Development of a methodology for optimizing the urban route in the metropolitan area

A N Novikov¹, S V Eremin¹ and A G Shevtsova²

¹Orel State University named after I.S. Turgenev, 95, Komsomolskaya St., Orel, 302026, Russia
²Belgorod State Technological University named after V.G. Shukhov, 46, Kostyukova St., Belgorod, 308012, Russia

E-mail: shevtsova-anastasiya@mail.ru

Abstract. One of the urgent tasks is to determine the composition of the bus fleet to serve each route. At the same time, it is necessary to be able to vary the type and number of buses that have different technical characteristics, in this regard, in the framework of the study, the issues of optimizing bus movement modes on city routes were considered. Basically, on the city route network, buses stop at all stopping points. However, quite often there is a situation when there is a sufficiently large unevenness of passenger traffic at various stopping points. In this regard, design schemes for analyzing the effectiveness of combined and shortened routes are proposed. Key relationships include empirical estimates of passenger flows. The parameters of the models are the volume of the bus fleet, the irregular production of buses, the probability of a denied boarding at individual stopping points.

1. Introduction

As part of the quality of service, the question arises of assessments of denied boarding and passenger waiting times [1–3]. Basically, the type of bus is determined by the presence of this type in the transport park of the city. In solving this problem, it is necessary to solve the problems of accounting for the stochastic nature of the route network and obtaining statistics on passenger flows.

The choice of type and number of buses is determined by many factors, including:

- economic (associated with the availability of material and technical base for their storage, repair, etc.);
- social (associated with the transport mobility of the population, given the assessment of the loss of time waiting for all passengers and the conditions of transportation comfort, etc.);
- technical (condition of the roadway and related structures, UDS throughput, permissible speeds, etc.);
- operational (climatic conditions, etc.);
- regulatory (environmental requirements, road safety requirements, maximum permissible bus occupancy, etc.).

The listed factors are the initial premises for solving optimization problems, and some of the listed factors can act as criteria, and some as limitations.

As a result of the occurrence of these factors and the presentation of special requirements for them, city routes are often not effective. To solve this problem, especially when developing and reorganizing routes in urban agglomerations, it is necessary to develop methods for optimizing urban routes.
2. Analysis of existing methods for optimizing urban routes according to the criterion of the park

In the general case, the task of choosing a bus depot for the maintenance of the route is multi-criteria, in which the main criteria, namely, the waiting time for passengers and the costs of the enterprise for the maintenance of the bus fleet, come into a compromise. It is necessary to minimize both the total waiting time \( T_{\text{exp}} \) of all passengers on the selected route and the expenses of the enterprise (taking into account the profit) \( R_{\text{ent}} \):

\[
T_{\text{exp}} \rightarrow \min \quad R_{\text{ent}} \rightarrow \min
\]

One of the approaches to solving such a problem is the formation of a generalized additive criterion [4, 5]:

\[
k_{\text{opt}} = \alpha T_{\text{exp}} + \alpha R_{\text{ent}}
\]

The values of the coefficients can be obtained from some social standards; however, the approach to the formation of their values does not have a formal setting. It is necessary to understand the cost losses in expectation in terms of the general economic task of improving the standard of living. Moreover, the multicriteria problem reduces to scalar optimization and when solving it there are no conceptual problems, only technical difficulties may arise (if a sufficiently adequate simulation model is used):

\[
k_{\text{opt}} \rightarrow \min
\]

Based on the analysis of existing methods, it was found that they propose to jointly use two models, namely, simulation and analytical, based on the use of relations (1) - (3) to form a generalized parameter that reduces to scalar optimization [6, 7]:

\[
F = \sum_{i=1}^{l} \{60t_i \cdot C(\sum_{j=1}^{m} T_{\text{exp}ji}S_{ji})\} + R_{\text{ent}} \rightarrow \min\]

where \( S_{ji} \) – determines the volume of passenger traffic on the corresponding interval of the route; \( T_{\text{exp}ji} \) – the average waiting time; \( m \) – the total number of stops, regardless of direction.

However, this model involves the simultaneous use of buses of only one capacity. In the general case, it is necessary to optimize the fleet of vehicles, taking into account the possibility of using buses of various capacities (from a certain number of passenger capacities set in advance for other reasons).

As a result of the analysis of existing optimization methods, it was found that they are based on two criteria – the waiting time and costs of the enterprise without performing an analysis of the capacity of roads, which is an extremely important task when optimizing city routes, especially in urban areas. In this regard, the next stage of the study is the development of methods for optimizing the urban route, taking into account previously unused data.

