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ANALYSIS OF THE FORMATION OF FLUCTUATIONS OF SERVICE TIME OF VEHICLES IN TRANSPORT-TRANSFER STATIONS OF URBAN PASSENGER TRANSPORT

Запропоновано розглядати процедуру визначення планового діапазону обслуговування транспортних засобів на основі обліку флуктуаційних процесів формування часу прибуття та простою транспортних засобів у транспортно-пересадочному вузлу. На основі виділеного загального складу чинників та наслідків їх впливу запропоновані механізми зниження флуктуації часу обслуговування транспортних засобів у транспортно-пересадочному вузлу.

Ключові слова: *міський громадський пасажирський транспорт, транспортно-пересадочний вузол, відхилення часу прибуття, час обслуговування.*

1. Introduction

The functioning of urban public passenger transport (UPPT) is a complex process, during which the implementation of a set of relevant technological operations. The main part of the UPPT functioning is the processes that have a purposeful impact on changing the state of its service-resource parameters and are oriented toward full and qualitative provision of meeting the population's needs for their mobility. Along with the main production processes, UPPT functioning is based on related operations aimed at providing the corresponding levels of parametric states of its technological media. These operations include various forms of use of urban transport infrastructure, the territorial space of cities, objects of passenger transport infrastructure and the like. The study of the regularities of the movement of vehicles along the UPPT routes shows the presence of a characteristic effect on the efficiency and quality of passenger traffic. The state of implementation of internal technological processes is largely determined by the level of ensuring the stability of the time parameters of internal and external operations that occur during the interaction of UPPT within the local objects of the passenger transport infrastructure. In the context of solving the problem of ensuring the effective UPPT interaction in transport-transfer stations (TTS) it is important to identify the range of production solutions aimed at stabilizing its functioning. Under such conditions, there is an urgent need to analyze the key structural components of the formation of fluctuations (deviations) in the temporal parameters of its technological processes, which is the basis for the subsequent identification of mechanisms to increase its service-resource efficiency.

2. The object of research and its technological audit

By their designation, UPPT technological processes can be divided into basic, auxiliary and providing. The main processes are those during which passengers move within the territorial space of the city. The supporting processes are aimed at ensuring the continuity of the implementation of the main processes and are an integral part of UPPT functioning. The main and auxiliary processes represent a single whole and are realized within the UPPT framework using its internal resources as a single production process. Processes related to those providing envisage the creation of appropriate conditions for the implementation of basic and auxiliary production processes. In the context of UPPT integration in the general structure of the urban environment, they largely determine the possibilities of achieving their effectiveness and effectiveness. The structure of UPPT functioning allows to reflect the characteristic relationship and is the basis for identifying the technological and organizational forms of their interaction within the relevant functional environments. An important stage in the organization of the UPPT work is the provision of effective interaction within the TTS framework. The character and conditions for the formation of fluctuations (deviations) in the time of arrival and idle time of vehicles at the transplant points have a significant impact on the TTS interaction. The presence of fluctuations in the service of vehicles leads to an increase in the probability of conflict situations in TTS and significantly affects the level of their stabilization. Reducing the range of possible service fluctuations (arrival time and simple) allows to reduce the duration of the planned service time of vehicles and increase the reserves of TTS production resources.

The object of research is the process of UPPT TTS functioning. An important characteristic of UPPT TTS functioning is the time parameters of the arrival and idle time of vehicles under the loading and unloading of passengers. Fluctuation of these parameters leads to the appearance of heterogeneity in the time of servicing of vehicles. Such heterogeneity is manifested in the formation of a random character of the arrival of vehicles at the appropriate times and in the future leads to the need

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to expand the planned service time, which leads to a decrease in the TTS total capacity. The scheme of influence of fluctuations on the value of the required range of vehicle service is shown in Fig. 1.

