Structured Risk Assessment for Prioritising Safety Mitigation at Railway Level Crossings

A. Permana[1]*, L. Suparma[1], S. Malkhamah[1]
[1]Magister Sistem dan Teknik Transportasi, Universitas Gadjah Mada, Yogyakarta, INDONESIA
**Corresponding author:* aidilpermana@mail.ugm.ac.id

ABSTRACT

Railway level crossings represent one of the highest-risk interfaces within railway systems due to the interaction between train operations and road users at the same grade. In Indonesia, the high frequency of accidents at level crossings highlights the need for a structured risk assessment approach to support the prioritisation of safety mitigation. This study aims to conduct a systematic risk assessment by estimating likelihood, assessing severity, and computing risk scores to classify hazards into Low, Moderate, High, or Extreme categories. The methodology includes hazard identification based on 2024 accident data, likelihood estimation using annual accident frequency, severity assessment based on a five-level consequence scale, and application of a semi-quantitative 5×5 risk matrix. The results indicate that unsafe road-user behaviour dominates the Extreme risk category, while infrastructure and environmental factors are generally classified as High to Moderate risks. This risk classification provides an objective and transparent basis for prioritising safety mitigation at railway level crossings.

Keywords: Railway level crossing, Severity, Likelihood, Risk assessment, Risk matrix.

1 INTRODUCTION

Railway level crossings are critical interfaces between rail and road transport systems. The operational characteristics of trains, including high mass, long braking distances, and relatively high speeds, result in severe potential consequences when accidents occur at level crossings. Despite the implementation of various technical and administrative interventions, accidents at level crossings continue to occur and remain a major contributor to public safety risk within railway systems.

In Indonesia, ensuring safety at both guarded and unguarded railway level crossings remains an urgent and under-addressed challenge. Data from the Directorate General of Railways (DGR) and PT Kereta Api Indonesia (Persero) show that a total of 1,499 level crossing accidents occurred between 2020 and 2024. As illustrated in Figure 1, the annual number of accidents demonstrates an overall increasing trend, rising from 269 incidents in 2020 to 337 incidents in 2024. The 2024 figure represents a 3% increase compared to the previous year, highlighting the persistent nature of level crossing risk within the national railway system.

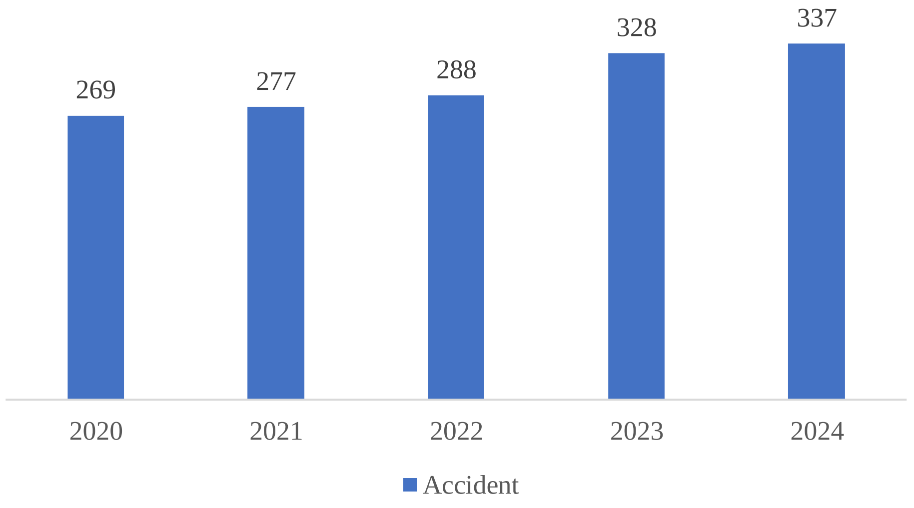

Figure 1. Total accident (PT. Kereta Api Indonesia, 2024).

Statistical records further indicate that the majority of level crossing accidents in Indonesia occur at unguarded crossings and are strongly associated with unsafe road-user behaviour, such as ignoring warning signals or misjudging train speed. These conditions suggest that level crossing safety problems are not solely technical in nature but are also influenced by human and environmental factors. Consequently, level crossings consistently remain among the most hazardous elements of the railway system.

