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Assessment of the impact of train visibility distance for pedestrians on the accident rate coefficient at railway pedestrian crossings

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Abstract. The paper presents an improved method for the quantitative assessment of pedestrian safety at railway pedestrian crossings. The method was based on the calculation of partial accident rate coefficients that take into account pedestrian and train traffic intensity, train visibility distance, the level of technical and informational equipment of the crossing, as well as the geometric and planning parameters of the pedestrian crossing. Multivariant modelling of changes in the resulting accident rate coefficient depending on the pedestrian train visibility distance and the simultaneous consideration of pedestrian and train traffic intensity was carried out. It has been established that at a pedestrian flow intensity of 100 persons/hour and a train traffic intensity of 30 trains/day, the minimum required visibility distance at railway pedestrian crossings located within an existing level crossing without a pedestrian train warning information system is 635 m, whereas when such a crossing is equipped with an information warning system, the required visibility distance is reduced to 435 m. For railway pedestrian crossings located outside existing level crossings, the minimum required train visibility distance should be 530 m. It has been determined that the implementation of a pedestrian train warning information system makes it possible to reduce the accident rate coefficient by up to 30% within existing level crossings and by 20% outside them. The obtained results can be used in the design and modernisation of railway pedestrian crossings across railway tracks

Keywords: safety assessment; risk perception; warning systems; infrastructure; hazardous situations

Introduction

The necessity of enhancing pedestrian safety when crossing railway tracks and improving approaches to assessing safety levels at pedestrian railway crossings represents a crucial step in reducing the number of accidents and ensuring reliable protection for citizens. Studies of pedestrian behaviour at railway level crossings show that the ability to detect an approaching train in a timely manner is a decisive factor in safely deciding whether to cross or refrain from crossing the tracks. Field observations reported by B.J. Russo *et al.* (2021) indicated that violations by pedestrians and cyclists are largely associated with risk perception shaped by train visibility and the condition of warning signalling. Under limited visibility conditions, even at equipped crossings, the likelihood of risky behaviour increases. The level crossing safety impact assessment approach by S. Turner *et al.* (2021) considered approach geometry and visibility conditions as fundamental parameters for risk assessment for all users, including pedestrians. The authors emphasised that visibility within level crossings is often better due to regulated sight zones, whereas outside crossings, pedestrian routes across tracks are formed without compliance with minimum visibility requirements. A generalised analysis by the European Road Safety Observatory (2021) confirmed that visibility restrictions caused by vegetation, landscaping elements, or engineering structures are among the key risk factors at railway level crossings. Informal crossings outside designated level crossings are characterised by significantly poorer sight conditions compared to regulated crossing areas. Z. Guo *et al.* (2022) demonstrated that in "train-pedestrian" interaction, track curvature, gradients, and longitudinal profile significantly reduce the available visibility range. Such conditions are typical for areas

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outside formal level crossings, where there are no requirements for the geometry of pedestrian approaches, increasing the likelihood of hazardous situations (Zawodny, 2023). V. Singhal *et al.* (2021) identified the main factors affecting safe visibility on approaches to railway tracks: road width, approach sight conditions, speed, gradient, pavement condition, and other geometric parameters. The authors demonstrate that the geometry of approaches significantly influences whether a user can detect an approaching train or other hazard in time. Improved visibility and a more favourable approach profile provide additional reaction time and reduce the risk of erroneous decisions. A separate part of the study presents a "road-to-track" model that accounts for train speed, track gauge width, and the crossing angle. This allows calculation of the minimum open sight distance required for timely detection of a train. Modelling results indicate that the recommended safe stopping distance is approximately 23% greater than that provided by traditional approaches. Although the study concerns vehicles, its principles are readily applicable to pedestrians, who similarly require sufficient visibility for decision-making. The findings can be used to determine minimum sight triangles at pedestrian crossings and to assess reaction time.

Particular attention is given to the fact that pedestrians have a lower eye level, and their ability to detect a train strongly depends on minor infrastructure elements such as fences, poles, landscaping, and track curvature. This approach not only allows assessment of how well a train is visible but also enables identification of specific obstacles that should be removed to enhance safety. Thus, three-dimensional scanning methods represent a useful tool for prioritising engineering solutions. A.J. Khattak *et al.* (2024) emphasised that non-motorised users, particularly pedestrians, are the most vulnerable at railway level crossings due to visibility limitations and the absence of specialised solutions outside formal crossing areas. The regulatory authority, the Office of the National Rail Safety Regulator, applied the ONRSR code of practice (2024), which directly establishes visibility requirements at level crossings and emphasised the need to maintain unobstructed sight zones. Although oriented toward all user categories, its provisions are also relevant for pedestrians, especially in the context of assessing minimum visible distance. The issue of visibility under low-light conditions is addressed in study by N.A.T. Nguyen *et al.* (2025), which demonstrated that night-time significantly increases risk at passive crossings. Proposed solutions for improving visual orientation are particularly relevant for areas outside equipped crossings. M.B. Kurhan *et al.* (2024) analysed technical and organisational solutions for modernising railway crossings in areas of 1,435 mm gauge track construction in Ukraine. Although the primary focus is on road-rail crossings, the authors emphasised that changes in approach profiles, object placement, and site micro-geometry directly affect train visibility for users. This makes the study relevant for pedestrian crossings as well, since similar factors influence risk perception. M.B. Kurhan *et al.* (2024) demonstrated a systematic approach in which infrastructure geometry is considered one of the key safety factors. The mathematical model of the final accident rate coefficient applied by the authors allows assessment of how changes in geometric characteristics affect risk levels. This may be useful for substantiating an updated methodology for assessing accident rates at pedestrian crossings. From a practical perspective, the study highlights that improving visibility – through site clearing, slope adjustment, and relocation of objects – is an integral part of crossing reconstruction, consistent with international experience.

