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IMPROVING METHODOLOGY FOR ASSESSING ACCIDENT INDICATORS INVOLVING PEDESTRIANS AT RAILROAD PEDESTRIAN CROSSINGS

Vitalii Kovalchuk
Corresponding author
Doctor of Technical Sciences, Professor*
E-mail: kovalchuk.diit@gmail.com
ORCID: https://orcid.org/0000-0003-4350-1756
Yulia Lesiv
PhD Student, Assistant**
ORCID: https://orcid.org/0000-0003-2732-100X
Ihor Mohyla
PhD, Associate Professor**
ORCID: https://orcid.org/0000-0001-9710-6191
Andrii Kuzyshyn
Doctor of Philosophy (PhD)*
ORCID: https://orcid.org/0000-0002-3012-5395
*Department of Railway Transport***
** Department of Transport Technologies***
***Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

This study assesses a method for estimating the final accident rate at railroad pedestrian crossings depending on the intensity of train and pedestrian traffic and taking into account the geometric and planning features of the pedestrian crossing and information support.

An improved method for estimating the accident rate at railroad pedestrian crossings has been proposed, taking into account the set of factors influencing the safety of pedestrian traffic when crossing railroad tracks. The method is based on determining the final accident rate, which integrates eight key factors that make it possible to define the level of danger of the crossing according to established standards. The method takes into account the intensity of train and pedestrian traffic, the information and technical equipment of the railroad pedestrian crossing, as well as the planning and geometric parameters of the crossing. It also considers the speed of pedestrians depending on their physiological and age characteristics.

Multivariate modeling of the influence of train and pedestrian traffic intensity on the final accident rate has been carried out; the effectiveness of using information systems for warning pedestrians about the approach of a train in the pedestrian traffic safety system was also assessed.

It was established that the average value of the reduction in the accident rate at railroad pedestrian crossings within the existing railroad crossings depends on the intensity of train and pedestrian traffic. When using an additional information system for warning pedestrians about train traffic, taking into account the influence of train traffic intensity, it is up to 22.1, and taking into account the influence of pedestrian traffic intensity with a constant number of train pairs, it is 27.74. The use of the information system for warning pedestrians about train traffic ensures a reduction in the accident rate of up to 30%. This increases the safety of pedestrian traffic when crossing railroad tracks

Keywords: railroad crossing, accident rate, pedestrian traffic intensity, train traffic intensity

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1. Introduction

Ensuring the safety of pedestrians when crossing railroad tracks is one of the most urgent tasks in railroad transport, especially under conditions of increasing intensity of pedestrian traffic and trains [1]. A significant proportion of traffic accidents with serious consequences occur precisely with the participation of pedestrians who cross railroad tracks both within the existing railroad crossings and beyond them. To improve the safety of pedestrians on railroads, railroad pedestrian crossings (RPCs) are installed. Fig. 1 shows a view of the crossing arranged on the Lviv railroad.

In scientific papers [2–4] it has been established that such crossings are often characterized by an insufficient level of information and technical equipment, limited visibility of trains, unfavorable planning and geometric parameters and disregard for the behavioral characteristics of pedestrians. In addition, the age and physiological properties of pedestrians have a significant impact on ensuring the level of pedestrian safety, which affect the maximum speed of pedestrian movement at railroad pedestrian crossings.

The main factors influencing the provision of pedestrian safety indicators at the level crossing are the intensity of train and pedestrian traffic. The application of information support for the level crossing is effective; it includes the use of information boards, light and sound signaling. The visibility of the train by pedestrians from the level crossing, the longitudinal slope of the approaches, and the parameters of the railroad track plan on the approaches to the level crossing also affect the safety indicators of pedestrian traffic. In addition, the safety of pedestrians is ensured by the speed of pedestrians and trains, the quality of the constructed railroad pedestrian crossing and the length of the crossing, which depends on the number of tracks.

Fig. 1. Railroad pedestrian crossing over a double-track section of the Lviv Railroad

Each of the above factors of influence on pedestrian safety indicators is described by partial accident coefficients. Based on the method of evaluating the final accident coefficient [5, 6], the level of pedestrian safety when moving along a railroad pedestrian crossing is assessed. Fig. 2 shows the safety levels of a railroad pedestrian crossing depending on the value of the final accident coefficient K_a. According to [5], the value of the final accident coefficient $K_a < 40$ indicates a safe crossing. In the case when the inequality $40 < K_a < 60$ is satisfied – the RPC is not very safe; when $61 < K_a < 80$ – the RPC is dangerous, and when $K_a > 81$ – the RPC is very dangerous. Therefore, at $K_a < 40$, it is considered that the safety indicators of pedestrian traffic on RPC are ensured.

Safe	Not very safe	Dangerous	Very dangerous
До 40	41 – 60	61 – 80	More than 81
Value of the final accident coefficient K_a			

Fig. 2. Safety levels of railroad pedestrian crossings depending on the value of the final accident rate coefficient K_a

Current methodologies for assessing the level of traffic safety in Ukraine, in particular the method of the final accident rate [5], focus mainly on road transport and are based on the analysis of road accident statistics. The application of these methods to railroad pedestrian crossings is limited as they do not take into account the intensity of pedestrian traffic, the speed of pedestrians, as well as the specificity of the "pedestrian-train" interaction when pedestrians cross railroad tracks.

