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An Investigation into the Highway-Rail At-Grade Intersection Safety—Case Study: Zambia Railways Rail Network

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Abstract

The transportation sector in Zambia faces many challenges, one of them being the deteriorating safety situation at highway-rail at-grade intersections (HRAGIs), sometimes called level crossings. Therefore, the aim of this research was to carry out an investigation into HRAGIs safety on the Zambia Railways rail network and find ways for improvement. Three critical (black spots) Class-A level crossings in the northern region, *i.e.*, Bwana Mkubwa in Ndola, Lukanda in Kapiri Mposhi and Kabwe Main in Kabwe were selected for investigation. The methodology involved field surveys, visual inspection, accident and hazard prediction, interviews and driver behavior assessment. The adopted Florida Accident and Safety Index Model, revealed that the safety indices for all the three level crossings, without and with gates, were unsafe and below the recommended marginal threshold of 60%. The safety indices (without gates) were, for Bwana Mkubwa (51.49%), Lukanda (48.34%) and Kabwe Main (53.31%) and were (with gates) 53.01%, 50.02% and 54.73% for Bwana Mkubwa, Lukanda and Kabwe Main respectively. On the other hand, the USDOT Accident Prediction Model initial accident prediction showed low accident probabilities, compared to observed accident rates, with an average of 0.20 accidents per year for the three HRAGIs with the second accident prediction showing Lukanda as more vulnerable at 0.28, compared to 0.21 for Bwana Mkubwa and 0.15 for Kabwe Main predicted accidents per year. Nevertheless, the USDOT predicated results were consistent with the observations made in the USA. The low predicated values could be attributed to low daily train volumes, reduced maximum legal train speeds of 40 km/h and enforced lower speeds (15 - 20 km/h). Other factors such as human error, vandalism of infrastructure and also lack of lighting at all the three crossing could have played a major role. Consistent data collection is needed to realize the development of local models through statistical modelling. Also, continuous maintenance and upgrades of HRGAIs from passive to active status including driver behavior sensitization is recommended going forward.

Keywords

Highway-Rail At-Grade Intersection, USDOT, Florida, Accident and Hazard Prediction Model, Zambia Railways

1. Introduction

Zambia, being a landlocked country, heavily relies on its railway infrastructure, operated primarily by Zambia Railways (ZR) and the Tanzania Zambia Railways which runs from Kapiri-Mposhi in Zambia to Dar-es-salaam in Tanzania [1]. The ZR rail network, a cape gauge track, extends from Chililabombwe in the north to Livingstone in the south, spanning over 1000 km and therefore key to connecting economic regions involving mining and agriculture. The significance of this railway corridor cannot be overstated, as it facilitates the transportation of goods, enhances trade efficiency, and contributes to the overall economic growth of the nation including the Southern Africa Development Community (SADC).

Though the ZR rail network, through its integration with the highway network has helped contribute to Zambia's economic growth in general, through increase in trade, there has been pressure on the highway and railway at-grade intersections (HRAGIs) as a result in increased vehicle traffic volumes. In recent years, safety concerns at HRAGIs have been expressed by the government and other stakeholders.

There are 33 rail level crossings on the ZR rail network of which 23 are Class-A level crossings. A Class A-level crossing, in the Zambian context, is a rail crossing that crosses an international route (trunk road Class T) or a main road with very high traffic. The major challenge of the HRAGIs in Zambia primarily involves the increased risk of conflicts between vehicles and trains, leading to train-vehicle collisions. The increased vehicle volumes on the major highways have resulted in accidents leading to fatalities, injuries and significant delays for both motor vehicles and trains. This is a serious set-back to commerce and trade.

Improvement of safety at HRAGIs will boost trade, enhance travel efficiency and contribute to socio-economic development in Zambia as well as the SADC region. Additionally, it would lower maintenance costs for both railway and highway infrastructure in addition to improved environment.

In this paper, the authors investigate Class-A HRAGIs in Zambia through accident and hazard prediction, and safety assessment on the northern region of the ZR rail network from Kabwe to Chililabombwe. Three critical points were selected for this investigation being, Bwana Mkubwa in Ndola, Lukanda in Kapiri Mposhi and Kabwe main in Kabwe. The evaluation was done through the USA-based generalized accident and hazard prediction models. Assessment of the infrastructure and driver behavior was also done. Limitations of these foreign models were well acknowledged and necessary adjustments were made to suit the local conditions.

