Запропоновано метод моделювання розповсюдження затримки у нециклічному графіку руху поїздів з урахуванням технічних та технологічних особливостей залізничної мережі змішаного руху пасажирських і вантажних поїздів. Розроблено процедуру дослідження впливу затримки поїздів у нормативному графіку руху поїздів на основі оптимізаційної математичної моделі побудови графіку руху поїздів з урахування заданої первинної затримки. Проведені експериментальні дослідження моделювання поширення затримки поїздів у нормативному графіку руху поїздів з урахуванням взаємоув'язки залізничних дільниць

Ключові слова: залізнична мережа, дільниця, поїзд, нециклічний графік руху поїздів, затримка, змішаний рух, мультиагентна оптимізація

Предложен метод моделирования распространения задержки в нециклическом графике движения поездов с учетом технических и технологических особеностей железнодорожной сети смешанного пассажирского и грузового движения. Разработана процедура исследования влияния задержки поездов в нормативном графике движения поездов на основе оптимизационной математической модели построения графика движения поездов с учетом заданой первичной задержки. Проведенные экспериментальные исследования моделирования распространения задержки в нормативном графике движения поездов на железнодорожной линии значительной протяженности

Ключевые слова: железнодорожная сеть, участок, нециклический график движения поездов, задержка, смешаное движение, мультиагентная оптимизация

UDC 656.222.3
DOI: 10.15587/1729-4061.2018.123141

DEVELOPMENT OF THE METHOD FOR MODELING THE PROPAGATION OF DELAYS IN NON-CYCLIC TRAIN SCHEDULING ON THE RAILROADS WITH MIXED TRAFFIC

T. Butko
Doctor of Technical Sciences, Professor*
E-mail: uermp@ukr.net

A. Prokhorchenko
Doctor of Technical Sciences, Associate Professor*
E-mail: andrii.prokhorchenko@gmail.com

T. Golovko
PhD, Associate Professor*
E-mail: andrii.prokhorchenko@gmail.com

G. Prokhorchenko
Assistant*
E-mail: galaproh@meta.ua

*Department of management of operational work
Ukrainian State University of Railway Transport
Feuerbach sq., 7, Kharkiv, Ukraine, 61001

1. Introduction

One of the important indicators of the railroad system is the reliability and accuracy of transportation, which are directly associated with the stability of functioning [1, 2]. Underlying the operation of the railroad system is a working timetable (WTT), which is an annual plan for the allocation of time required by the necessary number of trains of different categories to travel along the railroad network. Influence of different kinds of random factors leads to delays in the time of train motion, which, under conditions of interdependence of trains in the timetable, creates the process of delay propagation over long distances. A capability to assess the consequences of delay propagation in a train timetable affects the capacity of a railroad system to confront the disruption of accuracy while performing a transportation process. A characteristic feature of the current model of transportation process on the railroad networks of South America, Africa, Eastern Europe, including Ukraine, is the mixed motion of passenger and freight trains based on the non-cyclic train timetable. Given that a given motion rather negatively impacts the utilization of throughput capacity of railroad subsections, it is an important task to study complex processes of successive delay propagation. This would make it possible to properly distribute the magnitudes of time reserve in train timetables or, in the process of development, to alter train scheduling in order to reduce the influence of detected consequences of delay on the overall throughput capacity.

Thus, it appears relevant to solve the task on modelling a delay propagation in non-cyclic train scheduling on railroad networks in order to improve reliability of passenger and freight trains flows in line with the assigned transportation plan.

2. Literature review and problem statement

Solving the task of research into delay propagation in a train timetable on the railroad network of Ukraine and similar networks in the post-Soviet territories has received little attention [3, 4]. In paper [3], authors investigated delays of trains at the experimental subsection; by using methods of mathematical statistics, they established a dependence of the number of delays of trains at the subsection on the place of their occurrence. Study [4] is similar; its authors performed a statistical analysis of the quality of train timetable implementation at an intermediate station, located at the subsection with significant volumes of freight and passenger traffic. However, a given study addressed the analysis of existing actual delays only; this does not make it possible to examine different variants of delay occurrence and detailed dynamics in the formation of cascading delays. This is explained by the lower level of attention, paid over many decades, to keeping train scheduling on time, especially of freight trains, under actual operation of railroads, by the lack of tools for the automated construction of train timetables, as well as poor theoretical basis related to studying the reliability of train scheduling. However, those railroads where the train timetable is a key mechanism for the implementation of a transportation process, have contributed to the theoretical basis underlying the study into delay propagation. Much research has addressed a given task [5–8].

In paper [5], authors constructed a mathematical model of railroad traffic based on the activity graph, which examines the absorption of delays and allows calculations for the networks of large dimensionality. Research [6] addresses the stability and reliability of non-cyclic train scheduling of passenger trains applying the specialized software PETER, using a high-speed railroad line in China as an example. Work [7] reported a tool to predict delays of passenger trains on the railroads of Germany, designed to support decision making by dispatchers. However, studies based on the comprehensive approach to modeling the delays in non-cyclic train scheduling on railroads with mixed traffic are far from being perfect and fail to take into consideration the patterns of a system for interval train traffic control with respect to the motion of freight multi-car and heavy-weight (exceeding 4,500 tons) trains of different categories.

One of the first approaches to estimating delay propagation in train traffic schedule was outlined in paper [8]. The work employs the theory of mass service in order to model delays of trains at the subsection. The authors obtained an analytical approach to estimating the sequence of train delays based on the construction of the system of mass service. However, the results obtained are rather approximate because the assumptions implying the application of Poisson's distribution law to the number of trains arriving at a bottleneck are refuted by many studies [9].

Research paper [10] reports a method for modeling the dynamics of delay propagation of trains in time and space based on the non-stationary Markovian process. The evaluation of train delays for the sequence of events of arrival and departure is proposed to represent as a stochastic process by altering the time of each event according to the delay probability distribution. In addition, it is assumed that delays may have different probability distributions. However, in contrast to other approaches where such a probability of distribution is determined based on historical data on keeping the standard train timetable, a given study proposed taking into consideration the impact of information that arrives in real time on the uncertainty in the evaluation of train delays using the Markovian properties. It was assumed that the delay of a certain event in the future can be properly predicted based on known delays. That is why a train delay in the future depends on the current delay only, rather than on the delay in events that preceded it. This approach is quite interesting; however, the application of distribution laws and operational information on trafic situation, which is missing, makes its implementation impossible on the railroad network of Ukraine.

