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## THE REGULARITY OF INFLUENCE OF TRAFFIC PARAMETERS ON THE PROBABILITY OF REALISATION OF PLANNED PASSENGER TRANSFER AT TRANSFER NODES

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**Abstract.** The article deals with the definition of traffic parameters that ensure the minimum value of the transfer waiting time for passengers. On the basis of experimental studies results, a regression equation to determine the probability of realisation of the planned transfer between a pair of vehicles was proposed. Using the identified regression equation, the transfer waiting time can be assessed for any headway exceeding 7,5 min.

**Key words:** waiting time, transfer node, probability, simulation experiment, regression equation, arrival time, departure time.

## ЗАКОНОМЕРНОСТЬ ВЛИЯНИЯ ПАРАМЕТРОВ ДВИЖЕНИЯ ТРАНСПОРТНЫХ СРЕДСТВ НА ВЕРОЯТНОСТЬ ОСУЩЕСТВЛЕНИЯ ЗАПЛАНИРОВАННОЙ ПЕРЕСАДКИ ПАССАЖИРОВ В ТРАНСПОРТНО-ПЕРЕСАДОЧНЫХ УЗЛАХ

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**Аннотация.** Рассматривается зависимость времени ожидания пассажиров от параметров движения транспортных средств в транспортно-пересадочных узлах. По результатам экспериментальных исследований получено регрессионное уравнение, позволяющее определить вероятность реализации пересадки между запланированной парой транспортных средств, на основе которой возможно оценить затраты времени пассажиров.

**Ключевые слова:** время ожидания, транспортно-пересадочный узел, вероятность, имитационный эксперимент, уравнение регрессии.

## ЗАКОНОМІРНІСТЬ ВПЛИВУ ПАРАМЕТРІВ РУХУ ТРАНСПОРТНИХ ЗАСОБІВ НА ЙМОВІРНІСТЬ ЗДІЙСНЕННЯ ЗАПЛАНОВАНОЇ ПЕРЕСАДКИ ПАСАЖИРІВ У ТРАНСПОРТНО-ПЕРЕСАДОЧНИХ ВУЗЛАХ

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**Анотація.** Розглядається залежність часу очікування пасажирів від параметрів руху транспортних засобів у транспортно-пересадочних вузлах. За результатами експериментальних досліджень отримано регресійне рівняння, що дозволяє визначити ймовірність реалізації пересадки між запланованою парою транспортних засобів, на основі якої можна оцінити витрати часу пасажирів.

**Ключові слова:** час очікування, транспортно-пересадочний вузол, ймовірність, імітаційний експеримент, рівняння регресії.

### Introduction

Interchange nodes (transfer nodes) are the basis and necessary component for an effective net-

work of urban public transport (UPT). Along with the fact, the necessity to change a mode of transport or to transfer to another vehicle is negatively perceived by the population. Indeed, an

interchange process is accompanied by the need to re-fare, if integrated ticketing has not been implemented for UPT, transfer between stops and additional waiting time. The realisation of complex of technological measures for connection of several transport modes and improving the efficiency of the transfer process will reduce the value of the total travel time, making it more competitive. The priority measure to reduce the waiting time for passengers at a transfer node is the schedule synchronisation of UPT vehicles.

### Analysis of publications

Modelling the waiting time of passengers at stops is presented in numerous scientific publications. In [1] a simulation experiment for the determination of the distribution of the passenger waiting time and their parameters was conducted. A simulation model of the passengers waiting time was developed in paper [2], the input parameter of which is a random value of a headway. The schedules coordination of vehicles arriving at stops, and their impact on waiting time are not considered within the research. A schedule coordination of vehicles operating on different lines of UPT at joint areas is presented in [3]. The schedule development aimed at the passenger waiting time reduction at stops is proposed to realise by adjusting headways on lines and shifting the arrival time of vehicles at stops [4]. The research results presented in these publications do not provide recommendations for reducing the passengers waiting time carrying out transfers.