Analysis of the results from international scientific research [6, 7] has revealed that ignoring a set of behavioral, geometric, and infrastructural factors distorts the assessment of the level of danger. In addition, it leads to an underestimation of real risk values and prevents the formation of effective and justified decisions on improving safety at railroad pedestrian crossings.

During the analysis of statistical data, it was found that the majority of railroad accidents involving pedestrians have serious or fatal consequences [2]. Therefore, solving problems aimed at increasing the safety of pedestrians when crossing railroad tracks is a relevant task, which could make it possible to preserve the lives and health of pedestrians.

2. Literature review and problem statement

Some studies focus on the relationship between the geometry and operational parameters of crossings and pedestrian and cyclist violations. In [4], the authors, based on observations at railroad crossings, showed that the radius of the curve, the longitudinal slope of the approaches, the speed of trains, and the organization of pedestrian approaches significantly affect the probability of violations. In particular, crossing at prohibited signals and bypassing barriers. However, the issues of interpolating the intensity of train and pedestrian traffic into the accident rate with pedestrians when crossing railroad tracks remained unresolved.

The regulatory framework of the transport industry [5] lacks a clearly defined and legally enshrined concept of "railroad pedestrian crossing". This complicates the identification of such objects as part of the railroad infrastructure, their classification, and the establishment of unified requirements for safety and technical equipment. The basic tool for quantitative assessment of the level of traffic safety in transport is the methodology of determining the final accident rate [5]. It is based on the analysis of traffic accident statistics, the identification of dangerous areas by exceeding the limit values of the accident rate, and the subsequent justification of engineering and technical measures to improve traffic safety.

Studies aimed at taking into account the role of the human factor when crossing railroad crossings are reported in [6], which analyze the behavior of pedestrians who are distracted by the use of mobile devices, as well as the interaction of pedestrians and cyclists with the crossing infrastructure. The authors found that distraction (listening to music, using a smartphone, etc.) is a common phenomenon at railroad pedestrian crossings. At the same time, this has a dynamic nature, which is manifested in the following: some pedestrians stop distracting actions on the approach to the crossing, while others, on the contrary, activate them already when crossing the tracks, which makes it difficult to predict the risk.

In international scientific literature, the issue of ensuring and improving pedestrian safety on railroads is increasingly being considered through the prism of intelligent transport systems (ITS), behavioral and cognitive decision-making models [7]. Based on experimental studies [7], the authors showed that the design, color, shape, and type of message on warning signs for pedestrian railroad crossings significantly affect the probability of risky decisions. At the same time, successfully selected message combinations can reduce the share of violations by tens of percent. However, in work [7], no studies of the intensity of pedestrian and train traffic on the accident rate with pedestrians were conducted.

In [8, 9] it is emphasized that the absence of a formalized term for RPC leads to the consideration of pedestrian routes across the tracks as secondary elements of the transport system, or infrastructure "barriers". This, in turn, limits the possibilities of integrating safety measures when planning railroad crossings.

In [10] it is stated that the existing methodology [5] is focused on the interaction of "car – car (pedestrian)" under the conditions of the street-road network and does not take into account the specificity of pedestrian traffic across railroad tracks.

In [11], the scientific and methodological foundations of ensuring traffic safety on railroad transport are presented. It systematizes the factors that affect the level of accidents at crossings, in particular the technical condition of the infrastructure, the organization of traffic and the human factor. It also proposes approaches to assessing the state of safety taking into account operating conditions. However, the work does not provide a methodology for assessing the accident rate with pedestrians when crossing railroad tracks.

In [12], the feasibility of using integral indicators for safety analysis and identification of dangerous sections of railroad crossings is emphasized. However, the problems of ensuring pedestrian safety when crossing railroad tracks within railroad pedestrian crossings are not considered.

Further development of methodological approaches to assessing safety when crossing roads and railroads at the same level is given in [13, 14]. In particular, a methodological approach to assessing the safety of vehicle traffic at crossings is proposed, which is based on the analysis of operational and planning-geometric parameters of the crossing, traffic intensity, and visibility conditions. In [13], the necessity of adapting such methods to modern conditions of increasing traffic intensity and complication of transport processes is emphasized. The feasibility of introducing innovative technologies during the modernization of existing crossings, especially in the conditions of organizing high-speed train traffic, is substantiated, and the positive impact of modern technical means on increasing the level of safety is shown. However, the studies only assess the safety of vehicle traffic at level crossings, without taking into account pedestrian traffic.

The European Union Directive [15] stipulates that railroad infrastructure entities must use scientifically sound risk management methods. In parallel, studies are developing that consider pedestrian safety more broadly – in the context of urban mobility and sustainable development [16, 17]. However, the studies highlighted in [15–17] do not cover the problematic part of establishing the patterns of influence of train and pedestrian traffic intensity, as well as planning and geometric parameters of a pedestrian railroad crossing on the accident rate with pedestrians.