Many studies are aimed at defining, based on empirical data on the actual time of train traffic at stations and subsections, the laws of distribution of random variables, such as the number and duration of delays. For example, authors of paper [11], using the method of maximum likelihood (MLE), established the laws of probability distribution of the duration of train delays for various operations at the railroad station Den Haag HS in the Netherlands. These results could be used when predicting the propagation of train delays, especially in the absence of empirical data. There is a similar study [3] performed for operation conditions of the Ukrainian railroad network, but the results obtained demonstrate a significant error, which is why, when introducing the new train timetable, their representativeness might be compromised.

Study [12] outlines the search for dependences in parameters that describe the process of delay propagation. The authors, based on empirical data from the German railroads (Deutsche Bahn AG), established a function that is characterized by an exponential equation and describes a permissible total length of the queue (LWB) depending on the share of passenger trains in the total number of trains at the subsection. Based on the results of calculations, the authors found threshold values for the total duration of a delay on the railroad network Deutsche Bahn, which ranges from 130 to 300 minutes. However, according to [11], these dependences require further refining; sometimes they describe the actual processes inadequately. The established parameters of dependence satisfy the requirements of operations on the railroads in Germany only, and thus could not be used on the railroad network of Ukraine and those similar to it.

To improve the accuracy in estimating the parameters of train delay propagation on the network, the approaches based on stochastic optimization [13, 14] were employed. The example of software developed in order to study failures in operational work at the macro level of traffic timetable is the NEMO package [15]. An effective approach to the estimation of delay propagation at the macro level of train scheduling is the proposed algorithm for solving a linear system of equations based on max-plus algebra [16]. This algorithm could be applied to large-scale train schedules in real time. However, the application of a given approach to the non-cyclic train scheduling employed on railroads with mixed traffic, including Ukraine, is not possible.

Quite common are the micro-simulation models used in such software as SIMONE [11], RailSys [14], OpenTrack [17], ANKE, VIRIATO, or ATTPS [18], which make it possible to assess the impact of an initial delay on the propagation of the overall delay at a subsection. Though these software packages take into detail consideration the system of alarm and control, they are quite complicated for construction and cannot be applied for large-scale traffic timetables that cover the entire railroad network. It should be noted that in order to avoid these shortcomings, it is a rather popular practice to integrate the software for the micro- and macro levels of simulation, which makes it possible to improve the accuracy of research [19].

In addition to the stochastic uncertainty of the process of delay evaluation, there are methods that make it possible to represent the process of evaluation as a fuzzy uncertainty. Thus, paper [20] proposed, in order to model a delay propagation in the network, which is represented as an oriented graph, to apply a hierarchical fuzzy system, which consists of fuzzy knowledge bases of the Mamdani type. Though the authors proposed performing the optimization setting of fuzzy rule base parameters, the construction of these rules, however, is a subjective procedure based on expert estimation, and does not make it possible to take into consideration in full all the factors contributing to the occurrence of a delay in the network. In addition, a given approach is difficult to apply to the graph of a railroad network of great dimensionality.

Other transport sectors pay special attention to problems related to studying a delay propagation. There are many studies into delay propagation or congestions in complex networks in space and time performed for automobile transport [21–23].

Papers [21, 22] proposed mathematical models of the delay propagation dynamics in the flow of automobiles, based on the application of methods for modeling kinematic waves. This approach is based on the macroscopic approach and does not make it possible to obtain detailed parameters for the influence of each delay on other vehicles that move in the flow. Research [23] is different in that it employed imitation simulation at the microscopic level, which improves the accuracy of results; this, however, increases complexity of the calculations when tackling problems of large dimensionality.

Attention is also paid to studying the propagation of congestions or delays in air transportation networks. Quite interesting results were obtained in paper [24], which applied a model of the delay propagation dynamics in complex networks of air transport by analogue to modelling the spread of infectious diseases.

Based on the above analysis, studying the propagation of delay of moving units in the flow is given much attention to in all transport sectors. Given the range of research undertaken for railroads with cyclic train scheduling and separated traffic of freight and passenger trains, it becomes clear that there is no any comprehensive approach to thorough investigation of the process of train delay propagation in time and space for railroad networks with mixed traffic of freight heavy-weight and multi-car trains of different categories. There exists no method for the imitation simulation of train delay propagation in a standard train timetable, which makes it possible to conduct modeling for a ramified network of interconnected railroad stations. A statistical analysis is missing that would examine the dynamics of delay propagation process evaluation with respect to the conditions of acting standard train timetable. All the above necessitates conducting the research into this area, which would lay the foundation for the automation of processes to design a standard non-cyclic train timetable.

3. The aim and objectives of the study

The aim of present study is to examine the possibility of mathematical modeling of delay propagation in non-cyclic train scheduling on a railroad network with mixed traffic, in order to study the dynamics of delay transfer between trains, which would make it possible to reveal the most vulnerable points in train timetable and to work out compensating measures to improve the reliability of standard train taffic timetable.

To accomplish the aim, the following tasks have been set:

– to formalize the process of delay propagation in non-cyclic train scheduling for a railroad network with mixed traffic of passenger and freight trains;

– to study the process of delay propagation for various scenarios in the delay occurrence.

4. Development of a method for modeling the delay propagation in non-cyclic train scheduling on a railroad with mixed passenger and freight train traffic

4. 1. Study of the process of train delays in a traffic timetable

To implement the mechanism for the occurrence and propagation of train delays on a railroad network, it is important to define main components of the actual timetable of trains at subsections. Thus, the actual time of a train movement can be divided into components according to Fig. 1 [25].

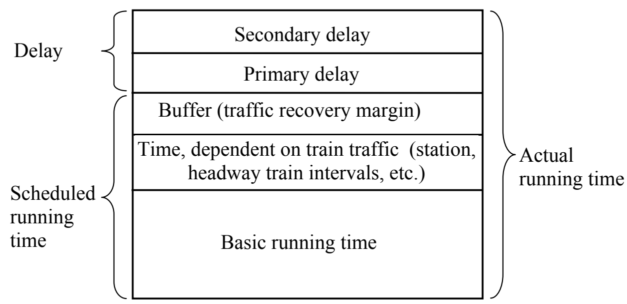


Fig. 1. Components of the actual train running time along the subsection

According to Fig. 1, the actual train running time along the subsection consists of the scheduled basic running time and delays. In line with UIC [26], the scheduled basic running time (a string) of train consists of the basic running time, a recovery margin, and a supplementary margin. The basic running time, or the minimum train running time along the subsection depends on running qualities of the rolling stock, the characteristics of infrastructure, and permanently enabled restrictions. It should be noted that on the railroads of Ukraine, a station-to-station running time, time of acceleration and deceleration of trains, are set by traction calculations in accordance with the applicable "Rules of execution of traction calculation for train operation" [27], based on the standards of train mass (unified or parallel) and taking into consideration the entire totality of permanently acting, as long as long-term, warnings about speed limits along station-to-station blocks and at stations. The time dependent on train traffic can be defined as the time that is added to the schedule to align the time for overtaking and crossover, as well as for passenger operations.

