Doctoral Dissertation

Development of Traffic Safety Oriented Road Maintenance Decision Support Analytical Framework

（交通安全を指向した道路維持管理の意思決定支援分析フレームワークの開発に関する研究）

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There are differing beliefs on whether life opportunities and luck or personal choices determine one's path in life. However, I believe that the ultimate architect of life and the universe holds the wheel. I express my gratitude and thanks to Almighty God and my savior Jesus Christ for the grace that has been bestowed upon me.

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Research Background

Roads play a critical role in the development of nations by enhancing mobility and accessibility. They are an integral part of people's daily lives, enabling them to access various services, including healthcare, education, and other facilities. Additionally, roads provide access to employment opportunities and markets, which are essential for the economic growth of a nation. One of the key benefits of roads is that they reduce commuter travel time. This not only saves time and money for individuals but also enhances the transportation system's efficiency. Furthermore, roads promote social and spatial equity by connecting people from different parts of a nation, promoting integration and inclusivity [1].

The impact of roads extends beyond the direct benefits for individuals and communities. They significantly impact other sectors, such as tourism, agriculture, and manufacturing. For instance, good road networks attract tourists, making it easier for them to explore different parts of a nation, promoting the growth of the tourism industry. Similarly, well-maintained roads facilitate the transportation of goods and services, promoting the growth of the agriculture and manufacturing sectors [1, 2, 3]. Therefore, roads are essential for both the micro and macro level impacts on the economic development of nations and global competitiveness.

Although roads offer many advantages, they also have negative consequences, particularly regarding road safety, which is a major concern worldwide since road traffic crashes are the leading cause of death for children and young people aged 5-29 [4]. This is a troubling fact, and it highlights the importance of ensuring that road safety is prioritized and that measures are taken to reduce the risks associated with road travel. The original statement also emphasizes that low- and middle-income countries are particularly vulnerable to the negative impacts of road traffic crashes, with 90% of fatalities occurring in these regions [4]. According to the World Bank countries' income level classification for the 2024 fiscal year, countries with gross national income (GNI) per capita below 1,135 are Low-income countries (LICs), above 13,845 are High-income countries (HICs), and between are Middle-income countries (MICs) [5]. The high number of traffic crashes in LICs and MICs significantly impacts their economic progress. For instance, LICs can lose up to 7.1% of their gross domestic product due to road traffic crashes, which can devastate the economy and contribute to poverty at the microeconomic level [6, 7]. This highlights the need to address road safety as a matter of public health and a crucial economic issue.

The United Nations (UN) has included road safety as a crucial element of its Sustainable Development Goals (SDGs) to address the issues related to road traffic crashes. Goals 3.6 and 11.2 are the specific SDGs related to road safety, and Goal 3.6 aims to halve the number of global deaths and injuries caused by road traffic crashes by 2030 [8]. Achieving these goals will require a concerted effort by governments, civil society, and other stakeholders. To make this happen, the UN has established 12 performance targets under five pillars to ensure road safety [4]. The five pillars include road safety management, enhanced road and mobility systems, improved vehicle safety, responsible road users, and efficient post-crash response. Within the second pillar, which focuses on road infrastructure, there are two specific objectives: Target 3, which aims to ensure that all newly constructed roads meet a safety standard with a star rating of three or higher, and Target 4, which aims to raise the safety level of over 75% of existing roads to a star rating of three or higher for all road users by 2030.

The achievement of the SDG goals relies on how well countries can meet global road safety performance targets. The UN has urged governments and stakeholders to adopt the safe system approach [8]. The safe system approach is distinct from the traditional approach in that it takes a forward-looking view of potential future crashes and suggests measures to prevent them. In contrast, the traditional approach looks back at past crashes and recommends ways to prevent similar ones from reoccurring [9]. Additionally, the two approaches differ in understanding the causes of road traffic crashes. The traditional approach places the blame on non-compliant road users, holding individual road users solely responsible for crashes. On the other hand, the safe system approach recognizes that people make mistakes and emphasizes the need for transport systems to accommodate human error, thus sharing the responsibility for crashes among road users and those who design, build, and manage roads and vehicles. The two approaches also differ in their objectives, with the traditional policy aiming to reduce the number of fatalities and serious injuries. On the contrary, the safe system approach considers the limits of the human body's ability to withstand crash forces. As a result, it aims to limit the kinetic energy during crashes, ultimately striving for zero fatalities and serious injuries resulting from road traffic crashes [9]. Summing up, the safe system approach provides a more proactive and comprehensive approach to preventing road traffic crashes compared to the traditional approach. It recognizes the shared responsibility of all stakeholders in ensuring road safety and aims to prevent fatalities and serious injuries rather than merely reducing them.

Road agencies are responsible for realizing road safety in line with the safe system approaches. They are responsible for proactively ensuring safe road infrastructure and managing their road network to achieve global road safety performance targets, explicitly targets 3 and 4. Moreover, as study results have indicated that road infrastructures are the leading causes of fatal crashes [10, 11], making roads safe can significantly reduce the devastating impact of road traffic crashes. Road infrastructure safety consideration requires a comprehensive approach in all phases. This includes designing safe roads for all users, such as pedestrians, cyclists, and motorists, and implementing safety features like guardrails, road markings, and traffic calming. It also involves maintaining roads to remain safe and functional over time, including regular inspections and repairs. Integrating road safety measures into the design phase is more cost-effective and efficient than improving the safety conditions of already-built infrastructures. However, it is crucial and pressing to incorporate safety measures into road maintenance to save lives because the current unsafe infrastructure presents an imminent danger to those who use the road.

Integrating safety in every step of the road maintenance process, from inspection and monitoring to planning and implementation, is crucial for ensuring the safety of all road users.

This approach is not only important for safety reasons, but it also proves to be cost-effective and time-efficient [12]. In addition to exacerbating road safety issues, the rapid deterioration of road networks causes nations massive financial losses, mainly in developing countries. For example, a study conducted in sub-Saharan Africa reveals that despite a large amount of road construction over three decades, approximately one-third of the roads have been lost due to a lack of proper maintenance [13]. Therefore, a comprehensive road maintenance decision-making framework and tools incorporating safety considerations can offer a twofold advantage. Not only will it help address road safety issues, but it can also save money by reducing the need for extensive repairs and reconstruction and also improves mobility. Furthermore, integrating safety considerations into the road maintenance decision-making process can help establish a safety culture within the organization responsible for road maintenance [12].

Previous research has focused on road maintenance, particularly pavement preservation, and considers road safety a separate area [14]. As a result, there has been a lack of proper safety management tools and methods that integrate road safety into the maintenance process and make safety an organizational culture. This has led to road safety being treated as an ad-hoc activity by road agencies, particularly in developing countries. Furthermore, studies that have attempted to incorporate road safety into the maintenance process have often neglected to consider the essential features necessary for the safety of non-motorized users [15]. Additionally, the available tools and methods are often unsuitable for low- and middle-income countries due to resource and data constraints [16]. Therefore, it is necessary to develop appropriate tools and methods that consider the unique challenges faced by LICs and MICs, as these countries experience a high burden of road traffic crashes. To address these challenges, it is crucial to have a simple and practical decision-support framework with appropriate methods that consider the safety of all road users in the maintenance process.

1.2 Problem Statement

The 2018 report on road safety by the World Health Organization (WHO) revealed that road traffic crashes caused the death of 1.35 million people annually [4]. This figure indicates that it is the primary cause of death for people aged 5-29 and the eighth leading cause of death

Table 1.1: Global trends in road traffic death changes (2013-2016)

Income Level	Number of countries		
	Increased in traffic death	No change	Decreased in traffic death
Low-income	27	1	0
Middle-income	60	15	23
High-income	17	7	25

for all ages. In addition, road traffic crashes are the primary cause of workplace fatalities and injuries [17]. This information highlights the importance of road safety for public health, which is reflected in SDG Goal 3: Good Health and Well-being. Unfortunately, SDG target 3.6, which aimed to halve the number of road fatalities by 2020, has not been achieved, and the target has been extended to 2030 [8]. The WHO report [4] also shows that the number of road traffic deaths in 104 countries increased between 2013 and 2016 as presented in Table 1.1. This increase was observed in 96.4% of low-income countries (LICs), 61.2% of MICs, and 34.7% of HICs. When comparing the percentage of countries that reduced the number of road traffic deaths, a significant proportion of HICs achieved this goal (51%), followed by MICs (23.5%). At the same time, none of the LICs managed to reduce the number of fatalities due to road traffic crashes. This highlights the need to focus on LICs and MICs to achieve road safety SDG goals. Therefore, there is a pressing need for developing countries to prioritize road safety measures to reduce the number of road traffic crashes and fatalities.

LICs and MICs account for less than 60% of the world's motor vehicles, yet they bear the burden of 90% of all road traffic deaths [8]. However, with the rapid pace of urbanization in these countries, the number of motor vehicles is expected to rise. The United Nations Department of Economic and Social Affairs predicts that urban areas in LMIC will grow faster than other regions [18]. For instance, LICs had a 32% urban population in 2018, projected to increase to 50% by 2050. While urbanization presents opportunities and threats to road safety, there is a chance to incorporate road safety measures into new roads and infrastructure needed to support urban expansion. Nevertheless, the lack of proper road safety management poses a significant threat to road safety, as it could lead to a potential surge in motorization and, consequently, more road traffic deaths. Accordingly, target 11.2 of Sustainable Development Goal 11, which focuses on creating sustainable cities and communities, includes enhancing road safety. This target aims to ensure everyone can access safe, affordable, and sustainable transportation systems, ultimately improving road safety by 2030. Accomplishing both SDG targets (3.6 and 11.2) necessitates substantial advancements in road safety, especially in LICs and MICs.

There is a consensus among nations and academia that implementing the safe system approach is the key to achieving sustainable road safety and meeting the SDG goals related to road safety [8, 17]. As one of the main pillars of a safe system and the leading cause of fatal crashes, road infrastructure needs to be addressed with higher attention. In this regard, various tools and methodologies are available to help manage road infrastructure safety, which have been successfully implemented in HICs [19]. These procedures aim to enhance road safety at all road infrastructure life cycle stages, from planning and design to construction and maintenance. However, these methods are not often generalizable to LICs and MICs due to differences in geographic, culture, and traffic characteristics [17, 20]. Thus, LICs and MICs must develop their own method based on international best practices for implementing safe system in their context. By doing so, LICs and MICs can implement an effective and sustainable approach to road safety that will help them achieve their SDG goals related to road safety.

LICs and MICs face challenges in developing and customizing road safety methods and appropriate tools for their situations. This is primarily due to a lack of knowledge and expertise in road safety [20]. The current road safety practices and research in LICs and MICs mainly focus on enforcing laws to regulate road users, neglecting other potential causes of road traffic crashes [21]. While this approach may be effective in some cases, it does not address other factors contributing to road traffic crashes, such as unsafe road infrastructure. Neglecting these factors limits the ability to implement a safe system in LICs and MICs, a holistic approach to road safety that considers the entire transportation system and its interactions. Hence, to develop effective road safety methods and tools in LICs and MICs, it is important to develop expertise in the field of road safety and to improve research efforts. This will involve identifying and addressing the unique challenges faced by LICs and MICs and developing tailored solutions that consider the local conditions. This includes developing simple and practical methods and tools applicable to ensure safe road infrastructure.

LICs and MICs urgently require a well-defined approach to managing road infrastructure safety based on best practices. Despite some efforts being made to consider road safety, there is a significant difference in the attention given to new roads versus existing ones. A World Bank report indicated that only 44% of LICs have an inspection (safety star rating) for existing roads, while 74% have a safety audit for new roads [22]. Similarly, for LICs and MICs as a whole, only 60% have safety inspection procedures for existing roads, compared to 82% for new roads. This lack of attention to existing roads is concerning, as they are the imminent source of road traffic crashes.Furthermore, a report on 54 countries found that existing roads are unsafe for vulnerable road users such as pedestrians, bicyclists, and motorcyclists. The report revealed that 88%, 86%, and 67% of existing roads are unsafe for pedestrians, bicyclists, and motorcyclists, respectively [4]. This highlights the urgent need to improve the safety of existing road networks while ensuring the safety needs of all road users are accounted for. Road agencies are responsible for making their road networks safe for all users, but currently, their planning and implementation of maintenance activities mainly focus on vehicular users [4].

In addition, research conducted in road safety often overlooks critical road features that are important for vulnerable road users [15]. Moreover, these studies typically focus on road maintenance and safety as separate issues [14]. However, it is crucial to integrate safety into the maintenance process to address this challenge and to make it part of the organizational culture. Likewise, in its road safety performance review, the United Nations recommended revising road maintenance manuals to integrate safety and ensure road safety becomes a corporate culture in road agencies [12]. Therefore, it is crucial to devise an appropriate framework with suitable methods and tools to integrate safety in road maintenance, considering the resource constraints of LICs and MICs. Any proposed method needs to be practical, simple, and address the safety needs of all road users.

1.3 Research Objectives

This research aims to design and develop a comprehensive framework that systematically integrates road safety into the road maintenance decision process. The framework will address the road safety challenges identified in the problem statement, particularly in LICs and MICs.

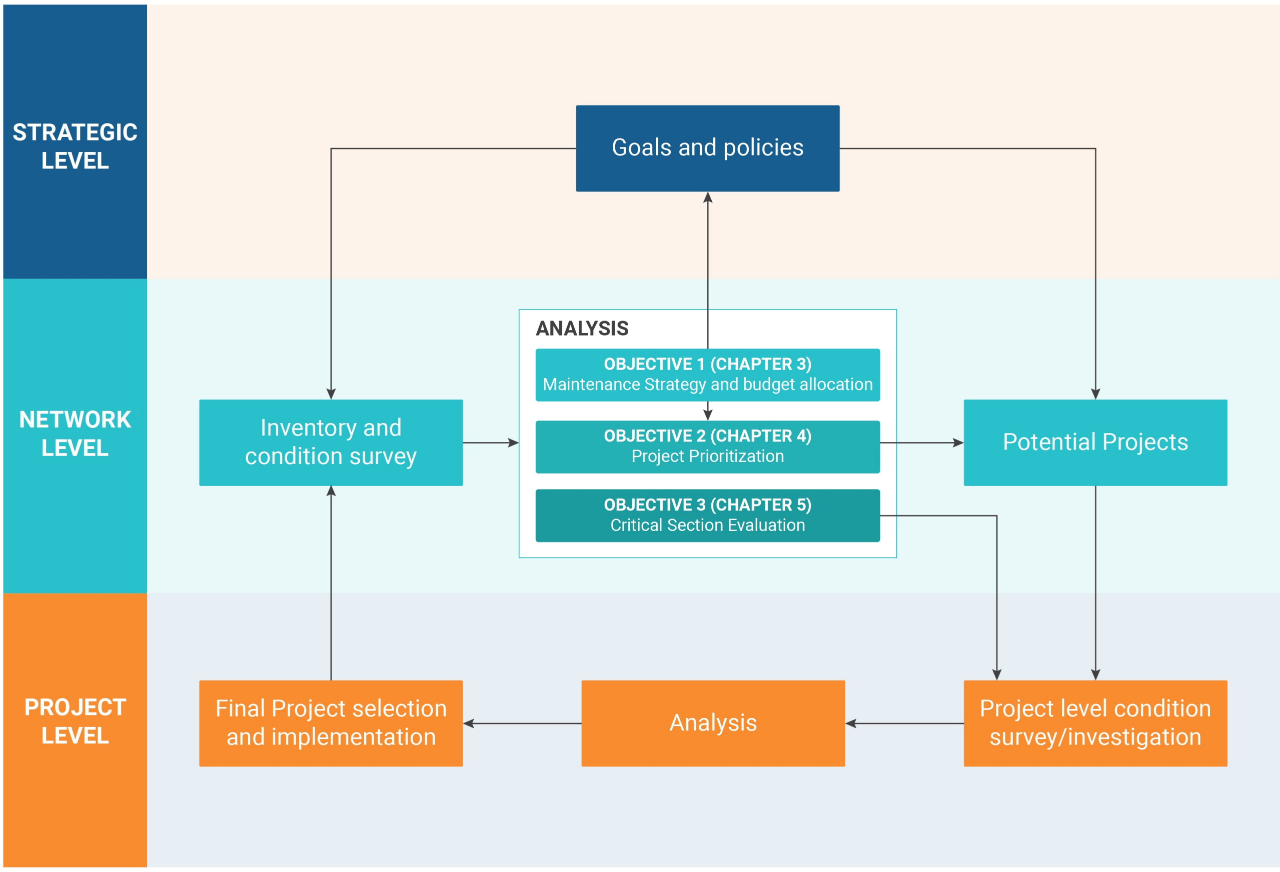

Figure 1.1: Research Objectives illustrated in the context of road maintenance decision support.

These include accounting for the safety needs of all road users and resource and expertise constraints in those countries. Additionally, the framework will be practical and easy to use, ensuring its effective application in real-world settings. To achieve this overarching objective, three specific objectives have been identified as follows:

1. Develop a safety-integrated network-level road maintenance strategy decision support analytical framework.

2. Develop a safety-oriented road maintenance prioritization analytical framework.

3. Develop critical road sections evaluation decision matrix considering safety and pavement performances.

The three objectives are individually addressed in chapters 3, 4, and 5. The diagram in Fig. 1.1 visually represents the general flow of the road maintenance process, highlighting the integration of the proposed framework and the interrelation between the analytics of the three objectives.

1.4 Research Contributions

The study develops a comprehensive road maintenance decision support framework that integrates safety. This research contributes to practitioners, academia, and the advancement of sustainable development.

Road agencies are responsible for providing safe road infrastructure for the users. To achieve this, they must evaluate and make safety-conscious decisions at every stage of the road's life cycle. Therefore, it is crucial to establish a safety culture at the organizational level to ensure safety concerns are included in all decision-making processes. To create this culture, it is necessary to have methods and tools that can be easily adapted to a specific situation and interests of the road agency. Accordingly, the proposed method can benefit road agencies, especially in LICs and MICs, in making safety-conscious road maintenance decisions while customizing the framework to their specific circumstances. Furthermore, the developed framework can assist road agencies in taking proactive safety measures and preventive pavement maintenance, saving time and money by avoiding unnecessary expenses due to road traffic crashes and extensive and repetitive maintenance. Therefore, this research contributes to practitioners in providing decision support tool that enables them to make inclusive (considering the safety of all road users), cost-effective, and sound road maintenance decisions.

There are increased research efforts in the field of road safety, resulting in the creation of useful road safety management methods and tools currently in use [19]. However, the issue with these researches is that they often separate road maintenance and safety [14], making it difficult to implement safety research results in practice, especially in LICs and MICs where road safety is often overlooked compared to maintenance. Additionally, the methods are not often practicable in LICs and MICs due to resource constraints and other factors [16, 17, 20]. Furthermore, road safety-related studies often consider vehicular road users and lack comprehensiveness in considering the safety needs of all road users [15]. In this regard, this study can contribute to the academic community by providing a reference point for future research and development of road infrastructure management decision support tools that integrate safety and are applicable globally while also considering the cases of LICs and MICs and other relevant factors.

The proper application of the proposed framework can have a significant effect in reducing fatality and serious injury resulting from road traffic crashes. This impact can be felt at various levels, including the individual, family, national, and global. This is particularly important because traffic crashes affect the economically active population [17]. Not only does reducing the impact of road traffic crashes directly affect achieving SDGs 3 and 11, but it also has a positive ripple effect on many other SDGs. Therefore, this study can play a crucial role in helping achieve SDGs by addressing one of the serious threats to the future of our people, which is road traffic crashes. By reducing the impact of these crashes, this study can contribute to the well-being of individuals, families, and society, leading to a more sustainable and prosperous future.

1.5 Structure of the Dissertation

This thesis comprises six chapters. Following the introductory chapter, **Chapter 2** will discuss developing countries' road asset management practices. This chapter provides a brief overview of infrastructure asset management and highlights the importance of the maintenance management process. Additionally, it examines and evaluates the road asset management practices of five developing countries as a case study. The aim is to illustrate these sample countries' current road asset management process and shed light on developing countries' challenges.

Chapter 3 introduces a safety-integrated network-level road maintenance decision support analytical framework. Using a Markov-based approach, the framework employs a two-tiered stochastic process to model pavement deterioration and repair. This model accounts for the limitations of road condition data in LICs and MICs. Road safety conditions considering all road user groups are measured and analyzed using the international road assessment program. The chapter explains how to set appropriate pavement and safety performance goals at the network level, develop a practical deterioration prediction model, and assess the life cycle cost and risk of maintenance strategies to achieve these dual performance goals – pavement and safety. The approach is empirically illustrated using data on a road network in Addis Ababa, Ethiopia.

In **Chapter 4**, a safety-oriented road maintenance prioritization framework is presented. This framework aims to develop a simple and practical analytical tool suitable for use under resource and data availability constraints, addresses all road users' safety needs, and accounts for methodological uncertainty. At its core, the framework used multicriteria analysis, a flexible and practical analytical approach. To overcome the limitations of this approach related to uncertainty, the framework employs sensitivity and uncertainty analysis followed by an uncertainty management scheme. In addition, a probabilistic exceedance approach is proposed to generate robust prioritization results. Finally, maintenance prioritization of 472.1km of Addis Ababa city road sections is presented as a case study to illustrate the proposed framework and compare it to the conventional approach.

Chapter 5 presents a decision matrix approach with a hierarchical structure that factors in the pavement deterioration rate, infrastructure safety, and crash history to identify critical road sections. A Markov mixed hazard model was used to assess each section's deterioration rate. The safety of the road sections was rated with the International Road Assessment Program star rating protocol considering all road users. Early detection of sections with fast deterioration and poor safety conditions allows for preventive measures to be taken to reduce further deterioration and traffic crashes. Additionally, including crash history data in the decision matrix helps to understand the possible causes of a crash and is useful in developing safety policies. The proposed method is demonstrated using data from 4725 road sections, each 100 m, in Addis Ababa, Ethiopia.

In **Chapter 6**, the research contents and results are holistically discussed in relation to the study's objectives. In addition, this chapter also highlights the limitations of the study. By identifying these limitations, the chapter provides opportunities for further research in areas where the current study may have fallen short or where additional research may be needed to confirm or extend the findings.

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Chapter 2

Road Asset Management Practices in Developing Countries

2.1 Road Asset Management: An Overview

The international organization for Standardization (ISO) [1] defines an asset as 'an item, thing or entity that has potential or actual value to an organization. This encompasses tangible assets, such as physical, financial, human, and environmental, and intangible assets, like information, contracts, legal rights, and reputation [2]. Road infrastructures are tangible assets that play critical roles in driving the economic growth of nations [3, 4, 5, 6]. These road networks significantly impact the development of countries in several ways. They reduce transportation costs and improve market access, thereby stimulating trade and contributing to growth [7, 8]. Additionally, well-established road networks have the potential to attract manufacturing firms and transform subsistence agriculture into commercial agriculture, further promoting national growth [9, 10]. Apart from facilitating economic development, road transport also plays a vital role in promoting inclusiveness by reducing rural poverty and providing access to job opportunities, education, and healthcare services [11]. Consequently, proper road asset management is of great importance.

Asset management typically entails balancing costs, opportunities, and risks against the desired performance of assets to attain organizational objectives [1]. In the context of managing physical infrastructure assets, asset management focuses on optimizing the entire life cycle of these assets to ensure they meet specific performance requirements [12]. The Federal Highway Administration (FHWA) has outlined a seven-step generic asset management system [13]. These steps encompass various stages, including setting goals and policies, conducting an inventory of assets, assessing their condition and modeling their performance, evaluating alternatives and optimizing programs within budget constraints, selecting projects, implementing programs, and monitoring performance (feedback).

The decision-making process in asset management is categorized into three levels: strategic, network (tactical), and project (operational) levels [14, 15]. At the strategic level, decisions are made regarding performance targets and asset preservation strategies. These decisions involve evaluating the tradeoff between funding allocation and organizational policies and goals. At the network level, repair strategies and project selection decisions are made. This level utilizes asset inventory and condition data as input, analyzing performance predictions under different repair strategies to achieve the performance targets set at the strategic level. Budget constraints and risks associated with attaining the targets are taken into consideration when determining the optimal repair strategy and project selection (prioritization). Project-level decisions are made at a micro level, focusing on individual projects or specific infrastructure components, such as road sections. At this level, repair designs, project costs, and activity schedules are fine-tuned [14]. Overall, asset management involves a comprehensive approach to ensure that assets are effectively managed throughout their life cycle, considering factors such as costs, risks, performance requirements, and organizational objectives. It encompasses strategic decision-making, network-level planning, and project-level implementation to optimize asset performance and achieve desired outcomes. Fig. 2.1 presents the general flow of the asset management process.

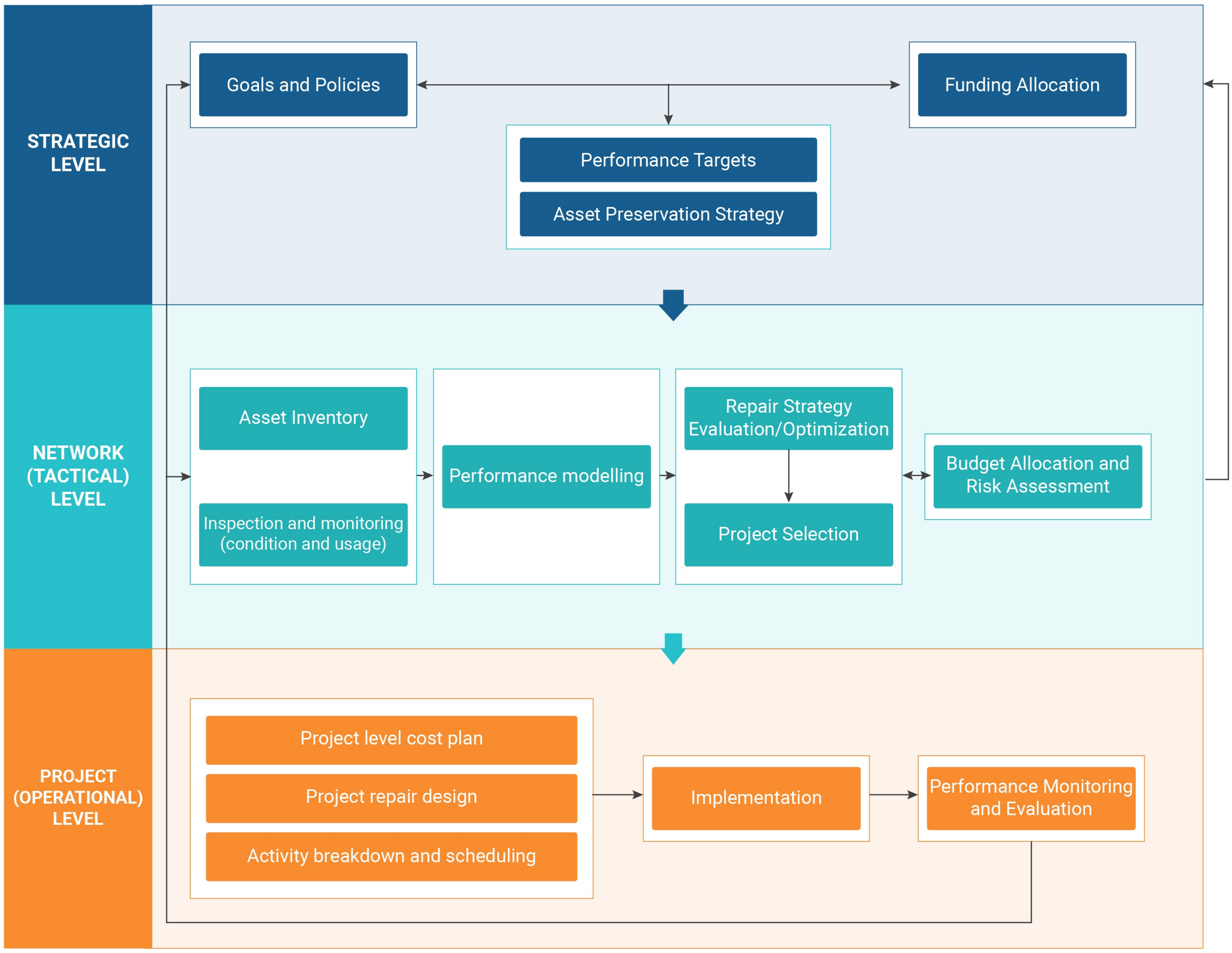

Figure 2.1: Infrastructure asset management process.

