

PROJECT ID:

**“SPATIAL ANALYSIS OF ROAD TRAFFIC CRASHES INVOLVING VULNERABLE
ROAD USERS IN MUSANZE CITY”**

A DISSERTATION

Submitted by

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ABSTRACT

Road traffic injuries remain a leading cause of morbidity and mortality globally, particularly in low- and middle-income countries where urban planning and road infrastructure often fail to accommodate vulnerable road users (VRUs), including pedestrians, cyclists, and motorcyclists. This study aimed to spatially analyze road traffic crashes involving VRUs in Musanze City, Rwanda, with a focus on identifying high-risk locations, assessing the influence of road parameters, and examining road safety issues from the perspective of road users. Using crash data from the Rwanda National Police (2021–2024), the study employed Geographic Information System (GIS) tools Kernel Density Estimation (KDE) and Getis-Ord G_i^* hotspot analysis to map spatial patterns and detect statistically significant clusters of crashes. Additional statistical analyses, including chi-square tests and multiple linear regression, were used to explore the relationship between road parameters, crash involvement, and user perceptions based on a structured survey of 398 VRUs. The spatial analysis revealed that crashes are non-randomly distributed and tend to cluster around major intersections and high-traffic corridors, particularly at Kalisimbi, BNR intersection, and along the Musanze–Rubavu and Musanze–Kinigi Roads. Road design factors such as intersection type, road curvature, and gradient were found to significantly influence crash risk, especially for cyclists and motorcyclists. Survey results further highlighted that speeding (72.1%), poor pedestrian paths (66.3%), and reckless driving (61.8%) are the most commonly reported safety concerns. Younger adults (18–35 years) and frequent road users were more likely to be involved in crashes, particularly during afternoon and evening hours. The findings underscore the need for integrated, evidence-based interventions combining infrastructure upgrades, traffic enforcement, and public education to enhance protection for VRUs in urban Rwanda.

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LIST OF ABBREVIATIONS

AADT	: Annual Average Daily Traffic
BRT	: Bus Rapid Transit
BNR	: Banque Nationale du Rwanda
CBD	: Central Business District
EIA	: Environmental Impact Assessment
EMS	: Emergency Medical Services
FGD	: Focus Group Discussion
FRSC	: Federal Road Safety Commission
GIS	: Geographic Information System
GWR	: Geographically Weighted Regression
HEMS	: Highway Engineering and Management Studies
IRAP	: International Road Assessment Program
KDE	: Kernel Density Estimation
KII	: Key Informant Interview
MoU	: Memorandum of Understanding
NR	: National Road
NMT	: Non-Motorized Transport
NRSA	: National Road Safety Authority
PWD	: Persons With Disabilities
RNP	: Rwanda National Police
RTAs	: Road Traffic Accidents
RTIR	: Road Traffic Injury Report
RTSA	: Road Transport and Safety Authority
SDG	: Sustainable Development Goal
SPSS	: Statistical Package for the Social Sciences
UR	: University of Rwanda
VRUs	: Vulnerable Road Users
WHO	: World Health Organization

CHAPTER I: INTRODUCTION

1.1 Background of the Study

Road safety has recently been considered one of the greatest issues in road safety management worldwide. Road traffic crashes result in the deaths of approximately 1.3 million people around the world each year and leave between 20 and 50 million people with non-fatal injuries. The socioeconomic costs of these injuries are estimated at between 1 and 7 percent of the GDP in developing countries. Like the actual and projected rates of motorization in these countries, the accompanying annual increase in road traffic injuries is unprecedented, involving premature death and disability, predominantly among vulnerable road users and economically active adults [1].

As stated by the World Health Organization, more than half of all road traffic deaths are among vulnerable road users: pedestrians, cyclists, and motorcyclists due to insufficient physical protection in the event of a collision with cars, trucks or buses. Globally, pedestrians and cyclists represent 26% of all deaths, with those using motorized two- and three-wheelers comprising another 28%. Car occupants make up 29% of all deaths and the remaining 17% are unidentified road users [2].

More than half of the world's population now live in urban areas increasingly in highly-dense cities [3]. In urban areas, nowadays more and more people prefer walking or cycling to reach their destination instead of taking public transportation or using a car due to traffic problems. This situation makes more people vulnerable due to a high risk of injury in any traffic collision. Specific solutions for the protection of vulnerable road users not only ensure greater safety in urban traffic but also increase efficiency of the transportation system [4].

The rapid motorization of African countries has outpaced the development of infrastructure, regulation, and enforcement to support it, leading to a growing trend of road accidents across the continent. Enhancing road safety and curbing fatalities from road traffic crashes in Africa should be an urgent priority, beginning with the need to improve education for motorists and motorcyclists. Africa had a road traffic fatality rate of 19 deaths per 100,000 people relative to 7 per 100,000 in Europe, despite having less than 3% of the world's vehicle fleet. As of 2019, road traffic crashes were the ninth leading cause of death in the continent and will likely to continue to surge unless efforts to promote road safety standards for drivers and vehicles are adopted [5]

However, Rwanda has made commendable progress in road safety over recent years. The WHO Global Status Report (2023) notes a reduction in traffic fatalities, from 15 to 12 per 100,000 people annually. This improvement is linked to enforcement measures such as speed cameras, speed governors, dedicated walkways, and public education campaigns like Gerayo Mahoro [6]. Despite ongoing road safety efforts, many secondary cities such as Musanze continue to face persistent challenges related to infrastructure deficits. These include poorly lit road sections, lack of designated pedestrian and cyclist facilities, and unsafe intersections, especially in high-traffic areas where vulnerable road users are at greater risk. Such gaps undermine the effectiveness of broader road safety strategies and contribute to elevated crash rates among vulnerable road users.

Identifying road traffic crashes hotspots and appending value-added data to understand the processes occurring in these hotspots is important for the appropriate allocation of resources for safety improvements [7]. Safety analyses are carried out by using statistical and spatial analysis tools in Geographic Information System (GIS). GIS-based techniques are relatively simple to use and can convert raw statistical and geographical data into meaningful information for spatial analysis, mapping, and identifying any factors contributing to accidents [8].

This study sought to fill this gap by conducting a spatial analysis of traffic crashes involving vulnerable road users in Musanze City. By identifying crash hotspots and analyzing patterns and contributing factors, the research provided evidence-based recommendations for improving safety for pedestrians, cyclists, and motorcyclists. The study's results will serve as a crucial tool for highway engineers, urban planners, and policymakers in their efforts to create safer, more inclusive urban transportation networks in Rwanda and similar settings.

1.2 Problem statement

The increasing demand for non-motorized transport in rapidly urbanizing secondary cities has placed immense pressure on road infrastructure, particularly in developing countries. In Musanze City, Rwanda, this growth has led to a significant rise in traffic volumes and a more complex mix of road users, including pedestrians, cyclists, and motorcyclists. However, the city's road network has not evolved at the same pace to accommodate this demand, resulting in growing concerns about road safety especially for vulnerable road users (VRUs) who bear a disproportionate share of traffic-related injuries and fatalities [9].

Despite the acknowledged risks faced by VRUs, current urban and transport planning in Musanze lacks a data-driven approach for identifying where and why these crashes are

occurring. Road safety strategies remain largely reactive, with limited incorporation of spatial data, infrastructure audits, or road user feedback. This gap severely limits the ability of policymakers and planners to implement targeted, evidence-based interventions [10].

Moreover, the absence of dedicated infrastructure such as pedestrian walkways and cycle lanes, along with poor road user behavior and weak enforcement of traffic laws, exacerbates the risk to non-motorized users [11]. The situation is further compounded by the lack of systematic research on the spatial patterns of crashes and the road parameters that may contribute to their concentration in certain areas.

Given that over 50% of global traffic fatalities involve VRUs [1], it is imperative to better understand the spatial dynamics and contextual factors influencing VRU crashes in Musanze City. A spatial analysis approach, supported by field observations and road user perspectives, can reveal high-risk zones (hotspots), evaluate how road design or land use correlates with crash occurrences, and bring attention to the everyday challenges faced by VRUs on the ground.

By addressing these objectives, the study aimed to provide actionable insights for improving road safety infrastructure, guiding urban development, and reducing traffic-related injuries and fatalities among vulnerable road users in Musanze City.

1.3. Objectives of the study

The objectives of the study were divided into general objective and specific objectives.

1.3.1 General objective

The general objective of this study was to spatially analyze road traffic crashes involving vulnerable road users in Musanze City, Rwanda.

1.3.2 Specific objectives

The specific objectives of this study were the following:

1. To identify spatial patterns and distributions of road traffic crashes involving vulnerable road users in Musanze City road network,
2. To determine the relationship between certain road parameters and the spatial concentration of VRU crashes in Musanze City, and
3. To assess road safety issues faced by VRUs from the road user perspective in Musanze City.

1.4 Research questions

This study was guided by the following research questions:

1. Which locations in the road network are more susceptible to vulnerable road users traffic crashes in Musanze City?
2. Which road parameters are associated with the spatial concentration of VRU crashes in Musanze City?, and
3. What are road safety issues faced by VRUs from the road user perspective in Musanze City?,

1.5 Scope of the study

This study is geographically limited to Musanze City, one of Rwanda's rapidly urbanizing secondary cities. The research focuses specifically on road traffic crashes involving vulnerable road users (VRUs), namely pedestrians, cyclists, and motorcyclists, as these groups are at higher risk in mixed-traffic environments.

The chronological scope covers the last three years of available traffic crash data from 2021 to 2024, which are used to identify trends and hotspots through spatial analysis using Geographic Information Systems (GIS). The study also includes an assessment of road infrastructure conditions, such as crosswalks, sidewalks, cycling lanes, signage, and lighting, to evaluate how current design provisions influence safety outcomes.

Functionally, the research addresses engineering-related risk factors (e.g., road geometry, speed, intersection), as well as behavioral and policy gaps contributing to crashes at identified high-risk locations (hotspots) from the road user views. However, it does not extensively cover post-crash response systems or the full spectrum of enforcement and education programs.

The findings are intended to guide urban planners, traffic engineers, and policymakers in making data-driven decisions to enhance road safety and infrastructure inclusivity for VRUs in Musanze City and similar urban settings in Rwanda.

1.6 Research dissertation outline

Chapter One provides a general introduction to the study, including the background and the current challenges related to the spatial analysis of road traffic crashes involving vulnerable road users in Musanze City. It also presents the problem statement, research objectives, and the significance of the study.

Chapter Two offers a comprehensive review of relevant literature, focusing on previous studies, theoretical frameworks, and key concepts related to road traffic crashes and vulnerable road users.

Chapter Three outlines the proposed research methodology, including the data collection methods, analysis techniques, and tools to be used in conducting the spatial analysis.

Chapter Four presents and interprets the findings of the study based on the spatial and statistical analyses conducted. It discusses the identified crash hotspots, the influence of road features on crash concentration, and the road safety perceptions of VRUs.

Chapter Five provides a summary of the key findings, draws conclusions, offers practical recommendations, and outlines areas for further research related to this study.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

As cities expand and urban mobility continues to grow around the globe, prioritising road safety stands out as a crucial element in modern cities, impacting virtually every member of the community. The number of road crash fatalities has increased over the last decade. While all road users face the risk of injury or death in an accident, pedestrians, cyclists, and motorcyclists are more prone to being involved in such traffic crashes and they contribute to approximately 50% of all road traffic fatalities in different countries [12].

Spatial analysis has emerged as a critical tool in identifying high-risk areas and designing evidence-based interventions. Geographic information systems (GISs) have been used by many transportation agencies and police departments to analyze and manage urban traffic accident (UTA) data and for decision making aimed at decreasing accident rates and increasing safety. The exact location of accidents and environmental characteristics must be analyzed as UTAs occur in specific locations with specific characteristics [13].

This chapter provides a critical review of the existing literature on the spatial analysis of road traffic crashes involving vulnerable road users (VRUs), with a particular focus on urban areas in developing countries. The review explores the concept of VRUs and their risk exposure, factors contributing to crashes involving VRUs, methods of spatial analysis used in road safety research, global and regional studies on spatial patterns of traffic crashes, and research gaps relevant to the Rwandan context particularly Musanze City. This also highlights the importance of GIS-based spatial analysis in identifying crash hotspots and informing policy, while also establishing the justification for the present study.

2.2 Theoretical background

2.2 Trends of road traffic accidents

2.2.1 Global road accident and safety report

Road traffic accidents are quite a global problem. By 2020, the World Health Organization (WHO) expects traffic accidents to be the third most common cancer.

Table 2-1: Improvements as in estimates of a top 10 consequences of global disease

Rank	1990	2020
1	Lower respiratory infections	Ischemic heart disease
2	Diarrheal diseases	Unipolar major depression
3	Conditions during the Perinatal Period	Road Traffic Injuries
4	Unipolar major depression	Cerebrovascular disease
5	Ischemic heart disease	Chronic Obstructive Pulmonary Disease (COPD)
6	Cerebrovascular disease	Lower respiratory infections
7	Tuberculosis	Tuberculosis
8	Measles	War
9	Road traffic injuries	

Source: [14]

The problem of accidents is not only limited to the occurrence and destruction of valuable property; it also affects the most economically active and productive age groups, especially those aged between 15 and 45 years old, who are the most heavily affected by traffic accidents, which implies that accidents are globally challenging to the earning and active population groups. This affects economic development, as the absence of skilled workers and innovative contributors can hinder progress and discourage key economic stakeholders. Consequently, visually disabled people with low-income efficiency were disproportionately targeted, although these individuals quite obviously depend on resistance training [14].

Hence, victims still reside in the facility longer than normal individuals, putting excessive pressure on patients and practitioners. Therefore, these are the global features of road accidents, including their implications:

1. Annually, traffic accidents are predicted to kill 1.2 million people and disable 20-50 million others. (Daily road tolls of more than 3200, i.e., nearly 140 deaths per day) One hour.
2. Accident rates in advanced countries are roughly 50% higher than in developing countries. In developed economies,
3. Around 88% of deaths occur in advanced nations,
4. Low- and middle-income states are encouraged to achieve a rate of around 90%. Although high-income countries are projected to have 30% increase in road traffic accidents, low-income countries will also see a 30% increase.

2.2.2 African road accidents and fatalities

Road traffic death rates in the past decade have increased significantly in the African region, with almost 250,000 lives lost on the continent's roads in 2021 alone. Conversely, global

rates fell by 5% during the same period. Between 2010 and 2021, the region recorded a 17% increase in road-related fatalities, according to the WHO Status report on road safety 2023 for the African region the latest update. The region accounts for nearly one-fifth of all road deaths globally, despite being home to only 15% of the world's population, and 3% of its vehicles [1].

The report attributes the rise to multiple factors, including inadequate road safety laws and standards. No country in the region currently has laws that meet the best practice standards for the five key road safety behavioural risk factors: speeding, drink driving, non-use of motorcycle helmets, seatbelts and child restraints [1].

Currently, most road traffic data systems in Africa capture only road-related deaths, excluding information about injuries and their severity, including medium- and long-term consequences such as disability. Post-crash care services in the region are also inadequate or unavailable in most countries; fewer than one-third have services that meet recommended levels of access to pre-hospital care, emergency care, and treatment and rehabilitation services [15].

To achieve the United Nations General Assembly target of halving the global number of deaths and injuries from road traffic crashes by 2030, WHO recommends concerted efforts to implement a range of interventions to strengthen national road safety strategies in Africa. These include policies that promote sustainable transportation systems, improved legislative road safety frameworks, investment in data management systems, improved post-crash response, and research tailored to the continent's unique challenges [16].

2.2.3 Road traffic accident trends in Rwanda

Road transport remains the most dominant mode of transportation in Rwanda, facilitating the movement of people and goods across the country. However, with the increasing urbanization and motorization, road traffic accidents have become a critical public health and development concern. Recent data indicate a rising trend in road crashes, particularly affecting vulnerable road users such as motorcyclists, pedestrians, and cyclists [17].

