A Combinatorial Problem of Generating a Network of Routes of Public Transport in Cities

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Abstract: The formulation and options for solving the problem of constructing a route network of public transport based on information about the current transport demand are proposed. The ways of formalization of the transport demand model based on the correspondence matrix are described. The statement and the first two iterations of solving a part of the combinatorial-optimization problem of forming a route network of public transport, which consists in the initial construction of a set of routes in the field of transport demand, are given. A scheme for choosing the second and third stops on the generated routes is given. The results of the second iteration of building a route network in the field of transport demand for the city of Berezniki in the Perm Region (Russia) are presented. An assessment is given of the generalized characteristics of the found routes and the entire network as a whole.

1 INTRODUCTION

With an increase in the level of motorization of the population, and, accordingly, a significant increase in the costs of the urban community for moving using individual transport, the tasks of ensuring transport accessibility of the population using public transport come to the fore. The pattern of settlement of most cities in the world, established in the middle of the last century, has undergone significant changes in recent decades.

The structure of transport mobility of the population is changing radically due to changes in the structure of employment of the population. The global processes taking place in the economy, affecting the employment of the able-bodied part of the population and the subsequent change in the structure of the settlement of people, require a serious revision of the operation of public transport, especially in large urban agglomerations.

The basis for the effective functioning of public transport is determined, first of all, by the configuration of its route network, as well as the types of facilities operating on individual routes and individual urban areas. The evolutionary process of optimizing and adjusting the route network, created decades ago, is not always able to meet the transport needs of the population that are currently required for public transport. In certain cases, when solving the problem of constructing an optimal route network, it is advisable to distance oneself from the configurations of familiar routes, modes and types of transport that have existed in a particular city for many decades.

It seems interesting to solve the problem of building a fundamentally new route network, based only on knowledge of the current transport demand in a particular city.

The object of the research is the system of public transport. The subject of the study is the route network of public transport.

2 MATERIALS AND METHODS

The initial data for solving the problem is a set of elements that determine the structure and characteristics of the transport demand that has developed in the territory, everything that is called the transport demand model in the process of transport modeling. At the same time, it should be noted that, in contrast to the creation of a transport demand

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model based on determining the study area to transport areas, in the case of setting and solving the combinatorial optimization problem of forming an efficient city transport system, the initial data, and, accordingly, the transport demand model should be detailed not to the transport area, but to each stopping point of public transport on the road network, as places of generation and consumption of passenger flows (Yakimov, 2017; Desaulniers, 2017; Buslaev, 2013; Buslaev, 2015).

In this regard, a set of initial data is presented as a set of several matrices: a correspondence matrix, a cost matrix for overhead lines, a cost matrix for a real network, an adjacency matrix, and a matrix of paired stops.

In addition, it is required to use geoinformation tools that allow linking data on transport demand to existing objects of the transport offer, namely, to the road network existing in the city (Zhao, 2003; Baaj, 1995; Murray, 2003).

It is possible to carry out the primary generation of the route network of public transport throughout the city in several iterations, with different accuracy, detail, and a set of initial data. The choice of the initial stop on the route at all iterations is determined on the basis of a set of data that represents an assessment of the volume of passenger traffic at the stop, as well as infrastructural opportunities for organizing the final stopping point, such as settling and turning areas, additional infrastructure that ensures a long stay of the bus at the stopping point and crew replacement. The more passenger traffic at a stop, as well as the more developed the technological infrastructure for servicing rolling stock, the more likely it is that this stop will be chosen as the initial stop of the route.

The first iteration is building routes based on distances between stops. The initial data are the coordinates of the stops and the distances between them. The assumption is that the routes are built without taking into account the road network, along straight sections between stops, taking into account the distances between stops (Figure 1).

The second iteration is the construction of routes based on the cost matrix and the correspondence matrix.

The initial data are the coordinates of the stops, the matrix of correspondences. The assumption is that the routes are built without taking into account the road network, along straight sections between stops, taking into account the correspondence matrix between stops.

