Simulation of an integrated public transport system by the example of a compact city

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Abstract. The effectiveness of the transport network depends on the coherence of all message options. Suburban rail transportation and route bus service are travel options often used in medium and large cities in developed and developing countries. Integrating these two travel options reduces total travel time. The study will consider the application of the operational integration model of suburban trains and urban public transport. The model includes two submodels: routing and planning. In the routing submodels, public transport bus routes are generated that pass through the railway station. The planning sub-model will allow developing suburban train schedules with the optimal coordination of timetables for urban bus routes. As an example, the railway station Angarsk and the urban route network are considered. Bus transportation is coordinated with the existing railway timetable for the arrival of local trains. Genetic algorithms are robust optimization techniques and can be used in planning submodels. The result of the study is to determine the routes that require changes in the timetable, taking into account the arriving trains.

1. Introduction

Most cities in developed and developing countries face problems of inefficient operation of the route network for lack of coordination between public transport and objects of aggression. The operation of the transport terminal is rarely taken into account in the operation of the urban network, and each infrastructure object is considered separately. They compete with each other instead of harmoniously interacting. Unhealthy competition leads to a duplication of transport services, an increase in travel time due to the long waiting time for a vehicle at a transfer hub. The efficiency of the transport system can be achieved through overall coordination of the transportation process. Rarely, optimization is carried out on several types of transport at the same time, more often studies are devoted to a specific area [1–4].

Earlier, attempts were made to route and plan the coordinated work of different types of transport in a complex transport system using analytical models. It was assumed that the street-road network is a rectangular area located parallel to one railway line, but its actual configuration was not always taken into account. As an example, let us consider the city of Angarsk, referring to the agglomeration of the Irkutsk region.

2. Experimental studies

The data was collected at the Angarsk passenger railway station, which is a transport terminal where passengers make a transfer to other mode of transport (private, public or taxi). The station is located on the Trans-Siberian Railway, belonging to the East-Siberian railway. All suburban and passenger trains
stop there. Neighboring stations are in the west – Kitoy, in the east – Sukhovskaya and Yuzhnaya. That is, there are 4 stations on the line in question. A railway station is a terminal where passengers change mode of transport [5]. At this station a sufficient number of urban public transports pass in different directions, routes no. 3, 7, 8, 9, 27, 28.

Movement surveys were conducted during the morning rush hours, that is, from 7 to 9 am. In the course of road traffic surveys, it was found that the maximum passengers number was from 7 to 8 am, and after 9 am, the suburban traffic decreases. During the survey, the number of passengers leaving the station was counted manually, and was 1304 passengers. The lack of coordination between the bus and train service is observed in the morning and evening rush hours.

The accountants took a selective survey of passengers (328 people), and it was about 25 % of the total. The questionnaire included the following questions: destination, mode of transport and travel time. The passengers who used individual transport or taxis for further travel were asked if they are ready to refuse in favor of public transport if the bus schedule is coordinated with the railway service. A group of passengers who do not need any mode of transport was identified, as the enterprises providing jobs are located within walking distance from the station (less than 5 minutes).

Table 1 shows the potential demand by direction.

| №  | Destination                  | 7.00–8.00 | 8.00–9.00 | 7.00–9.00 |
|----|------------------------------|-----------|-----------|-----------|
| 1  | Central market               | 13        | 23        | 36        |
| 2  | Shop “Zarya”                 | 17        | 18        | 35        |
| 3  | Shop “Magistral”             | 10        | 15        | 25        |
| 4  | Technical College            | 8         | 16        | 24        |
| 5  | Communication center         | 20        | 22        | 42        |
| 6  | 4th village                  | 21        | 7         | 28        |
| 7  | Gorgaz                       | 10        | 14        | 24        |
| 8  | Firm “Cars”                  | 5         | 12        | 17        |
| 9  | Medical Sanitary Unit-28     | 9         | 14        | 23        |
| 10 | 102nd quarter                | 8         | 21        | 23        |
| 11 | Orgstroyproekt               | 4         | 7         | 29        |
| 12 | Micrdistrict “Northern”      | 14        | 24        | 11        |
| 13 | AEMZ                         | 9         | 14        | 38        |

The percentage of passengers who agree to use public transport in the case of optimization route schedule is taken into account in Table 1. It was found 13 destinations, which respondents called more often. Thus, these nodes were identified as priority destinations that are important for the development of the route network.

To optimize the operation of the route network, matrices of potential demand (obtained by interviewing passengers arriving at the station) and consumption of time are required. The following data were used to calculate the matrix of time-consuming: distances to destinations obtained by measuring the route network, an average speed of 15 km/h was set by the time method. The matrices (dimension $14 \times 14$) include the station Angarsk and the 13 identified destinations listed in Table 1.