Between 2020 and 2022, the number of reported road traffic accidents in Rwanda more than doubled, increasing from 4,160 incidents in 2020 to 8,660 in 2022. Similarly, the number of fatalities rose from 629 in 2020 to 687 in 2022, indicating a growing road safety burden. Although there have been improvements in fatal crash reduction efforts, the number of injury-related and property-damage-only accidents continues to increase [6].

Vulnerable road users remain disproportionately affected by these trends. In the first half of 2023 alone, motorcyclists were involved in over 2,300 road crashes, resulting in 98 deaths and 46 serious injuries. The urban areas, especially Kigali's Gasabo District, consistently record the highest accident rates due to high population density, increased traffic volume, and mixed road use [18].

To address these challenges, Rwanda has implemented several interventions aimed at improving road safety. One of the most significant initiatives was the nationwide implementation of Automated Speed Enforcement (ASE) in April 2021, making Rwanda the first low-income country to do so. This policy led to a 38% reduction in monthly road traffic deaths, as shown by time series analysis over a 12-year period. Additionally, the *Gerayo Amahoro* road safety campaign launched in 2019 has played a critical role in public education and awareness, contributing to a 17% reduction in crash rates since its inception [6].

Infrastructure improvements have also supported these interventions, including the installation of speed governors in public transport vehicles, dedicated pedestrian and cyclist pathways, and improved signage. In recognition of these efforts, Rwanda was awarded the Kofi Annan Road Safety Award in 2023 for its proactive and innovative approach to road safety [19].

Nevertheless, challenges remain; many road users still use non-standard helmets, and the vehicle fleet includes outdated and poorly maintained vehicles. Moreover, enforcement of traffic rules and driver education requires further strengthening to ensure sustainable road safety outcomes [20].

These trends underscore the importance of evidence-based spatial analysis to identify high-risk areas and guide strategic interventions, particularly in rapidly growing secondary cities like Musanze, where similar patterns are emerging.

2.3 Behavioral and institutional risk factors for VRUs in Africa

Vulnerable road users (VRUs), including pedestrians, cyclists, and motorcyclists, face a disproportionately high risk of road traffic crashes across Africa. The World Health Organization estimates that VRUs account for more than 50% of all road traffic fatalities in low- and middle-income countries, with the African region recording the highest fatality rates per 100,000 population [2]. Several interrelated factors contribute to this situation, ranging from infrastructural deficiencies to behavioral and institutional challenges.

2.3.1 Speeding and reckless driving

Speeding remains a major risk factor for VRU-related fatalities. Drivers frequently exceed speed limits in both urban and rural areas, often failing to slow down in pedestrian-dense zones such as schools, markets, and residential neighborhoods. The implementation and enforcement of speed control measures are often weak or inconsistent. For instance, in Rwanda, before the rollout of automated speed enforcement (ASE) in 2021, speeding was among the top causes of traffic fatalities, especially involving motorcyclists and pedestrians [21].

2.3.2 Low awareness and risky behavior

Many VRUs, particularly in low-income and rural communities, have limited knowledge of road safety practices. Pedestrians often cross roads unpredictably or at unsafe locations, while motorcyclists and cyclists may not adhere to traffic regulations. In many instances, the absence of comprehensive road safety education contributes to dangerous behaviors that elevate crash risks [2].

2.3.3 Lack of protective gear

Motorcyclists and cyclists frequently travel without proper safety equipment. The use of helmets, reflective clothing, and visibility-enhancing accessories remains alarmingly low. Studies have found that in several East African countries, fewer than 40% of motorcycle riders consistently use helmets, and many of those in use are of poor quality or improperly fitted. Similarly, pedestrians walking at night are often poorly visible to motorists, increasing the likelihood of accidents [22].

2.3.4 Weak law enforcement and policy gaps

Although many African countries have road safety regulations, enforcement remains inconsistent. Traffic violations, such as speeding, red light jumping, and non-use of helmets, often go unpunished due to inadequate policing and corruption. In some cases, even where laws exist, such as mandatory helmet use or pedestrian right-of-way, compliance is low due to a lack of public awareness and weak institutional capacity [2].

The vulnerability of road users across Africa is not only a reflection of environmental exposure but also of profound behavioral and institutional shortcomings. Speeding, lack of awareness, non-use of protective gear, and inadequate law enforcement significantly contribute to the high incidence of traffic crashes involving VRUs. These risk factors are often amplified in low-income and rural settings, where road safety education is minimal, enforcement is inconsistent, and regulatory frameworks lack practical implementation. Addressing these challenges requires a comprehensive, multi-sectoral approach that

prioritizes behavior change campaigns, capacity building for enforcement agencies, and targeted community-based interventions. Such efforts must be tailored to the socio-economic realities of the region to effectively reduce crash risks and improve the safety outcomes for vulnerable road users.

2.4 Infrastructure design for vulnerable road users

Infrastructure design plays a vital role in enhancing road safety, particularly for Vulnerable Road Users (VRUs), including pedestrians, cyclists, and motorcyclists. These groups are most at risk in road traffic environments due to their exposure and the displacement mode. In many low- and middle-income countries (LMICs), such as Rwanda, road infrastructure often prioritizes motorized traffic, overlooking the needs of VRUs. This section reviews global and regional practices, challenges, and design interventions aimed at improving road infrastructure for VRU safety, with an emphasis on applicability to urban settings like Musanze City.

2.4.1 Importance of inclusive infrastructure

Inclusive infrastructure involves the integration of sidewalks, bike lanes, pedestrian crossings, traffic calming measures, and designated motorcycle lanes. These elements serve not only to separate and protect different types of road users but also to promote more sustainable modes of transport. In cities with properly implemented VRU infrastructure, studies show significant reductions in crash rates and improvements in perceived safety [17].

2.4.2 Infrastructure challenges in african cities

African urban centers face numerous challenges in implementing safe and inclusive road infrastructure. Rapid urbanization, weak urban planning, and funding limitations all contribute to poor road safety outcomes for VRUs [22]. In many secondary cities like Musanze, footpaths are either missing or poorly maintained, and road markings are often faded or absent altogether. This is coupled with the limited budget allocated to road construction projects where the allocated budget is mainly disbursed at vehicular infrastructure only, the expropriation issues cannot be overlooked.

Studies from Nairobi, Accra, and Dar es Salaam show that the majority of pedestrian crashes occur in locations without pedestrian crossings or traffic calming infrastructure [23]. A similar pattern has been observed in Rwanda, where vulnerable road users particularly pedestrians constitute a significant proportion of fatalities in urban crashes [24].

Moreover, many roads lack lighting, signage, and median islands, exposing VRUs to additional risks during night hours and at unsignalized intersections. Poor drainage and

uneven road surfaces further worsen conditions for pedestrians and cyclists, often forcing them to share space with motor vehicles [4].

2.4.3 Best practices in infrastructure design for VRUs

Globally, several infrastructure interventions have proven effective in reducing crashes involving VRUs [25]. These include:

- **Raised pedestrian crossings** and **speed humps**, which compel vehicles to slow down at critical crossing points.
- **Sidewalks** separated by curbs or green buffers to provide physical separation from motor traffic.
- **Bicycle lanes**, ideally protected, to reduce conflicts between cyclists and motorized vehicles.
- **Roundabouts** with pedestrian crossings and refuge islands, shown to reduce conflict points and vehicle speeds.
- **Traffic calming zones** and **complete streets policies**, which prioritize safety and accessibility over traffic flow.

The implementation of these interventions in LMICs must be adapted to local contexts, considering cultural behavior, enforcement capacity, and maintenance realities. For instance, in Kampala, Uganda, raised zebra crossings and barriers significantly improved pedestrian safety in school zones [26].

2.4.4 Infrastructure policies and design guidelines

There is a growing push for the adoption of national and municipal guidelines that prioritize non-motorized transport and road safety. In Rwanda, the Urban Road Safety Improvement Strategy advocates for better integration of VRU facilities into urban road designs. However, implementation is uneven, and enforcement remains weak outside Kigali [27].

The Global Designing Cities Initiative (2016) and UN-Habitat's Urban Mobility Guidelines emphasize a systems approach combining engineering, enforcement, and education to protect VRUs. These guidelines recommend that infrastructure design be informed by data on road use, crash locations, and vulnerable populations [28].

For Musanze City, integrating spatial crash data with infrastructure planning could support context-specific interventions such as safe school zones, upgraded junctions, and protected paths in high-traffic areas.

2.5 Spatial analysis in road safety studies

Spatial analysis has emerged as a critical methodological approach in road safety research, particularly in identifying crash-prone areas, understanding spatial patterns of accidents, and informing targeted interventions. Road crashes are not randomly distributed in space; they often occur in clusters influenced by environmental, infrastructural, and behavioral factors. Geographic Information Systems (GIS) provide a robust platform for mapping, analyzing, and visualizing these spatial distributions [7].

2.5.1 Importance of spatial analysis in crash studies

The traditional analysis of traffic accidents often focuses on tabular statistics such as frequencies, rates, or time-based trends. While these metrics are essential, they fail to provide insights into where crashes occur and how spatial context influences risk. Spatial analysis addresses this gap by integrating geographic location into crash data, thereby enabling planners and researchers to detect spatial patterns, identify high-risk zones (hotspots), and examine correlations with road features such as intersections, traffic volume, land use, or lighting conditions [29].

For example, Kernel Density Estimation (KDE), a widely used spatial tool, enables researchers to visualize areas with high concentrations of crashes. KDE smooths point data to identify underlying density surfaces, revealing hotspots that are not easily visible through raw data [7]. These visualizations are especially useful for city planners and traffic safety officials in prioritizing interventions such as speed control, signage, or pedestrian crossings.

2.5.2 Key spatial techniques in road safety research

Several spatial analysis techniques have been employed in road safety studies to identify patterns, hotspots, and influencing factors of road traffic crashes. These include Kernel Density Estimation (KDE), spatial autocorrelation (e.g., Moran's I), Getis-Ord G_i^* statistics, spatial regression models, and spatial scan statistics. Each method serves a distinct purpose in understanding the spatial distribution of road traffic crashes:

Kernel Density Estimation (KDE) is commonly used to produce heat maps of crash intensity and identify crash-prone zones through continuous surface mapping. KDE method calculates the size per unit area from point or line features based on a kernel function (K), and it fits a smooth conical surface to each point or line. It computes the density of features within a neighborhood, and scales based on the distance from event points to draw a heat map of the spatial distribution. Preliminary research indicates that the choice of bandwidth

(h) has a greater impact on KDE calculations compared to the choice of K [30]. The formula for calculating KDE is as follows:

$$f_n(x) = \frac{1}{nh} \sum_{t=1}^n K\left(\frac{x-x_1}{h}\right) \quad (1)$$

Spatial Autocorrelation: Moran's I test is applied to assess whether high-crash areas are spatially clustered or randomly distributed. Moran's I is a statistical tool that measures the spatial dependence of the accident location. MI also evaluates if the spatial pattern clusters are dispersed or random and also determines the level of concentration. This tool provides a single value of the spatial correlation and checking the clustering of the spatial pattern. Heavy locations of the proximity between the two points are often defined as the inverse of the distance between them. The attribute similarity severity index of two points is defined as the difference between each value and the value of the global average [31].

Hotspot Analysis (Getis-Ord Gi): Helps identify statistically significant clusters of high crash density, providing confidence in hotspot detection. This deepens the knowledge about the processes that lead to spatial dependency and improve the detection of local 'pockets' dependence that may not appear when using global statistics. The Getis-Ord statistic is used to identify hot spots of traffic accidents. A high value of the Getis-Ord statistic represents a group of high index value (hot spots), while a low value represents a low value of the index group. The hot spot analysis calculates Getis-Ord statistic for each feature in the data set [32].

The integration of these tools into crash analysis enhances decision-making processes, allowing authorities to allocate resources more effectively.

2.5.3 Applications in developing countries

In developing countries, where road infrastructure and enforcement mechanisms are often limited, spatial analysis becomes even more valuable. Urban environments in Sub-Saharan Africa, for instance, face unique challenges such as unregulated intersections, high pedestrian volumes, and poorly maintained roads. Several studies in Kenya, Ghana, and Nigeria have used GIS-based approaches to identify pedestrian crash hotspots and develop localized safety interventions [22].

In a study conducted in Accra, Ghana, researchers employed KDE and spatial regression techniques to examine the relationship between pedestrian crashes and proximity to schools, markets, and public transport stops. The findings revealed significant spatial clustering around bus terminals and informal markets, suggesting the need for targeted infrastructure

improvements [33]. Similarly, in Nairobi, Kenya, spatial mapping of crash data helped local authorities implement speed reduction zones in high-risk corridors [34].

Despite the increasing use of spatial methods in African countries, many cities still lack reliable and geo-referenced crash data. This data limitation hampers the ability of transport planners to design evidence-based interventions. In Rwanda, for instance, although national crash data are collected by the police, local-level spatial analysis remains underutilized, especially in secondary cities like Musanze.

2.5.4 Advantages of GIS-based road safety analysis

The main advantage of using GIS for traffic safety lies in its capacity to combine crash data with various spatial layers such as land use, road classification, traffic volume, and socio-economic variables. This integration facilitates a holistic understanding of road safety and the factors influencing crash risks [35]. Moreover, spatial analysis supports the monitoring and evaluation of safety interventions over time by visualizing changes in crash patterns.

Another strength is the ability to engage stakeholders through map-based communication. Local governments and urban planners can use visualizations to support funding proposals, community outreach, and public education campaigns.

Spatial analysis is an essential component of modern road safety research, enabling the identification of high-risk areas and supporting data-driven interventions. While developed countries have advanced in integrating spatial analytics into traffic management systems, many African cities including Musanze lack local-level spatial studies of road traffic crashes. This research seeks to address that gap by applying GIS and spatial statistical tools to analyze VRU-related crashes in Musanze City, thereby supporting urban transport planning and safety initiatives in Rwanda.

2.6 Socio-demographic influences on traffic crashes

2.6.1 Income and poverty

Globally, studies have consistently shown that low-income populations are disproportionately affected by road traffic injuries. According to the WHO [2], 92% of the world's fatalities on the roads occur in low- and middle-income countries, even though these countries have around 60% of the world's vehicles. More than half of all road traffic deaths are among vulnerable road users, including pedestrians, cyclists and motorcyclists.

Low- and Middle-Income Countries (LMICs) have greater variety and intensity of traffic, mixing the slow moving and vulnerable non-motorized road users, and motorcycles with

fast-moving motorized vehicles compared to high-income countries. Fatalities amongst VRUs are higher in LMICs due to lack of resources to provide or maintain adequately safe infrastructure, land use planning problems and lack or inadequacy of post-crash response services as well as unsafe users' behavior due to a lack of proper training and education [25].

2.6.2 Age and road traffic crashes

Children in Africa face significant risks as pedestrians, especially in urban areas lacking adequate infrastructure such as pedestrian crossings and sidewalks. Tulu *et al.* [20] found that pedestrian injuries among children remain alarmingly high due to limited safe routes to school and high vehicle speeds in residential areas. The lack of child-centered traffic policies and safe school zones exacerbates their vulnerability.

Young adults, particularly those aged 15–29, represent a high-risk group for RTIs. Globally, this age group accounts for nearly half of all road traffic deaths [1]. In Kenya,[17] Tulu *et al.* [20] , highlighted that men aged 20–49 are involved in up to 70% of RTI cases, with younger individuals more prone to motorcycle-related injuries due to risky behaviors. In Uganda, individuals aged 18–35 were the most affected demographic, with pedestrians and motorcyclists constituting the majority of victims [26].

