DEVELOPMENT OF ROAD SAFETY MANAGEMENT FRAMEWORK FOR THE NATIONAL ROAD NETWORK

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Master of Science (Major Component Research)

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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The above candidate has carried out research for the master's Dissertation under my supervision.

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10/12/2025

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ABSTRACT

Development of road safety management framework for the national road network

Road safety is a fundamental aspect of sustainable transportation systems, playing a vital role in protecting human lives, ensuring public well-being, and supporting socioeconomic development. However, many countries face persistent challenges in managing road safety at the national level due to insufficiently structured frameworks, inadequate data utilization, and limited analytical tools for identifying and addressing high-risk road segments. These limitations hinder the ability of road authorities to identify methodologies for effectively identifying critical safety issues, prioritizing high-risk road sections, and implementing targeted interventions within constrained budgets. To address these limitations, it is essential to adopt evidence-based approaches that enable the prioritization of road safety projects while considering financial and operational constraints. Furthermore, identifying long-term funding needs for high-priority safety improvements is crucial for sustaining progress. To achieve substantial progress in reducing road crashes and enhancing overall safety, it is imperative to adopt a structured road safety management framework that integrates systematic assessment procedures, clear operational roles, and accountability at all levels.

The framework begins by identifying the key objectives of the national road safety strategy and developing criteria for road segmentation using fixed or variable lengths based on the available crash data. Then the road segments are initially screened and classified as high-risk road segments through the combined application of comprehensive crash data analysis and appropriate black spot identification method.

This study proposes a comprehensive approach that includes three key road safety assessments: roadway environment assessment (which categorizes the roadside land use context as urban, suburban, or rural), road infrastructure safety assessment (which evaluates safety issues arising from roadway deficiencies), and crash risk assessment (based on historical crash data). The high-risk road segments identified during the initial screening are further evaluated through these three safety risk assessments.

The level of service of each road section (road safety performance) is then evaluated based on the outcomes of each risk assessment, through the development of performance matrices. Finally, a macro-level decision-making matrix and appropriate risk rating method are developed to determine the overall safety performance of the relevant sections. According to the safety management strategy, relevant road agencies and authorities will decide on the safe treatment strategies and the location of safety priorities they can adopt based on their budgetary restrictions.

Keywords: Road Safety, National Road, Road Segmentation, Risk Assessment, Crash data

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Description
HIC	High Income Countries
LMICs	Low- and Middle-Income Countries
RSMF	Road Safety Management Framework
WHO	World Health Organization
SDGs	Sustainable Development Goals
RDA	Road Development Authority
PRDA	Provincial Road Development Authority
AADT	Annual Average Daily Traffic
IRR	Infrastructure Risk Rating
ADB	Asian Development Bank
SLADMS	Sri Lankan Accident Data Management System
CSI	Cumulative Safety Index
SPF	Safety Performance Function
HSM	Highway Safety Manual
RSI	Road Safety Index
CMF	Crash Modification Factor
ECDF	Empirical Cumulative Distribution Function
RRI	Risk Rating Index

LIST OF APPENDICES

CHAPTER 1
INTRODUCTION

1.1 Research Background

1.1.1 The global burden of road traffic accidents

Road safety refers to the collective measures and practices implemented to minimize the risk of accidents, injuries, and fatalities on roadways. It encompasses a comprehensive range of strategies, regulations, and educational initiatives designed to create a secure and efficient environment for all road users, including pedestrians, cyclists, motorists, and passengers. Road safety has emerged as one of the most pressing public health and development challenges of the 21st century. Globally, over 1.19 million people die annually due to road traffic accidents, and tens of millions more suffer non-fatal injuries, many of which result in long-term disabilities or permanent impairments. The human cost of these tragedies is profound, impacting not only individuals and families but also the broader socio-economic fabric of nations. Despite progress in road safety initiatives in many high-income countries (HICs), low- and middle-income countries (LMICs) continue to bear a disproportionately high burden of road traffic fatalities and injuries, accounting for over 90% of the global toll [1].

According to the World Health Organization (WHO), road traffic injuries are the leading cause of death for people aged 5 to 29 years [1], with pedestrians, cyclists, and motorcyclists comprising more than half of all fatalities. While high-income countries have made significant strides in reducing road deaths through stringent legislation, advanced vehicle technology, and safer road designs, many developing regions face stagnation or worsening trends.

The WHO Global Status Report on Road Safety (2023) highlights that although LMICs possess only 60% of the world's vehicles, they account for more than 92% of road traffic deaths[2]. This alarming imbalance stems from multiple systemic issues, including poorly designed roads, lack of safe transport options, substandard driver behavior, insufficient post-crash care, and underinvestment in road safety research and management systems.

1.1.2 Road safety in low- and middle-income countries (LMICs)

In many low- and middle-income countries (LMICs), road safety remains a significantly underprioritized area, both in terms of policy enforcement and infrastructure development. As national road networks continue to expand rapidly in response to economic growth and increasing mobility demands, the corresponding implementation of safety measures has not progressed at a comparable rate. This imbalance has led to heightened risks for road users, particularly in environments where safety infrastructure and institutional frameworks are weak or poorly coordinated. Key challenges commonly encountered in LMICs include the absence of reliable and consistent crash data, insufficient enforcement of traffic regulations, limited integration of road safety audits and inspections, inadequate public awareness and road user education particularly among vulnerable groups and underdeveloped emergency response and trauma care systems. These systemic deficiencies collectively hinder the formulation and implementation of effective road safety strategies and highlight the need for a comprehensive and context-appropriate management framework to reduce crash risks and protect all road users.

As a developing and LMICs, Sri Lanka provides a relevant case study for these trends. Over the past two decades, the country has experienced a significant rise in both vehicle ownership and road crash incidents. Road fatality rates in Sri Lanka have remained over the years and averaging around 7-8 fatalities per day in the last 2-3 years, which means one death nearly in every 3 hours taken place due to a road crash. When the period of 20 years back is considered, the rate of deaths due to the crashes was around three deaths per day, (i.e., one death per eight hours). Within the period of these 20 years (1998-2018), the magnitude of the crashes that happen daily have increased by 167%, largely due to growth in motorization as well as the expansion of the road network [3].

The World Bank reported that annually, Sri Lanka experiences around 3,000 deaths and 8,000 injuries due to road accidents and around 20.7 fatalities rate per 100,000 population in 2016. Road crash fatalities and injuries place a significant economic burden on Sri Lanka, with estimates indicating a loss of 3–5% of the country's annual GDP (World Bank) (Global Road Safety Facility). With the continued increase in vehicle numbers and growing traffic congestion, this cost is expected to have risen even further in recent years [4].

Table 1.1 presents the distribution of road traffic accidents in Sri Lanka from 2008 to 2022, categorized by severity as fatal, grievous, and non-grievous. The data illustrate long-term patterns in crash severity and provide an overview of how the burden of road traffic injuries has evolved over the 15-year period.

Table 1.1 Overview of crashes in Sri Lanka for the years 2008-2022

Year	Accident Severity		
	Fatal	Grievous	Non-grievous
2008	2176	4941	11288
2009	2263	5379	10945
2010	2579	6124	12560
2011	2498	6966	13196
2012	2317	7209	14680
2013	2190	6872	13526
2014	2261	7071	12782
2015	2601	8187	13595
2016	2838	8933	14050
2017	2963	8667	13102
2018	2949	8475	12264
2019	2641	7693	10691
2020	2242	6950	8705
2021	2414	6401	8070
2022	2395	6231	8209

As illustrated in Table 1.1, the growth in reported road crashes in Sri Lanka appears to have been constrained in recent years, primarily due to reduced mobility following the economic crisis. Nevertheless, the overall fatality rates remain unacceptably high, indicating persistent challenges in road safety management [5]

1.1.3 Global commitments and the safe system approach

In recent years, road safety has gained prominence on the global development agenda, recognized not merely as a transport issue but as a critical public health, economic, and social concern. The international community has underscored the importance of improving road safety through key global frameworks, most notably the United Nations Sustainable Development Goals (SDGs). Specifically, SDG Target 3.6 aims to halve the number of global deaths and injuries resulting from road traffic crashes by the year 2030 [6]. This ambitious target reflects a growing consensus among policymakers, researchers, and international organizations that road traffic injuries are preventable and that urgent, coordinated action is required to address the growing burden, particularly in the area, where the highest fatality rates are recorded.

To operationalize SDG 3.6 and further mobilize efforts globally, the Decade of Action for Road Safety 2021–2030 was launched by the United Nations in collaboration with the World Health Organization (WHO) [7]. This global plan builds on lessons from the previous Decade of Action (2011–2020), which brought increased political attention to the issue but fell short of meeting its fatality reduction targets in many regions. The renewed framework places a strong emphasis on achieving systemic change by adopting the Safe System Approach a paradigm shifts in how road safety is conceptualized and managed. The Safe System Approach represents a transformative movement away from the traditional model that places responsibility primarily on individual road users. Instead, it acknowledges that human error is inevitable and that the road system must be designed to minimize the risk of death or serious injury when mistakes occur. The approach follows the five pillars of the safe-system model, which include safe roads and infrastructure, safe speeds, safe vehicles, safe road users, and an effective post-crash response system [8].

The adoption of the Safe System Approach has been associated with marked improvements in road safety performance in high-income countries such as Sweden, the Netherlands, and Australia, where it has been systematically integrated into national road safety strategies. However, its application in LMICs remains limited, primarily due to resource constraints, weak institutional frameworks, and competing development priorities. To realize the benefits of global commitments and the Safe System Approach in LMICs, countries must tailor implementation strategies to suit local contexts. This requires capacity-building, international technical cooperation, and long-term investment in safer infrastructure, enforcement mechanisms, public awareness campaigns, and robust post-crash care systems. Without these coordinated efforts, the ambitious goals of SDG 3.6 and the Decade of Action for Road Safety risk remaining unattained.

1.1.4 Towards safer rural mobility: integrating low-volume roads into national road safety management framework

Rural and sub-provincial low-volume roads form an essential component of national transport networks, providing critical access to education, healthcare, markets, and other services for remote communities. Despite their importance, these roads often receive limited attention in investment and upgrade programs when compared with major road classes.

These roads are typically characterized by poor geometric design, inadequate signage, lack of pedestrian and cyclist infrastructure, limited lighting, and weak maintenance regimes. Despite having lower traffic volumes compared to urban roads and highways, rural roads record disproportionately high fatality rates. This is due to several factors: high-speed travel on undivided narrow lanes, mixed traffic including pedestrians, animals, and agricultural vehicles, limited law enforcement presence, and delayed emergency response times. In LMICs, the challenge is further compounded by the absence of reliable crash data from rural areas, making it difficult to assess risks accurately and prioritize interventions. Recognizing these issues, several countries have begun implementing rural road safety audits, community-based interventions, low-cost engineering solutions (such as rumble strips and speed breakers), and improved road-user education campaigns tailored to rural populations. However, without a dedicated and integrated road safety management framework that includes rural and low-volume roads within national policy structures, the high burden of crashes in these areas will persist. Therefore, any comprehensive road safety strategy-especially in LMICs-must give priority to upgrading the safety of rural and secondary road networks, supported by context-sensitive design standards, local stakeholder engagement, and consistent funding mechanisms.

As an example, Table 1.2 presents the distribution of road crashes by severity across urban and rural road environments in Sri Lanka. The data clearly indicate a disproportionately higher number of crashes occurring on rural roads compared to urban areas. Specifically, approximately 66% of all fatal crashes were recorded on rural roads, underscoring the heightened risk of severe outcomes in less urbanized regions. Similarly, around 59% of grievous and non-grievous crashes also occurred in rural areas.

Table 1.2 No of Accidents occurred in Rural and Urban areas from 2008 to 2017

Year	Fatal crashes in		Grievous and non-grievous crashes	
	Urban roads	Rural roads	Urban roads	Rural roads
2008	813	1363	7259	8970
2009	803	1460	7187	9137
2010	861	1718	7805	10879
2011	868	1630	8570	11592
2012	782	1535	9079	12810
2013	692	1498	8341	12057
2014	725	1536	7782	12071
2015	830	1771	8251	13531
2016	946	1892	8493	14490
2017	984	1979	8629	13140

Source: Sri Lanka Traffic Police, Accident Data Management System [9]

1.2 Problem Statement

The lack of a comprehensive and systematic road safety management framework remains a critical challenge across the global road transport sector. Despite ongoing efforts to reduce traffic-related fatalities and serious injuries, many countries continue to experience a high incidence of road traffic crashes. This persistent issue highlights the limitations of current approaches, which are often reactive, fragmented, and not grounded in long-term strategic planning.

A major barrier to sustained improvement in road safety is the lack of an integrated framework that enables authorities to effectively manage safety risks across the entire road network. Due to the complex and location-dependent nature of crash occurrences-shaped by factors such as road design, traffic flow, land use, and human behavior-it is difficult to consistently identify high-risk segments and prioritize interventions. This complexity necessitates a systematic method for detecting and ranking crash-prone areas, particularly given that the total cost of road crashes often exceeds the investment required for preventive improvements.

In many contexts, road safety efforts are hindered by the absence of structured systems for identifying hazardous locations, allocating resources efficiently, and implementing evidence-based countermeasures. Without such a framework, road authorities are limited to isolated interventions that lack coherence and long-term impact.

These challenges highlight the necessity of developing a strategic road safety management framework tailored to national road networks. Such a framework should facilitate the identification and classification of high-risk segments, support the prioritization of safety interventions based on data-driven analysis, and guide the efficient use of available resources. Ultimately, this will enable transport authorities to move from ad-hoc safety responses to a more coordinated, proactive, and goal-oriented approach that enhances overall road safety and reduces crash occurrences on a national scale.

1.3 Research Objective and Organization

The primary objective of this research is to develop a comprehensive and empirically grounded Road Safety Management Framework (RSMF) tailored for national road networks. While Sri Lanka is used as the case study context, the proposed framework is designed to be adaptable and scalable, making it relevant for application in other countries with similar road safety challenges. The research aims to address current gaps in identifying, assessing, and mitigating road safety risks through a structured and evidence-based approach.

The specific objectives of this study are as follows:

- Formulate a comprehensive road safety management framework that can be effectively applied to national road networks.
- Identify high-risk road segments using historical crash data and advanced analytical techniques.
- Assess and prioritize hazardous road sections using a systematic risk assessment methodology.
- Offering actionable recommendations for road development and transport authorities to support the implementation of targeted safety interventions, with the goal of reducing crash frequency and severity and enhancing overall road safety performance.

This study is structured to guide readers through the development and application of the proposed framework, beginning with a global overview of road safety challenges, followed by methodological approaches, case study analysis, and recommendations for policy and practical implementation.

CHAPTER 2
LITERATURE REVIEW

2.1 Road safety management tools and their effectiveness

Effective road safety management depends on reliable decision-making tools that enable authorities to systematically identify high-risk road segments and prioritize interventions to improve safety. Various tools have been developed globally for network-level prioritization, aiming to identify road segments that require immediate attention rather than prescribing specific mitigation strategies. These tools generally fall into three categories: proactive risk assessment models, crash history-based analyses, and hybrid models that combine both approaches.

The tables below outline various methods used to calculate road network risks, including crash data-based methods that rely on historical crash records, risk index-based approaches (e.g., CSI) that combine multiple factors into a composite score, and HSM model-type methods that use predictive modeling to estimate crash frequencies and severities. Additionally, subjective methods based on expert judgment and qualitative assessments, as well as risk matrix approaches that prioritize interventions by categorizing risks based on crash likelihood and severity, are discussed. The table highlights each method's characteristics, advantages, disadvantages, and limitations in the context of Sri Lanka.

Table 2.1 Road safety risk assessment tools based on crash data applications

Crash data method		
Model and Characteristics	Another reactive traditional approach (common in many Western countries and also adopted in Asia) is to use historical crash data that identifies high-risk road segments based on past accident records. These methods range from basic crash frequency counts to advanced statistical modeling. For instance, network screening techniques calculate crash rates per million vehicle-kilometers or apply Safety Performance Functions (SPFs) to determine whether a location has an unusually high number of crashes relative to traffic exposure (PIARC, Road Safety Manual) Uses historical crash data (frequency, severity (fatal, grievous, and minor crashes), location) to identify high-risk areas. Required data Crash Data: Includes the number, type, and severity of crashes over a defined period.	1. High risk crash analysis U S department of transportation[10] 2. Identifying high crash risk segments in rural roads using ensemble decision tree-based models[11] 3. Road safety manual a manual for practitioners and decision makers on implementing

	Location Data: GPS coordinates or chainage information for accurate segmentation. Traffic Volume Data: Often expressed as Annual Average Daily Traffic (AADT). Road Characteristics: Road width, presence of intersections, and lane types. Temporal Data: Seasonal or time-of-day variations in crash occurrences.	safe system infrastructure key messages for managers[12]
Advantages	Provides evidence-based insights for decision-making. Helps prioritize high-risk areas for safety investments. Captures real-world crash outcomes specific to the study area.	
Disadvantages	Missing or incomplete crash data can skew results. Focuses on past incidents rather than proactive safety planning. Underreporting minor crashes or location inaccuracies can affect reliability.	
Limitations	Non-fatal crashes often go unrecorded in rural areas. Inconsistent crash location reporting (e.g., vague references to chainage). Missing AADT data or road inventory details for low-volume roads.	

Table 2.2 Road safety risk assessment tools based on risk index and rating methods

Risk index and risk rating method		
Model and Characteristics	The Risk Index quantifies the safety of a road segment by combining multiple factors, such as crash frequency, severity, and exposure, into a single composite score. It is used to prioritize interventions by ranking road sections based on their relative risk levels. Key component of finding risk index Crash Data: Frequency and severity of crashes (e.g., fatal, grievous, non-grievous). Exposure Measures: Traffic volume (AADT) or length of the road section. Road Characteristics: Road geometry, speed limits, presence of intersections, and other contributing factors. Weighting Factors: Each component is assigned a weight to reflect its relative importance. The risk index is typically calculated as: $$RI = w_1.F_n + w_2.S_n + w_3.E_n + ..$$ where F_n,S_n,E_n are normalized crash frequency, severity, and exposure values and w_1, w_2, w_3 are their respective weights. In this method combines crash data	1. Development and use of the Austroads Safe System Assessment Framework [13] 2. Incorporating road safety into rural road network pavement management [14]

	and road environment features and weight factors can be adjusted to reflect local priorities or data availability. Normalization techniques ensure compatibility across diverse datasets	
Advantages	Capture multiple dimensions of road safety. Enables ranking of road segments by risk level. Supports evidence-based prioritization of safety interventions. Applicable to national or regional road networks.	
Disadvantages	Requires reliable data for accurate results. Arbitrary weight assignment may bias the index. Results depend heavily on local crash patterns and data quality.	
Limitations	Limited crash reporting, especially in rural areas. Lack of consistent benchmarks for normalizing crash and exposure data. Insufficient local studies to guide weight calibration. Missing details on geometric or environmental factors for roads.	
Model & Characteristics	iRAP is a widely adopted tool globally (including Asia) that proactively assesses road infrastructure risk. It produces Star Ratings (1-star least safe, 5-star safest) for road segments based on how well the road's design protects users. It also generates Risk Maps using crash data when available to illustrate fatality and injury rates on each stretch. iRAP's methodology explicitly considers all road users – vehicle occupants, motorcyclists, bicyclists, and pedestrians – making it very relevant in Asia where vulnerable road users form a large share of traffic. Many Asian countries have local iRAP programs (e.g. IndiaRAP, ChinaRAP, ThaiRAP) to assess thousands of kilometers and flag high-risk highways for upgrades.	International Road Assessment Program (iRAP)[15], [16]
Advantages	Considers multiple road users (e.g., pedestrians, cyclists, motorcyclists, vehicle occupants) and evaluates safety conditions for each group.	
Disadvantages	Requires extensive data collection, which can be resource-intensive, particularly in developing countries	
Limitations	Some countries, such as Sri Lanka, may lack the infrastructure or data availability to implement and maintain the system effectively. The coefficients used in star ratings have to be calibrated for the Sri Lankan context, which is highly data extensive.	

Model & Characteristics	Like the start rating measures, each inspected road is given an IRR value concerning the roadside infrastructure arrangement. “IRR value is calculated by coding the following road and roadside features: land use of the area, the stereotype of the road, lane width, shoulder width, horizontal alignment, hazards from the roadside environment, intersection density, access points, traffic volume, operating and posted speed limits	Infrastructure risk rating (IRR) manual[16]
Advantages	Specific provisions for rural roads make it suitable for regions with significant rural road networks, like Sri Lanka.	
Disadvantages	May not account for behavioral factors (e.g., driver errors, pedestrian behavior) that contribute to crashes.	
Limitations	Traffic data and speed data are not available for Sri Lankan low-volume roads	

Table 2.3 Road safety risk assessment tools based on road safety audit and inspections

Road safety audit and Inspections		
Model and Characteristics	Road safety audits and inspections provide a proactive alternative to crash-based methods. These involve expert teams assessing road networks to identify hazardous features such as inadequate pedestrian facilities, poor lighting, or dangerous curves. This is a qualitative tool used in both Western and Asian countries to supplement data. For instance, the EU Road Infrastructure Safety Management directive mandates periodic network-wide safety inspections in addition to ranking by crashes. Some Asian countries have adopted similar practices (e.g. road safety inspection units in Malaysia or Vietnam) to identify high-risk segments where infrastructure deficiencies are obvious, even if crash data is sparse. While effective, audits/inspections are resource-intensive and subjective, so they are often used on priority routes identified by other means	1. Delivering road safety in Sri Lanka (leadership prioritize and initiative to 2030)[3] 2.Road safety audits practical guides for road safety auditors (TRACECA Region)[17] 3. Main guidelines in road safety audits: a literature review[18] 4. Vietnam National Road Safety Goals and Action plan Opportunities and Challenges [19] 5. Malaysia road safety plan 2022-2030 ministry of transport Malaysia [20]
Advantages	Captures information not available in crash databases or models.	

	Useful for identifying emerging risks or cultural-specific safety challenges Involves minimal use of technology or expensive data collection tools. Can directly inform targeted, small-scale safety interventions
Disadvantages	Opinions and assessments may vary between individuals, leading to inconsistent results. It is difficult to compare risks objectively or prioritize interventions systematically.
Limitations	Addresses the lack of comprehensive crash and traffic data, especially in rural areas. Useful for assessing partially completed or rural roads where data collection is incomplete. Challenging to apply across the entire national road network.

Table 2.4 Road safety risk assessment tools based on hybrid and specialized tools

Hybrid and Specialized Tools		
Model and Characteristics	Several tools combine infrastructure assessment with crash data. Australia's ANRAM (Australian National Risk Assessment Model), for example, merges iRAP star ratings with crash history to produce enhanced risk estimates for each road section. In Europe, EuroRAP produces both Risk Maps (using crash rates) and Road Protection Scores (similar to star ratings) to rank the network. Thailand has experimented with a "ThaiRAP Lite" star rating tool linked to their road asset database.	1. Australian National Risk Assessment Model (ANRAM) [21]2. The EuroRAP RPS method as a safety instrument[22]
Limitations	ANRAM's assumptions may not fully capture the complexities of Sri Lanka's Road network, where pedestrians, cyclists, and slow-moving vehicles often share the roadway with motorized traffic.	
Model and Characteristics	GIS-Enhanced Risk Matrices Often paired with GIS mapping tools to visualize high-risk areas across road networks and combine Geographic Information Systems (GIS) with the likelihood and severity framework to create spatially visualized risk assessments, helping to prioritize interventions based on geographic and contextual factors. The EuroRAP methodology includes GIS tools to create risk maps that highlight high-risk road sections based on matrix results. Additionally, GIS-based decision support systems are increasingly used in Asia – for example, Thailand's proposed "Safe Applica" interactive map lets	1. Thailand Road Safety Data and Analysis for Development of Road Safety Map Application[23] 2. EuroRAP Risk Mapping Protocol," European Road Assessment Programme, 2010 [24] 2. Road Safety Risk Evaluation

	authorities visualize crashes alongside road features and land use to spot high-risk locations. These hybrid tools acknowledge that no single data source is perfect and try to paint a more comprehensive risk picture.	Using GIS-Based Data Envelopment Analysis Artificial Neural Networks Approach[25]
Advantages	Enables visual mapping of high-risk areas, making it easier to communicate findings to stakeholders. Helps identify geographic patterns in accident-prone zones. Combines multiple datasets such as crash history, road geometry, land use, traffic volumes, and environmental conditions.	
Limitations	Coordination across agencies for data sharing is challenging. Limited and inconsistent crash and geolocation data in SLADMS.	

Table 2.5 Road safety risk assessment tools based on HSM models

HSM Models		
Model and Characteristics	HSM (Highway Safety Manual) models are statistical models used to predict crashes on roadways based on traffic volume, roadway characteristics, and environmental factors. These models aim to estimate the expected average crash frequency for specific roadway types and conditions. The HSM prediction models are primarily built using Safety Performance Functions (SPFs), regression models that relate crash frequency to roadway and traffic variables. Main component of HSM Safety performance functions are core predictive equations that estimate the number of crashes based on traffic volume (AADT) and roadway characteristics. Example SPF for a rural two-lane road $$E = a.AADT^{b}.e^{c.x_1 + d.x_2}$$ E is expected crash frequency. a,b,c,d, are Calibration coefficients. x_1 ,x_2 Roadway or traffic variables (e.g., lane width, shoulder width) Calibration Factors HSM models are developed using crash and roadway data from specific countries or regions, so to apply them in a local context calibration factor must adjust the SPFs to reflect local conditions. $$cf = \frac{observed\ crashes}{predicted\ crashes\ by\ HSM}$$ Crash Modification Factors (CMFs)	1. Highway safety manual 2010[26] 2. Safety Performance Function Calibration and Development for the State of Alabama:Two-Lane Two-Way Rural Roads and Four- Lane Divided Highways[27]

	CMFs are used to adjust the SPF's predicted crash frequency based on specific roadway treatments or conditions. Example: Adding a median to a road segment might reduce crashes by 30%, resulting in a CMF of 0.7. $E_{adjust} = E.cmf_1.cmf_2 \ldots \ldots$	
Advantages	Provides statistically validated predictions. Helps justify infrastructure improvements. Applicable to different road types and conditions.	
Disadvantages	The Highway Safety Manual (HSM) methods mainly focus on traditional factors like road design and traffic volume but may miss other important risks such as driver behavior, environmental conditions, or social and economic factors unique to a specific area.	
Limitations	Incomplete crash databases and missing AADT for rural areas. Road conditions in Sri Lanka (e.g., narrow lanes, mixed traffic) differ significantly from the settings in which SPFs were originally developed. Original SPFs were developed for developed countries with different traffic patterns.	

2.2 Influence of land use characteristics on road safety outcomes

Land use is a critical factor in road safety risk assessment, influencing traffic patterns, exposure to risk, and user interactions. The urban and rural contexts present distinct road safety risks shaped by their unique characteristics. In urban areas, high traffic density, mixed land use, and frequent pedestrian and cyclist activity create complex traffic environments, increasing the likelihood of low-speed collisions and conflicts between vehicles and vulnerable road users (WHO, 2018) [28]. Challenges such as congestion, poorly planned parking, and inadequate lighting further exacerbate risks [29]. In contrast, rural areas face higher-speed traffic, limited infrastructure, and longer travel distances, leading to more severe accidents, often compounded by factors like driver fatigue, wildlife crossings, and poor road maintenance [30]. Additionally, rural regions often suffer from delayed emergency response times and higher rates of alcohol-related incidents due to limited public transportation [31],[30]. While urban safety strategies focus on traffic calming, pedestrian-friendly designs, and efficient public transit [32], rural areas require improved road infrastructure, lower speed limits in high-risk zones, and enhanced emergency services (OECD, 2019) [33]. Understanding these contextual differences is essential for developing targeted road safety interventions that address the specific risks in each setting.

2.2.1 Functional Classification of Roads

The expanded functional classification system for highways and streets builds upon the current system to provide a better basis for the preliminary engineering of a design project. This system helps in developing the purpose and need of a project more effectively. It includes additional contexts beyond urban and rural areas, facilitates the accommodation of modes other than personal vehicles, and adds overlays for transit and freight. Since 1984, the AASHTO "Green Book" (A Policy on the Geometric Design of Highways and Streets) and other roadway design criteria have relied on a functional classification system. This system categorizes roads into a hierarchical network of arterials, collector roads, and local roads, with additional distinctions between urban and rural areas. The details of this classification system are outlined in Highway Functional Classification Concepts, Criteria, and Procedures [34].

