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Development of a method for studying the impact of the time reserve value on the reliability of the train schedule based on the epidemiological SIR model

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Abstract. It is important to find rational values of time reserves to compensate for delays during train movement to ensure train schedule reliability. This study proposes to investigate the impact of different categories of trains and their time reserve on schedule reliability. The main purpose of the study is to develop a method for studying the extent of the impact of time reserve on train schedule reliability based on the epidemiological model. Mathematical train delay propagation at the section model has been developed on the basis of the Susceptible – Infected – Removed (SIR) epidemiological model of adaptation type (taking into account the effect of using different train categories. It is suggested to use a binary genetic algorithm to search for parameters of delay propagation rate in the SIR model. According to a specially developed data acquisition algorithm, empirical data on the propagation of train delays at the station were obtained. Experimental studies have been carried out to search for train delay propagation velocity coefficients in the SIR model. The train movement restoration results during a delay at the station are given to study the impact of the time reserve value on train schedule reliability, taking into account the speed recovery delay set in the SIR model. The simulation results confirm the developed mathematical model adequacy.

1. Introduction
One of the important ways to increase the efficiency of rail transportation of goods and passengers is to ensure high quality indicators of basic transport services as a result of both constructive [1] and organizational measures [2, 3]. However, in railway systems with mixed traffic of passenger and freight trains with partial adherence to the timetable, there is a problem of ensuring the reliability of the transportation process. Improving the reliability of work schedules of train traffic is one of the important indicators of organizational decisions to ensure the competitiveness of railway transport. To achieve these indicators in the process of using the developed train schedule, it is necessary to conduct studies on the effect of train delays that may occur on the stability of movement of all other categories

of train flows. This will allow, at the stage of developing a working train schedule, to provide for temporary compensation zones with the possibility of restoring train movements, which are delayed with the least impact on network traffic. It should be noted that there are almost no effective methods for numerically determining the impact of trains of various categories and the size of their reserve time on the reliability of the train schedule without observing the freight train departure timetable. Taking into account that the mutual impact of train flows, in conditions of delays, on a railway section is nonlinear, characterized by a significant level of uncertainty, complicates the task of formalizing this process. Under such conditions, the goal is to develop a research method that will formalize the process of propagation of train delays on a railway line, taking into account the mutual impact of trains of various categories and the size of their reserve time. This will make it possible to assess the impact of delays that may occur on the section under the conditions of existing values of time reserves for finding rational parameters of the train schedule. As a result, based on the research results, it is possible to develop a method that will reduce subjectivity in making decisions on establishing the values of time reserves for various categories of trains with a mixed traffic system without observing the freight train departure schedule, and will increase the accuracy and speed of assessing the reliability of the train schedule before its implementation. This will ensure the stability of movement, high speed of trains, increase the capacity of the section and reduce the impact of delays on the stability of the line. Thus, studies aimed at improving the reliability of working train schedules for railway systems without adhering to the freight train departure timetable are relevant and have practical value.

2. Literature review and problem statement

A lot of work has been devoted to research in search of new effective methods for analyzing the effect of time reserves on the reliability of train schedules. In particular, in his studies author of [4] compares the effectiveness of various strategies for applying time reserves in Danish rail timetables to the recommendations of the UIC. In [5], based on an analysis of train delays on the railways of Holland, Switzerland, and Germany, threshold delays were determined for various categories of trains in these countries. There is research [6] focused on review of the state of practice and existing schedule planning procedures based on the rules of railway administrations from several European countries. A number of shortcomings were identified in the development of a motion schedule, one of which is the lack of effective modeling tools, optimization and data analysis methods for improving schedules. As part of the development of research methods for studying the impact of the time reserve value on the reliability of the train schedule, the accuracy of predicting the propagation of train delays in the network is important. Based on the analysis of various approaches for predicting the spread of train delays in the network, the following are distinguished: deterministic, stochastic, statistical.

Using the deterministic approach, it is possible to study the network response to delays, but its application does not allow for a realistic assessment of the dynamics of the distribution of delays of railway networks in which the planned train schedule is completely or partially missing [7]. The stochastic approach allows for more accurate and adequate prediction of the propagation of the delay [8], but requires verified input data regarding the parameters of the propagation of delays, which are not always possible to obtain. Many studies focus on statistical analysis of completed train schedules to find statistical patterns in the propagation of delays [9]. In addition, all approaches can be divided according to the level of detail into micro- and macro-modeling. Simulation models based on the principles of micromodeling provide more accurate results, but knowledge of the normative train schedule is important for their work. In the railway system of Ukraine and the like, freight trains depart from forming stations "on readiness" without observing the timetable, which complicates the analysis of the fulfillment of the train schedule for deviations from the standard transit time standards. It is for this type of movement that it is important to increase the reliability of the transportation process.