This study is limited to train-vehicle collision and vulnerability assessment and therefore does not include other forms of conflicts such as the train-pedestrian and train-cyclist.

2. Literature Review

HRAGIs, also known as level crossings, are critical points where roadways and railways intersect without a bridge or tunnel. Ensuring safety at these intersections has been the focus of numerous studies worldwide, as accidents at these crossings can have devastating consequences. This study titled "*An Investigation into the Highway-Rail At-Grade Intersection Safety—Case Study*: *Zambia Railways Rail Network*" aims to explore ways of predicting accidents and vulnerability, and finding ways of improving safety at these rail crossings. The next sections give a review of relevant literature that provides important insights into HRAGIs safety.

2.1. HRAGIs Safety Around the World

Economic growth and rising population around the world has led to transport challenges. Some of the challenges are safety related such as increased accidents at HRAGIs with government agencies and researchers gaining interest in accident and hazard prediction, and prevention technologies with the aim of gaining a deeper understanding and finding solutions for HRAGIs safety challenges.

In the Great Britain for-instance, Evans [2] investigated fatal accidents and fatalities at different types of HRAGIs from 1964 to 2009 in order to establish trends and causal factors at different rails crossing types, both passive and active. It was found that fatal accidents and fatalities were quite significant with pedestrians accounting for a large proportion.

In Finland, Laapotti [3], did a comparison of fatal motor vehicle accidents at passive and active at HARGIs in order to consider risk factors. He established that most accidents occurred at passive crossings. He recommended equipping most dangerous passive level crossings with warning devices.

Dina *et al.* [4] in Nigeria, examined the contribution of HRAGIs physical characteristics to accident occurrence at 12 crossings within Lagos City. Variables like gates, pedestrian traffic, car traffic lights, signage and vehicular traffic were taken into account using regression analysis. It was established that these attributes have an impact on HRAGIs and that active warning signs needed to be put in place.

2.2. Accident, Hazard and Severity Models

According to Pasha *et al.* [5], accident prediction models are used in forecasting the expected number of accidents over a specified timeframe while hazard prediction models are used to forecast the expected vulnerability of HRAGIs without specifying the number of predicted accidents.

In the far east many countries have been negatively affected by HRAGIs accidents. Hu *et al.* [6], investigated the causes of accident severity at railroad grade crossings by using a logit model. This model was used to predict the level of accident severity and the effects arising from train volumes and the enforcement of regulations.

The random parameters logit model was employed by Ren *et al.* [7], to investigate crashes on a non-divided two-way traffic in order to analyze injury severity. Factors like estimated vehicle speed above 25 mph, train speed above 45 mph, driving around the gate, old driver, female driver and motorcycles would increase the likelihood of more severe injury outcomes in HRAGIs crashes. This study was found useful for interventions aimed at enhancing safety at these crossings.

In Thailand, a developing country, research was done for HRAGIs in order to identify and understand the risk factors associated with injury severities. Crash data from 2012 to 2022 was analyzed using the mixed logit model. It was concluded that education and training programs for pickup car and truck drivers was vital. In addition, the installation hazard markers and traverse rumble strips, and considering physical barriers, to avoid overtaking near the rail crossing needed to be implemented [8].

Liang *et al.* [9] came up with an accident prediction model with the use of ordinary least-squares and nonlinear least-squares methods. The model showed improved accident prediction with a good accuracy.

Ercegovac *et al.* [10], in the Republic of Serbia, developed a model for calculating maximal risk at HRAGIs under the conditions of generating the maximum entropy in the virtual operating mode based on heterogeneous queuing system. The ratio of real and maximal risk enabled the calculation of the exact reliability of the HRAGIs, with further comparison to raise the level of safety.

Mathew and Benekohal [11], USA, developed a new model for predicting accidents for HRAGIs using the USDOT formula variables. The model called ZINDOT, utilizes a zero-inflated negative binomial model with the variables. It was observed that the new model was good for active rail crossings and can be used as an extension to the USDOT formula. This model was also proving to be more effective in predicting accidents, especially when factoring in local conditions such as the type of warning devices installed.

Newer models continue to emerge, such as the Safety Performance Function Model which offers greater accuracy by incorporating local conditions like weather, road quality and driver behavior [12].