The Expanded Functional Classification System (FCS) identifies five distinct contexts that represent unique land use environments. These contexts are rural, rural town, suburban, urban, and urban core. Each context requires different geometric design practices for factors such as operating speeds, mobility/access demands, and user groups.

A study done in Tehran by Mostafa Mehdian and his team found that, in addition to traditional factors like geometric design characteristics, parking lots, land use features, and accessibility; real-time data from the Sydney Coordinated Adaptive Traffic System (SCATS) and average speed of vehicles collected by Location-Based Services (LBS) are considered as new variables for estimating the FCS. Results show that on-street parking has the highest impact, and the land use variable has the lowest impact on speed that changes the FCS [35].

Tissa U. Liyanage's research explores traffic behavior in Sri Lanka's Southern Province across three different land use categories. The study examines 125 roads using data from a 24-hour traffic survey. The survey specifically focuses on areas within a 500m distance from the road start and categorized the road sections based on their distance from the coastline as follows: below 5 km as urban, 5 km to 15 km as semi-urban, and over 15 km as rural [36].

2.2.2 Analyzing the influence of land use patterns on Annual Average Daily Traffic (AADT) behavior

There are currently three principal approaches to the estimation of Annual Average Daily Traffic (AADT), which include econometric regressions, travel-demand modelling and neural network modelling. Explanatory factors are important in the regression model. Neveu (1983) considered population, automobile ownership, number of households, and employment as determinants of road [37]. Mohamad et al. (1998) emphasized the significance of road features and population characteristics in estimating the Annual Average Daily Traffic (AADT). Their approach likely involved the following aspects.

Road Features: Characteristics such as road width, number of lanes, type of road (highway, arterial, local), presence of intersections, and road condition. These factors can influence traffic flow and capacity, thereby affecting AADT estimates.

Population Characteristics: Population density, urbanization level, and socio-economic factors of the areas surrounding the road. Higher population density and urbanization typically correlate with higher traffic volumes. Economic activities in the region, such as commercial and industrial zones, also contribute to traffic levels.

By integrating these variables, Mohamad et al. (1998) aimed to create a more accurate model for predicting AADT. This methodology helps in understanding the interaction between road infrastructure and demographic factors, leading to more reliable traffic estimates which are crucial for planning, designing, and managing road networks.

Tsapakis et al. (2012) found that road class, population density and locations are key predictors for freight traffic. Thus, population, road types, employment, vehicle fleet and locations (e.g. urban or rural) are oft-cited factors in AADT modelling by this method, with population density being the most significant factor in the [38].

McCord et al. (2002) present a method to estimate AADT from a single image. Their approach is based on automatic recognition of satellite images and thus can be applied to a large area. However, as noise associated with the images can interfere with this process, a ground-based data source is needed to improve the estimation performance. Other limits in their approach are that on-street parked vehicles are usually mixed with moving vehicles in urban areas, and they extrapolate short period data to AADT by multiplying the length of [39]

The relationship between Annual Average Daily Traffic (AADT) and the roadway environment is crucial for understanding traffic dynamics and road safety. The behavior of AADT will be analyzed with the roadway environment to identify patterns and influences, further enhancing the effectiveness of road safety strategies. Always we can observe high AADT often correlates with urban areas with dense traffic and frequent intersections, whereas lower AADT is typical in rural areas with higher speeds and fewer traffic controls. Establishing this relationship helps in categorizing road sections, prioritizing safety measures, and designing targeted interventions to improve overall road safety.

The study done by the Department of Highway and Transportation Research, Korea Institute of Civil Engineering and Building Technology (KICT) has proven that distribution of AAHT by considering the roadway traffic characteristics and environment. They have done some reliability analysis of the Annual Average Hourly Traffic Volume Ratios to AADT Groups[40].

Table 2.6 Behavior of AADT with Urban, Suburban and Rural Road Context

Hour of Day	**Urban**			**Suburban**			**Rural**		
	AAHT	**H**	**ECDF**	**AAHT**	**H**	**ECDF**	**AAHT**	**H**	**ECDF**
1	308	0.0089	0.0089	156	0.0077	0.0077	48	0.0055	0.0055
2	204	0.0059	0.0148	98	0.0048	0.0125	30	0.0035	0.0090
3	158	0.0046	0.0193	76	0.0037	0.0162	24	0.0028	0.0118
4	158	0.0046	0.0239	78	0.0038	0.0201	26	0.0030	0.0148
5	260	0.0075	0.0314	130	0.0064	0.0265	44	0.0051	0.0198
6	620	0.0179	0.0493	338	0.0166	0.0431	102	0.0118	0.0316
7	1426	0.0411	0.0904	762	0.0375	0.0805	256	0.0295	0.0611
8	2388	0.0689	0.1593	1360	0.0669	0.1474	516	0.0595	0.1207
9	2520	0.0727	0.2320	1508	0.0742	0.2216	658	0.0759	0.1966
10	2078	0.0600	0.2920	1210	0.0595	0.2811	538	0.0621	0.2587
11	1982	0.0572	0.3491	1206	0.0593	0.3404	558	0.0644	0.3230
12	1912	0.0552	0.4043	1188	0.0584	0.3988	562	0.0648	0.3879
13	1812	0.0523	0.4566	1136	0.0559	0.4547	534	0.0616	0.4495
14	1954	0.0564	0.5130	1234	0.0607	0.5153	590	0.0681	0.5175
15	2030	0.0586	0.5715	1282	0.0630	0.5784	602	0.0695	0.5870
16	2080	0.0600	0.6315	1306	0.0642	0.6426	604	0.0697	0.6567
17	2200	0.0635	0.6950	1366	0.0672	0.7098	628	0.0725	0.7291
18	2546	0.0735	0.7684	1540	0.0757	0.7855	678	0.0782	0.8073
19	2506	0.0723	0.8407	1458	0.0717	0.8572	626	0.0722	0.8796
20	1760	0.0508	0.8915	954	0.0469	0.9041	358	0.0413	0.9209
21	1358	0.0392	0.9307	724	0.0356	0.9397	260	0.0300	0.9509
22	1092	0.0315	0.9622	566	0.0278	0.9675	202	0.0233	0.9742
23	794	0.0229	0.9851	402	0.0198	0.9873	138	0.0159	0.9901
24	516	0.0149	1	258	0.0127	1	86	0.0099	1

In this study at first, 536 permanent traffic volume counting stations were divided into urban, suburban, and rural area groups with the classification method using an administrative division system to prepare data for the analysis as done in the cluster analysis. Next, the average value of the annual average hourly traffic volume ratio to AADT of the stations classified into each group is used and the distribution of the annual average hourly traffic volume ratio to AADT of each of these groups is calculated. For each group, Table 2.6 outlines the annual average hourly traffic volume, annual average hourly traffic volume ratio to AADT, and cumulative annual average hourly traffic volume ratio to AADT to be used as the empirical cumulative distribution function (ECDF) in the analysis.

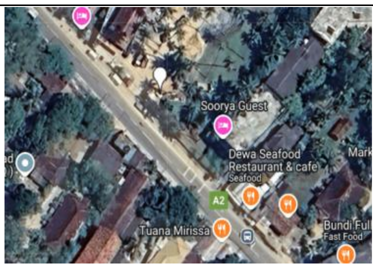
In another research, Fu et al. (2017) conducted an in-depth analysis to estimate Annual Average Daily Traffic (AADT) across different types of road environments, including urban, suburban, and rural areas. Their study employed a combination of high-resolution satellite imagery and ground-level observations to assess traffic patterns and land use. They found significant variations in AADT values corresponding to the distinct characteristics of each area. Urban areas showed high AADT due to dense traffic and numerous intersections, suburban areas exhibited moderate AADT reflecting mixed land use, and rural areas had lower AADT, characterized by higher speeds and fewer traffic controls. Based on this study the corresponding AADT data for different road environments are summarized in Table 2.7. This comprehensive approach provided a clearer understanding of how traffic volume varies with the roadway environment, offering valuable insights for targeted traffic management and safety interventions[41].

Table 2.7 Representing of AADT data in Urban and Rural Areas

	Type of roadway	Cars	LGVs	HGVs	Buses	MCs	Min	Max
AADTs Urban	Motorways	46,171	6207	3210	841	721	1758	81,516
	National ways	21,299	2890	1330	412	300	38	81,516
	Regional ways	13,193	1872	855	358	129	24	29,058
	Local roads(heavy)	7779	748	219	55	57	0	28,054
	Local roads(light)	5337	593	152	103	27	0	28,050
	Residential roads	140	9	1	0	2	0	418
AADTs Rural	Motorways	31,571	4255	3486	573	493	1459	81,516
	National ways	6585	900	602	113	97	96	61,990
	Regional ways	4478	660	345	88	36	8	28,561
	Local roads(heavy)	388	37	11	3	3	0	16,480
	Local roads(light)	444	49	13	9	2	0	12,825
	Residential roads	139	14	1	0	1	2	988

Table 2.8 presents the Average Daily Traffic (ADT) figures obtained from a comprehensive traffic survey conducted by the University of Moratuwa in 2017. The survey covered multiple regions across the country and recorded traffic volumes over a defined observation period. To derive the ADT values, the total observed traffic volumes were adjusted using a standard conversion factor of 1.4. This factor was applied to account for fluctuations in traffic flow and to normalize the data, thereby providing a representative estimate of average daily traffic conditions.

Table 2.8 Average daily traffic data for different land use area in Sri Lanka

<table>
<tr><td>Urban Environment</td><td>Sub-urban Environment</td><td>Rural Environment</td></tr>
<tr><td>
</td><td>
</td><td></td></tr>
<tr><td>Nugegoda division ADT 31544.8 veh</td><td>Balapitiya division ADT 19059.6 veh</td><td>Haliela division ADT 3172.4 veh</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Maharagama division ADT 53517 veh</td><td>Mirissa area ADT 20452.6 veh</td><td>Thanamalwila division ADT 2879 veh</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Colombo Union place ADT 55048 veh</td><td>Bandaragama division ADT 30236 veh</td><td>Mattala division ADT 2270 veh</td></tr>
</table>

The characteristics of the roadway environment are closely linked to traffic demand, which is typically quantified using the Average Annual Daily Traffic (AADT) metric. Different roadway contexts exhibit varying levels of traffic volume, reflecting differences in land use, population density, and economic activity. Table 2.9 illustrates the general relationship between roadway environments and corresponding AADT levels. As shown, areas categorized as urban core experience very high traffic volumes, while rural areas are associated with significantly lower traffic demand.

Table 2.9 AADT Levels Across Different Roadway Environments

Roadway environment	AADT
Urban core	Very high
Urban	High
Sub urban	Considerable
Rural town	Average
Rural	Very low

2.2.3 Relationship between AADT and crash collision frequency

The study done by, Baek et al. (2006) explored the relationship between Annual Average Daily Traffic (AADT) and crash collision frequency as shown in figure 2.1. Their research aimed to understand how variations in traffic volume influence the occurrence of road crashes. By analyzing extensive traffic and crash data, the study demonstrated a positive correlation between higher AADT levels and increased collision frequency. This relationship was particularly pronounced in urban areas where traffic density is higher[42].

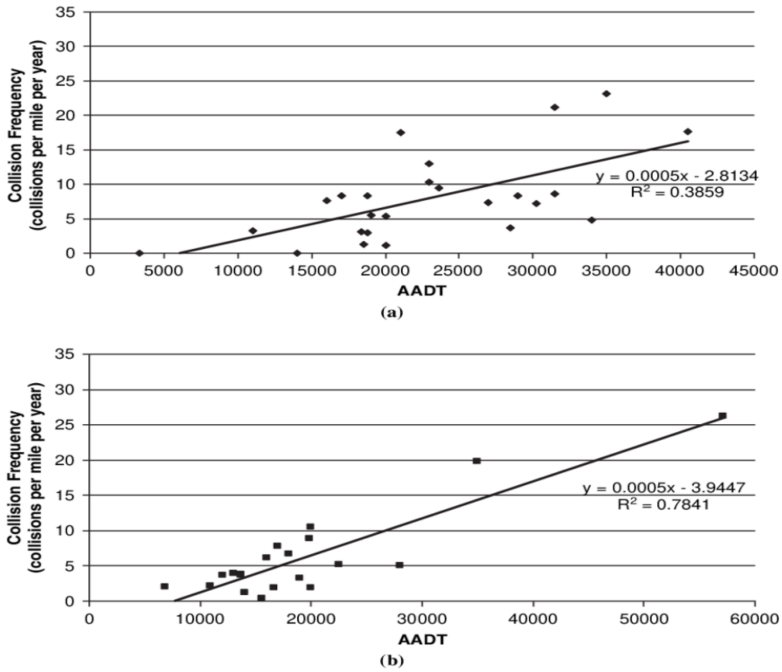


Figure 2.1 Distribution of Crash collisions with AADT

2.3 Influence of roadway deficiencies on road safety outcomes

Identifying roadway deficiencies is a crucial aspect of road risk assessment, as infrastructure-related factors significantly contribute to crash occurrences especially in the context of low- and middle-income countries. Deficiencies in road geometry, surface conditions, signage, lighting, and intersections can create hazardous conditions for road users. According to Mitra et al. (2021), inadequate road markings, limited visibility, sharp curves, and insufficient pedestrian infrastructure significantly contribute to elevated crash risks. The study also highlights that pavement deterioration, including potholes and uneven surfaces, poses additional hazards for vulnerable road users [43].

Kumar et al. (2015) proposed a Road Safety Index (RSI) model that evaluates road infrastructure safety by considering five key factors: roadway characteristics, traffic characteristics, roadside characteristics, pavement characteristics, and miscellaneous factors. The study involved selecting three different road stretches in Bengaluru, India, for RSI evaluation and validation. Various factors such as carriageway width, number of curves, gradient, speed limits, road markings, presence of obstacles, lighting, footpaths, pavement condition, and bus stop locations were quantified using expert-based value scoring methods [44]. The study assigned weightages to these factors based on expert opinions, aggregating them into a composite RSI score.

Kanuganti et al. (2017) conducted a comprehensive road safety analysis using a multi-criteria approach in India. Their study aimed to assess road safety by integrating various factors, including road infrastructure, traffic characteristics, and accident data. The research employed a multi-criteria decision-making (MCDM) framework to evaluate road segments based on safety performance. The authors highlighted the significance of incorporating both quantitative and qualitative criteria to prioritize high-risk road sections [45].

Ahmed et al. (2020) applied the Road Safety Index (RSI) to assess risks on rural roads, analyzing factors like lane width, surface roughness, median presence, and intersection spacing. Using GIS-based crash mapping and regression analysis, the study confirmed that lower RSI values correlate with higher crash frequencies, validating RSI as an effective tool for predicting infrastructure risks and improving rural road safety [46].

2.4 Road network segmentation strategies and their impact

Road network segmentation involves dividing a road network into smaller, more manageable segments for various purposes, including traffic analysis, road maintenance, safety assessments, and transportation planning. Effective segmentation strategies are essential for optimizing the performance and management of the road network. Here are some common strategies used in road network segmentation.

Machine learning algorithms can significantly enhance road network segmentation by analyzing large datasets to identify optimal segmentation points based on traffic flow patterns, accident data, and road conditions. These techniques involve collecting and preprocessing data, using clustering and time series analysis to identify traffic patterns, employing classification models to predict accident likelihood, and applying regression models and image analysis for road condition evaluation. By integrating multiple data sources and using segmentation algorithms, machine learning enables optimized traffic management, targeted safety interventions, efficient resource allocation, and data-driven decision-making, ultimately leading to a more efficient, safe, and well-maintained road network.

Static segmentation method

High crash road segments are identified in the study through a fixed-length segmentation approach. The road is divided into segments with specific lengths, and accidents within these segments are systematically counted.

Dynamic segmentation method

The study concludes that the length of high crash road segments can vary based on the diverse nature of accident causes along the road. It highlights potential limitations in using static segmentation methods, suggesting that such approaches may introduce errors in results analysis and compromise the accurate identification of high crash road segments [47].

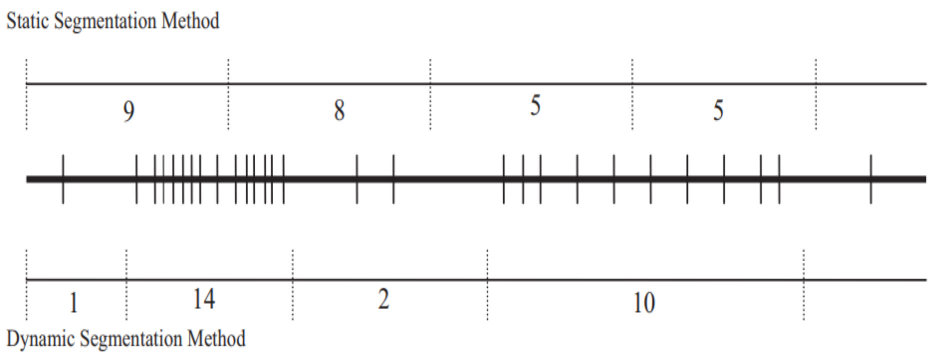


Figure 2.2 Illustration of static and dynamic road segmentation method

In Romania, high-crash road segments are identified using two definitions. Outside residential areas, a segment is considered high crash if there are at least 4 accidents in a length of less than 1000 m over 3 years. Within residential areas, a segment is identified as high crash if there are at least 4 accidents in a length of less than 100 m over 3 years. This method uses a template (100m or 1000m) for segmentation, as outlined by Elvik in 2008 [48].

A different method for road segmentation is proposed by Torke. In this approach, the road is divided into 0.2 km segments, which can either continue along the highway or be incorporated into other segments or intersections. In Austria, a fixed 2.5 km segment is used as a template that moves along the road. Segments that meet the specific criteria for high accident-proneness within this template are defined as high crash road [49]. Kononov and Allery (2003) studied the level of road safety service by dividing the road into 2-mile segments after separating certain parts of the road to identify high crash road segments [50]. According to a Federal Highway Administration report (1981), the length of high crash road segments should be 0.3 miles. Additionally, the Texas Transportation Institute suggests that the length of high crash road segments should be at least 0.1 [51].

In Belgium, a high-crash road segment is determined by police reports, identifying every segment where three or more accidents happen within three years. This method uses a template of 100 miles to pinpoint high-crash road segments. Consequently, segments with a maximum length of 100 miles and three accidents are documented, following the approach outlined by Geurts in 2006 [52]. Another study done by Pant et al. in 2003 uses road segments with a length of 0.25 miles. The segments are carefully chosen to avoid being too long or too short. The list of segments includes those that are less than 0.25 miles and those that are between 0.25 and 0.5 miles, depending on specific conditions [53].

In regions which are far from the residential areas, high crash road segment is defined while there are at least four accidents during three years in a segment with the length of less than 1 Km, but in residential areas, high crash road segments are defined if at least four accidents happen within three years in that segment with the length of less than 0.1 Km[54].

Table 2.10 presents a comparison of international criteria used to define high-risk or hazardous road segments in several countries. These definitions vary based on segment length, time duration, and accident severity or frequency thresholds [47].

Table 2.10 Definition of high crash road segments in some regions

Country	Definition
Germany	300 m road segments
	More than 3 accidents during 1 year and more than 5 accidents during 3 years
United Kingdom	300 m road segments
	The location in which the total number of accidents is more than 12 during 3 years.
Spain	1 km segments
	More than 5 injury accidents or 2 fatal accidents during 1 year
	More than 10 injury accidents or 5 fatal accidents during 3 years
Norway	100-meter road segments and more than 4 fatal accidents during one year
Czech Republic	A road segment of 250 meters
	At least 3 injury accidents during one year or 3 similar injury accidents during 3 years
	At least 5 similar accidents during 1 year
Netherland	At least 10 total accidents or at least 5 accidents with certain specifications

2.5 Data mining and clustering techniques for black spot identification in road safety analysis

In the realm of data mining, clustering techniques play a pivotal role, with several algorithms employed for diverse applications. Notable among these algorithms are K-means and K-modes. The K-means algorithm relies on a centroid approach, while the K-modes algorithm is tailored for nominal data. Specifically, the K-means algorithm stands out as a widely embraced method in data mining, particularly in the identification of clusters based on accident [55]. As indicated by Géron et al.2019, the DBSCAN clustering algorithm demonstrates proficiency in identifying clusters, specifically blackspot road segments, irrespective of their [56]. Additionally, both Géron (2019) and Szénási & Csiba (2014) [56], [57] emphasize a notable characteristic of the DBSCAN algorithm: it operates without the need for specifying initial centroids. Instead, it assesses distances to every point in the dataset, forming clusters based solely on spatial density surpassing a predetermined threshold and it has been adapted to work with road accidents identified by GPS coordinates.

In a study conducted by Lee et al. (2017), an examination was undertaken to compare the efficacy of the k-means clustering algorithm and the DBSCAN clustering algorithm. Subsequent to this comparison, the DBSCAN algorithm was employed for the identification of black spots. Following black spot identification, an in-depth analysis of their operational roadway factors was conducted, and recommendations for preventive measures against vehicle accidents were [58].

Another study done by Mirza Boroujerdian et al. 2015 presents an evolutionary algorithm for recognizing high and low crash road segments using Genetic Algorithm as a dynamic segmentation method. In this study, a novel chromosome coding method and a fitness function which are consistent with Genetic Algorithm are proposed. The proposed methodology is also validated by using two mathematical parameters. Therefore, a genetic algorithm was chosen to solve the optimization problem. Afterward, the proposed dynamic segmentation method is compared with the other static segmentation methods along 51 km of Shahrood–Sabzevar highway. The results illustrate that genetic algorithms can present an excellent solution for optimization of the problem well. One of the applications of the approach is to identify high and low crash road segments with variable lengths and their priorities so as to the safety of special road sections are improved before entering to the worse [54].

The sliding window method is widely used for analyzing road accident data, particularly in identifying accident black spots. This technique involves dividing a road into uniform segments and counting the number of accidents in each segment over a specified period. Segments with accident counts exceeding a certain threshold are flagged as potential black spots. This method is computationally efficient and relies solely on the accident database, making it a practical tool for initial analysis.

Several studies have explored the application of the sliding window method in various contexts. For example, research by Lee and Lee (2013) and Elvik (2008) highlights its traditional use, while Geurts et al. (2006) discuss its adaptability with variable window lengths to identify both small and large black spots. The method has evolved to include overlapping segments, enhancing sensitivity and identifying more potential black spots [59].

Grembek, O., & Medury, A. (2016). This study proposes a dynamic programming-based hot spot identification approach for pedestrian crashes, comparing it with the sliding window method. The research highlights that the sliding window method suffers from fixed window length assumptions, which can limit its effectiveness. The dynamic programming approach was found to generate more hot spots with higher crash concentrations while offering smaller segment lengths, proving more efficient for pedestrian crash hot spot identification [60].

Naderan, A., & Shahi, J. (2010). This research focused on developing a model for crash frequency analysis using a sliding window approach. By adjusting the window length and position, they were able to identify road segments with higher crash frequencies effectively. The study demonstrated that the sliding window method is beneficial for continuous monitoring and updating of hazardous locations on road networks [61].

CHAPTER 3
METHODOLOGY

This chapter outlines the methodological approach adopted to achieve the main objectives of the study, which focus on developing structured road safety management framework. The methodology integrates roadway environment characteristics, infrastructure conditions, and crash data into a structured and replicable assessment process. It establishes a systematic procedure for segmenting the road network, analyzing crash patterns, evaluating safety-critical attributes, and determining the overall risk level of each road segment. The framework is designed to function as a practical tool for national-level road safety management by ensuring consistency, transparency, and evidence-based decision-making.

The methodological structure presented in this chapter also reflects the broader intention of the study to develop an approach that remains scalable and adaptable across different roadway contexts. Although the case study focuses on Sri Lanka, the framework is suitable for application in other countries, particularly in low- and middle-income settings where structured, risk-based safety management practices are needed. The following sections describe each methodological stages in detail, outlining the analytical steps adopted to implement the framework.

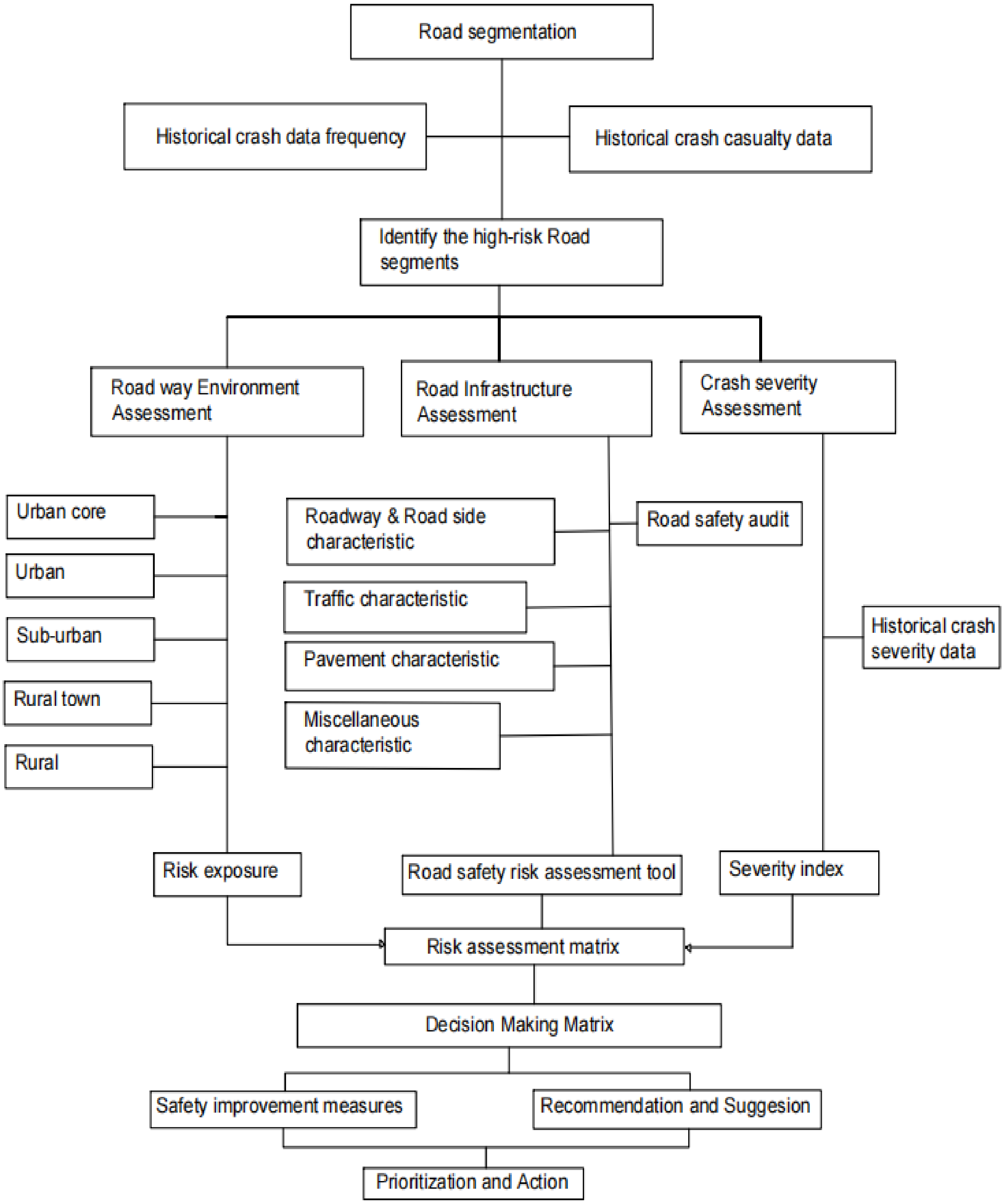


Figure 3.1 General flow chart for the methodology

3.1 Data collection

A fundamental component of the methodology is the structured collection of crash data that captures essential details such as chainage, crash severity, casualty counts, and contributory factors. In low- and middle-income countries, the quality and consistency of crash data vary widely, reflecting differences in institutional capacity and reporting practices. Police departments remain the predominant source of crash records; however, in more advanced or integrated systems, information is aggregated across multiple agencies including transport authorities, local governments, and healthcare institutions. Such multi-agency integration improves data completeness and reliability, enabling more robust and evidence-based road safety assessments.