2.2 Road Asset Management Challenges in Developing Countries

The potential impact of road infrastructure on sustainable and inclusive growth in LICs and MICs is substantial. These countries face significant challenges such as a lack of investment in transport infrastructure, both in rural and urban areas, as well as issues of weak management practice in the transport sector. Additionally, emerging large cities in these countries are experiencing a rise in social costs, including congestion, pollution, and traffic crashes [11]. In light of the fast-paced urban expansion in Africa and Asia, there is a pressing need to expand and properly manage road infrastructure to keep up with the growing demands.

The inadequate road infrastructure and substandard road conditions in Africa contribute to higher transportation costs than in other regions worldwide. The case of the Douala-N'Djamena route that connects Cameroon with Chad illustrates this fact. The cost of transporting one ton over a kilometer on this route is 11 US cents. In contrast, the same transportation distance in the United States and France costs only 4 and 5 US cents per ton-kilometer, respectively [16]. Therefore, the cost in Africa is more than double that of the US and France. The increase in transportation costs, which can be attributed to poor road conditions, has several implications. Firstly, it leads to higher operating costs due to reduced fuel efficiency. Vehicles have to consume more fuel to travel on poorly maintained roads, resulting in increased expenses. Secondly, the damage caused to vehicles due to poor road conditions leads to higher maintenance costs. The constant exposure to potholes and rough surfaces on the road increases wear and tear on vehicles, necessitating more frequent repairs and replacements.

Moreover, substandard roads negatively impact the lifespan of tires, requiring more frequent replacements and further adding to the expenses. Additionally, vehicles' reduced speed and overall efficiency on poor roads lead to lower vehicle utilization. This means that vehicles spend more time traveling at slower speeds, reducing the number of trips they can make and further impacting their profitability. Lastly, poor road conditions also affect the lifespan of trucks. The constant strain and stress on the vehicles result in a shorter operational life, necessitating more frequent replacements and investments in new trucks.

If efforts are made to improve the condition of poorly maintained roads in East Africa, significant cost savings can be achieved. For low-traffic routes, the improvement from poor to good road conditions can result in annual operating cost savings of approximately $8,878.6. On the other hand, high-traffic routes can save as much as $31,075.1 per year by upgrading the roads [16]. These potential savings demonstrate the economic benefits that can be obtained by investing in road infrastructure improvements, as it leads to reduced operating costs for transportation companies and promotes more efficient and cost-effective movement of goods and services.

Despite the critical importance of preserving road infrastructure to promote the sustainable development of nations, maintenance backlog poses a significant challenge in low- and middle-income countries [16, 17]. While there is consensus among various sources that the backlog in road maintenance stems from a shortage of funding, inadequate management, or both, the main issue lies in effectively addressing the lack of proper asset management practices, particularly in LICs and MICs [17, 18]. Insufficient maintenance of roads, primarily due to the absence of appropriate asset management practices, not only leads to increased transportation costs resulting from poor road conditions but also triggers a substantial rise in maintenance expenses. For instance, the cost of reconstructing a road is approximately five times higher per kilometer than overlaying and 25 times higher than applying a bituminous surface dressing [19]. Consequently, it becomes imperative to establish and implement efficient asset management strategies to ensure the optimal and effective functioning of the transportation system. By adequately managing road assets, LICs and MICs can optimize maintenance efforts, reduce costs, and improve overall road quality, thereby fostering sustainable economic growth and development.

Robinson and May [20] have identified three primary factors that impede the implementation of road asset management in LICs and MICs: external, institutional, and technical challenges. The most significant external problem is the financial constraint associated with implementing such systems. LICs and MICs often face a lack of adequate funds to effectively support road asset management systems implementation. This financial limitation poses a considerable barrier to establishing sustainable infrastructure management practices. One of the key institutional factors hindering the implementation of asset management systems is the scarcity of experienced personnel. LICs and MICs struggle to find and retain professionals with the necessary expertise in asset management. This shortage of skilled staff complicates establishing and maintaining asset management systems. Furthermore, the complexity of these systems poses an additional challenge, as local staff and domestic resources may not have the capacity to sustain and manage intricate asset management processes effectively. The lack of genuine commitment to implement a proper road asset management system is another institutional problem. One of the significant technical challenges hindering the implementation of road asset management in LICs and MICs is the inadequacy of data, encompassing road design, road conditions, and road inventory. Insufficient road design data, including information about specifications and structural details, makes it challenging to plan and manage road assets effectively. The absence of reliable road condition data, such as pavement quality, surface distress, and maintenance history, impedes informed decision-making regarding maintenance and rehabilitation priorities. Furthermore, the lack of comprehensive road inventory data encompassing various assets like bridges, culverts, signage, and drainage systems, hinders performance monitoring, critical maintenance identification, and future planning. Addressing these data deficiencies is crucial for developing robust asset management strategies, optimizing resource allocation, and promoting sustainable road infrastructure management practices in LICs and MICs.

2.3 Current Road Asset Management Practices: Case Studies from Developing Countries

This section presents the road asset management practices in five countries: two African nations (Ethiopia and Ghana) and three Asian countries (Laos, Myanmar, and Nepal). This study aims to highlight the current practices and challenges faced in these countries, providing insight into the road asset management approaches adopted by developing countries.

To carry out this study, five graduate students from Osaka University, one from each of the countries mentioned above, were involved. These students are affiliated with their respective road agencies and hold responsibilities in road management. They have accumulated significant work experience in the road sector, ranging from 8 to 18 years. The case study was conducted by triangulating the information gathered from the participants' reports and other official documents from road agencies.

2.3.1 Overview of the Case Study Countries

Ethiopia is situated in the eastern part of Africa and shares borders with Eritrea, Djibouti, Somalia, Kenya, South Sudan, and Sudan. On the other hand, Ghana is located in the western part of the African continent and is bordered by Burkina Faso to the northwest and north, Togo to the east, the Atlantic Ocean to the south, and Cote d'Ivoire to the west. Ethiopia is a landlocked country with a land area of 1,128,571.3 km2, while Ghana has a land area of 227,533 km2 with an additional 11,000 km2 of water, resulting in a total area of 238,533 km2 [21]. In terms of population, Ethiopia is the second most populous nation in Africa and the twelfth in the world, with a total population of 120.3 million, while Ghana has a population of 32.5 million as of 2021, according to the United Nations estimate [22].

Moving on to southeast Asia, Myanmar and Laos are neighboring countries in that region. Both countries also share borders with China and Thailand. Furthermore, Myanmar shares borders with India and Bangladesh, while Laos neighbors Vietnam and Cambodia. Myanmar has a total area of 676,578 km2, with 652,670 km2 being land and the remaining portion being water, making it the largest country in mainland southeast Asia. On the other hand, Laos has a land area of 230,800 km2 [21]. As for population, Myanmar had an estimated population of 53.6 million in 2021, whereas Laos had a population of 7.3 million [22]. Another country in South Asia, Nepal, shares borders with India and the Tibetan autonomous region of China. Nepal has a land area of 143,350 km2 [21] and a population of 29.7 million [22]. Fig. 2.2 presents the geographical location of the studied countries, while Table 2.2 summarizes the essential information.

2.3.2 Current Road Asset Management Practice in Five Countries

This section provides an overview of the current road asset management practices in the five countries included in the case study, specifically focusing on the national (strategic) roads.

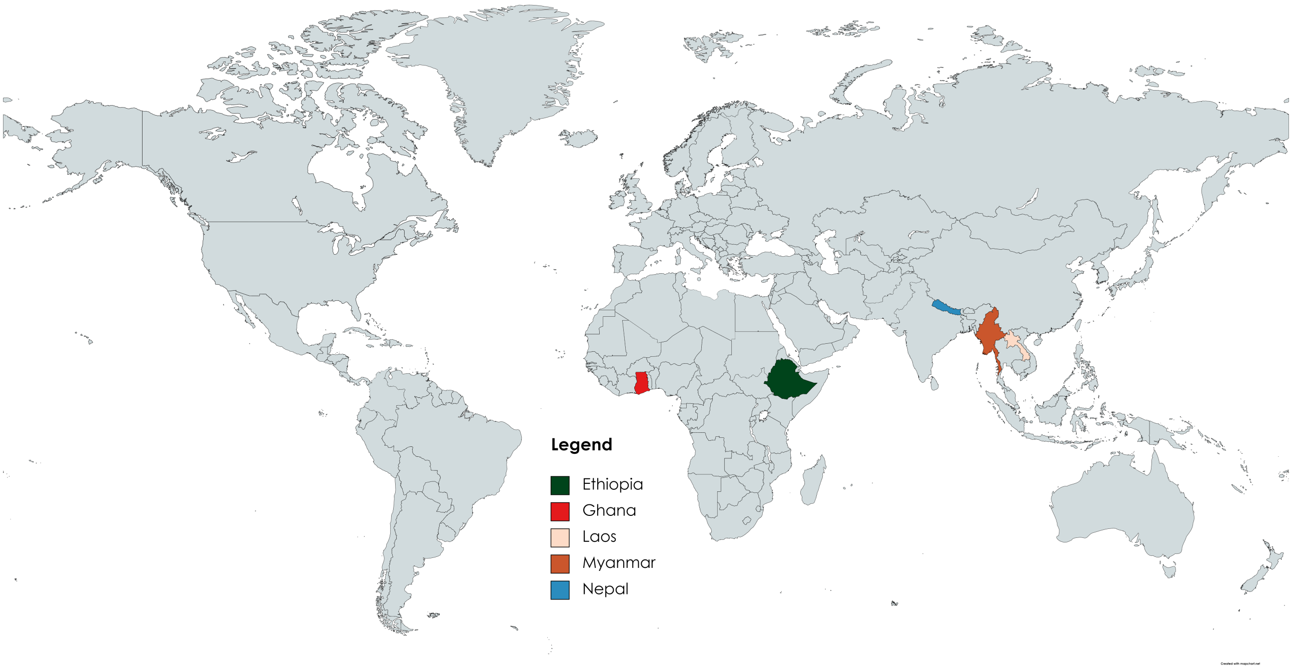

Figure 2.2: World map illustrating the geographic scope of the case study.

Table 2.1: Case study countries' basic information

Country	Land Area (km^2)	Population (millions)
Ethiopia	1,128,571.3	120.3
Ghana	227,533	32.5
Laos	230,800	7.3
Myanmar	652,670	53.6
Nepal	143,350	29.7

Ethiopia

As of 2021, Ethiopia has a total road network of 155,830.1km, consisting of 127,578.1km of regional and municipal roads and 28,252km of federal roads [23]. Among the federal roads, 16,315 km (56.8%) are paved, while the remaining 12,401km (43.2%) are unpaved. The Ethiopian Roads Administration (ERA) primarily oversees the management of federal roads. Regional and municipal roads, on the other hand, are administered by their respective regional and city road authorities. The federal road network is categorized into six functional classifications: Expressway, Trunk Road, Link Road, Main Access Road, Collector Road, and Feeder Road. However, the Toll Roads Enterprise manages the expressways, with ERA responsible for their construction. The expressways span approximately 300km [24]. It's important to note that the term "federal roads" refers explicitly to roads under ERA's administration. ERA operates under the Ministry of Transport and is directly accountable to its board. The country is divided into ten districts (branches), each responsible for managing their respective road networks.

Over the past five years, private consultants have been outsourced to conduct the road and bridge inventory and condition surveys previously carried out by the districts [25]. Manuals such as the pavement condition survey and bridge inspection have been developed to ensure consistent and high-quality data collection from multiple consultants. In 2006, ERA's Bridge Management System (BMS) was created by a bridge engineer and has been in use since then. The BMS has evolved from a desktop Windows application to a web-based Android server application, reaching version 7 with the collaborative efforts of bridge engineers and volunteer programmers. ERA has also been developing its own integrated Road Asset Management System (RAMS) [24]. Though ERA has the Highway Development and Management (HDM) software, it is not in use currently.

Visual road condition surveys of federal roads are conducted annually [26]. Bridge inspections are classified into three types: regular, major, and emergency. Regular inspections are carried out every year to assess the bridge condition from ground level visually, ensuring structural safety and traffic conditions. Regular inspections are relatively superficial, while major inspections are performed in detail every three years [27]. Emergency inspections are conducted when necessary, such as after natural disasters or severe traffic accidents. In recent years, private consultants have been responsible for the condition survey activities [24][24]. ERA lacks a deterioration prediction system, which is crucial for long-term planning and optimization. Instead, the road maintenance plan is primarily based on the annual condition survey results.

Based on the 2022 condition survey data, paved roads are categorized as 24% in good condition, 40% in fair condition, and 36% in bad condition according to the condition index (CI), which considers distress (cracks, potholes, raveling), roughness measured by the International Roughness Index (IRI), and rut depth. In contrast, unpaved roads are classified as 5% in good condition, 20% in fair condition, and 75% in bad condition [24]. The data indicates that paved roads are in better condition than unpaved roads. ERA's ten-year plan aims to improve the condition of paved roads to 65% in good condition, 20% in fair condition, and 15% in bad condition by 2030. Similarly, the target for unpaved roads is to achieve 50% in good condition, 30% in fair condition, and 20% in bad condition [28].

Ghana

The Ghana Ministry of Roads and Highways is responsible for overseeing the entire road network in the country. To fulfill its role in road infrastructure, the Ministry delegates specific responsibilities to different departments. The Ghana Highway Authority (GHA) is responsible for planning, administering, developing, maintaining, and controlling trunk roads. The Department of Feeder Roads handles rural roads, while the Department of Urban Roads manages urban roads and related facilities [29]. Ghana has a total road network length of 78,402km. The GHA focuses on national, inter-regional, and regional roads, which have a total length of 15,360 km [30].

The condition survey process follows the guidelines outlined in the GHA road maintenance operation manual. This manual provides a standardized approach to planning and collecting field data. It identifies common road surface distresses and associated features in Ghana. Two main levels of surveys are conducted: network-level and project-level surveys. The network-level survey involves data collection for both gravel and paved roads across the entire road network. It includes visual condition surveys and automated roughness measurements, which should be conducted at least once a year. The data collected from these surveys are used to prepare the annual road condition mix report and to identify sections for budget preparation. Project-level surveys provide detailed information about pavement strength, thickness, and the materials used in the road structure. These surveys focus on candidate roads that require maintenance, rehabilitation, or reconstruction. The selection of candidate roads for project-level studies is based on information obtained from the RAM software [29]. However, the RAM and the HDM software available at GHA are not used in the asset management process to the full scale.

Out of the total road network, 44% of the roads are in good condition, 34% are in fair condition, and 22% are in poor condition [30]. Moreover, according to the 2021 condition survey, 35% of the roads under GHA are in good condition, 46% are in fair, and 19% are in poor condition. Ghana aimed to achieve 70% of the road network in good and 20% in fair by 2037 [30].

Laos

The Ministry of Public Works and Transport (MPWT) oversees the management of the country's extensive road network, which spans a total of 58,876 kilometers. This network's 7,847 kilometers are classified as national roads [31]. The road hierarchy within the national road network is categorized using the "Core network levels." There are three levels in the core network: Core-1 (Level 1), which comprises vital national roads such as national economic corridor roads and ASEAN highway roads; Core-2, which includes roads connecting the capital city with provinces and provinces with each other; and Core-3, consisting of national roads with low traffic volume that are connected to urban and district areas.

With assistance from the World Bank, the Ministry of Public Works and Transport is upgrading the existing road maintenance system (RMS) to incorporate climate resilience parameters [32]. The Department of Road (DoR) and its provincial counterparts is responsible for conducting surveys and collecting data annually, typically after the rainy season. These surveys involve visual inspections, automated roughness measurements, and traffic surveys. The collected data is then inputted into the RMS system for analysis. The RMS utilizes the Highway Development and Management version 4 (HDM-4) software to generate data analysis, prioritize budget allocation based on road conditions and budget constraints, and calculate short-term (annual), medium-term (3-year), and long-term (10-year) maintenance plans for the road network. Maintenance prioritization takes into account factors such as traffic volume and pavement condition to make informed decisions. However, due to limited resources, the surveys have not been conducted yearly [32].

Based on the 2020 condition survey data, it was found that 34% of the national roads are in good condition, with IRI values below 4 m/km. The survey reveals that 59.4% of the roads are in fair condition, with IRI values between 4 m/km and 6 m/km. A small portion, around 5.7%, is in poor condition, with IRI values between 6 m/km and 8 m/km. Lastly, only 0.8% of the roads are in bad condition, with IRI values exceeding 8 m/km [32].

Myanmar

The Ministry of Construction comprises five departments: the Department of Highways (DOH), the Department of Bridges, the Department of Buildings, the Department of Rural Roads Development, and the Department of Urban and Housing Development. The DOH is responsible for the construction, upkeep, and management of the country's road infrastructure, while the Department of Bridges focuses on building and maintaining bridges. Other entities, such as municipal governments (referred to as city development committees in Myanmar), the irrigation department for certain frontage roads, the electricity and energy department, and the military, also have asset management responsibilities for roads under their mandate. As of 2020, the DOH oversees a total road length of 36,910.33 km [33].

Regarding road maintenance, the Department of Highways follows a specific inspection practice including road patrols, road cleaning, facility inspections (such as toll and drainage structures), and emergency inspections. Township Engineers and groups conduct regular inspections twice a year, and an Emergency Response Team takes immediate action during emergencies. Measurement tools like the Benkelman beam, laser profile, and bump integrator are utilized to assess road roughness, while the falling weight deflectometer is used for structural investigations [33].

The maintenance budget is requested annually from the Union and State/Region Budgets. The maintenance budget estimation is based on the length and type of roads rather than the actual road condition and performance evaluation. A proper evaluation procedure for predicting road deterioration is lacking to allocate the maintenance budget appropriately [33]. DOH is progressing to adopt the proper inspection and maintenance scheme regarding the infrastructure asset management approaches.

Nepal

The Ministry of Physical Infrastructure and Transport (MoPIT) is the governing body responsible for planning, developing, and managing transportation infrastructure. The road infrastructure network is divided into three main categories: strategic, local, and urban. The Department of Roads (DOR) oversees the management of 14,618 km of strategic roads out of the entire road network spanning 33,716 km [34].

In the past, the HDM-III and its successor, HDM-4, were extensively used for technical and economic evaluations of road investment projects. However, both of these tools are currently non-functional. Under the Planning Branch within DOR, the Highway Management Information System (HMIS) unit maintains a Geographical Information System (GIS) based inventory that encompasses 25 parameters for the roads under its jurisdiction. The HMIS, supported by funding from the Roads Board Nepal (RBN), collects data such as roughness, surface distress, and annual average daily traffic (AADT) annually. Using this data, a simple empirical method developed around 25 years ago is still employed to prepare the Annual Road Maintenance Plan. To facilitate further development, DOR is planning to establish a web-based road asset management system [35].

DOR assesses the performance of pavements by considering surface distress and roughness. Four levels of pavement ranking based on roughness (IRI value), similar to Laos, and three levels based on surface distress index (SDI) value are used [35]. The road condition ranking and the road network condition for the year 2022 are presented in Table 2.2. Depending on the SDI value, periodic maintenance is recommended for roads in fair condition, while roads in poor condition require rehabilitation or reconstruction. Periodic maintenance primarily involves cyclic resealing, typically performed at intervals of 5 to 8 years. The prioritization of maintenance activities is determined based on four criteria: road age, visual survey rating, traffic volume,

Table 2.2: Strategic road network condition of Nepal in 2022

Category	IRI (m/km^2)	Distribution (%)	SDI	Distribution (%)
Good	Less than 4	8	0 - 1.7	26
Fair	4 - 6	23	1.8 - 3.0	47
Poor	6 - 8	32	3.1 - 5.0	25
Bad	Greater than 8	29	-	-
No survey	-	8	-	2

and strategic importance [35]. The target of maintenance is to keep 95% of the road at least in fair condition, SDI value of 3 or below.

2.3.3 Comparison of Current Road Asset Management Practice with the Standard Process and Challenges in the Case Study Countries

The preceding sections summarize how road asset management is practiced in the case study countries. This section compares this practice with the standard procedure that relies on a generic asset management system. Then, the challenges these countries faced based on the informants' reports are presented. The assessment is based on the seven components of the FHWA's asset management system [13], and it assigns ratings on a scale of four levels: 0 (not implemented), 1 (partially implemented), 2 (mostly implemented), and 3 (fully implemented). The FHWA outlines a series of key questions the system's components must address [13]. Assessing the extent to which the available system adequately addresses these questions can serve as a basis for evaluation. The questions encompass:

- What is our mission? What are our goals and Policies?
- What is included in our inventory of assets? What is the value of our assets? What are their functions? What services do they provide?
- What was the past condition and performance of our assets? What is the current and predicted future condition and performance of our assets? How can we preserve, maintain, or improve our assets to ensure the maximum useful life and provide acceptable service to

the public?

- What resources are available? What is the budget level? What is the projected level of future funding?
- What investment options may be identified within and among asset component classes? What are their associated costs and benefits?
- Which option, or combination of options, is "optimal?"
- What are the consequences of not maintaining our assets? How can we communicate the impact of the condition and performance of our assets on the system and end-user?
- How do we monitor the impact of our decisions? How do we adjust our decision-making framework when indicated?
- How can we best manage our assets in order to least inconvenience the motoring public when we repair or replace these facilities?

According to Table 2.3, all countries scored below the average point when considering the maximum possible score of 21. However, a slight difference among the countries is observed. The complete implementation of the standard road asset management process faces four major challenges. The first obstacle is financial, as the allocated budget falls short of the required maintenance funds. Consequently, agencies hesitate to invest in system development, data collection, and processing. The second challenge revolves around a lack of commitment, where agencies struggle to consistently implement the road asset management process. This is evident in the underutilization of available HDM software, partly due to the demanding nature of data requirements and the need for trained personnel to operate the software effectively. The third hurdle lies in the complexity and sustainability of existing road asset management software, which poses difficulties in resource-constrained LICs and MICs. However, there is potential for sustainable utilization of tools and software tailored to local conditions, like the BMS in Ethiopia. The fourth challenge stems from a shortage of adequately trained personnel and a lack of interest among engineers to work in road asset management. Engineers in LICs and MICs

Table 2.3: Comparison of current road asset management practice in the study countries with standard process

Asset Mangement System Components	Ethiopia	Ghana	Laos	Myanmar	Nepal
Goals and Policies	3	3	2	2	3
Asset Inventory	2	2	2	2	2
Condition Assessment and Performance Modeling	1	1	1	0	1
Alternative Evaluation and Program Optimization	1	1	1	1	1
Short - and long-range plans	1	1	1	1	1
Program Implementation	1	1	1	1	1
Performance Monitoring	1	1	1	1	1
Total	10	10	9	8	10

often prefer construction and other projects, leading to a depletion of experienced personnel and leaving the road asset management system underutilized when they leave their positions.

2.4 Conclusions

The countries in the case study exhibit that more than 50% of their road network is in fair condition, which contradicts previous studies. However, it is important to consider the thresholds used for evaluation. The IRI thresholds vary significantly among countries. For instance, the IRI threshold for determining fair condition is 2.7 m/km in the US, 3.5 m/km in Brazil, 4.0 m/km in Chile, Uruguay, and Spain, and 6.0 m/km in Honduras [36]. Furthermore, the condition of the road network can vary depending on the performance indicator used, as seen in the case of Nepal. Therefore, it is crucial to recognize that the results are highly dependent on the specific indicator and threshold used, despite the common usage of terms like "good" or "poor."

The case study indicates that the current practices in the countries assessed do not adhere to the standard road asset management process, and the challenges identified by Robinson and May [20] for not implementing proper road asset management persist in LICs and MICs. However, there is an initiative to develop road asset management systems in all the countries studied, but the sustainable implementation of these systems depends on effectively addressing the root problems. Merely developing the system does not guarantee proper implementation as long as the underlying problems persist. Additionally, the case study reveals that the current practices do not take into account traffic safety.

Consequently, there is a crucial need for a simplified road asset management system that takes into account the constraints faced by LICs and MICs. Such a system should be designed to ensure sustainable implementation, considering the financial limitations, human resource shortages, and technical challenges specific to these countries. By developing a tailored and pragmatic asset management approach, LICs and MICs can overcome the barriers they face and establish effective systems for managing their road assets.

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Chapter 3

Safety Integrated Network Level Road Maintenance Decision Support Framework

3.1 Introduction

Roads constitute a vital social infrastructure of nations. Prior literature suggests that road infrastructure strengthens manufacturing, tourism, agriculture, and the overall development of a country by improving accessibility and mobility [1, 2]. These benefits of road infrastructure for socioeconomic development demand proper management to optimize asset value. Despite the importance of roads in providing mobility and accessibility, road traffic crashes have become a significant problem. Thus, integrating road safety into maintenance planning can shift conventional approaches that mainly use pavement conditions as a prioritization criterion, especially in developing countries. Pavement condition-oriented maintenance planning schemes prioritize motorists and overlook other road components such as sidewalks, streetlights, road markings, and crossing facilities important for non-motorized road users, particularly pedestrians and bicyclists.

In addition to traffic safety, the lack of proper road infrastructure management and timely maintenance is another concern in developing countries. For example, in sub-Saharan Africa, 150 billion US dollars were invested in road construction over three decades, but the value of one-third of that investment in social infrastructure has been lost due to a lack of proper maintenance [3]. Besides the high maintenance cost required due to deferred maintenance resulting from improper pavement management, poorly maintained roads will significantly increase vehicle operating costs and traffic crashes.

Multiple studies have established a strong link between road traffic crashes and pavement conditions [4, 5, 6, 7, 8, 9, 10, 11, 12]. The primary pavement characteristics influencing traffic crashes are roughness, rutting, and skid resistance. A study conducted by Elghriany et al. [4] revealed a positive correlation between crash rates and the international roughness index (IRI), indicating that deteriorating (rough) pavement conditions degrade traffic safety. Several other studies [6, 7, 8, 9, 11] have also reported similar relationships between crash rates and IRI. However, Tsubota et al. [5] found an inverse relationship between IRI and crash risk. On the other hand, Al-Massaeid [9] concluded that IRI does not significantly impact the overall crash rate but does show an inverse relationship with single-vehicle crashes. However, this study confirmed that higher IRI levels are associated with increased multiple-vehicle crash rates, consistent with previous research. Studies on rutting have also yielded comparable results, confirming that the increase in rut depth leads to a higher crash rate [5, 6, 7, 8]. For example, Mamlouk et al. [8] reported a critical rut depth of 0.4 inches, above which the crash rate increased. Additionally, research on skid resistance has shown a negative correlation with crash rates [7, 10, 11, 12] and crash severity [11]. Moreover, a study by Mayora and Piña [12] indicated that higher skid resistance values reduced crash rates on wet- and dry-pavement, with wet-pavement crash rates seeing a significant average reduction of about 68%. These findings highlight the significant impact of pavement conditions on road traffic crashes.

