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Method and Algorithm of the Automatic Warning System of Train Approaches to Railways

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***Abstract*— This paper presents an analysis of train warning systems on railway sections. Automatic signaling devices for the approach of trains to the railway sections through the railway rail chains, centralized complex information systems to inform passengers through communication speakers in the railway and station fleet, and automatic sound from the approach of trains and shunting vehicles to the workplace. the principles of operation of notification systems are studied. The causes of the accidents that are currently taking place on the railway sections have also been studied. Research has shown that it is proposed to change the method of the warning system and its algorithm, as it is not possible to warn pedestrians walking around the tracks with automatic warning systems for the approach of trains to the railway sections.**

In addition to the warning systems of signaling centralization blocking devices, in order to warn passengers or pedestrians wearing headphones around the railway about the approach of the train and reduce the number of accidents related to the railway: installation of noise generators in the cabins of rolling stock; installation of internal and external surveillance cameras to record driver movements and external movements; it is proposed to increase the illumination distance of locomotive lights and use an audible signal.

The article examines the operation algorithm of the method of warning passengers or pedestrians walking around the railway with headphones on the approach of the train, and the safety and reliability of the operation process using the Markov chain.

Keywords*—*train, station, railway crossings, signaling centralization blocking, noise generator, pedestrian, passenger

I. INTRODUCTION

Automation and telemechanics systems are used to ensure the safety of trains on railway sections: railway crossings, stations, hauls and pedestrian crossings [1-2].

Currently, the world's railways have developed systems to warn wild animals about the approach of trains to railway stations. It examines ways to prevent wild animals from colliding with trains on railway tracks and in the vicinity of railway tracks, using devices to warn trains of approaching railway tracks [3-19].

However, in today's automated and telemechanics systems that warn of approaching trains, it is not possible to send warning signals to passengers traveling along the tracks (Fig. 1) that the train is approaching, hitting passengers who use the tracks as a corridor and passengers crossing the tracks sending cases are increasing.

Today, the Commonwealth of Independent States (CIS) is located on long-distance stations using automation and telemechanics systems and devices that warn of the approach of different types of trains on the railways during the working hours of the staff, as well as small and large stations equipped with electric centralization, automatic warning signals of approaching vehicles are transmitted by radio to the areas served by employees, pedestrian and passenger areas. If in the sections where the railroad switches are located, there are road workers, not signaling centralization blocking (SCB) staff, in which case the shunt is connected to the railroad switch section where the railroad switch is located, and the message in the form of "music" is constantly repeated by radio communication. If the shunt is lost in the railroad switch section, the message "connect the shunt" is repeated over the radio [4-7].

The station duty officer (SDO) will be equipped with a notification panel along with the radio station. The shunt can be stored in the SDO and given to the employee during the employee's working hours on the railroad switch [4-7].

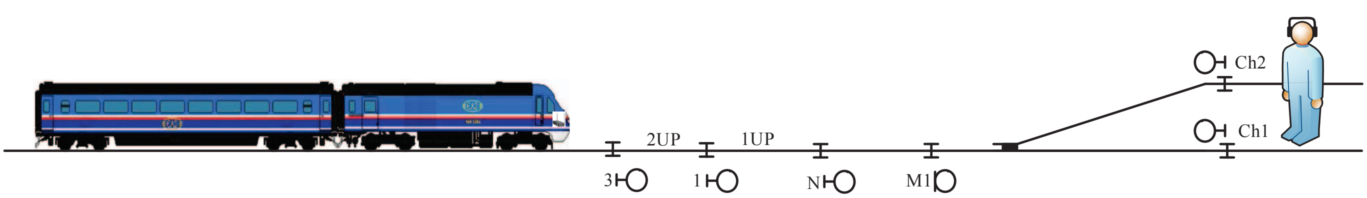

Fig. 1. Approach of trains to railway sections.

On hauls equipped with auto-locking, the contacts of the track relays, the contacts of the signal and warning relays can perform the functions of sensors to determine the location of the train. Railroad tracks, on the other hand, can serve as a channel for transmitting warning information to the workplace. This allows you to use the existing auto-locking system with maximum efficiency, implemented in accordance with the requirements of the highest reliability of technical means [2-14].

