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Estimation of Travel Time Spending by Urban Transport Passengers

Iosif V. SPIRIN

Spirin, Iosif V., *JSC NIIAT, Moscow, Russia*.*

ABSTRACT

The objective of the article is to obtain dependencies linking time spent by passengers on travel by public transport with the main factors that form the elements of this time spending. The research used methods of analytical modelling, mathematical and transport statistics, survey, analytical and logical analysis, methodology of transport research.

Mathematical models for estimating passenger travel time in cities using public transport are considered. Attention is drawn to formation of each of the elements of travel time and to the relationship of these elements with each other. Such elements comprise time of walking to the stopping point of departure and of walking from the stopping point of arrival to the destination of the trip; waiting time for boarding a vehicle; travel time spent in a vehicle along the route. The dependences of these elements on the factors that form time spending have been identified. The increase in time spent waiting for boarding a vehicle is investigated depending on reduction in the planned number of vehicles due to breakdowns. The above models can be used in transport planning and assessing quality of public transportation in terms of passenger travel time.

Keywords: *urban passenger transport, passenger's trip, passenger travel, passenger travel time, walking time, waiting time, route travel time, transportation quality.*

*Information about the author:
Spirin, Iosif V. – D.Sc. (Eng), Professor, Chief Researcher of JSC Research Institute of Road Transport (JSC NIIAT), Moscow, Russia, ivspirin@yandex.ru.

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For the original Russian text of the article please see p. 28.

Background.

Public urban passenger transport (PUPT) performs the bulk of passenger transportation in urban-type settlements in Russia, while the share of the urban population has reached 74 % of the total population of the country. Most of GDP is produced in cities. Motorization of the population cannot ensure mobility of the most of urban population due to economic, environmental, and urban planning constraints. Therefore, transportation of passengers by PUPT will now and in the foreseeable future retain its leading role in ensuring the «local» mobility of population of the cities. Public transport should provide passengers with such a quality of service that will stimulate citizens to use an alternative mode of transportation instead of cars, using PUPT vehicles. This will help mitigate numerous economic, urban planning, and environmental problems.

Passenger travel time is one of the most significant results of public transport activity. Therefore, the *objective* of this article is to determine a quantitative relationship between time spent by passengers on travel and individual elements of time spending with the main factors that form trip duration.

The research described in the article used review and analytical analysis of publications of domestic and foreign scientists, logical analysis, methods of analytical modelling, mathematical and transport statistics, methodology of transport research.

Studies carried out at different times show that time spent on daily travel is the most significant indicator of quality of transport services for passengers in cities [1–4]. Only for people with limited mobility and senior citizens (they constitute about 20 % of passengers), the opportunity to travel seated is more important than travel time. But even for those people travel time is among main indicators of transportation quality [5, p. 156].

According to the results of the studies by foreign researchers, travel time in public transport is also a leading indicator of quality of transportation services [6–8].

Thus, improving the methodology for estimating travel time spent by passengers is an urgent task of applied transportation science and practices. Reliable estimates of travel time serve as the basis for substantiating plans for development of PUPT systems and for identifying priority areas for funding most relevant technology for urban passenger transportation and improving transport infrastructure.

For a passenger, primary interest is the ability to complete a network trip[1] in the shortest possible time, that is, a trip from his location to the destination point. In the simplest case, a network trip can be reduced to a trip along a single route. With city growth, its area and the number of transport micro-districts in this area increase, which leads to an accelerated increase in transportation links between those micro-districts. It becomes physically impossible to provide all these connections with direct correspondence. Therefore, in many cases, a network trip is performed with transfers: a passenger sequentially uses several routes, performing a route trip on each of them.

Total travel time

The elements of total travel time are:

• time spent on walking to the passenger's stopover point T_{px1} and from the arrival stop point to the destination of the trip T_{px2}. On average, $T_{\mathrm{px1}} = T_{\mathrm{px2}}$, since the number of trips «there» and «back» as a whole per day is practically equal to each other. Therefore, we can assume that the amount of time spent on walking is equal to $2 \cdot T_{\mathrm{px}}$. If necessary, the walking time before boarding and after disembarking can always be taken into account in the calculations separately;

• time spent waiting for boarding a vehicle T_{wait}, min;

• time spent on travelling in a vehicle along the route between stopping points of embarkation and disembarkation T_{tr}, min.

