Capacity modelling to optimize the functioning of the transport network

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Abstract. The article discusses the model of reserve capacity, limited by a common factor for all pairs of departure and destination points, which will optimize the operation of the transport network. The concepts of ultimate and practical capacity are also given and their models are described. Establishing the capacity of the road network section will allow us to determine the permissible limits of the restrictions described in the reserve capacity concept. The analysis of the capacity for three different concepts on an abstract transport network was carried out, as a result of which it was revealed that the application of the model in practice helps to obtain information about the spatial distribution of user demand for transport services.

1. Introduction

The capacity of section network streets is an important characteristic taken into account when planning and managing traffic, since it makes it possible to assess whether a transport system has sufficient capacity to overcome traffic congestion. In transport, throughput has traditionally been measured on individual network elements, such as links (railway lines, road sections) and nodes (terminals, intersections). However, these elements do not constitute the throughput of the entire transport network. The maximum network capacity can be determined by the classic maximum flow problem in communication networks, distribution and power systems. But this approach is not applicable to the transport network, since the characteristics taken into account when modelling capacity are different: traffic includes flows of vehicles, pedestrians, cargo; transit delay increases with increasing flow due to overloading; when determining the maximum flow in an overloaded transport network, an alternative route choice must be taken into account; when establishing the maximum throughput, the level of service is not taken into account [1–3]. These characteristics affect the process of optimizing the transport network and are an urgent task.

2. Model of reserve capacity

The traditional solution to the problem of determining reserve capacity is based on the concept of the reserve capacity of the network, given by the authors in the literature [4–6]. This concept provides a route choice with determining the capacity of the transport network, but it is limited by the common largest factor $\mu$ for all pairs of departure points (O) and destination (D), which can be determined in the network without exceeding the bandwidth of the element’s network streets and the established level of service, and applied to the correspondence matrix.

2.1. Model description

The choice of route, taking into account capacity, can be mathematically expressed using a two-level model [5]: the upper level maximizes network bandwidth, taking into account the limitations:
\[
\text{max } \mu, \text{ subject to } v_a(\mu q) \leq C_a, \forall a \in A,
\]
where \( a \) – node of the road network, \( A \) – set of nodes network streets, \( v_a \) – flow to the node \( a \), \( C_a \) – capacity of the node \( a \), the value \( v_a(\mu q) \) is calculated by solving the route selection problem; and the lower level is a combined model of the distribution of the traffic currents:

\[
\text{min } \sum_{a \in A} \int_0^{v_a} t_a(x) dx,
\]
where \( t_a \) – travel time to node \( a \).

Route selection and determining the throughput are considered in the lower level problem, while the upper level problem determines the maximum factor of the O-D matrix taking into account the bandwidth limitations of the street road network section in equation (2). The lower level problem \( \mu \) is a network equilibrium problem that can be solved effectively for a given factor \( \mu \).

In addition, the constraints of conservation and equilibrium of flows and the condition of non-negativeness of the solution found are taken into account. The value \( \mu \) indicates whether the transport network in question has backup bandwidth: if \( \mu > 1 \), then the network has a backup capacity of 100 (\( \mu - 1 \)) percent of the initial value, otherwise, the network is congested.

2.2. Algorithm Reserve Capacity Modeling

The assignment procedure begins with determining the value \( \theta \) of the upper level problem. Based on the standard equilibrium distribution of traffic flows with a given throughput, the speed \( v \) is determined. These flows are transferred to the upper level problem to determine the maximum \( \mu \). Since the upper level problem has only one variable, it can be considered as a parameter in the lower level problem. Then the general two-level problem can be solved as a single-level one, changing the value of \( \mu \) until at least one of the traffic flows exceeds the throughput. The lower level problem is solved by applying the linearization algorithm, which was originally used to solve the quadratic programming problem with linear constraints, it is also known as the Frank-Wolfe method [5].

3. Maximum and practical network capacity

3.1. Model of maximum capacity

The maximum capacity is defined as the maximum value of the traffic flow passing per unit time through a certain section of the network streets with which the system can handle and prevent traffic jams. Unlike the reserve capacity model, this model reduces the value of the common factor \( \mu \), allowing it to be maximized. In addition, the concept of maximum throughput is considered in conjunction with the determination of the level of service [7, 8], in order to obtain a combined model of the distribution of flows on the serviced network. This allows users of the transport network to choose a route to their destination with minimal time and cost of travel.