Being a developing country, Ethiopia has faced socio-economic crises due to traffic crashes. The United Nations road safety performance review revealed that the number of road traffic fatalities and serious injuries in Ethiopia continuously increased in the twelve years between 2007 and 2018 [13]. In 2016, the Ethiopian government officially reported 4,352 road traffic fatalities [14]. However, the World Health Organization (WHO) suggested that the actual number is considerably higher, estimated at 27,326, over six times the figure provided by the government [15]. Addis Ababa, the capital of Ethiopia, faces a similar situation, with an average annual fatality rate of 391 between 2013 and 2016 [16]. Additionally, there was a 6% average yearly increase in road fatalities in Addis Ababa from 2010 to 2016, where pedestrian deaths constituted the largest share and accounted for up to 90 percent of all fatalities in 2016 [16]. The UN performance review report recommended integrating road safety into road maintenance to make road safety part of organizational culture, thereby strengthening road safety management [13].

Moreover, Ethiopia has also lost billions of dollars due to its flawed maintenance system for national roads. One of the primary reasons for this loss is the absence of a proper pavement management system (PMS) [17]. Likewise, Addis Ababa exhibits the same problem [18]. Gebre [19] highlighted the use of paper-based systems as one of the challenges affecting road maintenance management in Addis Ababa City, along with other factors. This reliance on paper-based processes has a direct impact on the effectiveness of road maintenance management. Similarly, Agidewu [20] acknowledged the deficiencies in the pavement maintenance management process, specifically the absence of crucial elements like proper condition assessment, prioritization, and planning schemes. In this regard, a PMS plays a salient role in preserving valuable assets. Furthermore, road agencies cannot devise long-term optimized maintenance strategies without a proper PMS that helps predict pavement deterioration and carry out maintenance type selection versus budget trade-off analysis.

Several approaches have been proposed to improve decision-making in pavement management processes. Han et al. [21] developed an intelligent decision-making framework for optimal maintenance and rehabilitation, utilizing a clustering-PageRank algorithm applied to big data. The framework was compared to an experience-based maintenance approach and showed promise in overcoming the limitations of relying solely on individual experiences. However, the framework was limited when dealing with a small sample size due to its reliance on data mining. De la Garza et al. [22] presented a relatively simpler method based on a linear programming framework for network-level optimization of pavement maintenance renewal strategies. The model's simplicity and ability to assess outcomes' sensitivity to input changes make it a strong option for decision-making. However, De la Garza et al.'s assumption of linearity in pavement deterioration, which is inherently nonlinear and stochastic, requires further improvement. Despite the tendency to neglect road safety in current research on maintenance decision support frameworks [23], notable efforts have been made to address this crucial aspect. For example, He et al. [24] developed a project-level maintenance decision support framework that considers pavement treatments' economic, social, and environmental impacts. This framework aids sustainable maintenance decision-making and includes factors such as user life cycle costs resulting from crashes. However, the consideration of crash costs is limited to those occurring during repair activities due to traffic disruption, as expressed by the volume over capacity parameter. Similarly, Singh et al. [25] considered the friction coefficient as a criterion in prioritizing road maintenance in the Jhunjhunu district, India, using Fuzzy Analytical Hierarchy Process (FAHP) and Fuzzy Weighted Average (FWA) methods. The results demonstrated the effectiveness of these models for agencies that lack proper PMS. However, relying solely on the friction coefficient can mislead decision-making, as it does not provide a comprehensive evaluation of the overall safety condition of the road section. Sayadinia and Beheshtinia [26]proposed a hybrid decision-making approach that combined the Analytic Hierarchy Process (AHP) and three different versions of the Elimination Et Choice Translating Reality (ELECTRE) method. They applied this approach to evaluate four streets in Tehran city, considering eight main criteria, including road safety. While the method proved useful for decision-making under budget constraints, the subjectivity inherent in the methodology limits its applicability.

The framework proposed in this chapter considers road pavement conditions and safety aspects while acknowledging the efforts and limitations of previous research and the difficulties faced in developing countries, such as scarcity of resources and data. A two-tiered Markov process–based approach was proposed for modeling the pavement deterioration and repair process. On the other hand, a deterministic approach was used to integrate the safety aspect into the PMS. The International Road Assessment Program (iRAP) protocol was utilized to assess the safety level for each group of road users, viz., vehicle occupants, motorcyclists, bicyclists, and pedestrians. In this chapter, a practical method that can be utilized by road agencies, mainly in developing countries, for implementing a strategic sustainable, and safety-incorporated PMS is proposed. The diagram illustrating the proposed framework is shown in Fig. 3.1.

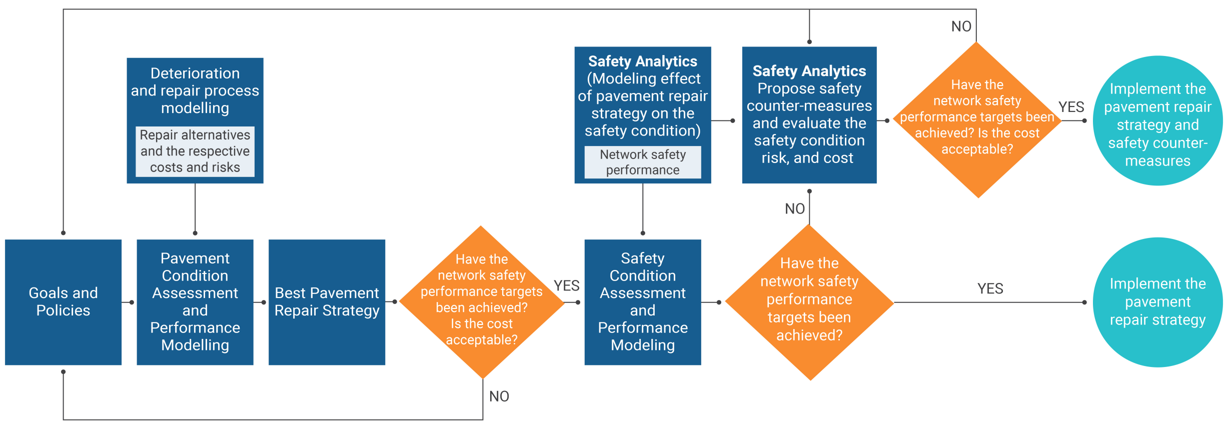


Figure 3.1: Network-Level decision support framework diagram.

3.2 Markov Process in Pavement Management

The Markov-chain model-based approach used in this framework involves two main processes, as shown in Fig. 3.2. The first is the deterioration process that forecasts pavement deterioration stochastically. The second is the repair process which is deterministic and depends on the agency's decision on the repair action and timing.

3.2.1 Markovian Pavement Deterioration Process

Due to loading and environmental effects, any infrastructure, including road pavements, deteriorates with time. Therefore, understanding the deterioration process and being able to predict the deterioration process can contribute to proactive actions. The proposed deterioration prediction model is discussed below.

The Deterioration Prediction Model

Markov chain models have been implemented widely in deterioration prediction [27]. Markov chain models are preferred due to their flexibility and operability, especially for network-level analysis [28]. In the Markov process, a transition from one condition state to the future state only depends on the current condition state regardless of the transition history. In Markov chain modeling, the transition probability π_{ij} is defined as the probability of the condition state i at calendar time τ_1 (present), $h(\tau_1) = i$, transitioning to the condition state j at calendar

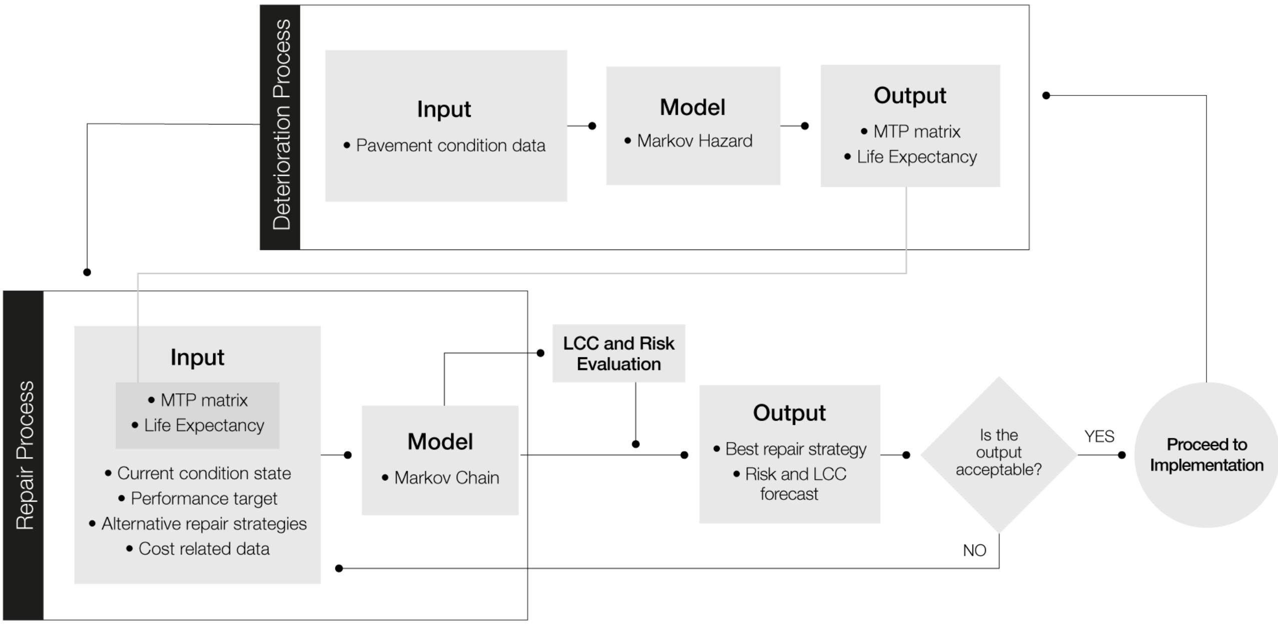


Figure 3.2: Simplified flow chart for Markov process-based decision-making.

time τ_2 (future), h(τ_2) = j.The values of variables i and j range from 1 (the best condition state) to the worst condition state J (condition state 5 in this study, which is also the absorbing condition state). The probability of transition from the condition state i observed at time τ_1 to the condition state j at future time τ_2 can be expressed as follows:

$$\pi_{ij} = \text{Prob}[h(\tau_2) = j \mid h(\tau_1) = i]. \tag{3.1}$$

All the transition probabilities within the time interval $Z(Z = \tau_2 - \tau_1)$, the period between inspections, can be presented in a matrix form as a Markov transition probability (MTP) matrix denoted by Π:

$$\Pi = \begin{bmatrix} \pi_{ij} & \dots & \pi_{1J} \\ \vdots & \ddots & \vdots \\ 0 & \dots & \pi_{JJ} \end{bmatrix} \tag{3.2}$$

On reaching the absorbing condition state J, the deterioration remains in the same state if no maintenance is carried out, so $\pi_{JJ} = 1$. Similarly, it will not be possible to regain a better condition state from a worse condition without maintenance; i.e., $\pi_{ij} = 0$ for $i > j$. Moreover, the summation of probabilities for transitioning from state i should be equal to 1, and from the definition of probability, $\sum_{j=1}^{J} \pi_{ij} = 1$. These general preconditions can be summarized as follows:

$$\begin{aligned} \pi_{ij} &= 0, \quad \text{for } i > j \\ \pi_{ij} &\geq 0, \quad \text{for } i \leq j \\ \sum_{j=1}^{J} \pi_{ij} &= 1 \end{aligned} \tag{3.3}$$

A Markov hazard model developed by Tsuda et al. [28] is used as a basis for pavement deterioration prediction. It allows the use of arbitrary inspection intervals, thereby avoiding the limitation of the conventional Markov chain model. This model utilizes maximum likelihood estimation for calculating the MTP. Han et al. [29] introduced the Bayesian estimation into the model, improving it by eliminating the maximization problem, which was often the limitation for similar models. Moreover, the improvement makes it suitable for a relatively small data set. It uses pavement condition data inspected at times τ_1 and τ_2 and the explanatory variables such as traffic volume and pavement thickness to calculate the MTP. Interested readers are encouraged to refer to Tsuada et al. [28] for details on the derivation and the background intuition of the Markov hazard model and Han et al.[29] regarding the Bayesian approach of the same model. The improved Markov hazard model, which employs the Bayesian estimation, was used to estimate the pavement deterioration rate.

To highlight the hazard model, assume that the condition state i starts from calendar time τ_{i-1} and changes to the condition state $i+1$ at calendar time τ_i. Thus, the duration of the survival of the condition state i, y_i, can be measured by setting y_i to zero when the condition i starts to exist at time τ_{i-1}. The life expectancy of a condition state i is assumed to be a stochastic variable with a probability density function $f_i(\zeta_i)$ and a cumulative distribution function $F_i(\zeta_i)$. The distribution function is defined as

$$F_i(y_i) = \int_0^{y_i} f_i(\zeta_i) d\zeta_i \tag{3.4}$$

Consequently, the survival function or reliability function indicating the probability of the condition state persisting longer than age (duration) y_i can be defined as

$$\text{Prob}[\zeta_i \geq y_i] = \tilde{F}_i(y_i) = 1 - F_i(y_i) \tag{3.5}$$

The hazard function $\theta_i(y_i)$, also known as hazard rate, is defined as the instantaneous rate of change in condition state from i to $i+1$ per unit time of y_i. Mathematically,

$$\theta_i(y_i) = \lim_{dy_i \to 0} \frac{\text{Prob}(y_i \leq \zeta_i < y_i + dy_i)}{dy_i} \tag{3.6}$$

The expression in the numerator in Eq. 3.6 is the conditional probability of a change in condition state i to $i+1$ in the interval $[y_i, y_i + dy_i]$, while the condition state i is still being observed at y_i. The term in the denominator is the width of the interval. The conditional probability may be written as the ratio of the joint probability that ζ_i is in the interval $[y_i, y_i+dy_i]$ and $\zeta_i \geq y_i$, which is $\text{Prob}(y_i \leq \zeta_i < y_i + dy_i)$ to $\text{Prob}(\zeta_i \geq y_i)$. The ratio can be expressed as $f_i(y_i)dy_i$ for small dy_i to $\tilde{F}_i(y_i)$. Replacing the numerator with this ratio in Eq. 3.6 gives the following:

$$\theta_i(y_i) = \frac{f_(y_i)}{\tilde{F}_i(y_i)} \tag{3.7}$$

Differentiating both sides of Eq. 3.5 with respect to y_i gives $-f_i(y_i)$ as the derivative of $\tilde{F}_i(y_i)$. Thus, Eq. 3.7 can be written as

$$\theta_i(y_i) = -\frac{d}{dy_i}(\log\tilde{F}_i(y_i)) \tag{3.8}$$

Assuming that the deterioration process satisfies the Markov property and that the hazard function is constant, independent of y_i, the hazard rate becomes a fixed value θ_i, where $\theta_i > 0$. The probability of life expectancy of the condition state i greater than y_i can be expressed as follows:

$$\tilde{F}_i(y_i) = \exp(-\theta_i y_i) \tag{3.9}$$

When the duration y_i is equal to the inspection period Z_i, the survival function becomes identical to the transition probability π_{ii} as the condition state i is observed at both the inspection times τ_1 and τ_2. Thus, $\pi_{ii} = \exp(-\theta_i Z)$. Similarly, the following mathematical formulas can be derived to estimate the Markov transition probabilities based on the exponential hazard model (Markov hazard model).

$$\pi_{ii} = \exp(-\theta_i Z) \tag{3.10}$$

$$\pi_{ii+1} = \frac{\theta_i}{\theta_i - \theta_{i+1}}[-\exp(\theta_i Z) + \exp(-\theta_{i+1} Z)] \tag{3.11}$$

$$\begin{gathered} \pi_{ij} = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k Z)] \\ \begin{cases} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} = 1, (\text{when } k = i) \\ \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} = 1 (\text{when } k = j) \end{cases} \end{gathered} \tag{3.12}$$

$$\pi_{iJ} = 1 - \sum_{j=i}^{J-1} \pi_{ij} \tag{3.13}$$

However, to utilize the formulated model, the hazard rate θ_i^k for the inspection sample $k(k = 1, ..., K)$ needs to be further explained as a function of the measurable explanatory variables x^k and the unknown parameters $\beta_i (i = 1, ..., J-1)$. The parameters β_i can be obtained using Bayesian estimation.

$$\theta_i^k = f(x^k : \beta_i) \tag{3.14}$$

Output of the Deterioration Prediction Model

Using the periodic inspection data, the prediction model gives two significant outputs. The first is the MTP matrix, which is the primary output in forecasting the pavement deterioration process. As explained, the matrix represents the probability of conditions' transition within a specific time interval Z. Therefore, the MTP matrix after n intervals multiplied with itself n times and can be calculated as

$$\Pi(nZ) = [\Pi(Z)]^n \tag{3.15}$$

The second output is the expected elapsed time during which a particular condition state stays the same before transitioning to another state in the deterioration process. The expected life expectancy of the condition state i of the inspection sample k, LE_i^k can be expressed as

$$LE_i^k = \int_0^\infty \tilde{F}_i(y_i^k)dy_i^k \tag{3.16}$$

Substituting Eq. 3.9 in Eq. 3.16 for inspection sample k results in

$$LE_i^k = \int_0^\infty \exp(-\theta_i^k y_i^k)dy_i^k = \frac{1}{\theta_i^k} \tag{3.17}$$

3.2.2 Markovian Pavement Repair Process

The Markov process involving repair or maintenance differs from the deterioration process in two aspects. The first is that the repair rule, pertaining to the repair timing and repair type, is decided by the road agency. Therefore, unlike the probabilistic deterioration process, the repair process is deterministic. Second, the repair process improves the condition states from worse to better, contrary to the deterioration process.

The Repair Model

As with other Markov-based models, the formulation of the transition probability matrix is the core requirement in the repair process. However, contrary to the deterioration process, the probability of the transition from state i to j, r_{ij}, after the repair action that constitutes the repair transition matrix and change in condition state due to each repair action is predetermined.

$$r_{ij} = \begin{cases} 1, & \text{for } \eta(i) = j \\ 0, & \text{for } \eta(i) \neq j \end{cases} \tag{3.18}$$

where $\eta(i)$ denotes the action vector

$$\eta = [\eta(1), ..., \eta(J)] \tag{3.19}$$

The action vector indicates the change in condition states due to the repair action. The repair action $\eta(i)$ stands for the transition from i to state $\eta(i)$. For instance, $\eta(i) = j$ indicates the state transition from i to j due to the repair action. If the repair is carried out, the state change follows the repair rule defined in the action vector; otherwise, it remains in its current state. Therefore, the Markov transition probability matrix for the repair can be defined as

$$R(\eta) = \begin{bmatrix} r_{11} & \dots & r_{1J} \\ \vdots & \ddots & \vdots \\ r_{J1} & \dots & r_{JJ} \end{bmatrix} \tag{3.20}$$

A road network with a pavement condition state vector $S(t_r)$ at a time of inspection t_r will change its state to $S(\tilde{t_r})$ after repair assuming that the repair is carried out immediately after the inspection.

$$S(\tilde{t_r}) = S(t_r)R(\eta) \tag{3.21}$$

As the deterioration and repair processes continue alternately during the service life of the road, the condition states before and after repair at the n^{th} inspection can be formulated using the initial condition state vector $S(t_0)$, the deterioration transition probability matrix $\Pi(Z)$, and the repair transition probability matrix $R(\eta)$ as follows:

$$S(t_n) = S(t_0)[\Pi(Z)R(\eta)]^{n-1}\Pi(Z) \tag{3.22}$$

$$S(\tilde{t_n}) = S(t_0)[\Pi(Z)R(\eta)]^{n} \tag{3.23}$$

3.2.3 Life Cycle Cost and Risk Evaluation

Optimum pavement repair strategies could be obtained through life cycle cost (LCC) analysis. According to Han [30], LCC comprises agency, user, and socioeconomic costs. A vast number of studies have applied the concept of LCC analysis in pavement management [31]. The definitions of LCC used in these studies differ depending on the LCC components they considered. Han [30] classified the essential and optional LCC components, as listed in Table 3.1. This paper considers agency costs, including maintenance and inspection costs, to evaluate maintenance strategies.

To express the agency cost mathematically, consider a repair action $\eta(i) = j$ with repair

Table 3.1: Classification of life cycle costs

Classification	Core level	Recommended level		Advanced level		
	Agency cost	User cost				Socio-environmental cost
		Vehicle operating cost (VOC)	Travel time cost	Accident	Work zone	Emission cost
Essential	· Maintenance · Inspection	· Fuel · Tire	· Travel time	· Property damage		· CO CO_2, NO_x
Optional	· Initial costs · PMS operation	· Depreciation, repair · Engine oil		· Injury · Fatality	· Travel time and VOC due to workzone	· SO_2, HC PM,Pb

cost $c_{i,j}$ and inspection cost C_I. The agency cost AC for one cycle of deterioration and repair period $[t_r, t_r + 1]$ with the road network pavement condition state vector at time t_r is $S(t_r)$, and the transition probability from a state i to j, $r_{i,j}$ can be calculated as

$$AC(t_r) = \sum_{i=1}^{J} \sum_{j=1}^{J} r_{i,j} c_{i,j} s_i(t_r) + C_I \tag{3.24}$$

Moreover, LCC can be calculated using the discount present value method with discount rate δ for the period of nZ

$$LCC(Z, \eta) = \sum_{r=0}^{\infty} \frac{\sum_{i=1}^{J} \sum_{j=1}^{J} r_{i,j} c_{i,j} s_i(t_r) + C_I}{(1+\delta)^{Zr}} \tag{3.25}$$

or using average cost method

$$LCC(Z, \eta) = \frac{\sum_{i=1}^{J} \sum_{j=1}^{J} r_{i,j} c_{i,j} s_i(t_r) + C_I}{Z} \tag{3.26}$$

As for Addis Ababa city's case, the whole network's inspection is carried out annually, irrespective of the proposed maintenance strategy. Thus, the repair (maintenance) cost remains the primary cost that should be used for maintenance strategy evaluation.

Risk can be expressed through three primary concepts: uncertainty and expected values, events/consequences along with uncertainty, and in relation to objectives [32]. In this study, uncertainty is linked explicitly to the deterioration process, while repair actions' consequences are known in advance. Consequently, the first two definitions of risk pertain to the consequences of repairs and how they differ from the established target, given the certain outcome of the repairs. Similarly, defining risk based on the objective yielded the same conclusion: risk involves deviation from the predetermined performance target. Hence, in this study, the risk was defined as the percentage of the road length that does not meet the performance target set by the road agency.

3.3 Road Safety Analytics

Safety-conscious road design, construction, and maintenance are vital in ensuring safe roads and reducing death and serious injury from traffic crashes. The need to consider road safety in all phases of the road life cycle is reflected in the UN Road Safety Performance Targets 3 and 4. Global Road Safety Performance Target 3 aims to have all new roads achieve a star rating of three or above, and Target 4 aims for more than 75% of travel on the existing roads to meet a star rating of three or better for all road users by 2030 [15].

The iRAP methodology was used for road safety analysis. The iRAP has five protocols: crash risk maps, star ratings, fatality and serious injury (FSI) estimations, safer roads investment plans (SRIP), and performance tracking [33]. The proposed framework applies the star ratings, FSI estimation, and SRIP. The online software ViDA was used to generate the star rating, SRIP, and FSI estimation from the road attribute data. The assessment based on star rating helped identify the level of risk of the whole network from a 100 m segmented analysis without detailed crash data, thus making it suitable for developing countries where crash data is scarce [33]. In addition to its advantage in not requiring crash data, the iRAP methodology's capability to evaluate the safety of the road for all road user groups and its benefit in providing the same traffic safety measurement scale with a global target makes it a favorable choice for road agencies. According to global road safety performance targets, roads that achieve a star rating of 3 or higher for all road users are considered to meet safety standards from a technical perspective [15]. There are 94 countermeasures (safety treatments) in iRAP that can be implemented to improve star ratings. These countermeasures can be chosen and prioritized per the target road's condition and other considerations such as cost, availability, ease of implementation, and so on to produce an effective and economically viable investment plan.

3.3.1 Safety Analysis Input

The input data required for ViDA coding is extracted from road survey data. The road survey data comprises of images or videos of roads, location, and distance data. A total of 78 attributes are grouped under seven categories as input for the analysis [34]. The seven categories are road details and context data, roadside data, midblock data, intersection data, flow data, VRU (Vulnerable Road Users' facilities and land use data), and speed data.

3.3.2 The Safety Model

The computational procedures of the three iRAP protocols, viz., star rating, FSI estimation, and SRIP used in this study, are presented below following the iRAP manual and fact sheets [34, 35, 36].

Star rating

A star rating of every 100 m segment for each road user group is produced based on a Star Rating Score (SRS). SRS quantifies the relative risk of death and serious injury for road users. It is calculated by summing up the scores of each crash type q ($q = 1, ..., Q$). Accordingly, three crash-type scores are considered for vehicle occupants and motorcyclists: head-on, run-off-road, and intersection crash scores. Pedestrian SRS is calculated by summing up walking along and across the road crash scores. Similarly, riding along the road and intersection crash types are used in the case of bicyclists [35]. Road attributes that influence the initiation and severity of a particular crash type are considered as risk factors. The condition of the risk factors determines the likelihood and severity of a crash. In addition to the likelihood and the severity, operating speed and external flow influence are used to calculate the crash type scores. Median traversability is another factor in calculating run-off and head-on crash scores [34] .

$$SRS = \sum_{q=1}^{Q} Crash\ type\ Scores \tag{3.27}$$

Table 3.2: Star rating bands

Star Rating	Vehicle occupants and motorcyclists	Bicyclists	Pedestrians		
			Total	Along	Crossing
5	0 to 2.5	0 to 5	0 to 5	0 to 0.2	0 to 4.8
4	2.5 to 5	5 to 10	5 to 15	0.2 to 1	4.8 to 14
3	5 to 12.5	10 to 30	15 to 40	1 to 7.5	14 to 32.5
2	12.5 to 22.5	30 to 60	40 to 90	7.5 to 15	32.5 to 75
1	22.5+	60+	90+	15+	75+

$$\begin{aligned} Crash\ Type\ Scores = Likelihood \times Severity \times Operating\ speed \\ \times External\ flow\ influence \\ \times Median\ transversability \end{aligned} \tag{3.28}$$

For example, paved shoulder width, type of roadside object, and the distance of the object from the road are the three risk factors that influence the severity of run-off crash score for vehicle occupants [36]. Let us consider the effect of paved shoulder width on the severity of the run-off crash. When a road does not have a paved shoulder, the crash modification factor (CMF) value is set at 1. However, the CMF value changes depending on the shoulder width if the road has a paved shoulder. For shoulder widths of 2.4 meters or more, the CMF value is 0.77. For widths greater than 1 meter but less than 2.4 meters, the CMF value is 0.83. And for widths up to 1 meter, the CMF value is 0.95. The CMF values show that the severity decreases as the shoulder width increases because the driver gets time to control the vehicle. The CMF values of each risk factor influencing the likelihood and severity will be multiplied to obtain the respective likelihood and severity risk factor scores. Similarly, the degree to which the risk changes with speed, external flow, and median traversability is considered in calculating crash-type scores. Based on the star rating score, a star rating of each segment can be determined as per the star rating bands in Table 3.2 [35].