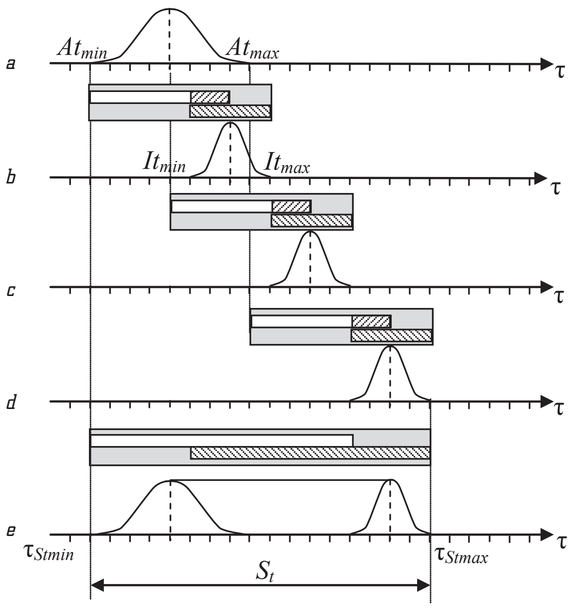

Fig. 1. Formation of a range of services:
a – arrival; *b* – early arrival; *c* – planned arrival; *d* – late arrival;
e – the total probable range of service

Reducing the fluctuations in the arrival of vehicles and their idle time allows to reduce the range of their possible location in TTS and reduce the planned service time. To develop a production program for interaction in TTS, it is necessary to have a clear idea of the composition, structure and actual duration of the fluctuation processes that arise when servicing vehicles. This task requires the creation of an appropriate analytical apparatus aimed at describing the conditions for the formation of service time in TTS and conducting experimental studies on the duration of its actual deviation.

3. The aim and objectives of research

The aim of research is identification of the conditions and areas for the formation of fluctuations in the temporal parameters of the location of vehicles in TTS when they are serviced.

To achieve this aim, it is necessary to solve the following tasks:

1. To distinguish the structure of the factors of fluctuations in the technological processes of UPPT functioning and to form the cause-effect relations of their elimination.
2. To carry out an analytical description of the constituent elements of the technological process of servicing vehicles from the standpoint of assessing their effect on the parametric areas of idle time fluctuations in TTS.

4. Research of existing solutions of the problem

The study of fluctuations in time parameters of UPPT technological processes was mainly considered in the formation of representations about the quality of passenger transport services and in the context of the development of automated traffic control systems. The distribution of existing studies of the UPPT fluctuations by the target goal allows to justify grouping them in two directions:

– assessment of the effect of fluctuations in the movement of vehicles as part of the total time of movement of passengers [1–3];
– highlighting the characteristic links of the influence of the territorial parameters of UPPT routes and the conditions for the implementation of the cycle of technological operations on the efficiency of their operation [4–6].

Consideration of traffic fluctuations from the viewpoint of assessing the quality of transport services [1–3] provides for a general analysis of the duration of excess passenger travel time by the UPPT route network. This consideration as a whole does not have as its goal the implementation of the procedure for the allocation of technologically-organizational prerequisites for their occurrence. Such form of analysis of fluctuations in UPPT internal processes is insufficiently adapted to solve production problems and can't be adapted to separate the cause-effect relationships of the formation of fluctuation influence on the functioning stability of the subjects of the passenger transport infrastructure.

Investigation of the processes of the origin of motion fluctuations along the sections of the routes, which are given attention in [4–6], is aimed at determining the internal technological impacts on the performance of individual elements of the UPPT route network. In these works, the appearance of fluctuations in the sections of routes is considered on the basis of an analysis of motion conditions for the aggregate of individual races. The main task of these works is study of the generalized processes of forming the time of deviation from the planned duration without distributing them to individual structural elements of the route. This form of presentation of the study of fluctuation processes concerns only the route network and does not allow the use of existing dependencies for analysis of technological operations within TTS.

The need for dispersion of fluctuation processes along the UPPT structural elements is based on the variety of reasons for their formation and the need to separate the research of technological operations within the subjects of the passenger transport infrastructure. Among these subjects, TTS is very important. The description of the components of the formation of fluctuations in the temporal parameters of motion is used in solving the problems of slot-coordination of the interaction of UPPT in TTS [7–9] and in determining the intervals of motion within individual stop points [10–12]. The main disadvantage of the presented approaches is the absence of a structured description of the reasons for the formation of the influence on the fluctuation of vehicle service and the generalized form of their accounting. Taking into account the revealed shortcomings of the existing studies of fluctuations in technological processes, it becomes necessary to analyze their occurrence factors and to analyze analytically the structure of their formation in the context of technological operations implemented within the TTS framework.