In order to model the accident prediction for HRAGIs, Yang *et al.* [13] collected data for inventory and historical accident from the Federal Railroad Administration (FRA). The ZINB model, which out-performed other five models in this study, was used and included the maximum time-tabled speed of train, exposure-related variables such as total through trains, highway traffic volume, rural or urban area, control devices types at rail crossings, followed by the minimum train speed, type of pavement surface type, and the number of traffic lanes. This study was useful in assisting decision-makers with an elaborate decision-making tool.

In India, Chhotu and Suman [14], carried out a cost analysis and accident prediction of HRAGIs. A monkey-based modular neural system (MbMNS) was developed to identify accident cost. The novel MbMNS had an accuracy of 96.29% and proved better than traditional approaches for accident prediction and cost analysis.

Ibtihal and Rifaat [15], Bangladesh, developed an accident prediction model for HARGIs. The field survey involved 121 HRAGIs. The CMP model used, was the best fit out-performing other models (Poisson, NB, ZIP, ZINB). Geometric orientation emerged as the strongest risk factor. As a remedy, reduction in accident frequency was achieved by fencing, speed bumps, higher crossing width-to-length ratios, and type A rail crossing design.

In Sri Lanka, Fernando and Amasarasingha [16], used linear regression to conduct a survey for the evaluation of characteristics of HRAGIS in an emerging country. Sight distance was found to be a major contributing factor to crashes. Strong iron galvanized gates and improved operator's wages were some of the proposals made to improve safety at HRAGIs.

In the USA, accident and hazard prediction models have played a key role in improving safety at HRAGIs. The USDOT Accident Prediction model in particular, has played a pivotal role in accident prediction. Efforts by state departments of transport have resulted in a number of accident and hazard prediction models. Examples include the Connecticut Hazard Rating Formula, Texas Priority Index Formula, New Mexico Hazard Index Formula, New Hampshire Hazard Index Formula, Florida Safety Index Prediction Formula and many more. These customized models are preferred due different local conditions and other practical considerations. However, data accuracy and availability still remain a major challenge in customized model implementation [17].

The USDOT Accident Prediction model apart from forecasting accident probabilities, provides a quantitative measure of each HRAGI safety. A study conducted on accident and hazard prediction models, found that the USDOT Accident Prediction Formula was the most popular in predicting the number of accidents at HRAGIs. However, it was stated that the US DOT Accident Prediction Formula still needed continuous refinement as it fails to account for key parameters such as highway approaches, sight distance and is more dependent on accident history [17].

The Florida Accident Prediction and Safety Index Formula, for hazard prediction, is applied to calculate safety indices at each HRAGI [18]. Abioye *et al.* [17] and also Pasha *et al.* [5] indicated that the model provided a more accurate ranking of HRAGIs compared to other alternative methods. Dulebenets *et al.* [19] indicated that this formula assesses potential hazards of a given highway-rail grade crossing based on the annual average daily traffic (AADT), average daily train volume, train speed, protection factor, and accident history parameter. In contrast to other accident and hazard prediction methodologies, this formula computes the accident history parameter based on the total number of accidents in the last five years or since the year of last improvement (takes care of any upgrades).

According to Ercegovac *et al.* [10], annual average daily traffic of trains, speed limits on railways, AADT of highway traffic and the number of traffic accidents per annum, road alignment, geometric factors like crossing width, crossing length and local factors at HRAGIs have a major role in the determination of accidents. Khattak and Liu [20] reviewed, nine models used within the USA. They concluded that vehicular exposure and protection devices were the major influencing factors of HRAGIs safety models. Notwithstanding, that most transportation agencies have used other models with AADT.

2.3. Human Behavior and Environmental Factors at HRAGIs

Several studies have delved into understanding the risks associated with HRAGIs. For instance, Sekasi and Solihu [21] conducted a comprehensive risk analysis at railway crossings along the Addis Ababa Light Rail Transit. The study identified human factors as the leading cause of accidents (22%), followed by technical issues (20%). Further findings stressed the importance of a structured risk management approach using the As Low As Reasonably Practicable model, suggesting that identifying and mitigating risks is crucial for reducing accidents. This study underscored the need for a systematic and continuous risk management process.

Edquist [22] conducted a comprehensive literature review of human factors safety issues at HRAGIs in Australia and concluded that human factors were a major contributing factor in rail crossing safety and that counter-measures must always be in place to ensure improved safety.