3. Development of a methodology for optimizing the urban route

For the main objective of the study - the optimization of the urban route, taking into account an expanded set of criteria, it is proposed to use a heuristic algorithm that involves less severe restrictions:

1. There is a set of capacities \( W_i \), \( i = 1..m \), which may have buses.
2. The minimum number of \( A_{\text{min}} \) buses can be set either by attracting the maximum capacity to the route, or by an acceptable interval.
3. The maximum number of \( A_{\text{max}} \) buses can be set based on the available:
   - the number of drivers in the enterprises;
   - the number of buses of the selected capacity;
   - the number of buses with a minimum capacity of \( W_{\text{min}} \);  
   - the smallest capacity of the streets and stopping points of the route \( \Omega_{\text{min}} \);
4. The quality of service is determined by the total number of passenger seats in all the bus in a given time interval, and it should be no less than the average traffic volume in the most stressful section for the same time interval [8].

This problem is an integer programming problem and can be formally presented as follows:
\{W_i\}, i = 1 \ldots m, W_i \in [W_{min}, W_{max}], \{A_i\}, i = 1 \ldots m, A_i \in [A_{min}, A_{max}]

\sum_{i=1}^{m} A_i W_i = W^{exp} \geq max(\lambda_i T^{exp}); \sum_{i=1}^{m} A_i \leq \Omega_{min}

where \(A_i\) is the number of buses with \(W_i\) capacity indicator \(W^{exp}\) - the total number of passenger seats in all buses.

The optimization function is a general function, and does not have continuity properties. Constraints in solving the optimization problem can lead to ambiguous solutions of the tuple \(\{A_i\}, i = 1 \ldots m\). As a solution to the problem, methods of integer multi-criteria search are used using search optimization procedures in MatLab.

The procedure contains the following steps:

1. For all \(W_i\), subject to restrictions, we find \(A_i\).
2. The problem of bandwidth limitation is separately solved \(\Omega_{min}\).
3. \(\forall \omega_j\), the permissible \(A_{min}\) is calculated and the value of the objective function \(F (A_{min})\) is determined.
4. Increase the value of \(A_{min}\) by 1.
5. We calculate the objective function \(F (A_{min} + 1)\).
6. If \(F (A_{min} + 1) \leq F (A_{min})\), a return is made to step 4 for the iterative repetition of the algorithm to find the minimum of the functional. Otherwise, go to step 7.
7. We consider 1 bus with a given capacity of \(\omega_j\) and go to step 4.
8. Subsequent steps 4–7 are repeated until the optimal tuple sets \(A = \{A_i\} i = 1 \ldots m\) are determined.

One of the variants of the algorithm for solving a similar problem [9-10] involves algorithmization in MatLab and gives an initial approximation of the distribution problem.

One option for the development of the method is to include the possibility at different time intervals (peak hours, day, late evening, etc.) to choose the composition of the buses in the necessary, but different quantity and different capacity.

As a result of the analysis of the algorithm, it was found that an increase in capacity reduces the probability of failure. At the same time, both the capacity and the number of buses directly proportionally affect the reduced costs of the enterprise. It is also shown that a small increase in the costs of the enterprise can give significant savings in reduced costs [11–13].

When considering a selected route, the following options are possible: a certain reduction in the costs of the enterprise with a simultaneous increase in passenger costs for waiting; both company expenses and waiting times are reduced. Reduction of expenses of the enterprise does not lead to a change in the waiting time; the reduction in waiting time does not increase the costs of the enterprise [14–15].

4. Experiment
To perform the experiment and evaluate the effectiveness of the algorithm proposed for development, the team of authors performed an analysis of two routes, namely No. 85 (fig. 1), which is the first in popularity, and No. 22, as the least loaded. Route number 85 passes through the historical center of the city of Krasnoyarsk, connecting it from west to east, passing through the October bridge.

Figure 1. Scheme of route No. 85
For the selected set of routes, the main characteristics of passenger flows are calculated, in particular, the unevenness coefficients for the hours of the day and others. So, it is clear that the structure of unevenness can be significantly different (Fig. 2).

![Figure 2. The structure of intraday unevenness of passenger flow](image)

As a result of the analysis of certain routes and testing of the developed methodology, it was found that the most significant characteristic of the random process is the autocovariance function, which is defined as $R(n)=\mathbb{M}\xi_{n+k}\xi_k$, and as its estimate in the analysis of the time series $(x_1, \ldots, x_N)$ of length $N$, the value is used:

$$\hat{R}_n(n, x) = \frac{1}{N-n} \sum_{i=0}^{N-n-1} x_{n+i} x_k (7)$$

This estimate is unbiased, i.e. on various routes, schedules of series of traffic volumes were constructed, including route No. 85 (Fig. 3)

![Figure 3. Time series of passenger flow of route No. 85](image)

The graph clearly shows the cyclical nature of the passenger flow, which is also superimposed on a linear trend, which makes the process unsteady in two respects. As part of the tasks of assessing the seasonality of passenger traffic, spectral analysis estimates were used, which assumed an assessment of the periodogram which is an estimate of spectral density.

For passenger flows of the chosen route, autocorrelation functions and periodogram were constructed (Fig. 4).