In [18], a comprehensive review of factors influencing pedestrian behavior and safety was conducted, emphasizing the importance of considering demographic characteristics (age, health status, cultural characteristics) when designing infrastructure and developing pedestrian safety measures. Although the study focused mainly on urban street crossings, its conclusions can be used in the context of railroad crossings. The age and physiological characteristics of users also determine the chosen crossing strategies and the time interval of stay in the high-risk zone.

In general, works [18, 19] demonstrate a trend towards a transition from simple "engineering" models based only on geometry and traffic intensity to integrated behavioral and technical models. At the center of the model is the pedestrian safety indicator, which is determined by the combined influence of traffic flow parameters, infrastructure characteristics [19], pedestrian behavior, and risk perception, as well as the actions of intelligent warning systems and adaptive traffic management tools. The interrelation of these components demonstrates the complex nature of risk formation and the need to simultaneously take them into account when assessing the accident rate and devising measures to improve safety at railroad pedestrian crossings. However, the issues of interpolating the intensity of train and pedestrian traffic into the accident rate with pedestrians when crossing railroad tracks remained unresolved.

Thus, our review of the literature [4–19] shows that the existing approaches are mostly focused on assessing the safety of vehicle traffic. At the same time, the specificity of pedestrian flows, the intensity of train traffic, the age and behavioral characteristics of pedestrians, as well as the complex influence of planning and geometric parameters of railroad pedestrian crossings remain insufficiently studied. This necessitates the further development of methods for assessing the accident rate with pedestrians when crossing railroad tracks at railroad pedestrian crossings. It follows that the problem of improving the method for determining the accident rate with pedestrians at railroad pedestrian crossings remains unresolved. In this case, the method must take into account the intensity of pedestrian and train traffic, the age and physiological characteristics of pedestrians, as well as the planning and geometric parameters of the railroad pedestrian crossing, and its information support for warning pedestrians about the movement of a train.

3. The aim and objectives of the study

The aim of our work is to improve the method for assessing the accident rate with pedestrians when crossing railroad tracks within the existing railroad crossings and beyond them. This will make it possible to increase the safety of pedestrians when crossing railroad tracks, taking into account the intensity of train and pedestrian traffic and information support of the crossing.

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

– to improve the approach to assessing the accident rate at railroad pedestrian crossings, taking into account the intensity of traffic and characteristics of the crossing

– to establish the patterns of changes in the final accident rate at railroad pedestrian crossings located within the existing railroad crossings, taking into account and without taking into account information from the pedestrian warning system about train traffic;

– to conduct a study on the final accident rate at railroad pedestrian crossings located outside existing crossings.

4. The study materials and methods

The object of our research is a method for estimating the final accident rate at railroad pedestrian crossings depending on the intensity of train and pedestrian traffic and taking into account the geometric and planning features of the pedestrian crossing and information support.

The principal hypothesis assumes that there is a functional relationship between the final accident rate at railroad pedestrian crossings and a set of operational and planning factors. These include such factors as the intensity of train and pedestrian traffic, geometric and planning parameters of the crossing, and the provision of the crossing with an information warning system. Therefore, it is assumed that improving the method for estimating the final accident rate by comprehensively taking into account these factors could ensure an increase in the reliability of assessing the level of danger of crossings. It would also make it possible to establish quantitative patterns of changes in the accident rate depending on the variation of individual parameters and their interaction. As a result of the implementation of this method, scientific foundations could be formed for substantiating engineering and organizational measures to improve safety at railroad pedestrian crossings.

For a multivariate assessment of the final accident rate at railroad pedestrian crossings, a calculation was performed within the existing railroad crossings. In this case, crossings with an information warning system (IWS) and without an IWS warning pedestrians about the movement of the train are considered, as well as at the level crossing outside existing crossings. Fig. 3 shows schemes for arranging railroad pedestrian crossings across the railroad track within an existing crossing; and Fig. 4 – outside an existing crossing.

The establishment of patterns of changes in the total accident rate at the level crossing was carried out depending on the intensity of train traffic (N_t) and pedestrians (N_p) crossing the level crossing. The study assumes that artificial lighting is available at crossings. The radius of the curve of the railroad track in the plan on the approaches to the level crossing is 200 m, and the longitudinal slope of the road on the approaches is 20%. The distance of visibility for a pedestrian of the train is 300 m. The intensity of pedestrian traffic is assumed to be variable N_p = 1–300 people/h. Pedestrians are mainly young people, their average speed is 5.4 km/h.

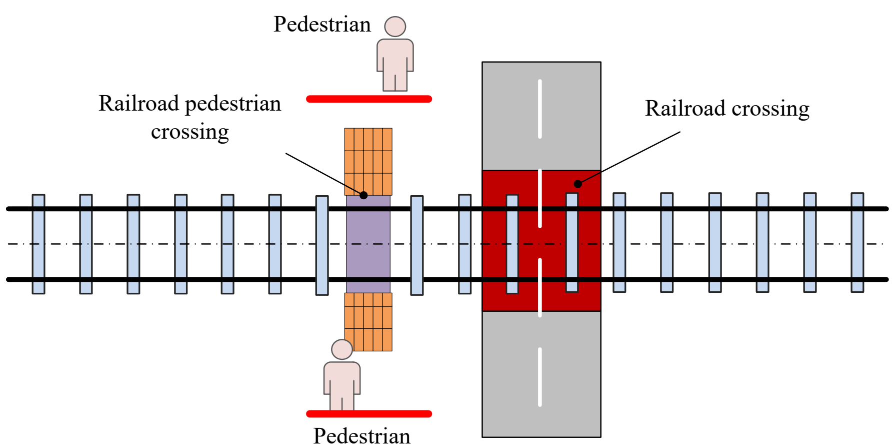

Fig. 3. Scheme of a railroad pedestrian crossing within an existing railroad crossing

