Modelling Urban Route Transport Network Parameters with Traffic, Demand and Infrastructural Limitations Being Considered

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Abstract: In recent years, there has been a significant increase in urban public transport. This has led to overabundant route networks; deteriorated conditions for moving route transport within cities; conflict situations at stop points occurring between vehicles of duplicating routes. Conflict situations occurring between vehicles of different routes at stop points when loading and unloading passengers prove the problem of optimizing urban route networks to be insufficiently investigated, with traffic, demand and infrastructure limitations being considered. Conflict situations at stop points are found to be dependent on route configurations and network parameters, with the number of conflict situations being inversely dependent on the number of combined intervals for route transportation through stop points and their throughout capacity. There has been developed an imitation model for moving vehicles of adjacent routes, with a model for optimizing urban route network parameters being presented. It reduces conflicts in number due redistributed vehicles of various types for routes, with the population’s demand for transportation being absolutely satisfied. Models and methods can be used by transportation companies, city administrations to develop and improve urban route public transport networks.

1. Introduction

Today the state and quality of urban transport systems depends to a large extent on the efficiency and safety of urban public transport as the most important system that ensures the economic development of cities and the population’s social well-being [1, 2]. For effective and safe operation of urban transport systems, it is required to ensure the coordinated operation of route transport, with the limitations of urban transport infrastructure being considered [3–5]. To create new routes in modern conditions of free competition in the urban public transport sector it is necessary to consider the parameters of route networks to avoid possible conflict situations between vehicles of different routes at stop points during passengers’ loading and unloading [6]. Conflicts at stop points adversely affect the transport process safety, lead to significant time losses for carriers and passengers, increase the costs of transportation companies.
The analysis of scientific works [7, 8] shows the issues of reducing conflict situations of urban route networks to have been insufficiently studied. There are no well-founded methods for these issues to increase the route transport operation efficiency as there exists a “gap” between the levels of automobilization and urban transport infrastructure development [9–12]. Therefore, the aim of increasing the efficiency and safety of urban public transport operation and route networks is of primary importance from a scientific and practical points of view, with conflict situations at stop points being thoroughly considered.

The aim of the work is to increase the efficiency and safety of functioning urban route networks by reducing conflict situations at stop points.

Thus, the research tasks are:
- to study the causes and mechanisms of conflict situations on route networks of urban public transport;
- to develop an imitation model for identifying conflict situations occurring at stop points of urban route public transport networks;
- to develop a model for optimizing the parameters of route networks to avoid conflict situations at stop points of urban route public transport networks.

2. Research methodology
The system approach, mathematical statistics, probability theory, mathematical modelling approach, mass service theory and optimization approach are the theoretical and methodological basis of the research to draw reliable conclusions.

3. Main part
Due to analysed scientific works concerning the problem of optimization of urban route networks the concept of “conflict situation” is specified [13, 14].

Conflict situations at stop points of urban route transport networks are understood as cases of conflicts of interests occurring between vehicles of competing carriers concerning their priority of used transport infrastructure facilities (stop points) as the throughput capacity of stop points makes their simultaneous and free usage difficult.

As researches have established, time losses due to conflicts at stop points in the cities of Chelyabinsk region on average per year are the following: the losses of vehicles caused by waiting are 575 (thousand vph/year); the passengers’ losses caused by trips increased in duration are 1.43 (million pph/year).
Recently in the large cities of the region (Troitsk, Miass and Chelyabinsk), there has been an increase in the capacity of route networks due to increased public transport routes and vehicles for these routes. During the period from 2005 to 2016 the number of public transport routes doubled and more, with the number of vehicles for these routes increasing more than fivefold.

Fig. 1 provides the information on the use of transport facilities according the traffic volume and passenger turnover, as well as the share of small buses in the structure of traffic fleets in the cities of Chelyabinsk region.

The situation caused by overabundant transport facilities of duplicating routes is worsened by the tendency of decreasing public traffic in the municipalities of Chelyabinsk region.

According to [15], there is a steady tendency of decreasing passenger traffic on all types of public transport in the region.