Given these persistent safety challenges, there is a clear need for a systematic and structured approach to risk assessment at railway level crossings. Rather than treating all crossings or hazards uniformly, a risk-based approach enables hazards to be classified according to their likelihood of occurrence and potential consequences, allowing safety mitigation to be prioritised more effectively. Accordingly, this study aims to conduct a structured risk assessment by estimating likelihood, assessing severity, and calculating risk scores to classify hazards into Low, Moderate, High, or Extreme categories as a basis for prioritising safety mitigation at railway level crossings.

2 LITERATURE REVIEW

2.1 Risk Assessment in Transport Safety

Risk assessment at railway level crossings varies significantly across countries, shaped by differences in infrastructure development, regulatory enforcement, technological adoption, and road user behaviour. Nations such as the United States, the United Kingdom, Japan, Australia, and Indonesia have adopted distinct strategies to manage these risks. While technologically advanced countries have integrated predictive analytics and intelligent transport systems, others rely on conventional warning systems and community outreach. A common finding across the literature is the persistent role of human error and the disproportionately high risk associated with unguarded crossings. In contrast to Japan’s widespread use of intelligent transport systems, countries with limited resources often struggle with enforcement and infrastructure investment. In this context, applying ISO 31000 to level crossings provides a systematic process for establishing the context, assessing risks (identification, analysis, and evaluation), and treating those risks, with the ultimate goal of making the crossing safer for all users. This can be achieved through targeted design changes, infrastructure upgrades, or, in some cases, the permanent closure of high-risk sites. Embedding ISO 31000 into the research framework ensures that the risk assessment process not only aligns with international best practice but also offers a transparent and adaptable basis for decision-making across different national contexts.

(Khan et al., 2024) introduced a semi-quantitative risk matrix approach to evaluate safety risks at over 3,000 level crossings in Pakistan. This method integrates longitudinal accident data (2013–2020) with expert-derived severity scores to assign risk values, offering a structured framework that balances data-driven insights with practical applicability. The process follows three key stages: risk identification (through documented accident trends), risk analysis (estimating likelihood and consequence severity), and risk control (prioritising mitigation actions). The scoring system classifies hazards into four levels: low, moderate, high, and extreme, and facilitates targeted interventions such as engineering controls, administrative measures, and workforce training. The study found that unmanned crossings had the highest risk scores, underscoring the method’s utility in prioritising urgent improvements.

This approach is particularly suited to developing countries, where accident data may be limited, but expert insights are accessible. Furthermore, Khan et al. emphasize that risk assessment should not operate in isolation but as part of a continuous improvement process.

The risk evaluation phase in this study involves a semi-quantitative assessment method that systematically quantifies the hazards identified in railway crossing environments. As adopted from Khan et al. (2024), this is achieved by assigning values to two critical parameters: likelihood, which reflects the probability of occurrence of an event, and severity, which denotes the magnitude of the potential’s impact. The combination of these parameters yields a risk score, providing a measurable indicator of overall risk exposure.

The estimation is performed using equation (3.1), in which $n_E(t)$ is the frequency of any specific accident related to the railway and t represents the duration in which the accident occurred. The expression $f_t(E)$ is determined by dividing the number of accidents by the respective time period, providing a quantitative measure of how often such incidents occur.

$$f_t(E) = \frac{n_E(t)}{t} \qquad (1)$$

For better understanding, the accident frequencies are usually converted into percentages for each accident over the time period. Subsequently, these percentages are categorised on a likelihood scale ranging from 1 (very low) to 5 (very high), as depicted in Table 1. In the subsequent step of risk analysis, the consequence aspect of risk assessment is used to classify accidents based on their severity. The classification considers factors such as fatalities, injuries, environmental impact, and property or equipment damage, as outlined in Table 2. The severity levels are catastrophic, critical, significant, major, and minor. To ensure consistent interpretation of event frequencies, this study applies a standardised likelihood classification that maps observed counts to ordinal likelihood classes. Severity is assessed by plausible consequences, ranging from minor service disruption to catastrophic events involving multiple fatalities.

