Route capacity in designing urban public passenger transportation

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Abstract. Public transport is of crucial importance for urban agglomerations - it is the only transport system that can satisfy the mobility of the population with acceptable quality at minimum cost with less negative impact on the environment. In the tasks of designing public transport, ensuring the capacity of the routes is of particular relevance. This problem does not have an unambiguous solution, and in the majority of research, possible excess of capacity of vehicles, as a rule, are ignored. The paper presents the developed mathematical model, which allows us to calculate the highest intensity passenger flow from the transport demand for a day of transport operation and on this basis to determine the necessary throughput capacity at the established limits of rolling stock capacity. An example of calculation of dependence of intensity and interval of movement on nominal capacity of rolling stock is given, in which an example of the performance of restrictions of the capacity of rolling stock is provided on a section of a route with passenger flow of the greatest capacity.

1 Introduction

For urban agglomerations, public transport is of crucial importance - it is the only transport system that can satisfy the mobility of the population at a minimum cost with less negative impact on the environment. Balanced development of public transport, coordinated with other elements of urban infrastructure, ensuring the conformity of transport demand and supply is the most important modern problem [1]. Formation of effective regional strategies for the development of passenger road transport is an urgent problem [2].

2 Materials and methods

2.1 Problem statement

In the process of designing transportation by public transport, the tasks of forming a transport offer are solved, such as developing a system of routes, establishing the intensity (intervals) of traffic along the routes, designing the structure of the rolling stock fleet, etc. [3, 4]. When solving them, the applied mathematical models, as a rule, take into account the

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goals of passengers, operator and society aimed at the sustainable development of the transport system by minimizing the weighted sum of costs [5]. The operator's costs depend on the number of buses, equipment needed to operate electric buses. Passenger costs are conditioned by waiting and travel time, time spent on transfers. Pollutants emitted by conventional buses are considered as public (environmental) costs.

The optimality criterion is usually weighted average costs of the operator, passenger and society with the application of conversion factors [6]. In some sources [7], when solving the problem of route network design, in addition to traditional criteria (related to the interests of passengers and the operator), it is suggested to take into account the negative impact on the environment (CO₂ emissions).

The approaches used to solve these problems often have significant limitations, they do not necessarily provide optimal solutions, and they rely on a number of unrealistic assumptions and simplifications, such as constant demand, absence of delays in the schedule, fixed fleet size or unlimited capacity of vehicles [3].

In [8], the problem of determining the structure of the rolling stock fleet, i.e., the number and capacity of vehicles, is considered. As an optimality criterion, it is recommended to take the cost of transportation of one passenger in compliance with the maximum permissible traffic interval and guaranteed satisfaction of demand for transportation services, including peak time on the busiest sections of routes.

In the tasks of transportation design, the special relevance is the provision of throughput capacity of routes [9]. This problem does not have an unambiguous solution, in most studies possible exceeding of vehicle capacity is usually ignored [10]. It is usually assumed that all buses are of the same size, although some studies set the task of a heterogeneous fleet of rolling stock of different capacity [9, 11] or modifications (e.g., electric buses) [5].

2.2 Calculation of throughput capacity

Capacity is determined by the capacity and frequency (interval) of rolling stock movement along the route. In accordance with the established limits on the capacity of the rolling stock it is necessary to ensure that the capacity of passenger flow and the capacity of the route correspond to the capacity of all passengers:

\[
\frac{N_l^{\text{max}}}{\lambda_h} k_h \leq q_n,
\]

where: \( N_l^{\text{max}} \) defines hourly passenger flow of the busiest section of the route;
\( \lambda_h \) - intensity of rolling stock traffic along the route at the \( h \)th hour of transport operation;
\( q_n \) – nominal capacity of rolling stock;
\( k_h \) - intra-hour passenger traffic irregularity coefficient.

Passenger flow capacity is the number of passengers traveling per unit of time through a certain cross-section of the transportation network (Larin O. N. «Organization of passenger transportation», 2005)

The total traffic intensity of the routes shall not exceed the capacity of the section of the transportation network with the highest public transport traffic intensity. Passenger capacity at the point of maximum lane utilization of an urban street bus can be determined by multiplying the product of the lane capacity and the permitted passenger load on board an individual bus by the rush hour factor [12].

\( k_h \) is calculated (Efremov I. S. «Theory of urban passenger transportation», 1980):
\[ k_h = \frac{q_{\tau}^{\text{max}}}{q_\tau}, \]  

(2)

here: hour is divided into several intervals \( \tau \);
\( q_{\tau}^{\text{max}} \) - the largest number of passengers in the interval \( \tau \);
\( \bar{q}_\tau \) - average number of passengers in the interval \( \tau \);

In [12], the peak hour factor is used to adjust hourly passenger traffic to account for 15-minute intervals:

\[ PHF = P/(4P_{15}), \]  

(3)

here: \( P \) - rush hour traffic;
\( P_{15} \) - peak period passenger traffic 15 min.

Obviously:

\[ k_h = \frac{1}{PHF}. \]  

(4)

In practice, the coefficient of intra-hour irregularity \( k_h \) ranges from 1.1 to 1.4².
Typical PHF values range from 0.60 to 0.95 [12], i.e., \( k_h \) - from 1.1 to 1.7.