Total travel time of a passenger for a route trip [1; 4]:

$$T_{route} = 2 \cdot T_{\mathrm{px}} + T_{wait} + T_{tr}. \qquad (1)$$

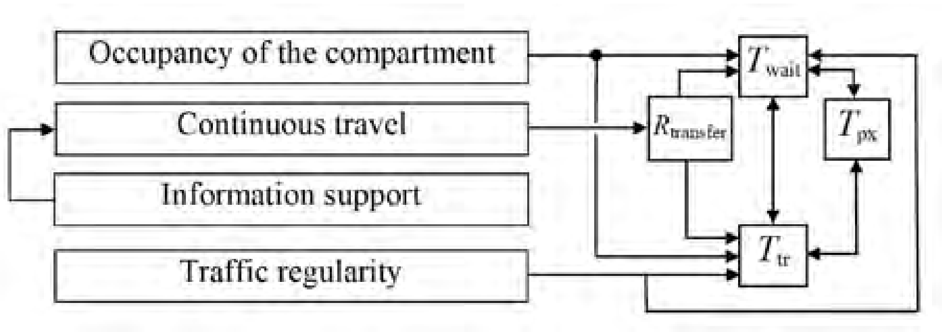
Total travel time of a passenger for a network trip [1; 4]:

$$T_{net} = 2 \cdot T_{\mathrm{px}} + (T_{wait} + T_{tr}) \cdot R_{transfer}, \qquad (2)$$

where $R_{transfer}$ is transfer rate (average number of passenger embarkations in vehicles of various routes during a network trip).

When transferring along the route, there is also a time spending for making transfers between routes T_{transfer}. In most cases, a transfer

[1] The term «network trip» emphasizes that movement is carried out through a transportation network.



Pic. 1. The relationship between elements of travel time and indicators of quality of transportation service.

to a vehicle of a different route is made at the same stopping point at which the passenger arrived during the previous route trip. Otherwise, $T_{transfer}$. should be considered, which can be established according to a large-scale plan of the corresponding urban area, considering the average walking speed of 4 km/h. Due to the limited volume of the article, we will focus on considering only transfers carried out at one stopping point.

With various options for organizing traffic of public transport in the city, it should be borne in mind that formation of elements of travel time is influenced by occupancy of passenger compartments of vehicles (with overcrowding of compartments, T_{wait} and T_{tr} increase), the continuous communication (affects $R_{transfer}$), regularity of traffic (with an unplanned increase in the intervals between the vehicles, T_{tr} and T_{wait} increase). Awareness of passengers about the transport network and timetables affects $R_{transfer}$. When comparing the options for traffic organization, one should take into account the mutual influence of various elements of time consumption on each other (Pic. 1). These relationships are detailed in the dependencies below. In transportation planning, considering these links can be provided by an iterative process implemented using a computer model.

Passengers evaluate psychologically time spent on certain elements of the trip in different ways according to its usefulness. Passengers' perception of the expenditure of their time does not always coincide with its physical flow. According to American scientists, a 30-minute journey by passengers sitting in a bus was perceived as equivalent to 18 minutes. Standing passengers rated the duration of the 30-minute trip as 53 minutes. In this experiment, the passengers did not use the watch, they gave estimates of time «by eye» [9].

The research carried out by the author on a representative sample of passengers allowed him to conclude that the relative (psychological) assessment of travel time by passengers is differentiated by its elements and can be represented by a utility coefficient: the ratio of the apparent duration of a trip element to its real duration. The flow of time while travelling in the bus is perceived by the respondents to be practically equal to «physical» time. Therefore, utility coefficient for T_{tr} element was taken as the basis for comparison (equal to one). Statistical processing of the experimental results showed that the averaged value of the utility coefficient for the element is equal to 1,21, and for T_{wait} is equal to 1,82. Psychological assessments by passengers of travel time are formed under the influence of the fact that in their minds the passenger sets aside a certain time for the trip, which is organically connected with the feeling of movement in space. No movement is performed while waiting for boarding. Therefore, the passenger's biological clock is in a hurry due to the mismatch between the target and the actual state of the ongoing process. With walking, this misalignment is felt to a lesser extent, since movement in space is carried out, but at a much slower pace than during the trip itself.