Models and optimisation methods for the synchronisation are presented in many articles of foreign authors [5–10]. Although the authors consider some characteristics of subprocesses as random variables [8–10], a functional dependence of the impact of their parameters on the waiting time is not studied. An investigation of the influence of random variables of vehicles arrival and departure time on the passenger transfer waiting time at a transfer node requires a special research for the designing synchronised schedules of UPT with minimal waiting time.

### The aim and problem statement

The study aims at determining characteristic conditions of a movement of vehicles at a transfer node, which ensure the minimum value of the passengers waiting time. The object of the

study is waiting time at the transfer node, and the subject is the influence of traffic parameters on the probability of the planned transfer realisation and passengers waiting time. To achieve the aim it is necessary to develop a mathematical model of the passengers waiting time, conduct the experimental study of determining the probability of realisation of the planned transfer and passengers waiting time, processed results using regression analysis.

### Experimental studies on the passengers waiting time at transfer nodes

A transfer node, in which two UPT lines interact:  $i, j$  – indexes of lines from and on which the transfer is conducted, respectively.  $b$  – an index of a bus, operating on the  $i$ -th line  $b = \overline{1, B_i}$ ;  $d$  – index of a bus, operating on the  $j$ -h line,  $d = \overline{1, D_j}$  is considered.

Each vehicle is idle a certain period of time at the transfer node, during which technological operations are performed, which can be defined as a service time. It consists of time spent on manoeuvring, opening/closing doors, dwell time, etc. In order to consider this part, the waiting time for transferring passengers is determined as the difference between the departure time of the bus of  $j$  line and arrival time of the bus of  $i$  line, taking into account the walking time between stops of these lines. The passenger transfer waiting time is defined according to the following mathematical expression

$$\tilde{t}_{ij} = \tilde{M}d_j^{(d)} - (\tilde{M}a_i^{(b)} + tw_{ij}), \quad b = 1, d = 1, \quad (1)$$

where  $\tilde{t}_{ij}$  is the transfer waiting time for one passenger;  $\tilde{M}d_j^{(d)}$  is the departure time of  $d$  vehicle of  $j$  route from the transfer node;  $\tilde{M}a_i^{(b)}$  is the arrival time of  $b$  vehicle of  $j$  line at the transfer node;  $tw_{ij}$  is walking time between the stops belonging to lines  $i$  and  $j$  at the transfer node.

A negative value indicates that the transfer between a specified pair of buses cannot be realised, and passengers have to wait for the next bus of  $j$  line, i.e  $d+1$ .

$$\tilde{\pi}'_{ij} = \tilde{M}d_j^{(d+1)} - (\tilde{M}a_i^{(b)} + tw_{ij}). \quad (2)$$

Assuming equal headways  $I_i = I_j$  it is sufficient to coordinate the departure of the first pair of vehicles,  $b = d = 1$ .

The UPT vehicles travel time has a stochastic nature as it is influenced by various environmental factors. In scientific studies, researchers use normal, log-normal, gamma and exponential distribution to describe both the travel time and the arrival time at a stop, being random variables [10].

Since the arrival and departure time of vehicles are random variables, the transfer between a specified pair of buses can occur with a probability  $p$  and the transfer waiting time is calculated by the formula (1), or does not occur with probability  $1-p$ , then the calculation is performed using the formula (2).

Considering the probabilistic nature of the transfer process, the objective function of the passenger transfer waiting time is presented as follows

$$p(\tilde{t}_{ij} \geq 0) \cdot E(\tilde{t}_{ij} | \tilde{t}_{ij} \geq 0) + (1 - p(\tilde{t}_{ij} \geq 0)) \cdot E(\tilde{t}_{ij}) \rightarrow \min, \quad (3)$$

where  $E$  is the expected value.

The study is conducted under the following assumptions:

- arrival and departure time are normally distributed;
- walking time between stops of lines  $i$  and  $j$  at the transfer node is deterministic value and equal for all groups of passengers;
- equal headways for lines that interact  $H_i = H_j$ .

