

Risk Analysis of Hybrid Rising-Barrier Systems at Railway Level Crossings using FMEA (Case Study: West Sumatra, Indonesia)

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Abstract

Safety at railway level crossings in Indonesia remains a critical concern, particularly at crossings without physical barriers or those relying solely on early warning systems (EWS). Spatial constraints, high dependence on human operators, and low compliance among road users increase the likelihood of system failure and the risk of accidents. This study aims to identify potential failure modes and evaluate the safety performance of a hybrid rising-barrier-based level crossing protection system using the failure mode and effects analysis (FMEA) approach. The methodology focuses on the systematic identification of key system components, the determination of critical failure modes, and the assessment of risk parameters including severity, occurrence, and detectability to calculate the risk priority number (RPN). A comparative evaluation of pre- and post-mitigation conditions was conducted to examine the effectiveness of proposed technical and operational risk reduction measures. The analysis was applied to level crossings in West Sumatra, Indonesia, representing environments with high accident exposure and limited infrastructure capacity. The results indicate that the hybrid rising-barrier system demonstrates improved safety robustness compared with conventional systems, particularly in reducing risks associated with road-user violations and reliance on manual operation. The implementation of targeted mitigation strategies led to a substantial reduction in risk priority number values, especially for failure modes related to delayed activation and failures in object detection. The study demonstrates that the FMEA approach can support systematic risk identification and their prioritization for railway level crossing protection systems under Indonesian operational conditions.

Keywords: FMEA, level crossing, railway safety, rising-barrier, risk analysis.

Abstrak

Analisis Risiko Sistem Penghalang pada Perlindungan Sebidang Kereta Api dengan Metode FMEA (Studi Kasus: Sumatera Barat, Indonesia): Keselamatan perlintasan sebidang kereta api di Indonesia masih menjadi perhatian kritis, khususnya pada perlintasan tanpa palang fisik atau yang hanya mengandalkan early warning system (EWS). Keterbatasan ruang, tingginya ketergantungan pada operator manusia, serta rendahnya tingkat kepatuhan pengguna jalan meningkatkan kemungkinan terjadinya kegagalan sistem dan risiko kecelakaan. Penelitian ini bertujuan untuk mengidentifikasi potensi mode kegagalan serta mengevaluasi kinerja keselamatan sistem perlindungan perlintasan sebidang berbasis palang naik (hybrid rising-barrier) dengan menggunakan pendekatan failure mode and effects analysis (FMEA). Metodologi penelitian berfokus pada identifikasi sistematis komponen utama sistem, penentuan mode kegagalan kritis, serta penilaian parameter risiko yang meliputi tingkat keparahan (severity), frekuensi kejadian (occurrence), dan kemampuan deteksi (detectability) untuk menghitung risk priority number (RPN). Evaluasi komparatif antara kondisi sebelum dan sesudah mitigasi dilakukan untuk menilai efektivitas langkah-langkah pengurangan risiko secara teknis dan operasional yang diusulkan. Analisis diterapkan pada perlintasan sebidang di Sumatera Barat yang merepresentasikan lingkungan dengan tingkat paparan kecelakaan yang tinggi dan kapasitas infrastruktur yang terbatas. Hasil penelitian menunjukkan bahwa sistem hybrid rising-barrier memiliki tingkat ketahanan keselamatan yang lebih baik dibandingkan sistem konvensional, khususnya dalam mengurangi risiko yang berkaitan dengan pelanggaran pengguna jalan dan ketergantungan pada operasi manual. Implementasi strategi mitigasi yang terarah menghasilkan penurunan signifikan pada nilai risk priority number, terutama pada mode kegagalan yang terkait dengan keterlambatan aktivasi dan kegagalan deteksi objek. Penelitian ini menegaskan bahwa metode FMEA merupakan kerangka kerja yang terstruktur dan efektif dalam mendukung perancangan keselamatan berbasis risiko serta pengambilan keputusan untuk sistem perlindungan perlintasan sebidang dalam kondisi operasional di Indonesia.

Kata kunci: Analisis risiko, FMEA, keselamatan perkeretaapian, perlintasan sebidang, rising-barrier.