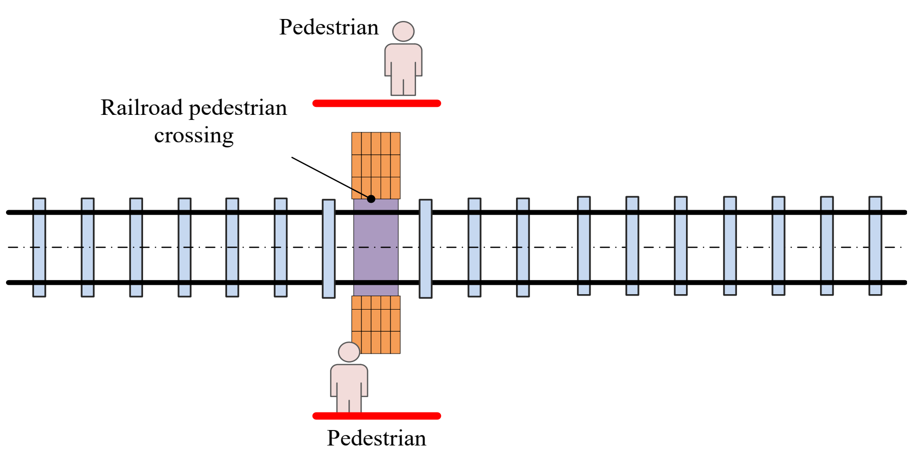

Fig. 4. Scheme of a railroad pedestrian crossing outside an existing railroad crossing

For RPCs located within existing railroad crossings, it is assumed that they are equipped with automatic traffic lights. At the same time, the study of the accident rate at the railroad pedestrian crossing located outside the existing crossing is carried out taking into account the availability of an information system for warning pedestrians about train traffic.

5. Establishing the patterns of changes in the total accident rate at railroad pedestrian crossings

5. 1. Improving the approach to assessing the total accident rate at railroad pedestrian crossings

Improving the approach involves taking into account a number of factors influencing the total accident rate with pedestrians. Such factors include the intensity of train and pedestrian traffic, taking into account the geometric and planning parameters of the railroad pedestrian crossing, and taking into account the information support at the crossing. The total accident rate K_a is proposed to be determined by multiplying eight partial accident rates. The formula takes the following form

$$K_a = \prod_{i=1}^{n} K_i = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6 \cdot K_7 \cdot K_8, \quad (1)$$

where K_1 is the coefficient that takes into account the daily intensity of train traffic on RPC; K_2 – coefficient that takes into account the intensity of pedestrian traffic on RPC; K_3 – coefficient that takes into account the distance of visibility of the train from RPC by a pedestrian; K_4 – coefficient that takes into account the information and technical support on RPC; K_5 – coefficient that takes into account artificial lighting on RPC; K_6 – coefficient that takes into account the radius of the curve in the plan on the approaches to RPC; K_7 – coefficient that takes into account the longitudinal slope of the road on the approaches to RPC; K_8 – coefficient that takes into account the speed of pedestrian traffic.

The value of the partial accident rate coefficient K_1 [5, 14], which takes into account the intensity of train traffic on RPC, is calculated from the following formula

$$K_1 = \frac{N_t}{3 + 0.1 \cdot N_t}, \quad (2)$$

where N_t – intensity of train traffic on RPC, trains/day.

Coefficient K_2, which takes into account the intensity of pedestrian traffic on RPC, is determined from the following formula

$$K_2 = 0.02 \cdot N_p + 0.423, \quad (3)$$

where N_p – pedestrian traffic intensity, persons/hour.

Coefficient K_3, which takes into account the distance of visibility of the train by a pedestrian from RPC, is determined from the following formula [14]

$$K_3 = 0.87 \cdot Ln\left(L_v\right) + 6.387, \quad (4)$$

where L_v is the distance of visibility of the train by a pedestrian, m.

When calculating the accident rate K_3, the distance of visibility from the level crossing in different directions should be taken into account, as it may differ.

In work [14], the value of the partial accident rate, which takes into account information support and equipment of the railroad crossing, is recommended to be determined from the following formula

$$K_4 = 0.925U^2 - 2.115U + 2.775, \quad (5)$$

where U is the value that represents the equipment at the crossing. In the presence of mechanized barriers without signaling $U = 4$; in the presence of mechanized barriers with signaling mechanism $U = 3$; in the presence of automatic traffic light signaling $U = 2$ and; in the presence of automatic barriers with automatic traffic light signaling $U = 1$.