The psychological assessment of total travel time by passengers forms their transport fatigue. Hence, when assessing the impact of travel time on quality of transportation services and planning, one should consider not the astronomically determined time spending, but its psychological perception by passengers (seeming time spending T_{seem}), considering the correction for the utility coefficients of the corresponding elements:

$$T_{seem} = 2(1{,}21 \cdot T_{px}) + 1{,}82 \cdot T_{wait} + T_{tr}. \quad (3)$$

According to the results of the research, passenger transport fatigue is proportional to the seeming travel time.

Let us consider further the models of formation of travel time for various elements of the passenger trip.

Time for passenger walking

The average walking speed of a pedestrian in cities is V_{ped} = 4 km/h (for cities with a population of 1 million inhabitants or more, V_{ped} = 5 km/h) [10]. Therefore, time T_{px} is determined by remoteness of places where the passenger starts and ends walking from the corresponding stopping points. Taking into account the layout of streets and intra-block passages, the passenger's path will deviate from a straight line, however, regardless of the actual configuration of the pedestrian approach route, the distance covered by the passenger on foot can be geometrically decomposed into two components:

• moving from the depths of the block to the street along which the route passes (l_{x});

• moving along the street to the nearest stopping point of the route (l_{y}).

On average $l_{\text{x}} = 1/(3\delta)$, where δ is transport network density, km^{-1}. After approaching of the transport highway, the passenger walks to the nearest stopping point. Average walked distance the street is $l_{\text{y}} = l_h/4$, where l_{h} is the average length of the route haul, km. Hence, time spent on walking T_{px} (one way) is (60 is the coefficient for converting hours into minutes):

$$T_{\text{px}} = \frac{60}{V_{\text{ped}}}\left(\frac{1}{3\delta} + \frac{l_{\text{h}}}{4}\right) \approx 15\left(\frac{1}{3\delta} + \frac{l_{\text{h}}}{4}\right) \text{ min.} \quad (4)$$

The frequency of location of stopping points is among the indicators that require rationalization. When stopping points are frequently met, time of walking along the route is reduced. But, at the same time, speed of travelling decreases, which requires an increase in the number of vehicles or a proportional increase in their passenger capacity to ensure the estimated carrying capacity of the route. In intracity traffic, up to 60 % of the traction power consumption is associated with acceleration and deceleration of vehicles due to frequent stopping points [11].

With an increase in the average length of the haul, other things being equal, time spent waiting for boarding decreases. This is due to a decrease in the turnaround time on the route. In case of irregular movement of vehicles during long intervals of arrival of vehicles to neighboring stops, the number of passengers accumulates at stopping points, which exceeds the calculated value. As a result, the time for making a passenger exchange increases, which leads to a decrease in travelling speed and to an increase in passenger time spent on travelling along the considered route.

Based on the balance of interests the rational length of the haul should be about 500 m on average.

Currently, the average haul length is less than this value. Therefore, normalization of the average length of the haul is relevant by bringing this indicator to the standard. In order not to worsen quality of passenger service, it is necessary to determine how the walking distance of a passenger will change when the length of the haul is normalized. So, if the average length of the haul is 330 m, the passenger on average walks along the route 330 m / 4 = 83 m. Dividing by 4 is since a passenger leaving the internal part block and going to the street along which the PUPT route passes, on average gets either to the right or to the left half of the corresponding haul. Next, the passenger will go towards the nearest stopping point. The walking distance in that case, on average, will be half of the half of the length of the haul, i.e., one-fourth of the haul.

With an increase in the average length of the haul to the standard value, a passenger will pass 500 m / 4 = 125 m. The increase in the average walking distance will be 42 m, which will increase the passenger's travel time by an additional 42 m • 60/4000 m = 0,63 min ≈ 36 s! Therefore, normalization of the length of hauls will practically not affect the level of quality of passenger service.

