Distribution of Stops in City’s Transport Routes

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Abstract. The organization of the city's passenger transport route system is the most important task of transport planning. Public transport stops in places with high demand for transportation are hubs of passenger traffic and are used jointly by different routes. This leads to queues of vehicles and causes delays in the movement of buses and trolleybuses. Reduce vehicles queues is achieved when the stops are distributed by dividing them into several landing pads. The purpose of the article is to develop recommendations to rationalize the location of urban transport stops to improve the quality of passenger service and ensure transport mobility. Methods are used in the preparation of the article: mathematical modeling, queue theory, and the results of transport research. Recommendations for transport planning have been developed: a) distribute stops into multiple parts proposed using a queue theory model, b) some models for the rational placement of landing pads at a combined stop are proposed.

1. Introduction

Sustainable development is aimed at an interconnected solution to a set of environmental, social, and economic problems for present and future generations [1, 2, 3]. The solution to sustainable development depends in large part on overcoming the urbanization crisis [4]. In developed countries, the urban population exceeds 75%. Cities produce more than 70% of GDP, supply about 85% of carbon pollution, and consume from 60 to 80% of the energy produced. But cities occupy only 1% of the land area. Urbanization has therefore led to a concentration of economic, environmental, and social problems [5, 6, 7, 8].

Transport has been a pioneer on the path of sustainable development for several objective reasons. The experience of developed countries has shown that the sustainable development of urban passenger transport must be based on transport planning. In Europe, urban transport development based on the use of Sustainable Urban Plans (SUMPs) [9, 10, 11]. In Russia, transport planning is just beginning to be carried out. Previously, social and environmental outcomes were not taken into account when organizing urban passenger transport.

The development of transport plans is currently difficult for the following reasons: the transport planning methodology is fragmented and needs to be improved; there are no qualified transport planners; a monitoring system should be set up to gather information for transport planning [10, 12, 13].

The organizers of the public transport movement will equip stopping points on the routes for the entry and exit of passengers into vehicles. Some stops are used by vehicles on different routes. At such stopping points (the so-called combined stops, or CS), there may be situations in which vehicles of...
different routes form queues waiting for the opportunity to board and exit passengers. There are delays in vehicles and the quality of passenger service is reduced. The prevention of such delays is possible with the correct organization of the local use of CS by vehicles of different routes.

Therefore, the purpose of this article is to study the causes of vehicle delays for CS, and to develop recommendations for the rational use of those stops.

2. Materials and methods
The methodology used in the preparation of the article includes general scientific methods combined with methods of mathematical modeling, queue theory, and research results in the field of public urban transport. At the same time, the statistical representativeness of the proposed models was confirmed.

The practical application of the developed models and recommendations of the authors is based on the use of available information about the operation of transport and does not require additional costs.

3. Research and discuss
According to our observations, vehicle delays at stops are on average equal to 25% of the duration of the travel time. The location and number of stops affect the reliability of the schedule [14, 15]. When solving the problem of organizing the operation of stops, modern information technologies are used [16, 17].

The total duration of the bus delay at the stop is determined by two reasons:

- firstly, it is the time spent waiting for the opportunity to drive up to the stop (only in the case when this stop is occupied by another vehicle);

- secondly, it is the total duration of the exit and entry of passengers.

If a stop is used simultaneously by vehicles of several routes, there may be delays due to the first reason. When waiting for the opportunity to drive up to the stop, the vehicle can be located behind the bus located at the stop, or wait on the second lane of the road. A bus waiting in a queue interferes with other road users. Delays of vehicles at stops limit passenger mobility. When organizing traffic, you need to consider the possibility of congestion of vehicles at stops [18]. Chinese researchers have developed "a bio-objective optimization model" based on the Pareto criterion to find a balance between the time spent by passengers on trips and the frequency of stops [19]. The rational distance between neighboring stops should be about 400-500 m. The speed of the message ($V$ – the average over-all travel speed) increases as the distance between adjacent stops ($d$) increases (Figure 1).