1. Introduction

Railway level crossings represent one of the most critical safety interfaces between rail and road transport systems. Despite ongoing safety improvement programs, level crossing accidents remain a persistent problem in many developing countries, including Indonesia. A large proportion of crossings operate without physical barriers or rely solely on early warning systems (EWS) [1], which provide visual and audible alerts but lack physical enforcement mechanisms [2].

Previous studies have shown that warning-only systems are highly vulnerable to road user violations, delayed reactions, and behavioral non-compliance, particularly in mixed-traffic and low-enforcement environments [3]. In Indonesia, the safety challenge is further intensified by spatial constraints [4], limited funding [5], and the widespread presence of informal [6] or community-built crossings [7]. Conventional barrier-gate systems, while effective in principle, are often impractical due to their high installation [8] and operational costs, continuous reliance on human operators, and minimum geometric requirements [9] that cannot be met on narrow Class II and Class III roads [10]. As a result, many crossings remain inadequately protected, increasing exposure to severe collision risks.

Recent international practices have demonstrated the effectiveness of integrating physical deterrents with automated warning technologies to improve compliance and reduce accident risk. Hybrid safety systems combining obstacle detection [11], automated barriers [12], and emergency override mechanisms [13] have been implemented or piloted in countries such as Japan, South Korea, and the United Kingdom, showing measurable reductions in risk levels at high-risk crossings [14]. These systems emphasize layered safety, automation, and reduced dependency on human intervention, which are key principles in modern railway safety engineering [15].

However, despite these technological advancements, there remains a significant research gap in the systematic safety evaluation of hybrid level crossing systems within the Indonesian operational context. Existing studies predominantly discuss technological feasibility, regulatory frameworks, or accident statistics, but they provide limited structured risk-based analysis of potential system-level failure modes prior to implementation. In particular, there is insufficient empirical evidence assessing whether hybrid rising-barrier systems can demonstrably reduce risk under spatial, behavioral, and infrastructural constraints typical of Indonesian crossings. This lack of quantitative, failure-mode-based evaluation creates uncertainty for policymakers and infrastructure authorities when prioritizing safety investments. FMEA has been widely applied in transportation and safety-critical systems to identify vulnerabilities, prioritize risks, and support safety-oriented design decisions [16].

Therefore, this study focuses on evaluating the safety performance of a hybrid rising-barrier-based level crossing protection system through a structured FMEA approach. The objective of this research is to identify critical failure modes, quantify risk levels using risk priority numbers (RPN), and assess the effectiveness of targeted mitigation strategies [17]. By applying the FMEA approach to a representative Indonesian case study, this research seeks to analyse potential system-level risks and mitigation priorities associated with hybrid rising-barrier level crossing systems [18].

2. Methodology

2.1. Data Collection

This study was conducted at selected railway level crossings located within the operational jurisdiction of the Class II Railway Engineering Center Padang, West Sumatra, Indonesia. The primary case study focuses on JPL 14 (KM 56+175 KI-PMN), which represents a high-risk level crossing characterized by road classification (Class II-III local road), mixed traffic composition dominated by motorcycles and light vehicles, limited geometric width (≤ 6 m carriageway), existing protection (early warning system) without full physical barrier, and high violation frequency and accident exposure.

As shown in Figure 1, the EWS primarily relies on user compliance and awareness, which highlights the importance of examining accident trends and operational data. Therefore, accident and operational data were collected from official safety reports covering the period 2017-2024. Technical specifications of the proposed hybrid rising-barrier system were derived from national regulatory documents and comparative international practices [19].

Figure 2 shows the distribution of railway level crossing accidents over the period 2017-2024, with a total of 179 recorded incidents. The annual data indicate fluctuations with relatively lower numbers in 2017 (15 cases) and 2020 (15 cases), followed by an increase in 2021 (31 cases) and 2023 (30 cases). Although no consistent downward trend is observed, the persistence of accidents highlights ongoing safety challenges at level crossings.



Figure 1. Early warning system installed at a railway level crossing in Indonesia [1].