Table 3.1 summarizes the primary data sources commonly used in road safety studies, highlighting their descriptions, advantages, and limitations. These sources, ranging from police crash reports to integrated national crash database.

Table 3.1 Common sources of road crash data collection

Source	Description	Strengths	Limitations
Police Crash Reports	Filed by traffic police at the scene of the crash or soon after	Widely available, standardized format	Underreporting of minor crashes, possible data inconsistencies
Hospital & Emergency Records	Medical data on crash victims collected from hospitals and emergency responders	Provides casualty severity details and health outcomes	Not always linked to crash location or road conditions
Insurance Claims	Reports submitted by vehicle owners to insurance companies	Includes financial and material loss info, often verified	May omit unreported crashes, access may be restricted
Roadway Site Investigations	On-site inspections by engineers or road safety auditors	Offers detailed context (e.g., road geometry, signage, environment)	Resource-intensive, usually done after major crashes
Local Government Reports	Data collected by municipal or regional transport agencies	Helps identify regional blackspots and infrastructure issues	Often lacks standardization; may duplicate police data
Integrated Crash Databases	Unified national systems (e.g., Sri Lanka's SLADBMS) combining multiple sources	More holistic view; supports big data analysis	Requires technical capacity and strong inter-agency collaboration

Table 3.2 provides a comparative overview of the primary road crash data sources utilized by selected countries. Each nation has developed its own systems, ranging from national databases to police and transport department reports, to systematically record, analyze, and manage road traffic accidents.

Table 3.2 Crash data sources used by different countries

Country	Main sources
USA	Fatality Analysis Reporting System (FARS), National Automotive Sampling System (NASS), State Police Reports
UK	A standardized dataset collected by UK police forces for all reported personal injury road traffic accidents. Road Accident In-Depth Studies
Canada	National Collision Database (NCDB), Provincial Police Reports
Australia	Road Deaths Database, State Transport Databases
New Zealand	Crash Analysis System (CAS)
European Union	Community Road Accident Database
Japan	Institute for Traffic Accident Research and Data Analysis (Japan) (ITARDA), Police Reports
South Korea	Traffic Accident Analysis System
India	National Crime Records Bureau – Accidental Deaths and Suicides in India NCRB (ADSI), Integrated Road accident database (iRAD) State Police Reports
Sri Lanka	Sri Lankan Accident Data Management System (SLADMS) Police Traffic Division Reports

3.2 Segmentation of national road network

To examine crash distribution and identify hazardous locations, this study applies a consistent spatial framework that subdivides the national road network into equal-length analytical units. International practice demonstrates considerable variation in segment length commonly between 100 and 500 meters or more because countries differ in the precision of their crash data, the physical characteristics of their road networks, and the safety management practices employed by relevant authorities. These differences highlight that the choice of segment length is inherently context specific. Consequently, selecting an appropriate segmentation scale requires balancing the need for fine spatial detail with the requirement for statistically reliable crash estimates.

In Sri Lanka, the Accident Data Management System (SLADMS) records crash locations at 100-meter intervals. In this study, the analysis relies on uniform 0.5-km (500-meter) segments constructed from the original SLADMS records, providing a consistent analytical framework. Segmenting the corridor at 500-meter intervals maintains sufficient spatial resolution to detect localized crash patterns while reducing the random fluctuations that commonly arise in shorter segments. This segmentation scale therefore provides a practical balance between spatial detail and statistical stability. The selection of the 0.5-km segment length reflects the characteristics of the available crash data and the analytical objectives of the study, highlighting the importance of context-specific decisions in roadway segmentation for safety evaluations.

To implement the segmentation framework, as an example, a 100-km road section is divided into 200 uniform segments of 0.5 km each. All crash records occurring within each segment are assigned to that unit and incorporated into the analysis. This approach enables each 500-meter unit to function as a fundamental analytical block, supporting a consistent and comparable assessment of spatial crash patterns across the route.

3.3 Identification of high-risk road sections

The identification of high-risk road sections is a fundamental step in developing an effective road safety management system. By locating segments with disproportionately high crash frequencies or severe accident outcomes, authorities can prioritize targeted interventions where they are most needed. This focused approach ensures the optimal use of limited resources and enables timely decision-making for corrective measures such as infrastructure upgrades, traffic calming strategies, or enforcement campaigns.

In this research, high-risk road segments are primarily identified based on two complementary criteria, crash frequency and crash severity. Crash frequency measures the number of accidents occurring within each road segment, providing insight into areas with a high concentration of incidents. Crash severity, on the other hand, evaluates the consequences of these accidents, for example by examining the number of casualties per incident, highlighting locations where crashes result in the most serious outcomes. This measured provides a more comprehensive understanding of road safety, as it highlights not only where accidents occur, but also where the most severe accidents are happening.

To identify high-risk road sections based on crash frequency, multiple analytical approaches were explored, including the sliding window method and K-means clustering. Two variations of the sliding window method, referred to Sliding window method 1 and Sliding window method 2 were analyzed and compared to determine the most suitable approach for further analysis. The sliding window approach allows for a dynamic analysis of crash frequency over overlapping road segments, helping to detect localized clusters of high crash concentration. In contrast, the K-means clustering method groups road sections based on similar crash patterns without being constrained by fixed distances. The outputs of all approaches were compared in terms of accuracy in identifying hotspots, fairness in data distribution, and practical suitability for implementation in a road safety management framework. Based on this evaluation, the most reasonable and adaptable method was selected for subsequent stages of the analysis.

For each analytical method, road safety data were processed using a Python-based algorithm specifically developed for this study. Sample programs and data analysis procedures are provided in Appendix C.

3.3.1 High risk segments identification using sliding window method 1

In road safety analysis, the moving average technique is widely employed to smooth crash data over a specified distance, facilitating the detection of underlying trends and the identification of high-risk (hotspot) segments. Among the various analytical tools, the sliding window method combined with moving average calculations is particularly useful in the context of crash data, as it enables the evaluation of local variations while minimizing the influence of outliers or short-term fluctuations.

For the present analysis, crash data aggregated into uniform 0.5-km segments (as described in Section 3.2) provide the basis for moving average calculations. For instance, all crash records occurring between chainages 2.0 km and 2.5 km are aggregated into one segment, followed by 2.5 km to 3.0 km, and so forth along the road network. This segmentation facilitates systematic analysis along the entire roadway.

The moving average is then calculated using several window sizes, namely 2, 4, 6, 8, 10, and 20 segments, corresponding to road lengths of 1 km, 2 km, 3 km, 4 km, 5 km, and 10 km, respectively. Each window represents the number of consecutive 0.5 km sections over which the crash data are averaged. For example, a window size of 2 aggregates data over 1 km (2 × 0.5 km), while a window size of 20 aggregates data over 10 km (20 × 0.5 km). These varying window sizes allow for both localized and more generalized evaluations of crash patterns.

In this research, a 5-km moving average, encompassing 10 consecutive 0.5-km segments, is employed to detect high-risk locations along the road corridor. The moving average is computed in both forward and reverse directions to ensure comprehensive coverage.

The forward moving average begins from the lower chainage (starting point of the road) and proceeds toward the higher chainage. For each 0.5 km road section, the average number of crashes is computed using that section and the next nine sections, effectively covering a 5 km length. For example, the forward moving average for the segment between 0.0 km and 0.5 km incorporates crash data from 0.0 km to 5.0 km. Similarly, the value for the 0.5 km to 1.0 km segment reflects data from 0.5 km to 5.5 km, and so on, continuing along the length of the road.

Conversely, the reverse moving average starts at the higher chainage (the end of the road) and moves in the opposite direction. For each segment, it averages crash data over the current and preceding nine sections, again spanning a 5 km window. This reverse calculation ensures that potential high-risk segments are not overlooked just because they might appear toward the end of the road. By calculating both forward and reverse moving averages, the analysis ensure that crash patterns are considered comprehensively from both directions, as road segments can exhibit different risk characteristics depending on how they are approached.

Figure 3.2 provides a visual illustration of the methodology used to calculate both forward and reverse moving averages for each road segment.

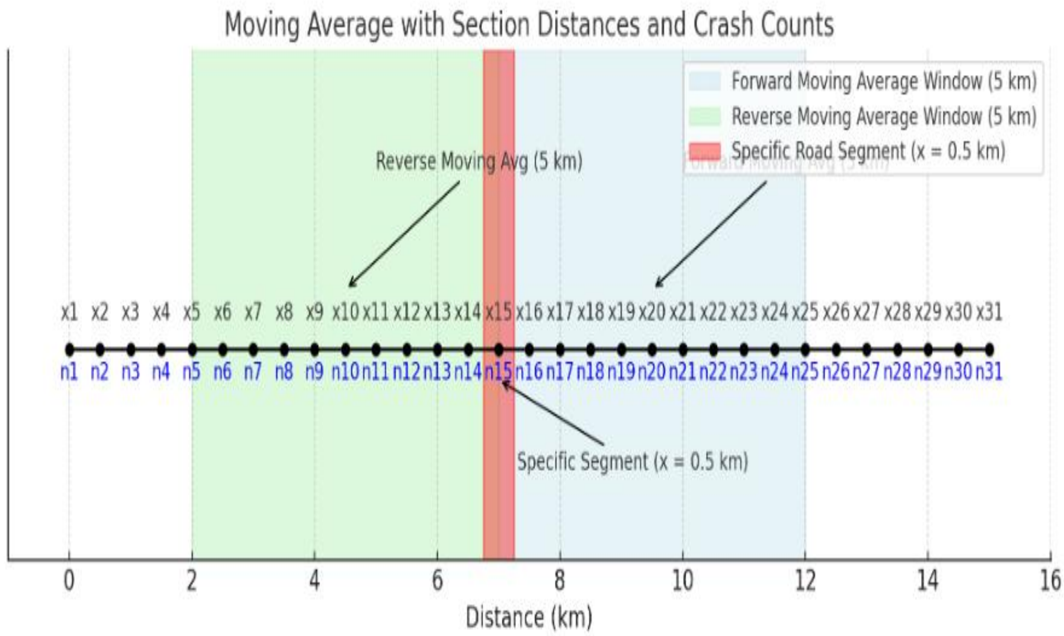


Figure 3.2 Illustration of extension version of moving average sliding window method 1

Rationale for Using 2.0x Threshold

In this study, high-risk road segments are identified using a threshold, defined as twice the moving average of crash counts within each segment. This threshold is adopted as a practical and empirically informed criterion to highlight locations exhibiting crash frequencies that are substantially higher than those of their neighboring segments. Using a multiple of the local moving average allows the method to respond to the inherent spatial variability of crash occurrences across the road network, ensuring that segments with unusually high crash concentrations are prioritized while minimizing the influence of random fluctuations in low-crash areas. The selection of the 2× multiplier is supported by empirical observations in road safety literature, where multiples of local averages are commonly employed in black spot detection and network screening practices [26]. Alternative multipliers (such as 1.5× or 2.5×) were considered; however, the 2× value offered a balanced and operationally effective threshold that identifies a meaningful number of high-risk segments without over-flagging locations where elevated crash counts may simply reflect statistical noise.

3.3.2 High risk segments identification using sliding window method 2

To identify high-risk road segments and uncover meaningful trends in accident data, this study utilizes the sliding window method in combination with moving average calculations. This approach is particularly effective in smoothing short-term fluctuations and emphasizing longer-term trends by averaging the number of accidents across adjacent road segments.

As illustrated in Figure 3.3, the sliding window technique involves defining a fixed-size window that traverses the dataset sequentially. At each step, the sum (or average) of the values within the current window is computed. The window then advances by one segment, removing the leftmost value and incorporating the next value on the right. The method is applied to accident data that have been segmented into 0.5-km intervals across the entire road corridor.

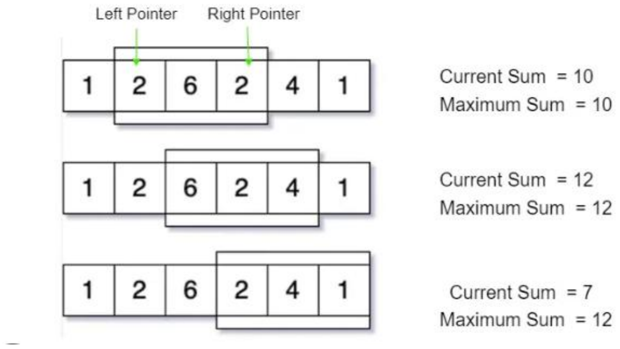


Figure 3.3 Illustration of Sliding Window Technique for Accident Data Analysis

Example of Sliding Window Operation

Figure 3.4 illustrates the concept using accident counts from six consecutive road segments and suppose the accident counts for six consecutive segments are given as:

[1,2,6,2,4,1]

Using a sliding window of size 3, the first calculation includes the values [1, 2, 6], yielding a sum of 9. The window then slides one step forward, covering [2, 6, 2], and the sum is updated to 10. In the subsequent step, the window shifts to [6, 2, 4], producing a sum of 12, which becomes the highest value observed so far. As the window continues to move forward, older values are dropped and new values added, allowing for real-time detection of peak accident concentrations across the road network.

This basic method ensures that each segment of the road is evaluated within an equally sized context, enabling consistent and comparative analysis of accident intensities across all segments.

Window Size Selection and Analysis Granularity

To capture accident trends at different scales, various window sizes are tested: 2, 4, 6, 8, 10, and 20 segments, which correspond to 1 km, 2 km, 3 km, 4 km, 5 km, and 10 km respectively (since each segment represents 0.5 km). Additionally, the variability in accident data for every 1 km, 2 km, 3 km, 4 km, 5 km, and 10 km sections will be checked. By examining the variability at these different lengths, we can determine the most appropriate distance for further analysis. The section length with the most adequate variability will be used for more in-depth analysis. A smaller window size is more sensitive to localized variations, while a larger window size smooths the data over longer distances, helping to identify broader trends.

High-risk segments are identified based on a 95th percentile threshold.

To pinpoint high-risk segments, we use a 95th percentile threshold. This means that segments with accident rates higher than 95% of all segments are considered high-risk. For example, if we have 1000 segments, the top 5% with the highest accident rates would be flagged as high-risk. This method allows us to focus on the most dangerous segments, ensuring that our safety interventions are targeted where they are needed most. By combining moving average analysis with this percentile threshold, we can effectively prioritize road safety measures and allocate resources to the areas with the greatest need.

3.3.3 High risk segments identification using k-mean clustering algorithm

K-means clustering is a statistical partitioning technique that groups data points into distinct clusters based on similarity. Applied to accident data, it identifies locations with high accident frequency by grouping road segments that exhibit similar crash patterns. The process consists of steps such as selecting the number of clusters (k), initializing centroids, assigning data points to the nearest centroid, and iteratively updating the centroids based on the mean of the assigned points until convergence. By applying K-means clustering to accident data with attributes such as location, number of accidents, and severity, we can identify spatial clusters of high accident frequencies.

These clusters highlight accident hotspots, enabling targeted interventions and resource allocation to improve road safety in those specific areas.

The analysis employs both the sliding window method and K-means clustering to identify high-risk segments within the road network and to provide a comparative assessment of their effectiveness. The sliding window method divides the roadway into uniform intervals, allowing accident frequency and severity to be evaluated systematically for each segment to detect high-risk locations. In contrast, K-means clustering groups accident data points into clusters based on attributes such as location, time, and severity, identifying spatial concentrations of high accident occurrence through iterative centroid adjustments. Applying these two approaches enables a comprehensive evaluation of high-risk segments and supports the selection of suitable methods for road safety assessment.

By integrating multiple high-risk road segment identification techniques, including the sliding window method and the K-means clustering approach, this study aims to evaluate the effectiveness of each method in highlighting critical areas. Based on a comparative assessment, the most appropriate and reliable technique will be selected for further in-depth investigation and analysis.

3.4 Evaluation of high-risk road segments according to the casualties per an accident

In addition to analyzing the frequency of road traffic accidents, this study also incorporates an assessment of accident severity by evaluating the number of casualties per accident for each road segment. This additional metric enables a more nuanced understanding of road safety conditions by identifying not only where accidents are most frequent, but also where the most severe accidents are happening.

The casualties per accident value is computed for each 0.5 km road segment by dividing the total number of casualties by the total number of accidents recorded within that segment. This ratio offers insight into the average severity of accidents in each segment, regardless of how frequently such incidents occur. For instance, even a road segment with relatively few accidents may still pose a significant safety concern if those incidents result in a disproportionately high number of casualties.

Incorporating this measure allows for the identification of road segments that may require targeted interventions aimed specifically at reducing accident severity. Segments exhibiting a high casualties-per-accident ratio could benefit from strategies such as enhanced emergency response capabilities, improved geometric road design, better signage, increased enforcement of speed limits, or promotion of in-vehicle safety technologies.

To systematically identify high-risk segments in terms of severity, a threshold-based approach is applied. This involves determining a cutoff value derived from the statistical distribution of casualties per accident across the entire road network. A percentile-based threshold is used, such as the 90th or 95th percentile to isolate segments where the severity of accidents exceeds typical levels. These segments are flagged as high-severity zones and are prioritized in the subsequent development of road safety intervention strategies.

By integrating both accident frequency and severity metrics into the analysis, the research facilitates a more balanced and comprehensive road safety management framework. This dual approach ensures that mitigation strategies address not only the occurrence of road traffic crashes but also the magnitude of their consequences, thereby improving the overall effectiveness of road safety planning and resource allocation.

3.5 Evaluation of high-risk road sections using roadway environment assessment

Most national road networks pass through a variety of environments, ranging from busy urban cores and city areas to suburban neighborhoods, small towns, and rural countryside. To better understand crash patterns and improve road safety, it's important to classify the road network based on these different environments. This helps provide more accurate analysis and supports the design of targeted safety solutions.

Crash data often show that these different environments have different safety challenges. Urban areas may have more frequent but less severe crashes, while rural areas often have fewer crashes but more serious ones. These differences highlight the need for tailored safety measures depending on the road environment. By classifying roads this way, road agencies can make smarter decisions about where to spend money like investing in traffic lights and crosswalks in cities or improving signage and emergency access in rural areas.

This section assesses road segments based on their roadway environment, with particular emphasis on functional classification and surrounding land use. Road sections are categorized into five distinct contexts: urban core, urban, suburban, rural town, and rural, reflecting variations in environmental characteristics that influence crash risk.

1. **Rural**: Areas with very low density, few widely dispersed houses or structures, minimal or no residential, commercial, and industrial development, predominately agricultural land with fenced areas, and typically large setbacks.

2. **Rural Town**: Areas with low density but diverse land uses with commercial Main Street character, potential for on-street parking and sidewalks, and small setbacks.

3. **Suburban**: Areas with medium density, mixed land uses within and among structures (including mixed-use town centers, commercial corridors, and residential areas), and varied setbacks

4. **Urban**: Areas with high density, mixed land uses and prominent destinations, potential for some on-street parking and sidewalks, and mixed setbacks.

5. **Urban Core**: Areas with highest density, mixed land uses within and among predominately high-rise structures, and small setbacks.

Figure 3.4 illustrates a conceptual transition of land use and development intensity along a typical roadway corridor, ranging from the dense urban core to urban, suburban, rural town, and finally rural areas. This spatial gradient is essential for understanding the changing roadway environment, as it influences traffic patterns, road user behavior, and associated safety risks [62].

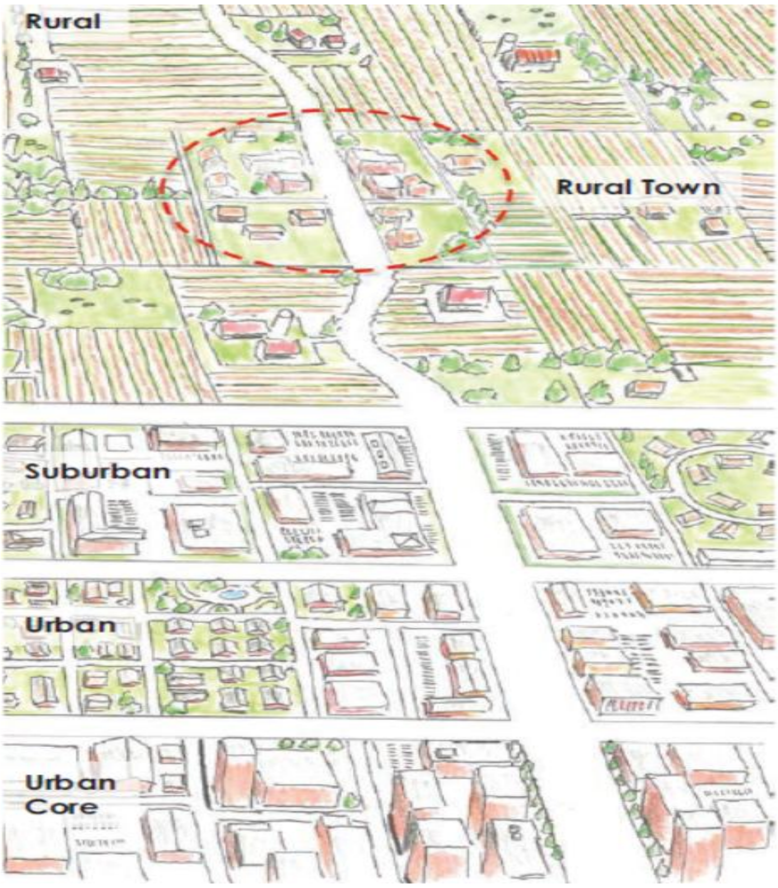


Figure 3.4 Identification and visually illustration of extension of roadway environment from urban core to rural areas

3.5.1 Development of guidelines and limitations of the roadway environment categories

Table 3.3 Identification of roadway environment context according to the speed, mobility and access

<table>
<tr><td colspan="2" rowspan="2">H – High
M – Medium
L - Low</td><td colspan="5">Context</td></tr>
<tr><td>Rural</td><td>Rural Town</td><td>Sub Urban</td><td>Urban</td><td>Urban core</td></tr>
<tr><td rowspan="4">Roadway</td><td rowspan="3">Principle Arterial</td><td>H-speed</td><td>M-speed</td><td>H/M-speed</td><td>L/M-speed</td><td>L-speed</td></tr>
<tr><td>H-mobility</td><td>M-mobility</td><td>M-mobility</td><td>M-mobility</td><td>M-mobility</td></tr>
<tr><td>L-access</td><td>H-access</td><td>M-access</td><td>M-access</td><td>M-access</td></tr>
<tr><td>Minor Arterial</td><td>H-speed</td><td>L/M-speed</td><td>M-speed</td><td>L/M-speed</td><td>L-speed</td></tr>
</table>

		H-mobility	M-mobility	M-mobility	M-mobility	M-mobility
		M-access	H-access	M-access	M/H-access	M/H-access

Source: An expanded functional classification for highways [62]

3.4 Regulations and Guidelines for the identifying roadway environment context

Context	Density	Land use
Rural	Low density, sparse residential with occasional agriculture-related structures	predominately agricultural land with fenced areas, few widely dispersed houses or structures, minimal or no residential, commercial, and industrial development
Rural Town	Single- and two-story buildings in a several-block area of low to medium density	Single-family residential and commercial with on street parking
Sub Urban	Medium density with primarily single-story buildings	Primarily strip and big box commercial uses; some multifamily and single-family residential (accessed by collectors)
Urban	High density, some multistory buildings	Mainly residential with some commercial uses; educational use; off-street parking
Urban core	High density, multistory and high-rise buildings; highest density within the corridor	Commercial, institutional (court houses and government offices), and residential uses; off-street parking and parking structures

Source: An expanded functional classification for highways [62]

In this study, the classification of urban and rural roadway contexts is primarily based on these key factors: the population and structural density of the area, and the dominant land use patterns surrounding the road segments. These contextual elements serve as indicators of development intensity and functional activity in the environment, which in turn influence traffic volume, road user behavior, and safety risks. For instance, areas with high population and building density (as referred to table 3.4, and table 3.3) -such as urban cores-are typically associated with increased pedestrian activity, mixed land use, and more complex traffic interactions. In contrast, rural areas are characterized by sparse development, lower traffic volumes, and predominantly agricultural or open land use.

3.5.2 Finding roadway environment contexts using land use pattern from high-resolution satellite images

High-resolution satellite imagery and ground-level images are visually inspected based on the guidelines and limitations outlined in section 3.5.1 to classify roadway environments into urban and rural contexts. Google Earth Pro is utilized to capture a combination of satellite and ground-level images, which provided high-resolution visuals for the initial categorization of road segments. This classification relies on visible features such as building density, road infrastructure, roadside development, and vegetation cover.

To estimate AADT, the methodology relies on land-use patterns as a practical proxy, assuming that areas with intensive commercial or residential activity generally attract higher traffic demand. This approach works well for conventional highways, but it does not suit expressways. Because expressways maintain controlled access and operate independently from adjacent land uses, their traffic volumes do not reflect roadside development. In those cases, the methodology directs users to adopt more robust approaches such as trip-generation models, OD-based forecasting, GPS-derived mobility data, or regional transportation planning tools to estimate AADT more accurately.

In order to address the temporal variability of roadway environments, this study incorporates a robust mechanism for updating the classification of road segments using freely available satellite-based tools. Google Earth Pro provides access to historical imagery through its time-slider function, enabling the examination of changes in land-use patterns, building density, and development intensity across multiple years. As Google regularly updates its satellite and aerial imagery datasets, the same road segments can be re-evaluated periodically using the most recent data. This allows researchers and road agencies to track urban expansion, rural development, and other contextual changes over time. By integrating this time-series satellite imagery into the methodology, the roadway environment classification becomes repeatable, adaptable, and capable of reflecting real-world conditions as they evolve, ensuring the long-term reliability of the analysis.

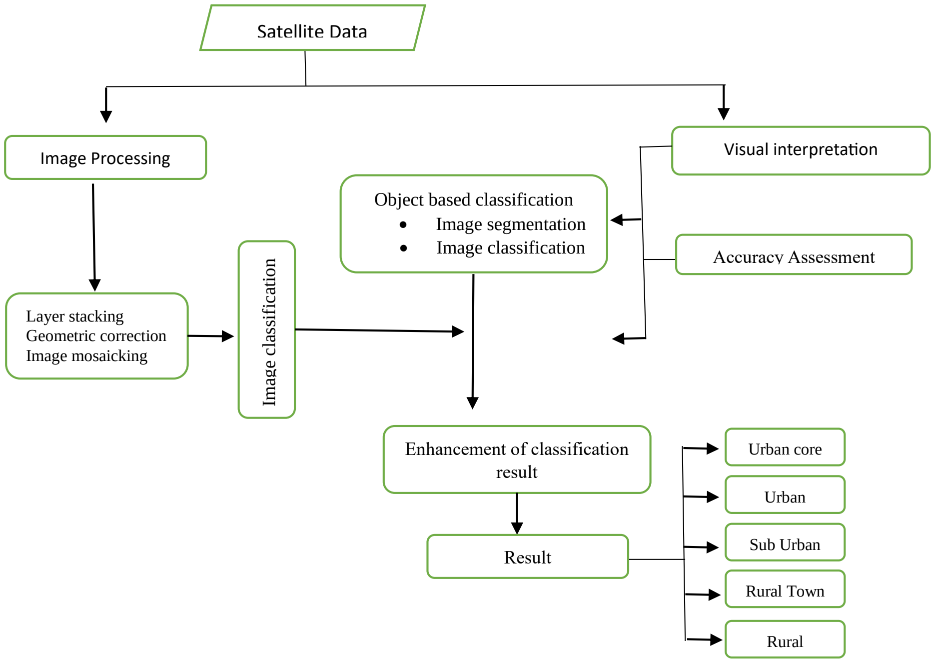


Figure 3.5 The process of identifying roadway context using google satellite data

To enhance the roadway environment classification, the methodology also incorporates ground-level images from Google Street View. These images provide a detailed, street-level perspective, offering valuable information about road conditions, signage, pedestrian pathways, and other features that are difficult to discern from satellite imagery alone. By combining aerial and ground-level views, the approach captures both macro- and micro-level environmental factors, resulting in a more accurate and comprehensive classification of road segments.