Thus, it is necessary to find the difference between expected values  $\Delta E$  of the departure time

$E(\tilde{M}d_j^{(d)})$  and arrival time of buses at the transfer node taking into account the walking time between stops of line  $i$  and  $j$   $E(\tilde{M}a_i^{(b)} + tw_{ij})$ , which ensures the minimization of the objective function (3)

$$\Delta E = E(\tilde{M}d_j^{(d)}) - E(\tilde{M}a_i^{(b)} + tw_{ij}). \quad (4)$$

A graphic representation of the shift value of the arrival/departure time of buses in order to find  $\Delta E$ , which provides the minimum passenger transfer time, is presented in Fig. 1.

In order to determine the difference between the expectations (4), which provides a minimum value of the passenger waiting time at the transfer node it is necessary to carry out a simulation experiment. Parameters of random variables of vehicles arrival and departure time, being normally distributed, i.e standard deviation ( $\sigma_i, \sigma_j$ ) and the difference of expectation  $\Delta E$  were chosen as input factors. For urban transportation permissible deviation of schedule is 2 minutes [11]. According to this, the lower limit of standard deviation is established; values exceeding 1,25 are not considered in the study. Thus, the limits of variation of a standard deviation are 0,5–1,25, with the increment of 0,25 for lines  $i$  and  $j$ . The variation bounds of  $\Delta E$  is established in accordance with the assumptions and chosen range of standard deviation. According to with the three-sigma rule, with 0,997 probability of the maximum deviation of vehicles arrival and departure time is  $\pm 3,75$  min at the standard deviation 1,25. That is when  $\Delta E = 4$  min, the probability of transfer between the pair of buses is close to 1.

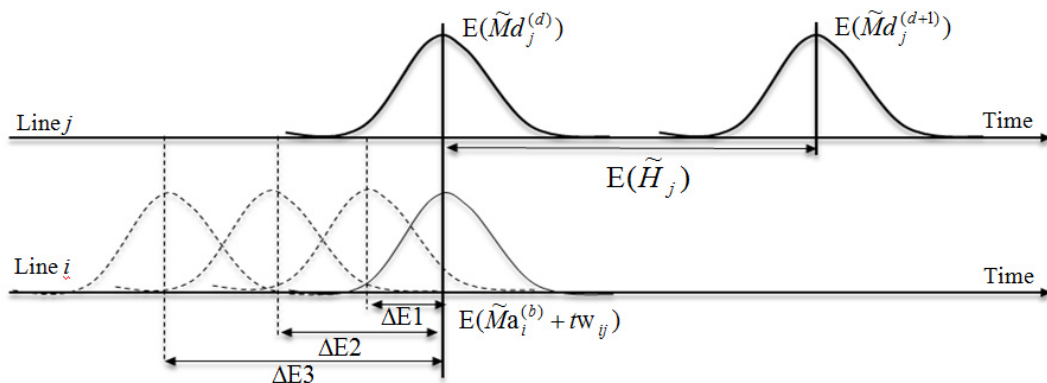


Fig. 1. A calculation scheme of shifting the arrival time of buses at the transfer node taking into account the walking time between stops and departure time

Thus, the designed simulation experiment (table. 1) contains 80 scenarios of experiments

and each consists of 100 experiments. A generation of random variables of arrival and departure

time of vehicles and calculations were conducted using MS Excel. Experimental studies were carried out for an interval of 10 minutes.

The probability of the planned transfer realisation was determined for vehicles to be synchronised for each scenario of experiments and the expected transfer waiting time was also calculated. On the basis of the obtained results of experimental studies, was built a graph of the waiting time changing at the same standard deviation for *i*-th and *j*-th lines (Fig. 2).

The graph shows that the least passengers transfer waiting time was recorded at  $\Delta E=2$  min. Moreover, the effect of synchronisation decreases with the increase of standard deviation of arrival (departure) time. The obtained results of

the simulation experiment were statistically processed through regression analysis carried out using the function analysis package MS Excel. Two hypotheses on the form of functional dependence of the transfer probability on the input factors were verified (table 2), was built.