In summary, contemporary scientific studies confirm that train visibility conditions for pedestrians differ significantly within railway level crossings and outside them, and that reduced visibility is directly associated with increased accident risk. This substantiates the need for quantitative visibility assessment and the implementation of additional pedestrian warning information systems, particularly on pedestrian routes crossing railway tracks outside formal level crossings. The purpose of this study was to quantitatively assess the impact of train visibility conditions on the accident rate of pedestrians crossing railway tracks by determining the accident rate coefficient within railway level crossings, outside them, and under the application of a pedestrian warning information system. To achieve this purpose, the following research objectives were set:

- to present a methodology for assessing the accident rate coefficient at railway pedestrian crossings (RPCs);
- to perform multi-variant calculations of the accident rate coefficient at RPCs, taking into account train and pedestrian traffic intensity as well as train visibility distance;
- to determine the threshold and rational train visibility distances from the railway pedestrian crossing at which an acceptable level of pedestrian safety is ensured.

The implementation of these objectives made it possible to develop a scientifically substantiated approach to determining the impact of train visibility conditions on pedestrian accident rates at RPCs, as well as to justify the feasibility of applying a pedestrian warning information system as an effective tool for reducing accident risk and preventing transport incidents.

Materials and Methods

Pedestrian safety factors at RPCs were represented as partial accident rate coefficients and integrated using the final accident rate coefficient (K_f) method to determine overall risk levels and classify crossing conditions. The study was conducted using mathematical modelling of pedestrian-rolling stock interaction at RPCs. The calculations were performed based on a simulation-analytical model for determining the accident rate coefficient, taking into account train traffic intensity, train speed, and visibility conditions. The computations were conducted using the licensed software package MATLAB 2025a, which made it possible to implement a step-by-step calculation of the accident rate coefficient and to determine the permissible visibility values required to ensure traffic safety. The study employed a classification-based approach to assessing safety levels, based on the interpretation of the values of the final accident rate coefficient. The classification of railway pedestrian crossing safety levels depending on the value of the final accident rate coefficient K_p is applied. Based on established threshold values, a safety scale is formed: $K_p < 40$ – safe crossing; 40-60 – low safety level; 61-80 – hazardous; $K_p > 80$ – very hazardous. Thus, the criterion $K_p < 40$ is adopted as the condition for ensuring an acceptable level of pedestrian safety at RPCs. According to the improved method for assessing pedestrian traffic safety indicators at RPCs J. Lesiv & V. Kovalchuk, (2025), the final accident rate coefficient K_p is determined by multiplying eight partial accident rate coefficients:

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

The explanation of the content of the partial coefficients is provided in Table 1.

Table 1. Partial coefficients K_1-K_8

Coefficient	Description of the coefficient
K_1	Accounts for the daily train traffic intensity through the RPC
K_2	Accounts for the hourly pedestrian traffic intensity
K_3	Accounts for the train visibility distance from the crossing
K_4	Accounts for the crossing equipment (pedestrian warning information system, traffic signals, barrier gates)
K_5	Accounts for the presence of artificial lighting at the crossing
K_6	Accounts for the horizontal curve radius of the railway track approaching the crossing
K_7	Accounts for the longitudinal gradient of the approaches to the crossing
K_8	Accounts for the age and physiological characteristics of pedestrians (walking speed)

Source: developed by the authors based on State Road Service of Ukraine (2008), J. Lesiv & V. Kovalchuk (2025)

Specifically, the coefficients used in the subsequent study are determined depending on train traffic intensity, pedestrian flow intensity, geometric and planning characteristics of the crossing, as well as its information support. One of the key coefficients is coefficient K_3, which accounts for the visibility distance from the crossing to the train. Coefficient K_3 describes the effect of the train visibility distance for pedestrians and is determined depending on the value of L_v (Fig. 1).

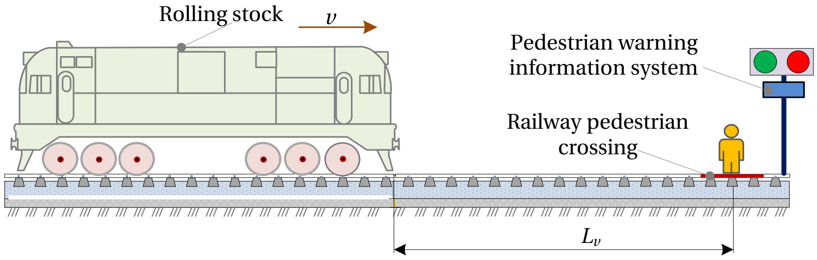


Figure 1. Diagram for determining the visibility distance from the crossing to the train L_v

Source: developed by the authors based on State Road Service of Ukraine (2008), J. Lesiv & V. Kovalchuk (2025)

At low visibility distances, the hazard level increases significantly, which is confirmed by the nonlinear graphical relationship (Fig. 2).