5. Methods of research

The mode of movement of vehicles along the UPPT routes depends on many internal and external factors, deviations from the planned timetable and fluctuates during the respective periods of work. The discrepancy between the actual driving schedule and the planned one is characterized by a fluctuation level that reflects the random deviation of the time per unit of the transport process from its mean value. The magnitude of fluctuations depends on the level of organization and management of technological processes. The basis for the study of formation processes of service fluctuations in TTS is the separation and systematization of the influence factors, taking into account their consequences and identifying mechanisms for their elimination (Fig. 2).

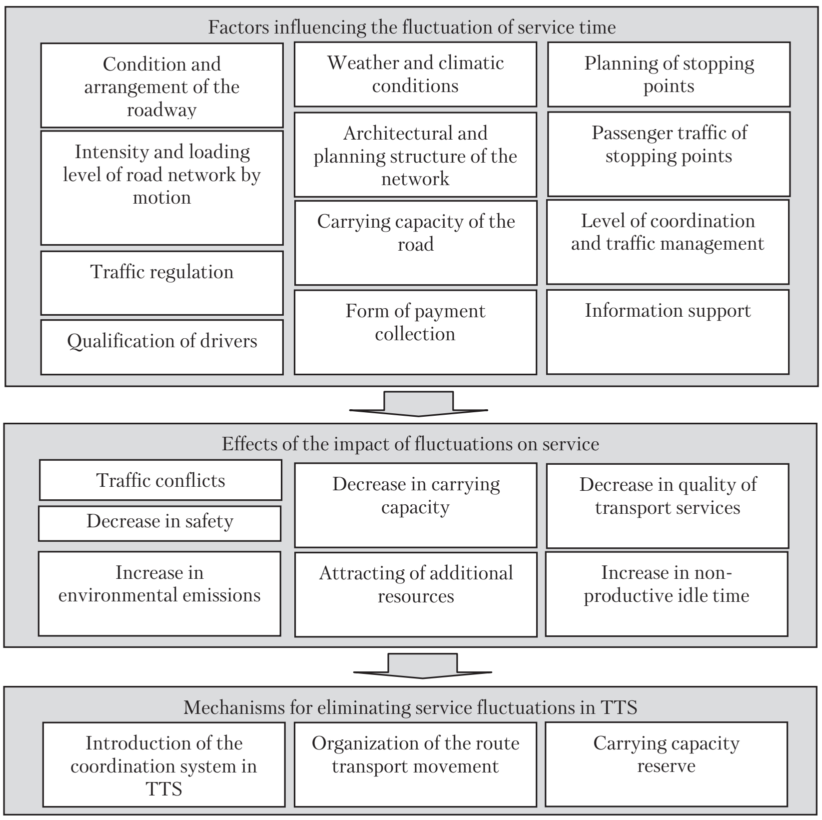

Fig. 2. Structure of service fluctuation factors in transport-transfer stations

The size of the fluctuations depends on the level of organization and management of the internal processes in UPPT and external resource entities that are used to realize their production functions. Analytical description of time parameters of IPPT service in TTS provides for the separation of the components of the structural elements of technological operations and the formalization of their duration. The process of the vehicle's movement along the route can be represented as a continuous movement in the territorial space, where the subjects are located, which directly affect the formation of the fluctuations of its movement. These subjects include road network elements (intersections of the carriageway, pedestrian crossings, road elements of maneuvering, etc.) and elements of the passenger transport infrastructure (stopping points). The model of the movement along the route connects statistically determined fluctuation data with the factors of its formation and allows it to be distributed over the corresponding parts of the space. In general, the mathematical expectation of the movement time along the route can be represented by the totality of the two basic parts characterizing the modes of traffic and idle of vehicles at the stopping points:

$$M(Ft_f)=\sum_{i=1}^{n}(Tm_{f_i}+M(Fl_{Tm_i}))+\sum_{j=1}^{m}(Tll_{f_j}+M(Fl_{Tll_j})), \quad (1)$$

where Tm_{f_i} – the planned time of travel along the route section, h; $M(Fl_{Tm_i})$ – mathematical expectation of traffic time fluctuations along the route section, h; n – the number of route sections; Tll_{f_j} – planned idle time at the stopping point, h; $M(Fl_{Tll_j})$ – mathematical expectation of fluctuations in the idle time at the stopping point, h; m – the number of stopping points on the route.