According to the analysis, which made it possible to identify the advantages and disadvantages of various approaches to modeling, the proposed macroscopic approach to modeling the propagation of

train delays is proposed for a railway system with partial observance of train schedules. One of the promising directions for modeling the propagation of train delays at the macro level is the use of modified epidemiological mathematical models used to simulate epidemics, the spread of viruses, and the like. A successful example of the application of the epidemiological model is [10], which proposed a mathematical SIR model for formalizing the congestion propagation on urban transit networks by a congestion susceptibility recovery process. However, the use of such a model for determining the time reserves in the schedule of movement of railway networks of mixed movement of passenger and freight trains without observing the latest timetables is impossible. The study [11] proposed an SIS model of epidemic spreading, which is able to reproduce the empirical distribution of train delays. This approach suggests the possibility of several delays for one train. The simulation results in terms of scheduled train traffic in the Italian railway network confirmed the adequacy of the mathematical model in the real processes of delay propagation. This proves the effectiveness of the chosen research area. Given that the macroscopic approach to modeling the propagation of train delays can more adequately describe the uncertainty of the parameters of the train flow system without observing the network traffic schedule, the main goal of the study is to develop a method for studying the impact of the time reserve on the reliability of the train schedule based on the epidemiological model.

3. Materials and methods

For railway systems not observing the freight train schedule, to which the Ukrainian railway belongs, the rules for establishing time reserves in the threads of trains of various categories are quite general, which requires studies of the impact of trains of various categories and the size of their time reserve on the reliability of the schedule on the section, taking into account that the most unexplored indicator is the time for recovery in the thread, distributed by the method of compensation for movement [12]. Compensation for movement consists of using the difference between the minimum train time for the section and the fact that the planned schedule contains a component – the regular addition time, which is attached to the train time for each section in accordance with the requirements of the infrastructure operator. The amount of addition time (time reserve) in different railway systems varies depending on the distance the train follows, the time it takes and the station to park. This reserve of time, when the train is late, allows for surge operation to accelerate the train in comparison with the planned schedule in order to reduce delay and avoid scenarios of cascading delays with significant costs. Figure 1 shows one of the possible practical examples of the application of surge operation in the event of an initial delay in the train schedule on a conditional double-track section A-B.

Upon departure from station B, freight train No. 2002 experienced an initial delay of $t_{\text{delay}} = 14$ minutes with two scenarios. Delay involves the development of a second scenario in which the stop of train No. 2002 at the station is inevitable in order to perform the overtaking operation (with 24 minutes of downtime) of passenger trains following a pack according to the normative schedule with the highest priority. If there is a reserve of time – compensation during movement, the course of events may change into scenario 1, which provides for the transfer of an order from the dispatcher to the freight train operator No. 2002 to accelerate the latter on the first stretch B-I of the second train by 2 minutes, on the second j-f – by 4 min; on the third f-e – by 5 minutes; on the fourth e-d – by 5 minutes; on the d-c – by 4 minutes, which will allow freight train No. 2002 to arrive at station A in accordance with the regulatory train schedule. One example of the development of scenarios in the practical conditions of the implementation of the motion graph proves the effectiveness of the existence of a reserve in the form of compensation time in the graph thread. However, if too long standby time is selected, the duration of the train occupying the infrastructure of the section increases, which leads to a decrease in the district speed and throughput of the section. Under such conditions, it is important to solve the problem of finding rational values of the compensation time in the threads of the train schedule of various categories. This will allow us to find a balance between the reliability of the traffic schedule and the practical throughput of the railway section.
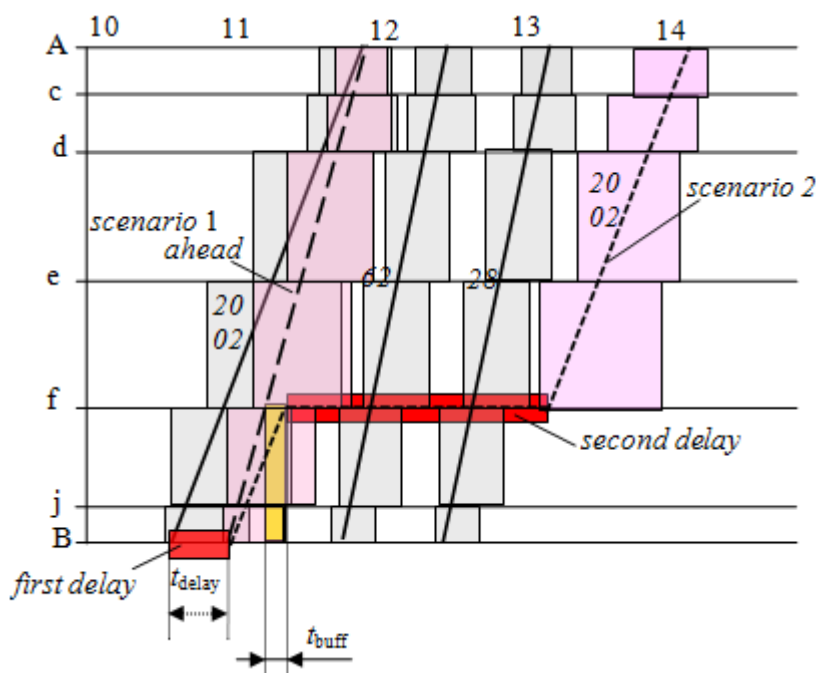
Figure 1. Scheme of train movement scenarios when a delay occurs on a double-track section: scenario 1 – implementation of the ahead operation; scenario 2 – overtaking with passenger trains.