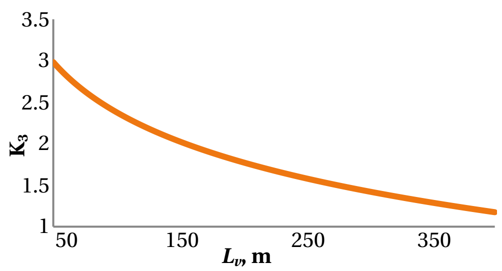


Figure 2. Graphical relationship between the partial coefficient K_3 and the train visibility distance for pedestrians L_v

Source: developed by the authors

When $L_v < 50$ m, the coefficient $K_3 = 2.98$, at $L_v = 100$ m, $K_3 = 2.38$, at $L_v = 200$ m, $K_3 = 1.78$, at $L_v = 300$ m, $K_3 = 1.42$, at $L_v = 400$ m, $K_3 = 1.17$. When $L_v > 400$ m, the value of the partial accident rate coefficient should be taken as $K_3 = 0.98$. In this case, according to the safety criterion, the required level of pedestrian safety at the RPC is achieved. The impact of information support and technical equipment of RPCs is taken into account by coefficient K_4. For regulated railway level crossings, the lowest values of K_4 correspond to the presence of automatic barriers combined with automatic traffic light signalling, whereas higher values are typical for crossings equipped with less advanced or partially mechanised warning systems. In the case of equipping existing railway level crossings with a pedestrian train warning information system (PWIS), the value of K_4 decreases compared to traditional solutions, indicating an increase in the safety level. For RPCs located outside existing level crossings and not equipped with standard signalling devices, the value of K_4 is higher, reflecting an increased level of risk. The influence of information support and technical equipment on the accident rate coefficient is clearly illustrated by a graphical relationship, which made it possible to assess the effectiveness of different technical solutions (Fig. 3).

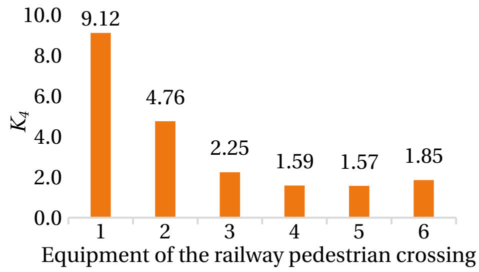


Figure 3. Dependence of the partial accident rate coefficient K_4 on information support and equipment at RPC

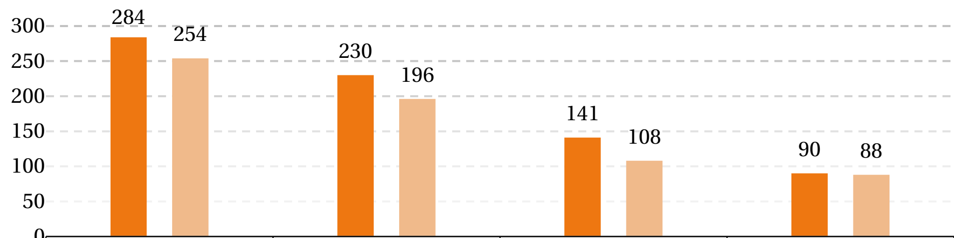
Note: 1 – mechanised barriers without signalling; 2 – mechanised barriers with warning signalling; 3 – automatic traffic light signalling; 4 – automatic barriers with automatic traffic light signalling; 5 – existing railway level crossings equipped with a PWIS; 6 – RPCs located outside existing level crossings and equipped with a PWIS

Source: developed by the authors

Additional equipment of RPCs with a PWIS reduces the accident rate coefficient by approximately 30% within existing level crossings $K_4 = 1.57$ and by 20% for crossings located outside them $K_4 = 1.85$, compared to the use of automatic traffic light signalling alone. The procedure for evaluating accident indicators involving pedestrians at RPCs involved a step-by-step modelling approach. At the first stage, the train traffic intensity was assumed to be $N_t = 12$ trains/day, while the pedestrian traffic intensity N_p varied within the range from 10 to 300 persons/hour. At the second stage, the train traffic intensity was taken as $N_t = 20$ trains/day, and at the third stage – $N_t = 30$ trains/day. At the same time, at each stage of the calculation, the pedestrian intensity remained variable within the range from 10 to 300 persons/hour. This made it possible, at each stage of modelling, to determine the minimum required visibility distance of a train for a pedestrian, L_v based on the criterion of not exceeding the value of the total accident rate coefficient $K_p < 40$. This procedure was carried out for different types of railway crossings, namely for crossings located within existing level crossings without PWIS and with PWIS, as well as for crossings located outside existing level crossings. The model validation was performed by comparing the obtained results with those presented by the authors in scientific works State Road Service of Ukraine (2008) and J. Lesiv & V. Kovalchuk (2025). The modelling methods used made it possible to identify key safety factors and assess the effectiveness of technical measures.