A significant impact on the interaction organization effectiveness in TTS is provided by reserving the resource capabilities of the capacity of its elements [13]. The main parameter that determines the level of TTS standby capacity is of the range of time during which there is a probability of arrival and service of vehicles. It determines the time that must be reserved for servicing the corresponding voyage in the general period of TTS work. The duration of such range depends on the arrival time fluctuation, which is formed on the route segment that is before TTS and the time of immediate idle TTS. The general view of the model for determining the dispersion of the vehicle arrival time fluctuations in TTS for an appropriate time τ point of the general period t can be represented as the equation:

$$D(Fl_{Tm_i}(\tau_{ar}))=\int_{\tau_{sv}}^{\tau_{ar}}Ca(\tau)\cdot Ffl(\tau)d\tau, \quad (2)$$

where τ_{ar} – the moment of arrival in TTS; τ_{ar} – the moment of voyage beginning; $Ca(\tau)$ – parameter that reflects the presence of mechanisms for controlling fluctuation factors; $Ffl(\tau)$ – function of the occurrence risk of motion time deviation.

The probability of occurrence of deviations from the planned timetable is of a complex nature and can be determined on the basis of taking into account the set of its distribution. Let's suppose that the distribution of the occurrence of deviations is random, which is determined by the component of the noise of its distribution. However, there is information about the interface of this probability relative to the lower and upper limits of the occurrence of events, which can be described as a distribution function of random variables. The function of the occurrence risk of deviation from the traffic schedule for an individual factor is determined by assessing its possible impact, taking into account the conditions for ensuring the absolute level of the timetable:

$$Ffl(u_i)_\tau = Z_i - f(g_i), \quad (3)$$

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where Z_i – the level of the value of the i-th factor that provides the absolute level of the timetable; $f(g_i)$ – function of the risk of influencing the stability of the motion of the i-th factor.

The value of the absolute influence absence level on the motion regularity is determined on the basis of the choice of the best function $f(g_{0i})$ from the set of effect parameters $G=\{g_i\}, (i=\overline{1,n})$. The distribution function of the level of occurrence of fluctuations from the i-th influence factor $P(u_i)$ is determined from the set $P=\{p_i\}, (i=\overline{1,r})$, which determines the corresponding density functions of the occurrence of motion deviation events.

Formalization of dependence function of the fluctuation formation on the factors of their occurrence is a complex multicriteria problem, the solution of which requires the use of a special technique for describing the cause-effect relationships of their formation. An estimate of the degree of influence of factors on the fluctuation of motion is proposed to be carried out proceeding from the minimax (pessimistic) model. The function of the risk of motion deviation can be represented as a total minimax function that reflects the level of risk and the probability of occurrence of an event:

$$Ffl(\tau)=\sum_{i=1}^{m}\min_{g_i\in G}\max_{p(u_i)\in P}\int Z(u_i)P(u_i)\,du_i, \quad (4)$$

where m – the number of factors influencing the fluctuation.

The number of influence factors is determined in conditions of their compliance with the established control list according to the territorial structures of the study of fluctuations. The parameter $Ca(\tau)$ that reflects the presence of mechanisms for controlling the fluctuation factors reflects the nature of the impact on them and, depending on the state of their implementation, assumes a single value from the set $\{0,1\}$.

The actual service time of the vehicle in TTS consists of constant and variable parts. The permanent component is determined by the conditions for performing technological operations related to the movement of vehicles across the TTS territory and door opening/closing operations. The variable part defines the idle time for the direct loading (unloading) of passengers, the time of performing the accompanying operations (collection of payment), the waiting time for additional passengers and the time of unproductive idles (service queue).

The duration of the permanent component of technological operations determines the mandatory guaranteed idle time of the vehicle in TTS:

$$St_p=t_{dt}+t_{od}+t_{cd}+t_d, \quad (5)$$

where t_{dt} – deceleration time on the way to the stop, h; t_{od} – door opening time, h; t_{cd} – door closing time, h; t_d – departure time of the stopping point, h.

Vehicle deceleration time on the way to stop:

$$t_{dt}=\frac{\sqrt{\dfrac{2l_a}{d_{dt}}}}{3600}, \quad (6)$$

where l_a – the length of the deceleration section, m; d_{dt} – vehicle deceleration, m/s.