Figure 3.6 illustrates a hierarchical classification of roadway environments, delineated into five distinct categories: urban core area, urban area, suburban area, rural area, and rural town area. Each satellite image serves as a representative example, highlighting the key spatial and infrastructural characteristics unique to its classification. The urban core area exhibits high-density development, mixed land use, and complex traffic networks, while the urban area demonstrates moderate density with structured transportation systems. In contrast, the suburban area displays lower-density residential zones interspersed with commercial corridors, and the rural area is characterized by sparse infrastructure and natural or agricultural landscapes, whereas rural towns are small communities with a mix of homes and local services.

Figure 3.6 Illustration of different roadway functional contexts based on google satellite image (source: Google earth pro)

(a -Urban core area b-Urban area c-Sub urban area d-Rural town area e-Rural area)

As discussed in the literature (referred to section 2.2.2 and 2.2.3), urban contexts pose a higher road safety risk than rural areas due to increased road user density, frequent interactions, and complex traffic patterns. Urban roads accommodate higher volumes of pedestrians, cyclists, and public transport, creating multiple conflict points that elevate crash likelihood. The prevalence of intersections, stop-and-go traffic, and frequent lane changes further increases the risk of rear-end and side-impact collisions. Additionally, commercial and residential land use contributes to congestion, with narrow lanes and limited maneuvering space leading to unpredictable vehicle movements. Although urban areas generally have lower speed limits, the sheer frequency of interactions results in a higher crash rate, necessitating targeted safety interventions. In contrast, rural roads, despite higher travel speeds, typically feature fewer intersections, lower traffic density, and minimal pedestrian activity, reducing overall crash exposure.

To better understand the variation in crash risks across different geographic areas, a Risk Exposure Index was developed. This index uses a scale from 1 to 5, where 1 represents the highest crash risk exposure and 5 represents the lowest.

Table 3.5 Risk Exposure Levels Across Different Road Environments

Road Environment	Risk Exposure
Urban core	E1 (Very high)
Urban	E2 (High)
Sub urban	E3 (Moderate)
Rural town	E4 (Low)
Rural	E5 (Minor)

The risk exposure levels, represented on a scale from 1 to 5, highlight the varying degrees of accident risk associated with different roadway environments:

1. **Urban core** (Risk Exposure: 1): Urban cores typically experience the highest level of risk exposure due to dense traffic, high pedestrian activity, numerous intersections, and frequent traffic congestion. The complex traffic dynamics in these areas increase the likelihood of accidents, necessitating rigorous safety measures and traffic management strategies.
2. **Urban** (Risk Exposure: 2): Urban areas also have high risk exposure but slightly lower than urban cores. These areas feature heavy traffic flow, significant pedestrian presence, and a mix of residential, commercial, and industrial zones. Effective traffic control and safety interventions are essential to mitigate accident risks.
3. **Suburban** (Risk Exposure: 3): Suburban areas exhibit a moderate level of risk exposure. These regions are characterized by a mix of residential and commercial land use, with moderate traffic volumes and fewer intersections compared to urban areas. Traffic speeds may be higher, but the overall traffic density is lower, leading to a balanced risk exposure.
4. **Rural town** (Risk Exposure: 4): Rural towns have relatively low risk exposure. These areas often have less traffic, fewer intersections, and lower pedestrian activity.

However, factors like higher vehicle speeds and variable road conditions can still contribute to accident risks, necessitating targeted safety measures.

5. **Rural** (Risk Exposure: 5): Rural areas present the lowest risk exposure. These regions typically have the least traffic density and pedestrian activity. However, higher speeds, limited road maintenance, and fewer traffic controls can still pose safety challenges, highlighting the need for specific interventions to address these unique risks.

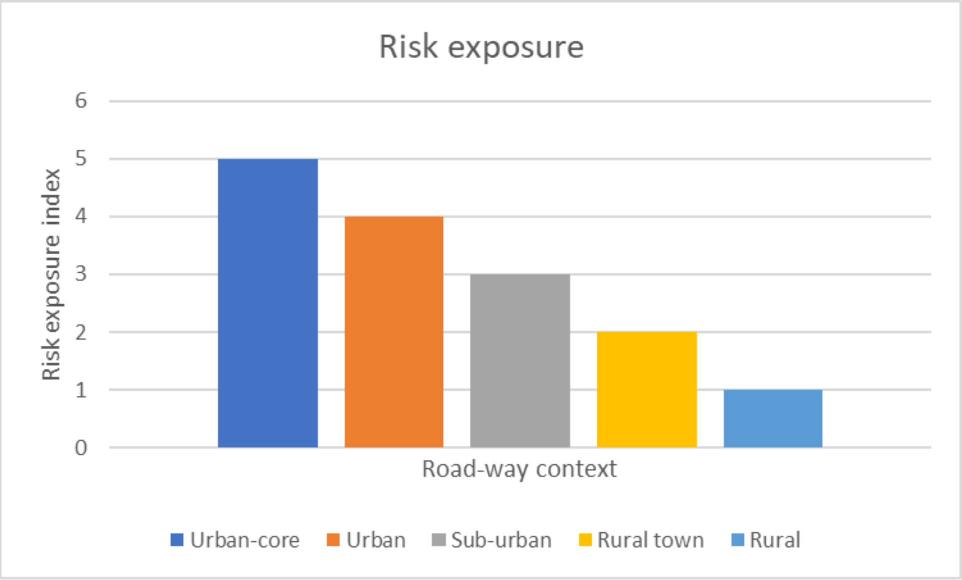


Figure 3.7 Assessing risk exposure in different geographic areas

3.6 Evaluation of high-risk road sections based on road infrastructure assessment

A comprehensive road infrastructure assessment is a vital element of an effective road safety management system because it examines the physical and operational characteristics of the roadway network that influence crash risk. This assessment considers key infrastructure features including road geometry, pavement condition, signage, lighting, guardrails, and intersections to identify deficiencies that may elevate safety hazards.

This section applies a Road Safety Index (RSI)-based framework to evaluate road infrastructure in a systematic and quantitative manner. The RSI integrates essential infrastructure parameters, such as geometric design, pavement quality, traffic control devices, and roadside safety features, to generate a single metric that reflects the relative safety level of each road segment.

To determine these index values, a detailed road safety audit is required to examine each parameter, identify potential deficiencies, and quantify their contribution to overall safety performance. This approach supports an evidence-driven evaluation of infrastructure conditions, enabling the prioritization of high-risk segments and the efficient allocation of resources for targeted safety improvements.

3.6.1 Development of road safety index

This assessment considers five key road characteristics in determining the Road Safety Index values. The table 3.6 outlines the key road characteristics considered in determining the Road Safety Index (RSI), along with their respective weightages. The Road Safety Index (RSI) is a metric used to assess the overall safety of road segments by evaluating several important factors. Each factor contributes a certain weight to the final index, reflecting its significance in influencing road safety.

Table 3.6 Road characteristics and their respective weightages

Road Characteristics	Weightage
Roadway Characteristics (RWC)	0.34
Traffic Characteristics (TC)	0.26
Roadside Characteristics (RSC)	0.18
Pavement Characteristics (PC)	0.13
Miscellaneous Characteristics (MC)	0.09

Each characteristic comprises multiple attributes, with assigned score values detailed in the section 3.6.2. The weightages and scores may vary depending on regional conditions, traffic behavior, and infrastructure features, and can be adjusted using expert judgment to reflect local realities. Some attributes and score values can be adjusted based on the local situation with expert judgment. Several studies have assessed these factors and their impact on road safety, each proposing different weighting and scoring systems for evaluating risk. However, the weightages proposed by Kumar et al. (2015) were selected for the case study of this study due to their close resemblance to local road conditions in Sri Lanka, and some score values were also adjusted as per the local situation.

Road Safety Index equation (RSI)

$$RSI = \sum_{i=1}^{n}(w_i \; x \; \frac{V_{ei}}{V_{si}}) \qquad (3.1)$$

Where, ‘n’ is number of groups that define the overall factors to contribute crashes,

‘W_i’ is the relative weightage allocated with ith service characteristics,

‘V_{ei}’ Value score for the ith factor in the observed situation, and

'V_{si}' Maximum possible value score for the ith factor (assumed to be 100 for normalization).

Based on the calculated RSI value, each road segment is categorized into one of five performance grades, ranging from Excellent to Very Poor. This grading system helps assess the overall safety of the road and prioritize improvement measures.

The gradation of road based on the level of service offered is shown in the Table.

Table 3.7 Desired level of services and class based on road safety index value

RSI	Level of Service	Class
0.80-1.00	Excellent	S5
0.60-0.80	Very Good	S4
0.40-0.60	Good/Average	S3
0.20-0.40	Poor	S2
0.00-0.20	Very poor	S1

3.6.2 Road Safety Index attributes and Valued Scores

Table 3.8 Attributes relating to the Roadway Characteristic

Roadway characteristic		
Parameters	Observed data	Valued scores
Carriageway width	4 lane with median	100
	4 lane without median	70
	2 lane with median	50
	2 lane without median	30
	1 lane	10
Number of curves	0	100
	1	80
	2	70
	3	40
	4	20
	>5	10
Gradient	Flat	90-100
	<5%	50-90
	>5%	10-50
Number of intersections and access paths /km	0	100
	1	90
	2	75
	3	50

	4	30
	>=5	10
Type of intersection	4-way junction (High crash risk due to multiple conflict points (vehicles from 4 directions))	30-50
	t- junction (Moderate crash risk; fewer conflict points than a 4-way junction)	50-70
	Access road (Relatively low crash risk, as these roads typically serve low traffic volumes and speeds)	70-90
	Roundabouts (Safer overall due to slower speeds and fewer severe crashes) but the score range can vary depending on the design of the roundabout, for example, poorly designed roundabouts (50–60), multi-lane roundabouts (60–80), and small roundabouts (80–90).	50-90

Table 3.9 Attributes relating to the Traffic characteristic

Traffic characteristic		
Parameters	Observed data	Valued scores
Speed	10% more than the speed limit	90
	10-30% more than speed limit	50
	30-50% more than speed limit	30
	50-80% more than speed limit	10
On- street parking	No parking	90-100
	With Parking	10-90
Road markings	Centerline marking, Lane marking, Zebra crossing & Stop line, edge marking.	50-100
	No marking or lack of marking	0-50
Speed Breakers/km	0	0-50
	1	50
	2	75
	>2	80-100
Number of Fatalities/km	Minor damage with fatal injury	80-100
	Serious Injury	40-80
	Property damage	0-40
Signs	With adequate signs	60-100
	No adequate signs	0-60

Table 3.10 Attributes relating to the Roadside characteristic

Roadside characteristic		
Parameters	Observed data	Valued scores
Presence of Obstacles	Advertisement Board, trees, distracting road users	0-50
	No	100
Shoulder	With average kerbs and levelled	60-100
	Not adequate	0-60
Street Lighting Interval	<=20m	50-80
	>20m	20-50
	No lighting	0

Table 3.11 Attributes relating to the Pavement characteristic

Pavement characteristic		
Parameters	Observed data	Valued scores
Pavement status	Good	100
	Average	40
	Poor	20
Potholes/km	No	100
	1 to 5	70-90
	5 to 10	50 -70
	>=10	0-50

Table 3.12 Attributes relating to the Miscellaneous characteristic

Miscellaneous characteristic		
Parameters	Observed data	Valued scores
Bus-stop distance from Intersection	>=120 m	100
	20 - 120 m	20-100
	0 - 20 m	0-20
Intersection visibility	Very Good	80
	Fair	40
	Poor	0
Presence of median	Wide (>1 m)	60-80
	Moderate (0.5–1 m)	30-60
	Narrow (<0.5 m)	10-30

3.6.3 Road infrastructure safety assessment process

For the evaluate road safety infrastructure assessment, a comprehensive road safety audit needs to be conducted to evaluate the desired score values for all the defined road characteristics. The audit integrates multiple assessment techniques to ensure accurate and context-specific evaluation. Drive-through inspections use onboard video cameras to obtain continuous visual records of the corridor, while walking inspections allow closer examination of localized issues that may not be visible from a vehicle. A structured checklist guides all observations, ensuring that each segment is assessed consistently and comprehensively.

These score values primarily follow the standardized criteria outlined in the appendix tables. However, when field conditions differ significantly from the predefined descriptions, the values are adjusted based on on-site observations made during the audit. The average score for each road characteristic is then calculated, and these averages serve as inputs for developing the Road Safety Index (RSI) using the formulation provided in Equation (3.1).

3.7 Evaluation of high-risk road sections based on crash severity assessment

3.7.1 Crash data analysis based on accident severity

As the final stage of the road safety risk assessment, high-risk road segments are identified through a detailed crash severity assessment. This evaluation is based on historical crash data and the severity levels associated with each incident. The primary metric used in this process is the Crash Severity Index (SI), which quantifies the overall severity of crashes occurring along each road segment. By incorporating past crash records, this method ensures that road sections with a history of more serious incidents are prioritized for safety interventions.

The severity levels will be categorized into four distinct levels, as outlined below.

Severity Index (1-4)

- **Index 1**: Represents minor accidents with low or no injuries and minimal property damage. (most related to damage only accidents)
- **Index 2**: Denotes accidents with moderate injuries and considerable property damage. (most related to non-grievous accidents)
- **Index 3**: Indicates accidents with serious injuries requiring medical attention and substantial property damage. (most related to grievous accidents)
- **Index 4**: Corresponds to severe accidents involving fatalities or critical injuries, leading to significant human and economic impact. (most related to fatal accidents)

$$\text{Severity index (Si)} = \frac{n_1 x1 + n_2 x2 + n_3 x3 + n_4 x4}{\text{n}} \tag{3.2}$$

The multiplication of crash frequencies by severity weights (1,2,3,4) reflects the relative impact of different crash types on overall road safety. The chosen weights align with the increasing seriousness of crash outcomes. Damage-only crashes (n_1) are assigned the lowest weight (1), as they involve no injuries. Non-grievous crashes (n_2) have a higher weight (2), reflecting the presence of minor injuries. Grievous crashes (n_3) are assigned a weight of 3 due to their more severe impact on victims. Fatal crashes (n_4) receive the highest weight (4), highlighting their catastrophic consequences.

By averaging the severity indices of all accidents that occurred within a specified road segment, we derive a severity per accident value, which reflects the cumulative risk for that segment. This approach ensures that the average severity index provides a representative measure of the overall risk in the specified section. By systematically calculating and analyzing the severity per accident value along with accident exposure, frequency and infrastructure conditions (RSI value), we can effectively evaluate the risk level of the road sections.

Assigning grades to road segments based on severity per accident values provides a clear and systematic way to identify and prioritize high-risk areas. This method helps in effective decision-making and targeted interventions to enhance road safety. We can classify these values into predefined ranges representing different risk levels, assigning grades from Class 1 (very high severity) to Class 5 (very low severity).

Table 3.13 Performance classification classes based on calculated Severity Index

Severity Index	Class
0 to 1	C5
1 to 2	C4
2 to 3	C3
3 to 3.5	C2
3.5 to 4	C1

3.8 Development of decision matrix based on the three risk assessment results

Table 3.15 outlines the recommended actions for road segments based on their desired grade classification, which is determined by the results of three safety risk assessments. Road segments are categorized into five classes (Class 1 to Class 5), where Class 1 represents the highest risk level and Class 5 represents the lowest risk level. In CLASS I, all road sections are considered critical, but the level of criticality varies across the sections. For instance, a road section with a vector of (1, 1, 1) is more critical than one with a vector of (1, 5, 5) despite both being in CLASS I. This is because the former has a level 1 category in all dimensions, indicating higher criticality. For each class, specific actions are recommended, ranging from detailed investigation and urgent interventions for high-risk segments to routine monitoring for low-risk segments. This approach ensures that resources are allocated effectively, prioritizing the most critical areas for immediate action while maintaining oversight of lower-risk segments.

Table 3.14 Recommended actions for road segments based on desired grade and safety risk assessment results

Desired grade	Recommendations
Class 1 (E1, S1, C1)	Detailed investigation/Urgent action
Class 2 (E2, S2, C2)	Detailed investigation/Need action
Class 3 (E3, S3, C3)	Intensive monitoring/Planned action
Class 4 (E4, S4, C4)	Regular monitoring/No action
Class 5 (E5, S5, C5)	Monitoring/No action

3.8.1 Development of Risk Rating Index (RRI)

Tables 3.15 and 3.16 present the integrated risk rating method developed in this study by combining the results of the three independent risk assessments: roadway environment assessment (exposure), road infrastructure assessment, and crash severity assessment. This approach was introduced to convert qualitative risk outcomes into a structured and measurable form, allowing consistent comparison and prioritization of road segments.

Table 3.15 illustrates the first step of the integration process. It combines the results of the environment assessment and the infrastructure assessment using a qualitative risk matrix (Matrix A). The interaction between these two dimensions reflects the combined effect of exposure (environmental conditions) and roadway deficiencies on overall crash likelihood. Each cell in the matrix represents a risk level-ranging from very low to critical-based on the relative position of a road segment in both assessments. This two-dimensional analysis helps identify segments where environmental risks and infrastructure risks reinforce each other, resulting in elevated crash potential.

Table 3.16 extends this process by incorporating the crash severity assessment. This step converts the qualitative outcomes from Matrix A into a numerical Risk Rating Index (RRI). Using a structured scoring system (1 to 25), each severity category interacts with the combined environment–infrastructure risk level to produce a numerical value. Higher scores correspond to segments with greater overall safety risk. This quantitative index provides a consistent basis for comparing different road segments, ranking them according to their risk level, and determining priority locations for safety improvement interventions.

By integrating all three assessments exposure, infrastructure condition, and crash severity the Risk Rating Index offers a comprehensive and objective method for identifying high-risk segments.

Table 3.15 Risk assessment matrix between road environment and infrastructure assessments

Matrix A	Infrastructure Assessment				
Environment Assessment (Exposure)	**Very Low Risk (S5)**	**Low Risk (S4)**	**Medium Risk (S3)**	**High Risk (S2)**	**Critical Risk (S1)**
Very Low Risk (E5)	Very Low	Low	Low	Medium	Medium
Low Risk (E4)	Low	Low	Medium	Medium	Medium
Medium Risk (E3)	Low	Medium	Medium	High	High
High Risk (E2)	Medium	Medium	High	High	Critical
Critical Risk (E1)	Medium	Medium	High	Critical	Critical

Table 3.16 Development of Risk Rating Index for all risk assessments

Risk Rating	Matrix A				
Severity Assessment	**Very Low Risk**	**Low Risk**	**Medium Risk**	**High Risk**	**Critical Risk**
Very Low Risk (C5)	1	2	3	4	5
Low Risk (C4)	2	4	6	8	10
Medium Risk (C3)	3	6	9	12	15
High Risk (C2)	4	8	12	16	20
Critical Risk (C1)	5	10	15	20	25

3.9 Case study

3.9.1 Application of the Road Safety Management System in Sri Lanka

The Sri Lankan national road network is utilized as a case study in this research to assess the applicability and effectiveness of the proposed road safety management framework within the constraints and conditions typical of developing nations. As a developing country, Sri Lanka faces numerous challenges related to road safety, including increasing traffic volumes, poor road user behavior, inconsistent infrastructure standards, and limited resources for road maintenance and safety improvements. The national road network spans a diverse range of roadway contexts from densely populated urban centers to sparsely developed rural areas making it a representative environment to test the applicability and adaptability of a comprehensive safety framework.

Additionally, diverse road user types such as pedestrians, cyclists, and mixed traffic including slow-moving vehicles often share the same road space, increasing the risk of crashes. Public awareness of road safety practices is also generally low, and emergency response systems are often under-resourced, leading to higher fatality rates. By applying this system to Sri Lanka, the study aims to generate meaningful insights that not only support the country's ongoing road safety initiatives but also offer a replicable model for other low- and middle-income countries facing similar issues. The expected outcome includes the identification of high-risk segments, prioritization of safety interventions, and the establishment of a scalable decision-making tool to enhance nationwide road safety planning.

3.9.2 National road network of Sri Lanka

Sri Lanka owns a very well spread-out road network of 116,000km. The current road density of Sri Lanka is 1.7 km of roads per square kilometer, a very high number when compared to its regional peers. Sri Lanka's Road network is classified into National, Provincial, Pradeshiya Saba, Local Authority roads and roads built under numerous development projects (e.g. under major irrigation schemes and hydro power complexes) according to their functionality and administrative responsibility. The 12,380km of National roads comprising of class "A" roads (trunk roads), class "B" roads (main roads), and Expressways (E) are administered by the central government through the Road Development Authority (RDA) as the executing agency.

Table 3.17 Current Sri Lankan Road network types and length

Road Class	Length
Class "E" Roads	312.586 km
Class "A" Roads	4,217.420 km
Class "AA" Roads	3,720.310 km
Class "AB" Roads	466.920 km
Class "AC" Roads	30.190 km
Class "B" Roads	8037.981 km
Total of "A" & "B" Class Roads in Sri Lanka	12,255.401 km
Grand Total of National Highways in Sri Lanka ("A", "B' and "E" Class Roads)	12,567.987 km

Source: RDA official website [63]

The national road network consists of nearly 12,000km of roads and accounting for about 10% of the network size, carries about 70% of the traffic. As urbanization and population growth continue, it is expected that traffic on national road networks will increase rapidly. The consequences of non-standard road design and the subsequent decrease in safety levels in the national road network, create significant hazards to the road [63]

National road network (A and B Class) of Sri Lanka Source:[64]

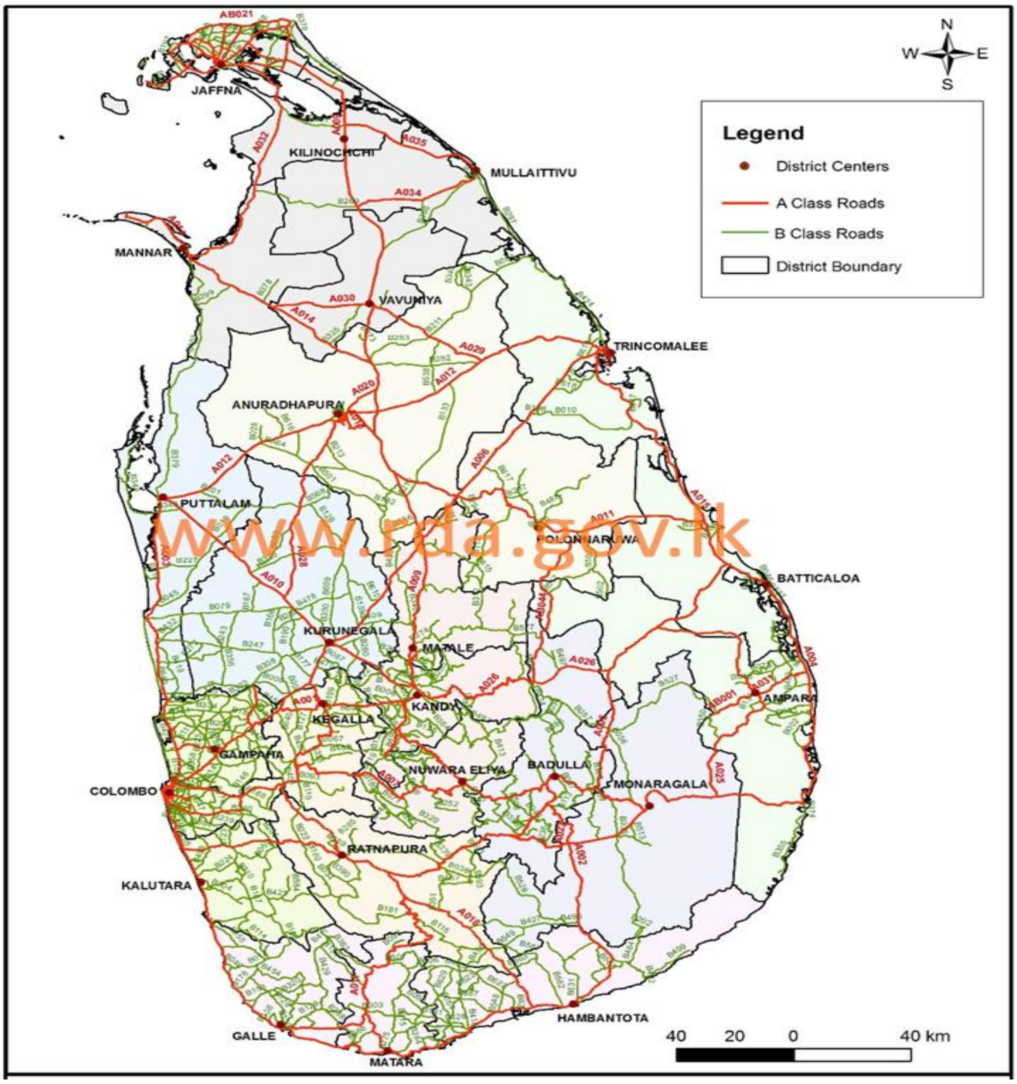


Figure 3.8 Extension Road map of Sri Lankan National Road Network

3.9.3 Introduction to study area

The A002 highway, also known as the Colombo-Wellawaya Road, is a crucial artery in Sri Lanka's transportation network. As part of the Asian Highway AH43, it is maintained by the Road Development Authority, ensuring its upkeep and functionality.

Route Information

South End: Wellawaya

North End: Colombo Fort

Major Junctions

The A002 highway traverses a diverse range of land patterns and connects several major cities and towns in Sri Lanka. These cities serve as significant junctions along the route:

Colombo: The capital city and economic hub of Sri Lanka, Colombo marks the northern end of the A002 highway. It is a bustling metropolis with a mix of modern urban landscapes and historic sites. The A002 highway continues south through Kalutara, Galle, Matara, and Hambantota. Hambantota has seen significant development in recent years with the construction of a new port and an international airport, making it an important economic zone in the southern region. The road ends in Wellawaya, located in the Uva Province, serving as the southern terminus of the A002 highway and a gateway to Sri Lanka's eastern and central highlands.

Land Patterns

The A002 highway passes through a variety of landscapes, reflecting Sri Lanka's rich geographical diversity. Along its route, the highway traverses various land use patterns, covering urban cores, suburban areas, and rural regions, connecting diverse landscapes and communities

CHAPTER 4
ANALYSIS AND RESULTS

4.1 Data collection: analyzing data through the Sri Lankan accident data management system (SLADMS)

The Sri Lankan Accident Data Base Management System (SLADBMS), managed by the Sri Lankan Police Department, functions as the national platform for recording and organizing traffic accident information across the road network. The system maintains detailed records on crash location, severity level, and casualty outcomes.

For this study, accident records from 2016 to 2021 were extracted from SLADBMS and prepared for analysis. The dataset underwent several preprocessing steps to ensure consistency and analytical suitability. These steps included verifying chainage information, removing incomplete or duplicate entries, standardizing severity classifications, and aligning crash locations with the predefined 0.5-km segmentation framework. Table 4.1 presents the detailed attributes recorded in the Sri Lankan Accident Data Management System, covering crash characteristics, roadway and environmental conditions, vehicle information, and casualty details [65].

Table 4.1 Recorded attributes provided from the crash database of Sri Lanka police

Crash Details	Element Details	Casualty Details
Date and time of crashClass of crash Status of environment (urban/rural) Status of the day (workday/holiday)Day of week Road number Road name Nearest lower km post Distance from nearestlower km post Coordinates of the location Collision type Information on a secondary collision Road surface conditionWeather Light condition Type of locationTraffic control Speed limit Action taken by police Number of casualties	Element type Vehicle ownership Driver/ rider/ pedestrian sex Validity of driving license Pre-crash factors contributing to accident (human, pedestrian, road, vehicle, crash factors, other factors) Alcohol test Whether driver/ rider/ pedestrian at fault	Traffic element number Severity according to penal code CategorySex Information about protection Whether hospitalized

4.2 Identification of high-risk road segments along the A002 (colombo-wellawaya) road

4.2.1 Results of analysis done using sliding window method 1

Table 4.2 provides a sample output generated from the sliding-window-based analytical algorithm (Method 1), which is used to identify high-risk segments along the A002 (Colombo-Wellawaya) corridor. The table summarizes the crash distribution in 500-meter sections and presents the key parameters required for hotspot detection. For each segment, the total number of recorded crashes is listed alongside the forward and reverse moving average values and corresponding 2× threshold values calculated for both directions.