The aim of the study is to develop a model for the operational integration of public transport timetables and railway communications [6–8].

3. Theoretical basis
The general methodology can be presented as follows.

1. Information gathering: data requirements are established; specification of the existing route and transport networks [9] (determination of the length, duration of movement and characteristics of the rolling stock involved in the transportation process); road traffic survey (assessment of the existing distribution of passenger traffic by mode of transport and potential demand by direction).
2. Routing, which bases its work on the data obtained in the previous stage and includes a realistic assessment of the road network and a matrix of demand distribution. Further, it is possible to use the route network generation algorithm for the purpose of designing.

3. Planning, which includes minimizing the distance of the route network (operating costs) and waiting time, coordinating the work of urban public transport (passenger costs) subject to constraints: load factor, transfer time and established demand.

Routing is performed using a heuristic approach to optimize the network by including additional nodes. When tested on a real network, it provides the best route, taking into account the location of various destinations (nodes), restrictions on communications in the station area and design without further interchanges. The routing algorithm is based on the demand matrix, as it is a fundamental aspect in network design. In addition, the waiting time for rolling stock should be taken into account, since its increase leads to a decrease in the quality of passenger service. To minimize the waiting time, it is proposed to optimize the bus schedule [10].

The proposed heuristic algorithm consists of two stages.
1. Determine the shortest distance from the station to the main destinations.
2. Calculate the deviations of the shortest distances by inserting other nodes into the chain.

A balance must be maintained when satisfying demand by including nodes and increasing the length of the route. The optimal route network is governed by the criterion of maximum demand and the minimum travel time - the distance should not increase more than 1.5 times, therefore, an upper limit is set. In our study, it is 15 km (1 hour) and is determined based on the location of the points of destination specified in the sample.

The limitation of the upper limit of the length is established in the case when the route has a large length. The inclusion of additional nodes in the route network with a small length allows increasing the efficiency of the transport infrastructure [11].

The route network optimization algorithm includes the following operations:
1. Determination of potential demand for stations and preparation of the matrix with node numbers.
2. Compilation of a distance matrix based on the existing route network and determining connectivity of nodes. Convert distance matrix to travel time matrix using average travel speed.
3. Identification of nodes with high demand in order to develop the shortest linking network.
4. Deleting an item from a chain of nodes that is included in the shortest connecting network. The remaining nodes are arranged in descending order relative to demand.
5. Including on the nodes continues until all nodes are set in motion.
6. End nodes are determined using the time minimization criterion.
7. After generation, all routes are checked for inclusion in the network twice [12, 13].

Let us consider a strategy for selecting and inserting nodes into a route. When designing optimal paths, narrow requirements should be established. The strategy of including a node with any priorities in the shortest route consists of 5 stages.

1. We determined by the best possible shortest path for any node to be included in the route. The best way (shortest) path to a concrete node can be determined on the basis of time saving relationships. This ratio is calculated for all shortest routes. The node is inserted into the shortest path that gives the largest value of this ratio.
2. After choosing the shortest path, the best way is indicated.
3. Sometimes, due to the presence of a node or group of nodes at the end of the shortest path, the route is extended. All possible solutions are analyzed and the variant that gives minimal additional delay to passengers is chosen. If this corresponds to their geographical location, to avoid additional delays for sites of higher demand.
4. Due to the presence of many nodes in the immediate vicinity of short routes, return to the same point can not be avoided. A repetitive path can increase the length of the route. To solve this problem – we combine several consecutive nodes and, thus, new routes are being developed.
5. All routes are checked with a stopover at the same node. There is a search for the best option of travel time.
Figure 1 shows the process of adding a node to different routes. The directions with demand above average: \( j_1, j_2 \) and \( j_3 \). The shortest paths starting from station are “\( i \)”: \((i, j_1), (i, j_2)\) and \((i, j_3)\). Knot to insert is “\( k_1 \)”. Restrictions from the railway station are “\( i \)” to “\( j \)”: \( D_{ij} \).

Restrictions from the railway station “\( i \)” to “\( k_1 \)”:\( D_{ik} \). The nodes on the shortest paths \((i, j_1), (i, j_2)\) and \((i, j_3)\) that are closest to “\( k_1 \)”:\( j_1^\sim, j_2^\sim \) and \( j_3^\sim \) (the shortest paths that are not connected with \( k_1 \) are omitted). Travel time along the shortest route\((i, j): t_m (i, j)\). Thus, if \( k_1 \) is inserted into the route\((i, j_1)\), the travel time will increase from “\( i \)” to “\( j_1 \)” due to the deviation of the shortest path. \( D_{ik} \) passengers must travel a distance \((j_1^\sim k_1)\) to reach \( k_1 \). Therefore, the travel time from “\( i \)” to “\( j_1 \)” through the node \( k_1 \) due to the insertion: \( t (i, j_1) \) increases:\( t (i, j_1) - t_m (i, j_1) \).