Studies have shown that rail tracks can be used as a reliable means of communication. The use of rail tracks as a communication channel reduces the external interference of warning systems to electrical circuits, communication devices and SCB systems and ensures their compatibility.

The approach of different types of trains on the railways is closely linked to the existing autoblocking systems and devices, and their connections, devices and their current sources are used.

Alarm devices provide automatic activation of warning signals about the approach of the train at a certain distance to the workplace, have high reliability and noise protection, work in various weather conditions and emergencies [3-14].

A centralized integrated data system is also used in the railway and station fleet to communicate through communication speakers. The system is based on a two-way communication channel of the dynamic warning park and visual information monitors (boards, lights), based on the data obtained from the control of train safety, to ensure the safety of passengers at railway stations, passenger platforms and stops at railway stations. is designed to automatically notify you of the approaching content:

- time of receipt (dispatch) of rolling stock together with the serial number of passenger and suburban trains;
- the approach of self-propelled vehicles on the railway;
- to ensure the safety of passengers in emergencies and other situations related to the maintenance and safety of passengers.

Existing automation and telemechanics warning systems when trains are approaching have the following advantages:

- safety of equipment maintenance workers will be increased;
- easily and clearly informs employees about the approaching train;
- due to the operation of radio waves of different frequencies, it is possible to connect the radio stations of many employees to the alarm systems;
- the system is easily adaptable, adapting to a particular landfill and local operating conditions;
- warning systems do not require additional equipment when used as part of relay, microprocessor-based electrical interlocking and dispatch interlocking systems;
- cable laying is not required when using the radio channel;
- works with the station's dispatch control system;
- the system can be used not only to send a voice message to the personnel servicing the devices, but also to the passengers and staff on the station platform to inform them that the train is approaching or for any other purpose.

Depending on the location of the train on the route, two types of voice messages can be sent:

- from the moment the route is set, until the train enters the previous section of the route, an audible message "Set to receive/send the route from the even (odd) side" is given;
- "Attention, train" will be sounded from the moment of occupying the section of the previous route until the section at the beginning of the route is occupied and the section is separated.

The SDO activates the notification distance on the control panel or automated workplace where the work is performed. Thereafter, when the train approaches the active distance, when the train enters the approach section and the neck of the station, the corresponding audible warning signals are sent to the radio station of the equipment service personnel brigade or to the dynamic loud alarm system[3-14].

II. A Method of Applying an Automatic Warning System for the Approach of a Train on Railway Sections

At railway stations, on hauls with autoblocking and semi-automatic interlocking systems, at railway crossings, at the workplaces of employees on the haul or station and at pedestrian crossings, wearing a headphones the method and algorithm of the system, which automatically transmits information about the approach of trains to ensure the safety of passengers, crossing the rails and railway personnel, are shown in Fig. 2 and Fig. 3.

In this proposed warning system, a noise generator is generated to locomotives moving on railway sections to send a high-frequency signal to passengers walking on the tracks with headphones, crossing the railway inadvertently, using or crossing the tracks as a corridor, sitting on the rails. , surveillance cameras are installed to record driver movements and outside movement. Two-way video surveillance will be able to prevent accidents and ensure the safety of train traffic and human life on railway sections.

III. Algorithm of Automatic Warning System of Train Approach on Railway Sections

The algorithm of the automatic approach warning system on railway sections is as follows: when the train is approaching the railway sections, the information about the approach of trains is sent to passengers, pedestrians and railway workers in the form of signals or messages through signaling interlocking systems and devices (Fig. 3).