Table 1. Illustration of Frequency of Likelihood Categories (Khan, 2024).

No	Categories	Descriptor	Scale
1	Very High	>20%/year	5
2	High	16-20%/year	4
3	Moderate	11-15%/year	3
4	Low	5-10%/year	2
5	Very Low	<5%/year	1

Table 2. Severity Categories and Consequences (Khan, 2024)

No	Categories	Descriptor	Scale
1	Catastrophic	Multiple fatalities, multiple major injuries, irreversible environmental damage, property loss worth more than $1M	5
2	Critical	One fatality, multiple major injuries, reversible with mitigation environmental damage, property loss ranges from $1M to $250K	4
3	Significant	One major injury, multiple minor injuries, reversible environmental damage, property loss ranges from $250K to $50K	3
4	Major	No major injury, multiple minor injury, reversible environmental damage, property loss ranges from $50K to $10K	2
5	Minor	One minor injury, reversible environmental damage, property loss less than $10K	1

These tables provide a structured basis for risk quantification. Likelihood categories are derived from annualised frequency thresholds, while severity scores are determined by evaluating the worst-case consequence of each hazard. This classification enables consistent comparison across different types of road users and supports prioritisation of intervention strategies. Table 3 presents the calculated risk scores, derived by combining the severity and likelihood scales defined in Tables 1 and 2 Based on the scoring system above, each identified hazard was assigned a likelihood and severity score, with the resulting risk score calculated as:

$$\text{Risk Score} = \text{Likelihood x Severity} \qquad (2)$$

Table 3. Risk Assessment Matrix (Khan, 2024)

Severity **Likelihood**	**5**	**4**	**3**	**2**	**1**
5	25 (>16 E)	20 (>16 E)	15 (10-16 H)	10 (10-16 H)	5 (5-9 M)
4	20 (>16 E)	16 (10-16 H)	12 (10-16 H)	8 (5-9 M)	4 (<5 L)
3	15 (10-16 H)	12 (10-16 H)	9 (5-9 M)	6 (5-9 M)	3 (<5 L)
2	10 (10-16 H)	8 (5-9 M)	6 (5-9 M)	4 (<5 L)	2 (<5 L)
1	5 (5-9 M)	4 (<5 L)	3 (<5 L)	2 (<5 L)	1 (<5 L)

Notes: Where risk score > 16 shows Extreme (E), 10–16 represents High (H), 5–9 indicates Medium (M), and < 5 illustrates Low (L) level of risk.

Other studies have adopted advanced statistical modelling to capture unobserved heterogeneity in crash severity (Mannering et al., 2016). For example, Ahmed, Corman, and Anastasopoulos (2023) employed a random parameters multinomial logit model using nine years of FRA data from two U.S. states, showing spatial inconsistency in the determinants of injury severity. Similarly, Ren and Xu (2024) based a random parameters logit model with heterogeneity in means to show how train speed, vehicle type, and driver behaviour significantly affect crash outcomes. Additional studies by Haleem and Gan (2015) and Khan and Khattak (2018) identified further influential variables, including driver age, land use context, and crossing geometry. These findings reinforce the need for flexible modelling approaches adapted to local contexts. Considering these methodological strengths, this thesis adopts the semi-quantitative risk matrix as a core component of the risk assessment phase.

3 METHODOLOGY

3.1 Research Location

The study was conducted in Operational Area (DAOP) 1 Jakarta under the jurisdiction of PT Kereta Api Indonesia (Persero). This area was selected due to its high operational intensity and the highest recorded number of level-crossing accidents in Indonesia in 2024. The study covers both guarded and unguarded level crossings, representing varied infrastructure and environmental conditions relevant to risk assessment.

3.2 Data Input

The risk assessment was based on secondary data obtained from official railway safety records for the year 2024. The primary dataset comprised level crossing accident records within Operational Area (DAOP) 1 Jakarta, including information on accident type, location, road-user involvement, and resulting consequences. These data were used to support hazard identification and to derive likelihood estimates for each identified hazard.