Fatality and Serious Injury (FSI) estimation

The number of fatalities of each road user group on the given road segment is calculated by summing up the estimate of fatalities per crash type. For example, we sum up vehicle occupant run-off-road (driver side and passenger side), head-on (loss of control and overtaking), intersection, and property access fatalities are summed up to estimate the number of vehicle occupant fatalities.

The vehicle occupant fatalities for the run-off road crash can be calculated as:

$$VO_{RO} = SRS_{RO} \times a(AADT_{NoN-MC})^{b} \times CF_{VORO} \times \frac{365}{10^{9}} \tag{3.29}$$

Vehicle occupant run-off road fatalities (VO_{RO}) are estimated by the product of SRS, annual average daily traffic (vehicle flow) for non-motorcycles ($AADT_{NON-MC}$), and calibration factor (CF) where a and b are constants. The same procedure is implemented for other road user groups as well. The total fatalities value is the sum of each road user group's estimated number of fatalities.

The number of serious injuries can be calculated by multiplying the estimated number of fatalities by the ratio of serious injuries to fatalities. The ratio can be determined from the crash data, or the 10:1 ratio can be used in the absence of actual data [36]. FSI is then calculated by summing up the fatalities and serious injuries.

Economic Analysis

In order to analyze the economic benefit of countermeasures and optimize different alternatives, the calculated FSI should be converted into monetary value. Therefore, the economic value of life and serious injury can be used whenever a well-established value is available; otherwise, 70 times GDP per capita can be used as a value of human life, and 25% of the human life value can be adopted for serious injury following iRAP methodology [36]. Thus, the number of FSI that can be prevented will be converted to the monetary benefit based on these values and considered an economic benefit. On the other hand, the countermeasure cost is used as an economic cost in the analysis.

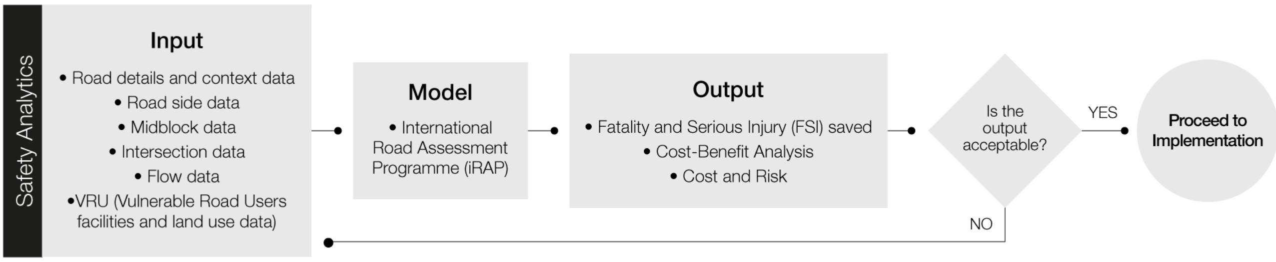


Figure 3.3: Simplified flow chart depicting the safety analytics process.

Safety Analysis Procedure

Using the attribute data and ViDA software, road agencies can objectively know the level of safety risk at the network level from every 100 m segment's star ratings. Based on baseline star rating information, the road agency can set the desired network level safety performance target for all road users.

After the target is set, countermeasures appropriate to improve the safety condition are selected for segments with low star ratings. Besides the star rating, the road attribute condition and vehicle (or road-user flow) are the prerequisite conditions (triggers) in countermeasures' selection in iRAP. For example, the delineation attribute should be coded 'poor' as a prerequisite to applying the 'improve delineation' countermeasure [36]. Moreover, road agencies need to consider the existing situation, such as budget, road users' behavior, the road environment, weather, availability of material and labor force, ease of implementation, and social setup, along with others, while selecting countermeasures. Then, the expected network level safety improvement upon implementing the selected countermeasures can be compared with the performance target.

The evaluation of the effect of countermeasures on safety improvement does not end with a comparison with the target value. Instead, the economic analysis of the proposed countermeasures needs to be carried out. The analysis compares the countermeasures' cost and benefits from FSI savings. Applying these procedures to different sets of countermeasures and comparing the cost and risk of each alternative can be done by the road agency to choose the best countermeasures. The diagram in Fig. 3.3 illustrates the safety analysis flow.

3.4 Empirical Analysis: Performance Goal Setting and Repair Strategy (Counter-Measures) Evaluation

The empirical analysis was done separately for pavement management and safety analysis first and then the best repair strategies were combined for creating annual maintenance and repair plans.

3.4.1 Pavement Management

The primary arterial, secondary arterial, and collector asphalt roads' pavement condition data in Addis Ababa, spanning over three consecutive years from 2018, were used for the empirical analysis. IRI was used in this study due to its objectivity, relatively low data-collection cost, and high correlation with road-user costs [37]. A road condition survey vehicle with a profilometer, camera, and global positioning system (GPS) receiver was used for data collection. The profilometer consisted of an accelerometer and a laser displacement sensor. Subsequently, a software application was employed to analyze the gathered data, produce a list of IRI values, and view images containing coordinates and inventory information. The system provided a class 2 (high accuracy) measurement at low speeds below 20 km/hr to account for the urban traffic environment [38]. The images from the system were also utilized to extract important road attribute data for safety analysis. A total of 9,418 data samples from a road network of 1000 km were used in the analysis. Data from road sections that underwent intervention activity during inspection intervals were excluded to ensure accurate deterioration modeling. The pavement condition states were ranked in five ranges based on the IRI value. According to the Addis Ababa City Roads Authority's road maintenance plan guideline, the pavement condition was classified into five ranks depending on the IRI value [39]. The ranking is presented in Table 3.3. The pavement deterioration MTP matrix calculated using the Markov hazard model is shown in Table 3.4.

Furthermore, as shown in Fig. 3.4, if no repair action is taken, the whole network will reach the worst condition (state 5) within 6.05 years on average, with the sum of the life expectancy of each condition state transitioning to the next state until it finally reaches the absorbing

Table 3.3: Pavement condition rating

Condition State	IRI (m/km)	Remark
1	IRI $\leq$ 2	Very Good
2	2 $\leq$ IRI $<$ 4	Good
3	4 $\leq$ IRI $<$ 6	Fair
4	6 $\leq$ IRI $<$ 8	Poor
5	8 $\leq$ IRI	Very Poor

Table 3.4: Pavement deterioration MTP matrix

Rating	1	2	3	4	5
1	0.309	0.386	0.181	0.077	0.048
2	-	0.350	0.300	0.183	0.168
3	-	-	0.229	0.282	0.488
4	-	-	-	0.158	0.842
5	-	-	-	-	1

state. This result agrees with previous studies which concluded that the road network of Addis Ababa showed a rapid deterioration trend [40, 41] . Alebachewu [40] argued that drainage and moisture-related problems were the main factors that contributed to the fast deterioration rates.

The network condition state vector that shows the distribution of each condition state at the most recent inspection year was determined as $S(t_0) = (0.13, 0.37, 0.24, 0.13, 0.13)$. Based on the current network conditions, the road agency should decide on the pavement performance target before proposing the repair strategies for evaluation. Accordingly, identifying the maximum network performance achievable with available repair technology and experience is the first task required before setting a target. Theoretically, the maximum network performance can be achieved using a repair action vector that restores all conditions into state 1, i.e., $\eta = (1, 1, 1, 1, 1)$. When Eq. 3.22 and Eq. 3.23 and the maximum repair action were applied, the road network condition state $S(t_r)$ became (0.31, 0.38, 0.18, 0.08, 0.05). The result shows that with the predicted pavement deterioration process, MTP, and applying the maximum repair action, the maximum possible network performance achievable was to bring 31%, 38%, 18%, 8%, and 5% of the road network to condition states 1, 2, 3, 4, and 5 respectively. Utilizing this information, the agency can set the target network performance.

For an empirical illustration, the set goal involved two targets, i.e., the lower target being

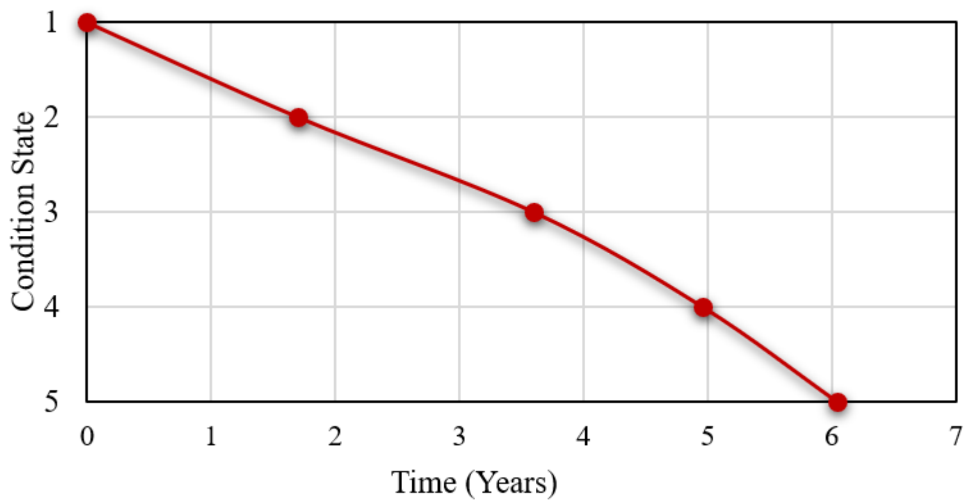


Figure 3.4: Life expectancy of condition states transition.

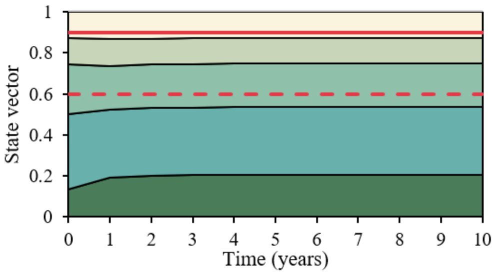
the minimum percentage of the network with at least the good condition state and the upper target being the allowable percentage of the road network with the worst condition. The first, lower target set was to keep at least 60% of the network IRI value below 4 (to keep at states 1 and 2) at any given inspection time t_r. The second target, the upper target, was to keep the network in poor condition (state 5) at or below 10% at any given inspection time t_r. Notably, the target should be set at most equal to the network performance achievable by the maximum repair action.

Four maintenance strategies with repair actions (1, 1, 2, 3, 1), (1, 2, 2, 3, 1), (1, 1, 2, 1, 1), (1, 1, 1, 1, 1), and no repair action cases were evaluated as an illustration for target-based maintenance/repair strategy evaluation. The repair strategies were developed by considering the repair types employed in Addis Ababa and the condition transitions resulting from each repair. The outcome of repair strategies was determined based on historical repair data and the maintenance guideline provided by Addis Ababa City Roads Authority [38], as depicted in Table 3.5. The effect of each strategy for ten years is depicted in Fig. 3.5(a)-(d), and in case of no repair, the performance of the network is as presented in Fig. 3.5(e).

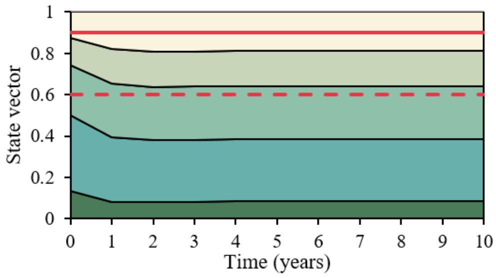
In addition to evaluating the repair strategies as to whether they have met the target, it was necessary to evaluate each strategy's cost implication and risk to make sound decisions. Therefore, the LCC per annum for each repair strategy was calculated following the average cost method. The results are shown in Fig. 3.6.

Table 3.5: Repair types and associated condition transitions

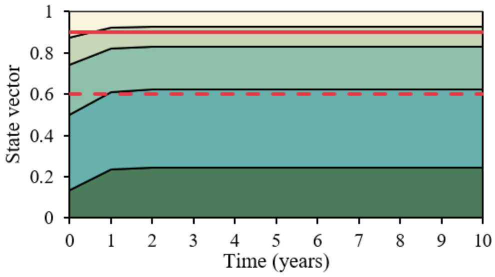
Repair Types	Repair action and condition transition
Preventive maintenance	$\eta(2) = 1$
Partial overlay and Patching	$\eta(3) = 2$
Mill and fill	$\eta(3) = 1$
Full overlay	$\eta(4) = 3$
Rehabilitation	$\eta(4) = 1$
Reconstruction	$\eta(5) = 1$



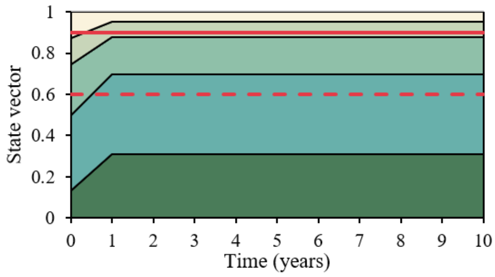
(a) Repair strategy 1.



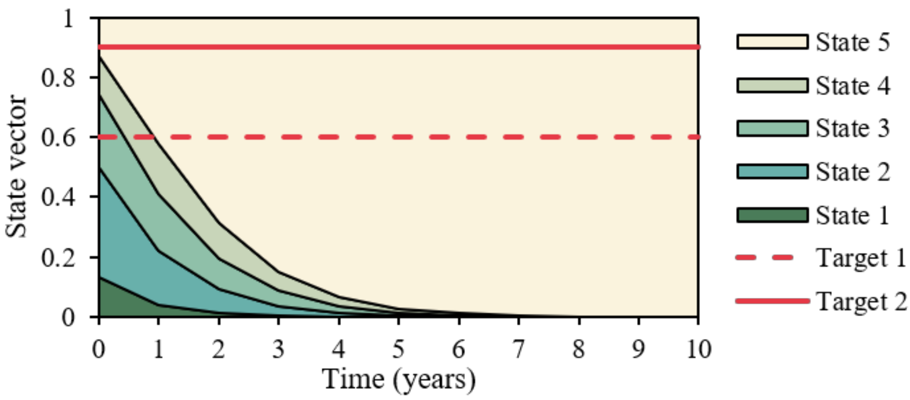
(b) Repair strategy 2.



(c) Repair strategy 3.

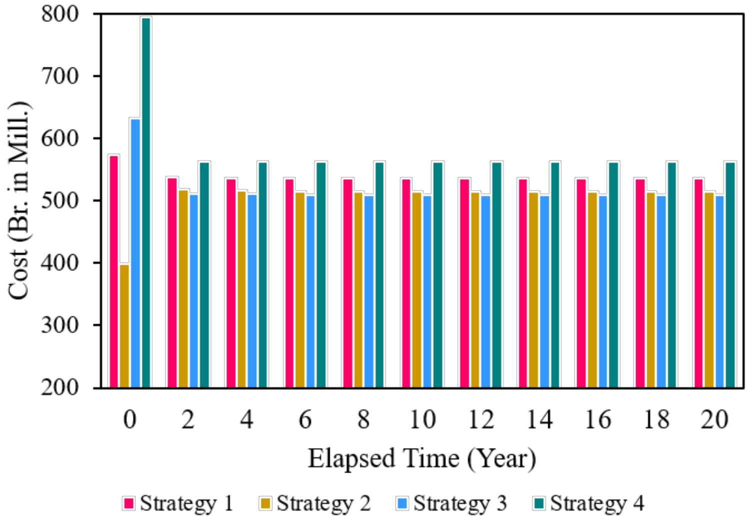


(d) Repair strategy 4.

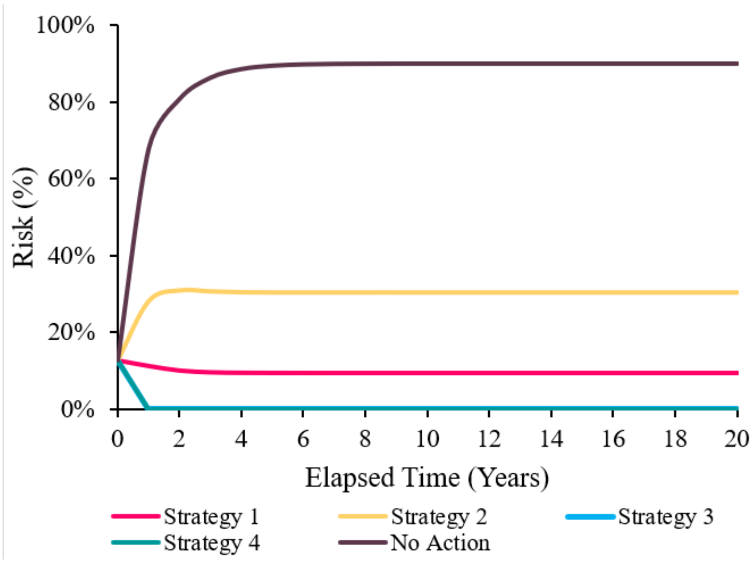


(e) No Repair.

Figure 3.5: (a)-(d) Performance of the road network with proposed repair strategies, e) no repair.



(a) Cost of Repair Strategies.



(b) Risk of Repair Strategies.

Figure 3.6: Cost and risk of pavement repair strategies.

Table 3.6: Baseline star rating

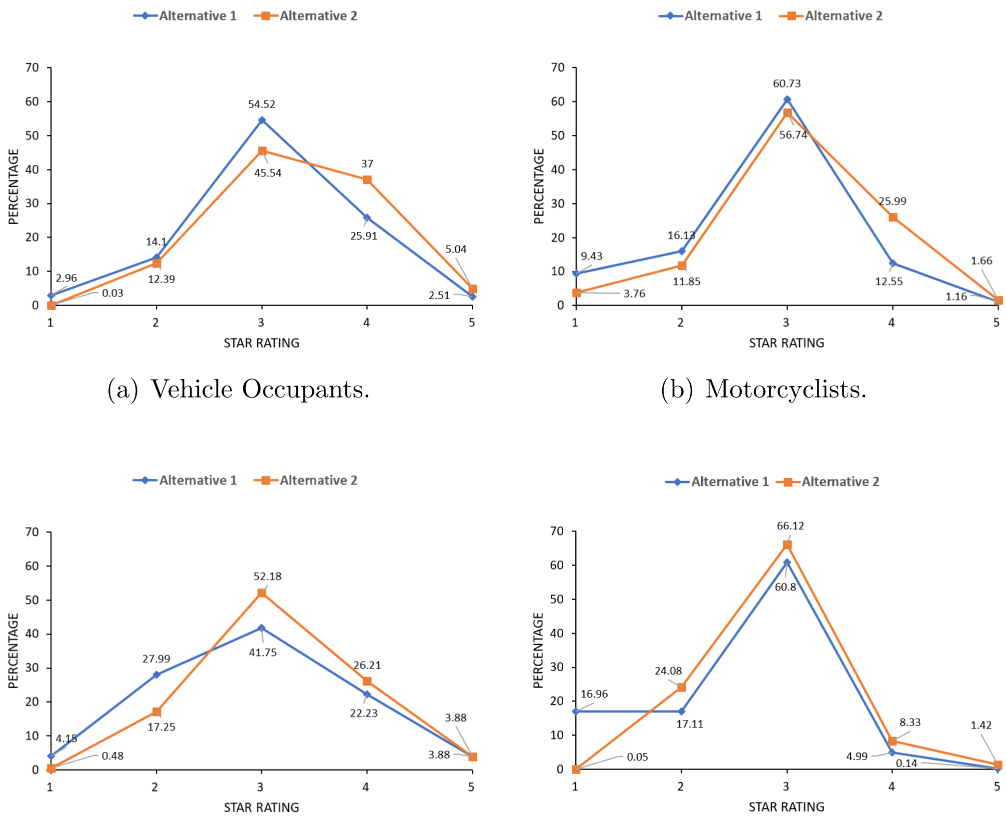
Rating	Road Network Safety Rating (%)			
	Vehicle occupant	Motorcyclist	Pedestrian	Bicyclist
1	7.14	16.45	24.89	24.91
2	19.12	23.46	36.78	26.06
3	52.47	50.25	29.54	47.00
4	19.48	8.89	8.35	1.93
5	1.79	0.95	0.44	0.10

3.4.2 Road Safety Analysis

The data used for safety analysis was extracted from ViDA (iRAP Ethiopia Addis Ababa Rev3 Project). In the road safety analysis, two alternatives (sets of countermeasures) were used for empirical illustration. The investment plan accessed from the iRAP database of the aforementioned project was used as the first alternative, whereas the second alternative was processed following the iRAP methodology by reducing the speed limit and operating speed through speed limit enforcement action. The analysis was done using ViDA version 3. In addition, the safety improvement due to pavement repair following the conventional approach was analyzed to compare it with the proposed safety-integrated approach results. The change in the safety condition of the road network due to pavement repair mainly resulted from improvement in road condition and skid resistance following the repair. Therefore, the road condition and skid resistance attributes were enhanced for road segments that would be repaired in line with the best pavement repair strategy selected, and the resulting improvement in the safety condition of the road network was assessed using ViDA.

The baseline star rating data for the road network of Addis Ababa city is presented in Table 3.6. The baseline data showed that 73.74%, 60.09%, 38.33%, and 49.03% of the road network achieved a rating of 3 stars or above for vehicle occupants, motorcyclists, pedestrians, and bicyclists, respectively. Accordingly, it can be said that the road infrastructure is relatively the safest for vehicle occupants and the riskiest for pedestrians.

Road agencies can set the safety performance target based on the baseline data. For this case study, 75% of the network achieving a rating of 3 stars or above for all road users was set as the target. This target is consistent with the UN road safety target 4. The expected star



(a) Vehicle Occupants.

(b) Motorcyclists.

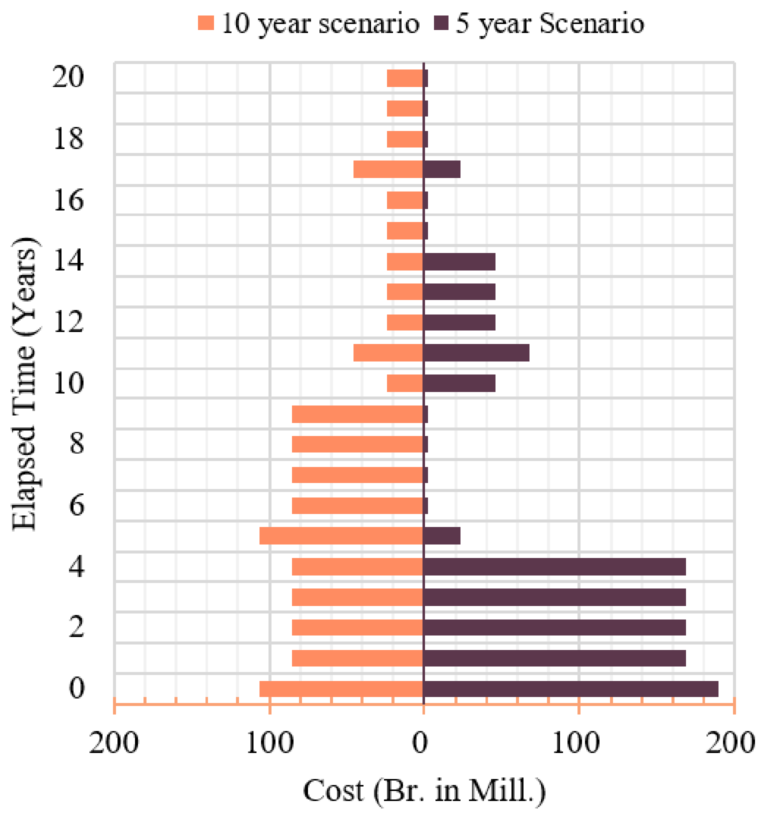
(c) Pedestrians.

(d) Cyclists.

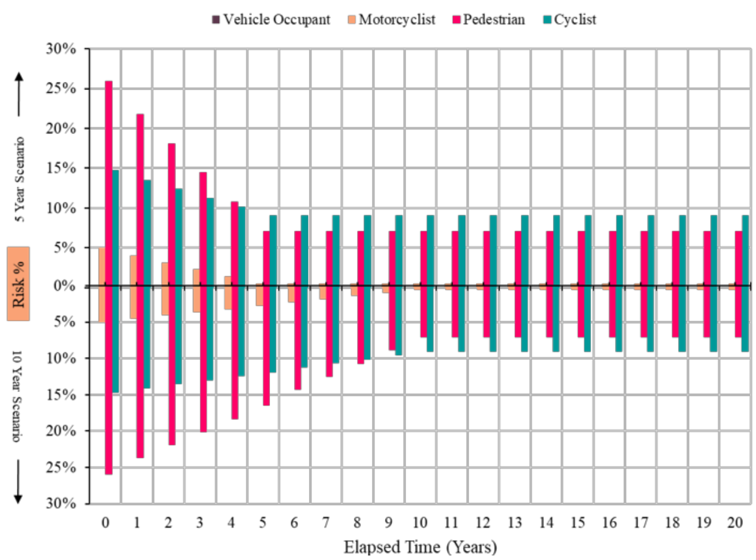
Figure 3.7: Network star rating results of road user groups for the two safety improvement alternatives.

rating of the road network upon implementing the first and second alternatives is presented in Fig. 3.7. Moreover, Fig. 3.8 presents the safety improvement strategies' cost and risk analysis results. The analysis was done by grouping the countermeasures based on their service life. The countermeasures selected in this safety analysis have a service life of 1, 5, 10, and 20 years. For instance, delineation has a service life of 5 years, meaning that the cost recurs every five years. However, the implementation plan to execute the network level delineation and other countermeasures in one year or an extended period depends on the agency's decision considering its resource and other factors. It also relies on the preset time frame to achieve the goal. Two scenarios were considered for this study. The first was to execute all proposed countermeasures within five years, and the second was within ten years. The countermeasures were assumed to perform effectively within their service life.

To generate the second alternative, segments that did not meet the target in the first



(a) 5-year safety implementation scenario.



(b) 10-year safety implementation scenario.

Figure 3.8: Cost and risk of the safety improvement strategy.

alternative were identified. Then, additional actions for the identified segments were proposed, and the entire road network was reevaluated. This trial-and-error procedure was carried out until the network achieved the set goals. Road agencies can use the same procedure to propose alternative intervention strategies and compare their relative costs and risks to their goals. FSI saved and cost-benefit analysis of each alternative can be obtained from the investment plan output. Finally, the annual budget plan can be extracted from the cost analysis based on the implementation plan (proposed execution period). These outputs can help the road agencies decide whether to implement the alternative that meets the set goals or the need to adjust the performance target.