To generate interconnected passenger flows (with cross-correlations similar to those obtained by statistical analysis, we propose a preliminary linear transformation of the elements of time series of passenger flows with one time index. So, if the random vector has the characteristics $\mathbb{M}\xi=m_\xi$ and $D\xi=||\text{cov}(\xi, \xi)||$, then for the random vector $\eta=L\xi+C$, the mathematical expectation vector of the vector $\eta$ will be $\mathbb{M}\eta=Ln_\xi+C$, and the dispersion matrix will be $\eta - D\eta = L D \xi L^T D$. Predetermined dispersion matrix of the resulting vector pre solve the system of nonlinear equations to find the matrix $L$. As a result, the proposed set of time series generating models of passenger covers the requirements for establishing an adequate simulation model parametrization streams obtained based on statistical analysis.
a) function

Figure 4. Characteristics of passenger traffic on route No. 85

Thus, the introduction of progressive forms of organization of bus movement on the route contributes to the improvement of public transport services. At the same time, there is often a redistribution of passengers between routes (in particular, the attraction of new passengers to high-speed and express lines), as a result of which the parameters of passenger flows $Q$, $Q_j$, $R_j$ change. These changes should be considered when planning and organizing transportation.

As a result of the experiment on the existing city route, it was found that the application of the proposed methodology allows to increase the efficiency of the selection of the necessary composition, taking into account the redistribution of passenger flow in the city metropolitan area.

5. Conclusion

Based on the analysis of the developed algorithm, it is shown in the work that an increase in capacity reduces the probability of failure. At the same time, both the capacity and the number of buses directly proportionally affect the reduced costs of the enterprise. It is also shown that a small increase in the costs of the enterprise can give significant savings in reduced costs.

When considering a certain selected route, the following options are possible: a certain reduction in costs with a simultaneous increase in passenger costs for waiting; both company expenses and waiting times are reduced. Cost reduction does not change the waiting time; reduced time waiting does not increase costs.

As a result of the study, the problem of optimizing the composition of the fleet for servicing routes was solved, which is formally presented in the form of a multi-criteria choice between the cost of maintaining the fleet and the time spent by passengers on travel. To solve the problem, a joint use of the analytical and simulation models is proposed. A solution to the problem of distributing buses along the routes of the city’s transport network is proposed.

References

[1] Pattnaik S B, Mohan S and Tom V M 1998 Urban bus transit route network design using genetic algorithmo J. of Transport. Engineer. 124(4) 368–75
[2] Toner J 2001 Organization of a tender for buses in London Principles and Practice. Report at the 7th Int. Conf. on Competition and Property (Molde, Norway: Public Transport)
[3] Tahmassebpour M 2016 Performance evaluation and scalability of IP-based and heuristic-based job scheduling algorithm backup systems Indian J. Sci. Technol. 9 17–24
[4] Bennett D, Xiao N and Armstrong M 2003 Using genetic algorithms to create multicriteria class intervals for choropleth maps Annals of the Associat. of American Geograph. 93(3) 595–623
[5] Nepal K and Park D 2003 Routing algorithms for transportation systems and service improvement projects in urban transportation networks Tech. rep., Department of Civil Engineering, Tokyo Institute of Technology (Tokyo, Japan: Ookayama, Meguroku)
[6] Mesjasz-Lech A 2014 Development of public transport in the city – a challenge for urban logistics in terms of sustainable development Forum Sci. Econo. 2(4) 63–75
[7] Paulley N 2006 The demand for public transport: The effects of fares, quality of service, income and car ownership Transport Policy 13(4) 295–306
[8] Mirotin L., Ignatenko A and Marunich V 2011 Logistic look at passenger traffic Logistics 4 31–3
[9] Regirer S A and Shapovalov D S 2003 Filling passengers with space in public transport Automat. and Remote Control 8 111–21
[10] Semenova O S 2009 Mathematical modeling in problems of optimizing the movement of urban passenger transport, taking into account the imposition of route schemes (Novokuznetsk)
[11] Novikov A N, Kulev A V and Peshekhonov M V 2013 Comparison of location systems and their application in intelligent transport systems World of transport and technolog. machines 2(41) 109–13
[12] Korchagin V A, Novikov A N, Lyapin S A and Rizaeva Yu N 2016 Complex self-developing transport systems World of transport and technolog. machines 2(53) 110–6
[13] Kulev A V, Novikov A N, Kulev M V, and Kuleva N S 2016 Increasing the efficiency of urban passenger transport functioning In the coll. Inform. Technol. and Innovat. in Transport mater. of the 2nd Int. Sci. and Pract. Conf. ed. by A N Novikov pp 378–82
[14] Zhankaziev S V, Novikov A N, Vorobyev A I, Kulev A V and Morozov D Y 2017 Efficiency of operation and functioning of the system of an indirect transport flow regulation and control Int. J. of Applied Engineer. 12(13) 3645–52
[15] Fernandez R 2010 Modelling public transport stops by microscopic simulation Transport. Rese. Part C: Emerging Technolog. 18(6) 856–68