To solve the problem of finding rational values of the compensation time in threads, it is proposed to apply the SIR-model (Susceptible-Infected-Removed model), which is used to model the spread of infectious diseases in a closed society, the spread of viruses in a computer network and cases of planned exposure on an agent in social networks [13]. Adapting this model to the problem of the impact of train delays on the railway network, it is possible to imagine the spread of infectious diseases as the process of spreading train delays and the associated effect on the movement of trains on the railway network. Within the framework of the adopted statement of the problem, to describe the effect of the time reserve in the train schedule threads of various categories, it is proposed to present the total number of trains in the calculation section in three states, each of which represents an outstanding stage in the development of delay propagation.

Thus, the total number of train threads (freight and passenger) should be divided into groups: $S(t)$ – delay-sensitive trains, which at time t follow the schedule but can be delayed when moving on the section (Susceptible) $I(t)$ – train, following with a delay infecting the movement of other trains, passing on a delay (Infected) $R(t)$ – train, during the passage through the railway section with a delay, compensated for the delay, followed the schedule, and did not cause the occurrence of delays in further movement (Removed). Figure 2 shows a graph of the process of transition of trains between states on the site.
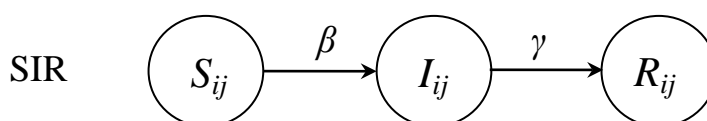

Figure 2. Graph of the transition process of trains between states in the section.

Given the importance of taking into account the different priority of traffic on a section of trains of various categories, it is proposed to expand the state groups into subgroups-classes in accordance with their category r. For a mixed model of site operation, in this study it is proposed to take into account the following categories of trains: $r=1$ – passenger trains; $r=2$ – community trains, $r=3$ – freight trains. According to current rules [14], the priority hierarchy corresponds to the indicated sequence of categories. It has been suggested that trains of each class have the same characteristics of delay transmission and motion recovery processes.

According to [15] a mathematical model can be written as a system of differential equations of the form

$$\begin{cases} \dfrac{dS^r(t)}{dt} = -\sum_l \beta^{r,l} S^r(t) I^l(t); \\ \dfrac{dI^r(t)}{dt} = \sum_l \beta^{r,l} S^r(t) I^l(t) - \gamma^r I^r; \\ \dfrac{dR^r(t)}{dt} = -\gamma^r I^r, \end{cases} \tag{1}$$

where S^r – the number of opportune trains in class r on the section, trains; $\beta^{r,l}$ – propagation speed of the delay from class r trains to class l trains in the area where $r = l, r, l \in R$; I^l – the number of infected class l trains in the section, trains; R^r – the number of class r trains that followed with a delay, but removed it, trains; γ^r– delay recovery speed in class r trains on a section; t – time or simulation step, hour. All system parameters have positive values.

The system of equations has a standardization condition of the form $N^r = S^r(t) + I^r(t) + R^r(t)$, where N^r – the total number of class r trains in the section $N = \sum N^r$, N – the total number of trains of all classes in the section. The initial conditions for the system (1) are the level $(S_0^r, I_0^r, 0)$, where S_0^r, I_0^r – the number of favorable and delayed class r trains in the section at $t = 0$, respectively.

Important parameters of the system (1) are the propagation rate of delay from trains $\beta^{r,l}$ and the recovery rate of delay in class r trains in section γ^r. In this study, it is proposed to conduct studies in the following sequence: at the first stage, develop a method for searching for parameters $\beta^{r,l}$ on the delay data of the real section, and then model the propagation of the delay with different delay recovery rates.

It is proposed to use the method of evolutionary calculations, in particular, the binary genetic algorithm, BGA [16], to search for parameters of the delay propagation velocity in the system of differential equations (1). In general, the parameter search problem $\beta^{r,l}$ can be represented as an optimization problem of the form

$$\begin{aligned} F(\beta) &\to \min \\ g(\beta) &= 0, \\ h(\beta) &\le 0, \ \beta \in \Re^n, \end{aligned} \tag{2}$$

where F – the objective function estimates between empirical values of the number of infected (delayed) trains I^r and model I_m^r obtained by solving the system of differential equations (1) taking into account the given initial conditions corresponding to real ones; $g(\beta) = 0$; $h(\beta) \le 0$ – the restriction of equality and inequality, respectively, corresponding to the problem statement by solving the system (1). Within the framework of solving the optimization problem (2) in the system (1), the parameters $\gamma^r = 0$.