3.5 Discussion

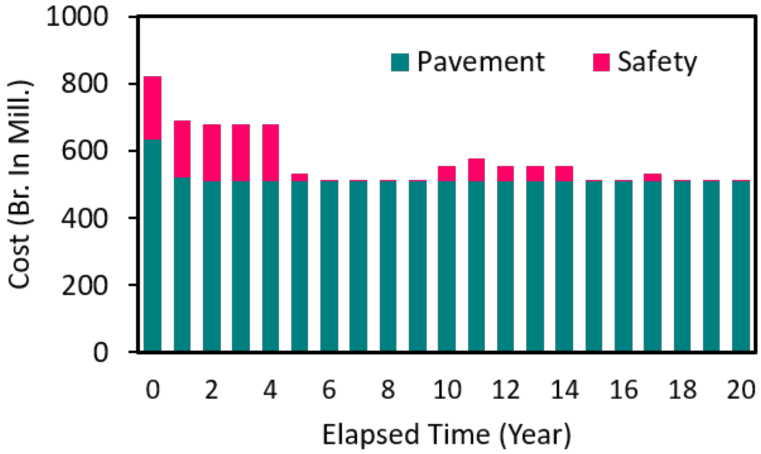
The network level pavement condition states achieved by implementing repair strategies 3 and 4 were (0.24, 0.38, 0.21, 0.10, 0.07) and (0.31, 0.38, 0.18, 0.08, 0.05), respectively. The percentage of pavements at least in the good condition state after implementation of repair strategies 3 and 4 were estimated to be 62% and 69%, respectively. Similarly, the percentage of pavements in very poor condition for repair strategies 3 and 4 were 7% and 5%, respectively. The Fig. 3.5 shows that strategies 3 and 4 met the network performance targets set among the four repair strategies. Consequently, the risk, as presented in Fig. 3.6 was zero for strategies 3 and 4. On the other hand, implementing repair strategies 1 and 2 resulted in the pavement condition states of (0.20, 0.33, 0.21, 0.13, 0.13) and (0.08, 0.30, 0.26, 0.17, 0.19), respectively. The percentage of pavements in a good condition state or better by implementing strategies 1 and 2 were projected to increase to 53% and 38%. Consequently, strategies 1 and 2 had a 7% and 22% deviation, respectively, from target 1, which aimed to keep 60% of the network at least in good condition. Moreover, 13% and 19% of the total pavements in the network were predicted to deteriorate to a very poor condition state if strategies 1 and 2 were applied, respectively. The strategies 1 and 2 resulted in a 3% and 9% deviation, respectively, from target 2, which aimed to keep the maximum percentage of the network in the worst conditions at 10%. By summing up the percentage deviation from both targets, strategy 2 had the highest risk, with 31% of the road network not meeting the goal set by the two targets, followed by strategy 1, which was 10%

risky. The risk of no repair action was shown to start from 13% and continuously increased until it reached the predicted life expectancy (6.05 years), where the whole network deteriorated to the worst state (very poor condition state) with IRI $\geq$ 8. The risk in the no repair case reached 90% when the whole network was estimated to degenerate to the worst state. This result implies that the maximum risk level was 90% as the agency allowed up to 10% of the pavement degrade to the worst state while setting the upper target.

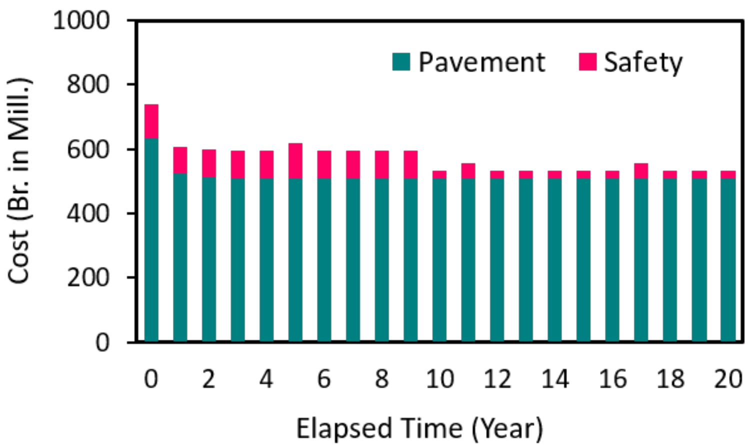
Though Strategies 3 and 4 achieved the target set by the agency, the results presented in Fig. 3.6 showed that strategy 4 was most costly than strategy 3. Therefore, according to this analysis, strategy 3 was the best alternative among the four proposed repair strategies.

The Fig. 3.7 presents the star rating percentage of the road network upon implementing the two safety improvement strategies (alternatives). The rating of 3 stars or above of vehicle occupants improved from 73.74% to 88.22%; likewise, enhancement from 60.09% to 71.05%, 38.33% to 73.40%, and 49.03% to 62.84% were attained for motorcyclists, pedestrians, and cyclists respectively if alternative 1 was implemented. However, 75% of the network achieving a 3-star rating or above was met only for vehicle occupants. Consequently, the percentage of the network that did not meet the target, the risk, for vehicle occupants, motorcyclists, pedestrians, and cyclists was 0%, 3.95%, 1.60%, and 12.16%, respectively. On the other hand, implementing alternative 2 resulted in 90.58%, 82.74%, 76.17%, and 78.91% of the network attaining a 3-star rating or above for vehicle occupants, motorcyclists, pedestrians, and cyclists, respectively. Hence, alternative 2 achieved the intended performance target for all road user groups. The cost–benefit analysis indices also supported the soundness of the investment plan. The estimated BCR was 2.85, implying that the benefit was more than twice the cost. Additionally, an FSI reduction of 13,940 was achieved over the analysis period of 20 years, considering alternative 2. The annual cost and risk distribution of alternative 1 applied over two implementation periods, 5 and 10 years, is presented in Fig. 3.8 as a typical cost-and-risk analysis with different implementation periods.

Therefore, strategy 3 of the pavement repair and alternative 2 of the safety improvement strategy fulfilled the road network performance requirements. Accordingly, the annual budget requirement was produced, as shown in Fig. 3.9 for 5- and 10-year safety implementation



(a) 5-year safety implementation scenario.



(b) 10-year safety implementation scenario.

Figure 3.9: Annual budget requirement.

scenarios. The maximum annual budget requirement was 822.8 and 739.64 million ETB (Birr, Ethiopian currency) for 5- and 10-year scenarios, respectively. These results show that the proposed method can enable road agencies to evaluate the alternatives for different scenarios and compare them against their budget allocation for robust decision-making.

If the conventional approach was followed, the network would have exhibited 89.3%, 74.77%, 75.36%, and 63.72% 3-star ratings or above for vehicle occupants, motorcyclists, pedestrians, and cyclists, respectively. Compared to the proposed safety-integrated approach, the conventional approach failed to fulfill the safety target for motorcyclists and bicyclists. The difference can further be explored by comparing the estimated FSI per annum of the two approaches. Consequently, an annual FSI of 55, 2, 102, and 24 for vehicle occupants, motorcyclists, pedestrians, and cyclists, which equals 183 FSI per annum, may be achieved by implementing a safety-integrated approach. On the other hand, an annual FSI of 74, 3, 122 and 60 for vehicle occupants, motorcyclists, pedestrians, and cyclists, which totals 259 FSI, was estimated in the conventional approach implementation. The results showed that the annual FSI estimate increased by 41.5% if the conventional approach was implemented instead of the safety-integrated one. The FSI difference for bicyclists was the highest, which more than doubled. Implementing the proposed safety-integrated approach prevented 60% of bicyclists' annual FSI that would happen in the conventional case. The difference in FSI between the two approaches can be multiplied by the analysis period to assess the significance of integrating safety in a given period.

Additionally, it is essential to note that the safety analysis for the conventional approach was carried out on the assumption that the skid resistance and road conditions of road segments would attain an adequate (the best) condition state through the pavement repair process. However, as the skid resistance and road condition attributes have three condition states, viz. adequate, medium, and poor in iRAP assessment, there was a possibility of a given segment failing to achieve the best condition after repair, which is divergent from the assumption. Thus, if road segments failed to attain the assumed adequate condition, the FSI estimate of the conventional approach had a higher probability of being more than what was used in the comparison.

The Fig. 3.10 shows the star rating map for the two approaches. A significant difference in safety conditions can easily be observed in parts of the outer ring road, (A) in the figure, in implementing the two approaches. This route is 32.1 km long, with 30.9 km of star 1 and the remaining 1.2 km of star 2 sections. The poor safety condition was mainly related to the driving speed. For example, 11.6 km of the road section had a speed limit of 40 km/hr; however, the mean operating speeds were 50 km/hr and 90 km/hr in 2.1 km and 9.5 km of this section, respectively. Similarly, 20.5 km of this route had a speed limit of 50 km/hr, whereas the mean operating speed was found to be 90 km/hr. Though the operating speed exceeded the limit in the whole section of the road, the worst violation was observed in 93.5% (30 km) of the route, where the mean operating speed was 90 km/hr.

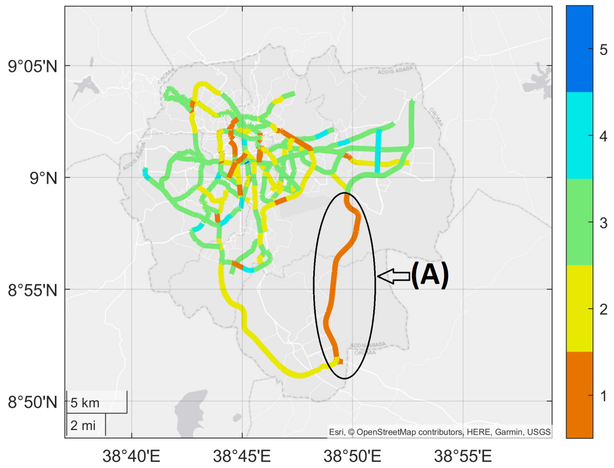
In addition to the speeding problem, poor facilities for vulnerable road users and poor quality of curves probably worsened the safety risk to road users. For instance, there was no physical separation to the sidewalk, such as pedestrian fencing, and no separate facility for bicyclists or motorcyclists, which exposed these vulnerable road users to speeding traffic, increasing their safety risk. The curved road sections need to have guiding signs and markings, to help drivers to judge the correct curvature and sight distance in advance and as they turn. The absence of signs and markings, such as chevron markers around the curved segments in the whole route, made the curve quality poor and increased the likelihood of a crash. The pictures in Fig. 3.11 show the current situation of the route.

Considering the situation, safety countermeasures, mainly traffic calming measures, were proposed in the safety-integrated approach. As a result, 30.9 km of this route with the worst star rating (1-star) was proposed for improvement to 3-star (14 km) and 4-star (16.9 km), which would fulfill the safe road standard, upon implementing the safety integrated approach. However, the safety risk remained unchanged if the conventional approach was applied as this approach does not address the speeding problem, the main problem in this road section.

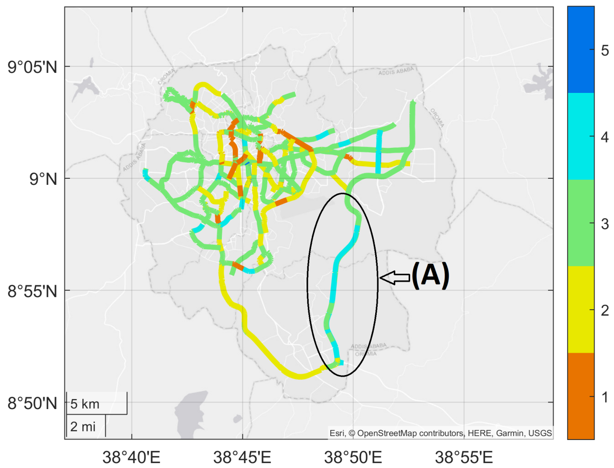
While the framework's effectiveness has been assessed using the case of Addis Ababa, it can be customized and implemented in any country. Its adaptability is particularly suitable for developing nations facing similar road safety challenges, limited data availability, and scarce resources. In addition, the framework's flexibility allows for adjustments to suit specific circumstances, including policy formulation and target setting, making it applicable in a wide range of contexts.

3.6 Conclusions

This chapter proposed an improved PMS approach by combining a Markov process–based pavement management practice and iRAP protocol–based road safety analysis. The models included in the approach involve stochastic deterioration prediction and deterministic repair and safety analysis methods. The aim was to address the safety concern seamlessly by incorporating it into the PMS. The approach enhances the conventional single-objective road maintenance planning practice exercised, especially in developing countries, by integrating road safety. The proposed pavement and safety analytics models are highly customizable for setting network-



(a) Conventional approach.



(b) Safety-integrated approach.

Figure 3.10: Road safety star rating map of Addis Ababa city.

(a) No physical separation from the sidewalk.

(b) Absence of guiding signs at curves.

Figure 3.11: Pictures of the outer ring road route.

level goals and analyzing alternative maintenance strategies based on the agency's situation. Moreover, they are suitable for agencies with scarce pavement and crash data. As illustrated in the case study, the approach allows road agencies to make dual maintenance policies and evaluate the consequences of maintenance strategies at the network level to make a proactive safety-conscious decision considering the cost and risk of strategies. The LCC evaluation can also be customized according to the available cost data and the agency's interest. Moreover, the case study results showed that the proposed safety-integrated approach enhanced the safety of road users by significantly reducing FSI compared to the conventional approach. The economic evaluation clearly showed the profitability of integrating safety in the conventional approach. Therefore, the proposed PMS approach can benefit nations, particularly developing countries, by addressing the financial and social burden of pavement deterioration and traffic crashes by enabling road agencies to make informed, optimized decisions to ensure safe roads.

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Chapter 4

Safety Oriented Road Maintenance Prioritization

4.1 Introduction

Though traffic fatalities are a global issue, the number of traffic fatalities in low- and middle-income countries is three times greater than in high-income countries (HICs) [1]. Traffic crashes cost low-income countries (LICs) up to 7.1% of their gross domestic product, which is above the global average value of 3% [2]. Additionally, traffic crashes are an underlying cause of poverty at the household and microeconomic levels [3]. As a result, road safety is explicitly contained in the Sustainable Development Goal (SDG) 3: Good Health and Well-being. By 2030, the global target is to reduce the number of fatalities and serious injuries by half [4]. Despite this target and road safety improvement in HIC, road trauma continues to increase in LICs and MICs [1]. Consequently, a comprehensive effort to reduce traffic fatalities and injuries is essential, particularly in LICs and MICs, which carry a disproportionate share of the burden of road safety crises.

To meet the global target associated with SDG3, the United Nations (UN) has called on governments and stakeholders to implement the safe system approach. The safe system approach recognizes road users are prone to making mistakes. Thus, preventing traffic-related fatalities and serious injuries requires making the transportation system to be traffic crash protective and forgiving if a crash does occur. Recognizing these needs, the safe system approach includes four main pillars: safe roads at safe speeds, safe vehicles, safe road users, and post-crash response [4]. Meeting each pillar of the safe system approach increases the likelihood of reducing the number and severity of crashes.

Road infrastructure is the leading cause of fatal crashes [5, 6]. Recognition of this is incorporated within the safe system approach via the safe roads at safe speed pillar. Nonetheless, in the LMIC, road safety practices and research are largely focused on traffic law enforcement, with less emphasis on infrastructure safety [7]. Furthermore, due to resource and data constraints, the available tools and approaches used to maximize road infrastructure safety in HIC are often not generalizable to LICs and MICs [8]. Thus, one of the challenges in making roads safer in LICs and MICs is the lack of applicable road maintenance planning tools and methods focused on increasing the safety of roads within the constraints experienced in these countries.

Road maintenance planning involves three hierarchical decision processes, including strategic, network, and project levels. Each of these levels requires road network condition analysis to make informed road maintenance-related decisions. The purpose of the network condition analysis is to effectively utilize available funds by prioritizing potential maintenance projects, hereafter referred to as a priority analysis [9]. Priority analysis can be broadly categorized into two groups: optimization methods and ranking [10]. In optimization methods, road maintenance and improvement projects are selected to meet a specific objective function (e.g., improving road network conditions) under specific constraints (e.g., funds available for road repair). Output from optimization models guides road maintenance and improvement decisions by providing a suite of alternatives that should be implemented but do not provide an indication of what order the alternatives should be completed in. Ranking methods rank the alternatives based on economic analysis or a composite index. The composite index-based ranking shows the most promise for priority analysis because it is simple and produces optimal results [10].

Prioritization of potential road maintenance projects using composite index-based ranking requires establishing different criteria (e.g., pavement condition, traffic volume) for comparison, thus constituting a multicriteria analysis (MA). Consequently, MA has been widely used as a decision support tool in road maintenance decision-making because it incorporates multiple criteria, making it more applicable to real-world decision-making [10, 11, 12, 13, 14, 15, 16]. Nevertheless, two gaps related to MAs must be addressed to increase the applicability and usefulness of model output to on-the-ground decision-making.

The first gap is that little attention is paid to evaluating uncertainties resulting from methodological choices incorporated at different stages of MA. Specifically, following the selection of criteria, composite index-based MA entails three steps: normalization, weighting, and aggregation. Normalization converts different criterion-measuring units to the same scale, weighting denotes the relative importance of criteria, and aggregation yields the composite index (score) of alternatives. Researchers using MA choose a single method from a suite of methods (e.g. equal weight versus the analytic hierarchy process [AHP] weighting methods) available at each step of the MA process. However, this single-method approach ignores that MA results vary when different methods are used [17].

The second gap that must be addressed in using MA for road maintenance decisions is that the criteria used either do not account for safety or use uncomprehensive criteria that cannot address the safety of all road users. Overlooking the safety of all road users in road maintenance decisions is widespread in conventional decision frameworks, including MA, and this is particularly prevalent in LICs and MICs [7]. For instance, most studies have reported using skid resistance-related indicators on pavements to account for road safety in MA [10, 11, 12, 13, 14, 15]. Though skid resistance is one of the most important factors, several factors influence the likelihood, magnitude and severity of a crash. Thus, the safety criterion associated with MA should consider more than skid resistance. Other criteria that should be incorporated include roadside conditions, road characteristics and conditions (e.g., curvature, sight distance, grade, delineation, skid resistance, and pavement condition), intersection type and quality, vulnerable road users' facilities (e.g., pedestrian crossings, sidewalks, bicycle lanes), and speed (operating speed, and speed management schemes.). Tighe et al.[18] have extensively considered relationships between skid resistance as a measure of road safety and various road factors (e.g., surface texture, roughness, and environmental and weather conditions) in their study. However, all road characteristics considered were associated with the pavement and the study did not account factors important for vulnerable road users, particularly pedestrians and bicyclists: intersection type and quality, vulnerable road users' facilities, and speed. This is not unexpected, as conventional maintenance project prioritization approaches often emphasize pavement condition and traffic volume as important factors. However, these maintenance schemes are favourable to vehicle occupants over other road users because they emphasize pavement condition and traffic volume. Moreover, road agencies consider the safety of non-vehicle occupants, such as pedestrians, to be beyond their responsibility. This raises the issue of equity among road users when other criteria more specific to non-vehicle occupants are not accounted for within road maintenance decision frameworks [19].

Clearly, there is a need to incorporate more safety-related criteria in MA to ensure road maintenance priorities are set such that they maximize human safety while also minimizing economic costs. Thus, this chapter presents a simple and practical analytical tool that 1) is suitable for use under resource and data availability constraints, 2) addresses all road users' safety needs, and 3) accounts for methodological uncertainty.

To address methodological uncertainty, sensitivity analysis and uncertainty treatment schemes are incorporated into MA. Moreover, the proposed framework considers the safety state of the road sections for each road user group (vehicle occupant, motorcyclist, bicyclist, and pedestrians) in the criteria set and thus prioritizes road sections for maintenance based on providing safe roads for all. The safety condition is assessed using the International Road Assessment Program (iRAP) protocol, which considers multiple safety factors that can influence each road user group. As a result, this study proposes a safety-oriented, robust decision-making support framework for road maintenance prioritization that can support road agencies, particularly in LICs and MICs, in making data-driven safety-conscious decisions to ensure safe roads. Therefore, the proposed framework is superior to the conventional one in terms of assigning the highest maintenance priority to unsafe road sections supplemented by its practicability.

4.2 Methodology

4.2.1 Multicriteria Analysis

The proposed framework largely incorporates MA, which is a flexible and practical modeling approach. MA is applicable in the decision-making of complex problems, such as road maintenance decisions, since it allows one to account for multiple criteria flexibly and to make structured and reliable decisions [20]. A MA typically involves the following stages: criteria setting, normalization, weighting, and aggregation. The aggregated criteria score can be used to prioritize maintenance projects such as road sections. The aggregated score, on the other hand, varies with the methods used at each stage of the MA process, resulting in methodological uncertainty [17]. The proposed road maintenance prioritization analytical framework handles this uncertainty via the addition of uncertainty and sensitivity analysis. These analyses were then followed by uncertainty management and a stochastic ranking scheme (**Figure 4.1**).

Criteria setting

The MA starts with establishing criteria against which the alternatives are compared for prioritization (**Figure 4.1**). The decision-maker's objective determines the selection of criteria and performance indicators. As a result, criteria are used to assess how well each alternative performs in achieving the decision-maker's objective [15]. To demonstrate the use of the proposed framework, three criteria were chosen for this study: pavement condition, traffic volume, and road safety. The conventional approach includes only pavement condition and traffic volume as factors. It is worth noting that the criteria used within the MA can be adjusted to suit the needs of the decision-maker while the framework procedure remains the same.

Pavement condition

The main goal of road maintenance is to keep the roads in good condition so that the mobility and comfort of road users can be realised. Consequently, pavement condition is one of the main criteria in prioritization frameworks because it influences mobility and comfort. There

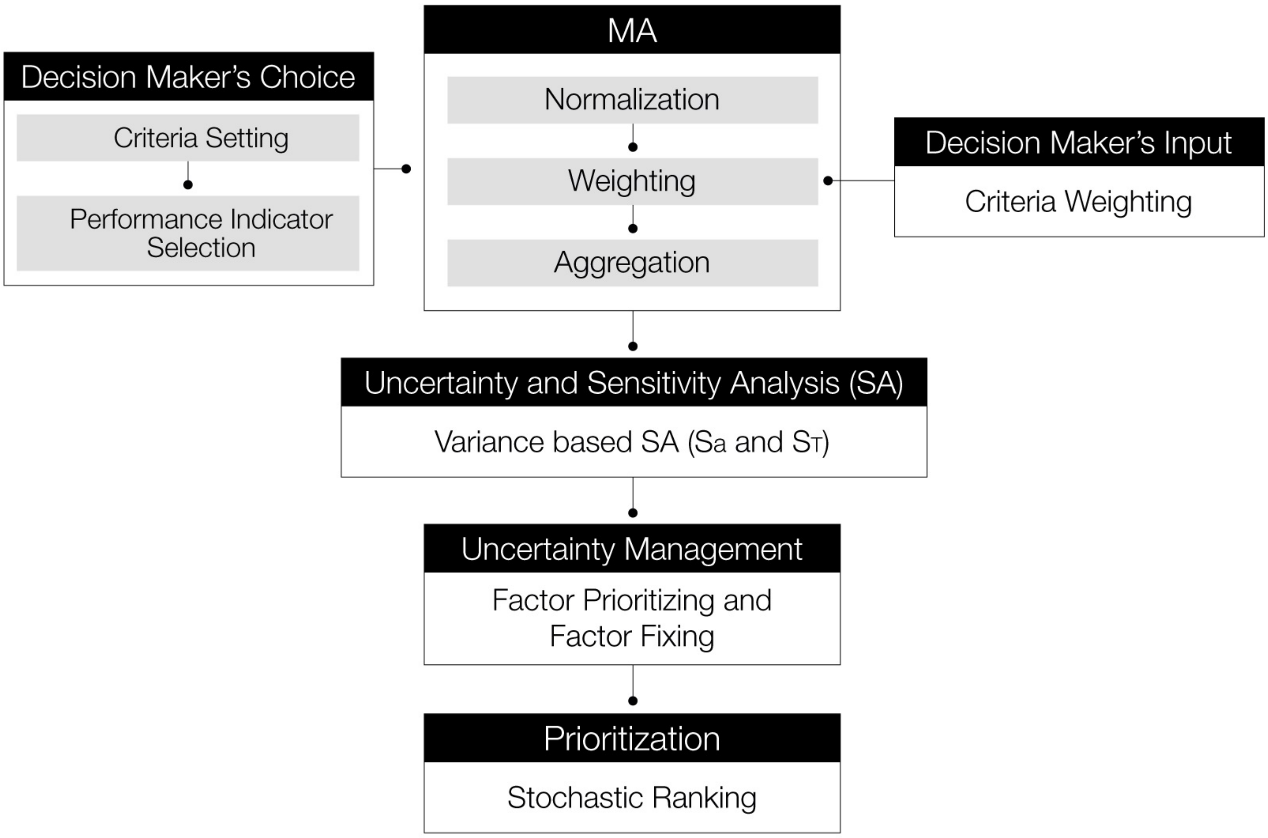


Figure 4.1: The proposed framework that accounts methodological uncertainty.

are several indicators that can be used to measure pavement performance. The International Roughness Index (IRI) is selected as a pavement performance indicator to objectively measure this criterion. IRI is selected due to its capability to indirectly measure user cost in addition to its primary measure of riding comfort, which is determined by measuring pavement surface smoothness [21]. Furthermore, its comparatively low cost of data collection makes it preferable [22].

Devices used to measure IRI are categorized into four classes based on their accuracy. Classes 1 and 2 are the most accurate and often employ a laser to measure the profile of road sections [23]. A class 2 pavement condition survey vehicle was used to collect the data used in the case study. Since the data were collected from Addis Ababa city, the capital of Ethiopia, it was critical to ensure measurement accuracy in the urban road environment. Though peak traffic hours were avoided during data collection to maximize efficiency, the survey vehicle was forced to stop-go and slow-speed drive due to traffic lights and traffic crowds in the city. Consequently, the condition survey vehicle was equipped with a measuring system that records profile data every 10cm at low speeds (less than 20km/hr) and high speeds. These high frequency measurements increase the accuracy of class 2 IRI measurements at varying travel speeds [24].

Traffic volume

Traffic volume is the other criterion commonly used in maintenance prioritization [10, 11, 13, 16, 25]. The importance of road sections is determined by traffic volume, which is dependent on the number of users. Like the conventional approach, annual average daily traffic (AADT) levels were used as an indicator of traffic volume in the MA.

Safety

The conventional road maintenance prioritization approach, mainly in LICs and MICs, does not include road safety measures [7]. However, road safety should be considered in all stages of the road management process since it has become a critical issue globally due to the effect of traffic crashes. As a result, much research has been conducted to incorporate road safety into the road management process, particularly in the pavement management system. Researchers have reported the use of four primary parameters to incorporate safety, including cost parameters (e.g., crash cost), crash parameters (e.g., crash rate, crash frequency), skid resistance parameters (e.g., skid number and, skid resistance), and pavement performance parameters (e.g., IRI, and, pavement performance-based risk) [26]. However, these parameters are either based on crash data or pavement conditions. One of the limitations of the methods based on crash data is they can only offer reactive measures because the analysis requires crash history. Another challenge in implementing such methods is the lack of detailed crash data, particularly in LICs and MICs [27]. Similarly, pavement condition-based safety analysis methods are questionable since they fail to consider road components important for some road user groups, such as sidewalks.