3.3 Risk Assessment

Following hazard identification, each hazard was evaluated using a semi-quantitative 5×5 risk matrix. The risk assessment framework, incorporating likelihood and severity parameters, was adapted from the semi-quantitative risk assessment model proposed by Khan et al. (2024) and contextualised to suit the Indonesian railway level crossing environment and the scope of this study.

Likelihood (L) was estimated based on the frequency of level crossing incidents recorded in 2024 and classified using a five-level ordinal scale ranging from Very Low to Very High. Severity (S) was assessed using a five-level consequence scale, namely Minor, Disruption, Significant, Fatality, and Catastrophic, considering casualty severity, asset damage, and operational disruption.

Risk scores were calculated by combining likelihood and severity values and subsequently classified into four risk categories: Low, Moderate, High, and Extreme. Risk tolerability was evaluated using the risk tolerability criteria defined by Khan (2024), where each category specifies the required level of control, ranging from acceptable with monitoring for low risks to immediate intervention for extreme risks. This approach ensures that risk management actions are proportional to both the likelihood and severity of each identified hazard.

4 RESULT

4.1 Risk Assessment Result

In the first step, this study estimates the likelihood of level crossing-related incidents at DAOP 1 Jakarta from one year of historical records. Following Table 4 from Khan et al. (2024), the likelihood for each risk scenario is computed using Eq. (3.1), where denotes the accident count for scenario E observed during the period t (in years), and t is the observation duration. Because the window is exactly one year (t=1), the annualised frequency equals the raw count (events per year). For interpretability and consistency with Khan's scheme, this is expressed as a percentage per year and mapped to a five-class ordinal scale (Very Low to Very High): <5 %/year = 1; 5–10 % = 2; 11–15 % = 3; 16–20 % = 4; >20 % = 5. These thresholds are applied uniformly across user types and scenarios. Zero counts are classified as Very Low (L=1); given the single-year horizon, small-sample effects are treated conservatively (no smoothing), with sensitivity checks reported separately. Table 2 reports one-year likelihoods for each type of accident.

Table 4. Likelihood Classification for Type of Accidents (t = 1 year)

User Type	Identified Hazard	Accidents count	Annualised Frequency $(f_t(E)) = \frac{n_E(t)}{t}$	Percentage per year (%)	Likelihood Scale	Likelihood Category
Car Driver	Low visibility due to vegetation, curves, or parked vehicles	1	1	6.67	2	Low
Car Driver	Traffic congestion near crossings	3	3	20	4	High
Car Driver	Barrier malfunction or incomplete closure	1	1	6.67	2	Low
Car Driver	Damaged or uneven crossing surface causing stalling or slipping	2	2	13.33	3	Moderate
Car Driver	Faulty or poorly maintained signalling systems (lights, bells)	1	1	6.67	2	Low
Car Driver	Vehicle stuck on the track due to driver error or panic	1	1	6.67	2	Low
Car Driver	Breaking or forcing crossing during active signals and barriers	6	6	40	5	Very High
Motorcyclist	Low visibility due to vegetation, curves, or parked vehicles	1	1	6.67	2	Low
Motorcyclist	Traffic congestion near crossings	2	2	13.33	3	Moderate
Motorcyclist	Barrier malfunction or incomplete closure	1	1	6.67	2	Low
Motorcyclist	Damaged or uneven crossing surface causing stalling or slipping	2	2	13.33	3	Moderate