To implement the optimization problem (2) within the framework of the genetic algorithm, the model variables are presented in the form of a fixed-length chromosome, taking into account the restrictions on their ranges and putting them into one numerical vector

$$C^h = \left(\beta^{1,1}, \beta^{1,2}, \beta^{1,3}, \beta^{r,l}, \dots, \beta^{3,3} \right), \tag{3}$$

where $h = \overline{1,K}$ – the chromosome number C, $\beta^{r,l} \in \{3 \times 3\}$ or $C^h = [1 \times 9]$, and the variable has limitations $0 \le \beta^{r,l} < 1$. The solution of the system of differential equations (1) within the fitness function of the BGA is proposed to be performed using the fourth-order Runge-Kutta method [17]. The criterion for evaluating the selection of variables in the optimization problem (2) applied the average absolute error (MAPE) between the empirical and the results [18]

$$F(\beta) = \frac{1}{M} \sum_{M,r} \frac{|I^r(t) - I_m^r(t)|}{I_m^r(t)} 100\% \to \min \tag{4}$$

where the indicator $F(\beta)$ is not defined for zero values $I_m^r(t)$, M – the number of rows of vectors of experimental data of the sample $\langle \bar{X}_q, \bar{y}_q \rangle$, $q = \overline{1,M}$; $I^r(t)$ – output sample vector $\langle \bar{X}_q, \bar{y}_q \rangle$, $I^r(t) \in \bar{y}_q$; $I_m^r(t)$ – the result of solving the system of differential equations (1) under initial conditions $(S_0^r, I_0^r, 0)$, corresponding to the q-th line of the sample $\langle \bar{X}_q, \bar{y}_q \rangle$, $(S_0^r, I_0^r, 0) \in \bar{X}_q$.

4. Results

To be able to obtain accurate data on the distribution of the number of delayed trains over time on the calculated railway section, taking into account the various categories of trains, a special data acquisition algorithm was developed. To generate train delays of various categories and their distribution in the traffic schedule, an optimization mathematical model [19] was used in this work. According to the developed procedure, the simulation of the distribution of train delays in the work schedule for 2017-2018 years was performed on the Liubotyn - Sovnarkomivska regional branch of the Southern Railway branch of Ukrzaliznytsya JSC. This section is a bottleneck in the movement of trains to stations of the Kharkov railway junction.

In the experimental studies, three scenarios were constructed according to which the delay of one train from the adopted class r was simulated with constant parameters of the infrastructure and the normative schedule. The delay was modulated in the odd direction of movement for the departure from the Lyubotyn station with a value of 25.17 minutes, according to the research of [19]. Initial conditions at $t = 0$ for modeling $N^{r=1} = 9$ trains, $N^{r=2} = 4$ trains, $N^{r=3} = 32$ trains. Visualization of the graphs of the dependences of the number of delayed trains of different classes with a cumulative total from the moment the model delay of the passenger train occurs is shown in figure 3.
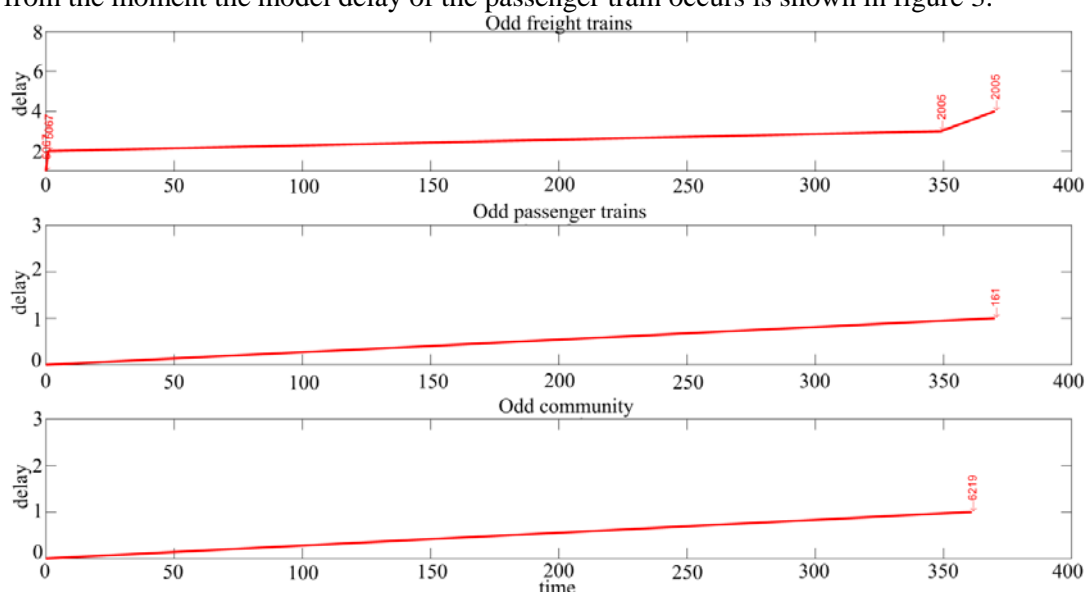

Figure 3. The dependence of the number of delayed trains of different classes with a cumulative total from the moment of model delay of passenger train No. 161 in the odd direction of movement on the Liubotyn - Sovnarkomivska section.