In the State of Florida, USA, Singh *et al.* [23] assessed train-vehicle accidents at HRAGIs. Their findings underscored the critical role of visibility and illumination, noting that nearly 41% of accidents occurred at crossings with no lighting. The study also highlighted driver behavior, with many accidents attributed to drivers attempting to drive around gates. This was also echoed by Lautala *et al.* [24].

2.4. Accident Prevention Systems

Several technologies offering solutions have been proposed to prevent accidents at railway crossings. Chandrapa *et al.* [25] suggested an automatic railway gate control system using infrared sensors designed to detect approaching trains and close the gates without human intervention. While this system was designed for India, it could be useful in developing countries where manual systems are widely used. Hellman and Ngamdung [26], reiterated the use of modern intelligent transportation systems, such as remote monitoring of gates and warning lights (solar powered) which have been successfully implemented in USA, Europe and Australia.

Dulebenets *et al.* [27] examined safety improvements at HRAGIs in Florida, focusing on maintaining the continuity of passenger and freight flows while implementing safety measures. The USDOT procedures provided insights into warning devices and technology that could improve safety. Warning devices such as flashing light signals, automatic gates and LED pre-emptive train warning signs were seen to be effective in reducing accidents. These technologies could be adapted in developing countries, where basic warning systems are currently in use.

The above case studies have shown that tailored approaches, combining international best practices with local considerations to address specific challenges is important especially in less developed countries like Zambia. However, robust data collection on traffic volume, train frequency and accident history, human characteristics and HRAGIs infrastructure inventory must be underscored. It can also be deduced that the safety of HRAGIs can be significantly improved by combining risk assessment models, predictive accident prevention technologies and automated gate control systems. Adaptation of these innovations in the midst of unique conditions, such as road quality, driver behavior, and infrastructure limitations, could lead to a notable reduction in accidents at HRAGIs.

3. Materials and Methods

This study employed a mixed-methods approach, combining primary and secondary data collection, and model-based assessments to evaluate the safety of HRAGIs, on the ZR northern region rail network. The methodology was designed to provide both quantitative and qualitative insights into accident risks and contributing factors at the three critical HRAGIs, *i.e.*, Bwana Mkubwa, Lukanda, and Kabwe Main.

3.1. Primary Data Collection

3.1.1. Field Surveys

On-site surveys were conducted at each HRAGI to measure vehicle traffic volumes with distinctions being made between vehicle types and peak/off-peak hours. Train volumes were also recorded, providing essential data on train frequency and timing at each of the three crossings. HRAGIs in this study are located on trunk roads equivalent to interstate category in the USA.

3.1.2. Visual Inspections, Expert Consultation and Stakeholder Engagement

Each of the three HRAGI Class A-level crossing was visually inspected to identify physical hazards. The current ZR operational speed and track class compares well with the USA FRA Class 1 - 3 classification which allows operation of goods and passenger trains with restricted speeds of between 10 - 40 mph and 15 - 60 mph for freight and passenger respectively [28]. HRAGIs were checked based on characteristics such as sight distances, signage, gates, lighting, vehicular and pedestrian traffic.

Rail and road transportation experts, police and other relevant stakeholders, through face to face interviews, were engaged to gain an understanding of their perspective on HRAGIs safety and also as a platform to understand other challenges.

3.1.3. Accident and Hazard Prediction Models

Due to their popularity and simplicity the Florida Accident Prediction and Safety Index (hazard prediction) and the USDOT Accident Prediction Model were employed to understand the levels of HRAGIs vulnerability and probable number of accidents respectively. Accident vulnerability and predictions were further refined by incorporating historical accident records and providing adjusted measures of ongoing risks at each HRAGI.

Unlike other accident and hazard prediction models which are at infant or localized level in application, the USDOT has been applied across the USA, a country which is wide and diverse in terms of human, economic, geographical and climatic factors, making it more of a generalized model. Despite the ZINDOT model's accuracy over the USDOT, it has not been widely used and was therefore not adopted.

The following conditions are provided for under the USDOT formulae and met the Zambian prevailing conditions: Passive HRAGIs with cross-bucks, annual average daily traffic at the crossing in both directions, number of main tracks, average number of through trains per day, condition of highway whether paved or not, maximum time table speed, highway type factor value and number of highway lanes. These parameters including accident history in the last six years, crossing upgrade records were readily available.