When equipping existing railroad crossings with a pedestrian information warning system (IWS) about the movement of the train, the value of $U = 1.2$. In the case of a crossing point located outside the existing crossing – $U = 1.7$.

Partial accident rate K_5 allows one to take into account the presence or absence of artificial lighting at the crossing point. It is taken equal to $K_5 = 1.0$ in the presence of artificial lighting at the crossing point and $K_5 = 1.5$ in the absence of artificial lighting at the crossing point.

The partial accident rate K_6 takes into account the radius of the curve in the plan on the approaches to the crossing point. For curve radii at $R = 151–200$ m its value is taken equal to 1.45 and at $R > 200$ m its value is taken equal to 1.0, according to the methodology from [5].

The value of the partial accident rate coefficient K_7, which takes into account the longitudinal slope on the approaches to the freeway, is determined according to work [14] from the following formula

$$K_7 = 0.041 \cdot i + 0.474, \quad (6)$$

where i is the longitudinal slope on the approaches to RPC.

The partial accident rate coefficient K_8, which takes into account the speed of the pedestrian, is determined from the following formula

$$K_8 = \frac{V_{ave}}{V_{ped}}, \quad (7)$$

where V_{ave} is the established average speed of a pedestrian, taken equal to $V_{ave} = 5.5$ km/h [20]; V_{ped} is the speed of a pedestrian depending on his/her age and physical characteristics.

In addition, the speed of pedestrians through a specific crossing will be affected by the condition of the pavement within the crossing. This should also be taken into account for each specific crossing.

Based on the results of calculating the final accident rate at the railroad crossing according to formula (1), a study was conducted on the influence of the intensity of pedestrian and train traffic on the accident rate at railroad pedestrian crossings.

5. 2. Study on the total accident rate at railroad pedestrian crossings within existing crossings

The pattern of changes in the total accident rate at the level crossing within the existing railroad crossing depending on the intensity of train and pedestrian traffic is shown in Fig. 5, 6. At the same time, Fig. 4 shows the pattern of changes in the total accident rate at the level crossing without the presence of a pedestrian information system about train movement, and Fig. 5 – with the presence of a pedestrian information system about train movement at the level crossing.

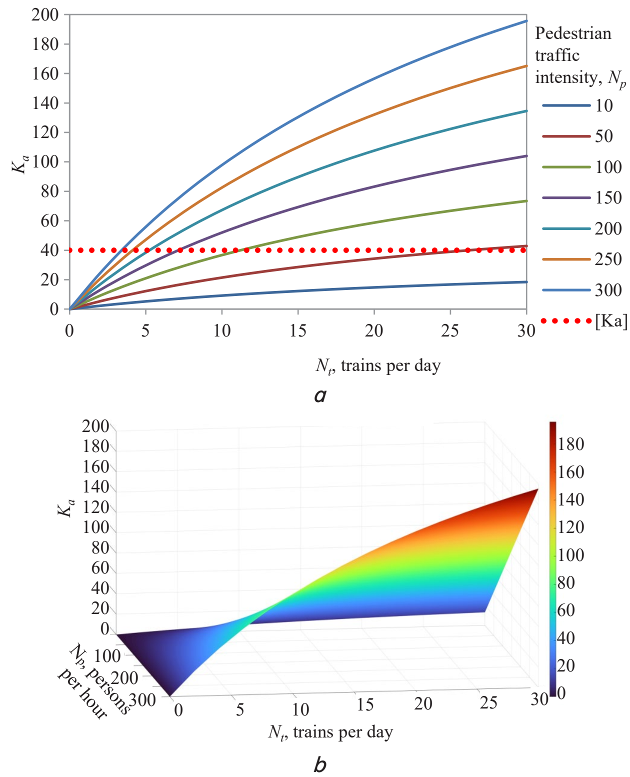

Fig. 5. The pattern of changes in the total accident rate coefficient depending on the intensity of pedestrian and train traffic at railroad pedestrian crossings without an information warning system within the existing railroad crossing: *a* – dependence $K_a = f(N_t)$; *b* – dependence $K_a = f(N_p, N_t)$

The results of our research show that an increase in the number of trains per day on RPC without IWS for pedestrians leads to an increase in the total accident rate (Fig. 5, *a*). At the same time, the total accident rate is affected by the intensity of pedestrian traffic (Fig. 5, *b*). At the intensity of pedestrian traffic $N_p = 10$ people/hour, the maximum value of the total accident rate was $K_a = 18.42$, which indicates that pedestrian traffic safety is ensured at the intensity of train traffic $N_t = 30$ trains/day and more. In the case of the intensity of pedestrian traffic $N_p = 50$ people/hour, the maximum value of the total accident rate at $N_t = 30$ trains/day is $K_a = 42.9$. In this case, RPC without IWS is not very safe. At a given intensity of pedestrian traffic, the RPC without IWS will be considered safe for pedestrian traffic at $N_t = 26$ trains/day since the final accident rate in this case is $K_a < 40$.