**Table 1.** Passenger traffic according to the public transport types in Chelyabinsk region, (million people)

| Transport types     | 2009   | 2010   | 2011   | 2012   | 2013   | 2014   | 2015   | 2016   |
|---------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Transport (total), including: |        |        |        |        |        |        |        |        |
| trains              | 30.1   | 21.6   | 16.1   | 16.4   | 15.2   | 14.7   | 11.4   | 9.3    |
| trams               | 396.8  | 355.6  | 245.1  | 193.3  | 143.6  | 128.9  | 115.0  | 109.9  |
| trolleybuses        | 280.6  | 173.1  | 101.6  | 85.3   | 68.0   | 66.3   | 53.0   | 47.9   |
| airplanes           | 0.5    | 0.2    | 0.0    | –      | –      | –      | –      | –      |
| buses               | 521.4  | 564.5  | 293.2  | 255.8  | 364.6  | 298.3  | 247.2  | 257.6  |

Over the previous eight years, the traffic volume decreased by 2.63 times. The route networks have a significant surplus of transport facilities: for the traffic volume it is over 60%, for the passenger traffic it is over 70%

Considering the results of the analysed dynamics of the transport facilities of urban route networks, the passenger traffic, the amount of public transport, the following is established:

- there is a steady tendency to reduce the passenger traffic volume along urban route networks in whole, due to high rates of automobilization;
- there is an increase in the transport facilities of urban route networks as private carriers prefer to purchase small vehicles;
- there is an increase in the total number of passenger transport routes with insignificant differences in the configurations of their patterns to satisfy the population’s needs within existing transport networks.

These tendencies as a whole being the main reason for such a negative phenomenon characteristic for urban route networks, conflicts between passenger vehicles of duplicating routes, routes duplicating each other lead to conflict situations between vehicles at stop points. Transportation delays caused by conflicts lead to significant time losses in the economy: up to 50 hours per year for one passenger vehicle while working on the route (about 12 minutes per day), up to 3 hours per year per passenger (about 20 seconds per one trip). Conflict situations at stop points impair the safe operation of transport and passengers’ loading-unloading at stop points, worsen the quality of transport services for urban population.

The problem of conflict situations of urban route networks is complex and is to be solved systemically [16, 17]. In this connection, it is necessary to develop theoretical aspects to identify duplicating routes, models for assessing conflict situations at stop points, and a method for optimizing the parameters of route networks to reduce conflict situations at stop points.

The causes and mechanisms of conflict situations on urban route passenger transport networks are investigated. The main prerequisite for conflict situations at stop points of urban route networks is the competition between different carriers of duplicating routes, this being caused by shortcomings in the management of urban passenger transport: when new routes appear, there are no information of their
influence on the transport facilities of route networks, the competition and economic results of carriers’ activities, on occurring conflict situations at stop points.

The main competitive models in the market of urban passenger transportation (commercial monopoly, free competition, municipal regulation), the features and stages of their formation, the specifics of carriers’ work: the conditions for their access to the market, the principles of route network formation and fare regulations are investigated. In the passenger transport sector there are two main forms of competition occurring on regular urban routes: competition on one route; competition on various (alternative and duplicating) routes.

Due to the results of factor analysis carried out with the help of mass service theory, the influence of the combined frequency of traffic and the time necessary for passenger transport servicing at stop points, as well as the facilities of stop points on the probability of conflict situations was established. To reduce conflict situations at stop points is possible by changing the combined interval for moving route transport provided that the passenger traffic is fully serviced.

The analysis of scientific works [18–21] revealed the absence of effective methodological developments for assessing and identifying duplicate routes, models and methods for optimizing the parameters of route networks, with the formation peculiarities of conflict situations at stop points being taken into account to ensure their reduction.