The choice of the initial stop on the route at all iterations is determined on the basis of an estimate of the passenger flow at the stops, i.e. the greater the passenger flow at the stop, the more likely it is that this stop will be selected. At the same time, routes should start at stops with the appropriate infrastructure, that is, settling and turning areas. Route end: reaching the average route length in the existing route network. Repeat stops in routes: starting stops of routes are controlled, the starting stop of a route cannot be the start of another route. Duplication of routes is possible no more than two stops in a row.

The algorithm is based on the choice of subsequent stops of the route in such a way as to minimize the costs of traveling to the end points of transport correspondence routes starting from previous stops. Let's consider the route construction algorithm.

The first stop is selected from the list of stops that are the final stops in the routes in the existing route network. Next, from the entire list of stops, the stop with the maximum volume of correspondence between the first and second stops is selected.

Stops for which the distance to the previous stop on the route is less than the distance to the last selected stop on the route become inactive. This is necessary so that the route does not change direction to the opposite and is more straightforward. The totality of such stops form an inactive zone.

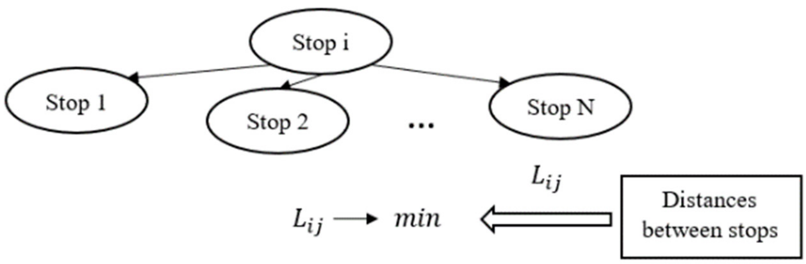

Figure 1: Sequence of stops when building routes based on distances.

$$l_{31} < l_{32} \rightarrow \text{stop 3 is inactive}$$
$$l_{61} < l_{62} \rightarrow \text{stop 6 is inactive} \qquad (1)$$

where l_{ij} - cost matrix value between stop *i* and stop *j*, meters; *i, j* – stop number.

After adding each stopping point, the correspondence matrix is adjusted. Those accumulated correspondences that had an added stopping point as a target are subtracted from the correspondence matrix (zeroed).

For those accumulated correspondences for which the targets are further away, the rows of the correspondence matrix are added to the row of the added stopping point, the original rows of the correspondence matrix are reset to zero. Thus, when building a route, the entrance and exit of passengers on a real flight is simulated.

$$x_{12} := 0 \qquad (2)$$

where x_{12} - correspondence matrix values between stop 1 and stop 2, people/day.

$$x_{2i} := x_{2i} + x_{1i}, i = \{4,5,7,8,9,10,11,12,13,14,15$$
$$x_{1i} := 0, i = \{4,5,7,8,9,10,11,12,13,14,15\} \qquad (3)$$

where x_{ij} - correspondence matrix values between stop *i* and stop *j*, people/day.

We also find the next stop within a radius of 500m. We count the plots for all suitable stops and select the stop with the maximum plot value. When a new stop is selected, the inactive zone also increases. Adding subsequent stops is done in a similar way (Figure 2).

$$l_{42} < l_{47} \rightarrow \text{stop 4 is inactive}$$
$$l_{52} < l_{57} \rightarrow \text{stop 5 is inactive} \qquad (4)$$

where l_{ij} - cost matrix value between stop *i* and stop *j*, meters.

$$x_{27} := 0 \qquad (5)$$

where x_{27} - correspondence matrix values between stop 2 and stop 7, people/day.

$$x_{7i} := x_{7i} + x_{2i}, i = \{8,9,10,11,12,13,14,15\}$$
$$x_{2i} := 0, i = \{8,9,10,11,12,13,14,15\} \qquad (6)$$

where x_{ij} - correspondence matrix values between stop *i* and stop *j*, people/day.