Let us consider the problem of determining the capacity of the route necessary to meet the transportation demand, which is given by the matrix of passenger correspondences in the design of transportation \( D = [d_{ij}] \), where \( d_{ij} \) is the number of passengers to be transported from node \( i \) to node \( j \) of the transportation network. Matrix \( D \) is formed as a certain average model of the population's demand for travel on the transportation network [4].

Some sources recommend applying the matrix of correspondences determined in the period of the highest passenger flow capacity, i.e. in the morning or evening peak period. However, this does not take into account that during peak periods on different routes, passenger correspondences of different periods differ significantly, which should be taken into account when solving transportation design problems [4].

Thus, it is required to determine the passenger flow of the highest intensity from the transportation demand for a day of transport operation. Passenger flows are uneven in time and space (Fig. 1). Unevenness in time is estimated by means of the coefficient of unevenness by hours of the day [13]:

\[ k_t = \frac{N_t^{\text{max}}}{\bar{N}_t}, \]  

(5)

\( N_t^{\text{max}}, \bar{N}_t \) - the largest and average hourly passenger capacity.
The passenger flow capacity can be determined according to the formula:

\[ N = \frac{P}{L_o}, \]  

where: \( P \) – transport operation; 
\( L_o \) – route length.

Accordingly, the average passenger capacity per hour is calculated as follows:

\[ \bar{N}_t = \frac{P}{L_o T_m}, \]  

where: \( T_m \) – route operating time.

The irregularity coefficient by hour of the day can be calculated as follows:

\[ k_t = \frac{P_{t}^{\text{max}}}{\bar{P}_t}, \]  

where: \( P_{t}^{\text{max}}, \bar{P}_t \) – the highest and average hourly transportation work.

The non-uniformity coefficient by the length of turnover along the route:

\[ k_l = \frac{N_{l}^{\text{max}}}{\bar{N}_l}, \]  

where: \( N_{l}^{\text{max}}, \bar{N}_l \) – the largest and average passenger flow capacity by turnover length. 
\( N_{l}^{\text{max}} \), determined for a particular route, corresponds to the average passenger flow capacity by turnover length \( \bar{N}_l \) and the peak hour of the peak period, i.e.:

\[ \bar{N}_t = N_{l}^{\text{max}}. \]  

As a result:

\[ N_{l}^{\text{max}} = \frac{k_l k_t P}{L_o T_m}. \]  

Thus,

\[ q_n \geq \frac{k_l k_t k_p}{L_o T_m \lambda}. \]  

From expression (12) it is possible to calculate the capacity utilization factor per route turnover during the period of the highest capacity of passenger flows:
\[ Y_{max}^n = \frac{\bar{N}_f}{q_n \lambda} = \frac{k_{tP}}{q_n t_w t_m \lambda}. \] (13)

### 2.3 Practical implementation

The transportation performance of existing routes is determined by means of instrumental survey of passenger flows [13]. To create effective solutions to the problems of urban agglomerations (including transportation), technologies based on the collection, integration and analysis of big data (urban computing, Big data, Internet of things) are being intensively developed [14]. The paper [15] presents a methodology for determining the demand for public transportation from validation operations of Electronic Travel Tickets developed within the framework of this trend.

The paper [4] presents a mathematical model for calculating the transportation work based on the results of passenger correspondence distribution over the network when solving the problems of transportation design by urban public transport.

We will consider the calculation of intensity (interval) of rolling stock movement on a real route of public transport of Krasnoyarsk, having the following parameters:

- Transportation volume, pass/day: 23345;
- Transportation work, pass-km/day: 153251;
- Average distance of a passenger trip, km: 6.6;
- Turnover length, km: 61;
- Transportation work time, hrs: 18;
- Coefficient of intra-hour irregularity of passenger flow: 1.33;
- Coefficient of non-uniformity by length of turnover along the route: 1.65;
- Coefficient of unevenness by hours of the day: 1.74.

Fig. 2 shows the dependence of intensity \((\lambda)\) and interval \((I)\) traffic along the route from the nominal capacity of the rolling stock, at which there will be no overcrowding of the vehicle cabin on the section of the route with the passenger flow of the highest capacity. The coefficient of capacity utilization per turnover along the route during the peak passenger flow period calculated in accordance with expression (13) is 0.46.

![Fig. 2. Dependence of intensity \((\lambda)\) and interval \((I)\) of traffic along the route during the period of the highest capacity of passenger flows. Source: compiled by the authors.](image-url)
3 Conclusions

1. In the tasks of transportation design, the task of determining the throughput capacity of the route necessary to meet the transport demand, which in the design of transportation is set by the matrix of passenger correspondence, which is an average model of the population's demand for movement on the transport network for a day of transport operation, is of particular relevance.

2. The performance capacity is determined by the capacity and frequency (interval) of movement of vehicles along the route. To satisfy all passengers within the established limits of rolling stock capacity, it is necessary to ensure the adherence of passenger flow capacity and route capacity.

3. The developed mathematical model allows us to calculate the passenger flow of the highest intensity from the transport demand for a day of transport operation and on this basis to determine the necessary capacity at the established limits of rolling stock capacity.

4. To assess the effectiveness of the mathematical model developed in the paper on the data of public passenger transport of the city of Krasnoyarsk, the dependence of intensity and interval of movement on the nominal capacity of rolling stock is calculated, in which on the section of the route with the passenger flow of the highest capacity is provided by the restrictions of rolling stock capacity. The coefficient of utilization of rolling stock capacity per turnover on this route in the period of peak passenger flow is 0.46. The obtained results correspond to the data of field survey of passenger flows.

References

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