ q+1;\ k_1,...,k_q,k_v;\ \xi_1,\eta_1,...,\xi_q,\eta_q,\xi,\eta_v),\ if \\ q+1 \leq q^M \ \wedge\ t_s + t_v \leq \alpha t_{ij}^M \ \wedge\ (k_1,...,k_q,k_v) - elementary\ \ sequence \\ \wedge\ (i,\xi_1,\eta_1,...,\xi_q,\eta_q,\xi,\eta_v,j) - elementary\ \ path. \\ \varnothing - \ otherwise\ . \end{cases} \tag{20}$$

The final stage in the formation of a database of movementpaths is the unification of data on the paths contained in arrays of pedestrian, non-stop and other paths: $H_{ij}^{n}, H_{ij}^{1}, H_{ij}^{2}, H_{ij}^{3}, H_{ij}^{4}$, and the creation of an array $H = \{H_{ij}\}$, records of which describe the arcs of the multigraph of links between the transport zones of the city.

Conclusion. The proposed method for describing the transportation process in a routed transport system, whose main element is formation of the database of transportation routes in the city, it makes possible to divide the modeling of the processes of servicing passenger traffic on routes. This, along with the developed queuing models on the route, allows to obtain more detailed characteristics of the movement processes in the transport system in comparison with the known methods.

Acknowledgements. This work carried out in the framework of the project IRN AP05133699 "Research and development of innovative information and telecommunication technologies using modern cyber-technical means for the intellectual transport system of the city".

В. В. Яворский, И. Т. Утепбергенов,
О. Ж. Мамырбаев, А. Т. Ахмедиярова

Ақпараттық және есептеуіш технологиялар институты, Алматы, Қазақстан

КӨЛІКТІК ЖҮЙЕ БАҒЫТТАРЫНДА
ЖОЛАУШЫЛАРДЫ ҮЛЕСТІРУДІ ТАЛДАУ ҮЛГІЛЕРІ

Аннотация. Мақалада қаладағы жолаушылар көлігі маршрутында қызмет көрсету процестерін сипаттауға және жол қозғалысын басқаруды жақсарту туралы шешім қабылдауға қажетті қалалардағы қозғалыс процестерін сипаттауға арналған математикалық модельдер қарастырылады. Қалада жол жүретін барлық рұқсат етілген маршруттардың дерекқорын құру ұсынылады. Қаланың кез-келген аудандарының арасында көптеген бәсекелес маршруттар бар. Ұсынылған жолдарды қалыптастыру алгоритмінің мәні көліктік байланыстардың типтік мультиграфтарын құру болып табылады. Әзірленген тәсіл маршруттар бойынша жолаушыларға қызмет көрсету процестерін модельдеуді ажыратуға мүмкіндік береді. Бұл маршруттағы жаппай қызмет көрсетудің дамыған үлгілерімен қатар, белгілі әдістермен салыстырғанда, көлік жүйесіндегі қозғалыс процестерінің сипаттамаларын алуға мүмкіндік береді.

Түйін сөздер: қалалық жолаушылар көлігі, көлік желісі, маршруттық желі, маршруттық байланыс, қозғалыс бағыттарының мультиграфы, көліктік мәлімет алмасу, маршрутты таңдау стратегиясы.

В. В. Яворский, И. Т. Утепбергенов,
О. Ж. Мамырбаев, А. Т. Ахмедиярова

Институт информационных и вычислительных технологий, Алматы, Казахстан

МОДЕЛИ АНАЛИЗА РАСПРЕДЕЛЕНИЯ ПАССАЖИРСКИХ ТРАФИКОВ
В МАРШРУТНЫХ ТРАНСПОРТНЫХ СИСТЕМАХ

Аннотация. В статье рассматриваются математические модели для описания процессов движения в городах, которые необходимы для описания процессов обслуживания на маршрутном городском пассажирском транспорте и принятия решений по совершенствованию управления движением транспорта. Предлагается создать базу данных всех допустимых путей движения в городе. Есть много конкурирующих маршрутов между любой парой городских районов. Предложен алгоритм формирования путей, суть которого заключается в построении типовых мультиграфов транспортных связей. Разработанный подход позволяет разделить моделирование процессов обслуживания пассажирских перевозок на маршрутах. Это, наряду с разработанными моделями массового обслуживания на маршруте, позволяет получить более детальные характеристики процессов движения в транспортной системе по сравнению с известными способами.

Ключевые слова: городской пассажирский транспорт, транспортная сеть, маршрутная сеть, маршрутная связь, мультиграф путей движения, транспортная переписка, стратегия выбора маршрута.

Information about authors:

Yavorsky V. V., Institute of Information and Computational Technology, Almaty, Kazakhstan; yavorskiy-v-v@mail.ru; https://orcid.org/0000-0001-6508-1954

Utepbergenov I. T., Institute of Information and Computational Technology, Almaty, Kazakhstan; i.utepbergenov@gmail.com; https://orcid.org/0000-0003-0758-4849

Mamyrbayev O. Zh., Institute of Information and Computational Technology, Almaty, Kazakhstan; morkenj@mail.ru; https://orcid.org/0000-0001-8318-3794

Akhmediyarova A. T., Institute of Information and Computational Technology, Almaty, Kazakhstan; aat.78@mail.ru; https://orcid.org/0000-0003-4439-7313

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