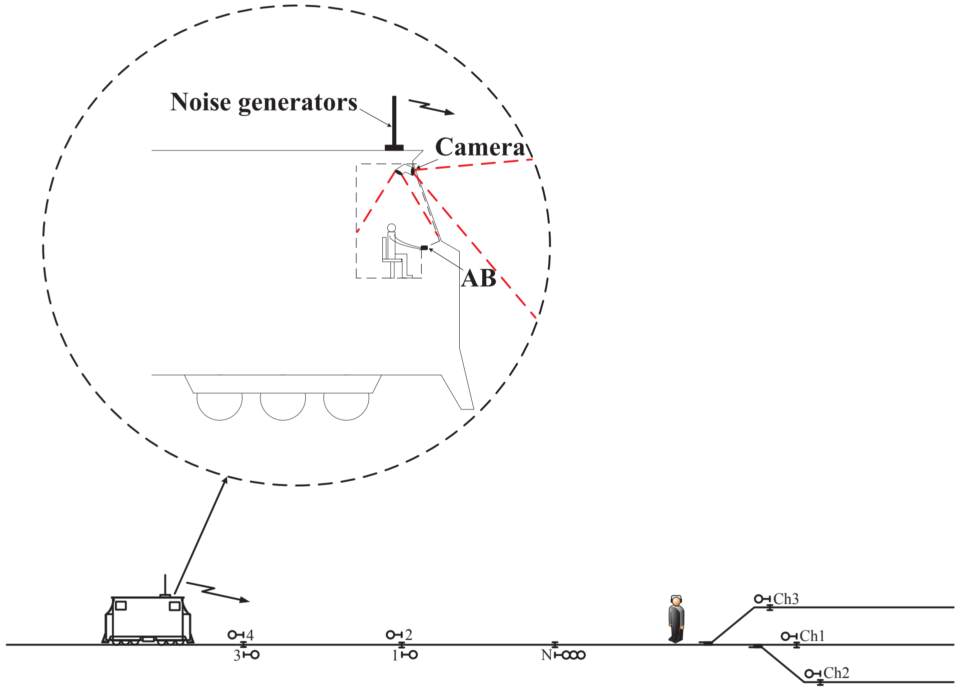

Fig. 2. Automatic warning of approaching passengers and pedestrians with headphones on railway sections.