Results and Discussion

An analysis of statistical data obtained in the countries of the European Union (EU) and in Ukraine indicates that pedestrian safety when crossing railway tracks remains a significant transport safety issue. According to Railway safety statistics in the EU (2025), in 2024 a total of 1,507 railway accidents were recorded in the European Union, resulting in 750 fatalities and 548 serious injuries. The majority of fatal cases were associated with unauthorised presence on the tracks, while at least 25% of all fatalities were level crossing users and pedestrians crossing railway tracks. This indicates that even despite the overall downward trend in the number of railway accidents, the risk of pedestrian injury when crossing railway tracks remains high. The statistical data on railway transport accidents in Ukraine for 2024 and for the first nine months of 2025 are presented in Figure 4.



	Total accidents	Accidents involving unauthorized persons	Fatalities	Injured persons
2024	284	230	141	90
2025	254	196	108	88

Figure 4. Accident rate at Ukrainian Railways for the January-September of 2025

Source: developed by the authors based on State Service of Ukraine for Transport Safety (2025)

As can be seen from Figure 4, during the first nine months of 2025, a total of 254 accidents were recorded, which is 11% fewer compared to the same period in 2024 (284 cases). The number of accidents involving unauthorised persons decreased by 15% (from 230 to 196 cases). The most significant reduction was observed in the number of fatalities – by 23% (from 141 to 108 persons). At the same time, the number of injured persons decreased by only 2% (from 90 to 88 persons), indicating that the level of injuries remains consistently high despite the overall positive trend. According to the State Service of Ukraine for Transport Safety (2025), a particular concern is the accident rate outside existing railway level crossings and at unauthorised pedestrian crossings, where engineering safety measures and pedestrian train warning systems are absent. This significantly reduces train visibility and shortens the time available for pedestrians to assess risk. One of the methods for improving pedestrian safety when crossing railway tracks is the arrangement of RPCs. An example of such a crossing installed on the Lviv Railway is shown in Figure 5.

Figure 5. View of the RPC on Kurmanovych Street, Lviv
Source: authors' photo

Safety at the level crossing shown in Figure 5 has been improved by installing warning signs, marking a clearly defined pedestrian crossing ("zebra crossing") and the placement of a pedestrian crossing road sign, which together raise awareness among pedestrians and drivers and reduce the risk of accidents. Thus, the conditions under which pedestrians perceive danger – among which train visibility and the possibility of its timely detection are key factors – play a decisive role in the formation of hazardous situations both within railway level crossings and outside them. At the same time, the assessment of safety levels at such railway sections remains insufficiently substantiated, as existing approaches do not fully reflect the specific features of the "pedestrian-train" interaction within the railway infrastructure environment. The safety assessment methodologies currently applied in Ukraine, in particular the method of the final accident rate coefficient State Road Service of Ukraine (2008), are primarily oriented toward road transport and are based on the analysis of road traffic accident statistics. Their application to RPCs is limited, as they do not take into account pedestrian traffic intensity, pedestrian speed, or the specific characteristics of pedestrian interaction with rolling stock. In previous studies J. Lesiv & V. Kovalchuk (2025) proposed a relevant approach to assessing the accident rate coefficient at RPCs, which considers the specific features of pedestrian movement and track-crossing conditions. In this regard, the limitations of existing methods for assessing pedestrian safety indicators when crossing railway tracks necessitate their adaptation or supplementation with parameters that reflect actual pedestrian movement conditions. In particular, it is relevant to consider train visibility conditions as a universal physical factor in accident risk formation, as well as to evaluate the effectiveness of information solutions aimed at providing timely warnings to pedestrians about an approaching train at a pedestrian crossing located either within existing level crossings or outside them. The study by M. Naghdi *et al.* (2024) was among the most advanced in the field of visibility assessment, as the authors applied three-dimensional light detection and ranging technology data to construct a realistic terrain model and determine the exact point from which a user can see an approaching train (Fig. 6). M. Naghdi *et al.* showed that traditional two-dimensional approaches often fail to account for small but significant obstacles such as vegetation, poles, and terrain irregularities. As a result, the actual visibility distance may be significantly shorter than that prescribed by standards. This is particularly relevant for pedestrian crossings, where individuals assess risk in an environment in which any object may obstruct the line of sight.

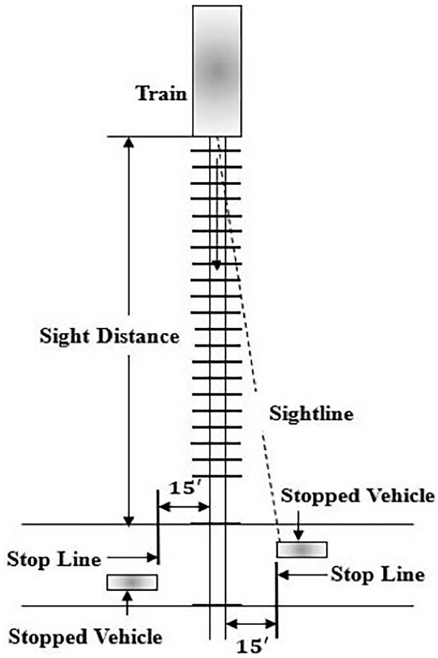


Figure 6. Sight distance for a stopped vehicle
Source: M. Naghdi *et al.* (2024)

Figure 6 illustrates the principle of determining the distance from which a user can see an approaching train. The study presents the "line of sight" from a stopped vehicle to the train and the actual available sight distance. It was established that any obstacle within the field of view immediately reduces the ability to detect the train in time. Under real conditions analysed by the authors, such obstacles are numerous, and their impact is particularly significant at pedestrian crossings. Moreover, M. Naghdi *et al.* (2024) identified so-called "visibility shadows" – areas where the train becomes temporarily invisible to the user. For pedestrians, who have a lower observation point and change their viewing direction more slowly, these zones are critical. The results demonstrate that instead of relying on a single visibility value, spatial analysis accounting for the actual crossing environment should be applied. This enables more accurate determination of required sight triangles, optimisation of viewing angles, and establishment of the minimum safe distance from which a pedestrian can reliably recognise an approaching train.