Time for the departure of the stopping point is determined by the formula:

$$t_d=\frac{\sqrt{\dfrac{2l_d}{b_a}}}{3600}, \quad (7)$$

where l_d – length of the exit section, m; b_a – vehicle acceleration, m/s.

The value of the variable part of the vehicle's idle time in the TTS, reflecting the process of formation of fluctuations, can be determined by the length of the operations that depend on the passenger turnover and the coordination level:

$$St_v=t_q+t_{l-u}+t_{wp}+t_p, \quad (8)$$

where t_q – idle time in the queue, h; t_{l-u} – the time of loading/unloading of passengers, h; t_{wp} – waiting time for passengers, h; t_p – time of payment collection, h.

The idle time in the queue is determined on the basis of the account of the conflict states in which overlapping service ranges in TTS are observed for various vehicles:

$$t_q=\sum_{i=1}^{t}\tau_{rc-fl_i}, \quad (9)$$

where τ_{rc-fl_i} – the moment of time in which the state of the conflict in TTS is observed; t – duration of the study period, h.

The time spent on the passengers' loading-unloading is determined based on its volume and characteristics of vehicles:

$$t_{l-u}=\frac{k_{sp}\cdot q_n\cdot\tau_{pas}\cdot k_{ud}}{3600\cdot N_d}, \quad (10)$$

where k_{sp} – the hourly average coefficient of the passenger stop of the stopping point; q_n – nominal capacity of the vehicle, pass.; τ_{pas} – time spent by one passenger to loading or unloading, s; k_{ud} – coefficient of uneven loading or unloading of passengers behind the vehicle door; N_d – the number of doors to enter and exit the vehicle.

The average hourly rate of the passenger route at the stopping point:

$$k_{sp}=\frac{(Q_d+Q_a)}{t\cdot A_b\cdot q_n}, \quad (11)$$

where Q_d – the number of passengers departing from the stopping point for the period, pass.; Q_a – the number of passengers arriving at the stopping point for the period, pass.; t – duration of the calculation period, hours; A_b – number of buses on the route, units.

Time of payment collection:

$$t_p=\frac{k_{sp}\cdot q_n\cdot\tau_p\cdot k_{ud}}{3600\cdot N_d}, \quad (12)$$

where τ_{pas} – time spent by one passenger to pay for travel, s.

The waiting time for passengers t_{wp}, the value of which depends on the technological parameters of the route. In practice, it is adopted, based on the current situation in TTS, the level of filling the vehicle compartment and the driver's subjective desires.

When planning the technological process in TTS, the duration of its components related to the movement and execution of transfer operations is determined based on the actual location of the stopping points and the importance of the passenger destination. Fluctuation is simple due to the emergence of a queue of vehicles at the entrance to the corresponding service areas of TTS and unreported simple waiting passengers. Dispersion of these parameters along with the dispersion of arrival time is decisive in calculating the fluctuation of the service range in TTS. Proceeding from this and taking into account the dependence of formation of the fluctuations in the arrival of vehicles, it is possible to present the general model for determining the reserved time range for servicing in TTS:

$$St = D(Fl_{Tm_i}(\tau_{ar})) + St_p + t_{l-u} + t_{A?} + D(t_q) + D(t_{wp}). \quad (13)$$