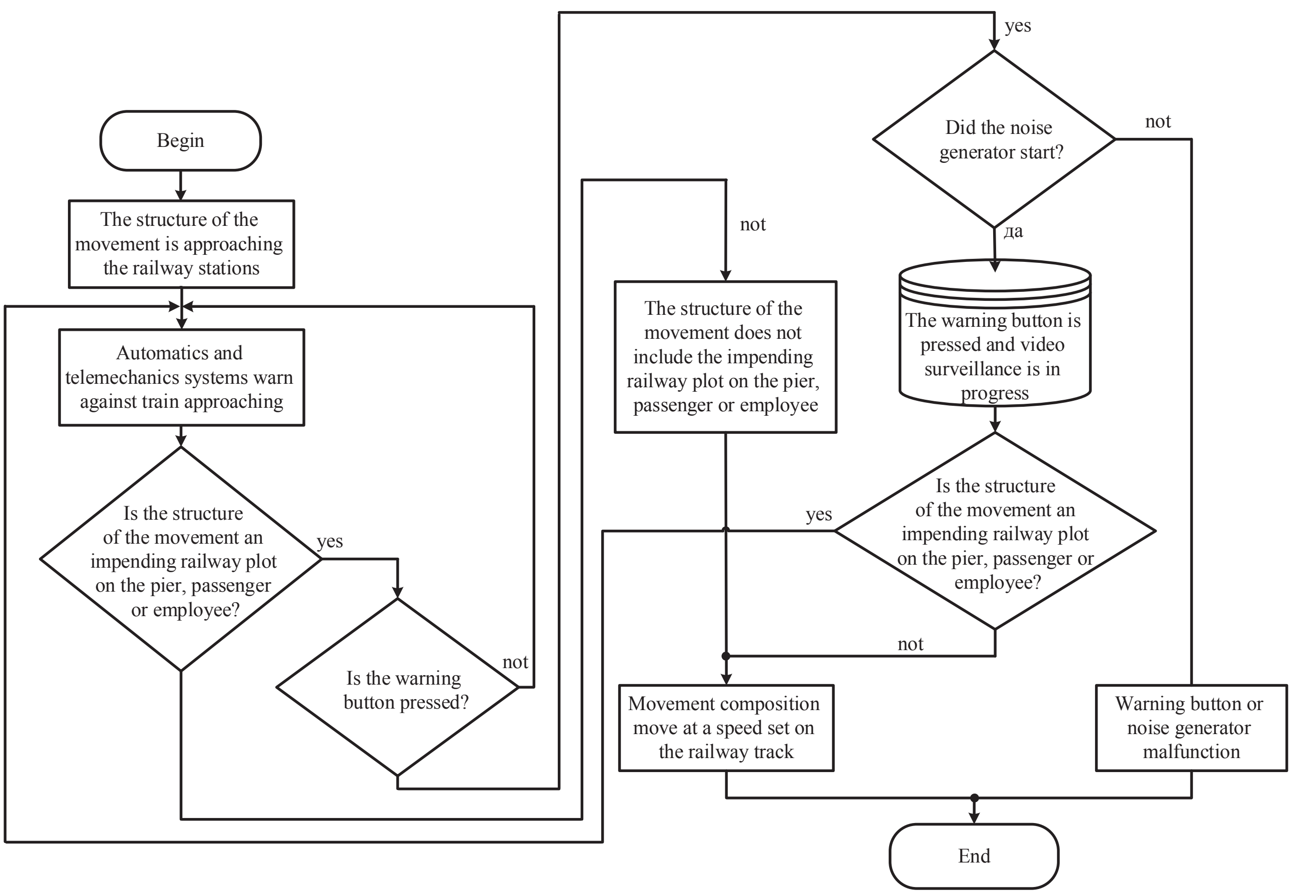

Fig. 3. Algorithm of operation of the system of warning of trains approaching railway sections.

If pedestrian, passenger and railway workers do not obey the warning signals of SCB devices and systems, then the AV button in Fig. 2 is pressed to warn pedestrian, passenger and railway workers and the noise generator is activated. The noise generator sends a high-frequency signal to pedestrians, passengers, and railroad workers who are wearing headphones and turns off speech or music through the headset, resulting in a person traveling on a railroad track not being able to use the headset. At this time, the pressing of the AV button and the start of the noise generator is sent to the database and a two-way video is recorded and an audio signal is sent (the first image records the driver's movements in the train cabin, the second video footage of pedestrian, passenger and railway workers on the railway section)takes.

If the noise generator does not start when the AV button is pressed, the approach of trains to the railway sections is warned by the SCB system or device.

IV. Mathematical Substantiation of Safety of Automatic Warning System of Train Approach on Railway Sections

SCB systems and devices automatically notify the approach of trains to the railway sections. However, as noted above, we mathematically substantiate the operation of a system that automatically uses a headset as a corridor for pedestrians and an automatic warning system for passengers crossing the tracks as trains approach them using the Markov chain [19-21]. To do this, it is necessary to include several cases in accordance with the process of sending trains approaching the railway sections (Fig. 4):

1 – The SCB warning system is in good condition, and information about the approach of trains is being sent to people wearing headphones around the railway.

2 - When the SCB warning system fails, information about the approach of trains is sent to people wearing headphones around the railway.

3 – In the case of the SCB warning system, information about the approach of trains will not be sent to people wearing headphones around the railway.

4 - If the SCB warning system fails, information about the approach of trains will not be sent to people wearing headphones around the railway.

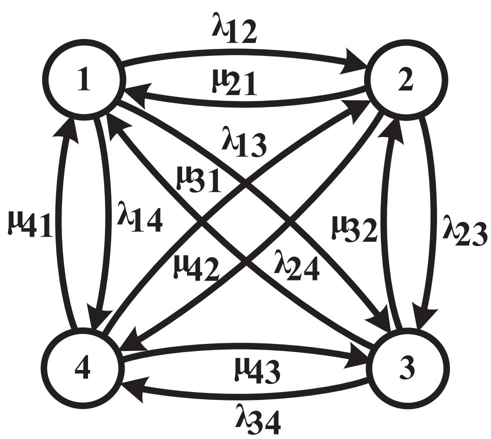

Fig. 4. Diagram of the status of the scb warning system on the markov chain and the dependencies in the process of sending a message about the approach of trains to people wearing headphones around th e railway.