However, limitations with regard to the Zambian environment were recognized. The average through trains volume records in Zambia do not distinguish day or night. Caution was exercised with regard to units in terms of empirical or metric. It is also important to note that USA-based models are developed based on a lot of data useful for statistical modelling which Zambia does not possess currently. The two models do not take into account human behavior or error. Additionally, the Florida Accident Prediction and Safety Index Model tend to be biased towards safe safety index zones in its rating. Notwithstanding, other USA based generalized models or formulae with wide applications have been used before in Zambia though with appropriate caution and adjustments. These include the AASHTO pavement design and Highway Capacity models.

3.2. Secondary Data Collection

3.2.1. Historical Accident Data

Historical data on accidents, including frequency, severity and timing were sourced from ZR and other authorities such as Zambia Police. This data provided a baseline for understanding risk levels and identifying trends in accident occurrences at HRAGIs.

3.2.2. Infrastructure Data from Databases

Information such as crossing type, control measures and accident records was collected from the ZR organizational databases.

4. Results

This section is aimed at providing data collected and results for each of the three critical HRAGIs studied, *i.e.*, Bwana Mkubwa, Lukanda and Kabwe Main which mainly involved operational, physical and environmental aspects to understand accident risk factors. Specifically, data collected and results included AADT, annual train volumes, annual total accident events (train-vehicle collisions). Vulnerability safety indices and predicted probable number of accidents using the Florida Accident Prediction and Safety Index and USDOT Accident Prediction Models respectively is also highlighted.

4.1. Average Daily Traffic Volumes

Traffic counts are vital to understanding vehicle flow which is likely to influence the rate of accidents at HRAGIs. Data was collected on a daily basis for five consecutive days (from 0500 am to 0700 pm) in order to determine the average daily traffic (ADT) (two-way flow) which is approximately equivalent to AADT, distinguishing peak, off-peak hours and vehicle types key in risk assessment. Table 1 below, shows the traffic count ADT at each HRAGI with Bwana Mkubwa recording daily traffic of 9900 vehicles per day, Kabwe Main at 9400 vehicles per day and Lukanda at 9200 vehicles per day.

Table 1. ADT (vehicles/day) at the three HRAGIs.

HRGAI	Bwana Mkubwa (Ndola Town)	Lukanda (Kapiri-Mposhi Town)	Kabwe Main (Kabwe Town)
ADT	9900	9200	9400

4.2. Annual Train Volumes (2018-2023)

Annual traffic volumes per year (two-way flow) (ZR database) were collected as shown Table 2 below providing a broader view of train traffic trends and long-term patterns that may influence accident risk.

Table 2. Annual train volumes(two-way) 2018-2023.

HRAGI/Year	Bwaba Mkubwa	Lukanda	Kabwe Main
2018	561	665	598
2019	167	212	201
2020	508	668	616
2021	165	197	177
2022	197	198	192
2023	702	921	868
Annual Average	383.33	476.83	442.00
Daily Average	1.050	1.306	1.211

As can be seen from Table 2 above, the train volumes for Lukanda were 476.83 trains per year (1.306/day), followed by Kabwe Main at 442 trains per year (1.211/day) and Bwana Mkubwa at 383.33 trains per year (1.050/day). This was comparable with the observed train volumes per day from field surveys.

4.3. Annual Total Accident Events

Tracking the number of annual accidents at HRAGIs gives insight into safety performance. By analyzing these accidents, identification of high-risk crossings that require intervention can be established. The annual total accidents for the 23 Class A–level crossings on the ZR rail network, from 2018 to 2023, is as shown in Table 3 below with an average 0.725 accidents per crossing.

Table 3. Annual total accident on the Zambia Railway network.

Year	Total Number of Accidents
2018	16
2019	19
2020	15
2021	13
2022	19
2023	18
Annual Average	16.67
Annual Average/Class A-Level Crossing	0.725

4.4. Results from the Florida Accident Prediction and Safety Index and USDOT Accident Prediction Models

Table 4 below shows the Florida Accident Prediction and Safety Index Model analysis (without gates and with gates).

Table 4. Florida accident prediction and safety model analysis.