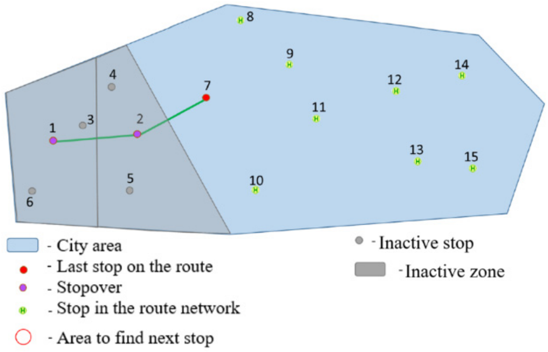

Figure 2: Choice of the fourth stop of the route.

With such a route construction, a case may arise when the route passes in the vicinity of a stop, but bypasses it. In this case, this stop is added to the route:

– The current section of the route is divided by n equidistant points (Figure 3).

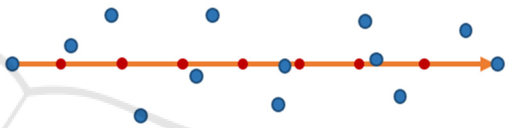

Figure 3: Example of splitting a route section to add intermediate stops.

– Let's find the intermediate stops lying in the vicinity of the route section at a distance r:

$$r = L \cdot 0,25 \qquad (7)$$

where *L* - the length of the segment, meters.

To do this, circles with radius r are built from the points of the route section. Belonging to the circle is checked by comparing the distance from the stop to the center of the circle (Figure 4).

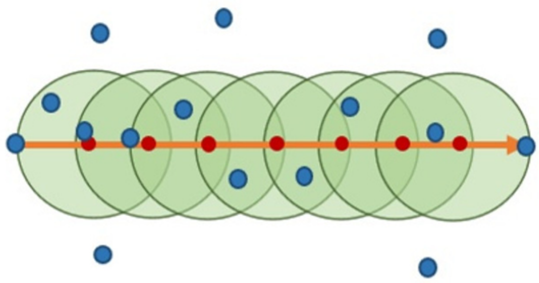

Figure 4: Search for intermediate stops in the vicinity of a route segment.

Stops that are inside the circle are added to the route. If there are several stops in one circle, they are added in ascending order of distance to the initial stop of the considered section of the route.

3 RESULTS AND DISCUSSION

The city of Berezniki (Perm Region, Russia) was chosen as one of the cities for testing scientific research.

A typical set of initial data was formed, consisting of:

- List of stopping points on the territory of Berezniki (224 stops);
- Coordinates of stopping points on the territory of Berezniki;
- List of starting and ending stopping points of the existing network of municipal regular transportation routes operating in the territory of Berezniki;
- Correspondence matrix linked to stopping points on the territory of Berezniki;
- Cost matrix linked to stopping points on the territory of Berezniki;
- Matrix of connectivity of stopping points on the territory of Berezniki.

On the basis of the above algorithms, on the basis of the criterion of minimizing the time costs of passengers, algorithms for generating a primary population (set) of regular transportation routes were developed and implemented.

Based on the generated standard set of initial data, using the developed algorithms, the first iterations of generating the primary population (set) of regular transportation routes for the city of Berezniki were made. As a result of the operation of the algorithm for the automated construction of regular transportation routes, the route network of the city of Berezniki was formed (Figure 5).

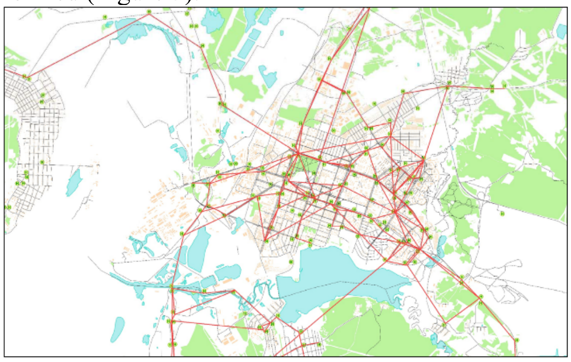

Figure 5: The route network of the city of Berezniki, formed as a result of the algorithm for the automated construction of regular transportation routes.