The International Roads Assessment Program (iRAP) star rating protocol is used in the proposed prioritization framework for multiple reasons. First, the rating does not require crash data and thus allows one to be proactive when prioritizing road maintenance activities. Moreover, the star rating enhances proactive decisions by providing objective measures of the safety level of a certain road section for all road user groups. Because each road user group is assigned a star rating, the safety level of a given road section and road component maintenance decision differs accordingly, promoting equity by incorporating road users' safety concerns into the process. Consequently, iRAP analysis considers 78 factors that affect road safety. The factors are categorized into seven groups: road details and context data, road-side data, midblock data, intersection data, flow data, VRU (Vulnerable Road Users' facilities and land use data), and speed data [27]. Finally, the iRAP star rating tool has become a standard measure of road safety in at least 114 countries [1]. Usage of the iRAP star rating protocol is likely to continue increasing as the United Nations' road performance target 3 calls for all new roads to have a star rating of three or better while target 4 calls for 75% of existing roads to have a rating of three or above [1]. The global level usage of the iRAP star rating as a standard is another reason to consider it as a performance measure of road safety in this study.

The star rating of a road section is produced independently for each of the four road user groups based on a Star Rating Scores (SRS) value. The SRS objectively measures a road user's relative risk of death or serious injury and is calculated by summing up the scores of each crash type $q(q = 1, ..., Q)$. For example, the SRS calculation for vehicle occupants considers head-on, run-off, intersection, and property access crash scores. In the case of a motorcyclist, a riding along- the road crash type score is also considered in addition to the four mentioned in the case of a vehicle occupant. The pedestrian SRS is calculated by adding the walking along and crossing crash scores. Similarly, SRS for bicyclists is calculated using run-off, riding along the road, and intersection crash-type scores. SRS is calculated using equations (4.1) and (4.2) [27, 28].

$$SRS = \sum_{q=1}^{Q} Crash\ type\ Scores \tag{4.1}$$

$$\begin{aligned} Crash\ Type\ Scores = {} & Likelihood \times Severity \\ & \times Operating\ speed \\ & \times External\ flow\ influence \\ & \times Median\ transversability \end{aligned} \tag{4.2}$$

The likelihood and severity measures used in calculating the crash type scores are based on road attribute risk factors for specific crash types. The likelihood and severity account for the chance of a crash occurring and the severity of the crash, respectively. The road and roadside features that influence the likelihood and severity of crashes are referred to as attribute risk factors. For example, the eight attribute risk factors that affect the likelihood of a runoff crash for a vehicle occupant and motorcyclist include lane width, curvature, curve quality, delineation, shoulder rumble strips, road condition, grade, and skid resistance. At the same time, the type of roadside object, distance from the roadside object, and width of the paved shoulder all influence the severity of runoff crashes. For example, if one considers the grade of a road, the likelihood of a runoff crash at a steep grade is greater than at a gentle grade. Hence, to compute the effect, grades are grouped into three; gentle ($< 7.5\%$), medium (7.5% to 10%), and steep ($\geq 10\%$). When the grade is gentle, a Crash Modification Factor (CMF) of 1 is used; similarly, for medium and steep grades, CMF values of 1.2 and 1.7 are used, respectively. The CMF correlates road attribute conditions with crash likelihood and severity. For instance; a motorcyclist traveling

Table 4.1: Star rating bands

Star Rating	Vehicle occupants and motorcyclists	Bicyclists	Pedestrians		
			Total	Along	Crossing
5	0 to 2.5	0 to 5	0 to 5	0 to 0.2	0 to 4.8
4	2.5 to 5	5 to 10	5 to 15	0.2 to 1	4.8 to 14
3	5 to 12.5	10 to 30	15 to 40	1 to 7.5	14 to 32.5
2	12.5 to 22.5	30 to 60	40 to 90	7.5 to 15	32.5 to 75
1	22.5+	60+	90+	15+	75+

on the road with a grade of 10% is 1.7 times more likely to encounter a runoff crash than one riding on a grade of less than 7.5%, assuming all other factors are the same. Paved shoulder width is an attribute risk factor that has a negative correlation with severity. The CMF value of 0.95 is used for paved shoulders with widths up to 1 m, 0.83 for those more than 1 m but less than 2.4 m, and 0.77 for widths more than 2.4 m. If the road does not have a paved shoulder, the CMF value is 1. Factors that account for the effect of speed and external flow are also used and multiplied by likelihood and severity scores to obtain crash-type scores, as shown in equation (4.2). Median transversability is only considered in runoff and head-on crashes involving motorcyclists and vehicle occupants. Following the determination of SRS, the star bands in **Table 3.1** are used to determine the star rating. The greater the star rating, the safer the road. The entire computational process is completed using free online ViDA software [27, 28, 29].

Normalization

Following setting criteria and determining the performance measurement scale for each, the next step in the MA process is normalization. Normalization is used to transform criteria values with different measurement units into a standard dimensionless scale. Various normalization methods have been developed, and a decision may change depending on which methods are used [30]. Thus, choosing a normalization method is one source of methodological uncertainty in MA. The normalization methods used in this study are listed in **Table 4.2**.

The normalization value of the alternative (road section) i for criterion j, n_{ij} , is calculated based on the performance indicators' value, x_{ij}, using the formulas in **Table 3.2**. Criteria

Table 4.2: Normalization methods

Normalization Method	Criteria Type	Formula
Linear Scale Transformation: Max [31]	Positive	$n_{ij} = \frac{x_{ij}}{{x_j}^{max}}$
	Negative	$n_{ij} = 1 - \frac{x_{ij}}{{x_j}^{max}}$
Linear Scale Transformation: Max-Min [31]	Positive	$n_{ij} = \frac{x_{ij}-{x_j}^{min}}{{x_j}^{max}-{x_j}^{min}}$
	Negative	$n_{ij} = \frac{{x_j}^{max}-x_{ij}}{{x_j}^{max}-{x_j}^{min}}$
Vector Normalization [31]	Positive	$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$
	Negative	$n_{ij} = 1 - \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$
Standardization: z and t-score	Positive	$Z_{ij} = \frac{x_{ij}-{x_j}^{avg}}{SD_j}, n_{ij} = t_{ij} = (z \times 10) + 50$
[32]	Negative	$Z_{ij} = \frac{x_{ij}-{x_j}^{avg}}{SD_j}, n_{ij} = 1 - t_{ij}$

are grouped into two based on how their performance indicators relate to the objective of the prioritization. A criterion with a performance indicator that increases maintenance priority as its value increases is considered positive, whereas a criterion is considered negative if its increase results in a decrease in priority. A high IRI value, for example, indicates poor pavement condition. This suggests that the greater the IRI value, the greater the need for maintenance. This ultimately increases the priority of the road section, thus, making pavement condition a positive criterion. Similarly, road sections with greater AADT are prioritized for maintenance over lower ones, making traffic volume a positive criterion. Conversely, safety is a negative criterion because road sections with high star ratings are relatively safer than those with lower star ratings, making sections with lower stars a priority for maintenance over those with higher stars. Based on these rationales, the formula in **Table 3.2** is selected for each criterion.

Weighting

Weights are assigned to criteria to reflect their relative importance. Weighting is another stage of the MA process where methodological uncertainty arises due to the availability of different weighting methods [32]. The decision maker can assign weights in consultation with stakeholders based on the policy objective and existing condition. In the case study, the equal weight and Analytical Hierarchy Process (AHP) methods were used. Equal weights are often preferred because they are simple, replicable, and straightforward, whereas AHP is widely used for its simplicity and flexibility [33]. Equal weights are used when the criteria are of the same importance or in case of insufficient knowledge to assign different weights to the criteria [34].

The AHP uses a pairwise comparison of relative importance between the criteria. To determine the degree to which one criterion is more important than another, the expert comparison uses a semantic scale ranging from 1 to 9, where 1 refers to equal importance and 9 to extreme importance. Because the criterion is compared to itself, the result is a square matrix with a diagonal value of 1. The upper and lower triangular matrices are reciprocal to each other (for example, $C_{1J} = 1/C_{J1}$) and are used to calculate the weights using equation (4.3) for J number of criteria. The consistency index, CI, is then calculated using the principal eigenvalue of the matrix, λ_{max}, and the number of criteria, J, as shown in equation (4.4). Finally, for a given number of criteria, the consistency during pairwise comparisons is measured by the Consistency Ratio (CR) calculated by dividing the consistency index by the random index (RI), following equation (4.5). The random index is derived from a randomly generated square matrix and can be obtained from a standard table based on the matrix size. If the value of the consistency ratio is less than 0.1, the pairwise comparison is considered reasonably consistent, and the weight will be accepted. Computational procedures of AHP were performed following Saaty's principles[35].

$$Comparison\ matrix = \begin{bmatrix} 1 & \dots & C_{1J} \\ \vdots & \ddots & \vdots \\ C_{J1} & \dots & 1 \end{bmatrix} \tag{4.3}$$

$$CI = \frac{\lambda_{max} - J}{J - 1} \tag{4.4}$$

$$CR = \frac{CI}{RI} \tag{4.5}$$

Aggregation

After adjusting the values for the criterion to the same scale during normalization and assigning weights to each, the results are aggregated to determine the score (**Figure 4.1**). Aggregation is another stage where methodological uncertainty in MA emerges due to the various aggregation techniques available. In this study, additive and geometric aggregation methods are used. The widely used additive technique sums up the weighted normalized performance indicator values of the criterion to determine the score, M, for each alternative (road section), i, as shown in equation (4.6), where J is the total number of criteria and W is the criteria weight [34]. It is well-regarded for its simplicity and transparency, as well as its ease of sensitivity and uncertainty quantification. However, preferential independence among the criteria is required, which necessitates there being no conflict or synergy among the criteria [33]. Conversely, the geometric technique applies a product rather than an addition function, which is presented in equation (4.7). Therefore, geometric aggregation is not as fully compensatory as additive aggregation. Unlike additive aggregation, it limits the ability of high-performance criteria to compensate for low-performance criteria [33].

$$M = \sum_{j=1}^{J} W_j n_{ij} \tag{4.6}$$

$$M = \prod_{j=1}^{J} {n_{ij}}^{W_j} \tag{4.7}$$

4.2.2 Uncertainty and Sensitivity Analysis

Methodological uncertainty in MA is unavoidable due to the multiplicity of techniques used in each stage, as discussed in the preceding sections. The subjective choice of techniques results in variation in the output of the MA and the associated decisions. Current conventional, analytical approaches to road maintenance prioritization do not account for this uncertainty. However, this problem was dealt with within the proposed framework by using uncertainty analysis to quantify output uncertainty and sensitivity analysis (SA) to allocate the uncertainty to the sources of uncertainty, which are referred to as factors, X [36]. Uncertainty can be measured statistically based on the variances and distribution functions of the output [36]. In this study, the set of scores, M, is calculated for each road section using different methodological combinations, and variance and probability density functions (PDF) are used to describe the uncertainty associated with the score obtained for each section. Variance-based SA was used to determine the contribution of each technique employed at each stage of MA (normalization, weighting, and aggregation) to the total model uncertainty.

Variance-based SA is a preferred method due to its model independency and other properties, including ease of interpretation and its ability to distinguish between the main effect (first order) and interaction effects (higher-order) [32]. The total variance (V) of the score, M, is the sum of all first-order and higher-order terms [37]. The first-order term, V_a, determines the contribution of individual factor X_a to the total variance, whereas the remaining terms (second-and higher-order) in equation (4.8) account for variation owing to interactions between factors. For example, V_{ab} accounts for the variance contribution due to the second-order interaction between factors X_a and X_b , whereas $V_{(12...k)}$ accounts for variance due to the kth-order interaction. Consequently, the decomposed variance is used to compute sensitivity indices. The first-order sensitivity index, S_a, is obtained by dividing the first-order term by the total variance, as shown in equation (4.9). Furthermore, the total effect (first order and higher orders) of the factor X_a can be captured by the total effect sensitivity index S_{Ta}, equation (4.10). In the absence of interaction among factors, the sum of first-order indices equals 1, otherwise less than 1. Similarly, the sum of the total effect index becomes 1 in the absence of interaction and greater than 1 if the factors interact [32].

$$V(M) = \sum_a V_a + \sum_a \sum_{b>a} V_{ab} + \cdots + V_{12...k} \tag{4.8}$$

$$S_a = \frac{V_a}{V(M)} = \frac{V(E(M \mid X_a))}{V(M)} \tag{4.9}$$

$$S_{Ta} = \frac{E(V(M \mid X_{-a}))}{V(M)} \tag{4.10}$$

4.2.3 Uncertainty Management

The first step in uncertainty management is to identify the most important factor or the one that contributes the most to output variance. The largest reduction in output variance is obtained by determining the true value of the most important factor. Factor prioritization is the process of ranking factors based on their importance using S_a values. Factor prioritization aims to identify the most important factor (i.e. with the highest S_a value) that deserves the maximum effort to reduce uncertainty. Factor fixing is the second process in uncertainty management. This refers to identifying non-influential factors that can be fixed at any value within their range of uncertainty without significantly affecting the output variance. Fixing non-influential factors aid in the reduction of model complexity [38]. Ideally, a factor should have an S_Ta value of zero to be considered non-influential. Factors with minimal main effect and interaction effect can also be considered non-influential. Although there is no established threshold used to determine the degree of influence each factor has on output uncertainty, factors with S_a and interacting factor $S_Ta - S_a$ values less than 0.1 are often considered non-influential [39, 40]. In this study, the same threshold was adopted to identify non-influential factors during the SA stage of the MA.

4.2.4 Stochastic Ranking

Despite their contribution to uncertainty management, factor prioritization and factor fixing procedures cannot eliminate uncertainty in decision-making as long as multiplicity in methodological choice is available. Using a deterministic value of the score M, such as the mean, can lead to a decision-making error by concealing the effect of methodological uncertainty [40]. Thus, the score under uncertainty is transformed into a random variable with a probabilistic distribution, necessitating the adoption of a stochastic approach to the prioritization process [41].

A stochastic approach allows for robust decision-making while informing the decision-maker of the associated risk, i.e., the probability of the decision being wrong [42]. Consequently, the methods used were comparable to those employed by Opon and Michael [40] for evaluating the sustainability of concrete mix, with some slight modifications. Specifically, their method has been enhanced in this study by incorporating a total stochastic score into the proposed MA.

The stochastic approach makes use of the probabilistic distribution function of the score (PDF). To handle unaccounted sources of uncertainty, a pairwise exceedance probability is calculated using the lower bound of a confidence interval associated with the mean score of each road section. The confidence interval is determined by bootstrapping the score M, and the lower bound is used as a reference for a conservative comparison [40]. For example, two road sections are compared, i and l, and the probability of exceedance of i from l can be computed as $P\_(i, l) = P(M_i \geq M\_(l \mid LB)$, which corresponds to the PDF area of road section i's score, M_i, above the lower bound of the score of section l, $M\_(l \mid LB)$. Similarly, the probability exceedance of road section l from i can be calculated as $P\_(l, i) = P(M\_l \geq M\_(i \mid LB)$. A pairwise comparison of all road sections, L in number, results in the L by L matrix of the probability of exceedance. The rank of a given road section i is determined based on the sum of the probabilities of exceedance of that section, G_i, as shown in equation (4.11). This probability sum, G_i , is referred to as a stochastic score to denote the underlying probabilistic process. It refers to the probability of the score of a road section above the referenced lower bounds of all road sections included in the prioritization at a given level of confidence. The higher the G_i, the higher the priority.

$$G_i = \frac{1}{L} \sum_{l=1}^{L} P\_(i, l) \tag{4.11}$$

Furthermore, Spearman's correlation coefficient, r_s, is used to measure the strength of the relationship between the prioritization ranks and the criterion. The values range from -1, perfect negative correlation, to 1, perfect positive correlation. Spearman correlation can be calculated without prior knowledge of the probability distribution that allows analysis of the correlation of ordinal measurements. Spearman coefficient correlation of given criteria to the rank, $R_{l,r}$, can be computed based on the rank of the performance indicator's value, $x_{l,r}$ using equation (4.12).

$$r_s = \frac{\sum_{l=1}^{L} x_{l,r} R_{l,r}}{\sqrt{\sum_{l=1}^{L} x_{l,r}^2 \sum_{l=1}^{L} R_{l,r}^2}} \tag{4.12}$$

4.2.5 Comparison of Methods

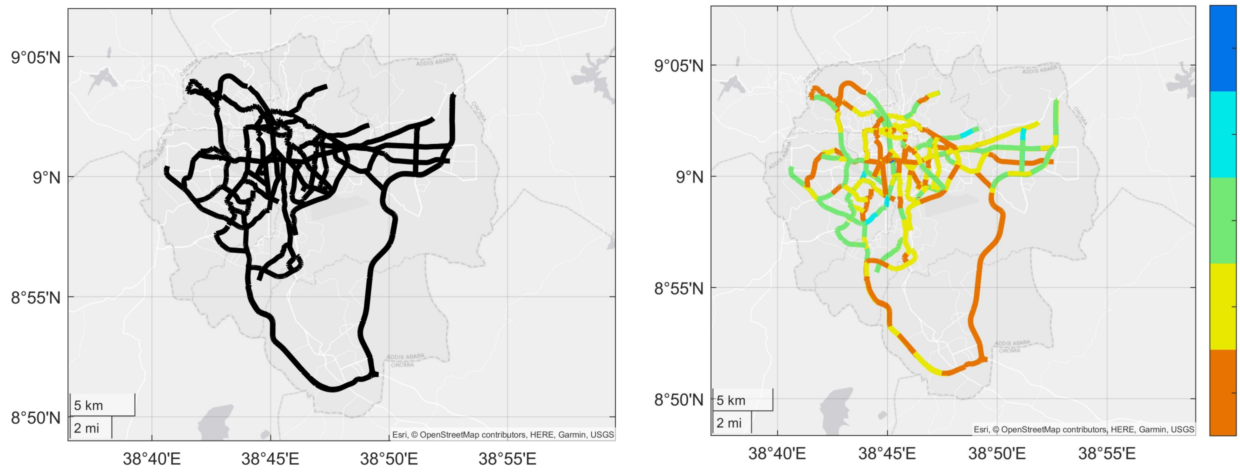
In addition to the rankings obtained from the proposed safety-oriented prioritization approach, road section prioritization rankings for the same road sections were obtained using a conventional approach. The conventional approach only considered pavement and traffic volume criteria, while the proposed safety-oriented prioritization framework also accounted for road safety. Additionally, unlike the proposed framework, the conventional approach did not incorporate uncertainty or sensitivity analyses. Using both model outputs, the average shift in ranking, $\tilde{R}_s$, was calculated between ranks using the safety-oriented approach, R_{so}, and the conventional rank, R_c, for a total of L road sections using equation (4.13).

$$\tilde{R}_s = \frac{1}{L} \sum_{l=1}^{L} R_{so} - R_c \tag{4.13}$$

4.3 Results

4.3.1 Case Study Area

The proposed framework is empirically demonstrated using data from Addis Ababa city. The city has a total of 4,843.15 kilometers of centreline length of road infrastructure. The road network is classified into five functional classes: ring roads (RR), principal arterial streets (PAS), secondary arterial streets (SAS), collector streets (CS), and local streets (LS). The RR, PAS, SAS, CS, and LS are, respectively, 37.98, 357.43, 166.49, 284.74, and 3,996.51 kilometers long [43]. The city roads are owned and managed by the Addis Ababa city roads authority (AACRA). Road networks are divided into five geographical regions, with five regional road asset management directorates in charge of road asset management in their respective region. AACRA's regional directorates are responsible for collecting road condition data, planning maintenance (including prioritization), and managing maintenance activities. As a case study, the proposed framework was used to determine road maintenance prioritization of 4,721 asphalt



(a) Study area. (b) Safety star rating.

Figure 4.2: Map of the study area.

concrete road sections with 100 m length each (472.1 km) on the major routes comprising RR, PAS, and SAS roads. 72.7% of the road sections included in the case study had a star rating below the global safe road standard of 3 stars (**Figure 4.2**).

4.3.2 Multicriteria Analysis

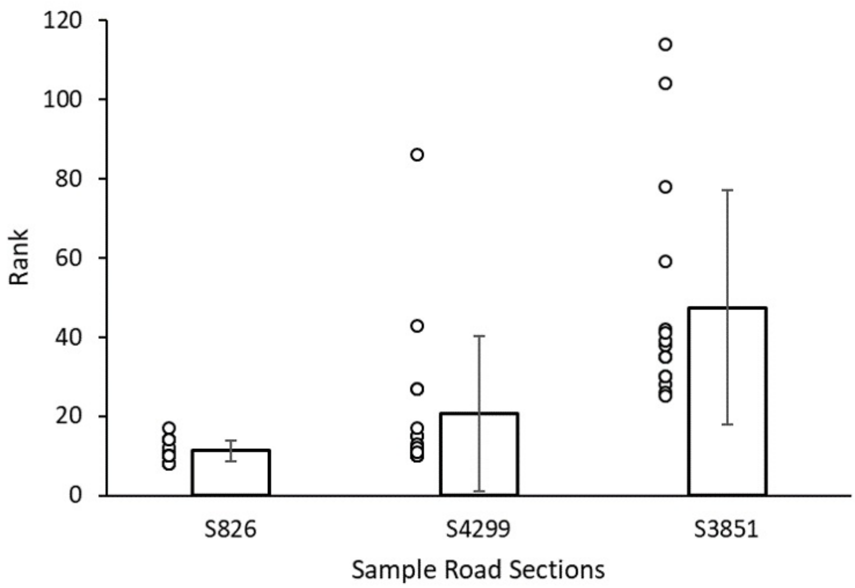
The five AACRA regional road asset management directors who are road maintenance prioritization decision-makers conducted a semantic scale-based pairwise comparison among criteria. AHP analysis yielded weights of 0.08, 0.12, and 0.8 for pavement condition, traffic volume, and safety, respectively. The CR value of 0.02, which is less than the cut-off value of 0.1, ensures consistency. In the absence of safety criterion, i.e., for the conventional approach, the same experts assigned 0.42 and 0.58 weights to the pavement condition and traffic volume criteria, respectively. The CR of 0.02 demonstrates that the pairwise comparison is consistent as it is less than 0.1. Equal weighting for all three criteria is used as an alternative method to AHP to reflect the methodological multiplicity of the weighting technique in the analysis.

In the MA process, different methodological combinations of two weighting, four normalization, and two aggregation methods produced 16 possible score results (scenarios) for each road section. For instance, a score result using the AHP weighting method, vector normalization, and additive aggregation gives one scenario. Accordingly, changing the methods one at a time results in 16 possible scenarios for each road section. The results of three road sections, one from each road class, S826 (RR), S4299 (PAS), and S3851 (SAS), are presented in **Figure 4.3** as a sample illustration. The dots in **Figure 4.3** indicate the ranks of the road sections using the score of 16 scenarios, and the columns and the error bars show the mean and standard deviation, respectively. Standard deviation bar size infers the variability of ranks; the smaller the bar, the lower the variation, and the larger the bar, the higher the variation. For instance, when using the different combinations of methods in the MA process, road section 826 (S826) has a relatively lower range of rank difference from 8 to 17 (the lower the rank, the higher the priority), indicated by a smaller standard deviation bar size with a standard deviation (SD) value of 2.64. On the other hand, S3851 has larger standard deviation bars, with an SD value of 27.5, accounting for a higher range of rank difference from 25 to 114. S4299 has a moderate rank dispersion ranging between 10 and 86, with an SD of 19.6. Therefore, whether large or small, the ranking range shows the presence of uncertainty. Similarly, the analysis of the 4721 road sections indicated significant variability in aggregated score results and the associated ranking ranges. This can be noticed from the probability density graphs of both approaches in **Figure 4.3**. The intersection and overlapping of the rank density curves among the three functional road classes infer the uncertainty in the score (M)-based ranking due to possible rank reversal among the road classes. Consequently, prioritization based on the value of M is uncertain and would lead to erroneous decisions.

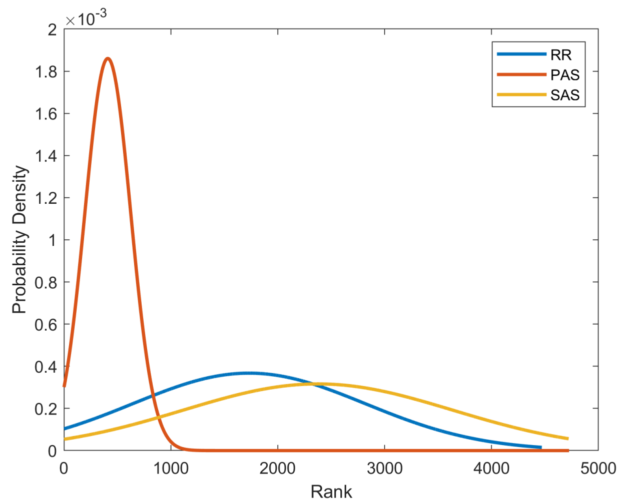
It is also evident from the density plot that principal arterial road sections have relatively the highest priority, followed by ring road sections in a safety-oriented approach. Conversely, the ring road sections take the lead, and principal arterial roads become the second on the priority list in the case of the conventional approach. Hence, this shows integrating safety in road maintenance prioritization resulted in rank reversal among functional road classes.

4.3.3 Sensitivity Analysis and Uncertainty Management

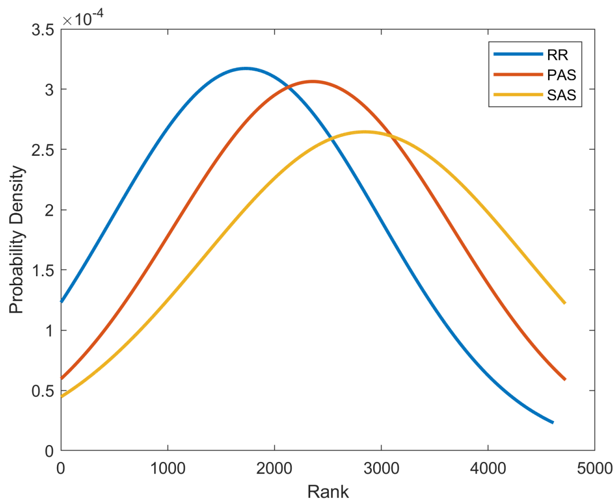
As explained above, the aggregated score result highly varies, and it is essential to investigate the role of factors in the variation in the MA process. The average contribution of individual factors to the total variance is indicated by the first-order sensitivity index, S_a , of 0.193, 0.287, and 0.225, for normalization, weighting, and aggregation, respectively. Furthermore, the variance



(a) Sample road sections' ranking.



(b) Ranking density among road classes using safety-oriented approach.



(c) Ranking density among road classes using conventional approach.

Figure 4.3: Uncertainty in score (M)-based ranking.