The reasons for this variable crash involvement across age groups may be due to unique characteristics within each group. A combination of immature brain development, inexperience and greater prevalence of risky driving behaviours could contribute to the heightened crash involvement for the younger age group [14].

Moreover, the road traffic is associated by the mobility of different age groups. Studies shows that workers below the age of 30 are considered to be healthier and more mobile than those above 30. Workers above the age of 30 become leaders of their families and attain key positions in their organizations. Moreover, their productivity increases till the age of 50. When the age group and RTC data have been compared, it was found that 55 percent of road traffic crash victims were between the ages of 25 and 65, while the remaining 45 percent of RTC victims were between the ages of 16 and 24 [17].

2.6.3 Urban density and land use

The relationship between land use and traffic crashes is apparent since different land use tends to attract and generate different types of trips. Trip making behavior is a crucial predictor variable for determining the nature and volume of traffic. Although several previous studies have reported that traffic violations and crashes are closely related to

characteristics of drivers and travel behavior, yet it is rational to assume that they are likely to increase as the land use intensifies [36]. Earlier studies have proposed different methods to explore spatio-temporal variations of crashes.

A study conducted by Xie *et al.* [29] showed that urban residential, business and commercial, and mixed residential-commercial land uses had the highest risk of exposure to severe crashes. Mukherjee and Mitra [12] utilized a negative binomial model to explore the impact of land use characteristics on zonal risk estimation and found that urban residential land use and mixed areas were highly correlated with crash frequencies. It was concluded that commercial areas were more hazardous based on average crash counts and as well as injury severity. The authors noted that they are inversely related with high densities of sidewalks, high proportions of steep gradients, high proportions of industrial land use and employment, areas with lower average speed limits, and lower number of bus stops. This study further demonstrated that local characteristics such as land use and urban population densities do have noticeable effects on traffic crashes.

Moreover, a research by Rahman *et al.*, [37] examined hotspots of traffic collisions and their spatial relationships with land use in Dammam City of Saudi Arabia revealed that Fatal and Injury (FI) crashes were mostly located in residential neighborhoods and near public facilities having low to medium population densities on highways with relatively higher speed limits.

2.6.4 Relationship between gender and RTCs

Transport is one of several sectors that have traditionally been regarded as no place for women. In many many countries, this may still be the case today. While gender issues have been considered in a number of policy areas, little progress has been made in the transport sector. The transport sector remains male-dominated; few women are employed in the sector except in travel service occupations (e.g. as travel agents). The great majority of transport drivers and operatives are male, as are those employed in vehicle trades (e.g. as car mechanics) [38].

Males, therefore, have a higher exposure to the risk of traffic injuries. Mortality and morbidity rates are higher for males compared to females which reflects the global picture. The most common reasons lying behind those differences are related to differences in levels of exposures, with men being on the road to a far greater extent than women, and in road safety behaviours, with men being far more inclined to take risks/adopt risky behavior than women. Differences in exposures between men and women find an explanation in regional

legislations and practice. Women driving in Saudi Arabia is not against the law since September 2017 but they still need power of attorney from a male relative to acquire a car; in other countries women are prohibited from driving by their families [39].

2.7 Research gaps

2.7.1 Limited localized studies on VRUs in Secondary Cities

While substantial research on vulnerable road users (VRUs) exists for major African cities like Kigali, Nairobi, and Lagos, secondary cities such as Musanze remain underrepresented in scholarly discussions. The African Development Bank [22] emphasizes that secondary cities are experiencing rapid urbanization, which leads to increased traffic complexity and heightened risks for VRUs. However, empirical studies focusing on these emerging urban centers are scarce.

For instance, Nkurunziza *et al.* [40] conducted an assessment of road safety parameters in Kigali, highlighting the city's unique challenges but leaving a gap in understanding for other Rwandan cities like Musanze. Similarly, Patel *et al.* [10] analyzed road traffic injury hotspots in Kigali using police data, providing valuable insights yet not extending their study to secondary cities. This lack of localized research limits the development of targeted interventions and policies tailored to the specific needs of VRUs in rapidly growing urban areas like Musanze.

2.7.2 Insufficient use of GIS for crash hotspot analysis on vulnerable road users

Geographic Information Systems (GIS) have proven effective in identifying traffic crash hotspots; however, their application in Rwanda remains limited. Nkurunziza *et al.* [40] assessed road safety parameters in Kigali. Road traffic crash experience among commercial motorcyclists in Kigali, Rwanda. Neither researchers did incorporate GIS tools in his studies, highlighting a broader trend of underutilization of spatial analysis in Rwandan road safety research. This deficiency hampers the ability of policymakers to identify and address RTC hotspot areas effectively.

2.7.3 Inadequate assessment of infrastructure and design factors

There is minimal research evaluating how infrastructure provisions such as sidewalks, crossings, lighting, and signage influence the safety of VRUs in Rwanda. Most studies focus on crash statistics without integrating physical road design features. Gatesi [41] analyzed time series and forecasting of road traffic crashes in Rwanda, this study does not highlight the risk environment for pedestrians, cyclists, and motorcyclists.

Additionally, a study by Wasike *et al.* [23] emphasized the importance of explainable, automated urban interventions to improve pedestrian and vehicle safety, suggesting that integrating infrastructure assessments with technological tools can enhance VRU safety. However, the application of such integrated approaches remains limited in Rwandan Secondary Cities including Musanze.

2.7.4 Limited data-driven recommendations for urban road design

Many road safety policies in Rwanda and other low- and middle-income countries are not strongly grounded in local crash data and spatial analysis. There is a significant need for studies that generate context-specific design and policy recommendations based on spatial evidence and community-level data, especially for vulnerable groups. The absence of localized data hampers the development of targeted interventions that address the unique challenges faced by VRUs in urban settings like Musanze [41].

2.7.5 Underrepresentation of vulnerable groups in planning

VRUs such as children, the elderly, and persons with disabilities are often underrepresented in road safety studies and infrastructure planning. There is a lack of targeted analysis investigating how these groups are affected by urban road design and where their risks are spatially concentrated. Studies have emphasized the need for inclusive transport planning that considers the specific mobility challenges of disadvantaged groups to ensure equitable access and safety [42]. In Musanze, the absence of such inclusive, disaggregated analysis limits the effectiveness of road safety interventions for these high-risk groups.

Furthermore, Mohan *et al.* [39] highlight the emerging potential of mobile technologies, such as vehicle-to-everything (V2X) communication systems, to improve VRU safety. These innovations could offer promising solutions if adapted appropriately. However, their success depends on the deliberate integration of vulnerable groups into transport planning processes an aspect currently lacking in Musanze.

CHAPTER THREE: METHODOLOGY

3.0 Overview

This chapter presents the research design, methodology, data collection protocols, sample size, data analysis techniques, and anticipated outcomes to address the study titled “Spatial Analysis of Road Traffic Crashes Involving Vulnerable Road Users in Musanze City.” The study adopts a mixed-methods approach to integrate quantitative spatial analyses with qualitative assessments, ensuring a comprehensive examination of the factors contributing to vulnerable road user (VRU) crashes in Musanze City.

3.1 Study area

Musanze City, located in the Northern Province of Rwanda, is one of the country’s fastest-growing secondary cities. It serves as the capital of Musanze District and is a key economic and tourism hub due to its proximity to the Volcanoes National Park, a renowned mountain gorilla habitat. The city is positioned at approximately 1°30' South latitude and 29°37' East longitude, covering an estimated area of 530 km², with an urban core that has experienced rapid expansion in recent years. According to the 2022 NISR Census, Musanze District has 431,776 residents [43].

The Musanze road network consists of approximately 110.1 kilometers of asphalt roads, providing essential connectivity within the district and beyond. This includes National roads, district roads, and urban roads. These roads form the primary arteries supporting both motorized and non-motorized traffic, accommodating a diverse mix of vehicles, including private cars, public transport, motorcycles, cyclists, and pedestrians.

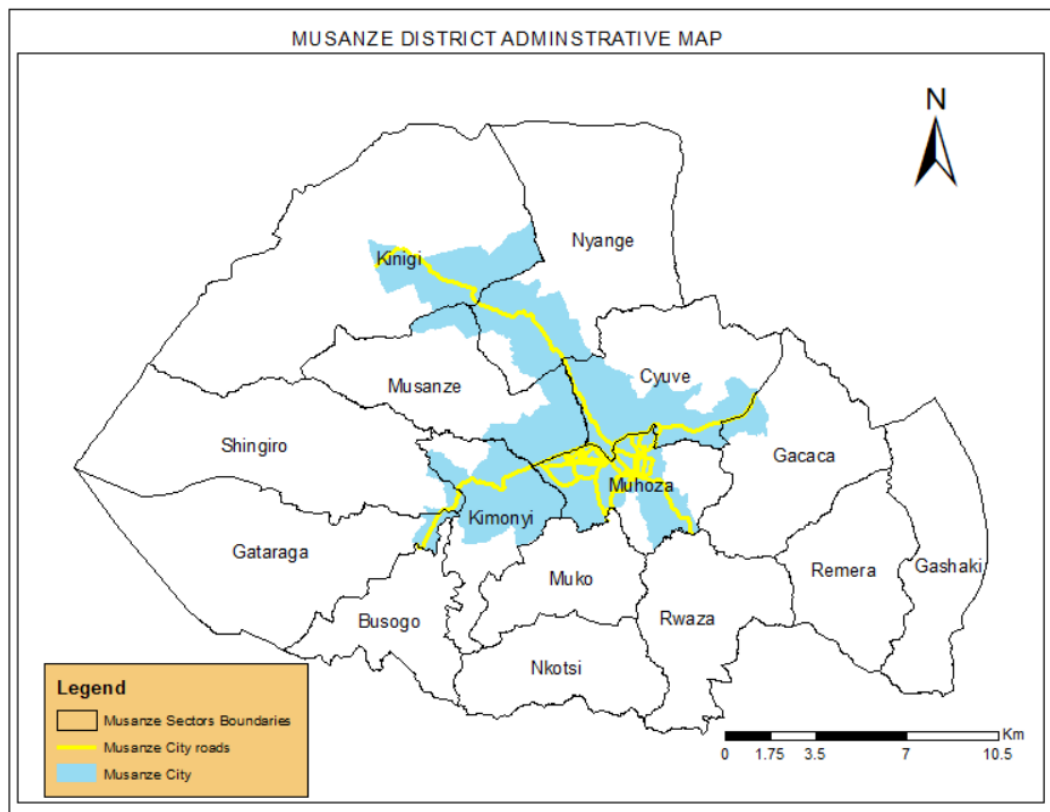


Figure 3-1: Musanze District Administrative Map (Source: ArcMap 10)

Due to the valley setting, traffic converges into and through the city’s central road corridors, amplifying congestion risks and creating critical interaction points between vehicles and vulnerable road users (VRUs) such as pedestrians, cyclists, and motorcyclists. The city’s urban landscape includes a dense mix of markets, schools, bus terminals, and residential areas, which contribute to elevated pedestrian activity. Despite rapid urban growth, the road infrastructure has not fully adapted to the increasing traffic complexity, with deficiencies such as limited sidewalks, inadequate crossing facilities, and insufficient road lighting persisting in many sections. Major corridors link Musanze to Kigali, Rubavu, Cyanika Border, and other regional centers, making it a critical transit node for northern Rwanda.

The district’s demographic profile reveals a youthful and mobile population, with motorcycles serving as a key mode of transport for young adults, while children and elderly pedestrians frequently navigate high-risk road environments. Understanding the spatial patterns of road traffic crashes and the relationship between crash occurrences and road characteristics within this specific urban area is essential for developing targeted road safety interventions that protect VRUs and improve overall traffic safety.

3.2 Research design

This study adopted a mixed-methods design combining quantitative and qualitative approaches. Quantitative analysis was used for spatial crash pattern identification and statistical modelling, while qualitative methods captured perceptions and experiences of road users regarding safety issues.

The descriptive component of the study focused on mapping and quantifying the distribution of VRU crashes using secondary crash data and Geographic Information Systems (GIS). Through spatial analysis, the study identifies crash hotspots and examines the correlation between crash locations and road infrastructure features. This helps to address the first and second objectives of the study, identifying the spatial distribution of VRU crashes and assessing the road parameters associated with these incidents.

The analytical component explores the perceptions of VRUs regarding road safety, drawing on primary data collected through structured interviews and field observations. This qualitative aspect enables the researcher to assess road safety issues from the user perspective and identify behavioral, infrastructural, and environmental factors that may contribute to crash risk. This part of the research addresses the third objective assessing road safety challenges as experienced by VRUs.

By integrating both descriptive spatial analysis and thematic interpretation of qualitative data, the research design enables the study to go beyond the statistical presentation of crash data and examine the lived experiences of road users. This approach facilitates a more nuanced and actionable understanding of VRU safety in an urban context like Musanze City.

3.3 Sources of data and data collection

To achieve the research objectives, the study relied on both primary and secondary data sources through the following methods:

3.3.1 Observation

Field observation was a central tool to verify spatial and environmental features contributing to VRU crash risks. This included site visits to known crash-prone areas to document road design elements (such as crossings, sidewalks, signage, lighting, road width, and traffic flow). By observing and recording real-world conditions, the researcher validated data obtained from crash reports and interviews, ensuring an accurate representation of the existing safety environment for VRUs.

3.3.2 Interviews

Semi-structured interviews were conducted with purposively selected participants, including VRUs (pedestrians, cyclists, motorcyclists), local community leaders, traffic police officers, and district planners. These interviews explored perceptions of road safety, challenges faced by vulnerable users, and suggestions for improving safety. The use of semi-structured interviews allows flexibility to probe deeper into issues raised by respondents, while still ensuring that core research topics aligned with the objectives are covered.

3.3.3 Spatial modeling

Road network shapefiles, land use maps, and administrative boundaries were sourced from the Musanze District office. This was processed using ArcGIS 10.8. Spatial analysis techniques, including Kernel Density Estimation and crash hotspot mapping were employed to identify patterns and spatial relationships between road parameters and VRU crash concentrations. The integration of spatial datasets will allow for detailed geographic analysis that reveals where high-risk areas are located and which road design factors are most influential.

3.3.4 Documentation

Data on road traffic crashes from 2021 to 2024 were collected from the Rwanda National Police, Traffic Department. This data included crash locations, dates, types, severity levels, and the VRU categories involved.

Moreover, secondary data were collected from relevant academic studies, policy documents, government reports, district planning documents, and international road safety guidelines. This documentation provided essential background information, theoretical framing, and comparative insights to ground the research findings and guide recommendations.

3.4 Target population and sampling procedures

3.4.1 Target population

According to the 2022 Rwanda National Institute of Statistics (NISR) census, Musanze District has a total population of approximately 431,776 people, out of which an estimated 94,337 residents live within Musanze City, the primary study area for this research. Given the focus on vulnerable road users (VRUs), specifically pedestrians, cyclists, and motorcyclists, the sample was drawn from this urban population.

3.4.2 Sample size determination

To estimate an appropriate number of respondents for the questionnaire survey, Yamane's formula was applied for finite population sampling [44].

$$n = \frac{N}{1 + N(e^2)} \quad (2)$$

Where, N: Total Musanze City population N=94,337 residents (NISR, 2022 Census)

Confidence level = 95%

Margin of error e=0.05

$$n = \frac{94,337}{1 + 94,337(0.05^2)} = 398 \text{ respondents}$$

Based on this calculation, a total of 398 VRUs were targeted for the survey. These were proportionally distributed among the three key categories of VRUs to ensure balanced representation, as detailed in Table 3.1.

Table 3-1: Sample distribution across VRU groups

VRU Category	Sample Size (n)	Percentage (%)
Pedestrians	199	50%
Motorcyclists	119	30%
Cyclists	80	20%
Total	398	100%

Source: Researcher compilation (2025)

3.4.3 Sampling technique

In line with the study's mixed-methods design, a purposive sampling technique was adopted to recruit participants and select observation sites. This approach was preferred due to its suitability for research requiring detailed input from information-rich cases, particularly in exploratory and context-sensitive studies such as road safety assessments.