The main indicators of the generated routes turned out to be good (Figure 6).

The length of all routes was 263,27 km. The total passenger traffic on all routes amounted to 83 053 passengers per day. A rather small number of uncarried passengers remained, the transport demand for which is tied to stops through which no route passed - only 1 person per day. In this set of generated routes, a rather large transfer coefficient was obtained - 1,9 (passengers quite actively use transfers from one route to another route). Also, the transport work on

Route number	Starting stop number of the route	The volume of departures from the initial stopping point, passengers / day	Route length, km	Passenger flow of the route, pass/day	Remaining untransported at the initial stop, passengers / day	Transport work on air lines, pass*km	Transport work on a real network pass*km
11	128810	551	9,3	1677	0,034	21 632,6	46 288,7
12	14167	480	4,6	1112	0	2 264,1	5 398,1
13	19339	413	7,8	[illegible]	[illegible]	15 298,7	28 444,4
14	4445	278	14,8	[illegible]	[illegible]	11 360,1	27 766,1
15	52941	189	7,9	[illegible]	[illegible]	293,1	4 064,4
16	18024	141	8,7	[illegible]	[illegible]	18 895,1	40 723,6
17	1476	114	9,4	[illegible]	[illegible]	1 578,2	4 919,7
18	1400	104	3,5	[illegible]	[illegible]	[illegible]	16 017,3
19	158962	102	14,3	[illegible]	[illegible]	[illegible]	124 421,8
20	128794	80	2,9	[illegible]	[illegible]	[illegible]	6 297,6
21	5125	68	19,7	2	0	[illegible]	29 274,0
22	235	57	8,9	4510	0	[illegible]	3 463,6
23	158966	29	19,6	4885	0	[illegible]	37 834,2
24	158975	7	19,2	3193	0	157,8	544,0
25	8526	0	11,8	5607	0	28,3	228,8
26	128798	0	15,45	5658	0	19 302,2	39 560,9
27	11081	0	13,4	3455	0	5 008,0	7 625,6
28	33651	0	9,8	908	0	73,0	342,7
	Total	**21004**	**263,27**	**83053**	**1,684**	**270 419,5**	**619 354,2**
		The value of each cell is the sum of the corresponding row of the correspondence matrix		Each cell - the number of passengers who traveled along the routes when building	Uncarried passengers go to stops through which, as a result of building routes, no route passes		

Transport work performed by route 16. When calculating the length of hauls, the route is calculated by air lines, passenger * km

Transport work performed by route 12. When calculating the length of hauls, the route was calculated using a real network, pass * km

Figure 6: Fragment of the table with the main indicators of the generated routes.

overhead lines and the transport work of routes, which are calculated on a real network, were determined. Transport work on overhead lines amounted to 270 419,5 pass*km, on the real network – 619 354,2 pass*km. The indicators of the generated route network for stopping points are also good. The average volume of departures from the stopping point is 197 passengers per day. The number of routes passing through the stop was 1,52 routes.

4 CONCLUSIONS

The above algorithm for searching for a primary set of routes in the field of transport demand represents the solution of the first part of the combinatorial optimization problem of constructing an efficient route network of a large city. The presented algorithm implements only the first two iterations of the search for the optimal set of routes. The resulting set of routes for the city of Berezniki (Perm Region, Russia) may be the necessary information for further refinement and optimization with the choice of the objective function when solving the problem of mathematical programming. Such an objective function can be a combination of time criteria for the implementation of transport correspondence for all passengers of the route network, as well as the efficiency of one unit of rolling stock. At subsequent stages, it is possible to use a wide range of optimization algorithms for solving problems of mathematical programming, as well as algorithms for changing the initial set of the parent route, called the general word "genetic algorithms", the main task of which is to modify the existing set by applying genetic operators (copying, crossing, mutation) (Benn, 1995, Bunte, 2006; Guan, 2003; Zhao, 2004; Zhao, 2006).

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