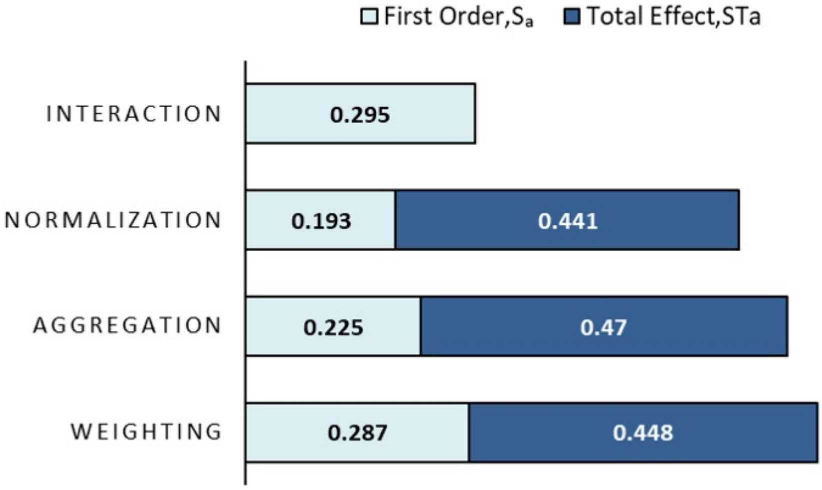


Figure 4.4: The contribution of different MA stages to the uncertainty in terms of sensitivity indices.

decomposition reveals that the interaction of factors accounts for 29.5% of the total variance. Hence, the uncertainty caused by the interaction of the three factors (synergistic effect) is greater than the uncertainty caused by the isolated effect of individual factors.

The total effect sensitivity index, S_{Ta}, provided values of 0.441, 0.448, and 0.470 for normalization, weighting, and aggregation, respectively. In this case, aggregation and weighting contribute more to the uncertainty. The total effect sensitivity index of each factor indicates the average fraction of variance due to the given factor. For example, on average the output variance remaining will be 44.1% of the total if all factors can be fixed but normalization. Consequently, because the first-order effect, S_a, and the higher order effect (interaction), $S_{Ta} - S_a$, are both above 0.1, all factors are considered influential and factor fixing is not applicable (**Figure 4.4**).

4.3.4 Stochastic Ranking

Stochastic ranking begins with a probabilistic pairwise comparison based on the PDF generated from the score M. For instance, the exceedance probability of S4299 from S826, $P\_(S4299, S826)$=$P(M_S4299$ $\geq M\_(S826 \mid LB)$, is 0.56. $P\_(S4299, S826)$ indicates the probability of the score of S4299, M_S4299, to be more than or equal to the lower bound of the score of S826 , $M\_(S826 \mid LB)$ (**Figure 4.5**). The probability of exceedance can be calculated for all road sections as well. The stochastic score G_i is then calculated using equation (4.11). For the sample road sections, G_i

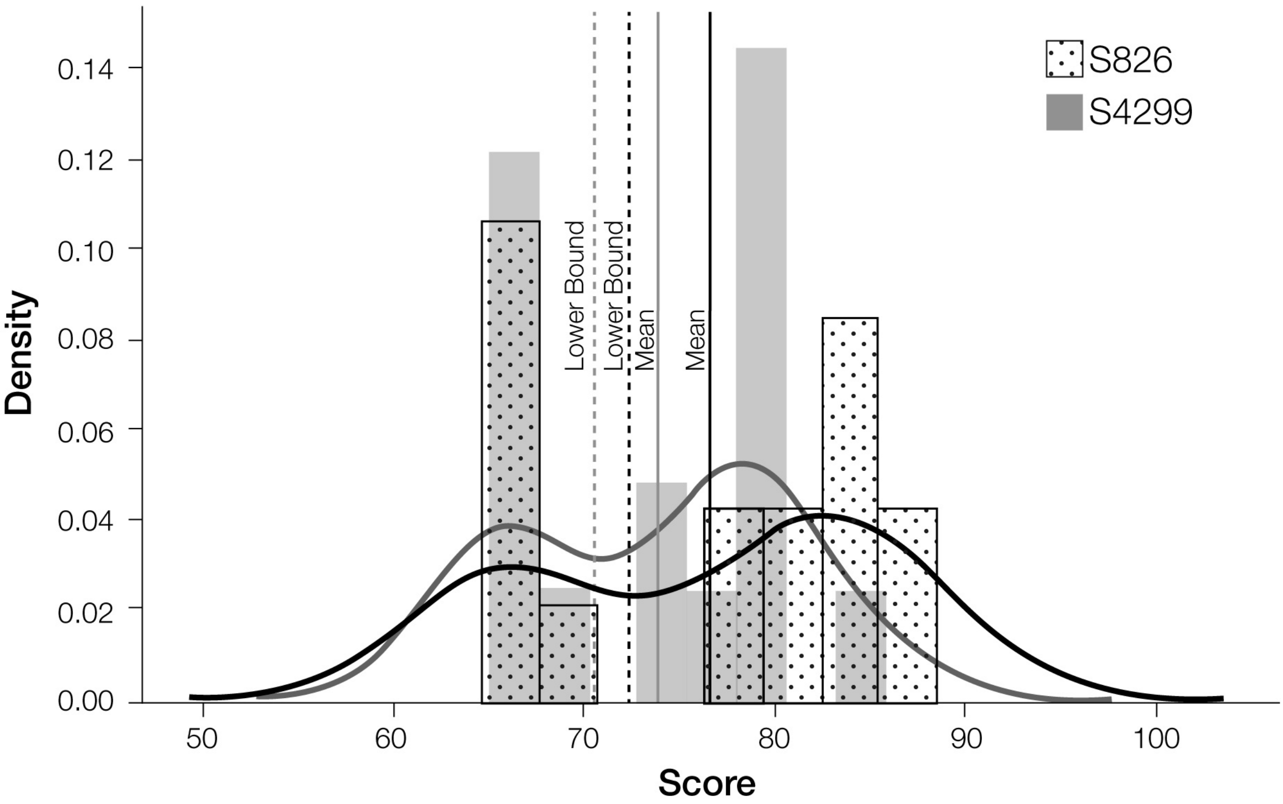


Figure 4.5: A comparison of probabilistic density functions generated from the score M between road sections S826 and S4299.

values of 0.993, 0.991, and 0.988 for S826, S4299, and S3851 were obtained, respectively. Based on their G_i value, S826, S4299, and S3851 ranked 10th, 14th, and 26th out of the 4,721 road sections examined, respectively.

4.3.5 Comparison of Methods

The use of the conventional approach resulted in an average shift in the ranking, $\tilde{R}_s$, of -524.6 on unsafe road sections (i.e., those with star ratings 1 or 2) when compared to the safety-oriented one. The negative sign indicates a decrease in the ranking. Specifically, when comparing the conventional approach to the safety-oriented one, 73.73% of the road sections with star ratings 1 and 2 exhibit a negative rank shift, whereas 26.21% have a positive shift, and only 0.06% remain on the same rank (**Figure 4.6**). Furthermore, when the outcomes of the two approaches were compared, 96.7% and 72.6% of road sections in the first half of the priority list were unsafe roads for the safety-oriented and conventional approaches, respectively. The top ten maintenance priority road sections have the worst safety condition (star rating 1) in the case of

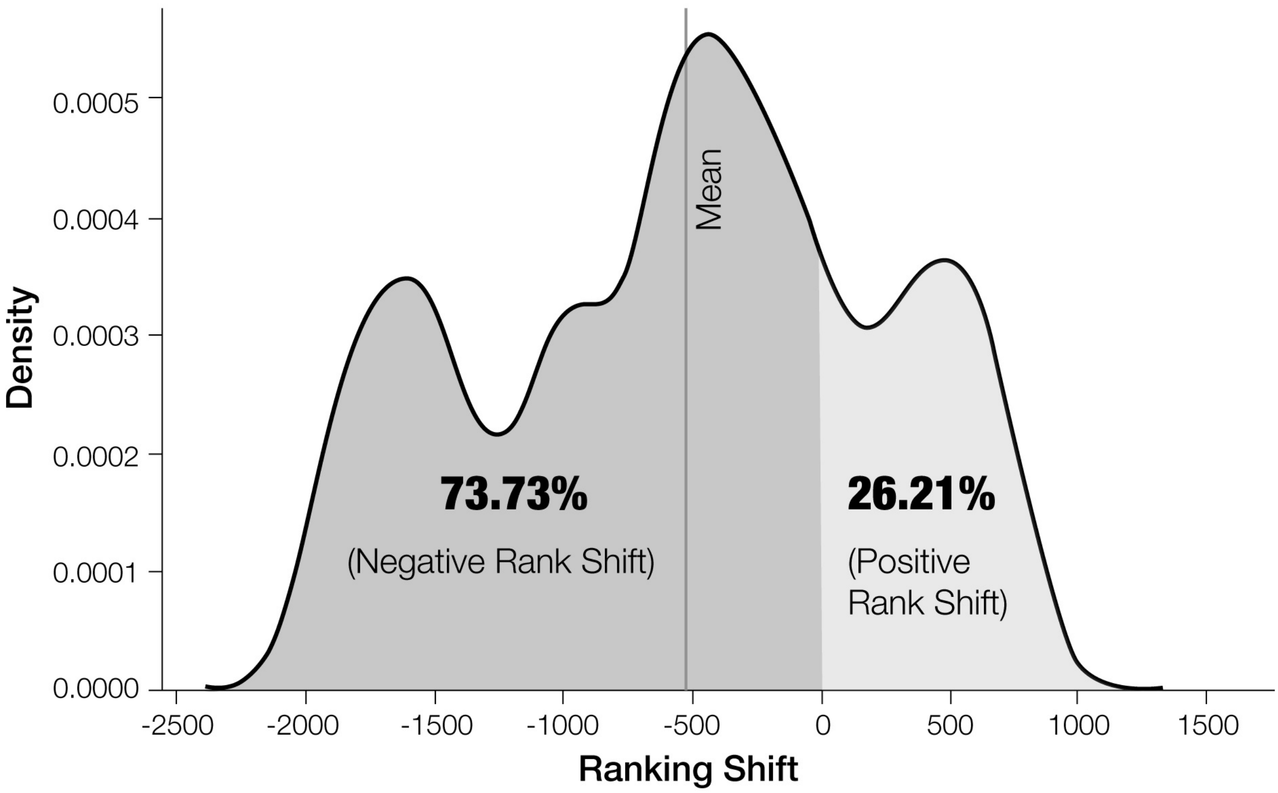


Figure 4.6: The density plot of ranking shift on unsafe road sections by implementing a conventional instead of safety-oriented approach.

safety-oriented. In contrast, only four of the ten are unsafe road sections in the conventional approach. Conversely, the ten-road sections at the bottom of the prioritization list are all the safe sections, and only two out of ten are safe sections based on the implementation of safety-oriented and conventional approaches, respectively. Consequently, the safety-oriented approach is superior in prioritizing unsafe road sections for maintenance.

Moreover, the result indicated that PAS road sections are dominant in higher priority lists in the safety-oriented approach followed by the RR. In contrast, RR takes the lead if the conventional approach is implemented (**Figure 4.3**). In addition, safety exhibits a strong correlation (r_s = -0.81) with the priority ranking, whereas moderate (r_s = 0.54) and weak (r_s = 0.17) correlations with the ranking were found for traffic volume and pavement condition, respectively.

4.4 Discussion

The highest weight obtained for the safety criterion indicates that the experts responsible for road maintenance planning at AACRA agree that safety is more important than the other two criteria. However, equal weighting assigns the same weights to the three criteria, and the weights of the criterion varied significantly between the AHP and equal weighting methods. For example, the AHP method calculated 0.8 and 0.08 weights for safety and pavement conditions, respectively, whereas 0.33 was the weight for both in equal weighting. Weighing indices with high sensitivity correspond to the high discrepancy discovered by the two weighting methods. As a result, weighting contributes the most to the total variance, followed by aggregation in individual factor contribution. To this end, when using MA for road maintenance prioritization, weighting should be given the most attention in terms of reducing methodological uncertainty, followed by aggregation.

Finding the true value of weighting and aggregation can significantly reduce the total variance. To reduce methodological uncertainty, a deliberate choice of methods for factors with high S_a, particularly weighting and aggregation, is necessary. According to the total effect sensitivity index, S_{Ta}, weighting and aggregation contribute more to methodological uncertainty than normalization. However, when considering its sole influence, weighting contributes the most to variance, while aggregation has the greatest influence when an interaction is considered. Though multiplicity in the normalization method has the least S_a and S_{Ta} values, it remains influential as the first-order and higher-order effects indices are above 0.1. The sensitivity results revealed that the methods used at each stage of MA have a significant influence on the prioritization outcome. Therefore, a prioritization result obtained by selecting a single method at each stage of MA is unreliable because method choice at all steps influences the outcome.

The analyses demonstrated that it is impossible to obtain stable prioritization ranks based on the score M due to the uncertainty introduced by the multiplicity of methods. Yet, stochastic score-based ranking is possible. The decision maker can identify the risk by subtracting the probability of exceedance, i.e., how probable one road section can be below the reference lower bound. For example, 56% of the probability of exceedance of S4299 from S826 has a 44% risk probability. In other words, the score of S4299 has a 44% probability of falling below the lower bound of S826. Because of this informative probabilistic property, the stochastic approach is more appropriate for making informed decisions in the face of uncertainty.

The sensitivity analysis demonstrated prioritization results vary significantly depending on which method is used at each stage of MA (normalization, weighting, and aggregation), and the sensitivity indices were above the threshold value of 0.1. Obtaining discrete results under methodological uncertainty is thus impossible, necessitating the use of a probabilistic approach incorporated into the proposed framework. Moreover, when using the conventional approach, fewer unsafe roads achieved higher priority compared to the safety-oriented approach. This is problematic because it decreases the priority for maintenance of unsafe roads and imposes preventable risks (crashes) to road users due to unsafe infrastructure. Comparing priority lists obtained via both approaches to road maintenance prioritization, it is clear that the safety-oriented approach is more appropriate for sustaining high maintenance priority for unsafe road sections than the conventional approach. Thus, the proposed framework presented in this study should contribute to road danger reduction.

The prioritization comparison between the two approaches revealed that PAS road sections take a significant proportion in the higher priority list, followed by RR. Conversely, RR overtakes PAS and becomes dominant as the top priority in the conventional case. The rank reversal between the priority of the road classes is associated with the inclusion of the safety criterion. Moreover, the strong correlation (r_s=-0.81) of the safety criterion with the ranking infers the potential of the safety-oriented approach in favoring unsafe road sections in the maintenance prioritization.

4.5 Conclusions

The sensitivity analysis result showed that the prioritization results significantly vary using different methods at each stage of MA, and the sensitivity indices were above the threshold value of 0.1. Obtaining discrete results under methodological uncertainty is thus impossible, necessitating the use of a probabilistic approach. Moreover, the case study revealed that when the conventional approach was used instead of the safety-oriented, 73.73% of the unsafe road sections' maintenance priority was lowered, and the proportion of unsafe roads in the first half of the priority list was reduced by 24.1%. This result demonstrates the framework's superiority in prioritizing unsafe road sections for maintenance compared to the conventional one. Moreover, the correlation coefficient and the maintenance priority inversion exhibited between RR and PAS road classes following the use of the two prioritization approaches demonstrate the strong correlation of safety criterion with the rank. Thus, considering road safety in the maintenance prioritization criterion has a favourable impact on prioritizing unsafe sections for maintenance, which can contribute to road danger reduction.

In conclusion, this chapter presents a safety-oriented decision-making support framework for road maintenance prioritization. A modified MA enhanced by sensitivity analysis and uncertainty management strategy is at the core of the proposed framework. Furthermore, in the context of methodological uncertainty, a stochastic ranking used in prioritization supports informed and robust decision-making. The modified MA method, coupled with stochastic prioritization, addresses the limitation of MA in terms of decision uncertainty due to methodological multiplicity. Furthermore, the simplicity and flexibility of MA can help road agencies in setting the criteria based on their priority concern during the criteria-setting process.

Furthermore, the iRAP star rating protocol used in the proposed framework considers the safety needs of all road users, making the decision process highly inclusive. Therefore, the framework can support road agencies, particularly those in LICs and MICs, in making data-driven safety-conscious decisions to ensure safe roads for all. In addition to its practicability, the framework presents a new comprehensive approach that integrates all road users' safety and takes methodological uncertainty into account.

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Chapter 5

Critical Road Sections Evaluation Considering Safety and Pavement Conditions

5.1 Introduction

In order to preserve safe and efficient road networks, it is essential to carry out proper and timely monitoring and maintenance operations. However, budget limitation makes it usually impossible to monitor and maintain the whole network at a time [1]. Moreover, not all roads have the same functional and safety conditions. Some road sections are in a better state and safer for travel compared to others, thus with different timing and level of preservation needs. Therefore, it is unavoidable for road agencies to identify critical road sections to concentrate monitoring and maintenance efforts and improve overall road conditions and safety.

In assessing critical road sections, the pavement condition can be used as one factor to evaluate the priority due to its direct effect on mobility and user costs [2, 3]. As presented in **Figure 5.1**, the pavement condition can be used in two ways: based on the level of deterioration and the rate of deterioration. The prioritization of road sections based on their level of deterioration considers highly deteriorated sections as critical. This method is considered reactive as it only identifies the roads as critical after significant damage has occurred. This approach is mainly used to determine road sections' priority for maintenance by establishing different criteria, and numerous studies have suggested various techniques [4, 5]. Criteria related to the pavement condition are fundamental in prioritizing road sections using those techniques [4]. Consequently, road agencies have mainly relied on pavement deterioration conditions to identify critical sections in their road infrastructure management process. For example, in Australia, the Victoria Department of Transport rates road sections based on roughness, rutting, and cracking. The length of road sections with distresses at an intervention level is compared to the whole network, and the resulting percentage is used as a performance measure [6]. Similarly, in the US, the Texas Department of Transportation rates road sections based on a condition score, which is calculated using distress and ride quality related to pavement condition [7]. The same approach is taken in Ethiopia, where the Addis Ababa City Roads Authority compares road sections based on the severity of four damage types: potholes, cracks, rutting, and raveling. Each damage type is assigned a weight, and the road section with the highest total severity is considered the most critical [8]. However, the pavement deterioration condition-based approach leads to a costly reactive maintenance scheme that does not address the underlying cause of deterioration.

In addition to creating a basis to evaluate the priority, identifying critical road sections based on the deterioration rate is a proactive approach as it allows early detection. This method helps identify critical sections which need a detailed investigation to identify the root cause and take timely action [9, 10]. The importance of a proactive approach to pavement preservation has been acknowledged for a long [11, 12]. Accordingly, much research focus has been placed on developing advanced methods for early detecting pavement distress and optimizing maintenance strategies in order to achieve proactive pavement preservation. Both distress detection and optimization techniques determine the timing for preventive maintenance over corrective maintenance [13, 14, 15]. However, these techniques do not account for the rate at which various road sections are deteriorating, preventing an understanding of the source of accelerated deterioration and potentially leading to repeated and costly maintenance. Despite the significance of considering the deterioration rate when identifying critical road sections, existing knowledge on how to identify rapidly deteriorating sections is comparably sparse [10].

Another important factor in identifying critical road sections is road safety [16]. With road

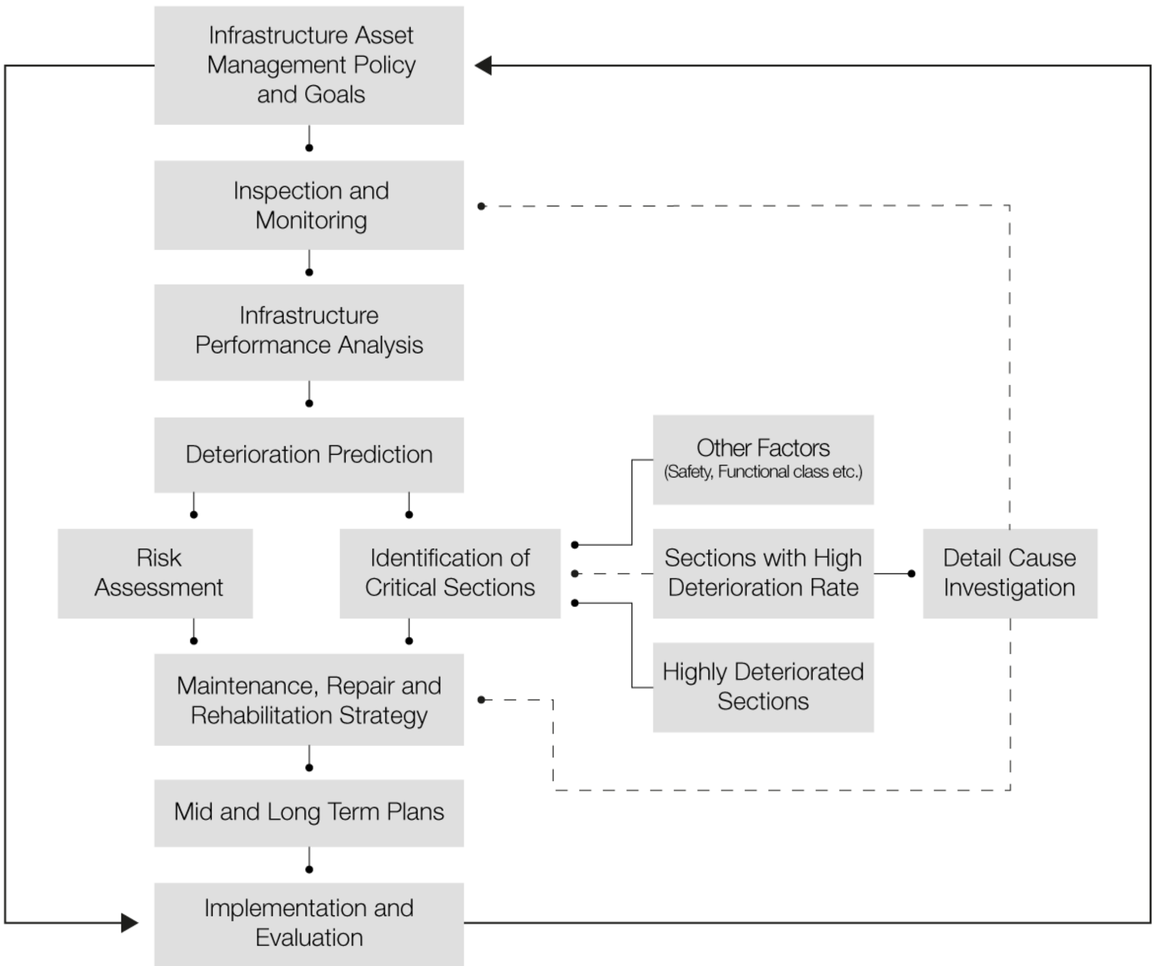


Figure 5.1: Simplified road infrastructure management flowchart.

traffic crashes being recognized as the eighth leading cause of death globally [17], enhancing road safety is becoming a vital objective for road agencies. The leading cause of fatal crashes is due to deficiencies in safety features of road infrastructure [18, 19]. Thus, improving road infrastructure safety condition can significantly reduce the social and economic costs resulting from traffic crash [16, 19]. Improving road infrastructure safety entails the identification of critical road sections that pose a high safety risk.

Road sections with high safety risks can be determined by analyzing either past crash history or the degree of infrastructure safety. The first approach classifies road sections with a high record of traffic crashes as critical sections. This approach only takes effect after a significant number of crashes have occurred and been documented [20]. In contrast, the second approach assesses road sections' potential for crashes and the level of protection against crash severity that they offer, taking into consideration the safety needs of all road user groups to determine which sections pose the greatest risk [18]. The latter approach, being proactive, does not necessitate waiting for crashes to happen to assess high-risk sections, making it preferable to identify critical road sections. However, analyzing previous crash records along with infrastructure safety data helps enhance road safety. This is because it provides a deeper insight into the causes and contributing factors behind crashes. This information can then be used to prevent similar crashes from happening in the future [18, 20]. For example, road segments with safe infrastructure but high crash history need to be evaluated to determine if the cause is due to other factors (human or vehicle factors), which can then be considered in road safety policy and regulations. Studies rarely consider the two approaches together, resulting in a deficiency in comprehending road infrastructure safety and the underlying causes of crashes, making it challenging to determine high-risk sections and effective mitigation.

There is an increased research effort in the area of road safety and pavement preservation to ensure safe and efficient road network. However, previous studies focus on specific pavement characteristics in relation to safety and tend to consider them as separate areas [21]. This approach lacks comprehensiveness in integrating pavement preservation and safety. Furthermore, the essential road features for the safety of non-motorized users have not been considered when identifying the critical section and road network improvement decisions [22]. Though the pavement condition is one factor in determining safe roads, features such as the road geometry, availability of safety infrastructures for vulnerable road users (e.g., walkways, bicycle lanes, etc.), availability of traffic calming measures play a vital role in assuring safe infrastructure for all. Neglecting to consider the safety needs of all road users raises concerns about transport equity among road users. Thus, it is important to evaluate pavement and infrastructure safety conditions from all road users' perspectives in identifying critical road sections.

This chapter presents a practical decision matrix to identify critical road sections while filling the research gaps. The proposed method employs a pavement condition and infrastructure safety-based proactive approach in identifying critical sections so that extra economic and social costs due to corrective actions can be prevented. The proposed decision support matrix employs the Markov mixed hazard model to estimate the pavement deterioration rate stochastically. Whereas the International Road Assessment Program (iRAP) protocol is used to evaluate the infrastructure safety level of road sections for each group of road users, including vehicle occupants, motorcyclists, bicyclists, and pedestrians. In addition, the evaluation of critical road sections also includes the analysis of crash history as an indicator to identify underlying factors beyond infrastructure, which is beneficial in developing safety policies and regulations. To this end, the proposed decision matrix is the first of its kind in incorporating proactive factors, pavement deterioration rate and infrastructure safety that considers all road users' safety needs, and a retroactive factor, crash history, to identify critical road sections. Furthermore, the decision matrix is used to form a hierarchy of critical sections based on their criticality levels, allowing for prioritization and effective decision-making under resource constraints. The proposed decision matrix is highly practical. Therefore, it is expected to help road agencies make informed decisions regarding monitoring and preserving their road networks to ensure safe and efficient mobility.

5.2 Methodology

A decision matrix is a tool used in the decision-making process by organizing all relevant factors in a matrix form. This helps the decision maker understand all the factors involved in the decision and make an informed choice. The study uses pavement deterioration rate, infrastructure safety, and crash history data to create a decision matrix for identifying critical road sections. The pavement deterioration rate is determined through a Markov Mixed Hazard (MMH) model. At the same time, the infrastructure safety condition of road sections for different road user groups is evaluated using the International Road Assessment Program (iRAP) protocol, while crash data is acquired from the responsible authority in charge of gathering it. The methodology used is presented in **Figure 5.2**.

5.2.1 Markov Mixed Hazard (MMH) Model

Over time, road pavements deteriorate like any other form of infrastructure. However, the rate they deteriorate differs due to their heterogeneous characteristics in terms of structure, loading, environment and unobservable factors. Understanding the factors contributing to the deterioration, particularly for fast-deteriorating sections, helps determine the appropriate action. Moreover, detecting those causes before the section's deterioration reaches conditions that require high investment to restore can help to preserve pavements with reasonably minimum cost. Therefore, identifying the critical sections based on their deterioration rate at an early stage is an important aspect to be addressed. Determining the deterioration rate in an absolute discrete measurement scale is difficult due to its stochastic nature and various attributing factors. However, a probabilistic approach based on pavement performance data is possible. Accordingly, MMH model is proposed to determine the deterioration rate of road sections in this study.

The MMh model, unlike the basic Markov hazard model discussed in section 3.2.1, takes into account the impact of infrastructure heterogeneity on the hazard rate when estimating the deterioration rate. The MMH's superiority over other Markov models in considering heterogeneity, combined with its capability to determine the life expectancy of infrastructures and quantify uncertainty, satisfies the deterioration model's requirements [23]. The MMH model is used in this study to assess the deterioration rate of pavement sections due to its advantageous features and practicality.