With the delay of one community train, the consequences are much less compared to the delay of the passenger train, which has a higher priority (figure 4).
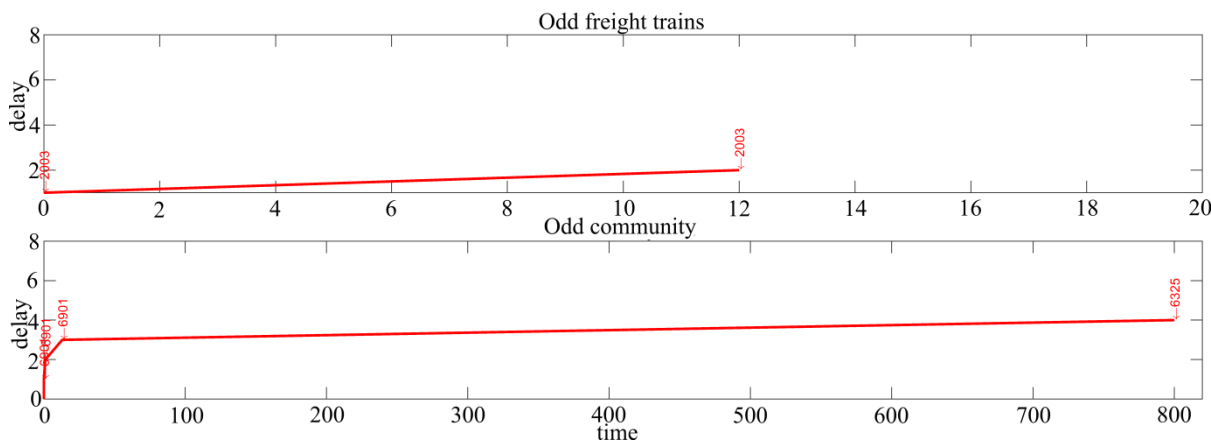

Figure 4. The dependence of the number of delayed trains of different classes with a cumulative total from the moment of model delay of the passenger train No. 161 in the odd direction of movement.

Delay of a freight train caused a cascade of delays of other freight trains in the section with the same high priority. Having the highest priority, passenger trains avoided delays, while one community train fell into the cargo delay zone, which was a consequence of its delay (figure 5).
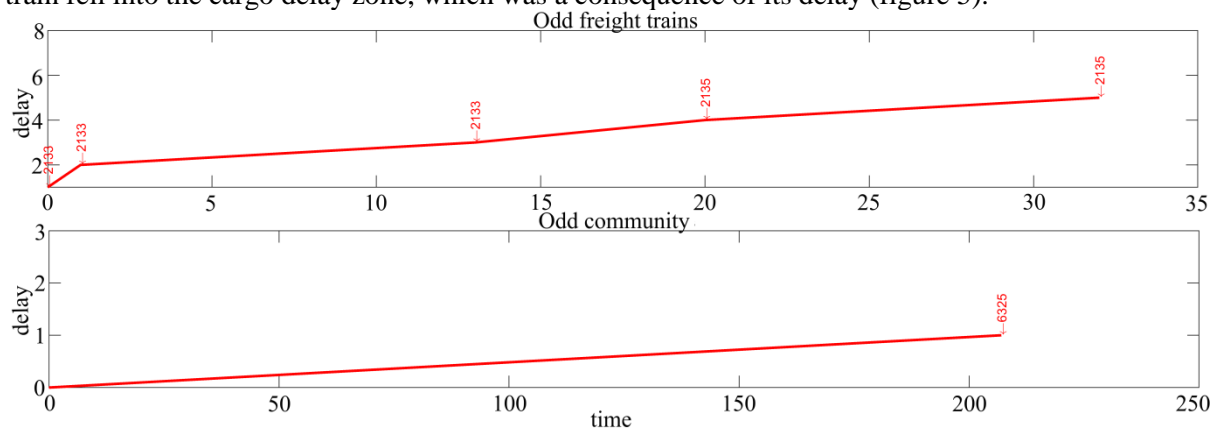

Figure 5. The dependence of the number of delayed trains of different classes with a cumulative total from the moment of model delay of the freight train No. 161 in the odd direction of movement.

The obtained data are presented as a set of vectors $\langle \bar{X}_q, \bar{y}_q \rangle$ for converting time from minutes to hours. The data are used to search for delay propagation velocity parameters in a system of differential equations by decoupling the optimization model (2) using the BGA method in the MATLAB environment. Visualization of the dynamics of changes in the values of the fitness function of BGA is shown in figure 6.