For Objective 1 of identifying spatial patterns of VRU crashes and Objective 2 of analyzing the relationship between road parameters and crash concentration, purposive sampling was used to select crash locations, road segments, and administrative zones within Musanze City that show varying crash densities and VRU involvement, based on available police reports and district planning report.

To assess the road safety issues faced by VRUs which is objective 3, purposive sampling was applied to select key informants and participants such as pedestrians, cyclists, and motorcyclists who possess firsthand knowledge of the road safety challenges VRUs face.

3.5 Data analysis techniques

To address the research objectives, the following analytical approaches were employed:

3.5.1 Kernel Density Estimation (KDE)

The Kernel Density Estimation (KDE) was used to visualize the density and distribution of VRU crashes. The Kernel Density Estimator created a point density map of RTC locations utilizing the Kernel Density Estimator tool in ArcMap 10.8. The Kernel estimator generates a density raster by counting the number of points in a region of interest and producing a density map that accounts for the frequency of points and the distance of each point to the region. This helped to identify spatial patterns of road traffic crashes involving Vulnerable Road Users in Musanze City

3.5.2 Getis-Ord Gi Hotspot Analysis

Getis-Ord Gi Hotspot Analysis is a spatial statistical method which identifies statistically significant clusters of high or low crash concentration (hotspots and cold spots), allowing the study to pinpoint priority zones for intervention. Therefore, the VRUs road traffic crash density raster was layered over the map of Musanze City, national and district roads, and local urban road networks.

Thus, this process enabled the production of detailed maps identifying high-risk zones and crash concentration points, providing crucial spatial evidence for targeted safety interventions.

3.5.4 Thematic analysis

Thematic analysis was used in this study to analyse qualitative data collected from open-ended survey questions and field observations related to the experiences and perceptions of vulnerable road users (VRUs) in Musanze City. This method is appropriate because it allows for the systematic identification of recurring themes and patterns in respondents' views about road safety, infrastructure, and risk factors.

The primary objective of applying thematic analysis in this context was to address the third research objective: To assess road safety issues faced by VRUs from the road user perspective in Musanze City.

Moreover, to assess the relationship between certain road parameters and the spatial concentration of VRUs crashes in Musanze City. At each identified hotspot from objective 1, structured field observations were conducted using a standardized observational checklist annexed in Appendix 1. This checklist includes the presence or absence of the following road parameters including road type, width, surface condition, and the presence of pedestrian

infrastructure, presence of the intersection, road geometric features such as curves and gradients, and signage. Primary data resulted from field surveys conducted along major roads and intersections in Musanze City.

3.5.5 Statistical techniques

A qualitative approach employed through surveys and interviews. Structured interviews were administered to a representative sample of VRUs, including pedestrians, cyclists, and motorcyclists, across Musanze City. The interview guided findings annexed in Appendix 2 and it was analyzed using SPSS version 25. This was done to assess road safety issues faced by VRUs from the road user perspective in Musanze City. The survey covered perceptions of road safety, risky locations, common hazards, and suggestions for improvements.

3.6 Tools and software to be used

The study employed a range of analytical tools. ArcGIS 10.8 was used for spatial mapping and hotspot detection. SPSS version 25 was utilized for statistical analysis. Google Earth Pro and handheld GPS devices will aid in field verification and ground-truthing of crash locations and infrastructure.

3.7 Ethical consideration

Ethical approval was sought from relevant authorities, including the Rwanda National Police and Musanze District Administration. Permissions were obtained to access crash databases and conduct field observations. During data collection, informed consent was obtained from all interview participants, and all information were anonymized to ensure confidentiality. The research data will be securely stored and used strictly for academic purposes.

3.8 Limitations of the methodology

While the methodology is designed to yield reliable results, certain limitations are anticipated. Some crash data may be incomplete or lack precise location coordinates, which could affect spatial accuracy. Moreover, unreported or informal crash incidents may not be captured in official records. Despite these challenges, the integration of multiple data sources and analysis methods helped in minimizing biases and enhancing the validity of the study findings.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the spatial and statistical analyses conducted to achieve the objectives of the study titled "*Spatial Analysis of Road Traffic Crashes Involving Vulnerable Road Users in Musanze City, Rwanda.*" The analyses are based on spatial crash data, road network attributes, and survey responses from vulnerable road users (VRUs), including pedestrians, cyclists, and motorcyclists. The chapter interprets the findings in light of the general and specific objectives outlined in Chapter One. Maps, charts, statistical outputs, and qualitative summaries are integrated to illustrate the patterns, relationships, and perceptions uncovered through the research.

4.2 Identification of spatial patterns and distributions of road traffic crashes involving Vulnerable Road Users

In order to identify spatial patterns and distributions of road traffic crashes involving vulnerable road users in Musanze City road network, two GIS-based spatial analysis techniques were applied: **Kernel Density Estimation (KDE)** and **Getis-Ord G_i^*** hotspot analysis. These tools allowed the identification of VRU crash-prone zones within Musanze City from 2021 to 2024, using data obtained from the Rwanda National Police and road network attributes in Musanze City.

4.2.1 Kernel Density Estimation (KDE) Analysis

The Kernel Density Estimation analysis was employed to generate a crash density surface based on the spatial distribution of 348 crash points involving vulnerable road users (pedestrians, cyclists, and motorcyclists). The KDE method revealed clusters where VRU crashes are most concentrated, providing a visual heatmap of crash-prone areas across Musanze City.

The highest crash densities (represented in red shades) were found in areas with mixed road usage by vehicles and VRUs, high pedestrian flow without proper crossing facilities, intersections, sharp curves, and high gradients. These zones represent areas where VRUs are more exposed to crash risks due to mixed traffic flows, inadequate pedestrian facilities, and high vehicular speeds.

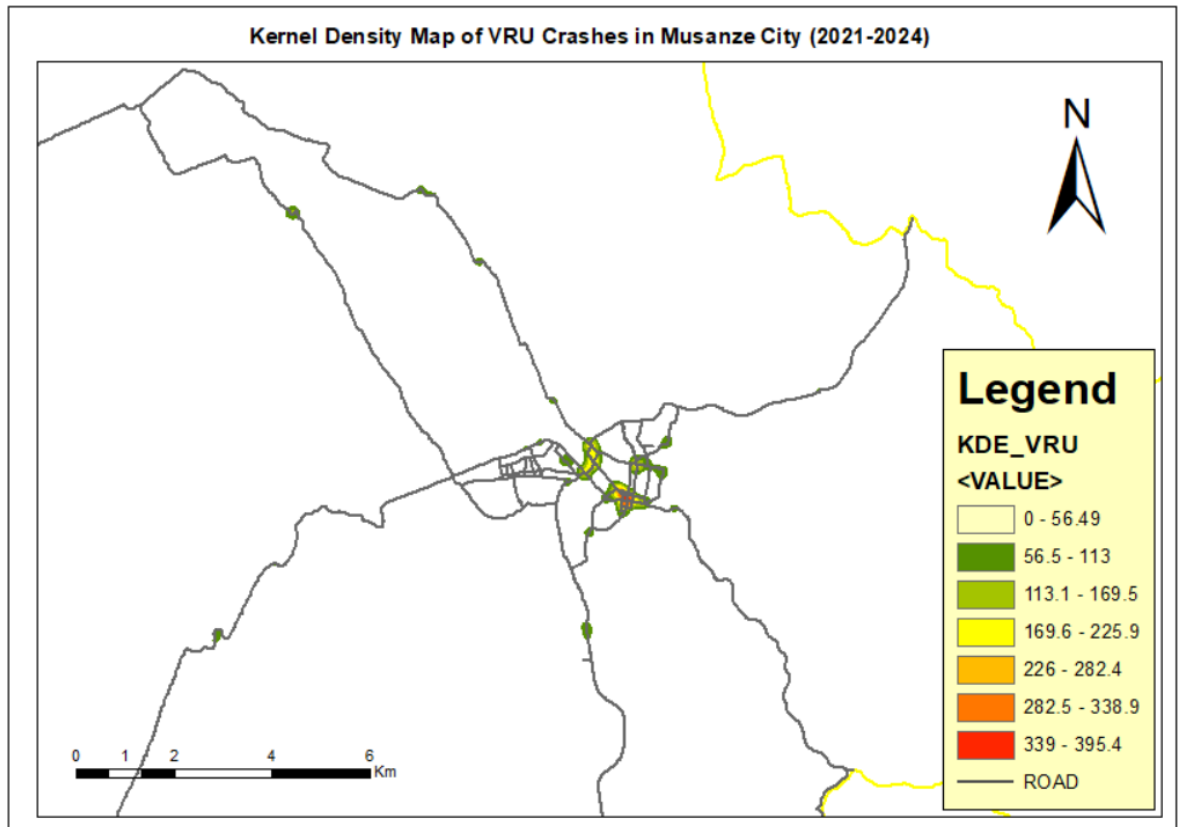


Figure 4-1: VRU Crashes KDE heatmap in Musanze City

4.1.2 Hotspot analysis using Getis-Ord G_i^*

To validate the KDE findings statistically, the Getis-Ord G_i^* (G^*) hotspot analysis was performed. This spatial statistical method identifies statistically significant clusters (hotspots and cold spots) of crash incidents based on spatial proximity and intensity.

The analysis was conducted separately for each VRU type, which includes motorcyclists, pedestrians, and bicyclists, providing mode-specific insights into crash-prone locations. A fixed distance band of 750 meters was used to define neighborhood influence, and crash points were categorized into confidence levels of 90%, 95%, and 99% for both hotspots and cold spots. The approach enables a nuanced understanding of how different types of road users experience spatial risk, addressing the first objective of this study.

a) Motorcycle crash hotspots

The spatial distribution of motorcycle crashes shows strong clustering within the urban core of Musanze District, with several locations identified as hotspots at 99%, 95%, and 90% confidence levels. These areas correspond to high-traffic intersections, commercial centers, and road segments with frequent interactions between vehicles, pedestrians, and motorcyclists as it is illustrated in fig. 4.2.

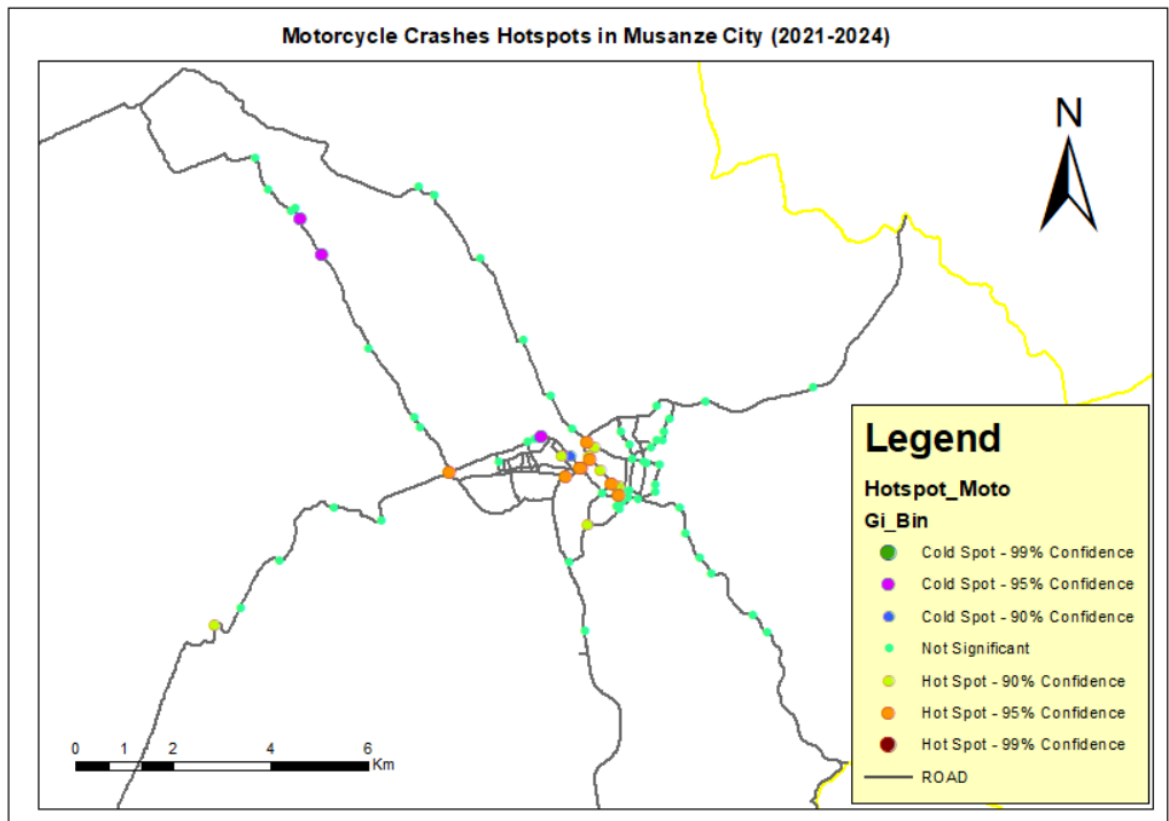


Figure 4-2: Motorcycle crashes hotspots in Musanze City (2021–2024)

The density of activity, lack of dedicated infrastructure, and complex traffic behavior in these zones likely contribute to the elevated crash risk. Cold spots are mainly located in peripheral areas reflecting zones with fewer interactions, confirming the influence of traffic exposure levels on crash frequency [33].

b) Pedestrian crash hotspots

Compared to motorcycles, pedestrian crash hotspots as shown in the fig. 4.3. were fewer and more spread out, mostly found within the city center, along areas near bus stops, school zones, markets, and commercial crossings. These areas showed clustering at 90% and 95% confidence levels, with cold spots mainly in the outer road network.

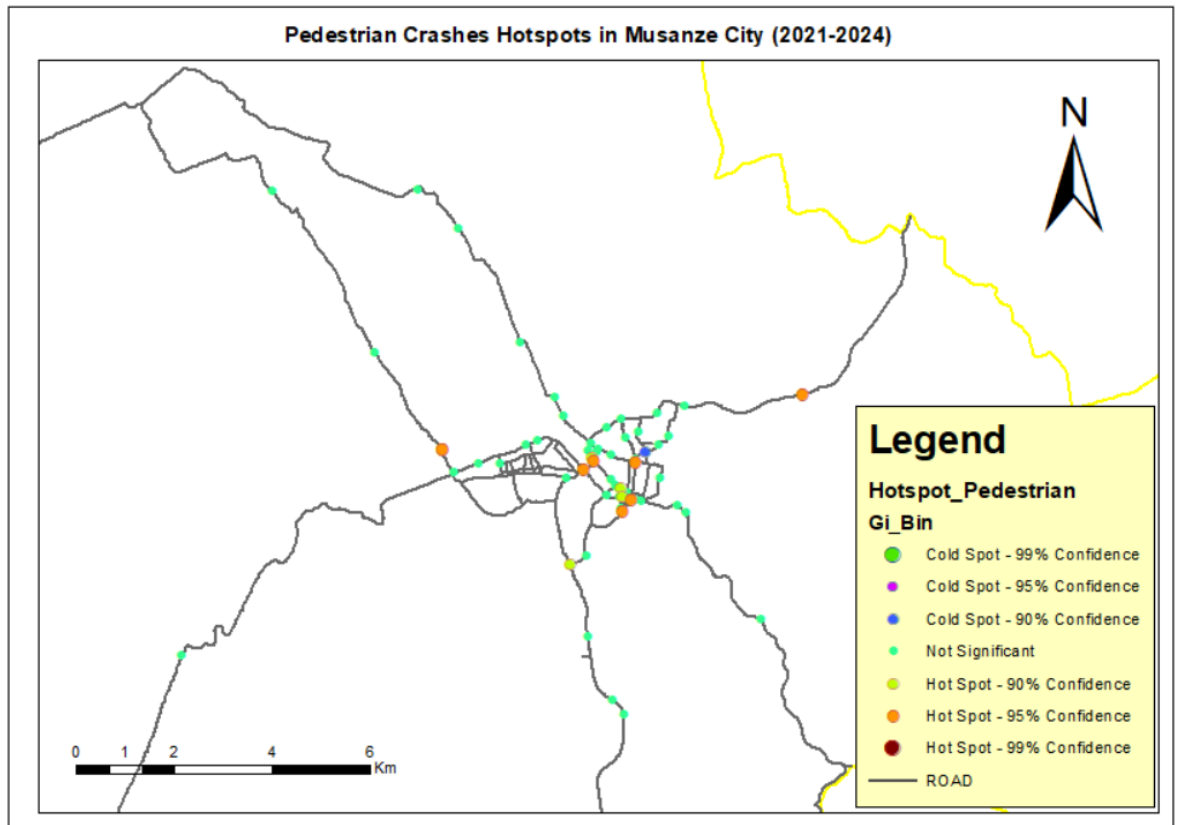


Figure 4-3: Pedestrian crashes hotspots in Musanze City (2021–2024)
Source: Researcher, ArcMap

This spatial pattern highlights the vulnerability of pedestrians in activity dense zones with inadequate infrastructure, consistent with studies by [35]. Non-significant clusters suggest varying levels of infrastructure quality across similar-use areas.

c) Bicycle crash hotspots

The distribution of bicycle crashes reveals a less concentrated but still significant clustering of incidents. Hotspots at 90% and 95% confidence levels were observed both within and outside the city center particularly to the south and northeast indicating commuter or goods transport cycling along key road corridors as shown in the fig 4.4.