In accordance with the processes of sending trains approaching stations, we can determine the performance of the processes that link several cases to each other. We need to take the maximum travel speed of trains on the section as well as the maximum length of the data transmission distance as indicators of the connecting processes. In this case, when sending information about the approach of trains to the railway sections and the operation of SCB warning systems, the rates of occurrence of the above-listed cases are as follows. Here:

$\lambda 12$ - Intensity of transition from SCB warning system and train approaching information to people wearing headphones around the railway, SCB warning system failing and train approaching information being sent to people wearing headphones around the railway;

$\mu 21$ - SCB warning system in case of failure, train approaching information is sent to people wearing headphones around the railway, SCB warning system in good condition, train approaching information is sent to people wearing headphones around the railway, the average time it takes to recover;

$\lambda 13$ - SCB warning system is in good condition, information about the approach of trains is sent to people wearing headphones around the railway, SCB warning system is in good condition, information about the approach of trains is not sent to people wearing headphones around the railway;

$\mu 31$ - SCB warning system is in good condition, train approaching information is not sent to people wearing headphones around the railway, SCB warning system is in good condition, train approaching information is sent to people wearing headphones around the railway, the average time it takes to recover;

$\lambda 23$ - SCB warning system in case of failure, information about the approach of trains is sent to people wearing headphones around the railway, SCB warning system is in good condition, information about the approach of trains is not sent to people wearing headphones around the railway;

$\mu 32$ - SCB warning system is in good condition, trains approaching information is not sent to people wearing headphones around the railway, SCB warning system is faulty, train approaching information is sent to people wearing headphones around the railway, the average time it takes to recover;

$\lambda 34$ - The SCB warning system is in good condition, information about the approach of trains is not sent to people wearing headphones around the railway, SCB warning system is out of order, information about the approach of trains is not sent to people wearing headphones around the railway;

$\mu 43$ - The average time it takes for the SCB warning system to return to a state where it is not sent to people wearing headphones, the SCB warning system is in a state where the information about the approach of trains is not sent to people who wear headphones;

$\lambda 14$ - SCB warning system is in good condition, information about the approach of trains is sent to people wearing headphones around the railway, SCB warning system is out of order, information about the approach of trains is not sent to people wearing headphones around the railway;

μ41 - The average time it takes for the SCB warning system to be sent to people wearing headphones when the SCB warning system is out of order is not being sent to the people who wear headphones around the railway;

In accordance with the dependence of the state of the SCB warning system on the Markov chain and the process of sending a message to people wearing headphones around the railway about the approach of trains, we create the Fokker-Planck (Kolmogorov) equation by recording them using differential equations:

$$\begin{cases} \frac{dP_1(t)}{dt} = -\lambda_{12} \cdot P_1(t) + \mu_{21} \cdot P_2(t) - \lambda_{13} \cdot P_1(t) + \mu_{31} \cdot P_3(t) - \lambda_{14} \cdot P_1(t) + \mu_{41} \cdot P_4(t), \\ \frac{dP_2(t)}{dt} = \lambda_{12} \cdot P_1(t) - \mu_{21} \cdot P_2(t) - \lambda_{23} \cdot P_2(t) + \mu_{32} \cdot P_3(t) - \lambda_{24} \cdot P_2(t) + \mu_{42} \cdot P_4(t), \\ \frac{dP_3(t)}{dt} = \lambda_{13} \cdot P_1(t) - \mu_{31} \cdot P_3(t) - \lambda_{34} \cdot P_3(t) + \mu_{43} \cdot P_4(t) + \lambda_{23} \cdot P_2(t) - \mu_{32} \cdot P_3(t), \\ \frac{dP_4(t)}{dt} = \lambda_{14} \cdot P_1(t) - \mu_{41} \cdot P_4(t) + \lambda_{34} \cdot P_3(t) - \mu_{43} \cdot P_4(t) + \lambda_{24} \cdot P_2(t) - \mu_{42} \cdot P_4(t) \end{cases} \quad (1)$$

$$P_1(t) + P_2(t) + P3(t) + P_4(t) = 1,$$

where: P_1, P_2, P_3, P_4 - probabilities of occurrence of 1, 2, 3, 4 cases.