All factors are statistically significant; the standard deviation has the reverse effect on the probability of the planned transfer realisation. According to the coefficient of determination, the second model was chosen ( $R^2=0,94$ ). It should be noted that the resulting formula for determining the probability of realisation of the planned transfer is valid for specified intervals of explanatory variables.

Table 1 A factors variation by the experiment scenarios

Number of scenario	The level of factors variation		
	Standard deviation of arrival time for vehicles of <i>i</i> -th line, $\sigma_i$	Standard deviation of departure time for <i>j</i> -th line, $\sigma_j$	The difference between expected values of arrival and departure time, $\Delta E$
1	0,5	0,5	0
2	0,5	0,75	0
...	...	...	...
80	1,25	1,25	4

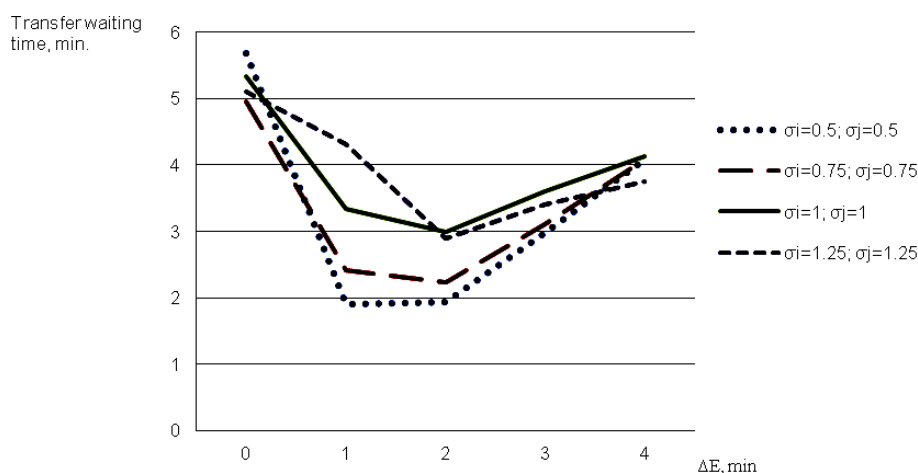


Fig. 2. Changing of the passenger waiting time by varying  $\Delta E$

Table 2 The results of hypothesis testing on the form of regression model

Hypothesis	Regression parameters				The coefficient of determination, $R^2$
	$a_0$	$a_{\sigma_i}$	$a_{\sigma_j}$	$a_{\Delta E}$	
$H_1: p = a_0 + a_{\sigma_i} \cdot \sigma_i + a_{\sigma_j} \cdot \sigma_j + a_{\Delta E} \cdot \Delta E$	0,75	-0,06	-0,06	0,09	0,71
$H_2: p = a_0 + a_{\sigma_i} \cdot \sqrt{\sigma_i} + a_{\sigma_j} \cdot \sqrt{\sigma_j} + a_{\Delta E} \cdot \sqrt{\Delta E}$	0,77	-0,13	-0,13	0,26	0,94

When a numerical value of the probability is greater than one, 1 is taken. The model can be

used for headways greater than 7,5 minutes, according to adopted limitations on standard deviation, which is 1,25.

### Conclusions

Simulation models allow to adequately describe the process of serving passenger at transfer nodes, taking into account the probabilistic nature of processes. Inputs of the developed model of the passengers waiting time are the standard deviation of traffic parameters and the difference between the expectations of their arrival and departure time.

On the basis of experimental studies, the functional dependence of the probability of the planned transfer realisation on input parameters was identified.

The obtained regression equation considers expected values of arrival time at the stops, taking into account the walking time between stops and departure time, as well as standard deviation, being the sum of square roots of factors. Using the identified regression equation, the transfer waiting time can be assessed for any headway of UPT exceeding 7,5 min. The results of experimental studies have shown that the least waiting time for transferring passengers achieved at  $\Delta E = 2$  min for the given conditions.

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