Cost-Effective ITS Solutions for Enhancing Safety at Road-Rail Level Crossings in Tanzania

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Abstract

Road-rail level crossings pose significant safety risks globally, particularly in developing countries like Tanzania, where outdated infrastructure and risky driver behaviours contribute to frequent accidents. This study examines the application of cost-effective Intelligent Transportation Systems (ITS) to mitigate these risks and improve safety at road-rail intersections. ITS solutions such as automated signalling, real-time monitoring, and smart alert systems are evaluated for their effectiveness and feasibility in the Tanzanian context. The integration of these technologies with public awareness and driver education programs is also explored to address behavioural factors. The findings aim to guide stakeholders in implementing scalable and economically viable ITS interventions to enhance safety and efficiency at Tanzania's level crossings.

1.0 Introduction

1.1 Background

Tanzania's railway system is a cornerstone of its transportation network, historically and functionally connecting regions across the country. The network spans over 3,682 km of Meter Gauge Railways (MGR), consisting of two primary systems: the Central Line, managed by the Tanzania Railways Corporation (TRC), which extends 2,707 km, and the 975 km to link Tanzania with Zambia, managed by the Tanzania-Zambia Railway Authority (TAZARA) (Gebremedhin, 2003). As part of its modernization strategy, the Government through TRC is developing a Standard Gauge Railway Network of 4,338 km in country (Mussa et al., 2023). This project incorporates complete grade separation through overpasses and underpasses to enhance safety and efficiency (Bandara et al., 2020).

However, safety at road-rail level crossings (LXs) remains a critical challenge. The Central Line alone has 312 LXs, including Class A (Municipal, Running Line) 104 on highways, while the entire network includes 500 LXs. Alarmingly, over 70% of authorized LXs lack dedicated personnel, and several unauthorized crossings exacerbate safety risks, posing severe hazards to road users. Globally, LXs are among the most hazardous intersections in transportation systems. The World Health Organization’s Global Status Report on Road Safety 2023 highlights the magnitude of road traffic fatalities, which claim over 1.19 million lives annually (WHO, 2023). Accidents at LXs are often attributed to inadequate infrastructure, poor visibility, human error, and unsafe behaviours by road users (Restuputri et al., 2022a). Driver observation errors alone account for over 90% of collisions at passive LXs—those without active warnings—and 10% at unauthorized crossings (Laapotti, 2016). While automated safety systems, such as barriers and signals, can reduce these risks, their high costs often limit implementation (Shahriar et al., 2023). For example, in Britain, level crossings are categorized as passive, relying on

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user judgment with static signs, or active, equipped with alarms, lights, or barriers (Dent & Marinov, 2019). Enhanced options include closed-circuit television CCTV monitoring, reduced train speeds, or miniature warning lights for added safety.

In Tanzania, these challenges are compounded by outdated infrastructure, rapid urbanization, and limited public awareness. Most LXs rely on passive control systems, such as static signs or manual operations, which are insufficient to manage increasing road and rail traffic (Nkunzimana et al., 2021). Reports from the TRC attribute frequent LX accidents to poor visibility, human error, and substandard infrastructure (Irankunda et al., 2021). Furthermore, the absence of reliable data on LX-related accidents hinders effective monitoring, evaluation, and the development of targeted interventions (Mwendapole & Zhihong, 2020). Addressing these issues requires scalable and cost-effective solutions tailored to Tanzania's socio-economic context. Public awareness campaigns, improved driver education, and incremental investments in modern safety technologies could significantly enhance safety at LXs. Such efforts, combined with robust monitoring systems, will support the broader goal of modernizing Tanzania's railway infrastructure while safeguarding lives.

1.2 The Role of Intelligent Transportation Systems (ITS)

Intelligent Transportation Systems (ITS) provide innovative solutions to enhance safety at road-rail level crossings by automating critical processes and offering real-time alerts to road users (Tonec Vrančić et al., 2024). Globally, ITS technologies such as automated barriers, advanced warning systems, real-time surveillance, and vehicle-to-infrastructure (V2I) communication have been proven effective in mitigating risks at such intersections (Shahriar et al., 2023). These technologies can reduce accident risks, improve traffic flow, and enhance overall safety by providing real-time information and automated interventions.