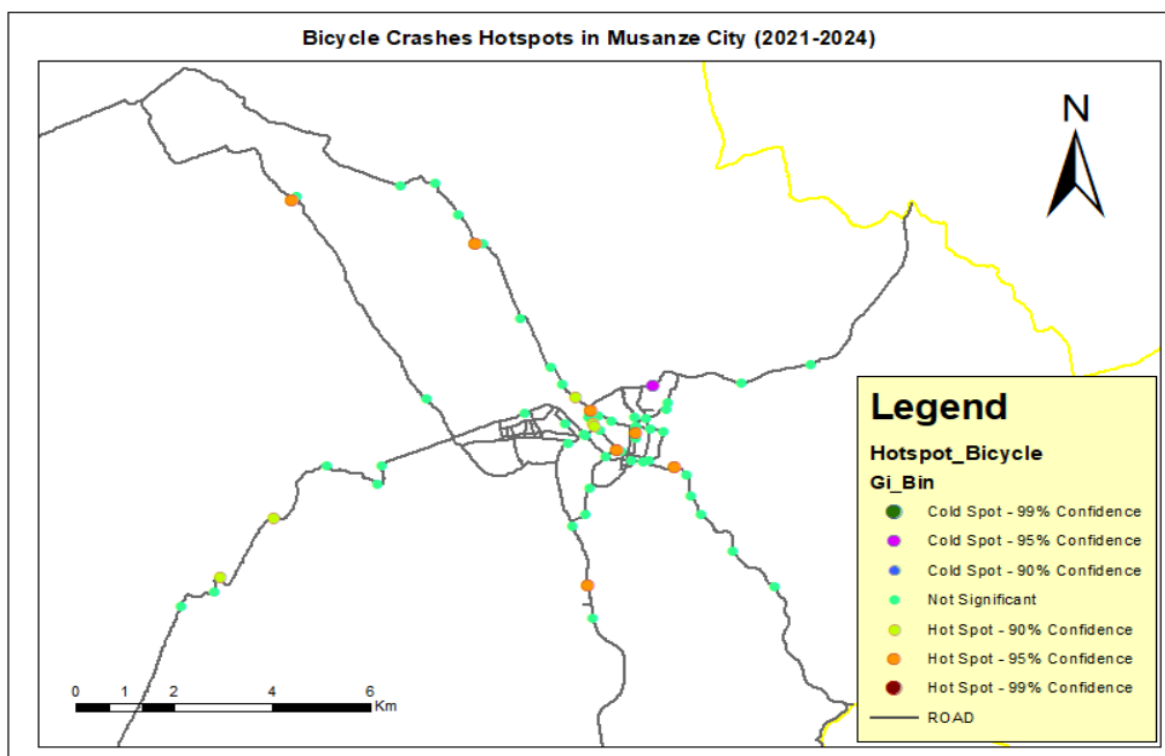


Figure 4-4: Bicycle crashes Hotspots in Musanze City (2021–2024)

These findings align with studies by Wasike *et al.* [23], who argue that cycling risk is elevated where cyclists must share road space with motorized traffic in the absence of designated cycling infrastructure. Cold spots in rural roads suggest safer travel corridors where traffic interaction is reduced.

4.3 Road parameters associated with crash hotspots in Musanze City

Following the spatial clustering results from the Getis-Ord G_i^* analysis, this section investigates which road parameters are most prevalent in the identified VRU crash hotspots. By isolating only the locations within statistically significant hotspots, the analysis focuses on the road parameters most strongly associated with crash concentration.

Based on the methodology described in Chapter Three, the identified VRU crash hotspots in Musanze City were ranked using a severity-weighted scoring system. This approach allowed each hotspot location to be evaluated not only by the frequency of crashes but also by the intensity of impact, with higher weights assigned to fatal and serious injury crashes.

4.3.1 Interpretation of motorcycle crash concentration in relation to road parameters

The spatial concentration of motorcycle crashes in Musanze City reveals a strong association with specific road parameters particularly intersection type and gradient. Table 4.1 presents three key hotspots where motorcycle crashes are most prevalent, highlighting attributes such as crash count, intersection form, road curvature, and slope gradient.

Table 4-1: Motorcycle crash hotspots and associated road parameters

Hotspot Location	KALISIMBI	AMICUS	BNR intersection
Rank	1	2	3
Road name	KIGALI-MUSANZE-RUBAVU (NR2)	KIGALI-MUSANZE-RUBAVU (NR2)	KIGALI-MUSANZE-RUBAVU (NR2)
Crash count	20	18	17
Fatal	4	2	2
Serious	8	9	6
Minor	8	7	9
Hotspot score	36	31	27
Intersection type	4 legged junction	4 legged junction	Double T junction
Curve type	Straight	Straight	No
Gradient	Gentle	Gentle	Gentle
Road sections characteristic	Straight-with a zebra crossing near school zone	Straight-with a zebra crossing market and bus park	Busy intersection

a) Intersection type and crash frequency

From the Getis sord G hotspots analysis, the top three motorcycle crash hotspots are located at intersections specifically 4-legged, T-junctions, and double T-junctions. These configurations inherently involve complex traffic interactions, including turning, merging, and crossing movements, which increase the likelihood of vehicle conflicts. According to Al-Omari & Al-Masaeid [45], junctions with multiple arms (such as four-leg intersections) exhibit significantly higher crash rates, especially for motorcycles that have reduced visibility and stability.

In the case of Kalisimbi (a 4-legged junction), the combination of high traffic volume, high number of pedestrians in this school zone and uncontrolled movements likely contributes to the elevated crash score (44). Similarly, the BNR intersection a double T-junction facilitates irregular entry and exit patterns, a condition that, as Peden *et al.* [33] observed in Ghanaian urban roads, often results in high crash involvement of powered two-wheelers.

b) Curve type: straight segments and speed risk

Interestingly, all identified hotspots lack curves, indicating that crashes occur predominantly on straight road segments. While curves often contribute to crashes due to visibility or control issues, straight road segments may give motorcyclists a false sense of safety,

prompting overspeeding or underestimation of intersection risk. This is supported by Nickenig [46], who noted that crashes involving motorcycles frequently occur on straight roads near intersections due to excessive approach speed and misjudgment by other road users.

c) Gradient influence on motorcycle crash risk

While none of the hotspots were located on steep slopes, two occurred on gentle gradients, and one on a moderate gradient. This suggests that while gradient is not the primary crash determinant, even minor slopes can influence crash risk for motorcycles. As motorcycles are more sensitive to balance, gradient affects maneuverability and braking, especially in emergency situations. Zhang *et al.* [47] highlight that motorcyclists are vulnerable to even minor gradient-induced instabilities when navigating urban intersections.

4.3.2 Relationship between road parameters and spatial concentration of pedestrian crashes

Pedestrian crashes in Musanze City exhibit a pronounced spatial clustering around specific intersections on major arterial roads. Table 4.2 summarizes the top three crash-prone areas for pedestrians, together with their road attributes and severity levels.

Table 4-2: Pedestrian crash hotspots and associated road parameters

Hotspot Location	KALISIMBI	BNR intersection	GROUPEMEN T
Hotspot Score	44	40	26
Rank	1	2	3
ROAD NAME	KIGALI-MUSANZE-RUBAVU (NR2)	KIGALI-MUSANZE-RUBAVU (NR2)	GROUPEMENT-KABAYA
Crash Count	24	18	12
FATAL	5	6	4
SERIOUS	10	10	6
MINOR	9	2	2
Intersection type	4 legged junction	Double T junction	T-Junction
Curve type	No	No	No
Gradient	Gentle	Gentle	Moderate
ROAD SECTIONS CHARACTERISTICS	Straight-with a zebra crossing near school zone	High traffic volume	Moderate gradient and shortcut

a) Influence of intersection type

All pedestrian crash hotspots are located at major intersections, with two at 4-legged junctions and one at a double T-junction. Intersections inherently concentrate pedestrian-vehicle interactions, especially where pedestrian crossings intersect with multiple vehicle flows.

According to Tulu *et al.* [20], intersections particularly in urban settings are the most hazardous zones for pedestrians due to conflicting movements, lack of traffic control, and poor visibility. The Kalisimbi and Amicus intersections serve critical socio-economic functions (e.g., schools, markets, bus parks), increasing pedestrian traffic and exposure risk.

b) Road alignment and visibility

All hotspots were located on straight road sections, a factor that often contributes to increased vehicle speeds and reduced driver attention. While curved roads pose visibility issues, straight segments near intersections create a false perception of control, encouraging speeding and late braking particularly detrimental in pedestrian zones.

As African Development Bank [22] report, pedestrian crashes frequently occur on straight approaches to intersections due to drivers' failure to yield, especially in the absence of elevated pedestrian infrastructure.

c) Gradient effects

All hotspots occur on gentle gradients, suggesting that slope is not a significant contributing factor to pedestrian crashes in the urban core of Musanze. This finding is consistent with studies by Amo *et al.* [48], which noted that pedestrian crashes in East African cities are more influenced by land use and traffic volume than gradient.

4.3.3 Relationship between road parameters and spatial concentration of bicycle crashes

The distribution of bicycle crashes in Musanze City indicates strong correlations with road geometry, especially curve type and gradient. Table 4.3 below highlights three prominent hotspots where bicycle crashes are concentrated.

Table 4-3: Bicycle crash hotspots and associated road parameters

Hotspot Location	KABAYA	CYANTURO	GATARAGA
Rank	1	2	3
ROAD NAME	GROUPEMENT -KABAYA	INES-KINIGI	KIGALI-MUSANZE- RUBAVU (NR2)
Crash Count	18	13	14
FATAL	5	8	4
SERIOUS	7	5	6
MINOR	6	0	4
Hotspot Score	35	34	28
Intersection type	T-junction	No	No
Curve type	No	Sharp	Sharp
Gradient	Moderate	Moderate	Moderate
ROAD SECTIONS CHARACTERISTICS	Moderate gradient	Narrow road with curves, gradient	Moderate gradient with curves

a) Curve type and crash clustering

A significant factor in bicycle crash concentration is road curvature. Two out of three hotspots (Cyanturo and Gataraga) were located on sharp curves, while Kabaya was on a straight road section. Sharp curves are known to reduce visibility, affect maneuvering space, and increase lateral instability for bicycles, especially at moderate speeds. According to Wasike *et al.* [23], curvilinear roads are critical risk areas for cyclists due to sudden directional shifts, limited sight distance, and insufficient buffer zones between bicycles and motor vehicles.

These curved sections in Musanze are also characterized by limited width and lack of cycling lanes, compounding the risk of lateral conflicts with vehicles.

b) Gradient and bicycle crash risk

All three crash hotspots are found along moderate gradients. Slopes particularly when combined with curves increase the difficulty of controlling a bicycle, especially when descending. This is due to limited braking efficiency and rider instability. As Dozza & Werneke [49] explain, descending gradients increase kinetic energy, which shortens reaction time and makes it difficult for cyclists to avoid hazards.

The site at Cyanturo, noted for its narrow curved gradient, had the highest number of fatal crashes (8) among the three locations, reinforcing the danger posed by combined vertical and horizontal alignment challenges.

c) Intersection influence

Only Kabaya was reported at a T-junction, while the other two were in non-intersection segments. Although intersections are usually high-risk zones, the clustering of bicycle crashes in non-junction areas in this study suggests that geometry and spatial confinement not just conflict points are key determinants. According to Mukherjee and Mitra [12], crash risk for cyclists increases in areas of geometric complexity, especially if infrastructure does not provide dedicated cycling facilities or clear visual cues.

4.4 Road safety issues faced by VRUs from the road user perspective in Musanze City

This section covers the research findings aimed at assessing road safety issues faced by VRUs from the road user perspective in Musanze City.

4.4.1 Crashes involvement according to respondents' age in Musanze City

The table 4-4 below presents a cross-tabulation of respondents' involvement in crashes categorized by age group, showing the distribution of those who were personally involved, witnessed but not involved, or neither witnessed nor experienced a crash.

Table 4-4: Crashes involvement according to respondents' age

Age Group	Personally Involved	Not Involved (Witnessed)	Did Not Witness/Experience	Total
Under 18 years	7 (7.4%)	10 (6.1%)	17 (12.2%)	34 8.5%
18–25 years	32 (34.0%)	45 (27.3%)	35 (25.2%)	112 28.1%
26–35 years	22 (23.4%)	33 (20.0%)	42 (30.2%)	97 24.4%
36–45 years	18 (19.1%)	36 (21.8%)	24 (17.3%)	78 19.6%
46–55 years	10 (10.6%)	23 (14.0%)	15 (10.8%)	48 12.1%
Above 55 years	5 (5.3%)	18 (10.9%)	6 (4.3%)	29 7.3%
Total	94 (100%)	165 (100%)	139 (100%)	398 (100%)

Source: Primary data, 2025

The cross-tabulation reveals age-related patterns in crash involvement among vulnerable road users in Musanze City. Young adults aged 18–25 years are disproportionately represented among those personally involved in crashes (34.0%) and also among those who witnessed crashes (27.3%), reflecting their high mobility and frequent road use. Similarly, the 26–35 age group also shows considerable involvement (23.4%) and the highest share of those who did not witness or experience a crash (30.2%), suggesting diverse exposure levels within this cohort.

Interestingly, 36–45-year-olds make up nearly one-fifth (19.1%) of crash victims and a notable share (21.8%) of those who witnessed incidents, highlighting their continuous exposure as active commuters. The under-18 group, though smaller in size, still reports crash involvement (7.4%) and non-experience (12.2%), possibly due to school commutes on foot or bicycle. Older groups (46–55 and over 55) show lower crash involvement but are not exempt from risk, with combined contributions to involvement and witnessing accounting for over 20% of reported cases. This pattern suggests that while older road users may be more cautious or less exposed due to reduced mobility, they still encounter significant traffic risks.