The time for recovery in a string (recovery margin) is established to compensate for delays, which can be divided into primary delays that occur randomly, and secondary delays that arise from reasons due to the primary delay of the first train and subsequent disruption of timetable of other trains that happen to be in the region of the delayed train [28]. Primary delays are exogenous and may occur for reasons of technical failures in the work of subsystems of the railroad infrastructure (contact network, track, rolling stock), errors in the operational work of dispatching personnel, exposure to weather conditions or interference in the work of railroads by a third party, etc. The number, duration, and sequence of secondary delays depend on the priority of strings of trains, train scheduling saturation, and location of trains of different categories relative to each other. Fig. 2 shows a diagram for rolling out the strings of trains along a two-track subsection in the case of occurrence of a primary delay and secondary delays.

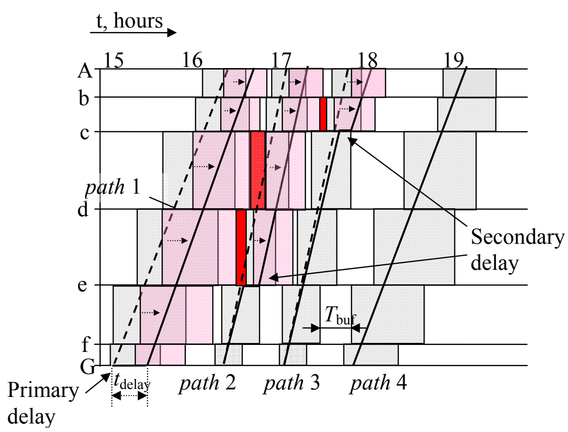
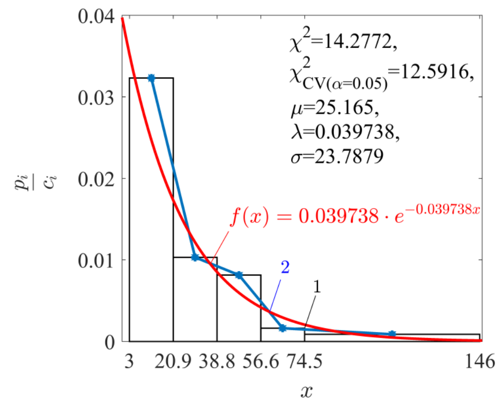


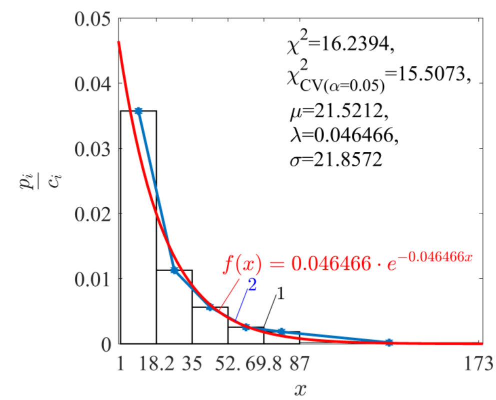
Fig. 2. Diagram of rolling out the strings of trains along a two-track subsection in the case of occurrence of a primary delay and secondary delays

On the railroad network of Ukraine, the accounting of delays is executed based on trains departing the station and their running time, which implies taking disruptions into account in the process when trains run between the stations. Therefore, primary delays have been studied sufficiently enough, and, as an example, in the course of our work a statistical analysis was performed of data on the duration of train delays for the first half of the year 2016 at the regional branch "Southern Railroad" of JSC "Ukrzaliznytsya". We established continuous laws in the distribution of delay duration for dispatching and running between stations (Fig. 3, *a, b*). It was found that the duration of delays of both types follow the exponential distribution with indicators: for dispatching λ_1=0.039738, and λ_2=0.046466, respectively, for running between stations. Mathematical expectation is, accordingly, μ_1=25.17 min. and μ_2=21.52 min. The proposed hypotheses about the agreement between experimental data and the assigned kind of the probabilistic law were tested for plausibility using the Pearson criterion with a significance level of 0.05.

While primary delays are random, which are almost impossible to avoid and predict, the propagation of secondary delays is an interconnected process, which represents so-called "cascading delay" or a "domino effect" [29]. Therefore, by knowing the train scheduling and duration of the primary delay, it is possible to predict, sequentially, the place and duration of the occurrence of cascade of secondary delays. Under conditions of secondary delay propagation, it is required to anticipate the impact of network effect [30] – there are many routes of trains that pass several railroad sections, which leads to the extraordinary interconnection between train timetable strings. The impact of a delay under conditions of high density of train traffic can spread over long distances and cause traffic jams in different places of the railroad network. Given such conditions, studying delay propagation on the rail network using mathematical modelling will make it possible to identify the most critical points in the schedule of trains that would enable changes in the timetables of trains in order to reduce the specified consequences of delays.



a



b

Fig. 3. Frequency histogram, empirical (1) and theoretical (2) distribution functions of train delay duration: *a* — for dispatching; *b* — for running between stations

4. 2. Procedure for studying the influence of train delays in non-cyclic train scheduling

To study the impact of the magnitude of initial delay on the reliability of the basic timetable of trains on a railroad network, we devised a procedure the block diagram of which is shown in Fig. 4.

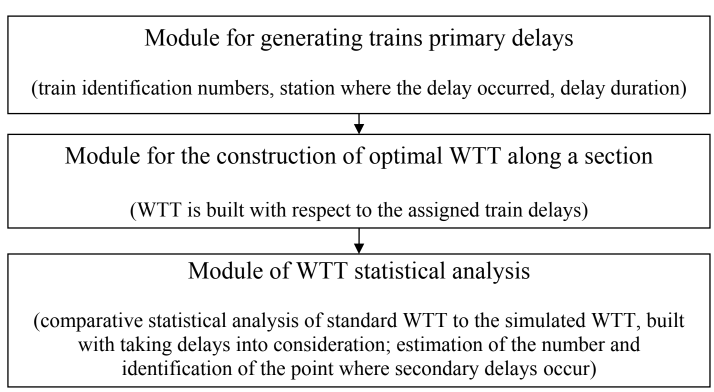


Fig. 4. Block diagram of the procedure for studying influence of train delays on the working timetable

Underlying the procedure is the imitation simulation using an optimization model for the construction of WTT, which implies generation of the assigned magnitudes of time of train delays and the station of their occurrence. Next, the construction of a rational WTT with respect to failures is performed, and statistical parameters of delay propagation are calculated. These parameters are the source data to search for the best variant of determining the magnitude of time reserve with respect to the minimization of risks of delay.