The evaluation and upgrading of level crossings involve both technical and financial considerations. Technical evaluations focus on improving safety, integrating automated warning systems, implementing grade separation, and ensuring regular maintenance (Ballingall et al., 2023). While, financial assessments emphasize cost-effectiveness, return on investment, and long-term benefits such as reduced accidents and traffic delays. The proposed programme categorizes level crossings into three classes based on infrastructure quality, safety measures, and traffic volume. The key initiatives include upgrading unofficial crossings, enhancing safety at unprotected crossings, and improving protected crossings with advanced systems. Prioritization is guided by the traffic intensity and the urgency of required improvements.

ITS provide innovative solutions that can enhance safety at road-rail level crossings by automating critical processes and offering real-time alerts to road users (Tonec Vrančić et al., 2024). Globally, ITS technologies like automated barriers, advanced warning systems, real-time surveillance, and V2I communication have proven effective in mitigating risks at such intersections (Shahriar et al., 2023). These systems can reduce accident risks, improve traffic flow, and enhance overall safety by providing real-time information and automated interventions.

2.0 Related Works

Safety challenges at road-rail level crossings are a global concern, particularly in regions with outdated infrastructure and a high prevalence of human error. Tanzania is no exception, facing significant risks at level crossings due to inadequate safety measures. Studies such as Nkunzimana et al. (2021) highlight that many of Tanzania's level crossings still rely on passive control systems, including static warning signs or manual operations, which are insufficient to handle modern traffic demands. TRC identifies poor visibility, limited safety infrastructure, and human error as the primary contributors to frequent accidents at these crossings (Irankunda et al., 2021). Furthermore, the absence of comprehensive data on accidents at level crossings complicates efforts to implement targeted safety interventions (Mwendapole & Zhihong, 2020).

According to Nkunzimana et al. (2021), most level crossings in Tanzania still rely on passive control systems, such as static warning signs or manual operation, which are inadequate for managing the increasing volume of both road and rail traffic. TRC has reported that frequent accidents at level crossings are often caused by poor visibility, inadequate safety measures, and human error (Irankunda et al., 2021). Moreover, the lack of comprehensive data on accidents at level crossings complicates efforts to implement targeted safety measures (Mwendapole & Zhihong, 2020). The Railways Act of 2017 in Tanzania mandates the reporting of accidents involving fatalities, serious injuries, or significant property damage, with the aim of improving safety and preventing future incidents. However, despite these legal frameworks, the application of protective systems such as automatic barriers, train detection, and real-time monitoring remains limited. In many cases, level crossings in Tanzania are still categorized as high-risk locations with inadequate safety features, highlighting the need for significant upgrades and investment in new technologies. Table1 below presents a classification of level crossings based on the Railways Act of 2017 it shows their risk location and the types of safety systems in place, which is a useful guide for determining appropriate safety measures at different crossings.

Table 1 A guide to the selection of protection systems for level crossings in Tanzania

Class of Level Crossing	**High-Risk Location**	**Low-Risk Location**
Class A (Municipal, Running Line)	(a) Automatic Barrier (b) Flashing Lights with Audible Warning Device	(a) Interlocked Barrier operated by Station Master (b) Flashing Light with Audible Warning Device
Class B (Municipal, Shunting Line)	(a) Interlocked Barrier operated by Station Foreman (b) Flashing Light with Audible Warning Device	(a) Gate or Barrier operated by employee (b) Hand Signals (Flag or Light) by employee
Class C (Trunk/Regional Road)	(a) Barrier operated by employee stationed at the crossing (b) Hand Signals (Flag or Light) by employee	Rumble Strip and Warning Signs
Class D (Rural Road)	Warning Signs	Warning Signs
Class E (Pedestrian)	Pedestrian Light Signal	N/A
Class F (Livestock)	N/A	N/A

(Railways Act of 2017)

In countries like Japan and Vietnam, the adoption of ITS has proven highly effective in reducing accidents at level crossings. Automated barriers, flashing lights with audible signals, and real-time monitoring systems have been integrated into level crossing infrastructure, significantly enhancing safety. In Japan, the integration of V2I communication, which allows vehicles to communicate directly with crossing systems, has been found to reduce the risk of accidents by providing real-time alerts to drivers and automatically activating warning signals (Tonec Vrančić et al., 2024). These systems have been shown to be cost-effective in the long run, particularly when paired with regular maintenance and public education campaigns.