When we change the expression of equation (1) to the Laplace equation, we get the expression in (2).

$$\begin{cases} s \cdot P_1 - 1 = -\lambda_{12} \cdot P_1 + \mu_{21} \cdot P_2 - \lambda_{13} \cdot P_1 + \mu_{31} \cdot P_3 - \lambda_{14} \cdot P_1 + \mu_{41} \cdot P_4, \\ s \cdot P_2 = \lambda_{12} \cdot P_1 - \mu_{21} \cdot P_2 - \lambda_{23} \cdot P_2 + \mu_{32} \cdot P_3 - \lambda_{24} \cdot P_2 + \mu_{42} \cdot P_4, \\ s \cdot P_3 = \lambda_{13} \cdot P_1 - \mu_{31} \cdot P_3 - \lambda_{34} \cdot P_3 + \mu_{43} \cdot P_4 + \lambda_{23} \cdot P_2 - \mu_{32} \cdot P_3, \\ s \cdot P_4 = \lambda_{14} \cdot P_1 - \mu_{41} \cdot P_4 + \lambda_{34} \cdot P_3 - \mu_{43} \cdot P_4 + \lambda_{24} \cdot P_2 - \mu_{42} \cdot P_4 \end{cases} \quad (2)$$

(2) expression of the equation to the Laplace table $F(s)=1/s \rightarrow f(t)=1$ mainly by modifying (3):

$$\begin{cases} \lambda_{12} \cdot P_1 - \mu_{21} \cdot P_2 + \lambda_{13} \cdot P_1 - \mu_{31} \cdot P_3 + \lambda_{14} \cdot P_1 - \mu_{41} \cdot P_4 = 1, \\ \lambda_{12} \cdot P_1 - \mu_{21} \cdot P_2 - \lambda_{23} \cdot P_2 + \mu_{32} \cdot P_3 - \lambda_{24} \cdot P_2 + \mu_{42} \cdot P_4 = 0, \\ \lambda_{13} \cdot P_1 - \mu_{31} \cdot P_3 - \lambda_{34} \cdot P_3 + \mu_{43} \cdot P_4 + \lambda_{23} \cdot P_2 - \mu_{32} \cdot P_3 = 0, \\ \lambda_{14} \cdot P_1 - \mu_{41} \cdot P_4 + \lambda_{34} \cdot P_3 - \mu_{43} \cdot P_4 + \lambda_{24} \cdot P_2 - \mu_{42} \cdot P_4 = 0 \end{cases} \quad (3)$$

In the mathematical calculation of the probability of occurrence of each case in the resulting expressions, we calculate the solution of expression (4) by setting the following boundary condition $P_i(t)|_{t\to\infty}$:

$$P_1 = P_1(t)|_{t\to\infty} = \frac{\dfrac{-(\lambda_{23} + \lambda_{24} + \mu_{21})(\lambda_{32} + \lambda_{34} + \mu_{31})(\mu_{41} + \mu_{42} + \mu_{43}) + \lambda_{24}\mu_{42}(\lambda_{32} + \lambda_{34} + \mu_{31})}{-(\lambda_{12} + \lambda_{13} + \lambda_{14})(\lambda_{23} + \lambda_{24} + \mu_{21})(\lambda_{32} + \lambda_{34} + \mu_{31})(\mu_{41} + \mu_{42} + \mu_{43}) - } - (\lambda_{23} + \lambda_{24} + \mu_{21})(\lambda_{32} + \lambda_{34} + \mu_{31})(\mu_{41} + \mu_{42} + \mu_{43}) + \lambda_{24}\mu_{42}(\lambda_{32} + \lambda_{34} + \mu_{31})}{\lambda_{24}\mu_{42}(\lambda_{32} + \lambda_{34} + \mu_{31})(\lambda_{12} + \lambda_{13} + \lambda_{14}) - \lambda_{14}\mu_{21}\mu_{32}\mu_{43} - \lambda_{13}\lambda_{24}\mu_{42}\mu_{31} + \lambda_{14}\lambda_{23}\mu_{32}\mu_{41} + \lambda_{12}\lambda_{34}\mu_{21}\mu_{43}}$$