![Figure 1. The dependence of the average over-all travel speed ($V$) on the distance between neighboring stops.](image)

According to our repeated observations, the flow of passengers arriving at the stop is fairly well approximated by Poisson's law [20]. Similar results were also obtained by many other researchers:

$$P_w = \frac{g^w e^{-g}}{w!},$$

(1)
where $P_v$ – the probability of occurrence of the number of passengers in a unit of time (for example, in 1 min), equal to $w$, people;

g – the mathematical expectation of the number of passengers coming to the stop, people.

Equation (1) is valid for a constant value of $w$. This requirement is met for peak hours in time intervals of up to 15 minutes, and for the inter-peak period of 1 hour approximately.

The time required for passengers to enter, and exit the vehicle depends on:

- the number of passengers who will enter the arriving bus is determined using the equation (1);
- the number of passengers getting off the bus at the stop.

The time of entry and exit of passengers will determine by the results of experiments. Features of vehicle design are taken into account when designing the model (height of the steps, their number, and so on) [21]. This model allows you to determine the time spent on the exit and exit of passengers.

The separation of the stop into two or more platforms (the landing pads) for passengers is made in the possibility of conflict situations when vehicles arrive at a stop. According to our research, the group should include routes that have the most similar passenger flows, and instead of the principle of similarity of the length of routes, the principle of coincidence of the interests of passengers should be used.

The platform for passengers at the stop should have a length sufficient to accommodate a group of vehicles. The group of routes with the highest frequency of traffic and heavy passenger traffic should be placed first in the direction of traffic flow. Near intersections (crossroads), such groups are placed closer to pedestrian crossings.

If splitting into two groups is not enough, you should divide the routes into three or more groups.

This method of performing calculations is considered in the following example. Suppose that the intervals of movement of the crews on the routes are equal (in minutes): $I_1 = 5, I_2 = 7, I_3 = 4, I_4 = 5, I_5 = 5, I_6 = 7$. The average time for passengers to exit and enter the vehicle is $T = 0.7$ min. The admissible probability of occurrence of delays more than $t_s=1$ min is $P(t>t_s) = 0.2$.

Firstly, check if the condition $T < I_m$ is satisfied, where $I_m$ is the average interval between the moments of arrival at the stop of buses of different routes. If this condition is not met, then there are constant rolling stock delays at the stop. In this case, the distribution of this stop is necessary. If the average interval is more than 8 times compared to $T$, the distribution is impractical. In the example under consideration, $I_m = 0.86$ min. The condition $T < I_m$ is satisfied. Therefore, we will further check the fulfillment of the requirement $P(t>t_s) = 0.2$.

The total flow of buses arriving at the stop consists of several independent bus flows of individual routes. Such this stream can be considered as the simplest random stream. Therefore, the probability of waiting time for the opportunity to drive up to the stop is determined by the dependence known from the theory of queues:

$$P(t > t_s) = \frac{T}{I_m} \exp \left[ - \frac{t_s}{T} \left( 1 - \frac{T}{I_m} \right) \right] = \frac{T}{I_m} \exp \left[ - \frac{t_s}{T} \frac{T}{I_m} \right], \tag{2}$$

where $P(t > t_s)$ is the probability of exceeding the delay time of arrival at the stop by more than $t_s$;

$T$ – the average time for passengers to exit and enter the vehicle, min (time of channel occupation);

$I_m$ – the average time between the arrival of buses at the stop (the interval), min.

Let's divide the routes into two groups. Let the first group contain routes 1, 2, and 3, and the second group includes routes 4, 5, and 6. Calculations using formula (2) showed that the average arrival interval at the bus stop of the first group buses is 0.69 minutes, and for the second group there is 0.84 minutes Further calculations will be carried out for the first group of routes since in this group the interval is smaller compared to the second group. Therefore, according to (3), the desired probability is:

$$P(t > 1 \text{ min}) = 0.7 \exp \left[ - \frac{1}{0.69} \left( 1 - \frac{0.7}{1.69} \right) \right] \approx 0.15 < 0.2. \tag{3}$$
Thus, the division of routes into two groups provides a solution to the task and the goal is achieved.