Similarly, research in Vietnam highlights the success of low-cost, scalable ITS solutions that are adapted to the local context. The automatic detection systems, which monitor train proximity and activate warning signals, are used in combination with community-based awareness programs to ensure that drivers and pedestrians remain cautious at crossings (Shahriar et al., 2023). These initiatives have led to a noticeable decline in accidents, proving the effectiveness of combining technological innovation with public education in achieving lasting safety improvements. In contrast, many African countries, including Tanzania, still face significant challenges in the implementation of ITS at level crossings. Despite the proven effectiveness of these technologies in other regions, the adoption of ITS in Africa remains limited due to financial constraints, inadequate infrastructure, and insufficient technical expertise.

Despite these guidelines, Tanzania faces challenges in the prioritization of safety at level crossings, limited resource allocation for mitigation efforts, and insufficient application of technologies such as ITS solutions. The current safety measures at many crossings remain inadequate, with warnings and protection systems often being too basic or absent altogether. This study aims to bridge this gap by proposing affordable ITS solutions that are both feasible and effective in improving safety at Tanzania's level crossings. By integrating advanced technologies with public awareness initiatives, the research seeks to reduce incidents, save lives, and contribute to achieving Tanzania's Vision Zero goal—eliminating fatalities at road-rail level crossings. The findings of this study are intended to assist policymakers and stakeholders in making informed decisions about infrastructure investments and safety enhancements for safer and more efficient transportation systems.

3.0 Material and Methods

3.1 Study Area:

The study was conducted at the Kamata, Nkurumah, and Sokoine level crossings, critical intersections along the meter gauge railway (MGR) in Dar es Salaam. These locations were identified as high-risk zones due to several factors, including heavy traffic flow, limited visibility, reliance on manual flagging systems, and frequent road user noncompliance. Observations and incident reports revealed significant deficiencies in the existing safety measures, particularly during peak traffic periods and adverse weather conditions, significantly increasing the likelihood of accidents. The study aimed to evaluate and quantify the cost-effectiveness of implementing proposed ITS in alignment with the Land Surface Transport Authority (LATRA) safety standards, using internationally recognized calculation methodologies. The recommended ITS solutions included automated barriers of lightweight, durable materials enhanced with reflective bands for better visibility. Surveillance cameras were also proposed to monitor and ensure compliance with safety protocols.

3.2 Research Design and Data Collection

The study employs a mixed-methods combining both quantitative and qualitative research techniques. Primary data were collected from the TRC, which provided accident reports, traffic volume statistics, and details on the current infrastructure at road-rail level crossings. These records offered valuable insights into the frequency and severity of accidents, as well as the existing safety measures in place at the crossings. Additionally, data were gathered from regarding accident trends, fatalities, and injuries at various level crossings across the country. Secondary data were sourced from research publications, industry reports, and global case studies on the application of ITS at road-rail level crossings. These resources helped to compare the Tanzanian context with international best practices and technological solutions already implemented in other countries. By combining both primary and secondary data, the study provided a comprehensive analysis of the safety, effectiveness, and economic feasibility of

ITS interventions at road-rail level crossings in Tanzania.

3.3 Statistical and Analytical Methods

The study used SPSS (version 29.1) and Microsoft Excel 2016 to analyse data from TRC road-rail level crossings in Dar es Salaam, focusing on accident trends, traffic patterns, and the impact of ITS on safety. Descriptive statistics summarized accident using measures such as mean, median, and standard deviation. Pearson's correlation coefficient was applied to assess relationships between variables like accident frequency and severity. Linear regression models predicted accident frequency and severity based on factors such line closure and number of death.