Increasing the intensity of pedestrian traffic leads to a decrease in the number of trains at which the highest level of pedestrian traffic safety will be ensured at the level crossing without IWS, according to the criterion of the final accident rate $K_a < 40$. In the case of $N_p = 100$ people/h, pedestrian traffic safety is ensured at the maximum number of trains $N_t = 12$ trains/day. Accordingly, at $N_p = 150$ people/h – $N_t = 8$ trains/day, at $N_p = 200$ people/h – $N_t = 6$ trains/day, at $N_p = 250$ people/h and more at the intensity of train traffic $N_t = 4$ trains/day.

The introduction of an additional IWS for pedestrians about train traffic at existing railroad crossings leads to a decrease in the accident rate. Fig. 6 shows that pedestrian safety is ensured at a pedestrian traffic intensity of up to 100 people/hour, and at the same time at a train traffic intensity of up to $N_t = 30$ trains/day. In this case, the accident rate is less than $K_a < 40$ and is $K_a = 39.25$, which indicates that pedestrian safety is ensured.

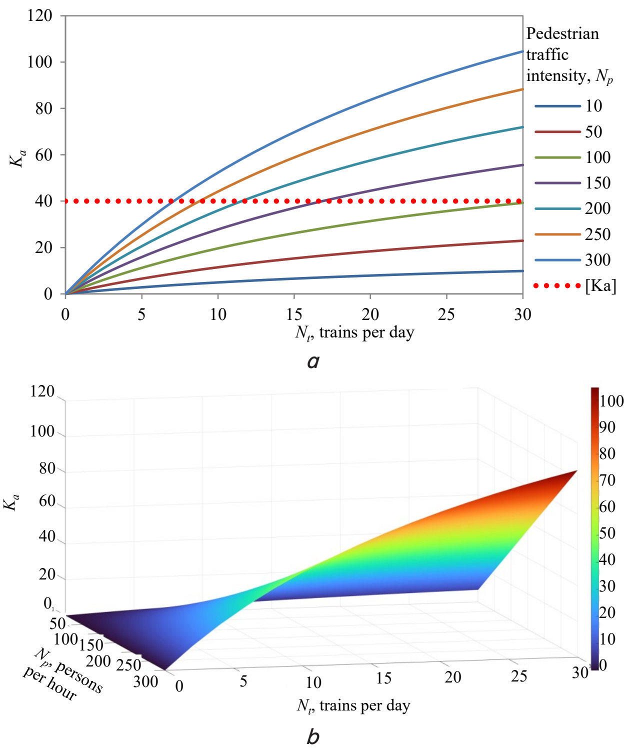

Fig. 6. The pattern of changes in the total accident rate at railroad pedestrian crossings located within the existing railroad crossing depending on the intensity of train and pedestrian traffic in the presence of an information warning system: *a* – dependence $K_a = f(N_t)$; *b* – dependence $K_a = f(N_p, N_t)$

Further increase in pedestrian traffic intensity leads to an increase in the accident rate on RPC with IWS. At pedestrian traffic intensity $N_p = 150$ people/hour, the accident rate is lower than $K_a < 40$ at train traffic intensity $N_t = 18$ trains/day. Accordingly, at $N_p = 200$ people/hour – $N_t = 12$ trains/day and at $N_p = 300$ people/hour, pedestrian safety is ensured at $N_t = 8$ trains/day.

5. 3. Study on the final accident rate at railroad pedestrian crossings located outside existing crossings

The results of calculating the final accident rate at railroad pedestrian crossings outside existing crossings showed that an increase in the intensity of train traffic leads to a decrease in the intensity of pedestrian traffic, at which pedestrian safety is ensured (Fig. 7).

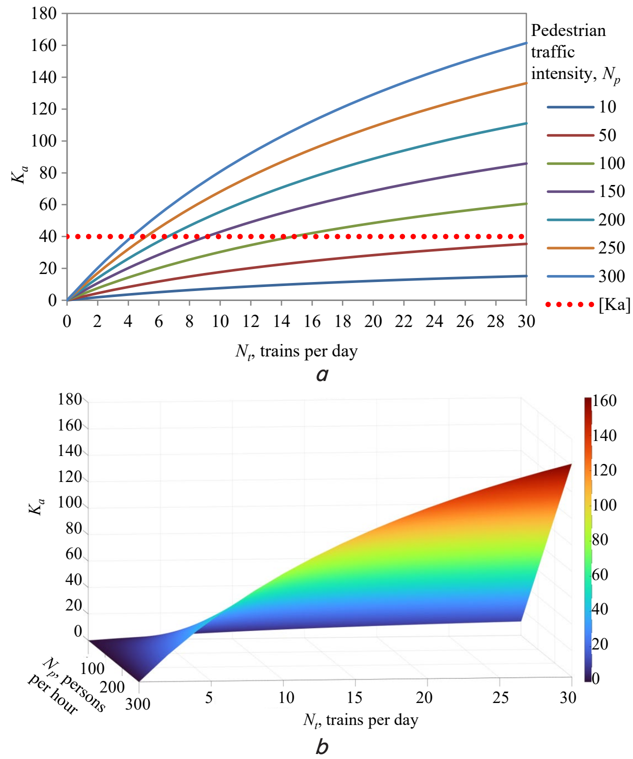

Fig. 7. The pattern of changes in the total accident rate at railroad pedestrian crossings located outside existing railroad crossing depending on the intensity of train and pedestrian traffic in the presence of an information warning system: *a* – dependence $K_a = f(N_t)$; *b* – dependence $K_a = f(N_p, N_t)$

It was established that with pedestrian traffic intensity up to $N_p = 50$ persons/hour and trains up to $N_t = 30$ trains/day, the maximum value of the accident rate is $K_a = 35.4$, which indicates that pedestrian traffic is safe.

