The task of determining the optimal structure of the rolling stock fleet of urban passenger transport

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Abstract. The task of determining the optimal structure of the capacity of the rolling stock fleet of urban public passenger transport is considered. In the article, on the basis of the balance between the intensity of passenger flows and the carrying capacity of the rolling stock fleet of public transport. This balance is determined on the basis of the analysis of technical and economic parameters of large, medium and small capacity buses. The break-even intervals relationship on the route of buses of different classes is considered. The article formulates a mathematical model for calculating the optimal structure of the fleet taking into account the interaction of routes; provides an algorithm for solving the problem, based on the principle of directed enumeration of options. The results of applying the proposed method on the example of passenger transport in the city of Krasnoyarsk are presented.

1. Introduction
One of the most important tasks is to ensure a balance between the intensity of passenger flows and the carrying capacity of the public transport rolling stock [1]. The carrying capacity of the fleet is determined by two parameters: capacity and intensity of movement along the routes. The structure of the vehicle fleet capacity is determined by transport demand [2, 3], the mutual influence of routes [4] and economic factors [5, 6, 7], as well as the capacity of the road network [8, 9].

In the process of solving the problem of determining the optimal structure of the rolling stock fleet we will conduct a comparative analysis of the technical and economic parameters of buses in order to determine the areas of their most effective use.

2. Description of the task
We formulate the problem of optimizing the rolling stock of urban regular routes as follows.

Routes are organized on the transport network, and there are sections along which several routes have been laid (overlapping, crossing routes). The presence of competing routes leads to the fact that some passenger correspondence can be served in several ways. As a result, the number of passengers transported along a specific route depends on the traffic intensity: due to the redistribution of passenger correspondence, it increases with decreasing interval of vehicles and vice versa decreases with increasing interval. At the same time, a decrease in the interval of movement, despite a slight increase in the transported passengers along the route, leads to a decrease in the number of passengers per vehicle. The amount of income from transportation (which is determined by the current passenger tariff and the norm of budget subsidies) determines the level of financial resources that can be spent on the transport process.
The calculation of the rolling stock fleet structure determines for each route the capacity class and the number of rolling stock with the established limitations (standards) of technical and operational indicators. When calculating the structure of the fleet, the following parameters vary: the use of capacity (filling) of vehicles and the interval of movement along the routes.

The solution to this problem will be considered on the example of buses. To assess the use of rolling stock of different capacities, we will analyze the technical and economic parameters of buses (figure 1).

We divide the classes of buses by capacity as follows: large - more than 90 passengers (sitting and standing); middle - 60-70 passengers; small - about 40 passengers.

In figure 1, the parameters of high-capacity buses are taken as 1. When using buses of lower capacity, the cost of one kilometer is reduced, but this decrease is not proportional to the decrease in capacity. As a result, the cost of one seat-kilometer of small capacity buses significantly exceeds this indicator of large capacity buses. Thus, with the same degree of capacity utilization, transportation by large-class buses has a lower cost compared to the rolling stock of the middle and small classes.

![Figure 1. Technical and economic parameters of the classes of buses: Cost - the cost of transportation, rubles / km; Cap - the capacity of the bus, pass; Cost / cap - the cost of a passenger seat, rubles / place-km.](image)

The ratio of breakeven points of buses of large, small and middle classes is illustrated in figure 2. Specific revenues from transportation are determined by mileage along the route, i.e. inversely proportional to the traffic interval (in this case, we do not take into account the redistribution of passengers among routes depending on the traffic intervals). In the given example, the applied tariff level determines the break-even interval for large buses of 8.8 minutes, the middle class - 7.5 minutes, the small class - 6.7 minutes. With an increase in the passenger fare (or the standard for budget subsidies), the break-even interval will decrease, with a decrease, it will increase.