The model of the maximum network capacity with uneven distribution of the transport stream is also two-level and is presented in the form:

\[
\text{max } \sum_{i \in I} o_i, \text{ subject to } v_a(o) \leq C_a, \forall a \in A,
\]
where \( o_i \) – total number of trips from \( i \)-point;

\[
\text{min } \sum_{a \in A} \int_0^{v_a} t_a(x) dx \text{ + } \frac{1}{\theta} \sum_{i \in I} \sum_{j \in J} q_{ij} \ln(q_{ij} - 1),
\]
where \( q_{ij} \) – total transport demand between a pair of departure and destination points, \( \theta \) – impedance parameter.

The upper-level problem (3) maximizes the value of zonal trips, taking into account the limitations of the road network and throughput, and the lower-level problem (4) is a combined model for distributing flows and determining the route to the destination.

The impedance parameter \( \theta \) for the distribution of transport demand reflects the sensitivity of network users to the duration of movement along the route.
3.2. Model of practical capacity

The network capacity from a practical point of view is defined as the sum of the current and additional demand for traffic, which varies at different time intervals. According to the theory presented in the authors’ work [5], the choice of route and destination based on the cost of the trip and attractiveness indicators is estimated in additional demand, while the current value remains unchanged.

In this model, the upper level problem (5) maximizes the additional number of zonal trips, taking into account the limitations of the network streets and throughput, and the lower level problem (6) is a combined model of flow distribution and determination of the route taking into account the variable costs of the trip:

\[
\max \sum_{i \in I} \tilde{o}_i, \text{subject to } v_a(o) \leq C_a, \forall a \in A, \tag{5}
\]

where \(\tilde{o}_i\) – additional number of trips to \(i\)-point;

\[
\min \sum_{a \in A} \int_0^{v_a} t_a(x) dx + \frac{1}{\theta} \sum_{i \in I} \sum_{j \in J} \tilde{q}_{ij} (\ln \tilde{q}_{ij} - 1) + \sum_{j \in J} q_j(0) + \int_0^{v_a} c_j(y) dy, \tag{6}
\]

where \(\tilde{q}_{ij}\) and \(\bar{q}_{ij}\) – additional and current transport demand between departure and destination points, accordingly, \(c_j\) – cost of destination to \(j\)-point.

3.3. Algorithm for determining maximum and practical capacity

For models of maximum and practical network bandwidth, it is noted that the distribution of traffic flows and the duration of the route between the points of departure and destination are non-differentiable functions related to the number of departures, which makes it difficult to apply standard optimization approaches for solving a two-level problem. In this case, a genetic algorithm is used to determine the network capacity, which operates on a set of solutions, which distinguishes it from stochastic solution search methods.

In this study, the genetic algorithm method was adopted for the final and practical problems of network capacity, because it works on a set of solutions, and not on one solution, as in most stochastic search methods. An approach to the implementation of this algorithm for determining network throughput is that upper-level variable values are encoded through successive iterations. During each iteration, these values are estimated based on the suitability measure, which is calculated by solving a lower-level problem [9–11]. Thus, by repeatedly changing the totality of individual decisions, the best of a number of possible ones is selected.

4. Experimental studies

As an example, consider a transport network consisting of nodes and straight sections of a network street that connect departure and destination points (Figure 1). The initial data are the values of transport demand at each section of the route, the duration of movement in the conditions of free flow and the throughput of sections of the road network.
The analysis of reserve capacity was carried out taking into account randomly changing transport demand along the routes. Among the considered options for the distribution of transport demand, the highest value of the reserve capacity is achieved in the initial version, equal to 356, which exceeds the initial value by 2 times.

The concept of maximum throughput allows all users of the transport network to select a destination and a route to it. As noted above, the impedance parameter $\theta$ for demand distribution reflects the sensitivity of network users to the duration of movement along the route. Therefore, increasing the parameter increases the frequency of movement along the selected O-D route. Figure 2 shows the results of modeling the maximum network throughput and the distribution of the transport stream for various impedance parameters.

Figure 1. Model transport network.

Figure 2. Modelling flow distribution based on maximum capacity.
For the network in question (Figure 1), the range of the impedance parameter is set from 0.01 to 1. At its minimum value, a uniform distribution of flows between departure and destination points is noted. When modeling a transport network, it is necessary to take into account its topology to obtain the most optimal value of throughput. In this case, the highest throughput is achieved when the impedance parameter is 0.5.

5. Conclusion
During the testing of the presented model, the values of the maximum network bandwidth were obtained. It was established that in each pair of O-D points the demand is constant, and when using the demand model, the throughput of street road network elements can increase in accordance with its limitations. The models used, in which the correspondence matrix corresponds to the network topology, make it possible to optimize the work most effectively taking into account the throughput of its elements.

The study examined three models of network bandwidth: backup, maximum and practical. The considered algorithms for determining the throughput can be used to optimize the functioning of both the existing and planned transport network.

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