To model delay propagation in non-cyclic train scheduling for different variants of failures, we propose applying an optimization mathematical model for building a train timetable, which represents a procedure for rolling out the strings of WTT along a section as the problem of optimal allocation of limited resources over time, which in terms of the scheduling theory can be formalized in accordance with a flow-shop problem [31, 32]. According to previous study [33], mathematical model for calculating the schedule of trains has an objective function:

$$F=\sum_{j=1}^{m}\left[\sum_{i=1}^{n}\left[c_{\text{train-hours}}(g_{i,j+1}-t_{i,j+1}-g_{ij})+\delta_{ij}c_{ij}^{\text{delay}}\right]\right]+$$
$$+\sum_{i=1}^{n}c_i^{\text{fine}}\max(0,(g_{ij=L}-D_{iL}))\to\min, \tag{1}$$

and constraints

$$\begin{cases} g_{ij}>0;\ g_{ij}\le T, i\in I, j\in J;\\ g_{i,j+1}=g_{ij}+t_{ij}+t_{ij}^{stop}\cdot\delta_{ij}+t_{ij}^{\text{accel}}\cdot\gamma_{ij};\\ g_{ij}-I_j\le g_{i+1j}-t_{ij};\\ \varsigma\left[g_{ij}+\tau_{crj}\le g_{i+1j}-t_{ij}\right];\\ \varsigma\left[g_{ij}+\tau_{nsj}\le g_{i+1j}-t_{ij}\right];\\ \varsigma\left[\sum_{i}^{n}x_{ijt}\le 1\right],\\ \text{where}\, x_{ijt}=1 \text{ for } g_{ij}-t_{ij}\le t<g_{ij} \text{ and 0 otherwise, } t\in T, i\in I;\\ \eta\left[\sum_{i}^{n}x_{ijt}\ge 0\right], i\in I;\\ \sum_{j}^{m}x_{ijt}=1, j\in J;\\ g_{ij=L}\le D_i, \end{cases} \tag{2}$$

where i is the number of string along which a train runs, i=1, 2,..., n; j is the number of subsection along a section, j=1,2,...,m; $c_{\text{train-hours}}$ is the cost of train idling at an intermediate station, UAH; g_{ij} is the endpoint of train i at subsection j; g_{ij+1} is the endpoint of train i at subsection j+1 min; $t_{i,j}$ is the basic running time of the i-th train along subsection j, min; δ_{ij} is the Heaviside function, where δ_{ij}=1 if the i-th train stops at the j-th subsection; $\delta_{ij}=0$, if it does not stop there; c_{ij}^{delay} are the costs related to the attenuation and recovery of energy of the i-th train at a stop on the j-th subsection, dependent on a subsection profile, UAH; c_i^{fine} is the cost of a fine for the late arrival of the i-th train to the station of destination, UAH; L is the section that precedes the destination station of the train, L=1, 2,.., m; D_{iL} is the required time of arrival of the i-th train from section L at the station of destination, min; T is the period of planning, T=1,440 min; t_{ij}^{stop}, t_{ij}^{accel} are, respectively, the rated time for acceleration and braking of the i-th train along the j-th section, min; γ_{ij} is a function where $\gamma_{ij}=1$, if the i-th train accelerates along the j-th section, and $\gamma_{ij}=0$ if a train passes the station without stopping; I_j is the interval between trains along the j-th section, min; ς is the section's identifier that accepts a value of ς=1 if it is a one-track section, ς=0 for a two-track section, $\varsigma\in\{1;0\}$; η is the identifier of the section that takes a value of η=1 if it is a two-track section, η=0 otherwise, $\eta\in\{1;0\}$; τ_{crj} is the station crossover interval, min; τ_{nsj} is the station interval of non-simultaneous arrival at the j-th section, min; x_{ijt} is a function that accepts a value of x_{ijt}=1 if at time point t section j is taken by train i, and x_{ijt}=0 otherwise, $i\in I, j\in J$, $|I|=n, |J|=m$, t=1, 2,..., T.

The developed criterion (1) makes it possible to minimize the cost of idling and stopping of passenger and freight trains of different categories at a section, which is important under conditions of heavy-weight and multi-car freight trains traffic since large amounts of energy resources are spent during stops and traffic restoration. The third component is a fine for failing to meet the required timing of arrival at the destination station for trains of different categories.

Given the complexity of compiling WTT, it is possible to accept, to serve as an estimated section for which one constructs a timetable of trains, both a one-track line and a two-track line, limited by technical stations that handle most flows of trains. To solve the mathematical model designed, we applied one of the methods for multi-agent optimization, the Artificial Bee Colony Algorithm (ABC) [34], which is based on modeling the behavior of bees in natural environment. The advantage of applying the ABC algorithm is its better rate in the search for rational WTT compared to classical methods of optimization.

To implement the simulation of delay propagation in train traffic schedule taking into consideration a network effect, it is proposed to represent the railroad network of Ukraine in the form of graph $G(V, U)$ consisting of a set of vertices V that represent the totality of technical stations at railroad network $v\in V$, and a set of edges U, where $u\in U$ are the railroad sections according to the train sections in a standard train timetable. The estimated section is accepted to be a railroad line section, which is limited by technical stations (sorting, subdivision, or cargo-handling that perform the functions of subdivisions). Each section U can comprise one-track or two-track sections based on the assigned identifier $\varsigma\in\{1; 0\}$ and $\eta\in\{1; 0\}$.

Given the complexity of automated calculation of WTT for the entire rail network or a line, we implemented a procedure for the decomposition of section-based calculations by connecting these sections to the direction of rolling out the strings in a schedule. The procedure for WTT construction applied implies rolling out the strings in a timetable according to the preset points of departure or arrival of trains of different categories at the stations of the section. An example of the connection scheme along a railroad direction using different modes for rolling out the strings in a timetable is shown in Fig. 5.

The implementation of rolling out modes makes it possible to match the calculations of WTT at adjacent sections according to geographical location. The first section can be estimated, in line with the purpose of building WTT for different rolling out modes: "From both directions", "In odd direction", "In even direction". For example, under the mode "From both directions" – trains in odd and even directions are set out from the point of departure in the direction of their basic traffic. For further alignment between through strings in the schedule, the next section is automatically connected to the preceding one under the mode "In odd direction" – trains in the odd direction (top-down running direction) are set from the point of departure. The trains in even direction are set from the point of arrival in the opposite direction to their movement along the section (Fig. 5).