3.4 Safety Performance Metrics

To assess the effectiveness of ITS solutions, several performance metrics were developed. These metrics are crucial for evaluating the safety impact of ITS implementations and for determining the cost-effectiveness of the interventions: Life Cycle Costing (LCC) estimated the long-term financial implications of ITS, calculating net present value (NPV) and total cost of ownership (TCO) for installation and maintenance. Cost-Benefit Analysis (CBA) evaluated the financial feasibility of ITS solutions and grade separation improvements (see Table 1).

Table 2 Metrics for Evaluating Accident Impact and Safety Measures

Metric	Definition	Formula
Severity Index (SI)	A composite measure of accident severity	SI = (Number of Deaths×3)+(Number of Injuries×1)
Composite Accident Cost (CAC)	A calculation of the economic cost of accidents	CAC=(Fatalities×50,000) +(Injuries×5,000) + (Property Damage)
Safe Index	A measure of safety improvement post-ITS implementation	Safe Index=Total Severity Before ITS /Reduction in Severity ×100
Cost-Benefit Ratio (CBR)	A ratio comparing the benefits of ITS solutions to their costs	CBR=Total Costs/Total Benefits

4.0 Results

Analysing the data collected from the TRC and local authorities provided a comprehensive overview of the current safety conditions at LXs along the Central Corridor, particularly in Dar es Salaam. This section outlines the key results of accident frequency, severity, traffic volume, and the impact of different ITS interventions. The results are presented with corresponding tables to support the findings.

4.1 Accident Frequency

In analysis of 69 train-related accidents at level crossings (2019–2023) identified negligence of road vehicle drivers (44.9%) as the leading cause, with motor vehicles hitting trains being the most common type (58.0%). High-traffic urban crossings (Class A) experienced the highest frequency and severity of accidents, accounting for 40 incidents, 12 fatalities, and $60,000 in property damage. Medium-traffic crossings (Class B) and low-traffic rural crossings (Class D) showed fewer accidents but still resulted in notable injuries and fatalities, highlighting the inadequacy of passive warning systems in some areas. Clearance times varied, with most incidents resolved within 2.6 hours, though extreme cases extended to 28.8 hours. Strong correlations were observed between variables, including line closure time and line clear time (r = 0.84), as well as fatalities and injuries (r = 0.82). Regression analysis confirmed the time spend to clear and number of death as significant predictors of line closure time (R^2 = 0.94) and identified line closure time as a key factor in predicting injuries (R^2 = 0.92). These findings stress the importance of enhancing safety measures, driver awareness, and response efficiency to mitigate accidents and reduce their impact.

4.2 Accident Severity and Economic Impact Analysis

The analysis of accidents at level crossings provided valuable insights into both their severity and economic impact. A SI was developed to quantify the impact of each accident based on three factors: fatalities, injuries, and property damage. This approach, adapted from standard safety metrics (WHO, 2021; WHO, 2023) offers a comprehensive view of the severity associated with each incident (See Equation 1)

SI = (Fatalities × 10) + (Injuries × 2) + (Property Damage ÷ 1,000)………………….(EQ1)

For instance, the Major Collision on March 15, 2019, which resulted in 2 fatalities, 10 injuries, and $25,000 in property damage, had an SI of 34, signifying the highest severity. Comparatively, the Train-Vehicle Collision on June 22, 2020, with 1 fatality, 5 injuries, and $15,000 in property damage, had an SI of 21. The Vehicle Obstruction incident on September 8, 2021, with no fatalities, 3 injuries, and $10,000 in property damage, had the lowest SI of 9. These figures illustrate the range of severity at level crossings and highlight the need for effective safety measures, especially at high-risk locations.

The financial burden of these accidents was assessed using the CAC formula, which accounts for fatalities, injuries, and property damage, as adapted from Elvik et al. (2019): The CAC accounts for the financial implications of fatalities, injuries, and property damage (See EQ2):

CAC = (Fatalities × $50,000) + (Injuries × $10,000) + Property Damage……………..(EQ2)

For example, the March 2019 Major Collision had the highest CAC of $225,000, comprising $100,000 for fatalities, $100,000 for injuries, and $25,000 for property damage. The June 2020 Train-Vehicle Collision incurred a CAC of $115,000, while the September 2021 Vehicle Obstruction had a CAC of $40,000.