Table 4.2 Representation of sample data analysis done from machine learning algorithm

Chainage	Total Crashes	Forward Moving Avg	Reverse Moving Avg	2x Threshold
2.0 km - 2.5 km	1	1	5.1	10.2
2.5 km - 3.0 km	0	0.5	7.5	15
3.0 km - 3.5 km	2	1	11.1	22.2
3.5 km - 4.0 km	1	1	11.7	23.4
4.0 km - 4.5 km	1	1	11.6	23.2
4.5 km - 5.0 km	1	1	13.6	27.2
5.0 km - 5.5 km	8	2	15.6	31.2
5.5 km - 6.0 km	1	1.88	14.8	29.6
6.0 km - 6.5 km	10	2.78	14.7	29.4
6.5 km - 7.0 km	26	5.1	16.1	32.2
7.0 km - 7.5 km	25	7.5	14.1	28.2
7.5 km - 8.0 km	36	11.1	15.9	31.8
8.0 km - 8.5 km	8	11.7	12.8	25.6
8.5 km - 9.0 km	0	11.6	15	30
9.0 km - 9.5 km	21	13.6	15.2	30.4
9.5 km - 10.0 km	21	15.6	15.9	31.8
10.0 km - 10.5 km	0	14.8	14	29.6
10.5 km - 11.0 km	0	14.7	18.6	37.2
11.0 km - 11.5 km	24	16.1	19.2	38.4
11.5 km - 12.0 km	6	14.1	18.3	36.6
12.0 km - 12.5 km	43	15.9	18.7	37.4
12.5 km - 13.0 km	5	12.8	17.3	34.6
13.0 km - 13.5 km	30	15	18.9	37.8
13.5 km - 14.0 km	2	15.2	17.1	34.2
14.0 km - 14.5 km	28	15.9	17.7	35.4
14.5 km - 15.0 km	2	14	15.5	31
15.0 km - 15.5 km	46	18.6	15.5	37.2
15.5 km - 16.0 km	6	19.2	11.2	38.4
16.0 km - 16.5 km	15	18.3	10.7	36.6
16.5 km - 17.0 km	10	18.7	10	37.4
17.0 km - 17.5 km	29	17.3	9.3	34.6
17.5 km - 18.0 km	21	18.9	6.8	37.8

18.0 km - 18.5 km	12	17.1	5.1	34.2
18.5 km - 19.0 km	8	17.7	4.1	35.4
19.0 km - 19.5 km	6	15.5	4.2	31
19.5 km - 20.0 km	2	15.5	3.8	31
20.0 km - 20.5 km	3	11.2	3.9	22.4
20.5 km - 21.0 km	1	10.7	4.6	21.4
21.0 km - 21.5 km	8	10	6.8	20
21.5 km - 22.0 km	3	9.3	7.1	18.6
22.0 km - 22.5 km	4	6.8	9	18
22.5 km - 23.0 km	4	5.1	9.9	19.8
23.0 km - 23.5 km	2	4.1	10.6	21.2
23.5 km - 24.0 km	9	4.2	11.1	22.2
24.0 km - 24.5 km	2	3.8	11.6	23.2
24.5 km - 25.0 km	3	3.9	11.7	23.4
25.0 km - 25.5 km	10	4.6	12.2	24.4
25.5 km - 26.0 km	23	6.8	11.6	23.2

The traffic crash frequency rate along the 320 km length of the A-002 road in Sri Lanka demonstrates a highly variable pattern as shown in figure 4.1, with significantly elevated crash counts concentrated within the initial sections of the route. Notable peaks are also visible at several intervals further along the corridor, suggesting the presence of recurrent high-risk segments.

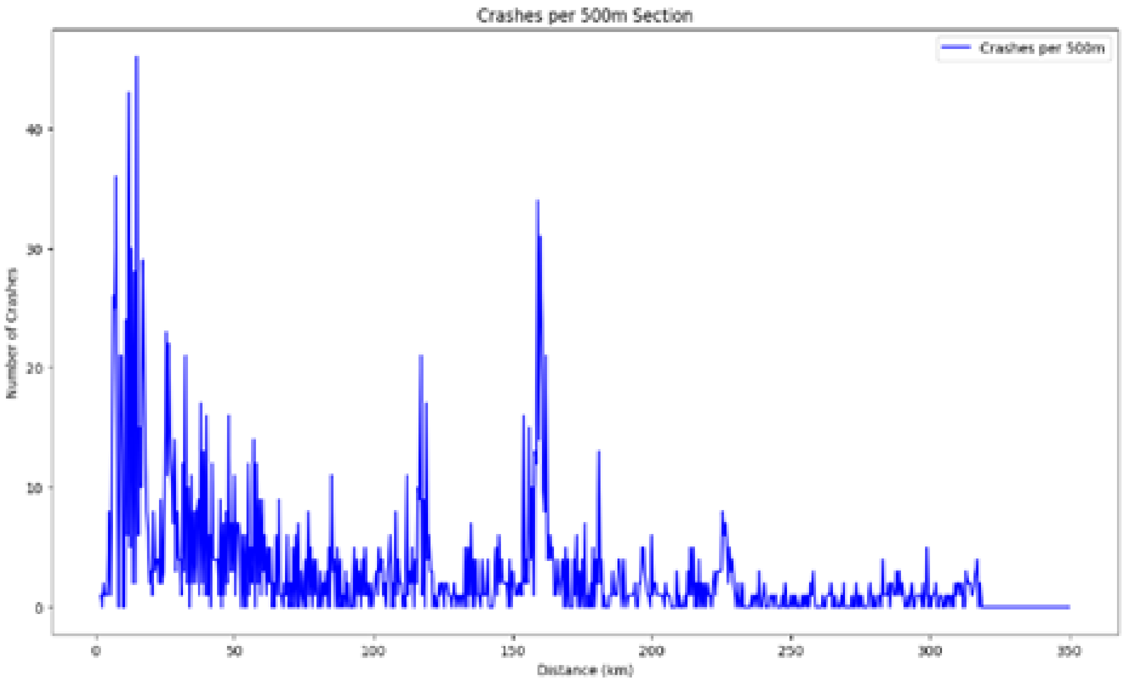


Figure 4.1 Plot series 1: Accident frequency along the A002 road Sri Lanka

The study identified high-risk road segments along the A002 corridor as described in sliding window method 1, which evaluates crash frequency within fixed 500-meter intervals. The blue curve in the figure illustrates the crash count for each segment, highlighting spatial variations in crash occurrence across the corridor. To distinguish abnormal crash concentrations from background fluctuations, the dynamic threshold defined as twice the moving average of crash counts is shown by the red dashed line. Segments with crash frequencies exceeding this threshold are classified as high-risk locations and are marked with red dots.

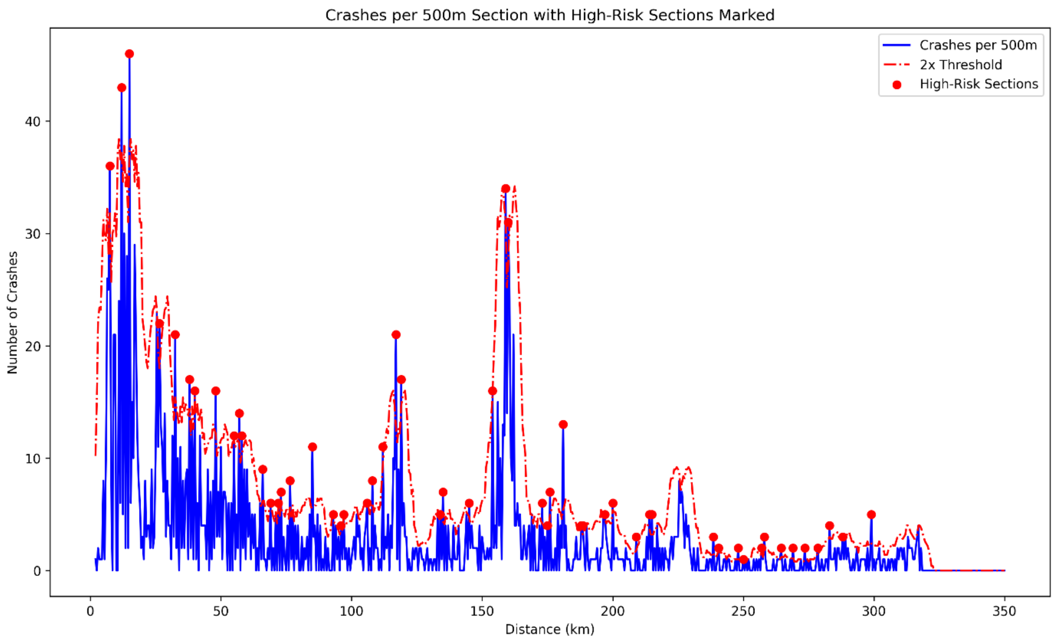


Figure 4.2 Identification of high-risk road sections from sliding window algorithm

4.2.2 Results of identifying high-risk road segments analysis done using sliding window method 2

This section presents the results of the high-risk road segment analysis conducted using Sliding Window Method 2. The analysis applies multiple window sizes to evaluate crash concentrations along the A002 corridor, allowing a flexible assessment of localized crash patterns. The results obtained from each window sizes were compared to determine the most effective configuration for capturing high-risk areas. Figures 4.3 to 4.8 present the output charts generated for each window size applied in Sliding Window Method 2. These charts illustrate the segment-wise crash distribution along the A002 corridor, highlighting the high-risk road segments identified for each configuration. By visually comparing the outputs across the different window sizes, the analysis assesses how window length influences the detection of localized crash concentrations.

- for window size 2 (1km section) accident frequency and high-risk areas

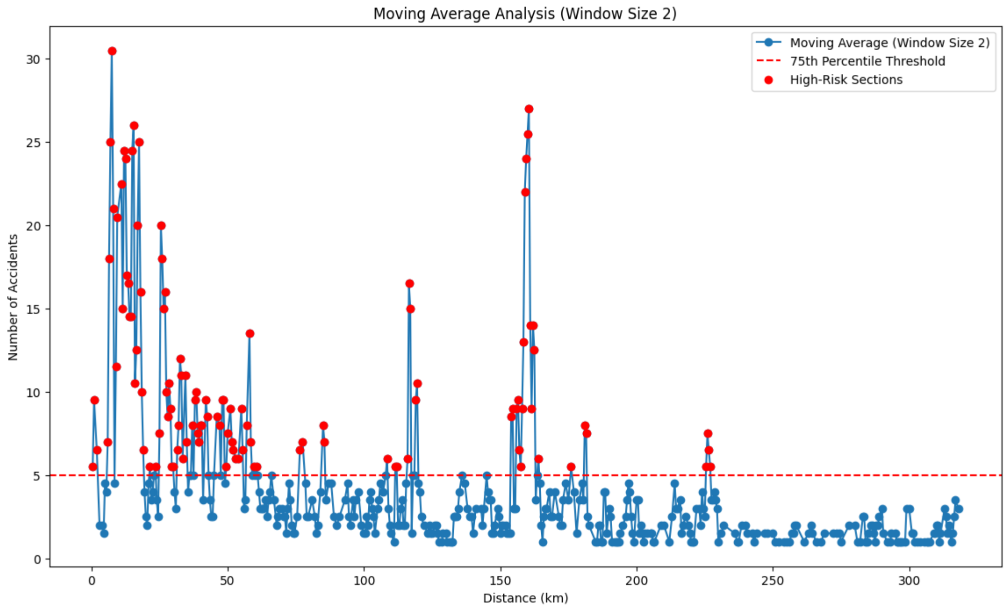


Figure 4.3 Accidents frequency analysis and identification of high-risk area for k=2 (1 km sections)

- for window size 4 (2km section) accident frequency and high-risk areas

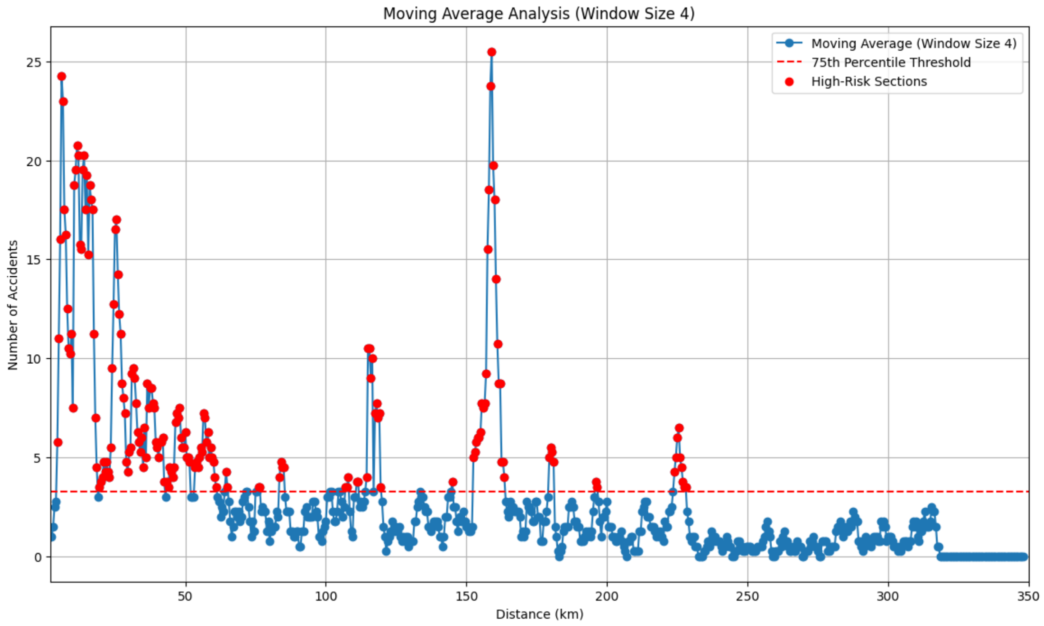


Figure 4.4 Accidents frequency analysis and identification of high-risk area for k=4 (2 km sections)

- for window size 8 (4km section) accident frequency and high-risk areas

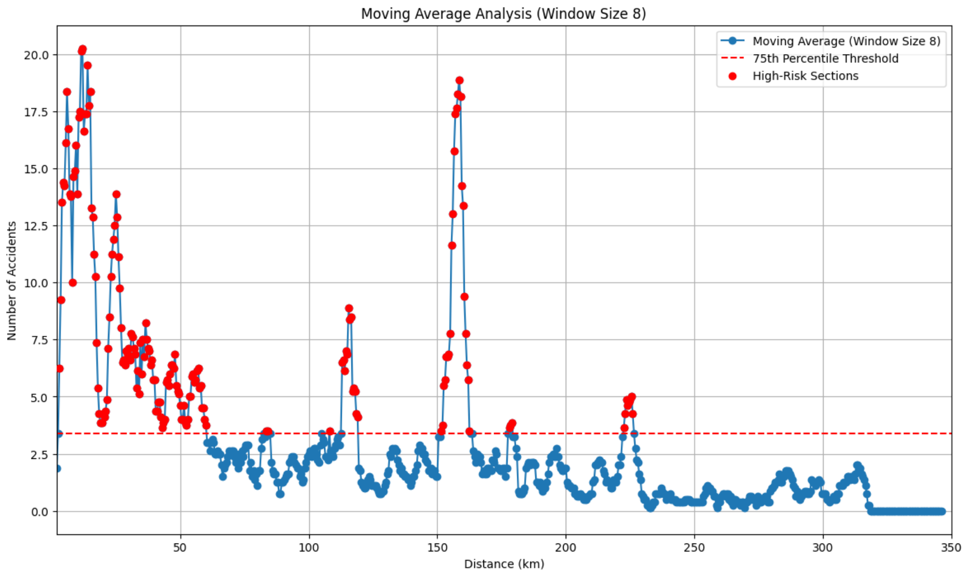


Figure 4.5 Accidents frequency analysis and identification of high-risk area for k=8 (4 km sections)

- for window size 12 (6km section) accident frequency and high-risk areas

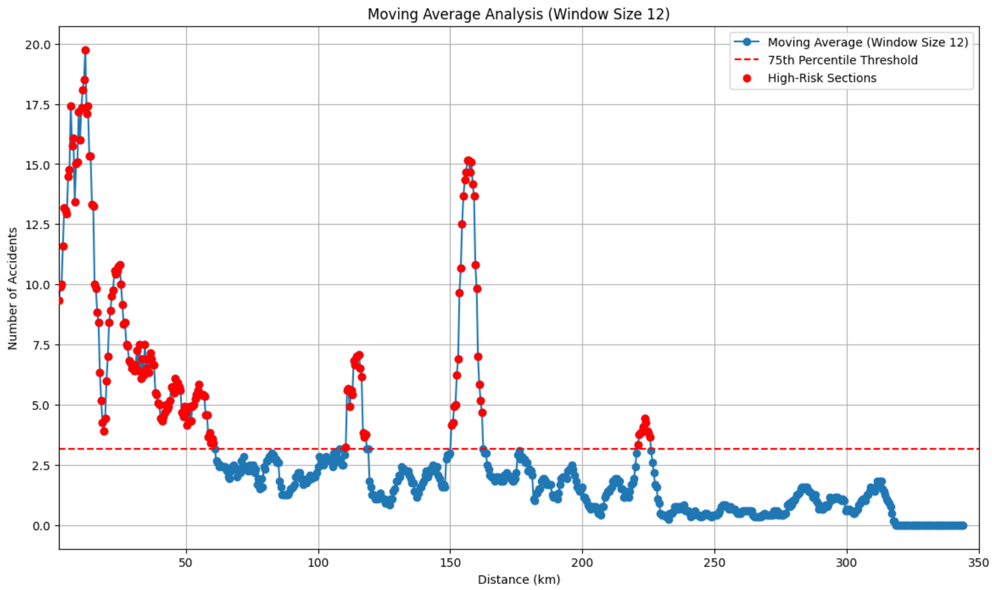


Figure 4.6 Accidents frequency analysis and identification of high-risk area for k=12 (6 km sections)

- for window size 16 (8km section) accident frequency and high-risk areas

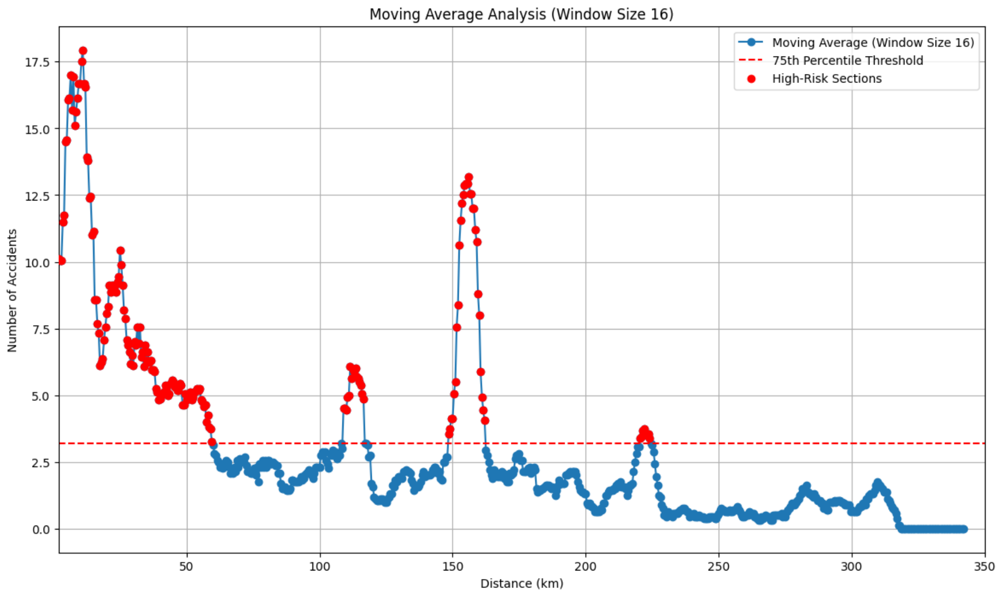


Figure 4.7 Accidents frequency analysis and identification of high-risk area for k=16(8 km sections)

- for window size 20 (10km section) accident frequency and high-risk areas

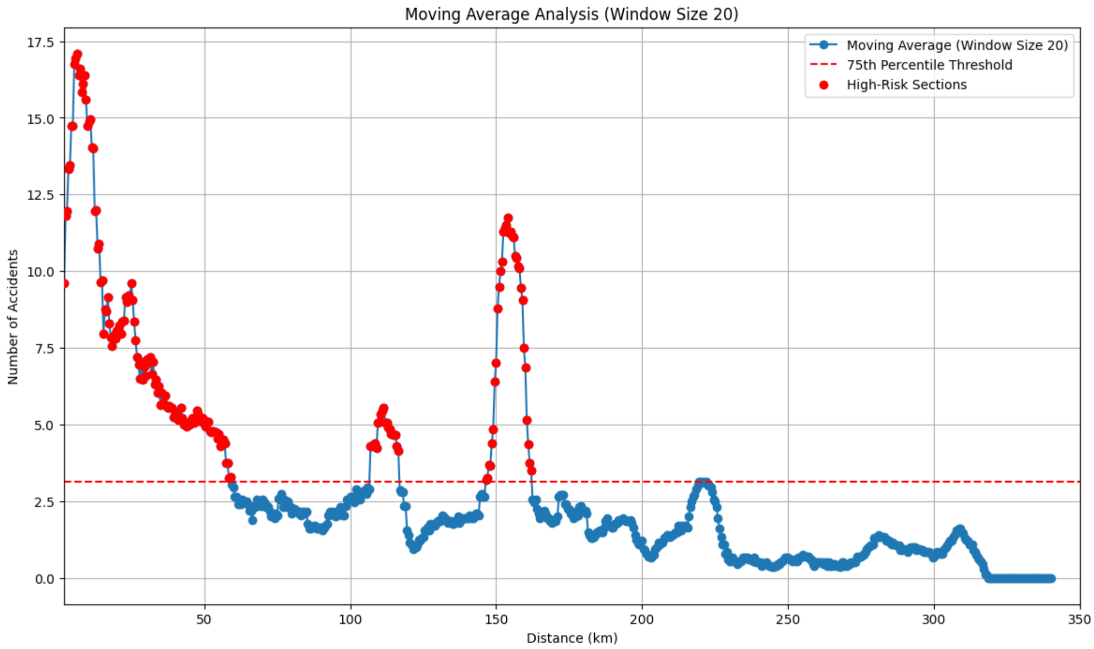


Figure 4.8 Accidents frequency analysis and identification of high-risk area for k=20 (10 km sections)

4.2.2.1 Determining the Optimal Window Size for High-Risk Segment Identification

Small Windows (High Granularity)

Provide high spatial resolution but suffer from high variability and noise due to sparse crash counts in small segments. This can lead to unreliable identification of high-risk locations, as random fluctuations dominate.

Large Windows (High Aggregation):

Reduce variability by aggregating data over larger areas but may obscure localized high-risk areas by blending hazardous locations with safer ones. This results in a loss of meaningful local variation and can wash out critical hotspots.

Finding the ‘Optimal’ or ‘Meaningful’ Window

It is needed to be consider to find an “optimal” window size that balances statistical reliability (low variance) and sensitivity to localized patterns (low bias).

Justification of the Optimal Window Size

Based on the sensitivity analysis, a segment length of 4 km was selected as the optimal window size for the following reasons:

Statistical Justification:

The variability at 4 km strikes a balance between reducing random noise (observed in smaller windows) and preserving meaningful local patterns (lost in larger windows).

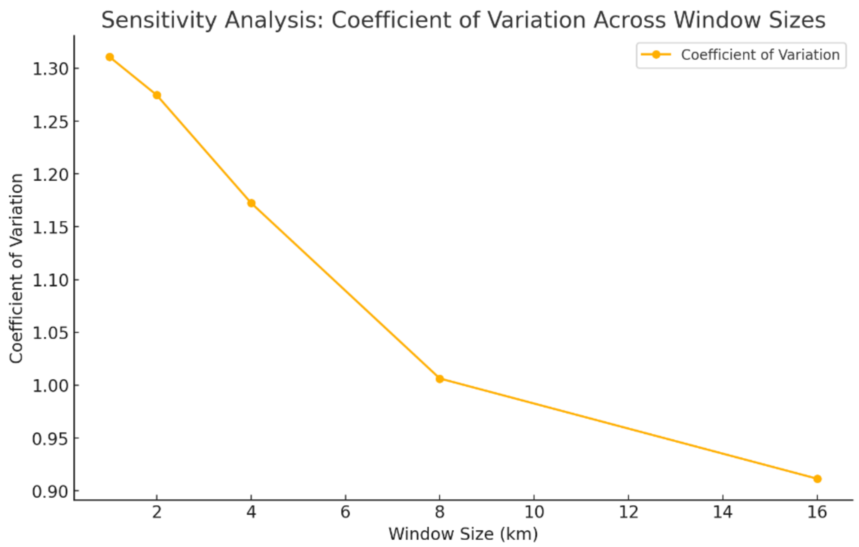


Figure 4.9 Comparison between coefficient of variation and window sizes

As the window size increases, the coefficient of variation decreases, indicating that larger windows reduce variability but may also smooth out important local details. The "optimal" point, where noise is reduced without losing too much granularity, seems to be around a window size of 8 (4 km), as the coefficient of variation stabilizes below this point.

Practical Considerations:

The 4 km window is granular enough to detect localized high-risk areas without excessive noise in our case. This segment length aligns with best practices in road safety studies, as recommended by organizations such as AASHTO and Austroads, which advocate for intermediate resolutions to balance statistical reliability and practical applicability in black spot identification. Additionally, the Black Spot Program guidelines in Australia emphasize the treatment of road lengths of 3.0 km or more to ensure that the selected road segments exhibit a consistent crash history comparable to that required for a discrete site [66]

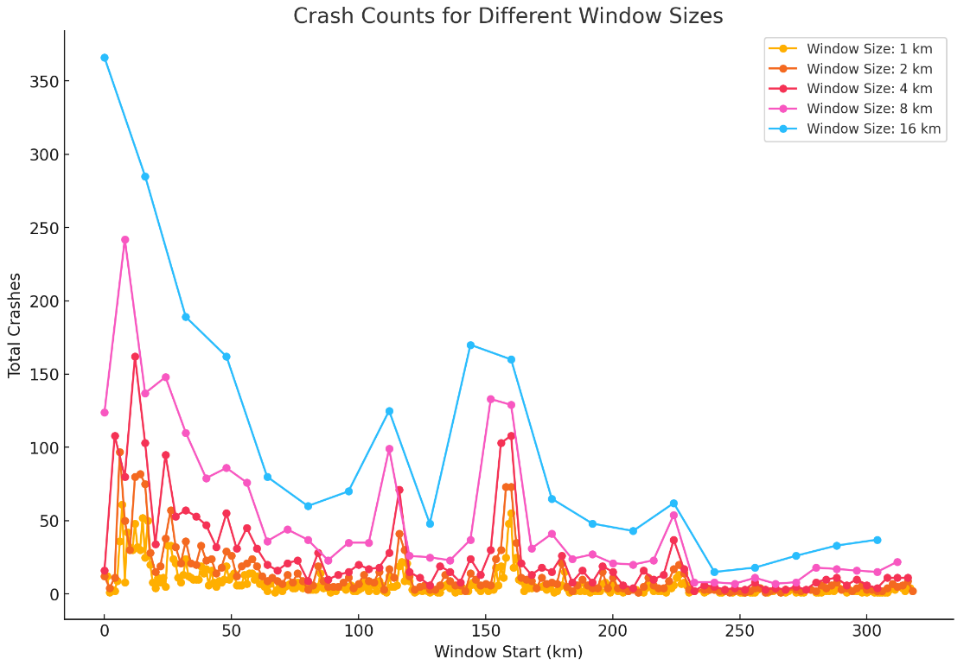


Figure 4.10 Variation of crash frequency for the different window sizes

Table 4.3 The list of high-risk road sections identified using sliding window method 2

High-risk sections	
window size	Distance
2(1km)	02.00 km - 61.50 km
	76.50 km - 78.50 km
	85.00 km - 86.50 km
	108.50 km - 120.50 km
	154.00 km - 165.00 km
	176.00 km - 177.00 km
	181.00 km - 182.50 km
	225.50 km - 228.00 km
4(2km)	02.00 km - 21.50 km
	25.50 km - 61.50 km
	86.00 km - 89.00 km
	116.50 km - 122.50 km

	155.00 km - 165.50 km
	181.00 km - 183.00 km
	226.50 km - 229.00 km
6(3km)	06.50 km - 23.00 km
	25.00 km - 63.50 km
	116.50 km - 125.00 km
	156.00 km - 167.50 km
	228.00 km - 231.00 km
8(4km)	03.00 km - 64.00 km
	83.50 km - 88.00 km
	108.00 km - 183.00 km
	222.50 km - 230.00 km
10(5km)	06.50 km - 67.00 km
	118.00 km - 126.00 km
	158.00 km - 170.50 km
12(6km)	02.00 km - 66.50 km
	110.50 km - 124.00 km
	150.50 km - 168.00 km
	221.00 km - 231.50 km
16(8km)	02.00 km - 67.50 km
	109.00 km - 124.50 km
	148.50 km - 170.00 km
	220.50 km - 232.00 km
20(10km)	02.00 km - 69.00 km
	107.00 km - 126.50 km
	146.50 km - 172.00 km

4.2.3 Identification of high-risk road segments using K-mean clustering method

This section presents the results of identifying high-risk road segments using the K-Means clustering method. The crash data obtained from the Sri Lanka Accident Data Management System (SLADMS) were analyzed using developed python-based K-mean clustering analysis algorithm, which groups road segments into clusters based on similarities in crash patterns. The objective of this method was to categorize segments with relatively high crash frequencies into distinct clusters, allowing for a more data-driven identification of hazardous locations. Unlike threshold-based methods, K-Means clustering does not require predefined limits, making it suitable for detecting underlying patterns in the data.