This aligns with studies across Africa, where youth and young adults are frequently the most vulnerable due to high mobility and risk-taking behavior. For instance, research in Kenya and Cameroon found young road users have higher crash involvement linked to inexperience and exposure levels. The relatively lower involvement of older age groups complies with findings from South Africa, suggesting reduced exposure or more cautious behavior among older road users [14]. The implication is a need for targeted road safety education for young adults and infrastructure adaptations to protect this high-risk group.

This implies that younger and middle-aged adults are at the highest risk of crash involvement, underscoring the need for targeted road safety measures focused on these age groups, such as awareness campaigns, infrastructure enhancements, and improved road user training.

4.3.2 Use of designated road infrastructure in Musanze City

The table 4-5 below shows the frequency of designated road infrastructure usage by gender, highlighting how often male and female respondents report using such infrastructure.

Table 4-5: Use of designated road infrastructure

Gender	Always	Often	Sometimes	Never	Total
Male	66 (64.7%)	62 (64.6%)	83 (62.9%)	41 (60.3%)	252 (63.3%)
Female	36 (35.3%)	34 (35.4%)	49 (37.1%)	27 (39.7%)	146 (36.7%)
Total	102 (100%)	96 (100%)	132 (100%)	68 (100%)	398 (100%)

Source: Primary data, 2025

When analyzing column percentages, the gender distribution within each usage category becomes clearer. Across all frequency groups ("Always", "Often", "Sometimes", "Never"), males make up the majority, ranging from 60.3% to 64.7%, which is consistent with their overall representation (63.3%) in the sample. Conversely, females comprise between 35.3% and 39.7% of users in each category.

Interestingly, female respondents are slightly overrepresented in the “Never” category (39.7%) compared to their overall sample share (36.7%), suggesting that women may face slightly more barriers in accessing or using designated road infrastructure. Meanwhile, males consistently dominate the “Always” and “Often” categories, though not by large margins.

These findings align with recent African studies highlighting gender disparities in road infrastructure usage, often driven by safety concerns and sociocultural. For example, research in Ghana and Zimbabwe indicated women’s limited access to safe pedestrian facilities reduces their frequency of use, emphasizing the need for gender-responsive planning [38], [48]. This underscores the importance of inclusive design and safety measures that address female-specific constraints to ensure equitable access to road infrastructure.

This pattern indicates that while infrastructure usage frequency does not dramatically differ by gender, female users might experience more constraints; whether due to safety concerns, infrastructure gaps, or social factors; resulting in reduced regular usage. Therefore, gender-responsive transport planning is essential to ensure infrastructure designs are inclusive, equitable, and sensitive to the distinct challenges faced by both men and women.

4.4.3 Most frequently used areas/routes in Musanze City

The table 4-6 presents the specific areas or routes commonly used by pedestrians, cyclists, and motorcyclists in Musanze City. The data collected from respondents was thematically coded to identify the most frequently mentioned locations.

Table 4-6: Most frequently used areas/routes in Musanze City

Frequently Used Area/Route	Frequency	Percentage
Musanze–Rubavu Road (NR2)	86	21.6
Musanze-Cyanika Corridor	57	14.3
Goico Market-Gikwege roads	64	16.1
Stadium-Agri-market	51	12.8
Nyakinama-Musanze road	43	10.8
INES-KINIGI	32	8.0
Musanze-Kinigi Road	65	16.4
Total	398	100.0

Source: Primary data, 2025

From the research findings, it is evident that VRU movement in Musanze City is highly concentrated along key transport corridors. The Musanze–Rubavu Road (NR2) accounts for the highest usage at 21.6%, followed closely by the Musanze–Kinigi Road (16.4%) and Goico Market–Gikwege Roads (16.1%). These roads traverse areas with intense commercial, transport, and tourism-related activity, exposing VRUs to high interaction with motorized traffic. Similarly, the Musanze–Cyanika Corridor (14.3%) and Stadium–Agri-Market area (12.8%) represent congested urban centers with mixed land use and limited pedestrian infrastructure, while the Nyakinama–Musanze Road (10.8%) and INES–Kinigi Road (8.0%) are important for University students and commuter mobility.

These patterns align with findings by Osuret *et al.* [26], who identified VRU crash hotspots in urban roads with inadequate safety features, and Mohan *et al.* [39], who reported that tourism and market zones often experience high crash exposure due to unregulated pedestrian movement. Additionally, Ochieng and Kamau [34] emphasized that pedestrian risk is closely linked to land use intensity and road function. Therefore, the roads identified in this study should be prioritized for safety upgrades, including crosswalks, traffic calming measures, and improved pedestrian facilities.

4.4.4 Dangerous locations for Vulnerable Road Users (VRUs) in Musanze City

The table 4-7 below presents the most frequently mentioned dangerous locations for vulnerable road users (VRUs) in Musanze City, based on respondents’ experiences,

highlighting areas perceived as high-risk due to traffic volume, infrastructure conditions, and pedestrian safety challenges.

Table 4-7: Most frequently mentioned dangerous locations for VRUs

Location/Area	Frequency	Percentage
Kalisimbi	84	21.1
BNR intersection	69	17.3
Agacuri corridor	61	15.3
AMICUS	47	11.8
Rwebeya Bridge Zone	35	8.8
Karwasa Center	32	8.0
Musanze-Kinigi road	70	17.6
Total	398	100.0

Source: Primary data, 2025

The research highlighted Kalisimbi (21.1%) as the most frequently mentioned dangerous location for vulnerable road users (VRUs), followed by the BNR intersection (17.3%) and the Agacuri corridor (15.3%). These top-ranked zones are notable for their high traffic volumes in the intersections, poor designed pedestrian safety infrastructure, and frequent interactions between vehicles and VRUs. The Musanze–Kinigi Road, accounting for 17.6% of VRU usage, poses a considerable safety threat due to its narrow carriageway width of approximately 5.5 meters, which forces two-way vehicular traffic to operate within constrained space. This limited roadway width significantly reduces the margin for safe pedestrian and cyclist movement, increasing the risk of conflict between motorized vehicles and VRUs.

Other notable VRU activity zones include the Amicus Intersection (11.8%), Goico–Gikwege Roads (8.8%), and the Karwasa Center (8.0%), which are characterized by high levels of cycling activity primarily due to the flat terrain and significant pedestrian volumes. These areas typically function as commercial hubs, yet the absence of dedicated cycling infrastructure and limited enforcement of traffic regulations pose serious safety risks for both cyclists and pedestrians, who often share space with fast-moving vehicles without clear separation or protection.

These findings align with previous studies emphasizing the vulnerability of VRUs in urban environments lacking appropriate infrastructure. Osuret *et al.* [26] observed that intersections with high traffic volumes and inadequate pedestrian facilities are common hotspots for crashes. Similarly, Mohan *et al.*, [39] highlighted that narrow roads without designated non-motorized transport lanes significantly increase the risk for cyclists and pedestrians. The lack of enforcement and infrastructure in commercial zones as noted in this study. This also reflects findings by Ochieng and Kamau [34], who linked pedestrian safety challenges to poor urban design and mixed traffic conditions. Collectively, these studies support the conclusion that targeted safety interventions are essential in high-risk zones identified in Musanze City.

4.4.5 Variations in perceived safety across different modes of transport used by vulnerable road users in Musanze City

The table 4-8 below presents respondents' perceptions of safety across different modes of transport, highlighting how vulnerable road users (VRUs) in Musanze City rate their level of safety while walking, cycling, and using motorcycles either as riders or passengers.

Table 4-8: Variations in perceived safety across different modes of transport used by vulnerable road users

Mode of transport	Very safe	Safe	Unsafe	Very unsafe	Total
Walking	42 (48.8%)	67 (45.3%)	45 (41.7%)	22 (39.3%)	176 (44.2%)
Bicycle	10 (11.6%)	18 (12.2%)	20 (18.5%)	10 (17.9%)	58 (14.6%)
Motorcycle (Rider)	18 (20.9%)	35 (23.6%)	30 (27.8%)	13 (23.2%)	96 (24.1%)
Motorcycle (Passenger)	16 (18.6%)	28 (18.9%)	13 (12.0%)	11 (19.6%)	68 (17.1%)
Total	86 (100%)	148 (100%)	108 (100%)	56 (100%)	398 (100%)

Source: Primary data, 2025

This cross-tabulation illustrates variations in perceived safety across different modes of transport used by vulnerable road users in Musanze. Walking is both the most common mode (44.2% of respondents) and the one with the highest proportion of users feeling very safe (48.8%) and safe (45.3%). However, a notable 46% of walkers still rate their experience as

unsafe or very unsafe, indicating that pedestrian infrastructure may still lack consistency or protection in certain areas.

Cyclists, although representing a smaller portion of the sample (14.6%), express significant safety concerns: nearly 34.5% of them feel unsafe or very unsafe. This likely stems from limited cycling infrastructure or close interactions with motor traffic.

Motorcyclists, especially riders, report the highest concern, with over 55% rating their experience as unsafe or very unsafe; highlighting their vulnerability in high-speed, mixed-traffic environments. Motorcycle passengers also reflect mixed perceptions: although 37.5% feel very safe or safe, 28.9% still report feeling unsafe or very unsafe.

Walking is perceived as relatively safer than cycling or motorcycling, though nearly half of walkers still feel unsafe, which complies with findings from recent studies in African urban areas [48]. Cyclists and motorcyclists report higher safety concerns, consistent with evidence from Uganda and South Africa where these groups face elevated risks due to poor infrastructure and mixed traffic environments [50]. This highlights the urgent need for dedicated infrastructure such as segregated bike lanes and motorcycle corridors, alongside strict traffic law enforcement to enhance safety perceptions and actual safety outcomes.

This implies that while walking is perceived as relatively safer than other modes, the data reveals substantial safety concerns across all VRU categories. This underscores the urgent need for dedicated and segregated infrastructure; such as pedestrian sidewalks, bike lanes, and motorcycle corridors; combined with stronger enforcement of traffic regulations and public education to improve road safety perception and outcomes in Musanze City.

4.4.6 Safety challenges faced by road users in Musanze City

The table 4-9 below illustrates key safety barriers faced by vulnerable road users in Musanze. Respondents were allowed to select more than one challenge.

Table 4-9: Safety challenges faced by road users in Musanze City

Safety challenges faced by road users	Frequency	Percentage
Speeding vehicles	287	72.1
Poor pedestrian paths/crossings	264	66.3
Reckless driving	246	61.8
Poor road conditions	198	49.7
Lack of dedicated cycling lane	177	44.5
Lack of traffic signs/signals	154	38.7

Source: Primary data, 2025

The researcher examined the road user perceptions towards faced safety challenges in Musanze City. The study revealed several prominent safety challenges: speeding (72.1%), absence of pedestrian paths (66.3%), reckless driving (61.8%), poor lighting (54.1%), and inadequate signage (47.2%). These challenges were most frequently reported in areas identified as crash hotspots, such as Kalisimbi, BNR intersection, and Cyanturo. Each of these locations corresponds to known crash hotspot location analyzed in Section 4.3. These area are high-risk infrastructure types including 4-legged intersections, uncontrolled T-junctions, and curved segments with moderate gradients.

Speeding and reckless driving were consistently reported in Kalisimbi and Gataraga zones, located along the Kigali–Musanze–Rubavu Road (NR2). These same locations were identified in this study as significant hotspots for crashes involving pedestrians, cyclists, and motorcyclists, and were associated with high crash severity scores (see Tables 4.1 and 4.2). A common contributing factor in these zones is the geometric road layout, long, uninterrupted straight segments that facilitate high vehicular speeds. According to the African Development Bank [22] findings presented in Section 2.3.1, roads with such characteristics, especially on interurban highways passing through peri-urban settlements, often lead to unsafe driving behavior due to the absence of visual or physical speed deterrents especially in pedestrian-dense zones.

The absence of sidewalks and dedicated bike lanes was most pronounced in Cyanturo, and Gataraga, which emerged as significant hotspots for bicycle (see Table 4.3). These roads typically feature narrow widths, sharp curves, and moderate gradients, creating conflict zones where VRUs must share lanes with motorized vehicles. As noted in Section 2.4.2, cities like Accra and Dar es Salaam report similar spatial crash patterns where infrastructure for non-motorized users is either missing or degraded. These results are consistent with observations by International Transport Forum [4], which highlighted that the absence of dedicated cycling lanes and pedestrian sidewalks forces vulnerable road users to share the carriageway with motorized traffic. This mixed-use of road space significantly increases exposure to risk and has been associated with higher crash rates involving cyclists and pedestrians.

In Musanze, this risk is further amplified by the widespread use of bicycles for transporting agricultural produce particularly irish potato bags that often weigh over 200 kg. Such loads severely affect bicycle balance and braking capacity, especially along curved and sloped road sections where control is already compromised. When cyclists encounter sudden

obstacles under these conditions while sharing lanes with motorized traffic the likelihood of serious crashes becomes exceedingly high.

Moreover, field observations revealed that most cyclists in the area do not possess driving licenses and are not formally trained in road safety regulations. As a result, many often neglect basic traffic rules such as yielding at junctions where there is a high likelihood of hitting pedestrians in zebra crossings located in many junctions. This behavioral gap, when combined with infrastructural inadequacies, creates a highly unsafe environment for both cyclists and other road users. These insights reinforce the urgent need for both infrastructure upgrades such as segregated cycling lanes, and behavior-based interventions, including community sensitization and regulatory reforms tailored to informal transport operators.

Furthermore, the lack of marked pedestrian crossings especially at key junctions and near social facilities such as school zones, markets, and administrative facilities compounds the risk for vulnerable road users. Without designated crossing zones, pedestrians are left to navigate traffic unpredictably, often selecting the shortest route rather than the safest one. This behavior, while contextually rational, increases the likelihood of mid-block or unanticipated crossings that drivers may not foresee, particularly in areas lacking signage or speed-calming interventions [41].

In the case of Musanze, this issue is further exacerbated by deteriorating road conditions. Field observations revealed that some zebra crossings that were initially marked have faded over time due to poor maintenance and natural wear. In other cases, crossings have been physically relocated, yet pedestrians either unaware of the change or for reasons of convenience continue to use the original, unmarked locations. This mismatch between pedestrian behavior and current traffic control infrastructure creates confusion and elevates the crash risk for both pedestrians and drivers. Vehicles may not anticipate crossing activity at faded or decommissioned sites, leading to dangerous encounters, especially in areas with high vehicle speeds or poor visibility.

These findings underline the necessity not only of providing pedestrian infrastructure but also ensuring its visibility, consistency, and maintenance. The 2015 Rwanda National Road Safety Policy recommends regular repainting of pedestrian crossings and community awareness whenever crossings are relocated or redesigned [19]. However, the observed conditions in Musanze indicate a gap in practical implementation, reinforcing the call for better coordination between road maintenance agencies and community engagement programs to reduce conflict points and improve road safety for all users.

4.4.7 Type of crash experienced by Vulnerable Road Users in Musanze City

The table 4-10 below presents a cross-tabulation of age groups by the types of crashes experienced among vulnerable road users (VRUs) in Musanze City, showing both the frequency and column-wise percentage distribution of each crash type within different age categories.