In this study, the final accident rate coefficient at RPCs is calculated as a function of the train visibility distance perceived by pedestrians L_v. The calculations were performed assuming a train traffic intensity of 12 trains per day. The analysis considers pedestrian crossings located within existing railway level crossings equipped with automatic light signalling and an PWIS, crossings without PWIS, as well as crossings located outside existing level crossings. The pedestrian flow intensity varies within the range N_p = 10-300 persons/hour. The pedestrian crossing is equipped with artificial lighting, and the longitudinal slope of the approaches is 20‰. The relationships between the final accident rate coefficient, visibility distance L_v, and pedestrian flow intensity N_p for different types of crossings are presented in Figures 7-9.

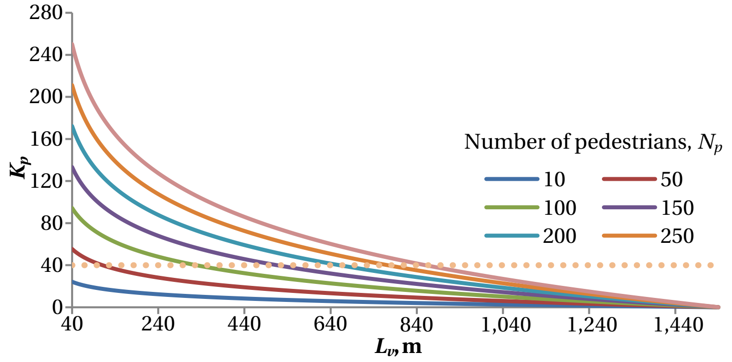


Figure 7. Relationship between the accident rate coefficient, visibility distance, and pedestrian flow intensity at N_t = 12 trains/day on the railway crossing without PWIS within existing crossings

Source: developed by the authors

The results indicate a significant dependence of the accident rate coefficient on the train visibility distance at RPCs. An increase in visibility distance leads to a decrease in the accident rate coefficient. For crossings without an information warning system located within an existing level crossing, at a pedestrian flow intensity of N_p = 10 persons/hour and a visibility distance of L_v = 40 m, the accident rate coefficient is K_p = 22.48 (Fig. 7), while with the implementation of PIWS it decreases to K_p = 16.41 (Fig. 8). For crossings located outside existing level crossings, the coefficient is K_p = 20.03 (Fig. 9). In this case, pedestrian safety is ensured since K_p < 40. At a pedestrian flow intensity of N_p = 50 persons/hour and L_v = 40 m, the accident rate coefficient for crossings without PIWS within existing level crossings is K_p = 53.6, while with PIWS it is reduced to K_p = 34.4. For crossings outside existing level crossings, the value is K_p = 44.3. These results indicate that, under the given conditions, pedestrian safety is not ensured for crossings without PIWS within existing level crossings and for crossings located outside level crossings at a visibility distance of 40 m. Safety conditions for pedestrian movement at N_p = 50 persons/hour are achieved at a minimum visibility distance of L_v = 110 m for crossings within existing level crossings and L_v = 60 m for crossings located outside level crossings. When the pedestrian flow intensity exceeds N_p = 100 persons/hour and at a visibility distance of L_v = 40 m, the accident rate coefficients at the considered RPCs exceed the permissible value $[K_p]$ = 40. For N_p = 100 persons/hour, the final accident rate coefficient satisfies the safety condition $K_p < [K_p]$ at a visibility distance of L_v = 320 m for crossings without an information warning system (Fig. 7) and L_v = 150 m for crossings equipped with PIWS (Fig. 8). For crossings located outside existing level crossings, the minimum visibility distance required to ensure pedestrian safety is L_v = 225 m (Fig. 9).

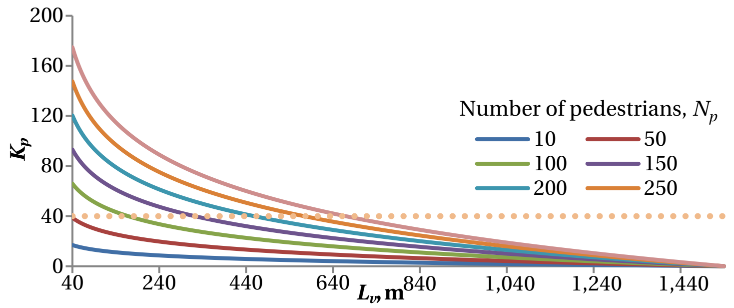


Figure 8. Relationship between the accident rate coefficient, visibility distance, and pedestrian flow intensity at N_t = 12 trains/day for RPCs with an PWIS within existing level crossings