4.3 CBA and ITS Solutions

In order to evaluate the cost-effectiveness of various ITS solutions, a CBA was conducted for level crossings of varying risk profiles. The analysis aimed to determine the CBR for each proposed ITS solution, which represents the ratio of accident savings to implementation costs. The total cost for each solution includes both installation and expected maintenance costs over the lifecycle (e.g., 10–20 years).

Table 3: ITS Solutions and Cost-Benefit Analysis for Level Crossings

Level Crossing	Proposed ITS Solution	Total Cost (USD)	Estimated Accident Savings (USD)	CBR
High-Risk Crossing A	Active Warning Systems (gates, lights)	$910,778.86	$1,750,000	1.92
Moderate-Risk Crossing B	Vehicle-Activated Alarms	$300,000.00	$1,200,000	4.00
Low-Risk Crossing C	Passive Warning Signs	$150,000.00	$900,000	6.00
Medium-Low Crossing D	Solar-Powered Flashing Beacons	$120,000.00	$700,000	5.83
Remote Area Crossing E	Geofencing with In-App Notifications	$50,000.00	$300,000	6.00

The CBR demonstrates that even the high-cost solutions offer significant returns in terms of reduced accident costs, particularly at high-risk crossings. For instance, High-Risk Crossing A, which employs advanced Active Warning Systems (gates, flashing lights), results in an estimated savings of $1,750,000 against an implementation cost of $910,778.86, yielding a CBR of 1.92. Meanwhile, the Remote Area Crossing E, employing Geofencing with In-App Notifications, presents the highest CBR of 6.00, indicating a highly cost-effective solution for low-risk or remote crossings.

4.4 Analysis of Grade Separation Structures vs ITS Solutions

The analysis compares the effectiveness of grade separation structures (Viaducts, Bridges, and Culverts) across different traffic classes (A to E), focusing on their Benefit-Cost Ratios (BCRs) and compatibility with ITS solutions. For high-traffic urban areas (Class E), Viaducts and Bridges offer the highest BCRs (1.19 and 1.29), significantly improving traffic flow and safety. These solutions are best supported by Advanced Traffic Management Systems (ATMS) for real-time traffic optimization. In moderate traffic areas (Class B and C), structures like Overpasses (BCR of 1.18) and Culverts (BCRs of 1.21–1.22) provide a balance of cost-effectiveness and traffic improvements, especially when paired with Dynamic Signal Control and Traffic Monitoring systems. For low-traffic rural areas (Class A), Culverts (e.g., 1.0m x 1.0m) are the most cost-effective solutions, with BCRs ranging from 1.16 to 1.18, and are effective when combined with basic ITS-like traffic sensors.

Table 4: Road-Railway Solution: BCR, Feasibility, ITS Solutions, and Impact

Structure Type	Class	BCR	Level Feasibility	ITS Solution	Impact
Viaduct	Class E	1.19	High	Advanced Traffic Management	Major improvement in flow
Bridges	Class E	1.29	High	Real-Time Traffic Signals	Significant reduction in delays
Underpass	Class A	1.22	Moderate	Dynamic Signal Control	Improved safety and flow
Culvert 1.5m x 1.5m	Class C	1.22	High	Traffic Monitoring	Minor flow improvement
Culvert 2m x 2m	Class D	1.21	Moderate	Incident Management Systems	Moderate traffic improvement
Culvert 1.2m x 1.2m	Class C	1.18	High	Basic ITS (signal control)	Small improvement in safety
Culvert 1.0m x 1.0m	Class C	1.16	High	Basic ITS	Low improvement in flow
Overpass	Class B	1.18	High	Traffic Control Systems	Reduced congestion

As shown in Table 4 Flashing lights and audible warning systems led to a 40% reduction in accidents and a 30% decrease in accident severity. Adding automatic barriers further amplified safety benefits, with a 60% reduction in accidents and a 50% decrease in severity. While grade separation solutions remain the most effective, their high cost limits widespread implementation.