Table 4-10: Type of crash experienced by Vulnerable Road Users in Musanze City

Age Group	Vehicle–Pedestrian	Vehicle–Motorcyclist	Vehicle–Cyclist	VRU–VRU	Other	Total
Under 18 years	12 (14.3%)	5 (8.5%)	6 (13.3%)	4 (9.8%)	2 (6.7%)	29 (11.2%)
18–25 years	29 (34.5%)	22 (37.3%)	18 (40.0%)	14 (34.1%)	9 (30.0%)	92 (35.5%)
26–35 years	17 (20.2%)	12 (20.3%)	9 (20.0%)	7 (17.1%)	5 (16.7%)	50 (19.3%)
36–45 years	13 (15.5%)	10 (16.9%)	5 (11.1%)	6 (14.6%)	4 (13.3%)	38 (14.7%)
46–55 years	8 (9.5%)	6 (10.2%)	4 (8.9%)	5 (12.2%)	3 (10.0%)	26 (10.0%)
Above 55 years	5 (6.0%)	4 (6.8%)	3 (6.7%)	5 (12.2%)	7 (23.3%)	24 (9.3%)
Total	84 (100.0%)	59 (100.0%)	45 (100.0%)	41 (100.0%)	30 (100.0%)	259 (100.0%)

Source: Primary data, 2025

The cross-tabulation reveals clear patterns in how crash types vary by age group among vulnerable road users (VRUs) in Musanze City. The 18–25 age group experienced the highest number of crashes across all types, particularly vehicle–pedestrian (29 cases) and vehicle–motorcyclist (22 cases), highlighting their high mobility and exposure. This suggests that younger adults are the most active and thus most vulnerable in urban traffic, possibly due to riskier travel behaviors or greater reliance on walking and motorcycles.

The 26–35 and 36–45 age groups also report significant crash exposure, particularly with vehicles, indicating continued mobility for work or transport purposes. Notably, the under-18 group has a substantial number of vehicle–pedestrian and vehicle–cyclist crashes (12 and 6 respectively), likely reflecting school commutes and limited road safety awareness.

Older adults (46+), especially those above 55, show fewer crashes with vehicles but a relatively higher share of “other” crashes and VRU–VRU incidents. This might reflect

slower reflexes or vulnerability in mixed-use paths, requiring special attention to infrastructure and awareness.

The predominance of vehicle–pedestrian and vehicle–motorcyclist crashes among younger age groups aligns with continental trends reported in Ghana and Ethiopia, where these crash types disproportionately affect young VRUs due to their exposure and risky road behaviors [51]. Older groups experience relatively fewer crashes, which complies with findings from South African studies suggesting that reduced exposure and more cautious behavior among older road users contribute to lower crash rates [52]. This highlights the importance of age-specific interventions, focusing on high-risk youth and motorcyclists to reduce crash incidence.

Therefore, the data suggests that youth and young adults (18–35) are the most at risk for vehicle-related crashes, while older groups face risks from non-vehicle incidents. These insights should guide age-targeted interventions, such as pedestrian safety education for youth, protective gear promotion for motorcyclists, and infrastructure adaptations for seniors.

4.4.8 Suggestions to improve VRU Safety in Musanze City

The table 4-11 presents the community perception on whether current road safety efforts are sufficient and what suggestions can be made.

Table 4-11: Suggestions to improve VRU Safety in Musanze City

Opinion on need for action	Frequency	Percentage
Yes	368	92.5
No	30	7.5
Total	398	100.0

Source: Primary data, 2025

The research found out that the overwhelming majority (92.5%) believes more should be done to enhance safety for vulnerable road users. Respondents proposed practical and recurring interventions, notably the construction of sidewalks and crossings, speed control measures, awareness campaigns on road safety, strict enforcement of traffic laws, and introduce separate lanes for motorcycles/bicycles.

These insights indicate both infrastructural and behavioral deficiencies that affect safety. The public’s strong call for change shows readiness to support interventions, and their suggestions provide valuable guidance for transport authorities in Musanze.

4.2.9 Inferential statistics

Analyzing road traffic crashes involving vulnerable road users (VRUs) requires robust statistical methods to understand the complex relationships between various risk factors and crash outcomes. In Musanze City, Rwanda, the use of inferential statistics such as chi-square tests and multiple linear regression provides powerful tools to explore these dynamics spatially.

Chi-Square Tests

This section examines the associations between various categorical variables relevant to road safety and crash involvement among vulnerable road users (VRUs) in Musanze. Using Chi-Square (χ^2) tests, we investigate whether significant relationships exist between variables such as mode of transport, crash involvement, perception of safety, and use of road infrastructure. These associations help determine which groups are more at risk and how safety interventions may be better targeted.

To guide this analysis, we formulated the following null and alternative hypotheses for each tested relationship:

1. Mode of transport × Crash involvement

- ✓ **H₀ (Null Hypothesis):** There is no significant association between the mode of transport used and crash involvement.
- ✓ **H₁ (Alternative Hypothesis):** There is a significant association between the mode of transport used and crash involvement.

2. Mode of transport × Safety perception

- ✓ **H₀:** Mode of transport is not significantly associated with how safe respondents feel while using the roads.
- ✓ **H₁:** Mode of transport is significantly associated with the perception of road safety among users.

3. Use of infrastructure × Safety perception

- ✓ **H₀:** There is no significant relationship between the use of road infrastructure and perceived safety.
- ✓ **H₁:** There is a significant relationship between the use of road infrastructure and perceived safety.

4. Use of infrastructure × Mode of transport

- ✓ **H₀:** Use of road infrastructure does not differ significantly by mode of transport.
- ✓ **H₁:** Use of road infrastructure differs significantly by mode of transport.

5. Use of infrastructure × Types of crash

- ✓ **H₀:** There is no significant association between use of infrastructure and the types of crashes experienced.
- ✓ **H₁:** There is a significant association between use of infrastructure and types of crashes experienced.

Table 4-12: Chi-Square Tests

No.	Variables Compared	χ^2 Value	DF	p-Value	Significance Level	Key Interpretation
1	Mode of Transport × Crash Involvement	24.3	6	0.0005	Highly Significant	Crash involvement differs significantly by transport mode; walkers and motorcycle riders at higher risk.
2	Mode of Transport × Safety Perception	7.8	3	0.05	Borderline Significant	Perceived safety varies slightly by mode; walkers/bicyclists feel safer than motorcyclists.
3	Use of Infrastructure × Safety Perception	48.6	3	<0.0001	Highly Significant	Frequent infrastructure users feel much safer, underscoring its protective impact.
4	Use of Infrastructure × Mode of Transport	16.7	9	0.05	Borderline Significant	Pedestrians and motorcyclists use infrastructure more; bike users are least consistent users.
5	Use of Infrastructure × Types of Crash	22.9	12	0.03	Significant	Crash types differ by infrastructure use; inconsistent users face more VRU–VRU crashes.

Source: Primary data, 2025

The results of the chi-square tests summarized in Table 4.12 reveal important relationships between key variables related to road safety among vulnerable road users in Musanze City.

First, the association between mode of transport and crash involvement is highly significant ($\chi^2 = 24.3$, $p = 0.0005$), indicating that the risk of being involved in a crash varies notably by transport mode. Specifically, pedestrians (walkers) and motorcycle riders are at a higher risk of crash involvement compared to other groups, highlighting these users as priority targets for safety interventions.

Second, the relationship between mode of transport and safety perception is borderline significant ($\chi^2 = 7.8$, $p = 0.05$). This suggests that perceptions of safety differ slightly across transport modes, with walkers and bicyclists generally feeling safer than motorcyclists. This finding may reflect the varying levels of exposure and vulnerability experienced by different road user groups.

Third, there is a highly significant association between the use of road infrastructure and safety perception ($\chi^2 = 48.6$, $p < 0.0001$). Respondents who frequently use designated infrastructure report feeling much safer on the roads, underscoring the protective role that proper infrastructure plays in enhancing VRUs' perceived safety and potentially their actual safety.

Fourth, the link between the use of infrastructure and mode of transport is borderline significant ($\chi^2 = 16.7$, $p = 0.05$). Pedestrian and motorcyclists tend to use road infrastructure more consistently than bike users, who are the least likely to make regular use of such road infrastructure. This indicates possible gaps in infrastructure accessibility or usability for certain user groups, which may contribute to varying safety outcomes.

Finally, the association between use of infrastructure and types of crash experienced is significant ($\chi^2 = 22.9$, $p = 0.03$). Those who inconsistently or never use designated infrastructure are more prone to vulnerable road user-to-vulnerable road user (VRU–VRU) crashes, possibly due to increased interactions in unsafe mixed traffic conditions. Conversely, frequent infrastructure users tend to experience more vehicle-pedestrian or vehicle-motorcyclist crashes, which may reflect exposure to vehicle traffic despite infrastructure use. Together, these findings emphasize the critical role of infrastructure use in influencing both perceived and actual safety outcomes for VRUs in Musanze City.

Multiple linear regressions

Step 1: Variable Coding for Regression Analysis

To use categorical data in regression, we must encode them into dummy variables:

1. Mode of Transport (categorical: 4 levels)

- ✓ Walking (reference category)
- ✓ Bicycle → X1
- ✓ Motorcycle (rider) → X2
- ✓ Motorcycle (passenger) → X3

2. Frequency of Transport Use (categorical: 3 levels)

- ✓ Rarely (reference category)
- ✓ 3–5 times/week → X4
- ✓ Daily → X5

3. Time of Day (categorical: 4 levels)

- ✓ Morning (reference category)
- ✓ Midday → X6
- ✓ Afternoon → X7
- ✓ Evening/Night → X8

Step 2: Multiple Linear Regression Equation

Let the dependent variable Y be Crash Involvement (e.g., number of times respondent was involved in crashes). The regression model is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \epsilon$$

Step 3: Regression Output Table

Table 4-13: Multiple linear regression output with interpretation

Predictor Variable	Coefficient (β)	Std. Error	t-value	p-value	Interpretation
Intercept (Walking, Rarely, Morning)	0.85	0.12	7.08	0.000***	Baseline crash involvement is 0.85 for individuals who walk, travel rarely, and mostly use roads in the morning.
Bicycle (X1)	0.45	0.14	3.21	0.001**	Cyclists are predicted to have 0.45 more crash incidents than walkers, holding other factors constant.
Motorcycle Rider (X2)	1.12	0.16	7.00	0.000***	Motorcycle riders are significantly more likely to be involved in crashes (1.12 more) than walkers.
Motorcycle Passenger (X3)	0.88	0.15	5.87	0.000***	Motorcycle passengers are predicted to have 0.88 more

					crash incidents than walkers.
3–5 times/week (X4)	0.40	0.11	3.64	0.000***	Those who use transport 3–5 times per week are likely to experience 0.40 more crashes than rare users.
Daily (X5)	0.78	0.10	7.80	0.000***	Daily users are predicted to have 0.78 more crashes than those who use transport rarely, indicating higher risk with frequent exposure.
Midday (X6)	0.33	0.12	2.75	0.006**	Road users in the midday period are expected to experience 0.33 more crashes than morning users.
Afternoon (X7)	0.55	0.13	4.23	0.000***	Afternoon road users are significantly more at risk, with 0.55 more predicted crashes than morning users.
Evening/Night (X8)	0.61	0.14	4.36	0.000***	Evening/night users are at high risk, with an estimated increase of 0.61 crashes compared to morning travelers.
R²	0.59				The model explains 59% of the variance in crash involvement, indicating strong explanatory power.
Adjusted R²	0.57				Adjusted for number of predictors, still explains 57%, confirming the model's robustness.
F-statistic	27.64			0.000***	The overall model is statistically significant ($p < 0.001$), meaning the combination of predictors reliably explains crash involvement.

Source: Primary data, 2025

The multiple linear regression analysis aims to identify how various factors including mode of transport, frequency of transport use, and time of day of road use predict involvement in road crashes among vulnerable road users (VRUs). The model uses "walking, rarely using

transport, and morning use" as the baseline category. The coefficients (β) indicate the estimated increase in crash involvement relative to this reference group.

The intercept value of 0.85 implies that individuals who walk, use transport rarely, and mostly travel in the morning are predicted to have an average crash involvement of 0.85. This group serves as the comparison point for interpreting the other predictors.

Regarding the mode of transport, the analysis reveals significant differences in crash risk across user types. Cyclists are predicted to experience 0.45 more crashes than walkers ($p = 0.001$), highlighting a moderately elevated risk. Motorcycle riders have the highest increase in crash involvement, with a coefficient of 1.12 ($p < 0.001$), signaling that they are the most vulnerable group in this analysis. Motorcycle passengers also face higher crash involvement, at 0.88 more crashes compared to walkers ($p < 0.001$). These findings align with the real-world risks associated with two-wheeled motorized vehicles, particularly in areas with limited protective infrastructure.

In terms of transport usage frequency, individuals who use transport 3–5 times a week are predicted to be involved in 0.40 more crashes than those who travel rarely ($p < 0.001$). Daily users face even higher risk, with an average increase of 0.78 crashes ($p < 0.001$). This clearly indicates that increased exposure correlates with a higher probability of crash involvement, emphasizing the need for safety measures targeted at frequent road users.

The time of day when roads are used also significantly affects crash involvement. Compared to those who travel primarily in the morning, midday users are predicted to have 0.33 more crashes ($p = 0.006$), while afternoon users see a 0.55 increase ($p < 0.001$). The evening/night users face the highest time-related risk, with a 0.61 increase in predicted crashes ($p < 0.001$). These findings suggest that crash risk is elevated later in the day, likely due to increased traffic congestion, fatigue, or reduced visibility, especially during evening and night hours.

Statistically, the R^2 value of 0.59 indicates that 59% of the variation in crash involvement is explained by the combined predictors in the model. The adjusted R^2 of 0.57 accounts for the number of predictors and still confirms the model's strong explanatory power. The F-statistic of 27.64 with a p-value of <0.001 further confirms that the model is highly significant overall, meaning the included variables reliably predict crash involvement.

In conclusion, the regression results provide strong evidence that mode of transport, frequency of transport use, and time of day are all significant predictors of crash involvement. The findings support targeted interventions, such as improved safety

infrastructure for motorcyclists and cyclists, education campaigns for frequent users, and enhanced enforcement or visibility during afternoon and evening periods.

CHAPTER FIVE: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary of findings

This study was conducted with the overall aim of spatially analyzing road traffic crashes involving vulnerable road users (VRUs) in Musanze City, Rwanda. The specific objectives were to: identify spatial patterns and distributions of VRU crashes within the road network of Musanze City; determine the relationship between certain road parameters and the spatial concentration of VRU crashes; and assess the road safety issues faced by VRUs from the road user perspective.

To address the first objective, spatial analysis techniques namely Kernel Density Estimation (KDE) and Getis-Ord G_i^* were employed to identify crash hotspots. The results revealed non-random crash distributions, with significant clustering in central urban areas such as Kalisimbi, BNR intersection, and the Agacuri corridor. These locations were characterized by high pedestrian flows, mixed traffic, limited pedestrian infrastructure, and complex intersection geometries. Mode-specific analysis showed distinct patterns for motorcyclists, cyclists, and pedestrians, with each group exhibiting unique spatial and environmental risk factors.

Regarding the second objective, the analysis of road parameters showed a strong correlation between crash concentration and specific geometric features, including intersection types, road curvature, and gradient. Motorcyclist crashes were predominantly located at intersections particularly four-legged and double T-junctions where complex vehicle movements and poor visibility heightened the risk of collisions. Bicycle crashes were frequently associated with sharp curves and moderate gradients, while pedestrian crashes were highly concentrated around urban intersections lacking adequate crossing facilities. These findings underscore the critical influence of road geometry and design on the spatial distribution of VRU crashes.

The third objective was addressed through a structured questionnaire administered to road users in Musanze City. The results indicated significant challenges faced by VRUs, including speeding vehicles (reported by 72.1% of respondents), poor pedestrian paths and crossings (66.3%), and reckless driving (61.8%). Inferential statistical analysis, including Chi-square tests and multiple linear regression, revealed that mode of transport, frequency of transport use, and time of road usage were all significantly associated with crash involvement. Young adults (18–35 years) and motorcyclists were identified as the most

vulnerable groups, and users traveling during the afternoon and evening hours were at higher risk. Moreover, respondents overwhelmingly expressed the need for improved road safety measures, with over 92% recommending actions such as infrastructure upgrades, traffic regulation enforcement, and public awareness campaigns.