At the same time, the total number of stopping points on the route will decrease by approximately [100 – (330 m • 100/500 m)] = 34 %. Delays at stopping points take about 40 ... 60 % of the time spent for each trip of a vehicle. Hence, the total duration of the bus trip along the route (excluding parking at the final points of the route) due to normalization (decrease) in the number of stopping points will be reduced by approximately [(0,4 ... 0,6) • 0,34 • 100] = 13,6 ... 20,5 %. Accordingly, the traffic speed will increase, providing a proportional decrease in time T_{tr}. Reduction of time spent on travelling through the route will be more than sufficient to compensate for the increase in walking time, and will ultimately improve quality of transportation services for passengers.

It is also possible to reduce time spent by passengers on walking by increasing density of the transport network, which is restrained by density of the road network in settlements and by deficiency of streets with a sufficient width of the carriageway in the old part of the city.

Waiting time for boarding a vehicle

Time spent waiting for boarding T_{wait} is the most significant reserve for reducing the total travel time and is determined by three factors:

• time interval between vehicles [only public urban transport vehicles that serve the route are considered];

• accuracy of respect of the timetable;

• passenger capacity of the vehicles used.

The influence of the first two factors on T_{wait} is shown by the formula [1; 4; 11; 12, p. 286]:

$$T_{\text{wait}} = \frac{I}{2} + \frac{\sigma_I^2}{2I} = 0{,}5\left(I + \frac{\sigma_I^2}{I}\right) = 0{,}5 I_{\text{ef}}, \qquad (5)$$

where I is planned time interval between the vehicles on the route, min;

σ_I is root-mean-square deviation from the planned interval (characterizes the irregularity of traffic), min;

I_{ef} is effective (seeming) interval of movement on the route [4; 11], min.

Considering possible cases of denied boarding (impossibility to board due to lack of free seats) the formula will be:

$$\begin{aligned} T_{wait} &= \frac{I}{2} + \frac{\sigma_I^2}{2I} + P_{den} \bullet I_{ef} = \\ &= 0{,}5 I_{ef} + P_{den} \bullet I_{ef} = (0{,}5 + P_{den}) \bullet I_{ef}, \end{aligned} \qquad (6)$$

where P_{den} is probability of a passenger being denied boarding due to the limited passenger capacity of the vehicle [11].

The effective time interval $I_{ef} = I + \sigma_I^2 / I$ considers the increase in the planned interval from the point of view of a passenger at the stopping point, taking into account the uneven arrival of vehicles.

Root mean square deviation from the planned interval:

$$\sigma_I = +\sqrt{\sum_{i=1}^{n} \left(I - I_{acti}\right)^2 / n}, \qquad (7)$$

where n is total number of observations of the time interval in a considered place within the route;

I_{acti} is actual time interval according to the i-th observation, min.

During operation of automated traffic control systems and satellite navigation systems, statistics on regularity of traffic are accumulated automatically and the monitoring results can be used.

In most studies, distribution of deviations of the actual moment of arrival of the vehicle at the stopping point of the route from the planned moment according to the traffic timetable is assumed to be subject to the normal law of probabilities. But it is obvious that arrivals at a stopping point with significant advances in the schedule are less likely than those occurred late for the same time. In this regard, the use of a symmetric statistical distribution to characterize irregularity of traffic seems to be not entirely correct in all cases. Our studies allowed us to establish that more accurate results are provided by the Gram–Charlier function [13]:

$$P(\tau) = f(\tau) - \frac{r_3}{6} f^{(3)}(\tau) + \frac{r_4 - 3}{24} f^{(4)}(\tau), \qquad (8)$$

where $P(\tau)$ *is* probability of occurrence of a deviation τ;

$f(\tau)$ is function of normal distribution of probabilities τ;

r_3 and r_4 are third and fourth highlights of the aggregate of variance statistics;

$f^{(3)}(\tau)$ and $f^{(4)}(\tau)$ are third and fourth derivatives of the function $f(\tau)$.