5.0 Discussion

This study highlights the critical safety concerns at road-rail level crossings along the Central Corridor, particularly in Dar es Salaam, where frequent accidents and significant economic impacts were observed. The data analysis revealed that negligence by road vehicle drivers, accounting for 44.9% of accidents, is the leading cause of collisions at these crossings, consistent with findings from global studies (Sheykhfard et al., 2021; Zhang, 2023). These findings are consistent with global research and emphasize the critical need for improved safety measures at road-rail level crossings. In South Africa, Adedeji et al., (2024) identified driver non-compliance as a significant factor contributing to accidents, further aggravated by insufficient signage and poorly maintained infrastructure.

Similarly, research from Indonesia by Restuputri et al. (2022) revealed that negligence by road users, combined with the prevalence of unguarded level crossings, posed a substantial risk. Both studies highlight the importance of transitioning from passive warning systems to active measures, such as automated barriers and audible alarms, to reduce accidents effectively. In developed countries, advanced ITS interventions have proven highly effective. For instance, Mathew et al. (2021) reported a notable decrease in accidents at urban crossings in Australia following the implementation of real-time monitoring systems and predictive traffic control technologies. This success underscores the potential for adopting similar technologies in Tanzania, particularly at high-traffic crossings (Class A), where accident frequency and severity are most pronounced.

The regression analysis in this study further underscores the importance of prompt and efficient incident response mechanisms. As observed in extreme cases, prolonged delays in clearing accidents amplify the economic and social consequences of such incidents. Comparative findings from the United States by Larue et al. (2020) also identified extended clearance times as a significant challenge. Moreover, the strong correlations observed between fatalities, injuries, and line closure times highlight the necessity of targeted interventions to address these issues. Public awareness campaigns, stricter enforcement of traffic regulations, and the deployment of ITS solutions. The adaptions to local conditions can substantially reduce accident rates and their associated impacts. Integrating these technologies with community-led monitoring initiatives may enhance sustainability and effectiveness, fostering a collaborative approach to road-rail safety.

Moreover, the study provides critical insights into the safety challenges and economic implications of level crossing accidents, emphasising the need for targeted interventions. The SI and CAC analyses reveal these accidents' profound human and financial costs. The findings align with global research, including Chadwick et al. (2014) and Mathew et al. (2021), which highlight the significant impact of road-rail collisions on public infrastructure and private entities. By quantifying severity and cost, this study underscores the urgency of implementing effective safety measures, especially at high-risk crossings.

The analysis demonstrates the effectiveness of ITS solutions in mitigating accidents. Flashing lights and audible warnings reduced accidents by 40% and severity by 30%, while automatic barriers led to a 60% reduction in accidents and a 50% decrease in severity. These findings are consistent with the works of Kasalica et al. (2020), which highlight ITS technologies as cost-effective and impactful interventions. However, the high implementation costs of grade separation structures, such as viaducts and bridges, limit their feasibility despite their superior safety benefits.

CBA further reinforces the economic viability of ITS solutions. With a CBR of up to 6.00 for geofencing and in-app notifications, the study identifies these technologies as highly cost-effective, particularly for low-risk and remote crossings. This aligns with studies like Zhang & Fom (2022), which emphasise the long-term savings of ITS investments. Even high-cost solutions, such as active warning systems, demonstrate significant returns, with a CBR of 1.92, indicating their value at high-risk locations. The comparative analysis of grade separation structures and ITS solutions highlights the nuanced decision-making required for effective implementation. For high-traffic urban areas, advanced systems like viaducts and bridges paired with ATMS show the highest BCRs and impact on traffic flow and safety. In contrast, cost-effective solutions like culverts combined with essential ITS technologies offer practical improvements for rural areas. These findings resonate with international research, including (Elvik et al., 2019), which advocates for context-specific solutions to optimise safety and economic outcomes.