Properties/HRAGI	Bwana Mkubwa		Lukanda		Kabwe Main	
Presence of gate (P_g)	0	1	0	1	0	1
Vehicles per day (ADT)	9900	9900	9200	9200	9400	9400
Number of lanes (L)	2	2	2	2	4	4
Minimum SSD MASD (m)	115	115	115	115	115	115
Clear Sight Distance MCSD (m)	194	194	194	194	194	194
Required SSD RSSD (m)	184	184	184	184	184	184
Max speed of train (km/h) (S_t)	40	40	40	40	40	40
Yearly train volume/day (T)	1.0502191	1.0502191	1.3063835	1.3063835	1.2109589	1.2109589
t_p^a	−2.260402	−2.260402	−2.186808	−2.186808	−2.2141220	−2.2141220
t_a^b	−2.933126	−3.166126	−2.918380	3.1513807	−2.4746705	−2.7076705

Continued

V_v (posted speed limit)	20	20	20	20	20	20
N_{xbucks} (number of crossbucks)	2	2	2	2	2	2
Accident prediction y (using t_p)	0.084977	0.084977	0.091252	0.0912524	0.08887143	0.08887143
Accident prediction y (using t_a)	0.048384	0.0388859	0.049058	0.0394275	0.0743824	0.0597796
Accidents from last upgrade (H)	2	2	3	3	1	1
Years of accident History (P)	6	6	6	6	6	6
Adjusted accident Prediction Y	0.1269972	0.1138507	0.156618	0.1404058	0.1113421	0.0998162
X (school buses based factor)	80	80	80	80	80	80
Safety Index (R)	51.490658	53.006575	48.33993	50.023388	53.305623	54.725033

[a]ln (logarithm) of accidents predicted in 4-year period at highway-rail grade crossings with passive traffic control devices. [b]ln (logarithm) of accidents predicted in 4-year period at highway-rail grade crossings with active traffic control devices.

The results showed that the safety index (R) (without gates) were, for Bwana Mkubwa (51.49%), Lukanda (48.34%), and Kabwe Main (53.31%) while the safety index (R) (with gates) were 53.01%, 50.02% and 54.73% for Bwana Mkubwa, Lukanda and Kabwe Main respectively.

Table 5 below shows the predicted accident results using the USDOT Accident Prediction model. The initial accident prediction parameter A, Table 5, shows accident probabilities with an average of 0.20 accidents per year at all the three HRAGIs. However, when historical accident data were factored in using the second accident prediction parameter B in Table 5, Lukanda showed 0.28 predicted accidents per year, compared to 0.21 at Bwana Mkubwa and 0.15 at Kabwe Main. Historical data for the last 6 years, indicated that Lukanda had the most accidents over a six-year period (3 accidents), followed by Bwana Mkubwa (2 accidents) and Kabwe Main (1 accident).

Table 5. USDOT accident prediction model analysis.

Properties/HRAGI	Bwana Mkubwa	Lukanda	Kabwe Main
c (vehicles/day) (ADT)	9900	9200	9400
t (average trains/day)	2	2	2
mt (number of main tracks)	1	1	1
d (average day through trains/day)	1	1	1
hp (highway paved)	1	1	1
ms (maximum timed speed in mph)	24.854847	24.854847	24.854847
ht (highway type factor value)	1	1	1
hl (number of highway lanes)	2	2	4
K (formula constant)	0.002268	0.002268	0.002268
EL (exposure index factor)	46.29629497	45.17814921	45.50324478
MT (main tracks factor)	1.232938075	1.232938075	1.232938075

Continued

DT (average day through train factor)	1.270460032	1.270460032	1.270460032
HP (highway paved factor)	1	1	1
MS (maximum speed factor)	1.210922326	1.210922326	1.210922326
HT (highway type factor)	1	1	1
HL (highway lanes factor)	1	1	1
A (initial accident prediction) (accidents/year)	0.199162626	0.194352461	0.195750993
T_0 (formula weighting factor)	4.013443007	4.092449068	4.069159542
T_y (accident observation years)	6	6	6
N (number of accidents)	2	3	1
B (Second accident prediction) (Accidents/year)	0.213427308	0.281557238	0.146460613

5. Discussion

This section discusses the results from Section 4 above.

5.1. Vehicle Traffic and Train Volume Dynamics

Though relatively low train volumes and reduced train speeds (maximum of 40 km/h) and train volumes (approximately 1 train/day) may be seen to mitigate some risks, as fewer trains pass through the intersections at slower speeds, thereby reducing the chances of collisions, the reality on the ground is that high vehicle traffic exposes a large number of motorists to hazards and potential accidents on a daily basis. It was observed that during traffic and visual inspection surveys, most motorists did not stop at the HRAGIs. The possibility of increased potential for vehicle-train conflicts, particularly at Kabwe Main which is in town has high potential for accidents because of high vehicle and pedestrian traffic.