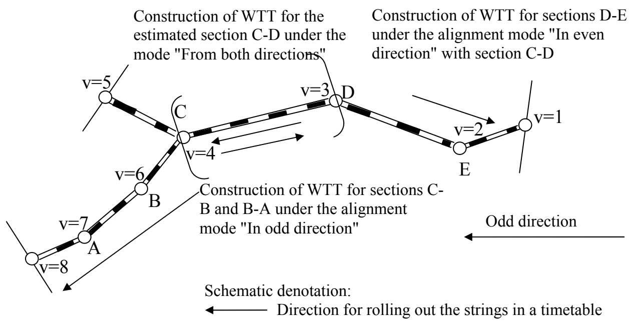


Fig. 5. Connection scheme of stations along the estimated rail network using different modes for rolling out the strings in a timetable

Based on a given variant, the identification numbers of trains at the station of connection with the first section are matched against the numbers of trains at the next section in the direction of connection. Trains with similar numbers are considered to be through trains, according to which the point of further roll-out along the next section is the time of arrival or departure of the through trains at the connecting station along the first section. The application of a section connection scheme, shown in Fig. 5, is possible in the case when section C-D in is the most loaded and needs urgent development of WTT, after which it becomes possible to make up a schedule for the sections adjacent to it.

According to the proposed procedure of simulation (Fig. 4), the first stage implies the construction of a standard train timetable for each interconnected section according to the above connecting scheme, and the timetable is kept for further analysis. Upon establishing the station and the duration of the initial delay, the construction of WTT is performed for each station of graph G taking into consideration delayed trains. At the last stage of modeling, in order to conduct a comparative analysis, an algorithm was designed, which automatically compares the standard train timetable with the model scheduling at the section, consistently according to the directions of train flows on the network. The analysis implies the calculation of the number and duration of secondary delays in the timetable.

4. 3. Results of the simulation of delay propagation in non-cyclic train scheduling using the line Lyubotin–Sovnarkomivska–Poltava-South–Potoki of the railroad network of Ukraine as an example

According to the developed procedure for studying an influence of train delays in the standard timetable (Fig. 4), we performed simulation of train delay propagation in the timetable on the railroad line Lyubotin–Sovnarkomivska–Poltava-South–Potoki of the Ukrainian rail network, which is part of the direction for the flow of trains from Kharkiv to Kyiv and Odesa. In the course of present research we used data from the standard train timetable for 2013–2014. Graph G of the rail polygon at the regional branch of the Southern Railroad of JSC "Ukrzaliznytsya" (PAT UZ), which includes train sections along the direction Lyubotin–Potoki, is shown in Fig. 6. Operational length of two-track sections is: Lyubotin–Sovnarkomivska – 6.1 km; Sovnarkomivska–Poltava-South – 109.8 km; Poltava-South–Potoki – 101.9 km. Total length of the line is 217.8 km.

A fragment of the standard train timetable in the programming environment Matlab, which was built based on the ABC optimization algorithm's solution to the developed mathematical model, is shown in Fig. 7.

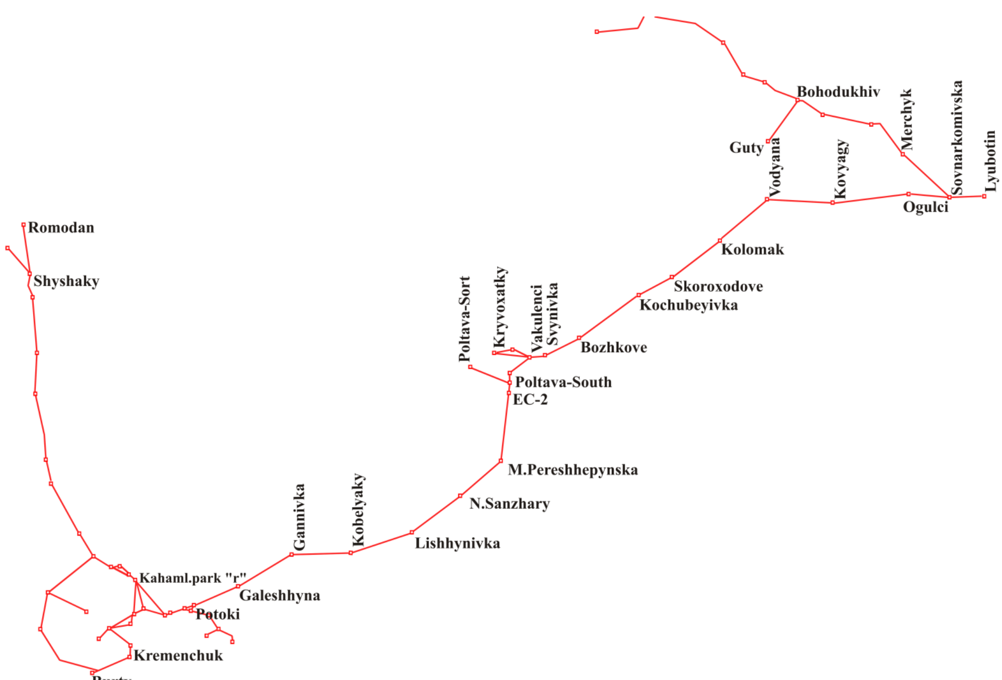


Fig. 6. Graph G of the rail polygon at the regional branch of the Southern Railroad of JSC "Ukrzaliznytsya", which includes train sections along the direction Lyubotin–Sovnarkomivska–Poltava-South–Potoki

To study delay propagation, it is proposed to simulate the initial delay of two high-speed passenger trains No. 161 and 162, which will run in different directions along the examined line only at sections Lyubotin–Sovnarkomivska–Vakulinci. A given scenario allows us to explore in detail the possibility of transferring the secondary delays to the section Poltava-South–Potoki, which the routes of trains with the primary delay do not pass. Based on the scenario of simulation, we delayed trains Nos. 161 and 162 by 15, 25, and 35 minutes at stations Lyubotin and Vakulinci, respectively. We calculated three variants of the model schedule of trains and performed a statistical analysis of delays along the entire estimated line. As an example, Fig. 8, 9 show dependence of the number and duration of delayed trains with a cumulative total on time of the occurrence of a delay in the timetable for the scenario implying a primary delay of 35 minutes.

Based on the parameters of the delay propagation dynamics, it was established (Fig. 8, 9) that, for the odd direction, the propagation time is 937 minutes, while for the even direction is 256 min, which is 27.3 % less than the time for the opposite direction. The total number of delayed trains is the same. However, for the odd direction, the delay with a cumulative total amounted to 52 minutes, while for the opposite direction the total delay is 2 times longer and reached 103 minutes. Therefore, the delay of train No. 162 at Vakulenci station is the most influential and requires establishing a time reserve in the standard train schedule in order to reduce the impact of a network effect on the operation of several sections along the railroad line.