4. Calculations

The duplicating routes are characterized by the predominance of combined elements on adjacent routes. To estimate the degree of such predominance of combined parts and stop points, the corresponding coefficients are found:

\[ \zeta_{ij} = \frac{l_{ij}}{l_{mi}} \]  

where \( \zeta_{ij} \) is the coefficient of combining the segments for the \( i \)th route (\( i = 1, 2, \ldots, n \)) with respect to the combined part of the \( j \)th route (\( j = 1, 2, \ldots, m \)); \( l_{ij} \) is the length of the combined part of the \( i \)th route relative to the \( j \)th route, km; \( l_{mi} \) is the total length of the considered \( i \)th route, km.

\[ \xi_{i} = \frac{\sum_{j=1}^{m} \xi_{ij}}{m} \]  

where \( \xi_{i} \) is the generalized coefficient of combined parts for the \( i \)th route with respect to all \( j \)th adjacent routes; \( m \) is the number of adjacent routes which have combined parts and stop points, units.

\[ \xi_{ij} = \frac{S_{ij}}{S_{mi}} \]  

where \( \xi_{ij} \) is the coefficient of combining the stop points for the \( i \)th route (\( i = 1, 2, \ldots, n \)) with respect to the combined stop points of the \( j \)th route (\( j = 1, 2, \ldots, m \)); \( S_{ij} \) is the number of stop points of the combined part of the \( i \)th route relative to the \( j \)th route, units; \( S_{mi} \) is the total number of stop points of the \( i \)th route, units.

\[ \xi_{i} = \frac{\sum_{j=1}^{m} \xi_{ij}}{m} \]  

where \( \xi_{i} \) is the generalized coefficient of combining stop points for the \( i \)th route with respect to all \( j \)th adjacent routes.

For duplicating routes, the coefficients of combining for parts and stop points approach to unity. The route duplication factor in the complex includes these coefficients and estimates the degree of combining the route elements:

\[ d_{mij} = \frac{\xi_{ij}}{2} \left( \frac{\xi_{ij} + \xi_{ij}}{2} \right) + \frac{\xi_{ij}}{2} \left( \frac{\xi_{ij} + \xi_{ij}}{2} \right) = \left( \frac{\xi_{ij} + \xi_{ij}}{2} \right)^{2} \]  

where \( d_{mij} \) is the route duplication factor.
Due to the route duplication factor and its value, the duplication degree of routes was estimated. The work of duplicating routes will be difficult, with the difficulties caused by passengers’ loading and unloading at intermediate combined stop points being also included. The value of the route duplication factor over 0.64 was considered as a criterion for identifying duplicating routes.

Adjacent routes can be considered as duplicating routes as route transport uses them in whole or partially ($\zeta_{ij} \geq 0.8$) as combined with the transport of other (duplicated) routes. These two transport types use the same stop points ($\xi_{ij} \geq 0.8$) along the combined road parts. The duplication factor on them is $d_{mij} \geq 0.64$.

On the basis of theoretical analysis and generalization of actual data on configurations of route networks, methods of forming adjacent routes and combining elements, a new standard model for urban route schemes was developed, i.e. a “route scheme with combined route elements”, which includes three basic types of route schemes:

1) route schemes without combined elements that consist of separate routes without combined areas and stop points;
2) route schemes with combined elements on all routes that consist of adjacent routes;
3) route schemes with combined elements on separate routes that include adjacent and isolated routes.

In modern conditions, urban route networks include several duplicating routes. For an integrated assessment of the duplication degree of urban route network in whole, the route duplication factor has been developed:

$$D_m = \frac{M_d}{M_c}$$  \hspace{1cm} (6)

where $D_m$ is the duplication factor of a route network; $M_d$ is the number of duplicating routes along a route network, units; $M_c$ is the total number of routes to make up an urban route network, units.

For urban networks with duplicating routes, the value of potential conflict situations at stop points was found.

An imitation model has been developed to characterize quantitatively conflict situations at stop points (frequency, number and duration of conflicts, etc.) on the basis of reproducing real working conditions of route passenger transport in cities, with the speed and intervals of its movement, as well as the capacity of stop points being considered.

The starting point of a possible conflict situation on duplicating routes is the beginning of the combined part. On “converging” routes the starting points of vehicle movements from duplicating routes does not coincide, i.e. before the combined part they cover a certain distance separately $l_{cd}$ from the beginning of the $i$th route (Fig. 2a). On “converging” routes, the combined movement of vehicles starts at the junction (as a rule, the intersection of roads) of their routes $l_{cd1} = l_{cd2} = l_{cd0}$. On “diverging” routes the initial point of a conflict situation is the common starting point for both routes $l_0 = l_{01} = l_{02}$ (Fig. 2b). Conflict situations are possible only on the part of combined movement.