On the basis of the results of the decoupling of the optimization model (2), the following coefficients are found; $\beta^{1,1} = 0.0004$; $\beta^{1,2} = 0.0011$; $\beta^{1,3} = 0.0001$; $\beta^{2,1} = 0.0012$; $\beta^{2,2} = 0.1784$; $\beta^{2,3} = 0.0015$; $\beta^{3,1} = 0.0001$; $\beta^{3,2} = 0.0001$; $\beta^{3,3} = 0.0023$. The magnitude of the coefficients characterizes the impact of some categories of trains on others, and allows for numerical evaluation of the mutual impact of trains of different priorities in the train schedule.
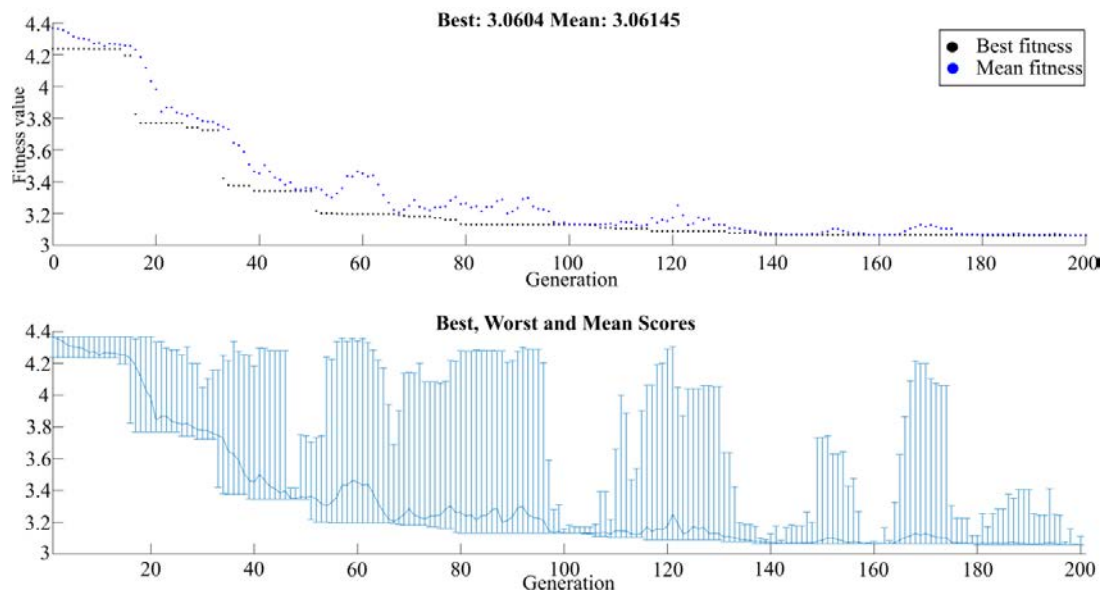
Figure 6. A graph of the best and average values of the objective function F versus the number of BGA iterations in the process of selecting delay propagation velocity coefficients.

According to the given input conditions $\langle \bar{X}_q, \bar{y}_q \rangle$, three delay scenarios ($q = 3$), the empirical results of which are shown in figures 3-5 and model results are obtained, which are shown in figure 7. The average absolute error (MAPE) between empirical and with the results is 3%, which is a high result.
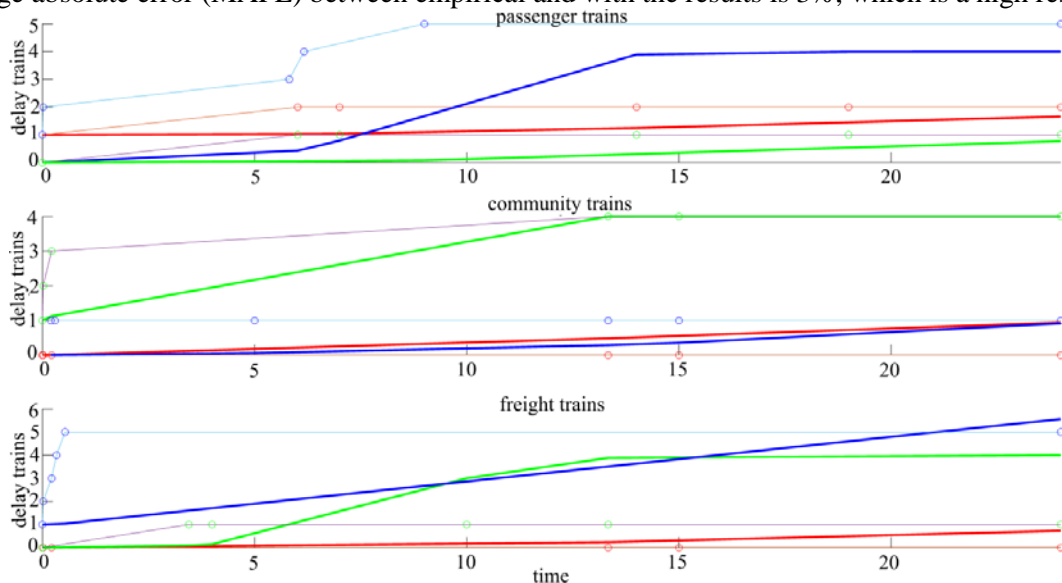

Figure 7. A comparative graph of the dynamics of the number of delayed trains between empirical values I^r and model I_m^r according to the three delay scenarios in accordance with $\langle \bar{X}_q, \bar{y}_q \rangle$ the calculated section: thin line with circles – empirical values I^r; bold line – model values I_m^r; red colour – passenger trains r=1; green colour – community trains r=2; blue colour – freight trains r=3.