The second and third terms in (7) reflect obliqueness and steepness of the distribution curve τ, respectively.

At intervals of more than 20 minutes, regular passengers get used to the rhythm of movement of vehicles through the stopping point. In this case, the actual waiting time for boarding will differ markedly from that calculated using the above dependencies, since uniformity of distribution of time for passengers' approach to stopping points within each interval is not observed. Therefore, when intervals are greater, the flow of passengers P(t) is described by the dependence:

$$P(t)=\frac{e^{M(t)}}{\int_0^t e^{M(t)}dt}, \tag{9}$$

where M(t) is utility function for the passenger depending on time t of his actual approach to the stopping point ($0 \le t \le I$).

Monitoring of regularity of fleet's traffic on routes is ensured using satellite navigation systems. The most serious violations of the traffic schedule and, at the same time, deterioration of quality of passenger service occur when trips are disrupted due to shortage of vehicles currently in operation.

In the absence of a part of vehicles on the route, the average time T_{wait} increases significantly:

$$T_{wait}=\frac{I_{ef}}{2}\bullet K_{AU}, \tag{10}$$

where K_{AU} is coefficient of increase in time spending;

A and U signify number of vehicles, that, respectively, was planned, and that left the route, units.

Vehicles that are currently absent on the route, may be differently listed in the sequence of service time provided for by the traffic schedule[2]. For example, if three vehicles are missing on the route, then three randomly generated situations are possible: all missing vehicles (vacancies) are in a sequence to start operation in a row; two vacancies are located in a row, and the third – elsewhere; all vacancies are located in different locations. The probability of these situations depends on the total number of units in service provided for by the traffic schedule. The most serious deviations occur when vacancies are concentrated in one place.

The performed analysis, considering the likelihood of various situations, showed that with vacancies located in different places of the sequence of being in service $K_{AU}=\frac{A+2\bullet U}{A}$, if all vacancies are concentrated in one and the same place, then $K_{AU}=\frac{A+U^2+U}{A}$.

Since the combination of vacancy placement is not known in advance, we should talk about the mathematical expectation of this coefficient M{K_{AU}}:

$$\frac{A+2\bullet U}{A}<M\{K_{AU}\}<\frac{A+U^2+U}{A}\,. \tag{11}$$

An attempt to analytically determine the dependence $K_{AU}=f\,(A,\ U)$ came across significant mathematical difficulties: complex combinatorial relations for accounting for various options for vacancies and the probabilities of their occurrence for a different number of vehicles, included in the traffic schedule. Therefore, the solution to the problem was obtained by direct enumeration on a computer of options for combining vacancies and other initial data. The calculations were carried out for the options when the number of buses varied from $A = 2$ to $A = 50$ units, with the number of vacancies from $U = 1$ to $U = (A - 1)$. The accuracy of calculations is $\pm 1{,}0^{-10}$. This accuracy, with a very large excess, provides an acceptable error based on the technologically determined values of the initial data and the desired results. In practice, this allows us to talk about the absolute accuracy of the calculations. As a result, a matrix of numerical values of K_{AU} coefficient was obtained for various combinations of A and U.

The analysis of the matrix allowed us to propose a formula that is completely identical in accuracy to the specified accuracy of the simulation result. This allows us to make the assumption that the following formula is accurate (in any case, its accuracy is more than a million times higher than the data errors actually observed on PUPT) analytical model of the indicator under consideration:

$$K_{AU}=\begin{cases}\dfrac{A+(U\ \ +1)}{A-(U-1)} & if \quad 0<U<A,\\ 1 \quad if \quad U=0, & \\ \infty \quad if \quad U=A. & \end{cases} \tag{12}$$

Formula (12) is relevant in cases where the dispatcher does not change the traffic schedule for the route (does not shift the intervals when part of vehicles leaves the route). If the traffic schedule is being promptly revised, and the intervals are uniformly increasing, the usual dependence should be used, and calculations should be made with new planned increased intervals for the route.