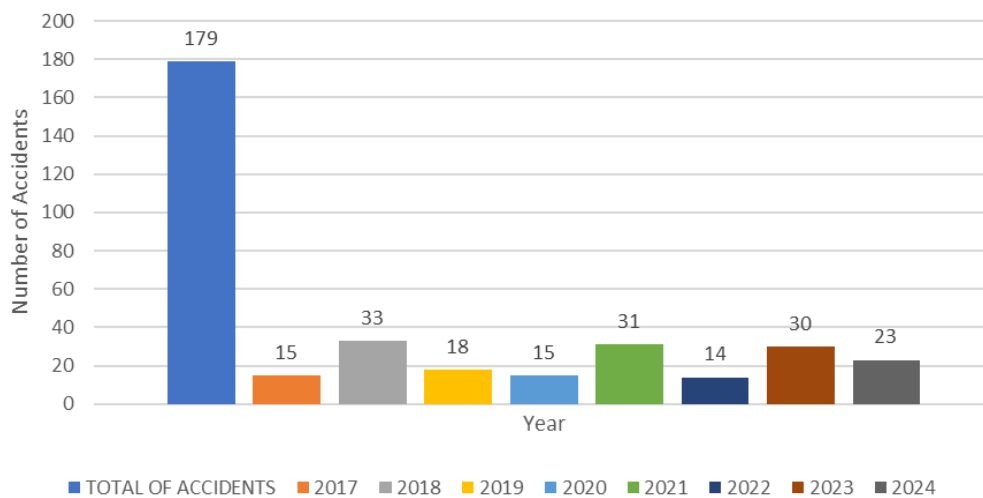


Figure 2. Total number of railway level crossing accidents from 2017-2024 [4]-[7].

2.2. Research Design

These findings underline the need for a systematic risk-based analysis to identify critical failure points and contributing factors [20]. Therefore, this research adopts an FMEA approach to evaluate potential system failures and improve safety performance. The methodological stages consist of system decomposition and functional mapping, identification of potential failure modes, risk parameter scoring (severity, occurrence, detectability), risk priority number (RPN) calculation, development of mitigation strategies, and post-mitigation risk reassessment. The analysis compares baseline (pre-mitigation) and improved (post-mitigation) system conditions.

Figure 3 illustrates the proposed hybrid rising-barrier system, integrating physical rising-barriers with conventional warning devices such as signals, signage, and road markings [21]. The system is designed to operate in coordination with train detection, where the barriers rise to physically block road access when a train approaches, preventing vehicle intrusion into the crossing area. Compared to conventional early warning system, this concept reduces reliance on user compliance by introducing a physical enforcement mechanism. The layout also demonstrates its adaptability to constrained road environments, making it feasible for typical level crossing conditions in Indonesia [22].

2.3. Expert Judgement and Risk Scoring Procedure

To ensure realistic and context-based risk evaluation, expert judgement was employed in determining severity (S), occurrence (O), and detectability (D) scores. A total of 6 experts participated in the evaluation process consisting of 2 railway signalling engineers (≥ 10 years experience), 1 level crossing operations supervisor, 1 railway safety regulator representative, 1 transportation systems academic, and 1 maintenance engineer with field experience in detection systems. All experts had direct professional involvement in railway safety, signalling systems, or level crossing operations in Indonesia.

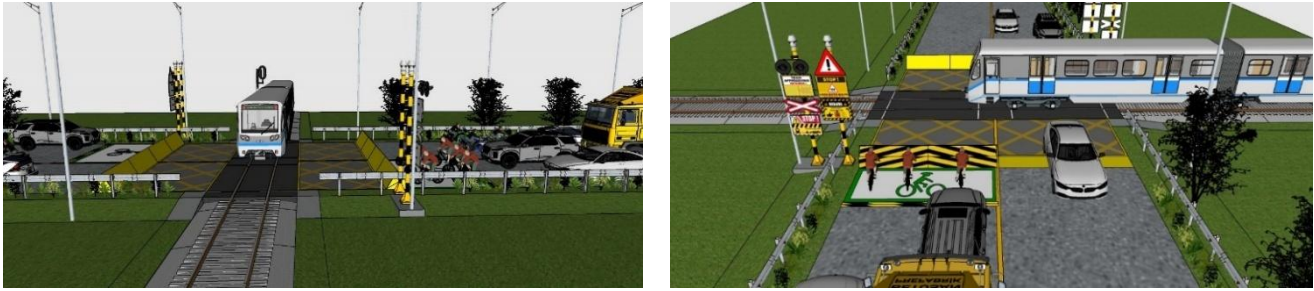


Figure 3. Rising-barrier concept.