5.2 Safety Vulnerability and Accident Prediction

The Florida Accident Prediction and Safety Model was developed to rank the HRAGIs for vulnerability. Normally, a safety index value of 70 is considered safe while a safety index value of 60, which represents one accident in nine years, is considered as marginal [19].

As can be seen from **Figure 1** below, the calculated safety indices values for the three HRAGIs were below the accepted marginal threshold of 60%. The safety index (R) (without gates) was, for Bwana Mkubwa (51.49%), Lukanda (48.34%), and Kabwe Main (53.31%). The safety index (R) (with gates) improved slightly with a score of 53.01%, 50.02% and 54.73% for Bwana Mkubwa, Lukanda and Kabwe Main respectively, but were still below 60% indicating that the three crossings were not safe, even with the introduction of gates which currently are non-existent.

The safety index values are consistent with the observation on the ground as a result of the passive nature of the type of crossings amidst very high vehicle traffic volumes with poor driver compliance and no lighting. Though, the Kabwe Main

HRAGI showed a slightly better safety index result, most probably due to four-lane highway, the risk remains unacceptably high at all the three crossings.

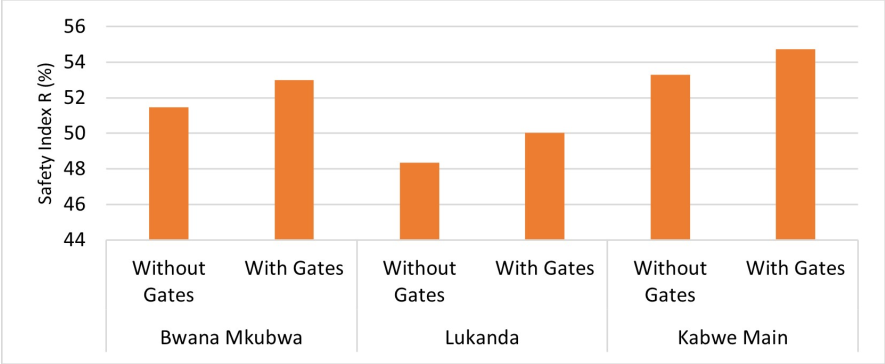

Figure 1. Safety Index Values R (%) for HRAGI (Without and With Gates).

The results further suggest that even though the introduction of gates would slightly improve safety, that would not be sufficient to bring the HRAGIs above the marginal safety threshold, as shown in Figure 1 above. This indicates that active safety measures, such as automated warning lights, traffic barriers, and increased signage, are necessary to effectively reduce the risk of accidents.

Figure 2 below, shows a comparison of predicted probable number of accidents and that of historical data at the three specific locations. It can be established that there is a close correlation between predicted values with historical data in terms of each HRAGIs relative exposure to accidents though a huge gap exits. This anomaly in the predicted to that of historical values may be attributed to the USDOT Accident Prediction Formula failure to account for sight distances, human error, local infrastructure details like passive or active control systems and other factors like lighting at night.

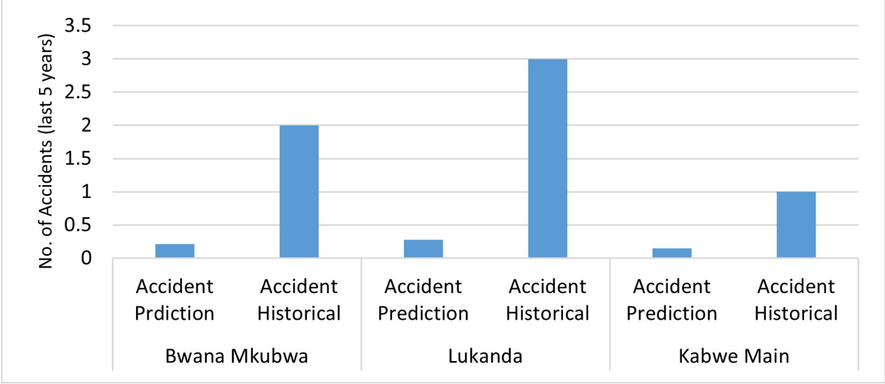

Figure 2. A comparison between accident predicated and accident historical values.