To study the effect of the time reserve on the reliability of the train schedule, the experimental results of modeling the restoration of train movement in the area under study were carried out. It is proposed to change the initial conditions – to delay 5 passenger trains out of the 9 trains available, $I^{r=1}$ (t=0) = 5 trains. Based on current standards, use the following parameters of the delay recovery speed for trains of class r in the section $\gamma^{r=1} = 0.05$; $\gamma^{r=2} = 0.0667$; $\gamma^{r=3} = 0.10$. Initial conditions at $t =$

0 for modeling $N^{r=1} = 9$ trains, $N^{r=2} = 4$ trains, $N^{r=3} = 32$ trains. The coefficients of the propagation velocity of the delay $\beta^{r,l} \in \{3 \times 3\}$ are taken in accordance with the given values of the decoupling of the optimization problem in Section 6 of this article.

The solution of the developed system of equations of the SIR model makes it possible to obtain the results of the restoration of train movement in the event of a delay of five passenger trains on the Liubotyn - Sovnarkomivska line (figure 8).
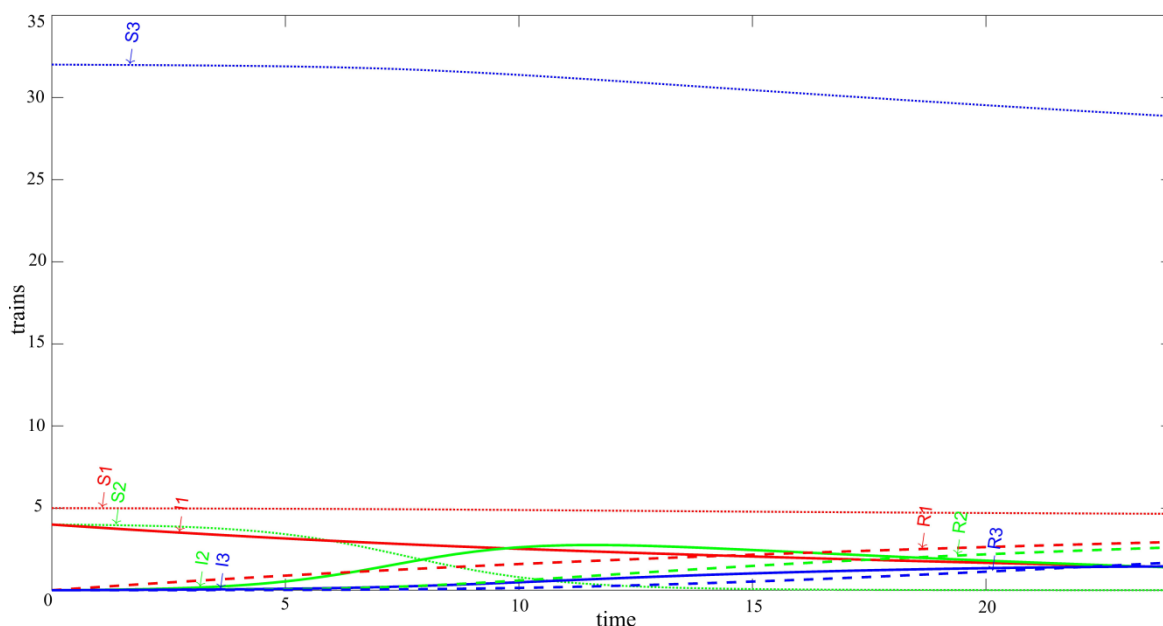

Figure 8. Graph of the dynamics of changes in the state of train flows under the conditions of restoration of train movement during the day (t = 24 hours) when there is a delay of five passenger trains on the Liubotyn – Sovnarkomivska line: red – passenger trains r=1; green – community trains r=2; blue – freight trains r=3.

The initial conditions and the value of the states of trains of different classes r on the line at t =24 hours are shown in table 1.

Table 1. The results of modeling the restoration of train movement during the day (t = 24 h) in the event of a delay of five passenger trains on the Liubotyn – Sovnarkomivska line.

States	Passenger trains, r=1	Community trains, r=2	Freight trains, r=3
Susceptible, S^r(t=0)	4	4	32
Infected, I^r(t=0)	5	0	0
Removed, R^r(t=0)	0	0	0
Susceptible, S^r(t=24)	3.699	0.003	28.735
Infected, I^r(t=24)	1.683	1.356	1.483
Removed, R^r(t=24)	3.618	2.641	1.783

The numerically determined effect of trains of various categories and the value of their time reserve on the reliability of the traffic schedule on the line was investigated for the first time. Of the five trains that were delayed, with a compensated recovery time of 20 minutes, it was possible to restore movement of 47% of the total number of trains detained. At the same time, the delay of five passenger

trains (the highest priority of traffic) led to delays of other trains. The set recovery time for suburban and important trains made it possible to restore movement of 51% and 83% of trains, respectively, of the total number of delayed trains.