Delay of passengers is \( D_{ij} \{ t (i, j_1) - t_m (i, j_1) \} \). An approach time for passengers is from \( j_1^\sim \) to \( k_1 \): \( t (j_1^\sim k_1) \). Savings in passenger-minutes thanks to the approach: \( D_{ik} t (j_1^\sim k_1) \).

Next, the coefficients are calculated for all routes, and the route for which this ratio is maximal is considered. In this case, the choice is given to the option with the maximum demand with less travel time.

The process of optimal planning of the route schedule is rather complicated, attempts were repeatedly made to solve this problem using computer simulation, considering only the transfer time, a combination of optimization models and mathematical procedures. Developing optimal traffic schedules is problematic even for a small transportation network. The task of coordinating a schedule consists of transferring at least between two modes of transport in order to reduce the cost of operating the rolling stock. Restrictions on load factors and transfer time are used to solve transport problems, but the use of a large number of variables and constraints in the objective function create difficulties in solving the problem by traditional optimization methods.

Therefore, genetic algorithms are a reliable optimization method and are suitable for the tasks used in this study. The main difference between the genetic algorithm and the alternative: coding of variables, and stochastic operators instead of deterministic ones are directly used [14–21]. All these functions make the search reliable, allowing one to apply it to a wide range of problems in coordinating traffic schedules.

Steps to define a coordinated schedule:
1. Determination of passenger traffic on the developed routes.
2. Decision by applying the objective function and constraints.
3. Use of a genetic algorithm to determine the optimal traffic interval.

The work of public transport should be aimed at meeting the demand of passengers, and minimizing the cost of carriers. For passengers, the level of availability of services, the frequency of rolling stock delivery intervals, and the reduction of waiting times are also important. Carriers are interested in
reducing operating costs, minimizing the amount of rolling stock produced on the line during the off-peak period, and increasing profits or achieving break-even levels. Thus, the target function includes the time consuming of passengers, minimizing the time of transfer from the railway to the urban passenger transport. The cost of time consuming is summarized with the operating costs of the rolling stock. Restrictions are connected with minimum and maximum load factors, transfer time and unmet demand [14]. Mathematically, the objective function and constraints can be represented as follows:

\[ C_1 \left\{ \sum_j \sum_u \sum_s \text{pass}_s \left( \text{bus}_s - \text{train} \right) \delta^u_j \right\} + C_2 \left\{ \sum_j f_j T_j \right\} \]  

Limitations:

\[ (\text{bus}_j - \text{train}) \leq T_{\text{max}} \]  
\[ (\text{bus}_j - \text{train}) \geq T_{\text{min}} \]  
\[ \frac{Q_{\text{max}}}{N_j \times \text{CAP}} \leq L_{\text{max}} \]  
\[ \frac{Q_{\text{max}}}{N_j \times \text{CAP}} \geq L_{\text{min}} \]  
\[ \sum_j d_{\text{unsat}} = 0 \]

where \( j \) – number of routes of railway transport;  
\( i \) – number of public transport routes;  
\( C_1 \) – cost of time, rub.;  
\( C_2 \) – cost of operating public transport, rub.;  
\( \text{pass}_j \) – number of passengers arriving at the station;  
\( \text{bus}_j \) – number of rolling stock departing from a stopping point on the \( j \)-th route;  
\( \text{train} \) – number of trains arriving at the station;  
\( \delta^u_j \) – coefficient taking into account the possibility of transportation of passengers (depending on the variant, it becomes equal to 0 or 1);  
\( f_j \) – bus departure frequency on \( j \) route (number of trips per hour);  
\( l_j \) – route \( j \) length, km;  
\( T_{\text{max}} \) – maximum allowable transfer time between arriving at the station and departing urban passenger transport;  
\( T_{\text{min}} \) – minimum allowable transfer time between arriving at the station and departing urban passenger transport;  
\( Q_{\text{max}} \) – number of passengers at the station on the \( j \)-th route for a certain period of time;  
\( N_j \) – number of bus trips during the entire considered period of time;  
\( \text{CAP} \) – bus capacity;  
\( L_{\text{max}} \) – maximum load factor (assumed to be 1.2);  
\( L_{\text{min}} \) – minimum load factor (assumed to be 1);  
\( d_{\text{unsat}} \) – unsatisfied demand.