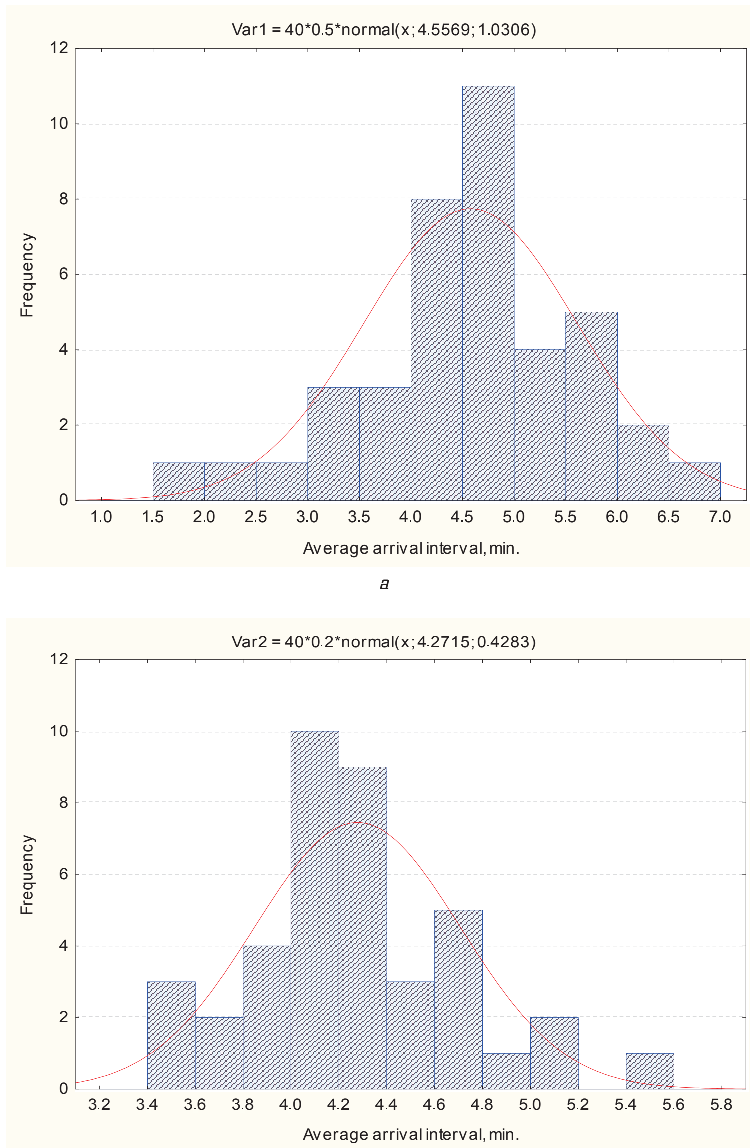
The proposed model for determining the service time range is used as the main parameter for assessing the efficiency of organization of technological processes for servicing vehicles in TTS.

6. Research results

In the framework of experimental studies with the help of simulation modeling, the tendencies of formation of the overall level of fluctuations in two parameters are analyzed: deviations in the time of arrival of vehicles in TTS and the duration of their total idle time. The simulation model of TTS allows to reproduce the processes that occur in real objects and, changing the corresponding control actions, obtain the value of the response function of the resulting parameters. Simulation of the processes was carried out for the real object of the passenger transport infrastructure of UPPT in Kharkov (Ukraine), the stopping point «Gvardiitsiv Shchyronintsiv Str. –Valentinivska Str.» (50°00′48.4″ N 36°20′27.2 ″E) is located within the framework of this facility, four routes of the UPPT are serviced, along with preliminary information on planned indicators of their movement on the segment before TTS. Based on field observations, actual volumes of passenger traffic and the established standards of the constant component of the service time of vehicles associated with maneuvering and loading and unloading of passengers were detected.

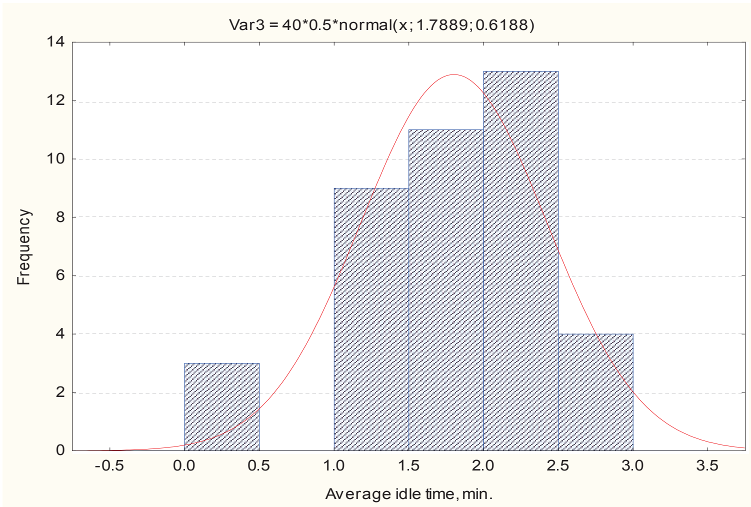
The aim of simulation is identification of the nature of the change in the parameters of vehicle service fluctuations when implementing the appropriate organizational and technological mechanisms for reducing it. The main used mechanisms are: organization of the movement of route transport on separate lanes, reservation of capacity and the introduction of a coordination system. The presented mechanisms within the limits of the allocated task of revealing regularities of fluctuation processes changes in TTS are considered as a generalized alternative technological program without detailed elaboration of separate stages of its implementation. Thus, it is proposed to consider the introduction of priority traffic on all sections of the routes. And the introduction of coordination is presented through the formation of a graph-analytical version of the slot-timetable for traffic through TTS based on an assessment of its compliance with the requirements of minimum overlapping periods for the simultaneous arrival of vehicles. Based on the obtained results, the histograms of the distribution of the arrival interval and the period of idle time of vehicles in TTS (Fig. 3, 4) make it possible to form a picture of their absolute level and general trends in the law of their distribution.