User Type	**Identified Hazard**	**Accidents count**	**Annualised Frequency $(f_t(E)) = \frac{n_E(t)}{t}$**	**Percentage per year (%)**	**Likelihood Scale**	**Likelihood Category**
Motorcyclist	Faulty or poorly maintained signalling systems (lights, bells)	1	1	6.67	2	Low
Motorcyclist	Overconfidence in judging train speed or clearance gap	4	4	26.67	5	Very High
Motorcyclist	failing to stop behind designated stop lines	1	1	6.67	2	Low
Motorcyclist	Breaking or forcing crossing during active signals and barriers	4	4	26.67	5	Very High
Pedestrian	Low visibility due to vegetation, curves, or parked vehicles	3	3	5	2	Low
Pedestrian	Market activities or dense settlements near crossings	3	3	5	2	Low
Pedestrian	Barrier malfunction or incomplete closure	2	2	3.33	1	Very Low
Pedestrian	Faulty or poorly maintained signalling systems (lights, bells)	1	1	1.67	1	Very Low
Pedestrian	Distraction or inattentiveness while crossing	14	14	23.33	5	Very High
Pedestrian	Overconfidence in judging train speed or clearance gap	15	15	25	5	Very High
Pedestrian	Intentional trespass/ self-harm	2	2	3.33	1	Very Low
Pedestrian	Breaking or forcing crossing during active signals and barriers	21	21	31.81	5	Very High

The severity classification was adapted from the parameters proposed by Khan et al. (2024) and contextualised to reflect the Indonesian railway operating environment. The adaptation considers local characteristics, including the high exposure of vulnerable road users, the prevalence of unguarded level crossings, and the significant operational impacts of incidents on dense mixed-traffic rail networks.

Severity was classified using a five-level ordinal scale: Minor (1), involving no casualties or minor injuries with minimal operational impact; Disruption (2), involving multiple minor injuries and short service delays; Significant (3), involving serious injuries and moderate service disruption; Fatality (4), involving one death or major operational disruption; and Catastrophic (5), involving multiple fatalities and/or major infrastructure damage resulting in prolonged service disruption. Boundary cases were resolved using predefined rules to ensure consistent classification. A summary of the severity scale and descriptors is provided in Table 5.

Table 4. Severity categories and consequences

No	**Safety**	**Asset Damage**	**Operational Disruption**	**Category**	**Scale**
1	≥ 2 fatalities / mass-casualty, or derailment / major infrastructure damage.	Major damage to rolling stock and/or infrastructure (rails, points/switches, primary signals).	> 6 hours of disruption or line closure.	Catastrophic	5
2	1 fatality or multiple serious injuries.	Special handling required; equipment damage may be present.	1–3 hours of disruption and/or several train movements affected.	Fatality	4
3	≥ 1 serious injury (e.g., fracture, amputation, head trauma).	Severe damage to road vehicle/rolling stock while the track remains usable.	30–60 minutes of disruption and/or 3–5 train movements affected.	Significant Incident	3
4	Several minor injuries, with no serious injury.	Moderate damage to vehicle/barrier, with no infrastructure damage.	15-30 minutes of delay (typically 1–2 train movements). No change to the operating pattern (no single-line working, no cancellations).	Disruption	2
5	No casualty or one minor injury (abrasion/bruise; outpatient care).	Light scratches/dents; equipment remains functional.	Normal operations or < 15 minutes of delay. Impact limited to the passing train; minimal knock-on delay	Minor	1

Severity was assessed independently of likelihood and assigned using the maximum consequence across three dimensions: safety, asset damage, and operational disruption, including the application of the 3–6 hour bridging rule where relevant. These severity classes form the consequence axis of the 5×5 risk matrix. Likelihood was derived from observed one-year event frequencies and mapped to a five-level ordinal scale. Both likelihood and severity were evaluated separately for each primary user group—car drivers, motorcyclists, and pedestrians—to reflect differences in exposure and outcome profiles.

Risk assessment results are summarised in Table 6, which presents risk scores by contributing cause and user type. Each risk score was obtained by combining the corresponding likelihood and severity classes to produce a risk category (Low, Moderate, High, or Extreme). For traceability, each entry is linked to a unique Risk ID corresponding to the identified hazard, with repetition across user groups retained to capture user-specific risk characteristics.