To reduce the number of conflict situations and improve the quality of passenger service, it is necessary to coordinate the timetables on common sections of the routes. As a result of coordinating the timetables, buses of different routes will arrive at stops in turn. The flow of buses becomes more even. Studies have shown that the coordination of the schedules of various routes should be carried out at intervals of more than 6 min. Movement intervals on coordinated routes must be multiples of the shortest of them. Another condition for the coordination of schedules is the requirement on the multiplicity of the difference between the flight times on coordinated routes and the shortest interval.

With very intensive passenger traffic and the presence of a dedicated traffic lane for buses or trolleybuses, it is advisable to use the organization of traffic on routes according to the “many units” system. The vehicles on the route operate in groups, usually consisting of two or three units. The timetable is not compiled for individual vehicles but for their groups. In each group, the movement of vehicles is carried out along the route with safety intervals between them. At the stop, passengers enter and exit the vehicles of the group at the same time. Research has shown that the creation of groups can improve the throughput of a stop if the interval for single vehicles is less than 5 min.

As a result of our research, it has been established that the speed of communication on various routes is a significant factor for placement at the bus stop of landing pads. The speed of communication depends on the dynamic dimension of the vehicle length. The speed of communication on the route also depends on the capacity of the vehicles used. The average speed of communication is the next for different vehicles:

- for the large capacity buses – 16-18 km/h;
- for the middle capacity buses – 17-20 km/h;
- for the small capacity buses – 18-24 km/h;
- for the trolleybuses – 15-17 km/h.

The speed of the message becomes faster when vehicles travel on dedicated traffic lanes.

In most cases, there can be 2 or 3 landing pads at a bus stop. To simplify the solution of the problem of the location of the landing pads, it is advisable to subdivide different routes according to the speed of communication into several categories. In the city of Voronezh, a statistically representative study of the speed of communication on routes using common stops was carried out. As a result, these routes were divided into 4 categories according to the speed of communication. The interval of speed values between adjacent categories is 3 km/h (Figure 2).

![Figure 2. Distribution of the routes into four categories.](image)

Therefore, bus routes of four categories follow three landing pads maximum. The solution to this problem was made by enumerating a few possible options for combining routes.
The main requirement for the coordinated operation of the rolling stock of various routes on common sections of the route network is compliance with the timetable. The CS bandwidth can be determined as follows:

\[ P_i = \frac{60 \cdot n}{T_i \cdot k_u \cdot k_l} \text{(the units per hour)} \]  \hspace{1cm} (4)

where \( i \) – is an index that indicates the type of vehicle;
\( n \) – is the number of landing pads on this stop, units;
\( T_i \) – is the middle time spent by the vehicle at the stop, min;
\( k_u \) – coefficient of the time irregularity's arrival of vehicles at a stop;
\( k_l \) – vehicle dynamic dimension coefficient.

Comparison of solutions for stops is recommended to be carried out according to dependence (5). Additionally, it is necessary to determine and compare the carrying capacity \( \rho \) of each route in two situations: the existing timetable, the proposed timetable.

\[ \rho = \frac{q \cdot N \cdot k_c \cdot k_u}{T_r} \text{(the number of passengers per hour)} \]  \hspace{1cm} (5)

where \( q \) – is the average capacity of vehicles (the number of passengers);
\( N \) – is the number of vehicles on the route, units;
\( k_c \) – is the passenger turnover rate along the route’s length;
\( k_u \) – is the utilization factor of the throughput of the stop, units;
\( T_r \) – is the time of the return trip on the route, h.

The simulation result should be checked in real working conditions. In addition, some other requirements should be considered. For example, the interests of people with disabilities should be considered first. The landing pads of such routes should be located closer to crossroads and places visited by passengers.

4. **Conclusion**

Vehicle queues before stops used jointly by different urban transport routes can cause traffic delays and poorer passenger service. To minimize such queues, you should apply the distribution of stops into several parts (landing pads). Each such part has a platform for passengers. The article proposes an analytical model for the rational distribution of stops by different routes of urban transport. The theoretical basis for the model is the theory of queues.

Recommendations have been developed for the rational division of a stop into three or two landing pads using a methodology available to designers.

5. **References**

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