The length of the combined part used by vehicles $A_{i1}$ and $A_{j2}$ is determined by the route network configuration and can not exceed the length of any route ($l_{cd} < l_{ai}$, $l_{cd} < l_{aj}$).

At a distance $l_k$ from the beginning of the combined part of the route, there is a place of a probable conflict where the vehicles $A_{i1}$ and $A_{j2}$ simultaneously arrive in some time period after moving along the routes $t_{k1}$ and $t_{k2}$, respectively: $l_k = v_1 \cdot t_{k1} = v_2 \cdot t_{k2}$.

The possible variants of the combined movement of vehicles on duplicating routes are considered (Figures 3–6).
The variant when route transport moves along two duplicating routes with $V_1=V_2$, $t_{02}=t_{01}$ is a special case of the variant shown in Fig. 6, so it is not given separately.

The number of conflicts is determined by:

$$n_k = \begin{cases} \frac{(l_1-l_{cd})}{l_2} & \text{when } (t_k + n_1 \cdot l_2) \leq t_{cd1} \\ \frac{(t_{cd1}-t_{kl})}{l_2} & \text{when } (t_k + n_1 \cdot l_2) > t_{cd1} \end{cases}$$

(7)

where $n_k$ is the number of conflicts, units; $l_1$, $l_2$ and $l_{cd}$ are the intervals of movement for vehicles $A_{1i}$ and $A_{2j}$ along the first and second routes and the combined interval of motion, respectively; $t_{cd1}$ is the time of $A_{1i}$ movement along the combined part; $n$ is the number of conflicting $A_{2j}$ vehicles during $A_{1i}$ movement along the combined part: $n = \frac{l_1-l_{cd}}{l_2}$.

Figure 3. Conflict situation does not occur

Figure 4. Conflict situation does not occur

Figure 5. Conflict situation does not occur

Figure 6. At point 1 a conflict situation occurs

If a conflict situation occurs at a stop point, then its loading is simulated, with the throughout capacity of the stop point and the time of passenger transport servicing being considered. The conflict situation is fixed if the vehicle cannot be serviced in proper time. The results of simulation showed that the number of conflict situations at the stop points of the object in question exceeds 10 thousand per day. The deviation between the calculation results and full-scale surveys does not exceed 10% on average. The total loss of route transport caused by conflict situations in Troitsk reached 4.1 million rubles a year.

A model for optimizing urban route networks has been developed. The route network $R = \{r_i\}$ ($i = 1, 2, …, n$) is the totality of the $i$th number of routes $r_i \in R$. On the route network $R$ there is a set
\[ S = \{ s_j \} (i = 1, 2, \ldots, m) \] of stop points included in the route network. In this case, each stop point \( s_j \) is identified separately, i.e. the same stop points located on different sides of streets, intersections, and also used by different routes and transport types, etc. are considered. In general, the \( j \)th stop points considered as belonging to the \( i \)th routes can be represented as the following matrix \( B \):

\[
B = \| b_{ij} \| = \begin{bmatrix}
b_{11} & b_{12} & \ldots & b_{1m} \\
b_{21} & b_{22} & \ldots & b_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
b_{n1} & b_{n2} & \ldots & b_{nm}
\end{bmatrix}
\] (8)

in which the elements \( b_{ij} \) can be equivalent to 0 or 1:

\[
b_{ij} = \begin{cases} 
  1, & \text{if } S_{ij} \in r_i; \\
  0, & \text{otherwise}
\end{cases}
\] (9)

The frequency of moving vehicles \( v_i(s_j) \) for each the \( i \)th route having the \( j \)th stop point to ensure passenger traffic to the full extent is calculated due to the maximum hourly capacity of passenger traffic \( Q_{hi} \) on the most used part of the route for a characteristic period of time and the estimated capacity \( q_p \) of a vehicle to be used on the route:

\[
v_i = \frac{Q_{hi}}{q_p}
\] (10)

The value of capacity is determined due to the established level of capacity utilization according to the number of seats for passengers to travel standing and sitting and meets the requirements for the due quality of passengers’ trips.