Table 6. Risk Assessment Result

User Type	**Risk ID**	**Identified Hazard**	**Likelihood Scale**	**Severity Scale**	**Risk Score**	**Risk Category**
Car Driver	C-01	Low visibility due to vegetation, curves, or parked vehicles	2	3	6	Moderate (M)
Car Driver	C-02	Traffic congestion near crossings	4	2	8	Moderate(M)
Car Driver	C-03	Barrier malfunction or incomplete closure	2	3	6	Moderate (M)
Car Driver	C-04	Damaged or uneven crossing surface causing stalling or slipping	3	2	6	Moderate (M)
Car Driver	C-05	Faulty or poorly maintained signalling systems (lights, bells)	2	3	6	Moderate (M)
Car Driver	C-06	Vehicle stuck on the track due to driver error or panic	2	2	4	Low (L)
Car Driver	C-07	Breaking or forcing crossing during active signals and barriers	5	2	10	High (H)
Motorcyclist	M-01	Low visibility due to vegetation, curves, or parked vehicles	2	4	8	Moderate (M)
Motorcyclist	M-02	Traffic congestion near crossings	3	4	12	High (H)
Motorcyclist	M-03	Barrier malfunction or incomplete closure	2	4	8	Moderate (M)
Motorcyclist	M-04	Damaged or uneven crossing surface causing stalling or slipping	3	4	12	High (H)
Motorcyclist	M-05	Faulty or poorly maintained signalling systems (lights, bells)	2	4	8	Moderate (M)

User Type	Risk ID	Identified Hazard	Likelihood Scale	Severity Scale	Risk Score	Risk Category
Motorcyclist	M-06	Overconfidence in judging train speed or clearance gap	5	4	20	Extreme (E)
Motorcyclist	M-07	failing to stop behind designated stop lines	2	4	8	Moderate (M)
Motorcyclist	M-08	Breaking or forcing crossing during active signals and barriers	5	4	20	Extreme (E)
Pedestrian	P-01	Low visibility due to vegetation, curves, or parked vehicles	2	3	6	Moderate (M)
Pedestrian	P-02	Market activities or dense settlements near crossings	2	3	6	Moderate (M)
Pedestrian	P-03	Barrier malfunction or incomplete closure	1	4	4	Low (L)
Pedestrian	P-04	Faulty or poorly maintained signalling systems (lights, bells)	1	4	4	Low (L)
Pedestrian	P-05	Distraction or inattentiveness while crossing	5	4	20	Extreme (E)
Pedestrian	P-06	Overconfidence in judging train speed or clearance gap	5	4	20	Extreme (E)
Pedestrian	P-07	Intentional trespass / self-harm	1	4	4	Low (L)
Pedestrian	P-08	Breaking or forcing crossing during active signals and barriers	5	4	20	Extreme (E)

Risk assessment result explained that the Likelihood values are taken from Table 6, the observed 2024 event counts per hazard are mapped to the five-level scale. The severity distribution is clearly user-type specific. For motorcyclists and pedestrians, most hazards carry a severity level 4 (serious injury or worse), reflecting their vulnerability and direct exposure at crossings. In contrast, hazards for car drivers are dominated by severity levels 2–3, with no level-4 ratings, consistent with the 2024 dataset in which no car-driver fatalities were recorded; vehicle protection and crashworthiness reduce injury severity relative to unprotected users.

From the 23 identified hazards, five (5) were classified as *Extreme*, three (3) as *High*, eleven (11) as *Moderate*, and four (4) as *Low*. Extreme risks are dominated by unsafe human behaviours, most notably forcing a crossing during active signals, misjudging train speed or clearance gaps, and distraction while crossing. These behaviours are most prevalent among pedestrians, who constitute the majority of recorded incidents in 2024, with a substantial share occurring at unguarded level crossings. This pattern is consistent with the fishbone analysis, in which human factors (Man) emerged as the principal contributor.

Extreme-risk causes are dominated by unsafe behaviours, particularly forcing a crossing during active signals, overconfidence in judging train speed or clearance gaps, and distraction while crossing. These behaviours were observed across pedestrians and motorcyclists, with pedestrians showing the highest exposure.

High-risk causes are concentrated in hazards where unsafe behaviours interact with infrastructure and environmental conditions. Examples include traffic congestion near crossings, damaged or uneven crossing surfaces, and vehicles becoming stuck on the track due to driver error or panic. These scenarios highlight how deficiencies in the Facilities and Environment categories amplify road user risks.