2.3.1. Elicitation Method

A structured individual scoring method was applied, followed by a focused group discussion (FGD) to reconcile significant scoring discrepancies. The elicitation process consisted of independent scoring of each identified failure mode using a 1-10 FMEA scale, compilation of scores and calculation of mean values, FGD session to discuss variations exceeding ± 2 score difference, and final consensus-based scoring for RPN calculation. This combined approach was adopted to minimize individual bias while ensuring technical validity.

2.4. Data Analysis

Data analysis is conducted using the FMEA framework. Each identified failure mode is evaluated by calculating its risk priority number (RPN), which represents the combined effect of severity, occurrence, and detectability. The analysis is performed in two stages, pre-mitigation analysis (representing existing or baseline system conditions) and post-mitigation analysis (incorporating proposed technical and operational mitigation measures) [23].

The effectiveness of mitigation strategies is assessed by comparing RPN values before and after mitigation [24]. Failure modes with high initial RPN values are prioritized for risk reduction, supporting evidence-based safety improvement recommendations.

$$RPN = S \times O \times D \quad (1)$$

$$Risk\ Reduction\ (\%) = \left(\frac{RPN^1 - RPN^2}{RPN^1} \right) \times 100\% \quad (2)$$

Table 1. Failure Mode and Effects Analysis (FMEA) [16]

Score	Severity (S)	Occurrence (O)	Detectability (D)
1	No noticeable effect	Remote (<1 in 20,000 cycles/year)	Almost certain to detect
2	Very minor effect. No safety impact	Very unlikely (<1 in 2,000)	Very high detectability
3	Minor effect, small inconvenience	Low likelihood (annual)	High detectability
4	Low safety risk, slight system degradation	Occasional (monthly)	Good detectability
5	Moderate effect, potential for property damage	Moderate (weekly)	Moderate
6	Moderate-to-high effect, may cause near miss	Moderately high (several times per week)	Low
7	High effect, system outage with safety implication	High (daily)	Very low
8	Very high, safety incident likely	Very high (multiple times/day)	Poor
9	Critical, risk of severe injury/fatality	Almost certain (every use)	Almost Impossible
10	Catastrophic, multiple fatalities almost certain	Inevitable (continuous)	Undetectable

Table 2. FMEA for rising-barriers system [16].

Component	Potential failure mode	Effect of failure	S	O	D	RPN
Rising-barrier mechanism	Failure to rise/lower	Vehicle-train collision risk	9	3	4	108
Axle Counter Sensor	Incorrect train detection	Delayed warning or false trigger	8	4	3	96
EWS Sirens / LED	Fails to activate	Road users not alerted	8	2	4	64
Emergency Push-Button	Not functioning during emergency	Trapped vehicle cannot escape	9	2	5	90
Power Supply	Blackout or unstable power	System shut down	7	3	4	84
CCTV Monitoring	Video feed failure	Reduced situational awareness	5	3	4	60

Table 1 presents the scoring criteria used in the FMEA, consisting of severity, occurrence, and detectability. Each factor is rated on a scale of 1 to 10, where severity reflects the impact of failure, occurrence indicates the likelihood of failure, and detectability represents the probability of detecting the failure before it occurs. These parameters are combined to calculate the RPN, which is used to prioritize critical failure modes for mitigation.

3. Results and Discussions

3.1. Risk Identification and Failure Mode Analysis

The first stage of the analysis focuses on identifying potential failure modes within the hybrid rising-barrier level crossing protection system. The system is decomposed into key functional components, including detection units, control logic, rising-barrier mechanisms, warning devices, power supply, and human–system interfaces. Failure modes are identified for each component based on operational conditions commonly found at Indonesian level crossings.