Source: developed by the authors

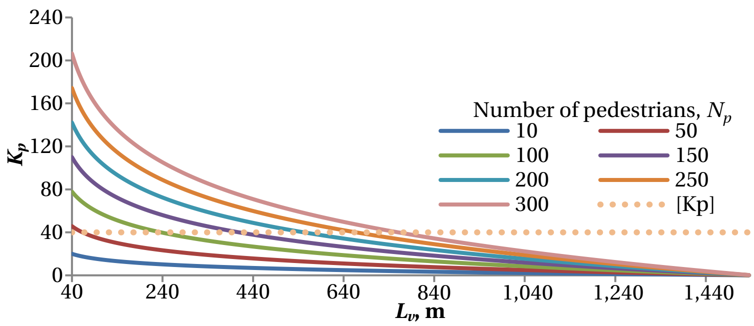


Figure 9. Relationship between the accident rate coefficient, visibility distance, and pedestrian flow intensity at N_t = 12 trains/day for RPCs located outside existing level crossings

Source: developed by the authors

At a pedestrian flow intensity of N_p = 150 persons/hour, the accident rate coefficient satisfies the condition K_p < 40 at a visibility distance of L_v = 495 m for crossings without PIWS within existing level crossings, L_v = 325 m for crossings with PIWS within existing level crossings, and L_v = 410 m for crossings located outside existing level crossings. For N_p = 200 persons/hour, the corresponding values are L_v = 660 m, L_v = 460 m, and L_v = 560 m; for N_p = 250 persons/hour – L_v = 775 m, L_v = 600 m, and L_v = 1,670 m. At a pedestrian flow intensity of N_p = 300 persons/hour, the minimum visibility distance required for pedestrian safety is L_v = 865 m for crossings without PIWS within existing level crossings, L_v = 670 m for crossings with PIWS, and L_v = 745 m for crossings located outside existing level crossings. The obtained relationships indicate a significant influence of the minimum train visibility distance on the value of the final accident rate coefficient, which directly affects the level of pedestrian safety. Therefore, this factor should be taken into account in the design and construction of RPCs. The study considered RPCs located within existing level crossings with and without a PWIS, as well as crossings located outside railway level crossings, in order to compare pedestrian safety conditions. The relationships between the minimum required train visibility distance and pedestrian and train traffic intensity, under which the safety criterion K_p < 40 is satisfied. These relationships were constructed by varying the model input parameters sequentially. For each combination of pedestrian traffic intensity (N_p), train traffic intensity (N_t), and visibility distance (L_v), the total accident rate coefficient K_p was calculated. The threshold values of L_v were determined as the minimum values at which K_p < 40 holds (Fig. 10). The calculations were performed through tabular modelling and the results were then generalised and presented graphically. The findings indicated that for a pedestrian traffic intensity of N_p < 30 persons/hour, a train traffic intensity of N_t = 12 trains/day, and a visibility distance of L_v = 40 m, an acceptable safety level is ensured for all considered RPCs. At N_p = 40 persons/hour, the criterion K_p < 40 is satisfied for crossings with a PWIS, both within and outside level crossings. However, for crossings without a PWIS within level crossings, safe conditions are only achieved when the visibility distance is increased to L_v = 70 m.

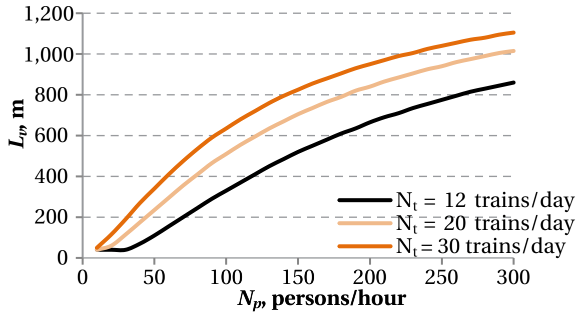


Figure 10. Minimum required train visibility distance for pedestrians depending on pedestrian and train traffic intensity at RPC without a PWIS within existing level crossings

Source: developed by the authors

With a further increase in pedestrian traffic intensity while maintaining a constant train traffic intensity of N_t = 12 trains/day, an increase in the accident rate coefficient at RPCs is observed. As a result, at a visibility distance of L_v = 40 m, its value exceeds the acceptable level (K_p > 40), which necessitates an increase in the train visibility distance.

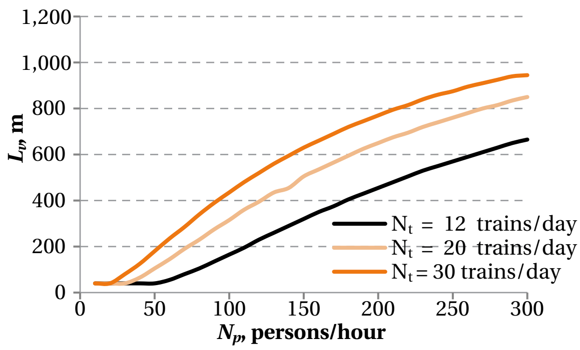


Figure 11. Minimum required train visibility distance for pedestrians depending on pedestrian and train traffic intensity at RPC equipped with a PWIS within existing level crossings

Source: developed by the authors

As pedestrian traffic intensity increases from N_p = 100 to N_p = 300 persons/hour, the required train visibility distance to ensure safety also increases. It is the smallest for RPCs equipped with a PWIS within existing level crossings, greater for RPCs located outside level crossings, and the greatest for RPCs without a PWIS within level crossings. At N_p = 100 persons/hour, the required visibility distance is L_v = 165 m (RPC with PWIS), 235 m (outside level crossing), and 330 m (without PWIS), whereas at N_p = 300 persons/hour, the required visibility distance increases to 665 m, 760 m, and 860 m, respectively.