Based on the results of the series of simulation experiments, data were obtained with respect to the absolute value of the fluctuations and the necessary planned ranges of service time for vehicles in TTS were determined (Table 1).



b

Fig. 3. Distribution of the average interval of arrival of vehicles: *a* – base version; *b* – design version



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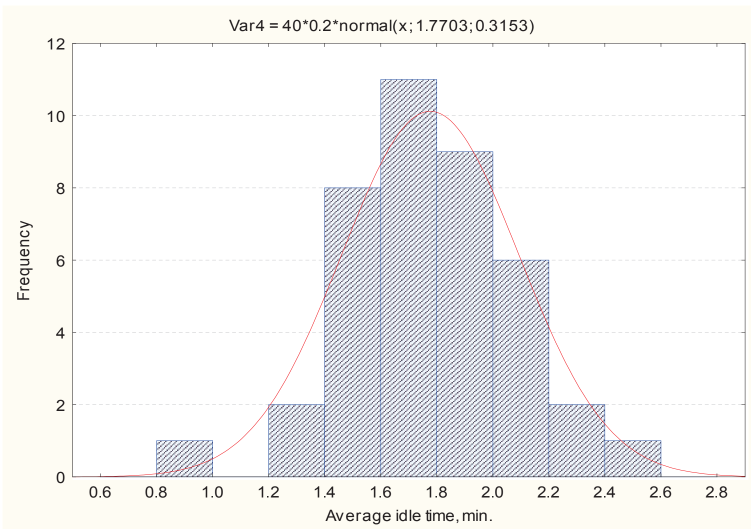

b

Fig. 4. Distribution of the average idle time of vehicles: *a* – base version; *b* – design version

Table 1

Indicators of vehicle service in TTS

Route	Fluctuation of arrival time, min.		Fluctuation of service time, min.		Average service time, min.	
	basic	design	basic	design	basic	design
34	2.4	1.6	1.8	1.3	5.7	4.4
42	4.8	2.7	1.7	1.1	8	5.3
52e	1.8	1.3	1.1	0.8	3.9	3.1
272e	5.2	2.9	1.0	0.6	7.2	4.5

Based on the analysis of the obtained results, regularities in the dependence of the fluctuations in the arrival of vehicles on the organization of traffic along sections of routes and on the level of coordination of interaction in TTS are revealed. So it is established that when implementing priority traffic on sections of the route:

– the average interval for the arrival of vehicles is reduced by 4.4 % (from 4.5 minutes to 4.3 minutes);
– the dispersion of this quantity directly determines the arrival fluctuation and is reduced by 49.1 % (from 5.5 minutes to 2.8 minutes). Due to the organization of slot-coordination of traffic, the dispersion of vehicle idle time in TTS is reduced by 40 % (from 3 minutes to 1.8 minutes). The reduction in the range of the probable location of vehicles in TTS for the corresponding routes is from 20.5 % to 37.5 % (from 0.8 minutes to 2.7 minutes). This indicates the importance of taking into account fluctuation processes in TTS planning and the prospects for introducing coordination of interaction in them.

7. SWOT analysis of research results

Strength. As a strength of research, it should be noted that the proposed form of estimating the fluctuations in the servicing of vehicles in TTS is based on the presentation of the cause-effect relationships of its formation through the description of the actual components of the technological process. The selection of areas for the formation of fluctuation processes and the sequence of searching for rational production solutions allows for a compromise in achieving the overall result of UPPT functioning and the laboriousness of considering various alternative options. Unlike the existing ones, this approach allows to increase the resource efficiency of TTS without creating new stopping points, which reduces the amount of necessary operating and investment funds.