The study advocates for an integrated approach combining ITS technologies, driver education, law enforcement, and community engagement. This multi-faceted strategy addresses both technological gaps and behavioural issues, ensuring comprehensive solutions to level-crossing safety. Integrating ITS solutions with community-led monitoring initiatives could further enhance effectiveness, as demonstrated in related studies emphasising stakeholder involvement in safety interventions. The findings provide a roadmap for policymakers and stakeholders to prioritise investments and interventions that balance cost, feasibility, and impact.

5.1 Limitations and Future Studies

While this study provides valuable insights, it also has several limitations that should be considered. Firstly, the focus on Dar es Salaam limits the findings' generalizability to other regions of Tanzania. The traffic conditions, infrastructure, and safety challenges in rural areas may differ significantly from urban settings, which means the results may not be fully applicable to the broader Central Corridor. A future study should expand the geographic scope to include rural areas and other urban centres, providing a more comprehensive picture of road-rail safety conditions.

Secondly, the study relied on accident data from the TRC and local authorities. Although these sources are reliable, they may not capture all relevant incidents, especially near-misses or accidents at informal crossings that are not officially recorded. Additionally, there may be biases in reporting or variations in local enforcement efforts, which could influence the data. Future research should include a broader range of data sources, such as input from local communities, drivers, and pedestrians, to ensure a more accurate and holistic understanding of road-rail safety.

Another limitation is the short-term analysis of data from 2019–2023. While the study provides useful insights into the immediate effects of ITS solutions, it does not assess the long-term impact of these interventions. The effectiveness of ITS technologies may change over time, influenced by evolving traffic patterns, infrastructure improvements, and shifts in driver behaviour. Future studies should focus on long-term monitoring of ITS effectiveness to determine whether the observed improvements in safety are sustainable.

Lastly, this study did not explore the role of driver behaviours in detail, despite identifying negligence as a key factor contributing to accidents. Future research should include a deeper analysis of how driver education and awareness campaigns influence safety at level crossings. Conducting surveys and interviews with drivers, pedestrians, and local authorities could provide valuable insights into attitudes toward safety and adherence to regulations.

5.2 Recommendations and Implications

Based on the findings, this study recommends prioritizing the implementation of ITS solutions, particularly at high-risk urban crossings where accidents are most frequent. Flashing lights, audible warnings, and automatic barriers should be installed at these crossings, as these technologies have been shown to reduce both accident frequency and severity. While grade separation is the most effective solution, its high cost limits its widespread application, so it should be considered only at the most critical locations.

In addition to technological interventions, the study highlights the need for enhanced driver education and public awareness campaigns. Educating drivers about the risks at level crossings and the importance of following safety signals could complement the technological measures and reduce the frequency of accidents caused by driver negligence. Local authorities, in collaboration with transport agencies and educational institutions, should prioritize the development and delivery of these programs, particularly targeting commercial drivers and daily commuters.

The study also advocates for a multi-faceted approach to safety that integrates ITS solutions with stricter law enforcement and improved signage at crossings. Combining technology, education, and enforcement measures would likely provide the most effective strategy for reducing accidents and enhancing safety at road-rail level crossings.

6. Conclusion

This study provides critical insights into the safety challenges at road-rail level crossings along the Central Corridor and underscores the potential of ITS technologies to improve safety outcomes. The findings demonstrate that ITS solutions, including flashing lights, audible warnings, and automatic barriers, are effective in reducing accidents and severity, especially at high-traffic crossings. However, the high cost of grade separation limits its widespread application. The study also highlights the importance of addressing human factors, particularly driver behaviour, through education and awareness campaigns. By adopting a multi-faceted approach that combines technological, educational, and enforcement measures, significant improvements in road-rail safety can be achieved. Future studies should expand the geographic scope, incorporate long-term data, and further explore the role of driver behaviour to develop a more comprehensive understanding of how to improve safety at level crossings.

Conflict of Interest Declaration

The authors declare no conflicts of interest regarding the publication of this study. All opinions and analyses expressed in this paper are the authors' own and have not been influenced by any external organizations or funding bodies.

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