Moderate-risk causes encompass a mix of behavioural and situational hazards, such as low visibility due to vegetation, curves, or parked vehicles, failing to stop behind designated stop lines, and technical deficiencies like Barrier malfunctions and faulty signalling systems. Although their severity remains significant, their relatively lower frequency places them in a tolerable but still important category for intervention.

Low-risk causes are limited to hazards such as incomplete barrier closures, faulty signalling systems in pedestrian incidents, and intentional trespass or self-harm. While these risks cannot be ignored, they occur infrequently and are best managed through routine monitoring, targeted deterrence, and maintenance

Overall, the quantitative results converge: behavioural violations, particularly among pedestrians at level crossings, are the primary drivers of extreme-risk incidents, with infrastructure and environmental shortcomings acting as amplifying factors.

5 CONCLUSION

Based on the risk assessment results for railway level crossings in DAOP 1 Jakarta, this study confirms that unsafe road-user behaviour is the primary driver of high and extreme safety risks, particularly among pedestrians and motorcyclists. From the 23 identified hazards, five were classified as Extreme risk and three as High risk, with extreme risks consistently associated with behaviours such as forcing crossings during active signals, misjudging train speed or clearance gaps, and distraction while crossing. Severity analysis shows a clear user-type distinction, where pedestrians and motorcyclists predominantly exhibit higher severity levels due to their vulnerability, while car-driver related hazards are generally limited to lower severity outcomes. Infrastructure and environmental factors, including traffic congestion near crossings, damaged crossing surfaces, and reduced visibility, were mainly classified as Moderate to High risks and act as amplifiers of behavioural hazards rather than primary causes. Overall, the application of a semi-quantitative 5×5 risk matrix enabled systematic classification of hazards into Low, Moderate, High, and Extreme categories, providing an objective and traceable basis for prioritising safety mitigation at railway level crossings in Indonesia.

REFERENCES

Ahmed, S. S., Corman, F., & Anastasopoulos, P. C. (2023). Accounting for unobserved heterogeneity and spatial instability in the analysis of crash injury-severity at highway-rail grade crossings: A random parameters with heterogeneity in the means and variances approach. *Analytic Methods in Accident Research*, *37*, 100250. https://doi.org/10.1016/j.amar.2022.100250

Haleem, K., & Gan, A. (2015). Contributing factors of crash injury severity at public highway-railroad grade crossings in the U.S. *Journal of Safety Research*, *53*, 23–29. https://doi.org/10.1016/j.jsr.2015.03.005

Khan, S., Pervez, A., Zhang, Y., Ahmad, S., Sharifzada, H., Ismail, E. A. A., & Awwad, F. A. (2024). Comprehensive risk assessment of Pakistan railway network: A semi-quantitative risk matrix approach. *Heliyon*, *10*(12), e32682. https://doi.org/10.1016/j.heliyon.2024.e32682

Khan, W. A., & Khattak, A. J. (2018). Injury Severity of Truck Drivers in Crashes at Highway-Rail Grade Crossings in the United States. *Transportation Research Record*, *2672*(10), 38–47. https://doi.org/10.1177/0361198118781183

Mannering, F. L., Shankar, V., & Bhat, C. R. (2016). Unobserved heterogeneity and the statistical analysis of highway accident data. *Analytic Methods in Accident Research*, *11*, 1–16. https://doi.org/10.1016/j.amar.2016.04.001

PT Kereta Api Indonesia (Persero). (2025). *Data perlintasan sebidang tahun 2024*. Division of Security, PT Kereta Api Indonesia (Persero), Jakarta.

PT Kereta Api Indonesia (Persero). (2024). *Total railway level crossing accidents in Indonesia (2020–2024)*. PT Kereta Api Indonesia (Persero).

Ren, Q., & Xu, M. (2024). Injury severity analysis of highway-rail grade crossing crashes in non-divided two-way traffic scenarios: A random parameters logit model. *Multimodal Transportation*, *3*(1), 100109. https://doi.org/10.1016/j.multra.2023.100109