Weaknesses. The weak side of research is the need to evaluate each alternative production program to reduce the fluctuations in the servicing of vehicles in TTS from the area of acceptable solutions and determine the level of their impact on the traffic conditions of other participants in the traffic of the urban transport network. This situation is caused by the absence of a clear form of the description of the function of response to the parameters of changing the conditions of traffic organization on individual elements of the route and the internal TTS network. The creation of a single multi-level urban transport management system allows, based on a comprehensive diagnosis of the state of all its types and components, to implement a procedure for identifying key areas of influence on which it is possible to organize priority traffic and to formulate a general program for managing slot-coordination on the TTS network.

Opportunities. The proposed approach to description of fluctuational processes of servicing vehicles in TTS reveals the prospects of using slot-coordination models to solve problems of increasing the UPPT system efficiency. In the context of the formation of a comprehensive production program, based on the nature of the connection «traffic conditions – time of unproductive idle time in TTS» it becomes possible to implement the procedure for isolating the segment of system-oriented technological solutions aimed at obtaining a complex multi-level effect within the existing functional processes of UPPT.

Threats. The complexity of the formation of a production program aimed at reducing fluctuations in service time is the need to obtain information about the actual passenger traffic at stop stations and its distribution on separate routes that pass through TTS. The idle time of vehicles under loading-unloading is not included in the range of fluctuations and for each individual case of arrival of the vehicle in TTS should be determined based on the actual needs of passengers. Obtaining objective information about the passengers on the basis of current monitoring will make it possible to generate relevant data on the regulatory idle time of vehicles in TTS. Under such conditions, it becomes possible to use this information as an integral part in determining the appropriate vehicle service time ranges.

8. Conclusions

1. It is established that the procedure for identifying the nature and conditions for the formation of random values of the actual deviation of vehicle service in TTS is an integral stage in the investigation of UPPT functioning. Its implementation is possible by isolating the factors of their occurrence within the subjects of the route network and the passenger transport infrastructure. The main factors in the formation of the level of fluctuations in the servicing of vehicles in TTS are the influence of traffic conditions on sections of the route network and the state of organization of internal technological processes. The need to clearly plan the UPPT interaction in TTS and assess its level of influence on service fluctuations makes it possible to justify the need to identify zones of parametric areas of possible reduction of the planned range of vehicle service.

2. On the basis of the analytical description of the constituent elements of the technological process of servicing UPPT in TTS, a characteristic relationship between the influence of organizational and technological solutions on the fluctuation of vehicle service is established. For the stopoing point «Gvardiitsiv Shchyronintsiv Str. – Valentinivska Str.» (50°00′48.4″ N 36°20′27.2 ″E) of the passenger transport infrastructure of UPPT in Kharkiv (Ukraine) possible areas for reducing service fluctuations are identified. Thus, due to the introduction of priority traffic along the network sections, the dispersion level of the arrival time of vehicles is reduced by 49.1 %, the dispersion of the service time by 40 %, and the average duration of the range of the probable location of vehicles in TTS in the range from 20.5 % to 37.5 %.

The obtained experimental data confirm the relevance of accounting fluctuational processes in the organization of TTS functioning and allow to substantiate the prospects of their integration into a general-functional model for assessing the efficiency of urban public passenger transport.

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АНАЛИЗ ФОРМИРОВАНИЯ ФЛУКТУАЦИИ ВРЕМЕНИ ОБСЛУЖИВАНИЯ ТРАНСПОРТНЫХ СРЕДСТВ В ТРАНСПОРТНО-ПЕРЕСАДОЧНЫХ УЗЛАХ ГОРОДСКОГО ПАССАЖИРСКОГО ТРАНСПОРТА

Предложено рассматривать процедуру определения планового диапазона обслуживания транспортных средств на основе учета флуктуационных процессов формирования времени прибытия и простоя транспортных средств в транспортно-пересадочном узле. На основе выделенного общего состава факторов и последствий их влияния предложены механизмы снижения флуктуации времени обслуживания транспортных средств в транспортно-пересадочном узле.

Ключевые слова: городской общественный пассажирский транспорт, транспортно-пересадочный узел, отклонение времени прибытия, время обслуживания.

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