The coefficient of capacity utilization at break-even intervals according to the classes of buses is 0.26, 0.35 and 0.52, respectively: cost-effective operation is possible with values of this indicator exceeding the given values. It means that, according to the criterion of transportation comfort, a large-capacity bus is more preferable, although its use causes a slight increase in the intervals of movement along the route in comparison with other capacity classes. With a break-even interval, the coefficient of capacity utilization of large-class buses is significantly lower compared to the small and middle classes.

It should be noted that the break-even interval of movement of a large-class bus is only 2 minutes different from the interval of a small-class bus. An increase in the interval of movement along the route by 2 minutes makes only one additional minute of the average passenger waiting time. So we can conclude that the use of rolling stock of a larger capacity class, all things being equal, is more efficient.
3. Problem statement

Thus, it is required to calculate the program for passenger transportation along the route network of urban passenger transport (transport offer), which meets the objective function of the minimum dynamic capacity utilization factor:

\[ \bar{\gamma} = \frac{\sum P_k}{\sum P_k} \Rightarrow \min \]  

(1)

under the following restrictions:

utilization ratio of the the rolling stock capacity

\[ \gamma_{\min} \leq \gamma_k \leq \gamma_{\max}; k = 1, n; \]  

(2)

route network bandwidth

\[ \sum_k a_i \leq a_{ij}^{\max}; i \in I_k, j \subset I_k; \]  

(3)

route traffic intensity

\[ a_{\min} \leq a_k \leq a_{\max}; k = 1, n; \]  

(4)

cost-effectiveness of the transportation program

\[ q_k^{km} \geq Q_m^{km}, k = 1, n, \]  

(5)

where: \( \bar{\gamma} \) - the average coefficient of dynamic use of the capacity of the transportation program; 
\( P_k \) - transport work of the transportation program along the \( k \) route; 
\( P'_k \) - nominal transport work along the \( k \) route (transport work with full use of rolling stock capacity); 
\( a_{\min}, a_{\max} \) - restrictions on the intensity of movement of rolling stock along routes; 
\( a_k \) - traffic intensity on the \( k \) route; 
\( q_k^{km} \) - the number of passengers per one km of the rolling stock along the \( k \) route; 
\( Q_m^{km} \) - the minimum number of passengers per km of the \( m \) class bus (used on the \( k \) route), ensuring cost-effective operation; 
\( \gamma_k \) - coefficient of dynamic capacity utilization on the \( k \) route;
\( \gamma_{\min}, \gamma_{\max} \) - restrictions on the coefficient of capacity utilization of vehicles;

\( I_k \) - a set of stopping points of the \( k \) route;

\( a_{ij}^{\max} \) - bandwidth limitations \( ij \) of the route network section.

4. The solution algorithm

To solve the problem, it is necessary to obtain the optimal values of these indicators in the sense of the objective function (1), by varying the class of vehicle capacity and the interval of their movement along the routes.

The following algorithm for solving the problem is proposed, based on the principle of directed enumeration of options

1. The first permissible transportation program (transport offer) is formed, i.e. for each route:
   - the minimum value of the intensity of movement \( a_{\min} \) is set;
   - the class of the bus with the highest capacity is set;
   - the number of passengers and passenger traffic is calculated.

2. The calculation of technical and operational indicators of the transportation program is carried out.

3. In accordance with the obtained value of the number of passengers per one kilometer for each route, the rolling stock class is established on the condition:

\[
q_k^{km} \geq Q_c^{km}
\]  
(6)

where: \( q_k^{km} \) - the number of passengers per kilometer along the \( k \) route;

\( Q_c^{km} \) - the minimum number of passengers per kilometer along the route necessary for the cost-effective operation of a vehicle of the \( c \) class.

As a result of the preparatory stage of the calculation for some routes, a low indicator of the number of passengers per kilometer along the route can be obtained, which does not allow the use of any of the available classes of vehicles. These routes (with low passenger flow) are subject to additional budget subsidies. For them, the class of vehicle is established in agreement with the customer (the organization that regulates the corresponding segment of the passenger transportation market). At the next stage, the restrictions on the minimum number of passengers per kilometer will not be taken into account for such routes.