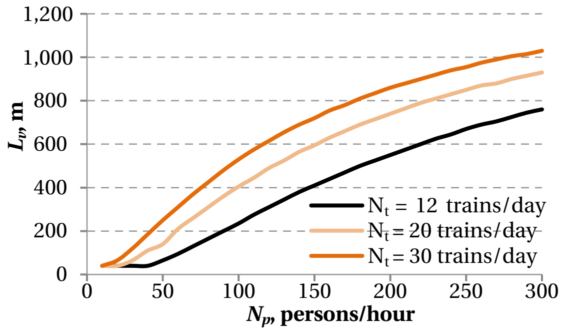


Figure 12. Minimum required train visibility distance for pedestrians depending on pedestrian and train traffic intensity at RPC located outside existing level crossings
Source: developed by the authors

With an increase in train traffic intensity, the minimum train visibility distance required to ensure pedestrian safety increases accordingly. For example, at a pedestrian traffic intensity of N_p = 50 persons/hour and a train traffic intensity of N_t = 20 trains/day, safe conditions are achieved at a visibility distance of L_v = 235 m for RPCs without a PWIS within existing level crossings, L_v = 105 m for RPCs with a PWIS, and L_v = 140 m for RPCs located outside level crossings. When train traffic intensity increases to N_t = 30 trains/day, these values rise to 340 m, 180 m, and 250 m, respectively. A similar trend is observed at N_p = 100 persons/hour: for N_t = 20 trains/day, the minimum visibility distance is 510 m, 315 m, and 405 m, respectively, whereas for N_t = 30 trains/day, it increases to 635 m, 435 m, and 530 m. At high pedestrian traffic intensity (N_p = 200-300 persons/hour), the requirements for train visibility distance increase significantly. In particular, at N_p = 300 persons/hour, the minimum required visibility distance is 665 m for RPCs with PWIS, 760 m for crossings located outside level crossings, and 860 m for crossings without PWIS. For N_p = 200 persons/hour, a similar trend of increasing visibility requirements is observed, with L_v values occupying an intermediate position between the results for N_p = 100 and 300 persons/hour. These ranges were obtained based on the analysis of threshold L_v values for different N_t values, as shown in Figures 10-12. This confirms that with an increase in pedestrian traffic intensity, the required visibility distance increases regardless of the type of crossing.

The sensitivity analysis of the model showed that the greatest influence on the value of the total accident rate coefficient K_p is exerted by coefficients K_3 (visibility of the crossing relative to the train) and K_2 (pedestrian traffic intensity). A 10% change in K_3 leads to a change in K_p within the range of 8-12%, confirming the decisive role of visibility in risk formation. The findings by V. Kovalchuk & Y. Lesiv (2024) confirm that the implementation of a PWIS is an effective engineering and informational measure for improving safety at RPCs. The warning system, based on determining the actual train speed and a fixed pedestrian warning time, allows synchronisation of the visual and audible signal with real train approach conditions. Unlike traditional systems with a fixed approach section length, the proposed approach reduces unjustified crossing closure time, lowers psychological stress, and decreases pedestrian waiting time, which is one of the key factors contributing to risky behaviour. The effectiveness of the PWIS is confirmed by the calculated minimum train visibility distances, which demonstrate substantially lower visibility requirements for RPCs equipped with a PWIS compared to those without it. From a practical perspective, the implementation of a PWIS is recommended primarily for RPCs with high pedestrian traffic intensity, as well as for RPCs located within existing level crossings where pedestrian and vehicular flows intersect. The system may be applied as a supplement to existing level crossing signalling or as an independent pedestrian information tool within urban environments.