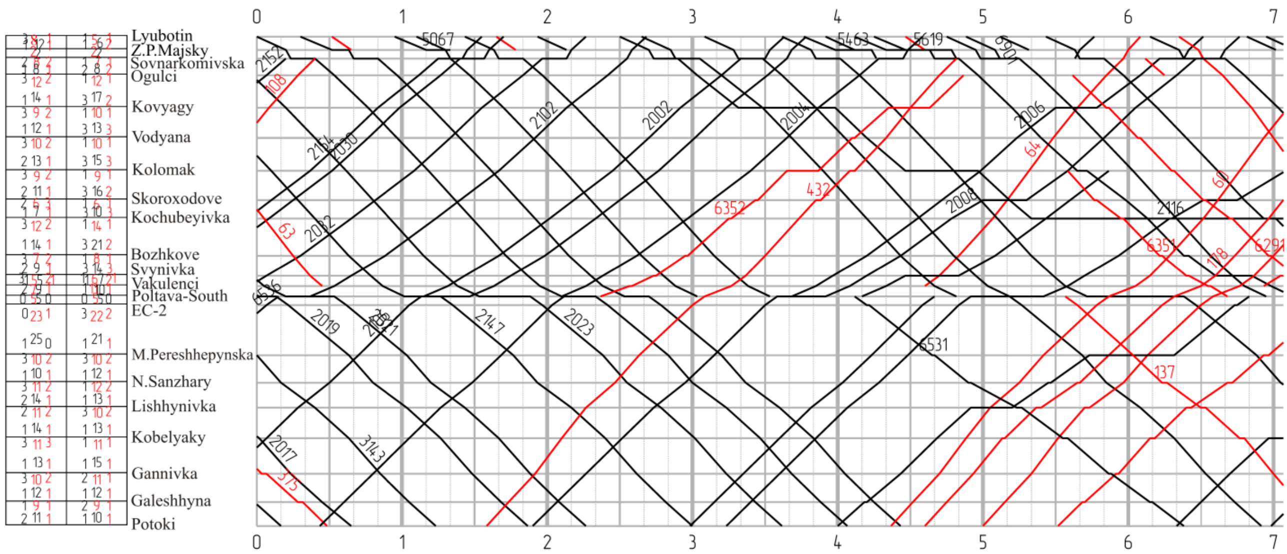


Fig. 7. Visualization of a fragment of the standard train timetable, which was calculated using the developed mathematical model, based on the solution obtained by applying ABC optimization algorithm in the programming environment Matlab

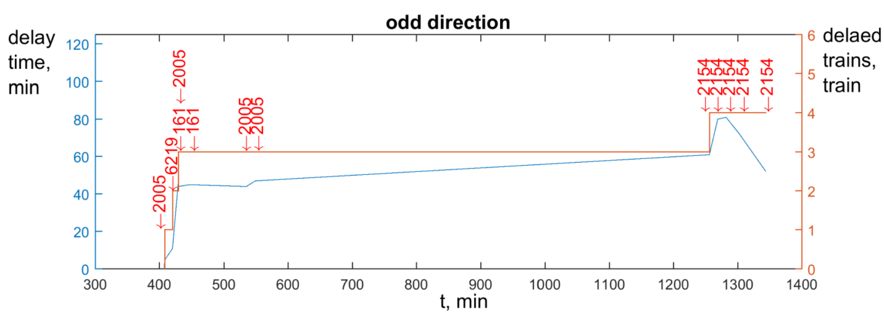


Fig. 8. Dependence of the number and duration of delayed trains with a cumulative total on time of the occurrence of delays in a timetable for the scenario implying the occurrence of an initial delay for train No. 161 by 35 minutes in the odd direction

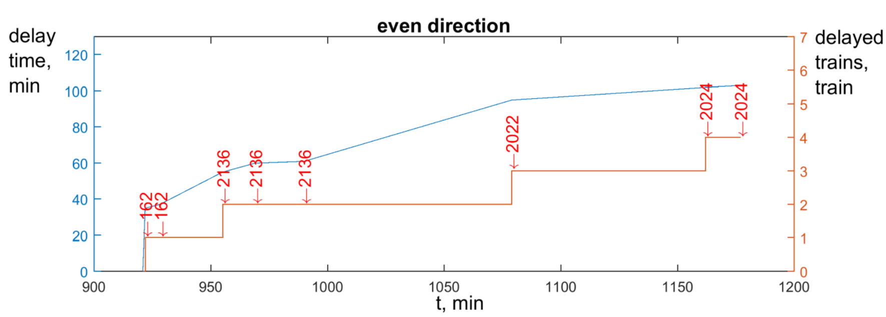


Fig. 9. Dependence of the number and duration of delayed trains with a cumulative total on time of the occurrence of delays in a timetable for the scenario implying the occurrence of an initial delay of 35 minutes in the even direction

To analyze spatial propagation of delays, Fig. 10 shows a chart of the number and duration of delayed trains relative to the point of delay occurrence in the timetable of trains along the line Lyubotin–Sovnarkomivska–Poltava-South–Potoki for the scenario of delays of trains Nos. 161 and 162 by 35 minutes.

To analyze the dynamics of delay propagation in a train timetable at the examined line, it is proposed to visualize the obtained dependences of delay duration on time of the occurrence of delays in the timetable for three scenarios of the occurrence of a primary delay in a three-dimensional space (Fig. 11).

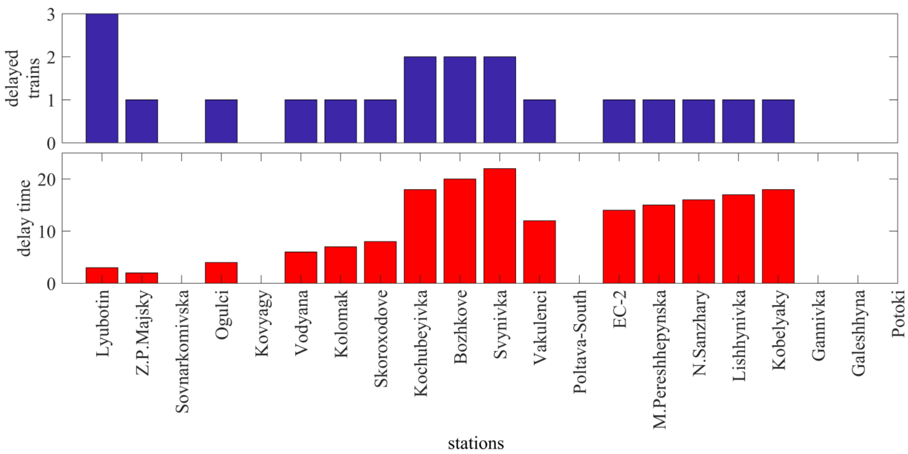


Fig. 10. Dependence of the number and duration of delayed trains on the point of occurrence in the timetable of trains along the line Lyubotin—Sovnarkomivska—Poltava-South—Potoki for the scenario of the occurrence of a primary delay of 35 minutes