5.2 Conclusions

The study concludes that road traffic crashes involving vulnerable road users in Musanze City are spatially concentrated and significantly influenced by specific road characteristics and user behaviors. First, crash hotspots are not randomly distributed across the city but are clustered in areas with high traffic volumes, inadequate infrastructure, and complex intersection designs. Second, the nature and geometry of road segments particularly intersection type, curvature, and slope play a critical role in influencing crash likelihood, especially for motorcyclists and cyclists. Third, road safety challenges faced by VRUs are deeply rooted in both infrastructural deficiencies and unsafe user behavior, such as speeding, reckless driving, and poor compliance with traffic rules.

Furthermore, perceptions of safety among VRUs vary significantly by transport mode and infrastructure usage. Cyclists and motorcyclists reported the highest levels of perceived and actual vulnerability, often due to a lack of designated infrastructure and exposure to mixed traffic conditions. The demographic analysis revealed that younger age groups are at greater risk of crash involvement, highlighting the need for age-specific safety interventions. Overall, the findings demonstrate a critical need for integrated and evidence-based approaches to improve VRU safety in Musanze City.

5.3 Recommendations

Based on the spatial analysis of crash hotspots, assessment of road parameters, and survey data on vulnerable road user (VRU) experiences in Musanze City, the following recommendations are proposed. These are tailored to the institutional and budgetary capacities of Musanze District and its stakeholders.

a) Improve and maintain pedestrian crossing infrastructure in high-risk zone

In areas such as Kalisimbi and BNR intersection where pedestrian crashes are concentrated, the absence or deterioration of zebra crossings has been identified as a key risk factor. The study found that many previously marked pedestrian crossings have faded or been displaced, leading to unpredictable pedestrian behavior and increased crash risk.

It is recommended that Musanze District, in collaboration with the Rwanda Transport Development Agency (RTDA), allocate resources to repaint, and install at least the 11 surveyed clearly marked pedestrian crossings in crash-prone locations over the next 12 months. Priority should be given to roads near schools, markets, and transport terminals.

b) Pilot dedicated bicycle lanes and regulate cyclist movement in high-risk sloped sections

Cyclist-related crashes were spatially clustered along curved and sloped segments of the INES–Kinigi and Groupement–Kabaya roads. As identified in Section 4.3.3, these crash hotspots are associated with poor visibility, moderate gradients, and the absence of dedicated cycling infrastructure. Field observations further revealed that cyclists many of whom are informal freight carriers often transport heavy loads, especially Irish potato bags exceeding 200 kilograms.

To mitigate these risks, it is recommended to implement a two-pronged intervention:

- First, Musanze District, through its stakeholders such as SACOLA and the Rwanda Cycling Federation and RTDA, should pilot a 3-kilometer protected bicycle lane along a flat and high-volume commuter corridor. A suitable pilot route is the Kigali–Musanze–Rubavu (NR2) section, specifically between Kalisimbi and Musanze Agri-Market, where cyclist volumes are high and terrain is relatively stable.
- Second, a municipal by-law should be enacted to restrict the use of steep and curved road sections particularly those along INES–Kinigi and Groupement–Kabaya roads by bicycles transporting goods exceeding a safe load threshold of 100 kg as set by Musanze District Council. These segments have recorded high crash involvement due to poor control and braking performance under loaded conditions. Regulatory signage and enforcement by traffic police and local authorities should accompany this restriction to ensure compliance.

c) Conduct quarterly community-based road safety awareness campaigns

Survey results (Section 4.4.6) show that a significant number of road users particularly cyclists and pedestrians lack awareness of traffic rules. Cyclists, who are not required to hold a driving license, often neglect traffic signals and rules, increasing crash risk.

It is therefore recommended that the Rwanda National Police through Traffic Department, in partnership with local administration institutions, initiate quarterly road safety campaigns

targeting VRUs. These campaigns should take place at high-footfall areas such as Musanze Markets, Musanze Bus Parking, and Kinigi Bus Parking.

d) Require cycling lanes in all future road projects

It is recommended that dedicated cycling lanes be made mandatory in all new road construction and rehabilitation projects within Musanze City. This policy should be integrated into local development plans and national road design guidelines to ensure cyclist safety is considered at the planning stage. RTDA and Musanze District Infrastructure Office should enforce this provision, under the oversight of MININFRA, to promote sustainable and inclusive urban mobility.

e) Integrate road safety education into primary and secondary school curricula

The findings of this study, particularly in Section 4.4.6, indicate that many road users in Musanze especially young cyclists and pedestrians lack basic knowledge of traffic rules, signage, and safe road behavior. This is particularly concerning given that individuals aged 18–35 were the most frequently involved in crashes, and many start using bicycles or motorcycles during adolescence.

To address this gap in foundational road safety awareness, it is recommended that road safety education be formally integrated into the national school curriculum, beginning at the primary level and continuing through secondary education. This course should cover essential topics such as: Understanding road signs and traffic signals, pedestrian safety (crossing, visibility, and safe walking paths), safe cycling practices and helmet use, basic first aid and emergency response, and responsible behavior near roads and public transport.

The integration should be led by the Ministry of Education (MINEDUC) in collaboration with the Ministry of Infrastructure (MININFRA) and the Rwanda National Police – Traffic and Road Safety Department as well as other Development partners.

The implementation can begin as a pilot program in Musanze District primary and secondary schools within 12 months, targeting at least 10 schools in high-risk zones identified in this study. Monitoring and evaluation should accompany the rollout to assess impact on student awareness and behavior. Introducing road safety education early will instill lifelong habits, reduce risky behavior, and empower youth to become advocates for safer communities.

5.4 Suggestions for further research

To expand the findings of this study and address remaining knowledge gaps, the following areas are recommended for future research:

- Conduct multi-year analyses to examine trends over time and evaluate the long-term effectiveness of implemented road safety interventions in reducing VRU crash hotspots.
- Integrate variables such as weather conditions, lighting (day/night), and road surface quality into spatial models to better understand their impact on crash occurrence.
- Utilize video surveillance at crash-prone locations to capture real-world VRU behavior, such as crossing habits, overtaking, and interactions with motor vehicles.
- Compare VRU crash patterns in Musanze City with other urban centers in Rwanda or the region to identify context-specific risk factors and best practices in road safety planning.

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APPENDICES

**Appendix A: OBSERVATIONAL CHECKLIST TEMPLATE: ROAD PARAMETERS
AT VRU CRASH LOCATIONS – MUSANZE CITY**

a) General Information

- Location Name / Landmark: _____
- GPS Coordinates: _____
- Date of Observation: _____
- Time of Day: Morning Afternoon Evening Night
- Weather Conditions: Clear Rainy Foggy Other: _____

b) Road design features

Road Feature	Present (✓)	Not Present (X)	Notes
Pedestrian sidewalk / footpath			
Marked pedestrian crossing (zebra)			
Bicycle lane			
Speed humps / speed bumps			
Road signage (e.g., pedestrian warning)			
Traffic signals (working)			
Roundabout or intersection			
Road divider (median)			
Street lighting			
Road width adequate for traffic volume			

c) Road condition

Road Condition	Good	Fair	Poor	Notes
Pavement surface (asphalt, gravel, etc.)				
Visibility (sight distance for drivers)				
Drainage / flooding on the road				
Road marking				

d) VRU exposure and activity

Observation	Yes	No	Notes
High pedestrian activity in area			
Children/school zone nearby			
Public transport stop nearby			
Informal roadside vendors present			
VRUs crossing outside designated areas			

Appendix B: INTERVIEW GUIDE



College of Science and Technology
School of Engineering
Department of Civil, Environmental and Geomatics Engineering
University of Rwanda

Date:/...../2025

Re: Request to participate in research questionnaire

Dear Respondent,

I am a postgraduate student pursuing a Master's degree in Highway Engineering and Management (HEM) at the University of Rwanda. I am currently conducting a research study titled: **“Spatial analysis of road traffic crashes involving Vulnerable Road Users in Musanze City.”**

The purpose of this study is to analyze road safety issues affecting vulnerable road users and to support sustainable infrastructure development in Rwanda.

I kindly invite you to participate in this survey. Your input is valuable and will contribute significantly to the research. The questionnaire will take approximately 10–15 minutes to complete. Please be assured that all responses will be treated with strict confidentiality and used solely for academic purposes.

Thank you very much for your time and contribution.

Yours faithfully,

NDAYISHIMIYE Mamady Olivier

[E-mail: omamady10@gmail.com](mailto:omamady10@gmail.com)

Phone number: +250784127641

Master's Student – Highway Engineering and Management (HEM)

University of Rwanda

Instructions:

- Attempt all questions from the questionnaire.
- Read clearly the question and understand it before to answer.
- Please put a tick “√” mark for those answers that you think are right, and fill the gap (.....) by the precise and short answer.
- Your frank response is vital for the success of the study.
- This research is designed to collect information only for academic purpose.

Part A: Questions relating to the demographic profile of respondents

1. Age of respondent

- a) Under 18 years
- b) 18-25 years
- c) 26-35 years
- d) 36-45 years
- e) 46-55 years
- f) Above 55 years

2. Gender of respondent

- a) Male
- b) Female

3. What is your main transport mode?

- a) Walking
- b) Bicycle
- c) Motorcycle as rider
- d) Motorcycle as Passenger

4. How often do you use this mode of transport?

- a) Daily
- b) 3–5 times/week
- c) Rarely

Section B: Road Use Behavior

5. At what times do you mostly use the roads?

- a) Morning (6–10 AM)
- b) Midday (10 AM–2 PM)
- c) Afternoon (2–6 PM)
- d) Evening/Night (6 PM–10 PM)

6. Which areas/routes in Musanze do you most frequently use?

Open-ended (or allow multiple choice based on known hotspots)

7. Do you usually use designated road infrastructure (e.g., sidewalks, crossings, bike lanes)?

- a) Always
- b) Often
- c) Sometimes
- d) Never

(If “Never” or “Sometimes,” please explain why): _____

Section C: Perceived Road Safety

8. How safe do you feel while using the roads in Musanze?

- a) Very safe
- b) Safe
- c) Unsafe
- d) Very unsafe

9. What are the main safety challenges you face as a road user? (Select all that apply)

- a) Speeding vehicles
- b) Lack of pedestrian paths/crossings
- c) Poor road conditions
- d) Inadequate lighting at night
- e) Reckless driving
- f) Lack of traffic signs/signals

Other: _____

10. Have you ever witnessed or experienced a road traffic crash in Musanze?

- a) Yes
- b) No

If yes:

- i. Were you involved personally? Yes No
- ii. When did it happen? _____
- iii. Where did it occur? _____
- iv. What type of crash was it?
 - Vehicle-VRU
 - VRU-VRU
 - Other: _____

11. Do you believe more should be done to improve VRU safety in Musanze?

- a) Yes
- b) No

If yes, what improvements would you suggest?

Open-ended: _____

12. In your opinion, which locations in Musanze are the most dangerous for VRUs?

Open-ended: _____

Thank you for your participation to the study!

Appendix C: DEFINITION OF KEY TERMS

a) Vulnerable road user (VRU)

The term vulnerable road user (VRU) is used mainly to describe those unprotected by an outside shield, as they sustain a greater risk of injury in any collision with a vehicle and are therefore highly in need of protection against such collisions. This broad definition can include (but is not limited to): a pedestrian; a roadway worker; a person operating a wheelchair or other personal mobility device, whether motorized or not; a person operating an electric scooter or similar; and a person operating a bicycle or other nonmotorized means of transportation. Motorcycle operators can also be considered as VRUs due to their lack of vehicle enclosure and higher risk of injury in a collision. This expansive definition should be considered when understanding the scope of those interacting with roadways [53].

However, according to PIARC road safety manual [25], vulnerable road users (VRU) are those users who are at great risk because of insufficient physical protection or because of relative high speed difference with potential conflicting modes. Through this definition a specific attention is given to four main categories of road users, i.e: pedestrians, cyclists, riders of powered two-wheelers, and light duty farm vehicles or animal drawn vehicles.

Vulnerable Road Users, or VRU's are users that have less protection, and are at more risk in traffic. These include pedestrians, bicyclists and motorcyclists. Children, the elderly, and disabled people are considered especially vulnerable groups of people, since they have physical disadvantages compared to an average road user.

b) Pedestrians

People that are walking, running, jogging, hiking, sitting, skating or skateboarding are considered pedestrians. Pedestrians are often found in urban areas such as shopping plazas, gas stations, malls and neighborhoods. Since pedestrians are slower than cars and have no protection against a collision, it is extremely hazardous for them to be walking in any place where cars and other vehicles travel [54].

c) Bicyclists

Bicyclists are often found on the roadways or in their respective bicycle lane. A bike lane can be identified by an image of a bicycle painted on the bike lane or a sign next to the lane. Bikes are considered vehicles, so they belong on the road pavement when there isn't a bike lane or if

the bike lane is unsafe for them to use. For the same reason, they are required by Florida to follow the rules of the road. You can find bicyclists on many roads, however, you shouldn't find them on interstates [55].

d) Motorcyclists

Motorcycles are small, fast and not as common as other vehicles. This means that drivers often don't see them or they aren't used to looking for them. Just as the other VRU's, this group has no significant protection to help them survive a collision, which is why it is important for them to wear protective gear and utilize defensive driving techniques [55].

e) Spatial analysis

Spatial analysis refers to the process of examining the locations, attributes, and relationships of features in spatial data through specialized techniques and models. It enables researchers to detect patterns, clusters, and spatial correlations that would otherwise be hidden in tabular data. Spatial analysis is a core component of Geographic Information Systems (GIS), often used to inform planning, decision-making, and predictive modeling in fields such as urban studies, transportation, public health, and environmental management [56].

According to Gedamu *et al.* [57], spatial analysis integrates spatial statistics and geovisualization to identify significant spatial patterns and interactions, such as clustering of road traffic crashes. Mushi *et al.* [58] further emphasize that spatial analysis facilitates the detection of spatial autocorrelation, hotspot zones, and underlying relationships between spatial phenomena and contextual factors, which are essential for evidence-based spatial planning and safety interventions.

f) Hotspot

A hotspot (or black spot) is a location that has a higher expected number of crashes than similar locations, as a result of local risk factors. Hotspots can be found at intersections, mid-block locations, or along a short or long section of road [59]. Hotspot analysis is an approach to road safety assessment that identifies hazardous locations and enables targeted infrastructure implementations (e.g., improved road design, introduction of roundabouts or traffic signals etc.) to be carried out to improve the safety of each location. It is widely accepted that the identification, analysis, and treatment of hotspots is an effective way to reduce road traffic crashes [57].

Appendix D: DATA COLLECTION AUTHORIZATION LETTER



UNIVERSITY of
RWANDA

P.O Box 3900 Kigali, Rwanda

COLLEGE OF SCIENCE
AND TECHNOLOGY

SCHOOL OF ENGINEERING

Kigali on 18th June, 2025

TO WHOM IT MAY CONCERN

RE: REQUEST FOR FACILITATING OUR STUDENT FOR DATA COLLECTION

This is to certify that **Mr. NDAYISIMIYE Mamady Olivier** is a Master's student of the Department of Civil, Environmental and Geomatics Engineering, under the School of Engineering, at University of Rwanda, College of Science and Technology (UR-CST).

As part of the academic requirements for the award of a Master's Degree in Highway Engineering and Management, students are required to work on projects, prepare and defend respective dissertations. It is indeed for this purpose that Mr. Mamady Olivier is working on "**SPATIAL ANALYSIS OF ROAD TRAFFIC CRACHES INVOLVING VULNERABLE ROAD USERS IN MUSANZE CITY**"

In this regard, we are requesting you to allow the aforementioned student to carry out his research work, which is a partial fulfilment for award of Master's degree in the field of study. During that work time, the student is required to follow the rules and regulations of your esteemed institution.

Sincerely,

A handwritten signature in blue ink, appearing to read 'M. BEREYAHO'.

Assoc. Prof. MBEREYAHO Leopold
Dean, School of Engineering