The objective function includes travel time between the railway station and vehicle operating costs proportional to the distance of movement. The constants \( C_1 \) and \( C_2 \) are used to convert the objective function into a currency. The first two limitations are related to the transfer time. Limitation (2) – the transfer time between the arrival of trains and the departure buses on one route must be less than the maximum value. Limitation (3) – transfer time should be minimal. During the survey, the minimum transfer time was 5 minutes. Limitation (4) and (5) ensure that the load factor lies within the maximum and minimum values, and the best level of service and availability are determined in the case of the minimum number of passengers. The maximum load factor is the ratio of the maximum and normal capacity of buses. The last limit is the maximum satisfaction of demand. The choice of constraints is linked to the goals of optimizing operation of public transport in a particular area, since none of the above restrictions is mandatory. These restrictions are set according to their relative importance and magnitude of demand.
4. Research results
In the process of modeling the real transport network, a genetic algorithm of the objective function and limitations (1)–(6) were used.

The load factors were taken in the range between 1 (minimum load factor) and 1.2 (maximum load factor), the percentage of unmet demand was set at the lower threshold, the waiting time – from 0 to 5 minutes. Demand satisfaction and traffic on different routes are two dominant factors, important for both passengers and carriers. As a result of the survey, it was revealed that the waiting time of transport may take in the range of up to 10 minutes, but when establishing such a high value, it is necessary to take into account the loss of a part of potential passengers for other transportation options (for example, a taxi).

Table 2 shows the schedule for the arrival of suburban trains at the station “Angarsk”.

Table 2. Schedule of arrival of suburban trains to Angarsk station

| №  | Itinerary                              | Arrival time |
|----|----------------------------------------|--------------|
| 1  | Malta → Bolshoy Lug                    | 05:57        |
| 2  | Cheremkhovo → Irkutsk Pass.            | 06:21        |
| 3  | Cheremkhovo → Irkutsk Pass.            | 07:10        |
| 4  | Irkutsk Pass. → Polovina               | 07:12        |
| 5  | Cheremkhovo → Irkutsk Sorting          | 08:17        |
| 6  | Irkutsk Sorting → Cheremkhovo          | 08:38        |
| 7  | Bolshoy Lug → Cheremkhovo              | 09:32        |
| 8  | Polovina → Bolshoy Lug                 | 10:10        |
| 9  | Zima → Irkutsk Pass.                  | 12:07        |
| 10 | Zima → Irkutsk Pass.                  | 13:40        |

Analyzing the time of arrival, it can be noted that in the period from 6 to 8 am, the suburban trains arrive every 30 minutes.

Table 3 shows the beginning of the movement and the interval of the public transport from the train station, which is the final stop.

Table 3. Schedule of public transport from the stopping point “Railway Station”

| №   | Driving route                              | Departure time | Interval of movement, min. |
|-----|--------------------------------------------|----------------|---------------------------|
| 1   | Route № 3 Railway Station – Shop “Magistral” | 06:02          | 8–9                       |
| 2   | Route № 7 Railway Station – 4th village    | 06:06          | 6                         |
| 3   | Route № 8 Railway Station – 12th microdistrict | 05:36      | 5                         |
| 4   | Route № 9 Railway Station – Shop “Miрия”  | 06:23          | 7                         |
| 5   | Route № 27 Railway Station – 211st quarter | 06:00          | 10–11                     |
| 6   | Route № 28 Railway Station – AEMZ          | 06:00          | 18                        |

When testing the model, the following results were identified: on routes no. 3, 7, 8, the timetable was compiled in such a way that allows passengers arriving at the station to wait for urban passenger transport less than 5 minutes (fig. 1). For routes no. 9, 27, 28 waiting time ranges from 10 to 20 minutes, which adversely affects the comfort of transportation.

As a result of the simulation, several solutions to the problem were obtained – reducing the traffic interval or optimizing the route schedule so that passengers arriving by train did not wait city transport for more than 5 minutes.
5. Conclusion
In this study, a model of operational integration of two transportation options was tested: urban public transport (bus) and rail service for one station. Simulation can be carried out at other stations after determining the potential demand for transportation. It will provide an integrated public transport system, in which the railway communication will be considered as the main option of movement, and buses – accompanying. This option will allow the regional transport system to work smoothly, to use routes of optimal length, in order to meet the needs of passengers.

Genetic algorithms are very effective in solving objective, non-linear tasks of coordinating train diagram. The model, tested in the study, allows developing a real transport network, which is important, both for the qualitative satisfaction of passenger demand and for optimizing the haulage contractor. It takes into account such restrictions as: service level (maximum load factor), economy of work (minimum load factor), minimum and maximum transfer times, availability of public transport for all passengers (limit on unmet demand) and maintaining a reasonable balance between load factor and demand satisfaction within an acceptable waiting time. Thus, the model is able to provide satisfactory results (routes and agreed schedules) for passengers and carriers. Therefore, it can be stated that this approach is an important contribution to the modeling of passenger traffic.

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