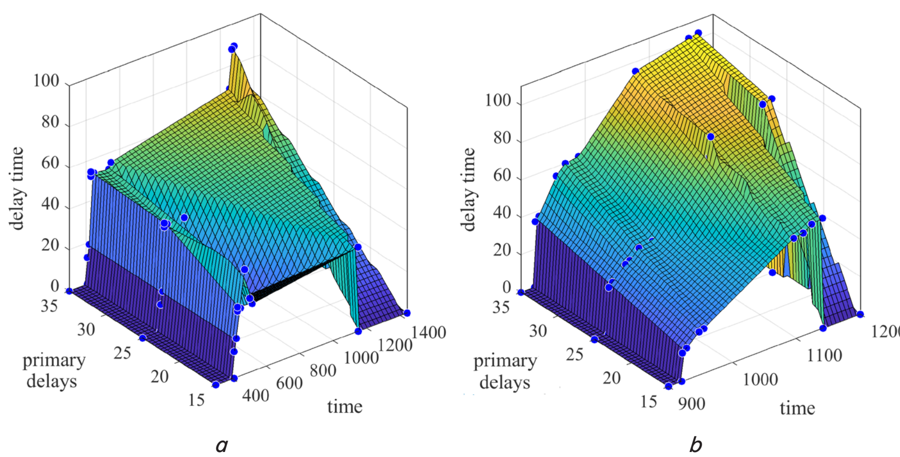


Fig. 11. Dependence of duration of delayed trains with a cumulative total on time of the occurrence of delays in a timetable for the scenario of the occurrence of a primary delay lasting for 15, 25, and 35 minutes: *a* — for the odd direction; *b* — for the even direction

The obtained results of delay propagation allow us estimate reliability of the existing standard non-cyclic train scheduling, and make it possible to explore the dynamics of formation of cascading delays. Based on the analysis of dependence in Fig. 11, it is possible to conclude that the process of delay propagation is nonlinear. This predetermines the complexity of modeling that requires accounting for a large number of factors, such as: the procedure for rolling out strings in a timetable, the number, duration, and place of the occurrence of a primary delay, section loading, etc. Under such conditions, the use of an imitation mathematical model for making up a schedule of trains makes it possible to fairly accurately account for the impact of interdependence of train traffic in a standard timetable. Expert analysis of the results obtained confirms the relevance of modelling to the actual processes occurring at interdependence of trains in the designed schedule.

5. Discussion of results of applying the developed method of simulation of delay propagation in non-cyclic train scheduling

The obtained results of application of the developed method correspond to the actual processes of the occurrence of disruptions in train traffic and prove the possibility of modeling delay propagation in non-cyclic train scheduling for railroads with mixed traffic using the railroad network of Ukraine as an example. All previous known studies, specifically published in [3, 35] performed analysis based only on statistical processing of empirical data on the number and duration of delays for the fulfilled train schedule in accordance with the periodic reporting from regional branches of PAT UZ. For the conditions of operation of railroads with a non-cyclic train scheduling, under traffic conditions of multi-car and heavy-weight trains, there is a lack of research aimed at modeling delay propagation in an actual standard timetable with detailed patterns of the process in time and space. Obtained dependences of the delay propagation dynamics allowed us to estimate the duration and number of failures in a standard train timetable relative to the initial delay. The research results are preliminary and need further improvement of the simulation mathematical model based on taking into consideration the random character of the process of reducing a delay in the movement of trains by allocating a time reserve and by transforming the problem into a multicriterial one to search for the Pareto-optimal solution. In addition, further research should improve the algorithm's capability to solve problems of large dimensionality.

6. Conclusions

1. We have devised a method for modeling delay propagation in non-cyclic train scheduling for railroad networks with traffic of passenger and heavy-weight or multi-car trains of different categories, which makes it possible to

explore the dynamics of occurrence of secondary delays in the schedule of trains and to estimate the number, point of occurrence, and duration. It is proposed, as a base for the developed method, to apply a mathematical model for the construction of non-cyclic train scheduling based on the multiagent optimization. To account for delay propagation on a railroad network of great dimensionality, we devised a procedure for connecting the interrelated sections, which makes it possible to decompose the general problem on the basis of the construction of a schedule of trains for separate estimated sections taking into consideration a network effect. It allows the automatization of one of the stages in making up a standard non-cyclic train timetable – defining the reserve in a standard train timetable, based on the prediction of consequences of train delays.

2. To analyze the impact of delay duration on the level of reliability of non-cyclic train scheduling, we studied the process of delay propagation for various scenarios of the occurrence of a delay using an example of the line Lyubotin–Sovnarkomivska–Poltava-South–Potoki of the Ukrainian railroad network. We performed analysis of the dynamics of propagation of secondary delays in a schedule of trains with detailed examination of changes in all parameters in time and space. The dependences were obtained of the number and duration of delayed trains on the point of occurrence in the train timetable along the estimated line. It was established that for the scenario of the primary delay of 35 minutes, the delay in odd direction with a cumulative total amounted to 52 minutes, while for the opposite direction, the total delay was 2 times longer and reached 103 minutes. This allowed us to conclude that the delay of train No. 162 at Vakulenci station is the most influential and requires allocating a time reserve in the standard train schedule in order to reduce the impact of a network effect on the work of several sections of the railroad line. The simulation results obtained correspond to the actual processes occurring at interdependence of trains when the timetable was fulfilled, which confirms the adequacy of the proposed procedure of simulation to the actual operation conditions of a railroad network with mixed movement of passenger and freight trains of different categories.