At the calculation stage, a step-by-step improvement of the transportation program is carried out. This stage being implemented until it is possible to form a new version of the transportation program that meets the established restrictions (2) - (5).

A new version of the transportation program is calculated according to the following algorithm:

1. The route with the highest capacity utilization factor (\( k \) route) is selected in the last program. If the capacity utilization factor of the selected route is less than the established limit \( \gamma_{\max} \), the calculation process is considered completed.

2. The traffic along the \( k \) route increases by step \( \Delta a \). The calculation of technical and operational indicators of the transportation program is carried out.

An increase in traffic along the \( k \) route due to the redistribution of passenger flows on routes interacting with the \( k \) may lead to violations of the restrictions on the capacity utilization \( \gamma_{\min} \) or the number of passengers per kilometer. The verification of these restrictions is carried out as follows: routes for which the considered restrictions are not fulfilled are selected. The following options for adjusting the transportation program are possible for these routes:

- decrease in the intensity of movement of the rolling stock by step \( \Delta a \). The possibility of reducing the intensity of movement along the route is limited by \( a_{\min} \);
to fulfill the limitation of the number of passengers per kilometer, the possibility of using rolling stock of another class with a lower value of the required number of passengers per kilometer along the route is checked.

Each of the possible options is checked for admissibility by calculating the technical and operational indicators of the transportation program.

If none of the options meets the specified restrictions (2) - (5), an increase in traffic along the k-th route is unacceptable, expert intervention is required to allow the blocking of interacting routes. A route blocking an increase in traffic intensity along the k route can be transferred to the category of subsidized ones or changed in such a way that an increase in traffic intensity along the k route becomes resolvable.

If, after increasing the traffic along the k route, all restrictions are fulfilled, the current transportation program is accepted.

We proceed to paragraph 1 to formulate the next permissible transportation program.

If for the k route in the current transportation program the restrictions are not fulfilled, the current transportation program is rejected. The transition to paragraph 1 is carried out.

5. Conclusion

The proposed algorithm for solving the problem has been used to calculate the structure of the rolling stock of public transport buses in the city of Krasnoyarsk (figure 3).

The population of Krasnoyarsk is about 1.1 million people. Bus is the main form of public transport - about 900 thousand units of rolling stock operate on routes. Krasnoyarsk also has tram and trolley bus, which currently serve a small number of passengers.

The methodology for calculating the optimal park structure defined in this article is implemented in the computer program. In 2007, it was applied as part of the research work carried out by the Siberian Federal University on the inspection of passenger flows and the design of an integrated public transport route system in Krasnoyarsk. The passenger correspondence matrix for this calculation was obtained by the analytical method based on the results of a continuous survey of passenger flows described in [10].

To calculate the distribution of passenger correspondence among routes, a discrete choice model has been used, in which it is assumed that each of the n alternatives is characterized by utility value $U_k, k = 1, n$. Utility value determines the probability of choosing the appropriate alternative, despite the fact that the selection process itself is stochastic [11].

It can be seen from figure 3 that, as a result of the spontaneous development of public transport in the structure of the Krasnoyarsk bus fleet by 2006 there was a significant imbalance between the models of large and small capacity. The specific gravity of small and large-capacity buses did not correspond to transport demand, which led to poor quality of transport services: small-capacity buses were operated with a significant excess of the permissible number of passengers determined by the manufacturer, especially during periods of peak passenger traffic.
The 2016 fleet structure (figure 3) was obtained from the passenger correspondence calculated as a result of processing fare payment transactions with magnetic cards [12] in accordance with current trends in monitoring the transportation needs of the population Urban computing [13]. Figure 3 shows that the structure of the fleet in 2016 almost corresponds to the structure of 2007. This indicates the efficiency of the methodology for determining the optimal rolling stock fleet of urban passenger public transport considered in the article.

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