It must be emphasized that though this discrepancy exists it is not entirely because of the Zambian local conditions at the HRAGIs but that this is consistent with a study done by Mathew *et al.* [29] in the USA where they compared the

USDOT model with the newer ZINDOT model. The latter model correlated well with the observed counts while USDOT did not. The two models were compared on the basis of predicted values with observed accident counts. Comparisons were made based type of HRAGIs such as gates, flashing lights or cross-bucks. The results obtained for cross-bucks only HRAGIs are very similar to what has been obtained in this study.

5.3. Safety and Accident Risk at the HRAGIs

Though all the accidents reported for last six years at the three critical crossings were train to vehicle related, there were no records as to the cause of accidents. Factors such as poor driver behavior, visibility issues, or substandard infrastructure, may be contributing to accidents at HRAGIs [24]. It was observed that the three critical crossings were passive in nature with no lighting making the HRAGIs unsafe at night. Bwana Mkubwa had deteriorating road pavement without road makings or even calming measures. On the other hand, Lukanda is located on a reverse curve with a lot of traders selling their farm produce to motorists right at HRAGI. Vandalism is also reportedly high on the ZR railway network making it yet another contributing factor to poor safety in general.

The foregoing suggests that current measures, such as cross-bucks, stop signs and passive safety controls are inadequate to mitigate risks at these three critical HRAGIs.

6. Conclusions

This investigation was focused on assessing the safety of HRAGIs in Zambia, with specific emphasis on critical locations, *i.e.*, Bwana Mkubwa, Lukanda, and Kabwe Main on the northern section of the ZR network. The study applied established but generalized hazard and accident prediction models from the USA. Local characteristics including driver and pedestrian behavior at the HRAGIs were also taken into account.

The findings revealed that all three level crossings are unsafe, with safety index values significantly below the marginal threshold of 60% using the Florida Accident and Hazard Prediction Model. Specifically, Bwana Mkubwa, Lukanda, and Kabwe Main scored 51.49%, 48.34%, and 53.31%, respectively and was consistent with what was observed on the ground. Even with the introduction of gates, the safety indices remained below the marginal threshold making all three HRAGIs still unsafe.

The USDOT Accident Prediction Model had low predicted values 0.20 accidents per year with initial parameter A, and 0.21, 0.28, and 0.15 accidents per year with second parameter B, for Bwana Mkubwa, Lukanda, and Kabwe Main respectively. The noticeable gap between the predicated and the observed accident values, though consistent with what has been observed in the USA [29], may be attributed to failure by the USDOT formula to account for other factors such as sight distance and human error. The passive nature of the HRAGIs, poor operational systems and absence of lighting could have also contributed to high historical accident rates. It must be stated that of the two USA based generalized models, the Florida formula was consistent with what was observed at each of the three HRAGI.

Though low train volumes and speeds help reduce the overall accident probability, the high vehicle volumes and limited safety infrastructure mean that these crossings remain dangerous. The low safety index scores indicate that the current safety measures, which are mostly passive, do not provide adequate protection for road users. Moreover, the low predicted accident rates may not effectively reflect the observed situation; hence there is the need for local based models which take into account human and environment factors at HRAGIs.

While implementing passive safety measures such as gates would marginally improve safety, these alone are insufficient to fully address the safety risks at HRAGIs. There is need to gradually upgrade critical HRAGI Class A-level crossings from passive to active besides driver and pedestrian education sensitization.

7. Recommendations

1) There is need to implement active warning systems such as flashing lights and automated gates at HRAGIs with high AADT and historical accident rates. These measures have been proven to reduce accident risks by alerting drivers.

2) Ensuring the enhancement of road markings and installation of better signage that can help mitigate risks and improve safety outcomes.

3) There is a need to enhance public awareness regarding the dangers of HRAGIs through educational campaigns for drivers and pedestrians to help reduce accidents due to non-compliance or unsafe practices at these crossings.

4) Enhancement of visibility at HRAGIs, especially in rural areas through installation solar-powered lighting to improve safety at crossings where night-time visibility is poor.

5) Conducting further research on the remaining black spots on the ZR southern network in order to explore additional risk factors.

6) The study relied on generalized accident and hazard prediction models from the USA including observed local characteristics at the three critical HRAGIs. It is recommended that future research focuses prediction and hazard analysis through other methods such as evaluation of HRAGIs characteristics through multiple regression, tailored to Zambia's unique HRAGIs conditions. This will provide more accurate risk assessments and improve resource allocation for safety interventions.

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Conflicts of Interest

The authors reiterate that they have no financial or personal interests that could be seen as exerting any influence on the research in this paper.

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