$$P_2 = P_2(t)|_{t\to\infty} = \frac{\dfrac{\lambda_{14}\mu_{32}\mu_{43} -}{-(\lambda_{12} + \lambda_{13} + \lambda_{14})(\lambda_{23} + \lambda_{24} + \mu_{21})(\lambda_{32} + \lambda_{34} + \mu_{31})(\mu_{41} + \mu_{42} + \mu_{43}) -} - \lambda_{12}\lambda_{34}\mu_{43}}{-\lambda_{24}\mu_{42}(\lambda_{32} + \lambda_{34} + \mu_{31})(\lambda_{12} + \lambda_{13} + \lambda_{14}) - \lambda_{14}\mu_{21}\mu_{32}\mu_{43} - \lambda_{13}\lambda_{24}\mu_{42}\mu_{31} + \lambda_{14}\lambda_{23}\mu_{32}\mu_{41} + \lambda_{12}\lambda_{34}\mu_{21}\mu_{43}} \quad (4)$$

$$P_3 = P_3(t)\mathrm{l}_{t\to\infty} = \frac{\lambda_{13}\lambda_{24}\mu_{42}}{-(\lambda_{12}+\lambda_{13}+\lambda_{14})(\lambda_{23}+\lambda_{24}+\mu_{21})(\lambda_{32}+\lambda_{34}+\mu_{31})(\mu_{41}+\mu_{42}+\mu_{43})-\lambda_{24}\mu_{42}(\lambda_{32}+\lambda_{34}+\mu_{31})(\lambda_{12}+\lambda_{13}+\lambda_{14})-\lambda_{14}\mu_{21}\mu_{32}\mu_{43}-\lambda_{13}\lambda_{24}\mu_{42}\mu_{31}+\lambda_{14}\lambda_{23}\mu_{32}\mu_{41}+\lambda_{12}\lambda_{34}\mu_{21}\mu_{43}}$$

$$P_4 = P_4(t)\mathrm{l}_{t\to\infty} = \frac{-\lambda_{14}\lambda_{23}\mu_{32}}{-(\lambda_{12}+\lambda_{13}+\lambda_{14})(\lambda_{23}+\lambda_{24}+\mu_{21})(\lambda_{32}+\lambda_{34}+\mu_{31})(\mu_{41}+\mu_{42}+\mu_{43})-\lambda_{24}\mu_{42}(\lambda_{32}+\lambda_{34}+\mu_{31})(\lambda_{12}+\lambda_{13}+\lambda_{14})-\lambda_{14}\mu_{21}\mu_{32}\mu_{43}-\lambda_{13}\lambda_{24}\mu_{42}\mu_{31}+\lambda_{14}\lambda_{23}\mu_{32}\mu_{41}+\lambda_{12}\lambda_{34}\mu_{21}\mu_{43}}$$

V. CONCLUSION

The analysis of the above-mentioned systems shows that today's automatic train warning systems do not have the ability to warn passengers who are walking on the tracks with their headphones on, carelessly crossing the railway, sitting on the rails.

In addition to the warning systems of SCB devices, the scientific article proposes the following in order to warn passengers or pedestrians walking around the railway wearing headphones about the approach of the train and to reduce the number of possible accidents related to the railway:

- installation of noise generators in the cabins of rolling stock;

- installation of internal and external surveillance cameras to record the driver's movements and external movements;

- increase the illumination distance of locomotive lights and the use of audible signals;

The article identifies the algorithm of operation of the method of warning passengers or pedestrians walking around the railway wearing headphones and the safety and reliability of the operation using the Markov chain.

REFERENCES

[1] A. B. Nikitin, S. T. Boltaev, A. M. Glybovskiy, “Specific features of realisation of interlocking functions for high-speed trains on hybrid lines,” News of the St. Petersburg University of Railway Transport, vol. 13, is. 2(47), pp. 215–228, Jun 2016. DOI: 10.20295/1815-588x-2016-2-115-128.

[2] A. Nikitin, A. Manakov, S. Boltayev, Modernization of running lines for high-speed traffic management on the basis of RFID-technology application. Bulletin of Scientific Research Results, vol. 1, pp. 132–142, March 2018. DOI: 10.20295/2223-9987-2018-1-132-142.

[3] S. V. Shchelkonogov, “Analysis of modern and promising warning systems for track workers about the approach of rolling stock,” Young Scientist, vol. 6, no. 41, pp. 61-63, June 2012. [Online]. Available: https://moluch.ru/archive/41/4977 / (accessed: 09.02.2022).