The combined frequency of moving vehicles through the \( s_j \) stop point is calculated as the sum of the frequency of \( v_i(s_j) \) moving vehicles for each the \( i \)th route passing through the \( j \)th stop point:

\[
v_{sj} = \sum_{i=1}^{n} (S_j), \ S_j \in S
\] (11)

The conflict index \( \omega_{sj} \) at the \( j \)th stop point is characterized by the deficit (reserve) amount of the throughout capacity of stop points, which is calculated as the difference between the value of the combined frequency \( v_{sj} \) of a moving vehicle through the \( j \)th stop point and the value of its throughout capacity \( \omega_{sj} \):

\[
\omega_{sj} = v_{sj} - w_{sj}
\] (12)

The indicator of the conflicting nature of a route network in whole \( \omega_s \) is calculated as the sum of the values of the level of conflict situations at all \( j \)th stop points:

\[
\omega_s = \sum_{j=1}^{m} \omega_{sj}
\] (13)

Thus, the indicator of the conflict nature of a route network is chosen as an optimality criterion of the parameters of the route network, which ensures a minimum number of conflict situations at stop points:

\[
\omega_s = \sum_{j=1}^{m} \omega_{sj} \rightarrow \min
\] (14)

The limits are set on:

- the number of vehicles available \( A_m \):

\[
\sum_{i=1}^{n} A_{mi} \leq A_m
\] (15)

- the value of established intervals \( l_{yi} \) when vehicles move along the routes:

\[
l_{yi} \leq l_{di}
\] (16)

where \( l_{di} \) is the maximum allowable interval of moving route transport on the route.

A mathematical model for optimizing the parameters of a route network is developed:
\[ F(\omega_s) = F(q_p, l_{yi}, A_{mi}) \rightarrow \min \]

when \( q_p \in G, q_p \geq 0, l_{yi} \leq l_{di}, l_{yi} \geq 0 \),

\[ \sum_{i=1}^{n} A_{mi} \leq A_m, A_{mi} \geq 0. \]

(17)

Thus, to solve the problem of forming optimum parameters for a route network to avoid possible conflict situations at stop points, vehicles of \( q_p \) capacity are chosen and distributed over the route network so as the combined frequency of traffic at the \( v_{yi} \) stop points will not exceed the \( w_{yi} \) throughout capacity of the due stop points or this excess (due to the existing fleet structure \( A_{wi} \) of passenger vehicles or permissible intervals of movement \( l_{di} \) of route transport) will be minimal for the entire route network in whole \( w_s \).

5. Research Results

Using the developed provisions, the route network was optimized using the example of the city of Troitsk, during which the total number of routes was reduced from 28 to 13, the number of rolling stock was reduced from 102 to 58 units, the structure of the rolling stock operating on routes to increase the number of rolling stock the total number of conflict situations at the stopping points for new parameters of the route network will decrease by 33.46 times, from 10163 to 313 conflicts. The total time of delays in queues before stopping points decreased by 32.4 times, from 18.8 to 0.6 hours. The duplication factor of the route network was 0.464. Consequently, the share of duplicate routes in Troitsk is almost half (about 46% of the total) of the total number of urban routes. The effect of reducing the time losses of carriers in the event of downtime due to conflict situations at the stopping points amounted to 3,985.8 thousand rubles.

6. Conclusion

Thus, the developed simulation model of vehicle traffic on adjacent routes takes into account the parameters of routes and stop points, allows to evaluate possible conflict situations at the combined stop points of route networks, to identify potentially conflicting stops and routes, and make informed decisions on the reconstruction of infrastructure facilities and optimization of route parameters network.

The optimized parameters of the route network ensure the full realization of passenger traffic in compliance with the requirements for the quality of transport services for the population on the use of the capacity of the rolling stock and the intervals of its movement.

The obtained results testify to the usefulness of the developed optimization model for practice. With its use, new variants of urban route networks can be developed, in which a minimum number of conflict situations at the stopping points will be ensured, with full satisfaction of the population's requests for transport by urban public transport.

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