In the case of increasing pedestrian traffic intensity up to $N_p = 100$ persons/hour and the existing train traffic intensity $N_t = 30$ trains/day, the accident rate is $K_a = 60.6$, which indicates a low safety of the crossing. In this case, the final accident rate will be less $K_a < 40$ with a maximum train traffic intensity $N_t = 16$ trains/day. Accordingly, with pedestrian traffic intensity equal to $N_p = 150$ persons/hour and train traffic intensity – $N_t = 10$ trains/day, with $N_p = 200$ persons/hour – $N_t = 8$ trains/day. Increasing the intensity $N_p = 250$ people/hour – $N_t = 6$ trains/day and at $N_p = 300$ people/hour the level of pedestrian safety is ensured at $N_t = 4$ trains/day.

The resulting values of the accident rate coefficient at the level crossings, which are located outside existing railroad crossings, were derived when the level crossings were equipped with an information system for warning pedestrians about train movement without the use of automatic traffic light signaling, which is present at railroad crossings.

Fig. 8 shows a graphical dependence of the difference in accident rates at the level crossings without use and with the use of pedestrian IWS about train movement depending on the intensity of train traffic and at $N_p = 100$ people/hour. Fig. 9 – the difference in accident rates at the level crossings without the use and with the use of pedestrian IWS about train movement depending on the intensity of pedestrian traffic at $N_t = 12$ trains/day.

In the case of the introduction of IWS about the movement of the train, the accident rate at the level crossing without the IWS within the existing railroad crossing decreases in comparison with the accident rate at the level crossing without the IWS. At a train traffic intensity of $N_t = 10$ trains/day, the accident rate without the information warning system is $K_a = 36.7$, and with the information warning system – $K_a = 19.62$. Accordingly, at $N_t = 20$ trains/day – $K_a = 58.7$ and $K_a = 31.4$ and at $N_t = 30$ trains/day – $K_a = 73.4$ and $K_a = 39.3$.

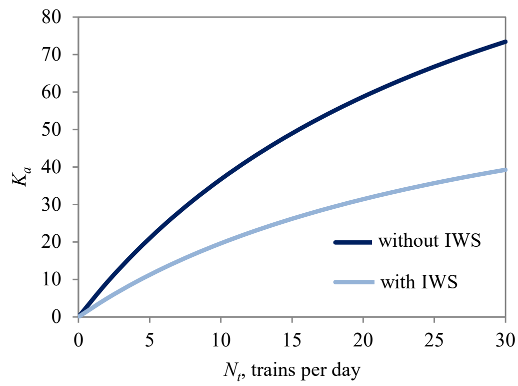

Fig. 8. The difference in accident rates at railroad pedestrian crossings without and with the use of an information system for warning pedestrians about train traffic depending on the intensity of train traffic at a pedestrian traffic intensity of $N_p = 100$ people/hour

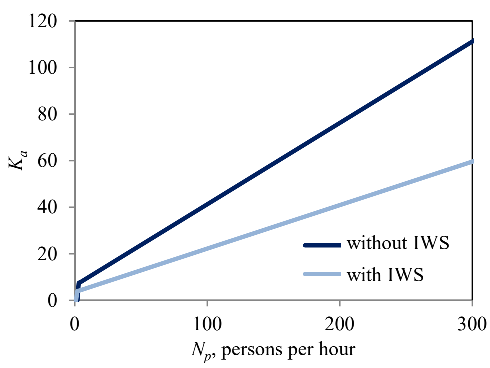

Fig. 9. The difference in accident rates at railroad pedestrian crossings without and with the use of an information system for warning pedestrians about train traffic depending on the intensity of pedestrian traffic at a train traffic intensity of $N_t = 12$ trains/day

At a pedestrian traffic intensity of $N_p = 100$ persons/hour and a train traffic intensity of $N_t = 10$ trains/day, the difference in accident rates is $K_a = 17.1$, at $N_t = 20$ trains/day – $K_a = 27.4$ and at $N_t = 30$ trains/day – $K_a = 34.1$.

Our studies prove that when implementing IWS at RPCs within existing crossings in the case of pedestrian traffic intensity of up to $N_p = 100$ persons/hour, the level of pedestrian traffic safety is ensured for up to 30 trains/day, since $K_a < 40$. At the same time, without implementing IWS at RPCs, the level of pedestrian traffic safety is ensured for up to 12 trains/day.

6. Discussion of results based on investigating the final accident rate at railroad pedestrian crossings

Our paper reports a method for estimating the accident rate at railroad pedestrian crossings, taking into account a number of factors in the model that affect the provision of pedestrian safety indicators. Unlike the final coefficient method given in recommendations [5] and in scientific works [11, 12], the improved method takes into account the intensity of pedestrian traffic on the railroad pedestrian crossing and their speed, as well as the planning and geometric parameters of the railroad pedestrian crossing. This will make it possible to establish the patterns of changes in the final accident rate at railroad pedestrian crossings, taking into account a set of factors. These include the intensity of train and pedestrian traffic, providing the pedestrian crossing with an information system for warning about the movement of trains, and taking into account the geometric and planning features of the pedestrian crossing.