Several critical failure modes are observed, including delayed barrier activation, failure of object detection within the crossing zone, malfunction of warning devices, power supply interruption, and improper response by road users. Among these, failures related to detection and activation functions pose the highest safety risk, as they directly influence the system’s ability to prevent vehicle-train conflicts.

Table 2 presents the FMEA results for the proposed rising-barrier system, identifying key components, their potential failure modes, and associated effects. The RPN values indicate that the most critical risks are related to the rising-barrier mechanism (RPN=108) and axle counter sensor failures (RPN=96), as these directly affect train detection and physical access control, potentially leading to vehicle-train collisions. Other notable risks include emergency push-button failure (RPN=90) and power supply issues (RPN=84), which may compromise system response during critical situations. In contrast, failures in CCTV monitoring and warning devices show relatively lower RPN values but still contribute to reduced situational awareness and user safety. Overall, the results indicate that detection and barrier activation functions represent the most safety-critical elements requiring priority mitigation. This finding is consistent with previous studies on railway level crossing safety systems [25].

3.2. Risk Priority Number (RPN) Evaluation

3.2.1. Pre-Mitigation Risk Assessment

Each identified failure mode is evaluated using the FMEA framework by assigning severity (S), occurrence (O), and detectability (D) scores. The calculated risk priority number (RPN) represents the baseline or pre-mitigation risk level of the hybrid system. Table 3 results show that failure modes associated with delayed barrier activation and object detection failure produce the highest RPN values. These risks are primarily driven by high severity scores due to the potential for catastrophic collisions, combined with moderate-to-high occurrence probabilities in environments with limited monitoring and frequent user violations caused by several factors such as mechanical activator wear due to frequent operation cycles, inadequate preventive maintenance, power instability or voltage fluctuation, obstruction from debris or unauthorized vehicle contact, and corrosion under tropical environmental conditions [26]. In contrast, failures related to auxiliary components, such as signage or secondary warning devices, yield relatively lower RPN values.

Table 3. RPN values before mitigation [16].

Component	S	O	D	RPN
Rising-barrier mechanism	9	3	4	108
Axle counter sensor	8	4	3	96
EWS sirens / LED	8	2	4	64
Emergency push-button	9	2	5	90
Power supply	7	3	4	84
CCTV monitoring	5	3	4	60

3.3. Mitigation Measures and Post-Mitigation Risk Reduction

3.3.1. Effectiveness of Risk Mitigation Strategies

This failure directly compromises the system's physical enforcement capability. If the barrier fails to close, vehicles may enter the track area during train approach, significantly increasing collision probability. Given the high severity score (S=9), this failure represents a catastrophic hazard with potential fatalities and major infrastructure damage.

3.3.2. Operational Implications

Operationally, barrier malfunction may require manual intervention, causing several implications such as delays in train operations, temporary crossing closure, or increased reliance on human operators [27]. Repeated malfunction reduces user trust and may increase deliberate violations.

3.3.3. Cost and Maintenance Implications

Mechanical failures increase corrective maintenance frequency, spare-part replacement costs, and long-term lifecycle expenditure. This highlights the necessity of redundancy and condition-based maintenance strategies [28]. Mitigation measures are proposed for failure modes with high RPN values, focusing on both technical and operational improvements. Technical measures include redundancy in detection systems, fail-safe barrier design, and integration with visual monitoring such as CCTV. Operational measures involve clearer warning logic, improved maintenance routines, and enhanced driver awareness mechanisms.

Post-mitigation analysis demonstrates a substantial reduction in RPN values across all critical failure modes. The most significant reductions are observed in failure modes related to detection and activation functions, where improvements in detectability and reduced occurrence probabilities lower the overall risk level. These results indicate that the hybrid rising-barrier system shows improved risk performance following the proposed mitigation measures.

Table 4 shows that after the implementation of mitigation strategies, including manual override installation, system redundancy, preventive maintenance, UPS backup, and enhanced sensor reliability, the post-mitigation RPN values show a substantial reduction across all system components. The mitigated RPNs range between 16 and 36, representing overall risk reductions of approximately 66%-75%. The reduction in occurrence (O) values is associated with the implementation of additional physical and operational safeguards, including automated barrier activation, redundant warning mechanisms, and improved traffic control measures, which reduce the likelihood of unsafe road-user behavior and system failure occurrence. Meanwhile, the reduction in detection (D) values reflects the improved ability of the system to identify and respond to abnormal conditions through enhanced monitoring components such as CCTV integration, warning redundancy, and emergency override mechanisms.