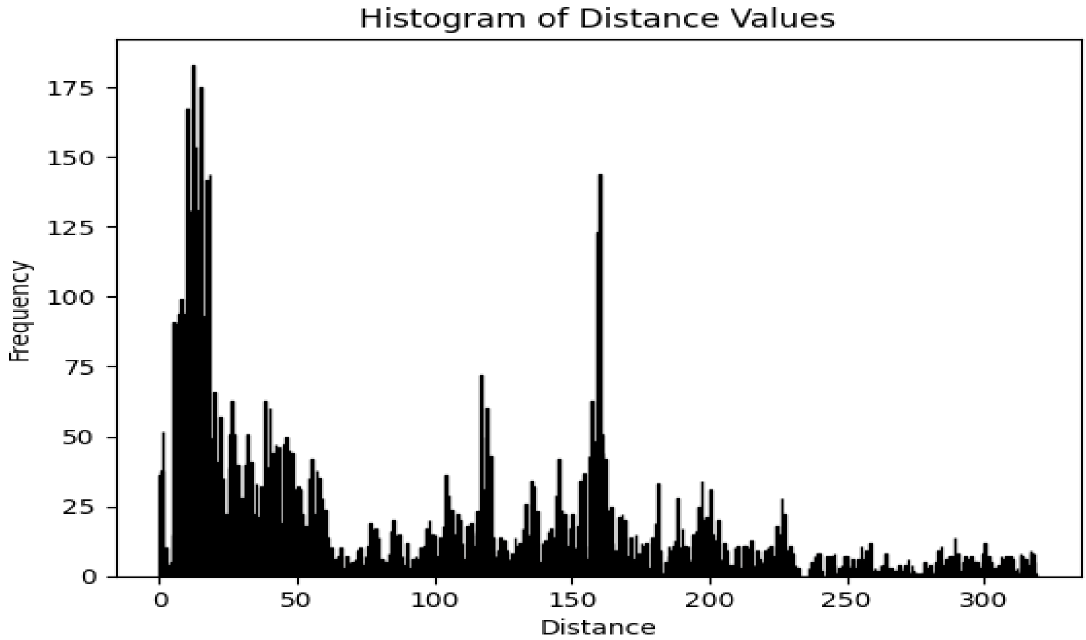


Figure 4.11 Visualization of accident frequency with distance of A002 road Sri Lanka

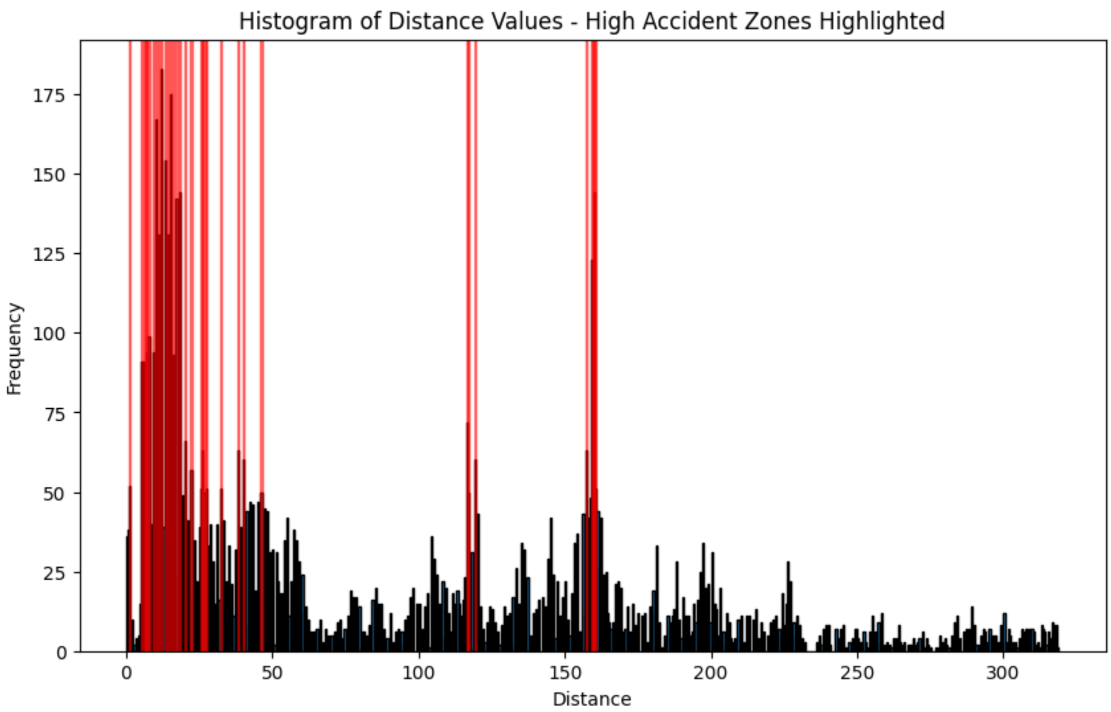


Figure 4.12 Visualization of high-risk road sections using K-mean clustering algorithm

Table 4.4 Results of High-risk areas and coordination with distances

High Risk Segments(km)	Distance (km)	Coordinate	
		From	To
1 -1.5	0.5	6.7713, 79.8825	6.9207, 79.8463
5 - 5.5	0.5	6.8922, 79.8561	6.88366, 79.85709
6.0 - 8.0	2	6.8805, 79.8588	6.86376, 79.86329
9 - 9.5	0.5	6.0936, 80.6233	6.09364, 80.62064
10 -18.5	8.5	6.8488, 79.8660	6.76392, 79.88616
20 - 20.5	0.5	6.7674, 79.8912	6.76834, 79.89122
22 - 22.5	0.5	6.7556, 79.8979	6.12575, 80.51914
25.5 - 27.5	2	5.1910, 78.9704	5.19102, 78.97046
32 - 32.5	0.5	6.1533, 80.4382	6.67338, 79.92626
38 - 38.5	0.5	6.6165, 79.9467	6.61747, 79.94645
40 - 40.5	0.5	6.6046, 79.9527	6.6003, 79.9548
46 - 46.5	0.5	6.5539, 79.9686	6.55121, 79.96998
116.5 - 117.5	1	5.1910, 78.9704	5.19102, 78.97046
119 -119.5	0.5	6.0366, 80.2325	6.03666, 80.23258
157 - 157.5	0.5	5.9418, 80.5176	5.94323, 80.52164
159 - 161	2	5.9478, 80.5338	6.27329, 81.22033

The comparative analysis of high-risk road segment identification methods highlights the strengths and limitations of each approach. While the K-Means clustering method is effective in detecting clusters of high crash frequency, it tends to be biased toward areas with high traffic volumes due to its reliance on spatial density patterns and fixed cluster boundaries. This can lead to inconsistent risk representation across the network.

In contrast, the sliding window method offers a more balanced and uniform framework for risk assessment by evaluating all segments systematically, regardless of traffic density. Its use of overlapping segments allows for continuous and detailed analysis, reducing the likelihood of overlooking localized high-risk areas. Between the two sliding window approaches, Method 1 was found to produce the most reliable and unbiased results. Its enhanced sensitivity and granularity make it more suitable for identifying hazardous segments with greater precision.

After comparing the outputs of the different analytical approaches, the results obtained from Sliding Window Method 1 were selected for the final stages of this study, including conclusion development and decision-making processes. All Python-based data analysis algorithms developed and used to implement the methods described above were executed on the Google colab platform. The complete scripts are included in Appendix C for reference and reproducibility.

4.3 Analysis for identifying high risk road segments based on number of casualties per accident

This section presents the results of identifying high-risk road segments along the A-002 corridor based on the number of casualties per accident. As described in Section 3.4, a Python-based data analysis algorithm was developed and executed on the Google colab platform to calculate casualty-to-accident ratios using five years of crash data from SLADMS. Table 4.5 provides a representative sample of the output, illustrating calculated ratios for 5 km segments (window size = 10) across selected sections of the corridor and results highlight locations where accidents result in disproportionately high casualties.

Table 4.5 Sample output results generated from algorithm for casualty per accident ratio

Road section	Casualty per accident ratio
2.0 km - 7.0 km	0.44
12.0 km - 17.0 km	0.45
25.5 km - 30 .5 km	0.8
71.5 km - 76.5 km	1.41
102.5 km - 107.5 km	0.77
122.0 km - 127.0 km	1.49
167.5 km - 172.5 km	1.69
236.5 km - 241.5 km	1.14
283.0 km - 288.0 km	1.86
299.5 km - 304.5 km	1.5
306.5 km - 311.5 km	1.46

4.3.1 Graph visualization of High-Risk Area with regards to the Casualties per Accident

High risk Road Sections According to the 95% of threshold

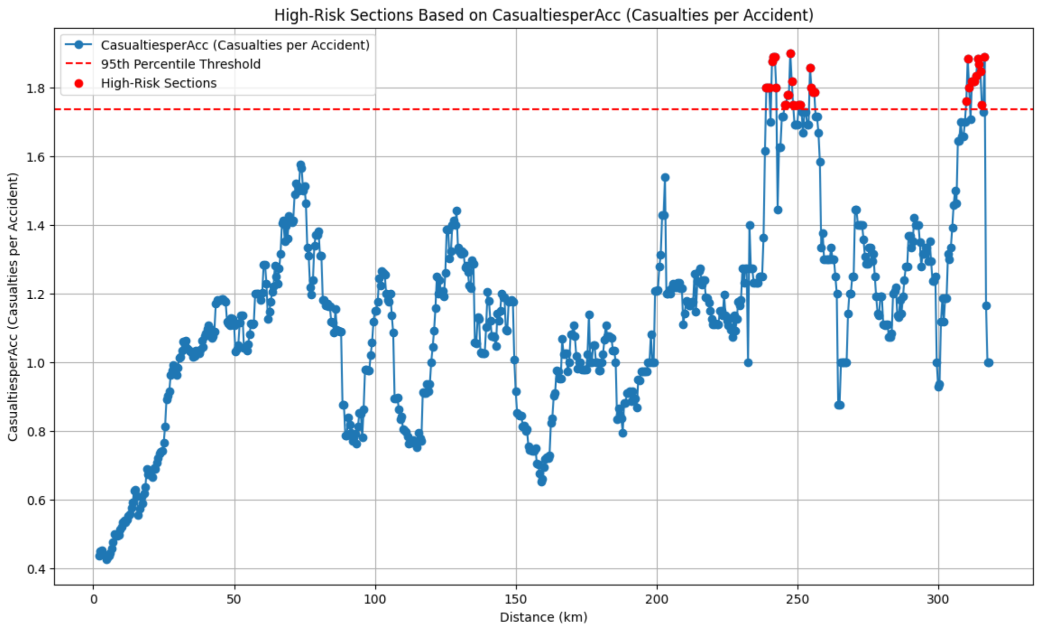


Figure 4.13 High risk road section based on casualties per accident (95% of threshold)

High-risk road segments based on the CasualtiesperAcc (casualties per accident):

239.0 km - 266.0 km

310.0 km - 326.5 km

The analysis of the graph highlights high-risk road segments, primarily in rural or low-traffic areas, where the Casualties per Accident (CasualtiesPerAcc) exceed the 95th percentile threshold. These segments are often influenced by isolated, high-severity crashes rather than overall crash frequency. To address this, the focus should be on minimizing fatalities and injuries in the event of a crash. Key measures include installing roadside safety features such as guardrails, crash barriers, and rumble strips to reduce crash severity, improving road design with enhanced visibility, signage, and shielding hazardous roadside features, and strengthening emergency response systems by establishing trauma centers and emergency call stations in remote areas. Additionally, driver awareness campaigns and speed reduction strategies should be implemented to encourage safer driving behavior, and advanced monitoring systems can be introduced to warn drivers of dangerous conditions.

High risk Road Sections According to the 85% of threshold

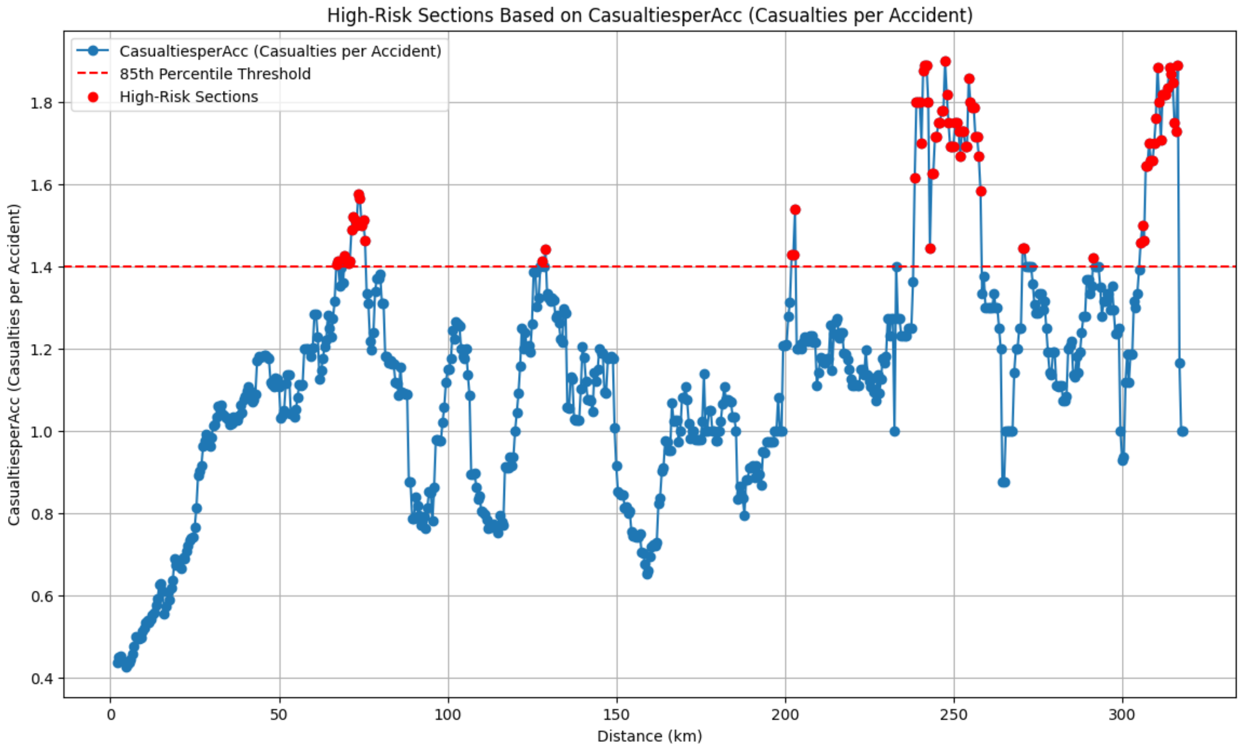


Figure 4.14 High risk road section based on casualties per accident (85% of threshold)

High-risk road segments based on the CasualtiesperAcc (casualties per accident):

67.0 km - 77.5 km
69.5 km - 85.5 km
128.0 km - 139.0 km
202.0 km - 213.0 km
238.5 km - 268.0 km
270.5 km - 281.0 km
291.5 km - 301.5 km
305.5 km - 326.5 km

The analysis based on the 85th percentile threshold indicates that in addition to high-risk segments in rural areas, there are also urban road sections with elevated Casualties per Accident (CasualtiesPerAcc). In urban contexts, these high-risk segments are often linked to factors such as increased pedestrian activity, proximity to schools, densely populated areas, and commercial zones with high traffic volumes. The concentration of vulnerable road users like pedestrians and cyclists, coupled with complex traffic interactions, significantly raises the risk of severe accidents in these locations.

Urban areas may also experience inadequate pedestrian infrastructure, such as a lack of safe crossings, poorly lit roads, and limited speed control measures, which further exacerbate the risk. Addressing these issues requires targeted interventions, including traffic calming measures, enhanced pedestrian facilities, proper land-use planning, and stricter enforcement of speed limits. A focused approach to urban high-risk segments can reduce casualty rates and improve overall road safety.

High risk Road Sections According to the 75% of threshold

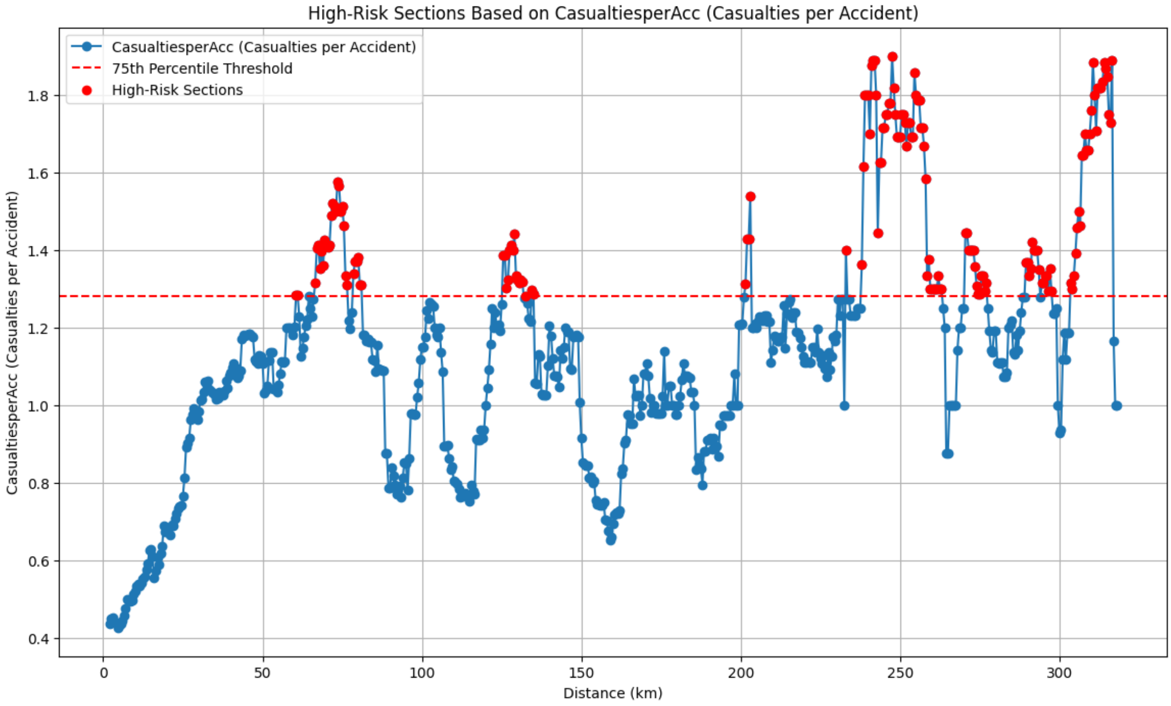


Figure 4.15 High risk road section based on casualties per accident (75% of threshold)

High-risk road segments based on the threshold for CasualtiesperAcc (casualties per accident):

60.5 km - 71.0 km
66.5 km - 91.0 km
125.5 km - 145.0 km
201.5 km - 213.0 km
233.0 km - 243.0 km
238.0 km - 273.0 km
270.5 km - 287.0 km
289.5 km - 326.5 km

The following road segments were identified as high-risk locations along the A-002 road based on outputs from both sliding window analyses: method 1, which highlights segments with high crash frequency, and method of crash severity (casualty per acc method), which focuses on segments with elevated casualty-to-accident ratios. These locations indicate critical zones requiring further safety assessments and potential interventions.

Table 4.6 High risk area from both high frequency and casualties per accident method

07.00 km -8.00 km	based on high frequency of accidents
12.00 km - 15.5 km	based on high frequency of accidents
26.00 km - 27.00 km	based on high frequency of accidents
32.50 km - 33.00 km	based on high frequency of accidents
38.00 km - 40.50 km	based on high frequency of accidents
48.00 km - 48.50 km	based on high frequency of accidents
55.00 km - 58.50 km	based on high casualty rate per an accident
66.00 km - 77.00 km	based on high casualty rate per an accident
85.00 km - 85.50 km	based on high casualty rate per an accident
93.00 km - 97.50 km	based on high casualty rate per an accident
106.00 km - 108.50 km	based on high frequency of accidents
112.00 km - 112.50 km	based on high frequency of accidents
117.00 km - 119.5 km	based on high casualty rate per an accident
134.00 km - 135.50 km	based on high casualty rate per an accident
145.00 km - 145.50 km	based on high frequency of accidents
154.00 km - 154.50 km	based on high frequency of accidents
159.00 km - 160.5 km	based on high frequency of accidents
173.00 km - 176.50 km	based on high casualty rate per an accident
181.0 km - 189.0 km	based on high casualty rate per an accident
197.00 km - 200.50 km	based on high casualty rate per an accident
209.00 km - 215.50 km	based on high casualty rate per an accident
238.50 km - 241.0 km	based on high casualty rate per an accident
248.0 km - 250.50 km	based on high casualty rate per an accident
257.0 km - 258.50 km	based on high casualty rate per an accident
289.5 km - 299.5 km	based on high casualty rate per an accident
305.5 km - 309.5 km	based on high casualty rate per an accident
315.5 km - 319.5 km	based on high casualty rate per an accident
322.5 km - 329.5 km	based on high casualty rate per an accident

The created map in figure 4.16 visualizes identified high-risk segments along the A0022 road corridor in Sri Lanka.

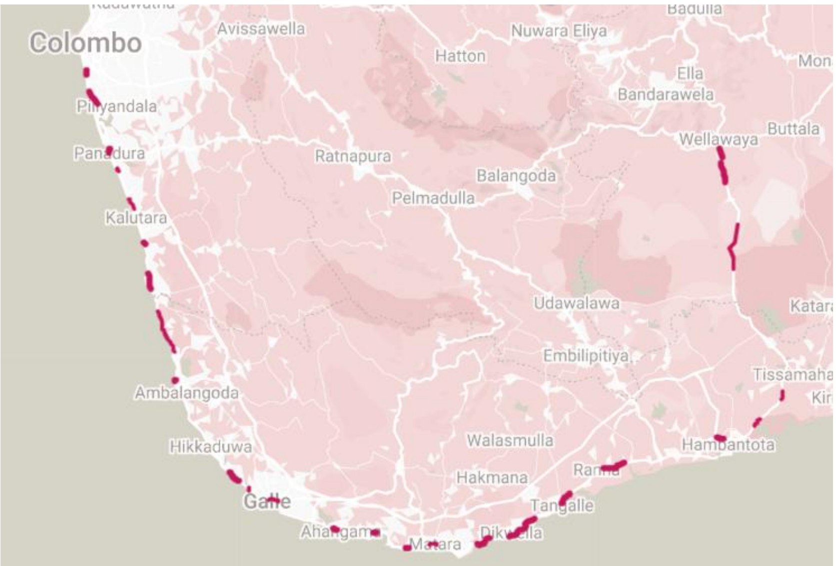


Figure 4.16 Spatial visualization of high-risk road segments along the A-002 road

After identifying high-risk road segments, the study examined contributing factors through a comprehensive three-part assessment, focusing on the roadway environment, infrastructure conditions, and crash severity, as described in the methodology.

4.4 Application of roadway environment assessment in the case study

4.4.1 Road segment classification for safety assessment

This map presents a classification of the A002 road corridor based on roadway environment characteristics, as outlined in Methodology Section 3.5 of this study. The classification segments the route into five distinct land use contexts Urban Core, Urban, Sub-urban, Rural Town, and Rural each represented by a different color to visually communicate the varying environmental and development intensities along the corridor.

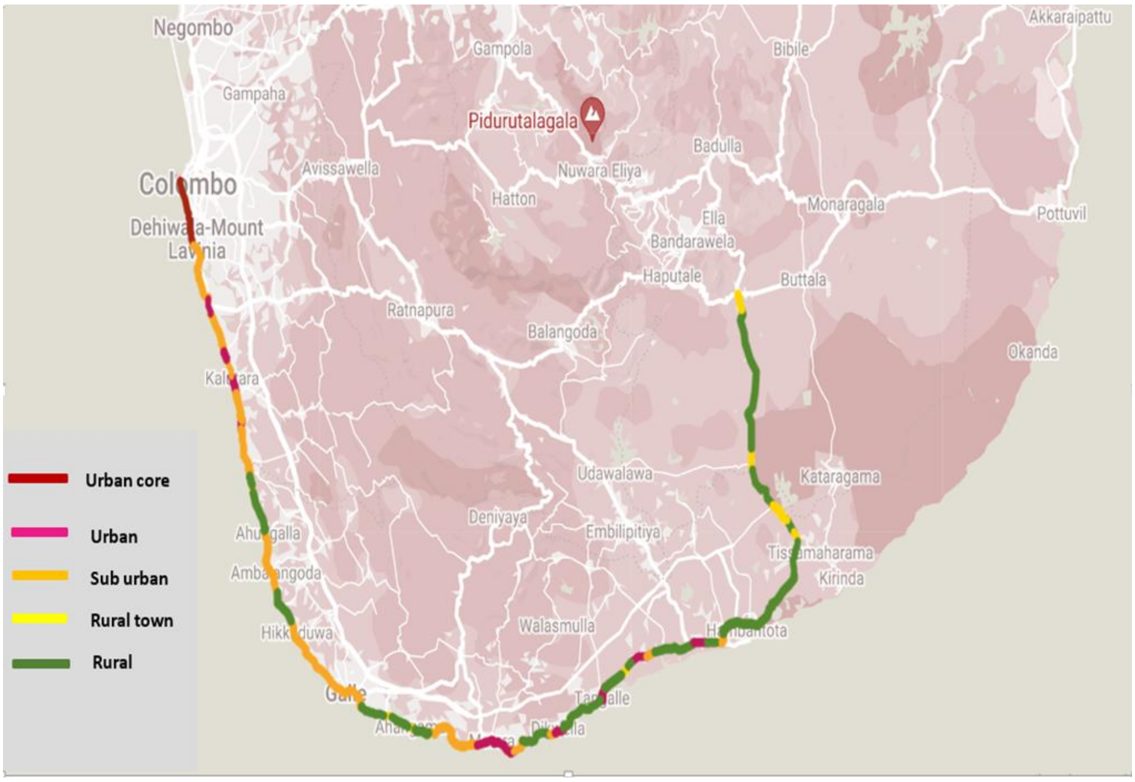


Figure 4.17 Classification and highlight of A002 road as per roadway environment guidelines

The same classification was also applied to the A001 road to demonstrate the method's applicability across different geographic areas and roadway environments. The A001 road (commonly known as the Colombo - Kandy Road or just the Kandy Road) is an A-Grade trunk road in Sri Lanka. It connects the capital city of Colombo with Kandy. The A001 road from Colombo to Kandy passes through major cities, traverse mountainous terrain, goes through urban towns, and extends into rural areas.