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[2] [The author uses original Russian term that means «exit», referring to the fact that a vehicle, e.g. a bus, during its service hours exits vehicle park, and starts operation on the assigned route – *ed. note*] – conditional fleet unit, for which traffic schedule on the route established operation on the line on this particular day. In various work periods «exit» can be provided for to various vehicles and drivers.

Denied boarding occurs when the available number of seats in a vehicle is less than the number of passengers who wish to board. When organizing transportation and analyzing its quality, passenger service is provided in conditions of filling the cabin in accordance with the permissible standard (no more than 5 passengers/m^2) [14].

The probability of a passenger being denied boarding P_{den} means the relative number (proportion) of passengers who did not board the vehicle due to its overcrowding with passengers physically, plus the excess number of passengers who, although they managed to enter the cabin, were transported in unacceptably cramped conditions.

An adequate analytical model for determining the probability of a passenger denied boarding was developed and substantiated by the author in [4; 11]:

$$P_{den} = 1/\sqrt{2\pi}\int_x^{\infty} \exp\left(-y^2/2\right)dy\ ,$$

if $x = (q + 0{,}5 - I \bullet \lambda)/\sqrt{I \bullet \lambda}$ and $\infty \leq y \leq x$, (13)

where q is nominal maximum passenger capacity of a vehicle, pass.;

λ is average intensity of passenger traffic on the corresponding section of the route, passengers/min.

The calculation error for the presented model based on the results of field experiments is no more than 5 %. Considering the fact that the additional time spent by passengers due to denied boarding is usually no more than 15 ... 20 % of the total time spent waiting for boarding, this accuracy should be considered satisfactory (the overall error of T_{wait} is not more than 1 %).

In practice, it is often necessary to conduct an express analysis of the time spent by passengers waiting for boarding. For this, it is recommended, in the absence of specific initial data for calculations according to the above dependences, to take $T_{wait} = (0{,}7...0{,}75)\ I$. Note in this regard that in most practical applications a significantly underestimated estimate of time spent waiting for boarding is used: $T_{wait} = 0{,}5I$.

Time spent in a vehicle while travelling along the route

Travelling time spent in a vehicle, min [1; 4]:

$$T_{sl} = (l_{av}/v_s) \bullet 60, \quad (14)$$

where l_{av} is average distance of passenger trip along the route, km;

v_s is travel speed on the route, km/h.

The average trip distance in the absence of specific data is determined by the approximate formula proposed in [1] by Ph.D. (Eng) A. H. Zilbertal:

$$l_{av} = 1{,}3 + n_{pl}\sqrt{F} \approx 1{,}3 + 0{,}3\sqrt{F}\ , \quad (15)$$

where n_{pl} is empirical coefficient of the urban development structure of the city territory;

F is residential area of the city, km².

An adequate model for distribution of passenger trips by distance (l_t, km) is obtained using Erlang's law [13]:

$$f(l_t) = ((k / l_t)^k 1_t^{k-1} e^{-kl_n} / l_t) / (k-1)!\,, \tag{16}$$

where $f(l_t)$ is density function of distribution of trips by distance;

k is Erlang's positive integer, the «shape».

According to the experimental data, the k of Erlang's distribution for the case under consideration corresponds to the square of the ratio of the travel distance l_t to its standard deviation:

$$k \approx ((5l_t / l_{max}) - 1)^2, \tag{17}$$

where l_{max} is length of the longest route in the settlement, km.

The resulting value k is rounded to the nearest whole number. In the absence of data for the calculation, we take $k = 3$.

With a reduction in number of transfers and interchanges, due to improvement of the route system, the average distance of a route trip may slightly increase, but a network trip on average always becomes shorter.

Conclusions. The considered analytical models for determining the numerical values of travel time of passengers of public urban transport are based on the use of initial data extracted from the available reporting. The practical use of these models is possible in the following situations:

• development and improvement of transportation development plans in accordance with programs and strategies for development of urban passenger transportation by public transport;

• assessment and analysis of quality of passenger service on public transport routes (total travel time and individual elements of travel time spending);

• ensuring the calculation of external results when implementing measures towards sustainable development of the urban environment and transport infrastructure [15];

• organization of passenger transportation on the existing route network.

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