5. Discussion and conclusion

According to the results of this research, the process of propagating train delays on the railway line was formalized. This allowed to investigate how trains of different categories and the size of their time reserves were affected the reliability of the traffic schedule. The obtained results of modeling the recovery of train movement on the section indicate that the proposed method for studying the impact of the amount of the reserve time on the reliability of the train schedule based on the modified epidemiological SIR model permits to obtain numerical results with acceptable accuracy based on the macroparameters of the transportation process. The advantage of the proposed research method based on macromodeling is its versatility and the ability to gain knowledge about complex nonlinear processes of interaction between train flows in the event of delays from the historical data of previous periods of operation of the section. The proposed method for finding the coefficients of the propagation speed of the delay in the system of differential equations of the SIR-model allowed for the first time to numerically determine the mutual interaction of trains of different priority in the train schedule. It has been found out that the transfer rate of delay from passenger trains with the highest priority freight trains is 0.0001, while the transfer rate between freight trains is much higher and is 0.0023. This can be attributed to the better planned timetable for passenger trains with large intervals from freight trains. Whereas freight trains are quantitatively significantly predominant, and their movement is poorly planned, which leads to significant mutual interaction. Based on the simulation results, for the first time, the numerically determined impact of the availability of trains of various categories and the size of their reserve time on the reliability of the traffic schedule on the line. With a compensation time set in the schedule of 20 minutes for passenger trains and a delay of five, it is possible to restore the movement of 47% of trains of the total number of detained ones. The established recovery time for suburban and freight trains allowed 51% and 83% of restored trains to be, respectively, of the total number of detained trains. The simulation results confirmed the adequacy of the developed method.

The disadvantages of the developed method include the need to adjust the parameters of the mathematical SIR model for each area of the investigated. To improve this approach, it is necessary to conduct additional research on the application of machine learning methods to obtain knowledge from the historical data of the operation of lines. It will increase the versatility of the approach to conducting research on grouping in terms of the operational parameters of various sections on the network. This will make it possible to reduce the dimension of the problem and speed up the calculations by using the found parameters of the SIR model for lines that are similar in terms of performance to each other.

From a practical point of view, the application of the proposed mathematical SIR-model, taking into account the different priorities of train traffic, will allow to automate the complex process of searching for rational values of compensation time on the lines of trains of various categories for train schedules of railway lines within the software applications. This will allow to increase the punctuality and reliability of regulatory train schedules.

References

[1]   Fomin O, Lovska A, Pistek V and Kucera P 2020 Research of stability of containers in the combined trains during transportation by railroad ferry *MM Science Journal* **03** 3728

[2]   Matsiuk V et al 2019 Improvement of efficiency in the organization of transfer trains at developed railway nodes by implementing a "flexible model" *Eastern-European Journal of Enterprise Technologies* **2/3**(98) pp 32–9

[3]   Moroz M M, Korol S O and Boiko Y O 2016 Social traffic monitoring in the city of kremenchuk *Actual Problems of Economics* **175** pp 385–98

[4]   Schittenhelm B 2011 *Planning with timetable supplements in railway timetables* (Trafikdagepå Aalborg Universitet) p 18
[5]   Kroon L G, Dekker R and Vromans M J C 2007 Cyclic railway timetabling: a stochastic optimization approach, railway optimization *Springer Verlag* **4359** pp 41–66
[6]   Olsson N O E and Hiselius L W 2018 The Planners' perspective on train timetable errors in Sweden *Journal of Advanced Transportation* **8502819** 17
[7]   Kariyazaki K, Hibino N and Morichi S 2013 Simulation analysis of train operation to recover knock-on delay under high-frequency *13th WCTR (Rio de Janeiro: Brazil)* pp 1–14
[8]   Yuan J, Goverde R M P and Hansen I A 2006 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* **40** pp 95–104
[9]   Rößler D, Reisch J and Kliewer N 2019 Modeling delay propagation and transmission in railway networks *14th Int. Conf. on Wirtschaftsinformatik (Siegen, Germany)* pp 98–112
[10]   Zeng Z and Li T 2018 Analyzing congestion propagation on urban rail transit oversaturated conditions: a framework based on SIR epidemic model *Urban Rail Transit* **4** pp 130–40
[11]   Monechi B, Gravino P, Di Clemente R and Servedio V D P 2018 Complex delay dynamics on railway networks from universal laws to realistic modeling *EPJ Data Science* **7** 35
[12]   *UIC leaflet 406 R Capacity UIC International Union of Railways* 2013 (France 2e édition) p 60
[13]   Diekmann O and Heesterbeek J A P 2000 *Mathematical Epidemiology of Infectious Diseases* (Chisteter: UK/John Wiley&Sons)
[14]   *Rules of technical operation of railways of Ukraine* 1996 (Kyiv: Ministry of Transport of Ukraine) p 132
[15]   Watson R K 1972 On an epidemic in a stratified population *Journal of Applied Probability* **9** pp 659–66
[16]   Sivanandam S and Deepa S 2008 *Genetic Algorithm Implementation Using Matlab. In: Introduction to Genetic Algorithms* (Berlin, Springer)
[17]   Hunt B R, Lipsman R L, Osborn J E and Rosenberg J M 2019 *Differential Equations with Matlab* (3rd Edition) 304
[18]   Spanos A 1999 *Probability Theory and Statistical Inference: Econometric Modeling with Observational Data* (University of Cyprus) p 844
[19]   Butko T, Prokhorchenko A, Golovko T and Prokhorchenko G 2018 Development of the method for modeling the propagation of delays in noncyclic train scheduling on the railroads with mixed traffic *Eastern-European Journal of Enterprise Technologies* **1/3(91)** pp 30–9