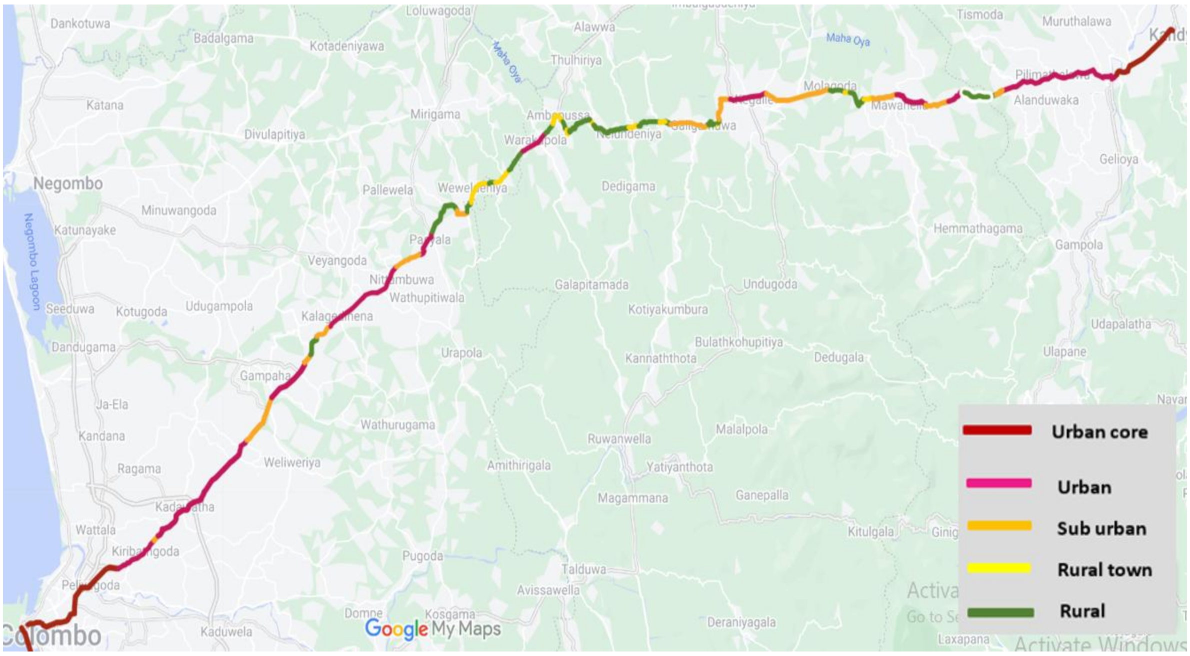


Figure 4.18 Classification and highlight of A001 road as per roadway environment guidelines

The identified high-risk road sections were evaluated through the first stage of the comprehensive assessment framework, roadway environment assessment. This evaluation classified each segment based on its surrounding land use and development context. The results of this assessment are summarized in the table below, indicating the corresponding environmental context assigned to each segment.

Table 4.7 Risk assessment for the high-risk section based on Roadway Environment context

Distance (Km)	Roadway Environment	Class
07.00 km -8.00 km	Urban core	E1
12.00 km - 15.5 km	Urban core	E1
26.00 km - 27.00 km	Urban core	E1
32.50 km - 33.00 km	Urban	E2
38.00 km - 40.50 km	Sub Urban	E3
48.00 km - 48.50 km	Urban	E2
55.00 km - 58.50 km	Sub Urban	E3
66.00 km - 77.00 km	Sub Urban	E3
85.00 km - 85.50 km	Sub Urban	E3
93.00 km - 97.50 km	Sub Urban	E3
106.00 km - 108.50 km	Rural town	E4
112.00 km - 112.50 km	Sub Urban	E3
117.00 km - 119.5 km	Sub Urban	E3
134.00 km - 135.50 km	Rural	E5
145.00 km - 145.5 km	Rural	E5
154.00 km - 154.50 km	Rural	E5
159.00 km - 160.5 km	Rural	E5
173.00 km - 176.50 km	Rural town	E4
181.0 km - 189.0 km	Sub Urban	E3
197.00 km - 200.50 km	Sub Urban	E3
209.00 km - 215.50 km	Rural	E5
238.50 km - 241.0 km	Rural	E5
248.0 km - 250.50 km	Sub Urban	E3
257.0 km - 258.50 km	Rural	E5
289.5 km - 299.5 km	Rural town	E4
305.5 km - 309.5 km	Rural	E5
315.5 km - 319.5 km	Rural	E5
322.5 km - 329.5 km	Rural	E5

4.5 Application of road infrastructure assessment in the case study

The infrastructure assessment considered factors such as road design, traffic control devices, pedestrian infrastructure, roadside hazards, lighting and other related factors. A road safety audit program was carried out to evaluate the high-risk locations identified along the A002 corridor. The assessment involved several key steps, including video recording of selected sites, on-site walking inspections, and the use of a standardized checklist to ensure consistent data collection.

The assessment examined each location based on five key road characteristics, as described in Section 3.6. For each characteristic, the study assigned scores to specific attributes using criteria adapted to local road and traffic conditions based on the audited results. The study used these scores to calculate the Road Safety Index (RSI) values, providing a quantitative measure of infrastructure-related risk at each site.

Table 4.8 Calculation of Road Safety Index value based on different characteristics

Distance (Km)	factors					RSI
	Roadway characteristic	Traffic characteristic	Roadside characteristic	Pavement characteristic	Miscellaneous characteristic	
07.00 km -8.00 km	83	79.16	39.4	78	66.8	0.72
12.00 km - 15.5 km	75	66.6	50.2	70.5	40	0.65
26.00 km - 27.00 km	65	70	50.55	45	64.22	0.61
32.50 km - 33.00 km	79.4	75	61.56	51	33.33	0.67
38.00 km - 40.50 km	72	69.5	40	33	33.33	0.57
48.00 km - 48.50 km	74	70	52	38	20	0.59
55.00 km - 58.50 km	50	44	55.55	40.54	50	0.48
66.00 km - 77.00 km	61.8	76.33	33.33	87.5	6.67	0.59
85.00 km - 85.50 km	55	66	40.33	82.4	6.67	0.54
93.00 km - 97.50 km	54	45.54	33.33	25.5	33.33	0.43
106.00 km - 108.50 km	48.3	45.2	25.6	12.65	21.5	0.36
112.00 km - 112.50 km	55.9	33.33	32.5	6.67	20	0.36
117.00 km - 119.5 km	68.4	42.3	33.33	6.67	23.6	0.43
134.00 km - 135.50 km	68	31	78	33.33	6.67	0.50
145.00 km - 145.50 km	76	54	63	10	6.67	0.53
154.00 km - 154.50 km	56	40	30	7	33.33	0.37
159.00 km - 160.5 km	44.5	38.5	25.9	10.33	10.33	0.32
173.00 km - 176.50 km	76	55	49.2	25.6	35.9	0.56
181.0 km - 189.0 km	44	39	34.33	6.67	10.33	0.33
197.00 km - 200.50 km	71.33	69.8	61.5	59.8	55	0.66

209.00 km - 215.50 km	65	55	44.3	20.33	10.33	0.48
238.50 km - 241.0 km	76.8	72.2	45.6	55	35.3	0.63
248.00 km - 250.50 km	75	66.66	25.8	20.33	45.5	0.54
257.00 km - 258.50 km	46.3	53.6	12.8	10.33	10.33	0.34
289.50 km - 299.50 km	61.8	62.5	20.33	33.33	33.33	0.48
305.50 km - 309.50 km	54.2	37	45	22.5	6.67	0.40
315.50 km - 319.50 km	74.9	28.6	56	12.5	10.33	0.46
322.50 km - 329.50 km	65.8	36.5	24.5	12.5	10.33	0.39

The road safety audit results and the sample calculation for determining the Road Safety Index (RSI) are presented in appendix A and appendix B, respectively.

4.6 Application of crash severity assessment in the case study

Under this assessment, the study determined the Severity Index values using five years of crash data from the Sri Lankan Accident Data Management System (SLADMS). This index enabled the study to classify accidents according to their severity and quantify the overall severity level within each road segment. SLADMS recorded each accident using numerical codes corresponding to four severity levels: fatal, grievous, non-grievous, and damage-only. To quantify the severity within each road segment, damage-only crashes receive a score of 1, non-grievous crashes a score of 2, grievous crashes a score of 3, and fatal crashes a score of 4, with higher scores indicating greater severity. The study calculated the Severity Index for each road segment based on the severity of individual crashes, using Equation 3.2 as outlined in Section 3.7.1. Each accident received a weighted value according to its severity level from minor to fatal allowing the cumulative impact of crashes within each segment to be quantified.

Crash severity variations along the A-002 corridor are spatially visualized, facilitating the identification of road segments with disproportionately high severity levels in figure 4.19.

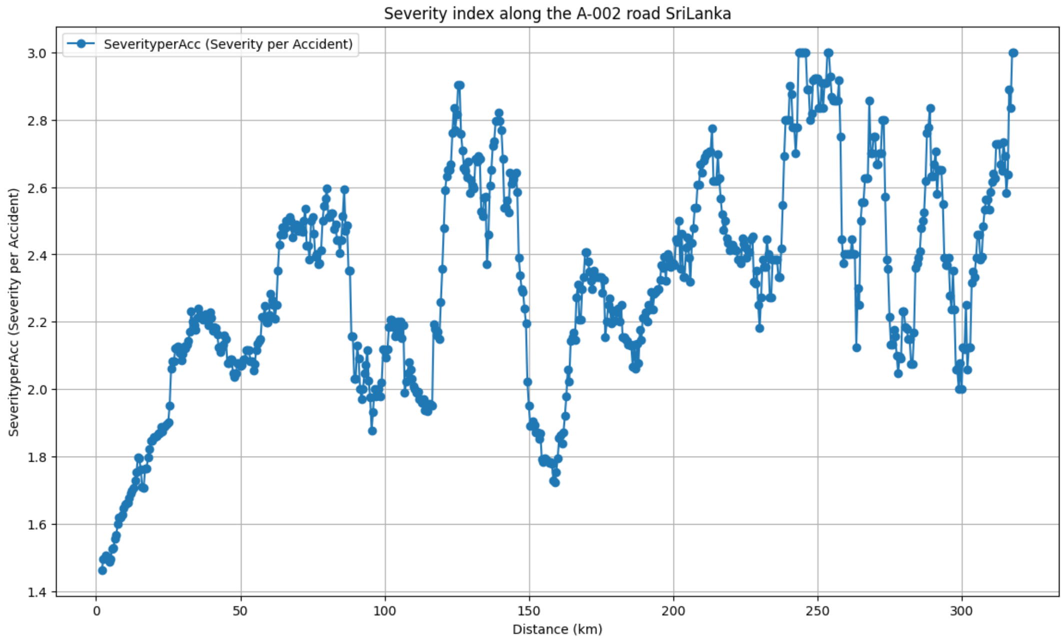


Figure 4.19 Illustration of severity index values for A-002 road

The table below summarizes the results of the road safety risk assessment conducted based on crash severity levels for the previously identified high-risk road sections along the A-002 corridor.

Table 4.9 Results of Road Safety risk assessment based on crash severity level for the identified high risk road sections

Distance (Km)	Severity Index	Class
07.00 km -8.00 km	3.54	C1
12.00 km - 15.5 km	3.31	C2
26.00 km - 27.00 km	3.13	C2
32.50 km - 33.00 km	2.86	C3
38.00 km - 40.50 km	2.84	C3
48.00 km - 48.50 km	2.89	C3
55.00 km - 58.50 km	2.79	C3
66.00 km - 77.00 km	2.5	C3
85.00 km - 85.50 km	2.6	C3
93.00 km - 97.50 km	2.53	C3
106.00 km - 108.50 km	3.01	C2
112.00 km - 112.50 km	2.81	C3
117.00 km - 119.5 km	2.1	C3
134.00 km - 135.50 km	2.63	C3
145.00 km - 145.50 km	2.61	C3
154.00 km - 154.50 km	3.21	C2
159.00 km - 160.5 km	2.73	C3
173.00 km - 176.50 km	2.56	C3
181.00 km - 189.00 km	2.6	C3
197.00 km - 200.50 km	2.45	C3

209.00 km - 215.50 km	2.18	C3
238.50 km - 241.00 km	2.25	C3
248.00 km - 250.50 km	2.14	C3
257.00 km - 258.50 km	2.95	C3
289.50 km - 299.50 km	2.37	C3
305.50 km - 309.50 km	2.92	C3
315.50 km - 319.50 km	2.47	C3
322.50 km - 329.50 km	2	C4

Table 4.10 summarizes the results of this multi-dimensional analysis, offering a detailed classification of each segment based on observed performance indicators. This table provides a comprehensive view of the risk levels associated with each key factor, aiding in the prioritization of safety interventions and decision-making processes.

Table 4.10 The final results of road safety assessment for the selected high risk road sections along A002 road

Location (km)	Roadway Environment assessment		Infrastructure assessment			Crash severity assessment	
	Roadway Environment	Class	RSI	Level of Service (based on RSI)	Class	Severity index	Class
07.00 km -8.00 km	Urban core	E1	0.72	Very Good	S4	3.54	C1
12.00 km – 15.5 km	Urban core	E1	0.65	Very Good	S4	3.31	C2
26.00 km - 27.00 km	Urban core	E1	0.61	Very Good	S4	3.13	C2
32.50 km - 33.00 km	Urban	E2	0.67	Very Good	S4	2.86	C3
38.00 km - 40.50 km	Sub Urban	E3	0.57	Good/Average	S3	2.84	C3
48.00 km - 48.50 km	Urban	E2	0.59	Very Good	S4	2.89	C3
55.00 km – 58.50 km	Sub Urban	E3	0.48	Good/Average	S3	2.79	C3
66.00 km - 77.00 km	Sub Urban	E3	0.59	Good/Average	S3	2.5	C3
85.00 km - 85.50 km	Sub Urban	E3	0.54	Good/Average	S3	2.6	C3
93.00 km – 97.50 km	Sub Urban	E3	0.43	Good/Average	S3	2.53	C3
106.00 km - 108.50 km	Rural town	E4	0.36	Poor	S2	3.01	C2
112.00 km - 112.50 km	Sub Urban	E3	0.36	Poor	S2	2.81	C3
117.00 km - 119.5 km	Sub Urban	E3	0.43	Good/Average	S3	2.1	C3

134.00 km - 135.50 km	Rural	E5	0.50	Good/Average	S3	2.63	C3
145.00 km - 145.5 km	Rural	E5	0.53	Good/Average	S3	2.61	C3
154.00 km - 154.50 km	Rural	E5	0.37	Poor	S2	3.21	C2
159.00 km - 160.5 km	Rural	E5	0.32	Poor	S2	2.73	C3
173.00 km - 176.50 km	Rural town	E4	0.56	Good/Average	S3	2.56	C3
181.0 km - 189.0 km	Sub Urban	E3	0.33	Poor	S2	2.6	C3
197.00 km - 200.50 km	Sub Urban	E3	0.66	Very Good	S4	2.45	C3
209.00 km - 215.50 km	Rural	E5	0.48	Good/Average	S3	2.18	C3
238.50 km - 241.0 km	Rural	E5	0.63	Very Good	S4	2.25	C3
248.0 km - 250.50 km	Sub Urban	E3	0.54	Good/Average	S3	2.14	C3
257.0 km - 258.50 km	Rural	E5	0.34	Poor	S2	2.95	C3
289.5 km - 299.5 km	Rural town	E4	0.48	Good/Average	S3	2.37	C3
305.5 km - 309.5 km	Rural	E5	0.40	Poor	S2	2.92	C3
315.5 km - 319.5 km	Rural	E5	0.46	Good/Average	S3	2.47	C3
322.5 km - 329.5 km	Rural	E5	0.39	Poor	S2	2	C4

Table 4.11 Measured Risk Rating Index for the identified high risk road segments of A002 road

Location (km)	Risk Rating Index
07.00 km -8.00 km	15
12.00 km - 15.5 km	12
26.00 km - 27.00 km	12
32.50 km - 33.00 km	9
38.00 km - 40.50 km	9
48.00 km - 48.50 km	9
55.00 km - 58.50 km	9
66.00 km - 77.00 km	9
85.00 km - 85.50 km	9
93.00 km - 97.50 km	9
106.00 km - 108.50 km	12
112.00 km - 112.50 km	12
117.00 km - 119.5 km	9
134.00 km - 135.50 km	6
145.00 km - 145.5 km	6
154.00 km - 154.50 km	9
159.00 km - 160.5 km	9
173.00 km - 176.50 km	9
181.0 km - 189.0 km	12
197.00 km - 200.50 km	9
209.00 km - 215.50 km	6
238.50 km - 241.0 km	6
248.0 km - 250.50 km	9
257.0 km - 258.50 km	9
289.5 km - 299.5 km	9
305.5 km - 309.5 km	9
315.5 km - 319.5 km	6
322.5 km - 329.5 km	6

Table 4.11 presents the Risk Rating Index (RRI) for the high-risk road sections along the Colombo-Wellawaya (A002) corridor, as determined using the integrated risk rating matrix described in Section 3.8.1. The RRI combines the outcomes of the roadway environment assessment, infrastructure condition assessment, and crash severity assessment to produce a single numerical value representing the overall safety risk of each segment.

Higher index values correspond to segments with elevated combined risk levels. For example, segments with an RRI of 15 or 12 represent locations where severe crash outcomes, adverse roadway environments, and infrastructure deficiencies collectively contribute to high safety risk. Road segments with RRI values of 9 or 6 also indicate notable risk conditions, though to a comparatively lower degree.

The table highlights several discontinuous stretches across the A002 road that exhibit elevated RRI scores, indicating the presence of recurrent safety concerns. These segments are therefore recommended as priority locations for targeted safety interventions. The identification of these high-risk sections supports evidence-based decision-making and enables road agencies to allocate resources efficiently toward the most critical areas.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Recommendations and actions needed to be followed

DI = Detailed Investigation

UA = Urgent Action

IM = Intensive Monitoring

NA = Need Action

RM = Regular Monitoring

PA = Planned Action

To enhance the effectiveness of road safety management and prioritization, a systematic recommendation framework was developed based on the integrated evaluation of each road segment across three core dimensions: roadway environment, infrastructure safety, and crash severity. Table 5.1 presents the resulting recommendations aligned with the combined Level of Service (LOS) ratings for each segment, represented by composite classes (e.g., E1 S4 C2), where: E refers to the roadway environment class, S denotes the infrastructure condition class, and C indicates the crash severity class.

Table 5.1 Recommendations and actions suggested from the analysis for the identified high risk road sections

Location (km)	Level of Service	Recommendation
07.00 km -8.00 km	E1 S4 C1	DI/UA on roadway environment, crash severity and RM of infrastructure
12.00 km – 15.5 km	E1 S4 C2	DI/UA on roadway environment, crash severity and RM of infrastructure
26.00 km - 27.00 km	E1 S4 C2	DI/UA on roadway environment, crash severity and RM of infrastructure
32.50 km - 33.00 km	E2 S4 C3	DI/NA on roadway environment, IM of crash severity and RM of infrastructure
38.00 km - 40.50 km	E3 S3 C3	IM/PA on infrastructure safety, crash severity and roadway environment
48.00 km - 48.50 km	E2 S4 C3	DI/NA on roadway environment, IM of crash severity and RM on infrastructure safety
55.00 km – 58.50 km	E3 S3 C3	IM/PA on infrastructure safety, crash severity and roadway environment
66.00 km - 77.00 km	E3 S3 C3	IM/PA on infrastructure safety, crash severity and roadway environment
85.00 km - 85.50 km	E3 S3 C3	IM/PA on infrastructure safety, crash severity and roadway environment

93.00 km – 97.50 km	E3 S3 C3	IM/PA on infrastructure safety, crash severity and roadway environment
106.00 km - 108.50 km	E4 S2 C2	DI/NA on crash severity and infrastructure safety, RM on roadway environment
112.00 km - 112.50 km	E3 S2 C3	DI/NA on infrastructure safety and roadway environment, IM of crash severity
117.00 km - 119.5 km	E3 S3 C3	IM/PA on infrastructure safety, crash severity and roadway environment
134.00 km - 135.50 km	E5 S3 C3	IM/PA on infrastructure safety, crash severity
145.00 km - 145.50 km	E5 S3 C3	IM/PA on infrastructure safety, crash severity
154.00 km - 154.50 km	E5 S2 C2	DI/NA on infrastructure safety, crash severity
159.00 km - 160.5 km	E5 S2 C3	DI/NA on infrastructure safety and IM/PA crash severity
173.00 km - 176.50 km	E4 S3 C3	IM/PA on infrastructure safety, crash severity and RM of roadway environment
181.0 km - 189.0 km	E3 S2 C3	IM/PA action on roadway environment, crash severity and DI/NA of road infrastructure
197.00 km - 200.50 km	E3 S4 C3	IM/PA on roadway environment, crash severity and RM of road infrastructure
209.00 km - 215.50 km	E5 S3 C3	IM/PA on infrastructure safety, crash severity
238.50 km - 241.0 km	E5 S4 C3	IM/PA on crash severity and RM of infrastructure safety
248.0 km - 250.50 km	E3 S3 C3	IM/PA on infrastructure safety, crash severity and roadway environment
257.0 km - 258.50 km	E5 S2 C3	DI/NA on infrastructure safety and IM/PA action crash severity
289.5 km - 299.5 km	E4 S3 C3	IM/PA on infrastructure safety, crash severity and RM of roadway environment
305.5 km - 309.5 km	E5 S2 C3	DI/NA on infrastructure safety and IM/PA crash severity
315.5 km - 319.5 km	E5 S3 C3	IM/PA on infrastructure safety, crash severity
322.5 km - 329.5 km	E5 S2 C4	DI/NA on infrastructure safety and RM of crash severity

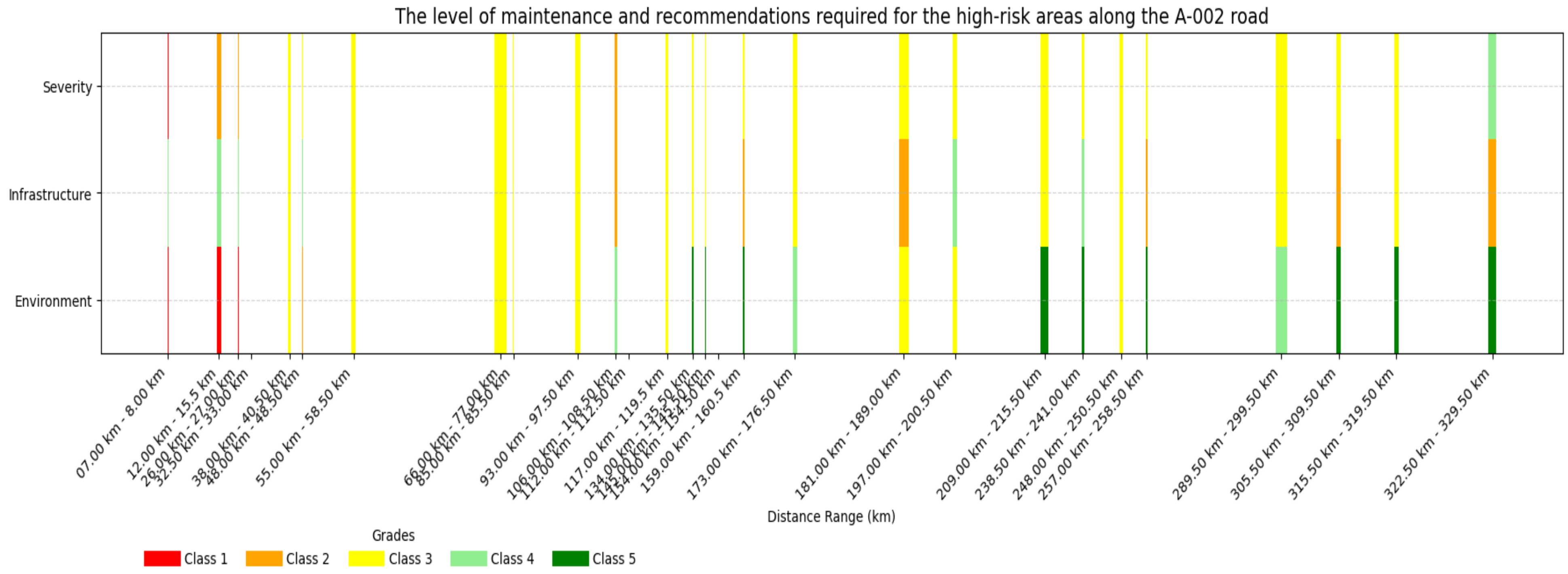


Figure 5.1 Graphically illustration of high-risk areas and desired level of service along A-002 road

This study introduces a comprehensive road safety management framework for Sri Lanka's national road network, addressing the critical challenges of reducing road traffic accidents and improving safety outcomes. By employing a structured methodology that integrates roadway environment assessments, infrastructure evaluations, and crash severity analyses, the research offers an evidence-based approach to identify, evaluate, and prioritize high-risk road segments. The findings also demonstrated the value of integrating advanced analytical techniques, such as K-mean clustering and the sliding-window approach to pinpoint high-risk locations more accurately and support targeted safety interventions.

The analysis of high-risk road identification graphs shows that casualty rate of traffic crashes is higher in rural areas farther from Colombo, primarily due to higher vehicle speeds, less congestion, limited speed enforcement, and inadequate safety infrastructure such as lighting and signage. In contrast, most accidents occur in urban environments because of higher traffic volumes, frequent vehicle interactions, and complex dynamics like pedestrian activity and multiple intersections, which increase the likelihood of collisions. The use of severity indices also supports the prioritization of segments where crashes have the most significant human and economic impact, ensuring resources are directed to areas with the highest potential for reducing severe injuries and fatalities.

The Road Safety Index (RSI) provided a structured approach to evaluating road infrastructure by incorporating key characteristics such as roadway geometry, traffic behavior, roadside features, pavement conditions, and miscellaneous factors like visibility and median presence. High-risk sections with poor RSI scores were often characterized by inadequate lane widths, frequent sharp curves, insufficient lighting, and poor pavement conditions, which contribute to increased crash severity. The findings from the RSI assessment demonstrate that enhancing road infrastructure in critical areas can significantly reduce crash risks and improve overall safety performance.

The Risk Rating Index developed in this study provides a comprehensive and evidence-based approach for identifying high-risk segments along the A002 corridor. By integrating roadway environment characteristics, infrastructure conditions, and crash severity outcomes into a unified scoring framework, the method allows for objective comparison across road sections with varying attributes. The resulting numerical index highlights priority locations where safety interventions are most urgently required. This systematic approach not only enhances the accuracy of risk identification but also supports efficient resource allocation for road safety management in Sri Lanka’s national road network.

Based on the identified high-risk sections, a series of targeted safety improvement measures are recommended. For segments with the highest RRI values (e.g., 12 and above), immediate short-term countermeasures such as enhanced signage, pavement marking upgrades, installation of rumble strips, and improved delineation are advised to reduce crash likelihood. Medium-risk segments (RRI = 9) would benefit from mid-term interventions including shoulder widening, guardrail installation, intersection improvements, and pedestrian safety enhancements in populated zones. Longer-term solutions, such as geometric realignments, sight-distance improvements, and full corridor-based redesign, may be required in sections where infrastructure deficiencies and environmental risks consistently overlap. Prioritizing these actions according to RRI intensity ensures that resources are directed toward the locations with the greatest potential for crash reduction.

In summary this research offers a scalable model for road safety management that can be adapted for use in other developing countries with similar challenges. It provides policymakers and road development authorities with actionable insights to implement targeted safety measures, optimize budget utilization, and achieve sustainable improvements in road safety performance.

REFERENCES

[1] “World Health Organization, ‘Road traffic injuries,’ World Health Organization, Jun. 21, 2022. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries.”

[2] “World Health Organization, Global status report on road safety 2023. Geneva: World Health Organization, 2023”.

[3] “The World Bank, Delivering Road Safety in Sri Lanka: Leadership Priorities and Initiatives to 2030, Washington, DC: International Bank for Reconstruction and Development / The World Bank, 2020.”.