References

1. Lomotko D. V., Alyoshinsky E. S., Zambrybor G. G. Methodological Aspect of the Logistics Technologies Formation in Reforming Processes on the Railways // Transportation Research Procedia. 2016. Vol. 14. P. 27262–2766. doi: 10.1016/j.trpro.2016.05.482
2. Research into resistance to the motion of railroad undercarriages related to directing the wheelsets by a rail track / Tkachenko V., Sapronova S., Kulbovskiy I., Fomin O. // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 5, Issue 7 (89). P. 65–72. doi: 10.15587/1729-4061.2017.109791
3. Balanov V. O. Analiz faktorov, vliyayushchih na obespechenie dvizheniya gruzovyh poezdov po raspisaniyu // Transportni systemy ta tekhnolohiyi perevezen. 2015. Issue 10. P. 5–9.
4. Zharkov M. L., Parsyurova P. A., Kazakov A. L. Modelirovanie raboty stanciy i uchastkov zheleznodorozhnoy seti na osnove izucheniya otkloneniy ot grafika dvizheniya // Vestnik Irkutskogo gosudarstvennogo universiteta. 2014. Issue 6 (89). P. 23–31.
5. Büker T., Seybold B. Stochastic modelling of delay propagation in large networks // Journal of Rail Transport Planning & Management. 2012. Vol. 2, Issue 1-2. P. 34–50. doi: 10.1016/j.jrtpm.2012.10.001
6. Yan F., Goverde R. M. P. Stability and Robustness Analysis of Acyclic Timetable // 6th International Conference on Railway Operations Modelling and Analysis. Narashimo, 2015. P. 391–350.
7. Kliewer N., Suhl L. A note on the online nature of the railway delay management problem // Networks. 2010. Vol. 57, Issue 1. P. 28–37. doi: 10.1002/net.20381
8. Schwanhäusser W. Die Besessung der Pufferzeiten im Fahrplangefüge der Eisenbahn: PhD thesis. Veröffentlichungen verkehrswissenschaftl. Institut RWTH Aachen, 1974. H. 20.
9. Hansen I. A. Increase of capacity through optimised timetabling // Computers in Railways IX. 2004. P. 529–538.
10. Kecman P., Corman F., Meng L. Train delay evolution as a stochastic process // Proceedings of the 6th International Conference on Railway Operations Modelling and Analysis: RailTokyo2015. 2015. 19 p.
11. Yuan J., Goverde R. M. P., Hansen I. A. Evaluating stochastic train process time distribution models on the basis of empirical detection data // WIT Transactions on State of the Art in Science and Engineering. 2010. P. 95–104. doi: 10.2495/978-1-84564-500-7/09
12. Schwanhäußer W. DVWG (Hrsg.): Schriftenreihe der Deutschen Verkehrswissenschaftlichen Gesellschaft Leistungsfahigkeit und Kapazitat // DVWG Reihe B: Seminar Bd. 17. 1994. P. 3–17.
13. Vromans M. J. C. M. Reliability of Railway Systems: PhD thesis. Erasmus University Rotterdam, 2005. 258 p.
14. Sipilä H. Simulation of rail traffic – Methods for timetable construction, delay modeling and infrastructure evaluation: Doctoral Thesis in Infrastructure. Stockholm, 2015. 98 p.
15. Kettner M., Sewcyk B., Eickmann C. Integrating Microscopic and Macroscopic Models for Railway Network Evaluation // In Proceedings of European Transport Conference. Strasbourg, France, 2003. 11 p.
16. Goverde R. M. P. A delay propagation algorithm for large-scale railway traffic networks // Transportation Research Part C: Emerging Technologies. 2010. Vol. 18, Issue 3. P. 269–287. doi: 10.1016/j.trc.2010.01.002
17. Nash A., Huerlimann D. Railroad simulation using OpenTrack // Computers in Railways IX. 2004. P. 45–54.
18. Viriato – Software for railways // SMA und Partner AG. 2012. 34 p. URL: http://www.railsystemsengineering.com/RSE/documents/SMA%20Viriato%20Brochure.pdf
19. Umiliacchi S. Improving railway operations through the integration of macroscopic and microscopic modelling with optimisation: Thesis (Ph.D.). UK, 2016. 128 p.

20. Delay Propagation in a Real Life Railway Network Controlled by a Fuzzy Logic Rule Base / Farkas M., Héray T., Rózsa G., Kóczy T. L. // Magyar Kutatók 10. Ne mzetközi Szimpóziuma 10th International Symposium of Hungarian Researchers on Computational Intelligence and Informatics. 2009. P. 423–433.
21. Daganzo C. F., Laval J. A. Moving Bottlenecks: A Numerical Method that Converges in Flows // Institute of Transportation Studies and Department of Civil and Environmental Engineering University of California. Berkeley, 2003. 56 p.
22. Control Strategies for Dispersing Incident-Based Traffic Jams in Two-Way Grid Networks / Long J., Gao Z., Orenstein P., Ren H. // IEEE Transactions on Intelligent Transportation Systems. 2012. Vol. 13, Issue 2. P. 469–481. doi: 10.1109/tits.2011.2171035
23. A behavioural car-following safety model for microscopic simulation of traffic flow with various driving characteristics / Wang W. H., Zhang W., Guo H. W., Bubb H., Ikeuchi K. // Transportation Research Part C: Emerging Technologies. 2011. Vol. 19, Issue 6. P. 1202–1214. doi: 10.1016/j.trc.2011.02.002
24. Application of Epidemiology Model on Complex Networks in Propagation Dynamics of Airspace Congestion / Dai X., Hu M., Tian W., Xie D., Hu B. // PLOS ONE. 2016. Vol. 11, Issue 6. P. e0157945. doi: 10.1371/journal.pone.0157945
25. Nyström B. Aspects of Improving Punctuality From Data to Decision in Railway Maintenance: Doctoral Thesis. Sweden, 2008. 276 p.
26. UIC leaflet 406 R, Capacity. UIC International Union of Railways, France, 2e dition. Version traduite. List of recent publications. 2013. 60 p.
27. TsD-0040. Instruktsiya zi skladannia hrafika rukhu poizdiv na zaliznytsiakh Ukrainy. Kyiv: Transport Ukrainy, 2002. 164 p.
28. An assessment of railway capacity / Abril M., Barber F., Ingolotti L., Salido M. A., Tormos P., Lova A. // Transportation Research Part E: Logistics and Transportation Review. 2008. Vol. 44, Issue 5. P. 774–806. doi: 10.1016/j.tre.2007.04.001
29. Schachtebeck M. Delay management in public transportation: capacities, robustness, and integration: PhD thesis. Universität Göttingen, 2010. 240 p.
30. Landex A. Network effects in railway systems // Association for European Transport and contributors. 2007. Issue 12. P. 16–20.
31. Garey M. R., Johnson D. S. Computers and Intractability: a Guide to the Theory of NP-Completeness. Freeman, San Francisco, 1979. 215 p.
32. Morton T., Pentico D. W. Heuristic Scheduling Systems, with Applications to Production Systems and Project Management. New York, 1993. 153 p.
33. Butko T. V., Prokhorchenko H. O. Formuvannia protsedury avtomatyzatsiyi rozrobky hrafiku rukhu poizdiv na osnovi alhorytmu shtuchnykh bdzholynykh koloniyi // Zbirnyk naukovykh prats Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana. Transportni systemy ta tekhnolohiyi perevezen. 2015. Issue 9. P. 10–15.
34. A comprehensive survey: artificial bee colony (ABC) algorithm and applications / Karaboga D., Gorkemli B., Ozturk C., Karaboga N. // Artificial Intelligence Review. 2012. Vol. 42, Issue 1. P. 21–57. doi: 10.1007/s10462-012-9328-0
35. Rezervy vremeni pri organizacii dvizheniya gruzovyh poezdov po raspisaniyu / Kozachenko D. N., Berezoviy N. I., Balanov V. O., Zhuravel' V. V. // Nauka ta prohres transportu. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana. 2015. Issue 2. P. 105–115.