Table 4. RPN comparison before and after mitigation [16].

Component	S ₁	O ₁	D ₁	RPN	S ₂	O ₂	D ₂	RPN ₂	Risk reduction (%)
Rising-barrier mechanism	9	3	4	108	9	2	2	36	66,7
Axle counter sensor	8	4	3	96	8	2	2	32	66,7
EWS sirens / LED	8	2	4	64	8	1	2	16	75,0
Emergency push-button	9	2	5	90	9	1	3	27	70,0
Power supply	7	3	4	84	7	2	2	28	66,7
CCTV monitoring	5	3	4	60	5	2	2	20	66,7

3.4. Safety Implications for Level Crossing Protection

The results confirm that a risk-based approach using FMEA provides meaningful insights into the safety performance of hybrid level crossing systems. Compared with conventional systems that rely heavily on human operators or warning-only mechanisms, the hybrid rising-barrier system demonstrates improved control over high-risk failure modes.

The structured reduction in RPN values highlights the importance of integrating physical enforcement with automated detection and monitoring [29]. This finding aligns with international safety engineering principles, which emphasize layered protection and redundancy as key strategies for managing safety-critical interfaces [30]. For Indonesia, where spatial and operational constraints limit conventional solutions, the hybrid approach offers a practical pathway for safety enhancement.

Figure 4 presents the risk matrix comparison for identified failure modes before and after mitigation. The results show a clear shift from higher-risk zones (red and yellow) to lower-risk zones (yellow and green) following the implementation of mitigation strategies [31]. Significant reductions in RPN values can be observed across all risks, indicating improved system safety and reduced likelihood-severity combinations. This demonstrates the efficacy of the hybrid rising-barrier system in mitigating critical failure modes and enhancing overall safety performance at railway level crossings [32].

RISK 1		Severity (before)					Severity (after)				
		Negligible	Minor	Moderate	Major	Catastrophic	Negligible	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain										
	Likely										
	Possible life										
	Unlikely					108					
	Rare										36
RISK 2		Severity (before)					Severity (after)				
		Negligible	Minor	Moderate	Major	Catastrophic	Negligible	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain										
	Likely										
	Possible life										
	Unlikely				96						
	Rare									32	
RISK 3		Severity (before)					Severity (after)				
		Negligible	Minor	Moderate	Major	Catastrophic	Negligible	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain										
	Likely										
	Possible life										
	Unlikely				64						
	Rare									16	
RISK 4		Severity (before)					Severity (after)				
		Negligible	Minor	Moderate	Major	Catastrophic	Negligible	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain										
	Likely										
	Possible life										
	Unlikely					90					

	Rare									27	
RISK 5		Severity (before)					Severity (after)				
		Negligible	Minor	Moderate	Major	Catastrophic	Negligible	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain										
	Likely										
	Possible life										
	Unlikely				84						
	Rare									28	
RISK 6		Severity (before)					Severity (after)				
		Negligible	Minor	Moderate	Major	Catastrophic	Negligible	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain										
	Likely										
	Possible life										
	Unlikely			60							
	Rare								20		

Figure 1. Risk Matrix of Rising-Barrier [16]

4. Conclusion

This study demonstrates that hybrid rising-barrier systems have the potential to improve safety performance at railway level crossings, particularly under spatial and operational constraints commonly found in Indonesia. The analysis indicates that integrating automated rising-barriers, detection systems, and warning devices can reduce the likelihood of vehicle-train conflicts by improving physical access control and reducing dependence on road-user compliance. The findings further suggest that failures associated with detection and barrier activation functions require priority mitigation to ensure reliable operation. With appropriate technical redundancy and operational controls, hybrid rising-barrier systems may provide a practical alternative for enhancing safety at high-risk level crossings where conventional barrier systems are difficult to implement. Future research should focus on field implementation, operational validation, and long-term performance evaluation under real traffic conditions.

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