[4] “The World Bank, ‘Sri Lanka’s Journey to Road Safety,’ World Bank, Nov. 4, 2021. [Online]. Available: https://www.worldbank.org/en/news/feature/2021/11/04/sri-lanka-s-journey-to-road-safety”.

[5] “Ministry of Transport and Civil Aviation, ‘Ministry of Transportation and Civil Aviation,’ 2023. [Online]. Available: https://www.transport.gov.lk/web/index.php?option=com_content&view=article&id=29&Itemid=149&lang=en.”

[6] “World Health Organization, ‘SDG Target 3.6: Road traffic injuries,’ World Health Organization, 2024. [Online]. Available: https://www.who.int/data/gho/data/themes/topics/sdg-target-3_6-road-traffic-injuries”.

[7] “World Health Organization, ‘Decade of Action for Road Safety 2021–2030,’ World Health Organization, 2021. [Online]. Available: https://www.who.int/teams/social-determinants-of-health/safety-and-mobility/decade-of-action-for-road-safety-2021-2030.”

[8] “Asian Development Bank. (2003). Road Safety Audit for Road Projects. Retrieved from https://www.adb.org/projects/documents/road-safety-audit-road-projects-sri-2003.”

[9] “Sri Lanka Traffic Police, Traffic Management and Road Safety Division, Accident Data Management System, Ministry of Defence, 2021. [Online]. Available: http://www.traffic.police.lk.”

[10] “S. Washington and W. Cheng, High Risk Crash Analysis, Final Report FHWA-AZ-05-558, University of Arizona, Tucson, AZ, prepared for Arizona Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration, Dec. 2005.”.

[11] M. Iranmanesh, S. Seyedabrishami, and S. Moridpour, “Identifying high crash risk segments in rural roads using ensemble decision tree-based models,” *Sci Rep*, vol. 12, no. 1, Dec. 2022, doi: 10.1038/s41598-022-24476-z.

[12] “World Road Association (PIARC), Road Safety Manual: A Manual for Practitioners and Decision Makers on Implementing Safe System Infrastructure, Paris, France: PIARC, 2015.”.

[13] J. Proceedings and C. Jurewicz, “Australasian Road Safety Research, Policing & Education Conference 28 th-30 th August,” 2013.

[14] Y. Li and Y. Bai, “Development of Crash-Severity-Index Models for the Development of Crash-Severity-Index Models for the Measurement of Work Zone Risk Levels Measurement of Work Zone Risk Levels Recommended Citation Recommended Citation Development of Crash-Severity-Index Models for the Measurement of Work Zone Risk Levels,” 2008.

[15] “iRAP Methodology Fact Sheet # 1.” [Online]. Available: http://www.who.int/violence_injury_prevention/publications/road_traffic/en/index.html.

[16] “State of Queensland (Department of Transport and Main Roads), Infrastructure Risk Rating (IRR) Manual, Nov. 2018. [Online]. Available: http://creativecommons.org/licenses/by/4.0/”.

[17] “A. Ross, D. Jovanov, R. Brankovic, H. Vollpracht, and F. Trajkovic, Road Safety Audits: Practical Guide for Road Safety Auditors (TRACECA Region), International Road Safety Centre, 2016.”.

[18] J. A. Calderón Ramírez, I. Núñez López, L. G. García Gómez, and M. A. Montoya Alcaraz, “Main guidelines in road safety audits: a literature review,” 2023, *Frontiers Media SA*. doi: 10.3389/fbuil.2023.1282251.

[19] “H.-J. Vollpracht, Road Safety Inspections in Romania and Vietnam, presented at the PIARC International Seminar, Lomé, Togo, Oct. 2006. [Online]. Available: https://www.piarc.org/ressources/documents/actes-seminaires06/c31-togo06/8719,2-RSI_in_Romania_and_Vietnam2_Vollp.pdf”.

[20] S. N. Abu Mansor, M. S. Ahmad Saman, T. M. S. Tengku Razman, and H. Masnel, “Road safety audit - What we have learnt?,” in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Apr. 2019. doi: 10.1088/1757-899X/512/1/012023.

[21] “Austroads, ANRAM User Guide, version 1.04, Oct. 2014. [Online]. Available: https://www.arrb.com.au/ANRAM”.

[22] “W. Vlakveld and W. Louwerse, The Relation Between Road Protection Scores (RPS) and the Casualty Rate at Road Sections in the Province of Utrecht, R-2011-7, SWOV Institute for Road Safety Research, Leidschendam, Netherlands, May 2011”.

[23] “Development of Compiled Road Safety Data And Analysis for Safety Research Phase 1-Review of Thailand Road Safety Data and Analysis for Development of Road Safety Map Application,” 2015. [Online]. Available: http://www.atransociety.com

[24] “S. Efstathiadis, Developing EuroRAP Risk Assessments in Greece, presented at the 3rd Session, Ioannina, Greece, Nov. 18, 2010”.

[25] S. A. R. Shah, T. Brijs, N. Ahmad, A. Pirdavani, Y. Shen, and M. A. Basheer, “Road safety risk evaluation using GIS-based data envelopment analysis-artificial neural networks approach,” *Applied Sciences (Switzerland)*, vol. 7, no. 9, Aug. 2017, doi: 10.3390/app7090886.

[26] “HIGHWAY SAFETY MANUAL USER GUIDE National Cooperative Highway Research Program 17-50 Lead States Initiative for Implementing the Highway Safety Manual.” [Online]. Available: www.highwaysafetymanual.org

[27] “Mehta, G., & Lou, Y. (2013). Calibration and Development of Safety Performance Functions for Alabama: Two-Lane, Two-Way Rural Roads and Four-Lane Divided

Highways. Transportation Research Record, 2398(1), 75-82. https://doi.org/10.3141/2398-09”.

[28] “GLOBAL STATUS REPORT ON ROAD SAFETY 2018 SUMMARY,” 2018. [Online]. Available: http://apps.who.int/bookorders.

[29] “J.-P. Rodrigue, ‘Urban Transport Challenges,’ The Geography of Transport Systems, 2024. [Online]. Available: https://transportgeography.org/contents/chapter8/urban-transport-challenges/”.

[30] “P. Raymond, S. Jackson, and C. Redden, America’s Rural Roads: Beautiful and Deadly, Governors Highway Safety Association, Washington, DC, USA, Sep. 2022. [Online]. Available: https://www.ghsa.org/resources/Americas-Rural-Roads”.

[31] H. K. Mell, S. N. Mumma, B. Hiestand, B. G. Carr, T. Holland, and J. Stopyra, “Emergency medical services response times in Rural, Suburban, and Urban areas,” Oct. 01, 2017, *American Medical Association*. doi: 10.1001/jamasurg.2017.2230.

[32] M. M. . Peden, *World report on road traffic injury prevention*. World Health Organization, 2004.

[33] *OECD Regional Outlook 2019*. in OECD Regional Outlook. OECD, 2019. doi: 10.1787/9789264312838-en.

[34] “Highway Functional Classification Concepts, Criteria and Procedures 2023 Edition,” 2023.

[35] M. Mehdian, H. Mirzahossein, and A. Abdi Kordani, “A Data-Driven Functional Classification of Urban Roadways Based on Geometric Design, Traffic Characteristics, and Land Use Features,” *J Adv Transp*, vol. 2022, 2022, doi: 10.1155/2022/9970464.

[36] T. U. Liyanage, R. G. Wimalasiri, and G. Dalpethado, “Traffic Behaviours at Minor Roads in Southern Part of Sri Lanka,” 2019.

[37] S. Islam, “Estimation of Annual Average Daily Traffic (AADT) and Missing Hourly Volume Using Artificial Intelligence,” 2016. [Online]. Available: https://tigerprints.clemson.edu/all_theses/2562

[38] C. H. V. Cooper, “Using spatial network analysis to model pedal cycle flows, risk and mode choice,” *J Transp Geogr*, vol. 58, pp. 157–165, Jan. 2017, doi: 10.1016/j.jtrangeo.2016.12.003.

[39] M. Fu, J. A. Kelly, and J. P. Clinch, “Estimating annual average daily traffic and transport emissions for a national road network: A bottom-up methodology for both nationally-aggregated and spatially-disaggregated results,” *J Transp Geogr*, vol. 58, pp. 186–195, Jan. 2017, doi: 10.1016/j.jtrangeo.2016.12.002.

[40] “Baek J. Highway Regional Classification Method Based on Traffic Flow Characteristics for Highway Safety Assessment. Sensors (Basel). 2021 Dec 23;22(1):86. doi: 10.3390/s22010086. PMID: 35009626; PMCID: PMC8747240.”.

[41] M. Fu, J. A. Kelly, and J. P. Clinch, “Estimating annual average daily traffic and transport emissions for a national road network: A bottom-up methodology for both nationally-aggregated and spatially-disaggregated results,” *J Transp Geogr*, vol. 58, pp. 186–195, Jan. 2017, doi: 10.1016/j.jtrangeo.2016.12.002.

[42] "Baek, Jongdae & Hummer, Joseph & Williams, Billy & Cunningham, Christopher. (2006). Reasonable Speed Limits on Suburban Multilane Highways with Curbs. Transportation Research Record. 1969. 10-17. 10.3141/1969-04. ".

[43] "INTEGRATING SAFETY INTO ROAD DESIGN MOBILITY AND TRANSPORT CONNECTIVITY SERIES B," 2022. [Online]. Available: http://www.worldbank.org/transport

[44] S. Kumar. U. G. tham. T, Pooja.M, "Study on Road Safety Index," *Int J Innov Res Sci Eng Technol*, vol. 4, no. 8, pp. 6879–6889, Aug. 2015, doi: 10.15680/ijirset.2015.0408025.

[45] S. Kanuganti, R. Agarwala, B. Dutta, P. N. Bhanegaonkar, A. P. Singh, and A. K. Sarkar, "Road safety analysis using multi criteria approach: A case study in India," in *Transportation Research Procedia*, Elsevier B.V., 2017, pp. 4649–4661. doi: 10.1016/j.trpro.2017.05.299.

[46] S. Afandizadeh and S. Hassanpour, "Evaluating the Effect of Roadway and Development Factors on the Rural Road Safety Risk Index," *Advances in Civil Engineering*, vol. 2020, 2020, doi: 10.1155/2020/7820565.

[47] A. M. Boroujerdian, M. Saffarzadeh, H. Yousefi, and H. Ghassemian, "A model to identify high crash road segments with the dynamic segmentation method," *Accid Anal Prev*, vol. 73, pp. 274–287, 2014, doi: 10.1016/j.aap.2014.09.014.

[48] "Elvik, R., 2008. A survey of operational definitions of hazardous road locations in some European countries. Accid. Anal. Prev. 40, 1830–1835.".

[49] "Troche, L.R., 2007. Methodology to Identify Hazardous Locations for Highways in Puerto Rico, Thesis submitted in partial fulfillment of the Requirements for the Degree of Master of Science.".

[50] "Kononov, J., Allery, B., 2003. Level of Service of Safety Conceptual Blueprint and Analytical Framework, Transportation Research Record 1840, Paper No. 03–2112, TRB, Washington, D.C.".

[51] "Federal Highway Administration, 1981. Highway Safety Improvement Program, FHWA-TS-81-218. US Department of Transportation, Washington, DC December.".

[52] "Geurts, K., 2006. Ranking and Profiling Dangerous Accident Locations Using Data Mining and Statistical Techniques. Doctoral Dissertation. Faculty of Applied Economics, Hasselt University, Hasselt.".

[53] "Pant, P.D., Rajagopal, A.S., Cheng, Y., 2003. Rational Schedule of Base Accident Rates for Rural Highways in Ohio (Phase II), (June). Report No. FHWA/OH-2003/008.".

[54] A. Mirza Boroujerdian, M. Fetanat, and V. Abolhasannejad, "Identification of High Crash Road Segment using Genetic Algorithm and Dynamic Segmentation," 2015.

[55] I. Chandrasekara, H. R. Pasindu, T. Wijayaratne, K. Kodithuwakku, S. Chamod Munasinghe, and S. Lanka, "Identifying High-Risk Road Segments in Arterial Roads using Spatial Analysis and Machine Learning, 2 Case Study in Sri Lanka."

[56] D. Deng, "DBSCAN Clustering Algorithm Based on Density," in *Proceedings - 2020 7th International Forum on Electrical Engineering and Automation, IFEEA 2020*, Institute of

Electrical and Electronics Engineers Inc., Sep. 2020, pp. 949–953. doi: 10.1109/IFEEA51475.2020.00199.

[57] S. Szénási and P. Csiba, “Clustering algorithm in order to find accident black spots identified by GPS coordiantes,” in *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, International Multidisciplinary Scientific Geoconference, 2014, pp. 497–504. doi: 10.5593/sgem2014/b21/s8.063.

[58] F. Huang *et al.*, “Research on the parallelization of the DBSCAN clustering algorithm for spatial data mining based on the Spark platform,” *Remote Sens (Basel)*, vol. 9, no. 12, Dec. 2017, doi: 10.3390/rs9121301.

[59] “Chang, Joong & Lee, W. S.. (2004). A Sliding Window Method for Finding Recently Frequent Itemsets over Online Data Streams.. Journal of Information Science and Engineering. 20. 753-762. ”.

[60] “Aditya Medury, Offer Grembek, Dynamic programming-based hot spot identification approach for pedestrian crashes, Accident Analysis & Prevention, Volume 93, 2016, Pages 198-206, ISSN 0001-4575”.

[61] “Abdulhafedh, Azad. (2016). Crash Frequency Analysis. Journal of Transportation Technologies. 06. 169-180. 10.4236/jtts.2016.64017. ”.

[62] “N. Stamatiadis, A. Kirk, D. Hartman, J. Jasper, S. Wright, M. King, and R. Chellman, An Expanded Functional Classification for Highways and Streets, pre-publication draft of NCHRP Research Report 855. Washington, D.C.: Transportation Research Board, 2017.”.

[63] “Road Development Authority, National Highways (Class A, B & E Roads), 2023, Available on http://www.rda.gov.lk/source/rda_roads.htm.”

[64] “Road Development Authority (RDA), ‘RDA Project Map,’ rda.gov.lk, [Online]. Available: https://rda.gov.lk/rda_project_new/map.”.

[65] “N. Amarasingha, ‘Motorcycle Crash Data Collection - Sri Lanka,’ presented at the 20th International Conference on Traffic Safety Data and Analysis, International Association of Traffic and Safety Sciences (IATSS), Tokyo, Japan, 2019. [Online]. Available: https://www.iatss.or.jp/en/event/entry_img/event20_7.pdf”.

[66] “Black Spot Program Guidelines, Dept. of Infrastructure, Transport, Regional Development, Communications and the Arts, Commonwealth of Australia, Canberra, Australia, Jul. 2024. [Online]. Available: https://www.infrastructure.gov.au”.

Appendix - A

Road safety audit of selected locations along the A002 road

No	Location (305.5 km - 309.5 km)	Safety issue	Comments	
1	From Ch 305.5 km to 306+020 km	a. Excessive pavement edge drop offs and cyclling hazard	1.a.1 The deteriorated base course creates an uneven and unstable road surface, increasing the risk of accidents, especially for two-wheeled vehicles like motorcycles and bicycles and weakened base course may cause vehicles to lose control, particularly during adverse weather conditions or when braking suddenly. Pedestrians may have to navigate around damaged road areas, such as potholes or uneven surfaces, making it difficult to find safe walking paths. Potholes and surface irregularities can obstruct the path of cyclists, potentially leading to falls and collisions.	
		b.Unsafe pedestrian walkway	1.b.1 The absence of designated walk paths may force pedestrians to share the road with vehicles, leading to potential conflicts and safety risks and pedestrians may have to navigate around detached particles, potholes, and surface irregularities, making it difficult to find safe walking paths.	

2	Ch 307+600 km	c. Unprotected bridges and culverts	2.c.1 The presence of uncompleted and unprotected culverts poses significant hazards for road users and the surrounding environment. These unfinished culverts can lead to several safety concerns and adverse impacts, necessitating considerable attention and appropriate measures.	
3	Ch 308+080 km	.d. Poor signage and lane marking at intersection	3.d.1 The absence of essential pavement markings, including lane lines, edge lines, centerline markings, pavement arrows, and stripes, presents significant safety and navigational challenges for road users. The presence of obsolete centerline markings at some locations can pose safety risks and create confusion for road users and lead to ambiguity about lane positions, causing drivers to drift across lanes or occupy incorrect positions, potentially resulting in collisions.	
4	Ch 309+200 km	e.Poor visibility at access roads	4.e.1 The poor visibility of the access road, particularly at night time, due to the growth of vegetation and incomplete road works, poses significant safety concerns for road users. Insufficient lighting and obstructed roadways may make it challenging for drivers to navigate the road safely, especially during nighttime.	

5	Ch 308+950 km	f. Open drains	5.f.1 The presence of unprotected and uncovered drains presenting a serious safety concern to pedestrians and cyclists who may accidentally fall into them or collide with their edges. Clear and visible warning signs should be installed near the areas with open drains to alert pedestrians of the potential hazard.	

No	Location (173.0 km - 176.5 km)	Safety issue	Comments	
1	Ch 173+260 km	a. Lack of signage, road markings at intersections	a.1 During the audit, it was observed that there are no signs indicating the presence of a T junction for road users approaching from the access route and no speed limit signs along the road section. The absence of speed limit signage hinders road users' ability to adhere to the appropriate speed limits, which are essential for ensuring safe and efficient traffic flow and drivers may exceed safe speeds, increasing the risk of accidents and compromising overall road safety. This lack of signage can lead to confusion among drivers approaching the intersection, particularly those who are unfamiliar with the road.	

2			a.2 Aabsence of pavement markings (including centerlines, lane dividers, arrows, symbols, side lines and other appropriate markings) and pedestrian crossing marks at the junction pose significant safety risks to road users, including both motorists and pedestrians,	
3	From Ch 174+100 to 174+560 km	b. Excessive pavement edge drop offs and cyclling hazard	b.1 Significant concerns were observed regarding the road surface condition, including the presence of potholes, rutting areas, uneven road surface,cracks. Potholes are depressions in the road surface, while rutting refers to the formation of grooves and indentations caused by prolonged vehicle traffic. These surface irregularities can pose hazards to motorists, cyclists, and other road users, leading to discomfort, vehicle damage, and potential loss of control.	
4	Ch 176+450 km	c. Inadequate Pedestrian Facilities near intersection area	c.1 Public transport users, including bus passengers, may face challenges in accessing and boarding vehicles due to inadequate infrastructure and unsafe conditions. It is important to provide safe and convenient access points, such as bus stops or designated waiting areas, with appropriate pedestrian facilities and shelters to ensure the safety and comfort of public transport users. It is crucial to establish well-defined pedestrian paths, separated from vehicular traffic, with appropriate signage and markings to ensure the safety of pedestrians	

No	**Location (55.00 km - 58.50 km)**	Safety issues	Comments	
1	Ch 55+450 km	a. Lack of signage, road markings at intersections	a.1 The discontinuity of road side edge line markings at intersection towards to the Morris road side poses significant safety risks to drivers. There will be some restrictions to enhance driver awareness, improve lane discipline.	
		b. Poor pedestrian facilities near intersection area	b.1 The location of the bus halt at the intersection can result in conflicts between pedestrians and vehicles. Pedestrians waiting at the bus halt may need to cross the road to access the bus or may be in close proximity to moving vehicles, increasing the risk of accidents and collisions. The presence of buses and their frequent stops at the intersection can create congestion and hinder the movements of pedestrians. Pedestrians may experience difficulties in navigating through the area, particularly during peak hours, leading to congestion, frustration, and potential safety hazards.	
		c. Open drains	c.1 Presence of open deep drainage along the road increases the safety risks to road users, particularly pedestrians, cyclists, and motorcyclists, and need to cover the open deep drainage with suitable covers or gratings to eliminate the risk of road users falling into the drain.	

2	Ch 55+700 km	a. Lack of signage, road markings at intersections	a.1 The absence of road markings including centerline markings, stop lines, crosswalks, and other necessary markings at the junction makes it challenging for drivers to maintain proper lane discipline.	
			a.2 Without appropriate signage indicating the junction ahead and pedestrians cross mark at 41+730km, pedestrians may be unaware of the designated crossing location and may attempt to cross the road in unsafe areas. This increases the likelihood of accidents and endangers the safety of pedestrians.The signage should be placed at a suitable distance before the crossing to provide advance warning to drivers and improve pedestrian safety.	
		b.Sight line issues at the junction	b.1 The location of the three-wheeler park obstructs the left turn movement of vehicles approaching from the Waduraba direction. The parked three-wheelers create sight line issues, making it difficult for drivers to have a clear view of oncoming traffic, pedestrians, and other potential hazards.	

3	Ch 56+320 to 49+460km	a. Poor visibility of signage and road markings	a.1 Observed that the Chevron Markers, specifically the red and white reflective markers, were not adequately visible at bend creating poor visual guidance to drivers, indicating the direction and alignment of the road ahead.	
			a.2 Wrong direction placement of the stop sign board, which poses a potential risk to road users.	
			a.3 Absence of road markings including centerline markings, stop lines, road boundary lines, crosswalks,	
		b.Poor visibility at access roads	b.1 The required signs and road markings are not existing to warn vehicles of junctions ahead on access roads connecting to the main road. Most of these locations where access roads are connecting to the main road do not have good visibility especially at night	
		c. Open drains	c.1 The presence of unprotected and uncovered drains presenting a serious safety concern to pedestrians and cyclists who may accidentally fall into them or collide with their edges. The absence of protective measures increases the severity of accidents and the likelihood of injuries.	

4	Ch 56+720 km	a. Poor visibility of signages and road markings	a.1 Pedestrian cross markings at certain locations along the road have been erased or are no longer clearly visible particularly during nighttime or adverse weather conditions. Pedestrians may face difficulty in identifying safe crossing points, while drivers may fail to recognize and yield to pedestrians at these locations.	
5	Ch 57+100 km	b.Poor visibility at access roads	b.1 The higher gradients on the access paths may obstruct the visibility of pedestrians and drivers. This creates a hazardous situation, as pedestrians may not be easily visible to motorists, particularly at intersections, driveways, or areas with limited sight lines.	
6	Ch 57+620 to 57+700 km	a. Excessive pavement edge drop offs and cycling hazard	a.1 Numerous potholes were observed along the road section. Potholes are not only a nuisance but also a potential hazard for motorists, cyclists, and pedestrians. They can cause sudden jolts to vehicles, leading to loss of control or damage to tires and suspension systems. Additionally, potholes may be difficult to spot, especially during nighttime or adverse weather conditions, increasing the risk of accidents.	

			a.2 There are visible loose construction materials, such as gravel, sand, or debris, along the roadside. These materials can be hazardous for pedestrians and cyclists. The presence of unprotected precast culverts along the road section(at Ch 51+660) is a significant concern. These culverts can obstruct sight lines for both motorists and pedestrians. Reduced visibility at these locations increases the severity of accidents.	
			a.3 The presence of standing water may make it difficult for pedestrians to cross the road safely, increasing the likelihood of slips, falls, or accidents. For cyclists, navigating through ponding areas can be challenging and unsafe	

Appendix - B

Example for a sample calculation of finding road safety index (RSI) based on road safety audit results

For the road section 55.00 km – 58.50 km

Roadway characteristic			
Parameters	Observed data	Valued scores	Average values
Carriageway width	2 lane with median	50	
Number of curves	0	100	
Gradient	Flat	80	72
Number of intersections/km	1	90	
Type of intersection	Perfect right angle	40	

Traffic characteristic			
Parameters	Observed data	Valued scores	Average values
Speed	10% more than the speed limit	90	
On- street parking	No parking	100	
Road markings	Some locations missing with Centerline marking, Lane marking, Zebra crossing & Stop line, edge marking.	18	
Speed Breakers/km	2	75	69.6

Number of Fatalities/km	Serious Injury	50	
Signs	No adequate signs	15	

Roadside characteristic			
Parameters	Observed data	Valued scores	Average values
Presence of Obstacles	Advertisement Board, trees, distracting road users	30	
Shoulder	With average kerbs and levelled	35	40
Street Lighting Interval	20m	55	

Pavement characteristic			
Parameters	Observed data	Valued scores	Average values
Pavement status	Average	40	
Potholes/km	>8	26	33

Miscellaneous characteristic			
Parameters	Observed data	Valued scores	Average values
Bus-stop distance from Intersection	120m	100	
Intersection visibility	poor	0	33.33
Presence of median	Median of 30 cm height	0	

RSI = (0.34*72+0.26*69.6+0.18*40+0.13*33+0.09*33.33)/100

0.57

For the road section 173.00 km – 176.5 km

Roadway characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Carriageway width	2 lane without median	30	56
Number of curves	3	40	
Gradient	1.40%	95	
Number of intersections/km	2	75	
Type of intersection	Perfect right angle	40	

Traffic characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Speed	35% more than speed limit	30	40
On- street parking	No parking	95	
Road markings	No marking.	0	
Speed Breakers/km	2	75	
Number of Fatalities/km	Property damage	20	
Signs	No adequate signs	20	

Roadside characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Presence of Obstacles	No	30	30
Shoulder	Not adequate	30	

Street Lighting Interval	>20m	30	

Pavement characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Pavement status	Poor	7	7
Potholes/km	>8	7	

Miscellaneous characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Bus-stop distance from Intersection	>100m	100	33.33
Intersection visibility	Poor	0	
Presence of median	No Median	0	

RSI = **(0.34*56+0.26*40+0.18*30+0.13*7+0.09*33.33)/100**

0.39

For the road section 305.5 km – 309.5 km

Roadway characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Carriageway width	2 lane without median	30	54.2
Number of curves	3	40	
Gradient	0.23%	90	
Number of intersections/km	1	90	
Type of intersection	T & two way junction	21	

Traffic characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Speed	70% more than speed limit	12	

On- street parking	No parking	90	37
Road markings	No marking.	0	
Speed Breakers/km	>2	50	
Number of Fatalities/km	Property damage	30	
Signs	No adequate signs	40	

Roadside characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Presence of Obstacles	Advertisement Board, trees, distracting road users	55	45
Shoulder	some areas with average kerbs and levelled	80	
Street Lighting Interval	No Lighting	0	

Pavement characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Pavement status	Poor	20	22.5
Potholes/km	>8	25	

Miscellaneous characteristic			
Parameters	**Observed data**	**Valued scores**	**Average values**
Bus-stop distance from Intersection	20m	20	6.67
Intersection visibility	poor	0	
Presence of median	No	0	

RSI = **(0.34*54.2+0.26*37+0.18*45+0.13*22.5+0.09*6.67)/100**

0.4

Appendix – C

Code-Based Supplementary Materials for Road Safety Analysis

To ensure transparency, reproducibility, and clarity of the data analysis procedures conducted in this study, a series of Python-based implementations were developed using Google Colab. These interactive notebooks document the step-by-step analytical workflows employed for road safety assessment, crash data segmentation, and high-risk location identification.

The analyses cover a range of methodologies including sliding window algorithms, clustering techniques, and severity index calculations. Each notebook corresponds to a specific analytical task performed during the study and is accessible through the respective hyperlinks provided below. These resources serve as supplementary material, offering detailed insights into the data processing, statistical computations, and visualization techniques adopted in this research.

The table below summarizes each analysis method and provides direct access to the relevant Colab notebooks:

No	Analysis Description	Google Colab Link
01	Implementation of the Sliding Window Method for Crash Data Analysis (Method 01)	https://colab.research.google.com/drive/1fDSEzEB_NhDfv_W4zh613jthZL5j0TX_?usp=sharing%0c
02	Implementation of the Sliding Window Method for Crash Data Analysis (Method 02)	https://colab.research.google.com/drive/12c58IUgX1ycKcoNtKz7yXXPDmpQqcwBJ?usp=sharing
03	Crash Data Analysis Using the K-mean clustering algorithm method	https://colab.research.google.com/drive/1A8Ys2dvBeJriETfleW7CWCTLerGX7kFK?usp=sharing
04	Analysis of Casualties per Accident Across Road Segments	https://colab.research.google.com/drive/1hYM3HVqzt18S63O2g0bbHkus5XHndxpY?usp=sharing
05	Computation of the Crash Severity Index for Road Safety Assessment	https://colab.research.google.com/drive/1qSLvPYJDoE5uYKwSerREHKhgUUpdOeh4?usp=sharing