[4] Research Laboratory of Computer Automation Systems. [Online]. Available: https://nilksa.ru/orp-mpk/.

[5] Computer Railway Technology Center Emperor Alexander I St. Petersburg State Transport University. [Online]. Available: https://crtc.ru/index.php.

[6] Research and Design Institute of Informatization, Automation and Communication in Railway Transport. [Online]. Available: http://www.vniias.ru/.

[7] M. B. Alekseev, “Digital centralization - the basis of digital control,” Automatics, Communications, Informatics, vol. 1, pp. 14-15, January 2019.

[8] Standard Materials for the Design of 410106 - TMP "Warning systems for path fitters for various EC systems", GUP Giprotranssignalsvyaz - 2001, Album 1-4.

[9] V. M. Ulyanov, etc. “Automatic device for notification of the approach of rolling stock,” Automatics, Communications, Informatics, vol. 5, pp. 38-42, May 2001.

[10] V. G. Novikov and I. I. Alabushev, “Coordinate control and notification system,” Bulletin of the Research Institute of Railway Transport, vol. 1, pp.45-48, February 2008.

[11] D. V. Ananyev and I. A. Tarasov, “Centralized CISOP information system,” Automatics, Communications, Informatics, vol. 1, pp. 39-41, January 2018.

[12] V. I. Zorin, I. I. Alabushev, and V. G. Novikov, “Distance meters in train safety devices,” Automatics, Communications, Informatics, vol. 10, pp. 25-26, October 2007.

[13] S. V. Bibikov, M. E. Markisonov, and S. A. Panasyuk, “Modern mobile train approach notification system,” News of Higher Educational Institutions. Instrumentation, vol. 2, is. 56, pp. 24-28, February 2013.

[14] A. N. Slyunyaev, D. V. Ananyev, V. S. Andrienko, and I. D. Blinder, “Centralized information and notification system,” Automatics, Communications, Informatics, vol. 8, pp. 6-12, August 2012.

[15] J. A. J. Backs, J. A. Nychka, and C. C. St. Clair, “Warning systems triggered by trains could reduce collisions with wildlife,” Ecological Engineering, vol. 106 pp. 563-569, September 2017. DOI: 10.1016/j.ecoleng.2017.06.024.

[16] S. Terabe, T. Kato, H. Yaginuma, N. Kang, and K. Tanaka, “Risk Assessment Model for Railway Passengers on a Crowded Platform,” Transportation Research Record: Journal of the Transportation Research Board, vol. 2673, is. 1, pp. 524–531, January 2019. DOI: 10.1177/0361198118821925.

[17] C. M. Rudin-Brown, M. F. S. George, and J. J. Stuart, “Human factors issues of accidents at passively controlled rural level crossings,” Transportation Research Record: Journal of the Transportation Research Board vol. 2458, issue 1, pp. 96-103, January, 2014. DOI: 10.3141/2458-12.

[18] J. A. J. Backs, J. A. Nychka, and C. C. S. Clair, “Warning systems triggered by trains increase flight-initiation times of wildlife,” Transportation Research Part D: Transport and Environment, vol. 87, pp. 1- 11, October 2020. DOI: 10.1016/j.trd.2020.102502.

[19] A. Toruń, A. Lewiński, P. Gradowski, “Modeling of ETCS levels with respect to functionality and safety including polish railways conditions,” in: J. Mikulski (eds), Telematics - Support for Transport. TST 2014. Communications in Computer and Information Science, vol. 471, Springer, Berlin, Heidelberg, October 2014, pp. 11–18. DOI: 10.1007/978-3-662-45317-9_2.

[20] Yu. E. Obzherin, S. M. Sidorov, and S. N. Fedorenko, “Semi-Markov model of a technical system with the component-wise instantly replenished time reserve,” MATEC Web of Conferences, vol. 224, p. 04008, 30 October 2018. DOI: 10.1051/matecconf/201822404008.

[21] S. G. Glech, S. M. Sidorov, and M. M. Nikitin, “Semi-Markov model of a technical system with maintenance and time reserve,” IOP Conf.Series: Materials Science and Engineering, vol.709, is. 3, 033028, January 2020. DOI: 10.1088/1757-899X/709/3/033028.