Overall, the results confirm the validity of incorporating visibility conditions and warning systems into the safety assessment of RPCs. The obtained findings are consistent with international research and are adapted to the specific characteristics of Ukrainian railway infrastructure. The proposed methodology enables quantitative risk assessment while considering a set of parameters not addressed in current regulations. Therefore, it can be applied in feasibility studies for selecting RPC types, planning infrastructure modernisation, implementing PWIS, and developing safe pedestrian traffic management schemes. The relevance of analysing real visibility conditions is supported by the study of Z. Magyari *et al.* (2018), who assessed visibility at railway level crossings using laser scanning and detailed three-dimensional terrain models. Their results demonstrated that even minor changes in terrain configuration, infrastructure placement, or engineering structures may significantly affect the ability of users to detect approaching trains in time. The importance of adequate visibility parameters as a critical safety factor at railway crossings was also highlighted by A. Kampczyk (2020) and M. Dedík *et al.* (2022), who demonstrated that insufficient sight conditions significantly increase accident risks and should be systematically evaluated during infrastructure design. These findings highlight the necessity of analysing actual site geometry rather than relying solely on simplified schemes or standard calculations, which aligns with the approach adopted in the present study. In addition, the classification of hazard levels based on the values of the final accident rate coefficient provides a practical tool for interpreting safety conditions at RPCs. A conceptually similar approach was applied by O. Voznyak & V. Havryliuk (2016) and M.I. Grilo *et al.* (2025), where qualitative hazard categories for railway infrastructure assets were determined using quantitative risk indicators. In that study, the interpretation of safety levels under practical conditions was supported by colour coding, which facilitated clearer understanding and decision-making. The use of visualised safety interpretation methods strengthens the applicability of quantitative assessment results in real operational contexts. Similar conclusions regarding the applicability of quantitative risk-based tools for selecting appropriate safety interventions at railway crossings were reported by C.-Y. Lin *et al.* (2023) and A. Di Graziano & V. Marchetta (2024), who demonstrated that risk assessment frameworks support prioritisation of infrastructure upgrades and optimisation of safety investments. Furthermore, the obtained results are consistent with international findings regarding the effectiveness of intelligent transport systems, particularly in enhancing situational awareness and reducing accident risks, as reported by M.V. Holotyuk *et al.* (2024). This correspondence confirms the relevance of integrating modern technological solutions into RPC safety management and supports the feasibility of implementing intelligent warning systems as part of infrastructure modernisation strategies.

Conclusions

Within the conducted research, the influence of train visibility conditions and pedestrian warning information systems on pedestrian accident rates at railway crossings was substantiated, revealing that existing safety assessment methodologies mainly focus on driver-train interaction and do not account for pedestrian-specific factors such as lower eye-level position and limited train visibility. The use of the final accident rate coefficient K_p as an integral quantitative risk indicator for pedestrians was substantiated, with the criterion $K_p < 40$ adopted as the condition for an acceptable safety level. The proposed scale makes it possible to classify RPCs by hazard level and apply a unified approach to comparative evaluation of different crossing arrangements. Modelling of the influence of train visibility conditions (coefficient K_3) showed that as pedestrian traffic intensity increases from $N_p = 30$ to 100 persons/hour at a constant train traffic intensity of $N_t = 12$ trains/day, the minimum required visibility distance increases from $L_v =$ 40 m to $L_v = 70$ m for RPCs without a pedestrian warning information system, confirming the direct dependence of accident risk on available sight distance. Assessment of the impact of the pedestrian warning information system demonstrated its high effectiveness. The application of a PWIS within existing railway level crossings reduces the accident rate coefficient by approximately 30% ($K_4 = 1.57$) compared to the use of automatic traffic light signalling alone, while for RPCs located outside level crossings the reduction is about 20% ($K_4 = 1.85$). This results in a significant decrease in the required train visibility distance. Threshold and rational values of train visibility conditions ensuring an acceptable level of pedestrian safety were determined. At $N_p = 100$ persons/hour and $N_t = 20$ trains/day, safe conditions are achieved at $L_v = 315$ m for RPCs with a PWIS, $L_v = 405$ m for RPCs outside level crossings, and $L_v = 510$ m for RPCs without a PWIS. When pedestrian traffic intensity increases to $N_p = 300$ persons/hour, the corresponding values increase to 665 m, 760 m, and 860 m, confirming the expediency of implementing a PWIS at crossings with high pedestrian flows. The obtained results may be applied in Ukraine in the design and modernisation of RPCs, the development of sectoral recommendations and regulatory documents, and the implementation of pedestrian warning information systems in order to reduce accident rates and enhance safety levels in railway transport.

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Conflict of Interest

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Оцінювання впливу довжини видимості поїзда пішоходом на коефіцієнт аварійності на залізничних пішохідних переходах

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Анотація. У статті запропоновано удосконалений метод кількісної оцінки безпеки пішоходів на залізничних пішохідних переходах. Метод ґрунтується на розрахунку коефіцієнтів часткової аварійності, які враховують інтенсивність пішохідного та залізничного руху, відстань видимості потяга, рівень технічного та інформаційного обладнання переходу, а також геометричні та планувальні параметри пішохідного переходу. Було проведено багатоваріантне моделювання змін коефіцієнта аварійності в залежності від відстані видимості потяга для пішоходів та одночасного врахування інтенсивності пішохідного та залізничного руху. Встановлено, що при інтенсивності пішохідного потоку 100 осіб/год та інтенсивності залізничного руху 30 потягів/день мінімальна необхідна відстань видимості на залізничних пішохідних переходах, розташованих в межах існуючого рівняння переходу без інформаційної системи попередження потягів, становить 635 м, тоді як при наявності такої системи відстань видимості зменшується до 435 м. Для залізничних пішохідних переходів, розташованих поза межами існуючих рівнянь переходу, мінімальна необхідна відстань видимості потяга повинна складати 530 м. Визначено, що впровадження системи попередження потягів для пішоходів дозволяє знизити коефіцієнт аварійності на 30 % на існуючих рівняннях переходу та на 20 % поза ними. Отримані результати можуть бути використані при проектуванні та модернізації залізничних пішохідних переходів через залізничні колії

Ключові слова: оцінка безпеки; сприйняття ризику; попереджувальні системи; інфраструктура; небезпечні ситуації