The results of multivariate studies showed that an increase in the intensity of train traffic leads to an increase in the difference between the values of accident coefficients obtained in the presence and absence of an information system for warning pedestrians about train traffic on the railroad crossing (Fig. 8, 9).

The results of our research (Fig. 8, 9) showed that the average value of the reduction in the accident rate at railroad pedestrian crossings within existing railroad crossings depends on the intensity of train and pedestrian traffic. When using an additional IWS for pedestrians about the movement of the train, depending on the number of pairs of trains per day, is up to 22.1, and depending on the intensity of pedestrian traffic with a constant number of pairs of trains, it is 27.74. The introduction of information systems for warning pedestrians about the movement of the train allows one to reduce the accident rate by up to 30% compared to conventional signaling devices. Such research results are consistent with the results from international studies on the effectiveness of using intelligent transport systems in the traffic safety system [21].

This emphasizes the effectiveness of the use of the information system for warning pedestrians at railroad crossings with pedestrian traffic, which ultimately allows one to increase the safety of pedestrians when crossing railroad tracks by pedestrians on specially equipped crossings.

Using the improved methodology, it is possible to perform multivariate calculations of the final accident rate at a railroad crossing, taking into account a set of factors influencing the safety of pedestrians when crossing railroad tracks. These include factors of train and pedestrian traffic intensity, information and technical equipment of the railroad crossing, taking into account the planning and geometric parameters of the crossing (plan and profile on the approaches to the railroad crossing), as well as taking into account the speed of pedestrians.

Comprehensive studies on the accident rate at railroad pedestrian crossings will make it possible to establish optimal parameters for designing railroad pedestrian crossings. This will ensure increased pedestrian safety when crossing railroad tracks, both within existing railroad crossings and beyond.

One of the limitations of such a study is the need to take into account reliable information on the intensity of pedestrian and train traffic when determining the accident rate with pedestrians. At the same time, the intensity of pedestrian traffic varies at different times of the day and year, as well as depending on the region of operation of the pedestrian railroad crossing. Therefore, when calculating the accident rate with pedestrians at railroad crossings and establishing the level of safety of the crossing, in accordance with Fig. 2, reliable statistical data on the intensity of pedestrian and train traffic should be taken into account.

One of the shortcomings of the research is the study of the patterns of influence on the accident rate of only the parameters of the intensity of pedestrian and train traffic at constant values of the geometric and planning parameters of the railroad pedestrian crossing. Further development of research may involve comprehensive studies on the inclusion of the influence of geometric and planning parameters of pedestrian crossings, pedestrian categories on the change in the accident rate at railroad pedestrian crossings.

7. Conclusions

1. The improved approach to assessing the final accident rate at railroad pedestrian crossings allows for a comprehensive assessment of the accident rate at crossings, taking into account a set of factors. These include factors such as the intensity of pedestrian and train traffic, planning and geometric parameters of the railroad pedestrian crossing, information support for the crossing, and the speed of pedestrians on the crossing and trains on the approach to the crossing. This will make it possible to close part of the problem under study, namely the lack of regularities in the influence of these factors on the accident rate with pedestrians when crossing railroad tracks, and to introduce requirements for railroad pedestrian crossings in order to improve pedestrian safety.

2. Our results of multivariate calculations of the final accident rate at a railroad crossing showed that equipping the pedestrian crossing with an information warning system leads to a decrease in the accident rate. At a pedestrian traffic intensity of 100 people/hour and a train traffic intensity of $N_t = 30$ trains/day, the final accident rate without an information warning system was $K_a = 73.44$, and with an information warning system – $K_a = 39.25$. In this case, pedestrian safety is ensured only if there is an information warning system for pedestrians about train traffic. This emphasizes the effectiveness of using an information warning system for pedestrians at railroad crossings with pedestrian traffic, which ultimately makes it possible to increase the safety of pedestrians when crossing railroad tracks.

3. The results of calculating the final accident rate at RPC outside existing crossings showed that an increase in the intensity of train traffic leads to a decrease in the intensity of pedestrian traffic, at which pedestrian safety is ensured. It was established that with an intensity of pedestrian traffic of up to $N_p = 50$ people/hour and trains of up to $N_t = 30$ trains/day, the maximum value of the accident rate is $K_a = 35.4$, which indicates that pedestrian safety is ensured. In the case of an increase in the intensity of pedestrian traffic of up to $N_p = 100$ people/hour and the existing intensity of train traffic of $N_t = 30$ trains/day, the accident rate is $K_a = 60.6$, which indicates a low-safety crossing.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Authors' contributions

Vitalii Kovalchuk: Conceptualization, Project administration; **Julia Lesiv**: Methodology, Validation, **Ihor Mohyla**: Methodology, Resources; **Andrii Kuzyshyn**: Investigation; Visualization.

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