As explained in section 3.2.1, the hazard rate denoted by λ_i can be expressed as a function of the explanatory variable, x, and the unknown parameter vector $\beta_i = (\beta_{i,1}, \ldots, \beta_{i,M})$ and β_i' is its transpose. Here, $m(m = 1, \ldots, M)$ represents the number of explanatory variables. Thus,

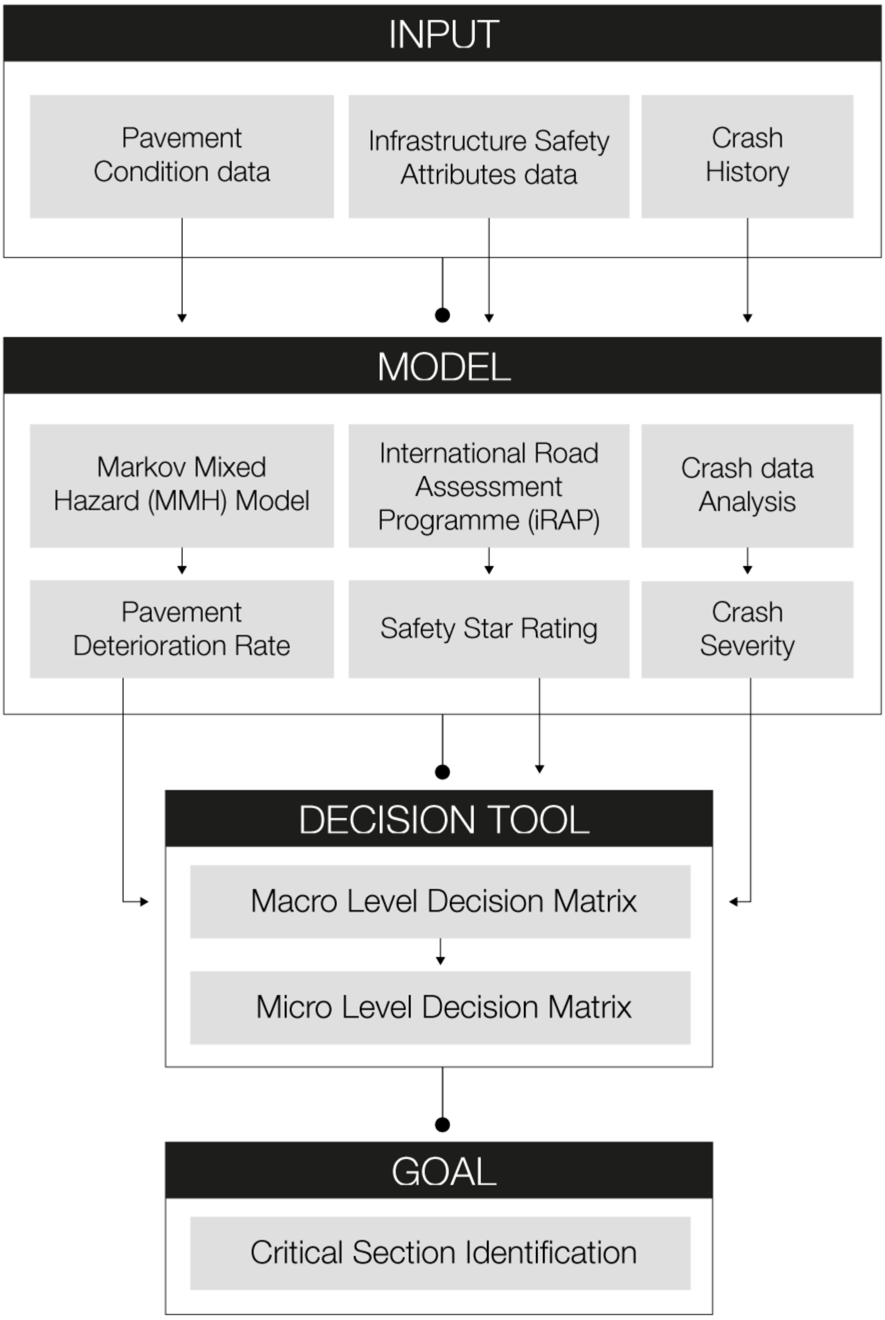


Figure 5.2: Research process diagram.

the hazard rate can be expressed as:

$$\lambda_i = f(x_m : \beta'_{i,m}) \tag{5.1}$$

To determine the MTP matrix and other important parameters, such as deterioration rate using the MMH model, consider a road network with pavement groups denoted by $k(k = 1, \dots, K)$ and a pavement section in each group, denoted by $s_k(s = 1, \dots, S_k)$. Pavement grouping is usually done based on characteristics such as pavement type, and each group k will have a total of S_k sections. The deterioration process for each pavement group or section is different and is characterized by the heterogeneity factor, ε^k. Therefore, utilizing a section that represents the average hazard rate of the entire network (referred to as the benchmark), $\tilde{\lambda}_i^{s_k}$, for condition $i(i = 1, \dots, J-1)$ it is possible to express the hazard mixture form as:

$$\lambda_i^{s_k} = \tilde{\lambda}_i^{s_k} \varepsilon^k (i = 1, \dots, j-1; s = 1, \dots, S; k = 1, \dots, K) \tag{5.2}$$

It is to be noted that the heterogeneity factor ε^k always has a positive value as it represents a relative deterioration rate to the benchmark. Thus, when $\varepsilon^k = 1$, it represents the benchmark condition, and as the value of ε^k increases, the deterioration rate also increases. The heterogeneity factor ε^k can be in the form of a function or stochastic variable. It is assumed to follow the gamma distribution with parameters α and γ, i.e., $\varepsilon^k \sim G(\alpha, \gamma)$. This means that it can be expressed using the following function:

$$f(\varepsilon^k : \alpha, \gamma) = \frac{1}{\gamma^\alpha \Gamma(\alpha)} (\varepsilon^k)^{\alpha-1} exp(-\frac{\varepsilon^k}{\gamma}), \tag{5.3}$$

where the Cumulative Distribution Function (CDF) is denoted by $\Gamma(.)$. By taking the product of gamma distribution parameters, α and γ,the average of the function $f(\varepsilon^k : \alpha, \gamma)$ can be obtained, while the variance is $\alpha\gamma^2$. Thus, when the average is set to 1, (i.e., $\alpha\gamma = 1$), and the variance $\alpha\gamma^2 = \frac{1}{\phi}$, the Probability Density Function (PDF) becomes:

$$\bar{G}(\varepsilon^k : \phi) = \frac{\phi^\phi}{\Gamma(\phi)} (\varepsilon^k)^{\phi-1} exp(-\phi\varepsilon^k) \tag{5.4}$$

The probability of pavement section s_k remaining in condition state i for a time period longer than y_i can be represented by survival or reliability function using Equation (5.5).

$$R_i(y_i^{s_k}) = exp(-\tilde{\lambda}_i^{s_k}\bar{\varepsilon}^k y_i^{s_k}) \tag{5.5}$$

We can rephrase Equation (5.5) as a transition probability of staying in the same condition state i, i.e., π_{ii}, for a time interval of y_i, where the symbol $[^-]$ indicates a measurable value. In the same way, if we consider different possible deterioration paths starting from condition state i, we can calculate the transition probabilities for each step, represented as $\pi_{ii}, \ldots, \pi_{(i,J)}$, over a fixed time interval of z as follows:

$$\pi_{ii}(z^{s_k} : \bar{\varepsilon}^k) = exp(-\tilde{\lambda}_i^{s_k}\bar{\varepsilon}^k z^{s_k}) \tag{5.6}$$

$$\pi_{ij}(z^{s_k} : \bar{\varepsilon}^k) = \sum_{s=i}^{j}\prod_{m=i}^{j-1}\frac{\tilde{\lambda}_m^{s_k}}{\tilde{\lambda}_m^{s_k} - \tilde{\lambda}_s^{s_k}} exp(-\tilde{\lambda}_i^{s_k}\bar{\varepsilon}^k z^{s_k}) = \sum_{s=i}^{j}\psi_{ij}^{s}(\tilde{\lambda}_i^{s_k}) exp(-\tilde{\lambda}_i^{s_k}\bar{\varepsilon}^k z^{s_k}), \tag{5.7}$$

where $\psi_{ij}^{s}(\tilde{\lambda}_i^{s_k}) = \prod_{m=i}^{j-1}\frac{\tilde{\lambda}_m^{s_k}}{\tilde{\lambda}_m^{s_k} - \tilde{\lambda}_s^{s_k}}(i = 1, \ldots, J-1; j = i+1, \ldots, J; k = 1, \ldots, K)$. Given the precondition $\sum_{i=1}^{J}\pi_{ij} = 1, \pi_{ij}$ can be estimated using Equation (5.8).

$$\pi_{iJ}(z^{s_k} : \bar{\varepsilon}^k) = 1 - \sum_{s=i}^{j-1}\pi_{ij}(z^{s_k} : \bar{\varepsilon}^k) \tag{5.8}$$

The possible probability transitions of condition states that constitute the MTP matrix can be calculated using Equations (5.6) to (5.8). However, to fully understand each pavement section's hazard rate, $\tilde{\lambda}_i^{s_k}$, it is necessary to explain it as a function of the explanatory variable,$\bar{x}_{s_k}$, and the unknown parameter vector $\beta_i = (\beta_{i,1}, \ldots, \beta_{i,M})$ as it is shown in Equation (5.1).

Now, to determine the MTP matrix elements, π_{ij}, a condition inspection data set $\bar{\xi}^{s_k} = (\bar{\delta}^{s_k}, \bar{x}^{s_k}, \bar{z}^{s_k})$ is necessary. $\bar{\delta}^{s_k}$ is a dummy variable that takes a value of 1 when $\bar{h}(\tau_1)^k = i$ and $\bar{h}(\tau_2)^k = j$; otherwise is 0. The life expectancy for a given condition state i, $LE_i^{s_k}$, can be determined by calculating the reciprocal of the hazard function of that state $\tilde{\lambda}_i^{s_k}(i = 1, \ldots, J-1)$. To find the total life expectancy from condition state i to the final state J, $LE_{iJ}^{s_k}$, can be obtained by summing life expectancies of each condition state. Equations (5.9) and (5.10) provide the formulas for these life expectancies.

$$LE_i^{s_k} = \int_0^\infty R_i(y_i^{s_k})dy_i^{s_k} = \int_0^\infty exp(-\tilde{\lambda}_i^{s_k}\bar{\varepsilon}^k y_i^{s_k})dy_i^{s_k} = \frac{1}{\tilde{\lambda}_i^{s_k}} \tag{5.9}$$

$$LE_{iJ}^{s_k} = \sum_{i=1}^{J-1} LE_i^{s_k} \tag{5.10}$$

Hence, the application of MMH model requires a set of inspection data, $\bar{\xi}^{s_k} = (\bar{\delta}^{s_k}, \bar{x}^{s_k}, \bar{z}^{s_k})$, and determination of the unknown parameter vector $\beta_i = (\beta_{i,1} \ldots, \beta_{i,M})$, heterogeneity factor ε^k , and the hyper parameter ϕ. The parameters can be denoted as $\theta = (\beta_i, \phi, \varepsilon^k)$. As explained above, the density function $\pi(\varepsilon^k)$ follows the gamma distribution $\varepsilon^k \sim G(\alpha, \gamma) = \varepsilon^k \sim G(\phi, \frac{1}{\phi})$ and the density function of the hyper parameter $\pi(\phi)$ also follows a gamma distribution $(\phi \sim G(\alpha_0, \gamma_0))$, where $\alpha\gamma = 1$ and $\alpha\gamma^2 = \frac{1}{\phi}$. Thus, the heterogeneity factor is drawn by a hierarchical process,$\pi(\varepsilon^k) = \pi(\varepsilon^k : \phi)$ and $\pi(\phi) = h(\phi : \alpha_0, \gamma_0)$. The parameter β_i is assumed to follow a multivariate normal distribution $\beta_i \sim N_M(\mu_i, \Sigma_i)$. To estimate the parameters using the Bayesian approach, one needs to use the likelihood function defined by the prior distribution and observed data. The posterior distribution $\pi(\theta \mid \bar{\xi})$ is proportional to the likelihood $L(\theta \mid \bar{\xi})$ and the prior distribution $\pi(\theta)$. Equation (5.11) gives the expression for the posterior distribution.

$$\begin{aligned} \pi(\theta \mid \bar{\xi}) &\propto L(\theta \mid \bar{\xi})\pi(\theta) \\ &\propto L(\theta \mid \bar{\xi}) \prod_{i=1}^{J-1}\prod_{k=1}^{K} \pi(\beta_i)\pi(\varepsilon^k : \phi)\pi(\phi) \\ &\propto \prod_{i=1}^{J-1}\prod_{j=i}^{J}\prod_{k=1}^{K}\prod_{s_k}^{S_k} \{\psi_{ij}^m(\tilde{\theta}_i^{s_k})exp(-\tilde{\theta}_m^{s_k}\varepsilon^k\bar{z}^{s_k})\}^{\bar{\delta}_{ij}^{s_k}} \\ &\cdot \prod_{i=1}^{J-1} exp\{\frac{-1}{2}(\beta_i - \mu_i)\Sigma_i^{-1}(\beta_i - \mu_i)'\} \\ &\cdot \frac{\phi^\phi}{\Gamma(\phi)}(\varepsilon^k)^{\phi-1}exp(-\phi\varepsilon^k) \end{aligned} \tag{5.11}$$

Sampling the values of the parameter $\theta = (\beta_i, \phi, \varepsilon^k)$ directly from the posterior distribution described in Equation (5.11) is difficult. Therefore, a non-parametric method called Markov

Chain Monte Carlo (MCMC) is used to estimate the parameter. Interested readers can refer to the works of Kaito et al. [24] and Han et al. [25] to explore further the MMH model and the use of MCMC in the parameter estimate.

5.2.2 International Road Assessment Program (iRAP) Star Rating

The aim of creating a safe road infrastructure is not only to reduce the likelihood of traffic crashes but also to make the infrastructure forgiving by minimizing the severity in the event of a crash. Achieving a safe road infrastructure requires creating a safe road environment for all road users rather than solely relying on managing road users' behavior to improve safety. In other words, the road system needs to prevent fatalities and serious injuries due to crashes that may be caused due to road users' errors [17, 20]. In this regard, consideration of the road sections' level of safety for each road user group is vital. To accomplish this, it is essential to consider the road features that are important for the safety of each group of road users. However, road safety assessment standards and tools have been carried out primarily based on motorized vehicle users, which limits their effectiveness. To address this limitation, the international road assessment program (iRAP) protocol has become the global standard, with 114 countries having adopted it by 2018, according to the World Health Organization [17].

The iRAP protocol utilizes an objective method to evaluate the safety of road sections. The analysis employs seven different data categories, which consist of 78 attributes that are used to examine safety. These categories comprise road context and details, midblock data, roadside data, intersection data, flow data, land use data and facilities for vulnerable road users (VRU), and speed data [43][26]. The iRAP assessment process assigns a star rating score (SRS) to road sections. SRS measures the relative risk of fatality and serious injury for an individual road user. The safety level is measured on a 5-star scale, with 1-star indicating the lowest safety standard (highest risk), and 5-star indicating the highest safety standard (relatively the lowest risk). The star rating for each road user group is assessed for every 100m road section [27]. As per the global road safety performance target, a road with a three-star rating or better is considered safe [17]. The computation of SRS is performed using Equation (5.12), and the procedure for determining SRS following the iRAP methodology [26] is described below.

$$SRS_u = \sum_{c=1}^{C} SRS = \sum_{c=1}^{C} L_{u,c} \times S_{u,c} \times OS_{u,c} \times EFI_{u,c} \times MT_{u,c} \tag{5.12}$$

where, u is the road user group and c is the crash type that the road user group u may be involved in. The factors considered in SRS calculation are: the likelihood of a crash, L, the severity of a crash, S, the operating speed, OS, the external flow influence, EFI, and median transversability, MT.

The types of crashes that different user groups can be involved in vary. When driving, vehicle occupants can experience run-off, head-on, intersection, and access point crashes while driving. In the case of motorcyclists, moving along the road is considered in addition to the vehicle occupants' crashes. Bicyclists may experience traveling along the road, intersection, and run-off (i.e., when bicyclist departs from the lane) crashes. Pedestrians may experience crashes while walking along or crossing the road. To calculate the SRS, safety performance indicator, for a particular user group, you need to determine the SRS for each type of crash that the group may encounter and then add them up.

The road environment features influence the likelihood of a crash and its severity. Such influences are considered in the model through risk factors (modification factors). For example, eight factors affect the likelihood of a bicyclist's run-off crash: lane width, curvature, curve quality, delineation, street lighting, road condition, grade, and skid resistance. On the other hand, the severity of the bicyclist's run-off crash is determined by the distance to roadside objects and the presence of objects. For instance, run-off crashes are more likely to occur on sharp curves than straight roads. A risk factor or crash modification factor is utilized to account for this fact. A risk factor of 1, 1.8, 3.5, and 6 for straight, moderate, sharp, and very sharp curvature, respectively, is used. This means that the likelihood of a bicyclist's run-off crash in very sharp curvature is six times greater than that in a straight road, assuming all other factors are constant. The risk factor values for all factors influencing the likelihood and severity of a particular crash will be determined based on the road section's characteristics. Finally, the likelihood and severity of the crash will be computed by multiplying the risk factor values of the factors that influence the likelihood and severity of the crash, which will then be employed in Equation (15).

The calculation of SRS requires consideration of additional factors, such as operating speed, external flow, and median transversability. The speed at which a vehicle travels can greatly impact the likelihood and severity of a crash, especially in the case of pedestrian fatalities, where 90% of deaths occur if a vehicle traveling at 80km/hr hits them [28]. The risk factor associated with different speeds can be determined from curves that relate various road user groups and crash types to the speed. For instance, for bicyclists' run-off crashes at an operating speed of 50km/hr, the risk factor is 0.011, while the risk factor for vehicle occupants' run-off crashes is 0.064. The external flow factor for different crash types can also be obtained from curves. Median transversability is another factor that should be considered. This factor takes a value of 1 if a median can be crossed and 0 otherwise, and it only applies to run-off and head-on crashes involving vehicle occupants and motorcyclists.

The SRS for a particular type of crash is calculated by multiplying the likelihood, severity, operating speed, external flow influence, and median transversability values. Then, by adding up the SRS values for each type of crash in a given road user group, the overall SRS value for that group can be determined. The final step is to assign a safety star rating to the road section for each road user group based on the rating bands outlined in **Table 4.1**.

5.2.3 Decision Matrix Formulation

Three factors are considered to identify critical road sections: pavement deterioration rate, infrastructure safety, and crash history. Each of these factors is further divided into three levels, with level 1 representing the highest criticality level and level 3 representing the lowest. The pavement deterioration rate is evaluated based on the heterogeneity factor, and the different percentiles that the heterogeneity values of road sections fall into determine the corresponding levels. Infrastructure safety levels are categorized based on star ratings, while the severity of crashes in a road section is used to categorize the levels based on crash history.

Road sections with a pavement deterioration rate below the road network's average rate are slowly deteriorating sections. These sections have a heterogeneity factor value of less than one and are in the first or second quartile of the heterogeneity value order. On the other hand, road sections in the third and fourth quartiles are considered to have a relatively higher deterioration

Table 5.1: Road sections' criticality levels

Category	Factors		
	Pavement deterioration rate (percentile of ε)	Infrastructure Safety (Star rating)	Crash history (Injury severity)
Level 1	$\geq 90^{th}$ percentile (D_1)	1-star (S_1)	Fatal (C_1)
Level 2	$75^{th} - 90^{th}$ percentile (D_2)	2-star (S_2)	Serious injury (C_2)
Level 3	Below 75^{th} percentile (D_3)	3-star and above (S_3)	Minor injury (C_3)

rate. On the other hand, road sections in the third and fourth quartiles have a relatively higher rate of deterioration. However, the road sections in the fourth quartile are of particular concern, especially those that fall within or above the 90th percentile. As a result, road sections in the 90th percentile and above are classified as having a level 1 deterioration rate, $D1$, while those between the 75th and 90th percentile are classified as level 2, $D2$, and those below the 75th percentile are classified as level 3, $D3$.

According to the United Nations, a road safety rating of 3 stars or higher is considered safe [29]. While both 1-star and 2-star rated roads are unsafe for users, there is a significant difference in the risk of serious injury and fatality. For example, McInerney and Fletcher [30] conducted a study and found that the costs of fatal and serious crashes per vehicle kilometer are 40% lower on 2-star roads compared to 1-star roads. Accordingly, road sections with a 1-star or 2-star rating are categorized as level 1, $S1$, and level 2, $S2$, respectively, while those with a 3-star or higher rating are categorized as level 3, $S3$. Similarly, road sections with a history of fatal and serious injury crashes are categorized as levels 1, $C1$, and 2, $C2$, respectively. In contrast, those with no or minor injury crash history are categorized in level 3, $C3$. **Table 5.1** presents the levels based on each factor.

A vector of the level of the three factors (D, S, C) is used to classify the road sections into three classes. The highest priority is given to $CLASSI$, which is classified as such if they have at least one factor with a level 1 category. Road sections in this class are the most critical and need detailed investigation and urgent action. The second class,$CLASSII$, road sections have at least one factor in the level 2 category and require intensive monitoring and planned action. Finally, the least critical road sections are those in $CLASSIII$, which have all vector values at

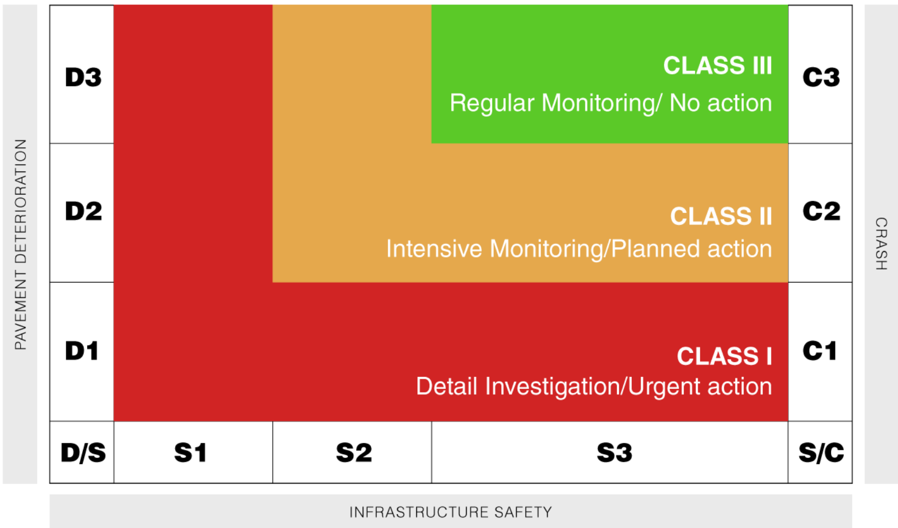


Figure 5.3: Macro level road section criticality decision matrix.

level 3 and only require regular monitoring. **Figure 5.3** shows the matrix representation of the three classes at the macro level.

Though all road sections in $CLASSI$ are critical, the criticality level differs across all sections. For example, while a road section with a vector of $(1,1,1)$ and one with $(1,3,3)$ are both in $CLASSI$, the former is more critical than the latter because it has a level 1 category in all factors. Accordingly, the first road section needs detailed investigation and urgent action on pavement and safety, while the second section requires urgency for pavement. Therefore, it is essential to establish a hierarchy within the same class in order to prioritize decision-making under resource constraints. Furthermore, subclasses make it possible to pinpoint the particular factor that requires greater focus within a specific section. Therefore, $CLASSI$ is subdivided into five matrix cells from highest to lowest criticality, denoted as $CLASSI(A)$,(B),(C),(D), and (E). $CLASSI(A)$ represents a vector of $(1,1,1)$ or $(D1,S1,C1)$, while $CLASSI(E)$ represents a vector of $(3,1,3)$ or $(D3,S1,C3)$. Similarly, $CLASSII$ is subdivided into three sections in order of criticality, denoted as $CLASSII(A)$,(B), and (C). Hence, the decision matrix at the subdivision level can be considered the micro level. **Figure 5.4** illustrates the matrix with the hierarchical division within a class.It is worth mentioning that when the three factors are considered equally important, the ordering of the vector does not alter the criticality level. Furthermore, suppose a section exhibits three distinct levels, such as $(2,1,3)$, where its criticality falls between $CLASSI(D)$ and $CLASSI(E)$. In that case, it is classified as part of $CLASSI(D)$

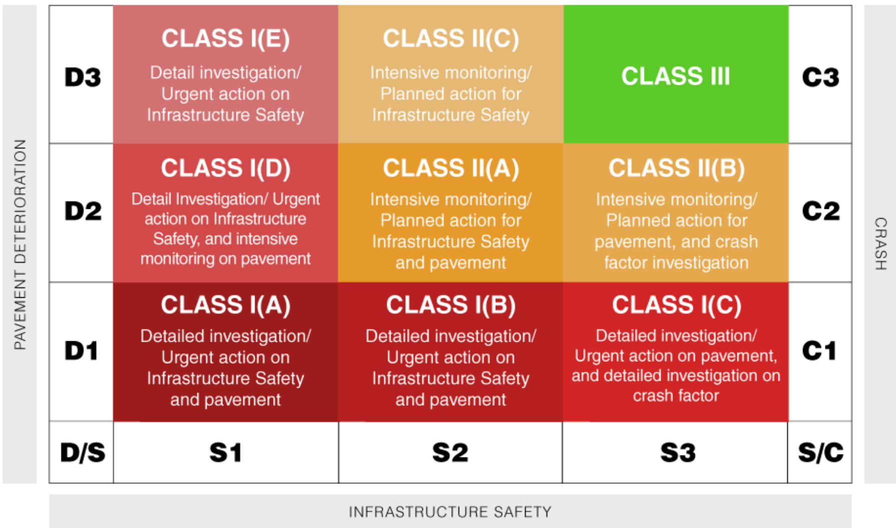


Figure 5.4: Micro level road section criticality decision matrix.

to ensure the utmost safety in decision-making.

5.2.4 Empirical Setting: Case Study

To demonstrate the proposed method empirically, actual data from Addis Ababa was employed. For this study, data was gathered from 472.5 km of asphalt concrete main roads, which were divided into 4725 sections, each spanning 100 meters in length.

International roughness index (IRI) data collected over three years period (2018-2020) were used for pavement deterioration analysis. Following, Addis Ababa City Roads Authority's (AACRA's) road maintenance guideline, the pavement condition is classified into five ranks [8]. Condition state 1 denotes the best condition, whereas condition state 5 represents the worst pavement conditions. The ranking is presented in **Table 5.2**. Similarly, road sections' data necessary for infrastructure safety analysis was obtained from iRAP which was collected in the same period in collaboration with AACRA. The crash data was obtained from Addis Ababa City Traffic Management Agency (TMA).

5.3 Results

The proposed method is illustrated using the road network of Addis Ababa City. The critical sections of the network are determined by analyzing three factors: pavement deterioration

Table 5.2: Pavement condition rating

Condition states	IRI (m/km)	Remark
1	IRI < 2	Very Good
2	$2 \leq IRI < 4$	Good
3	$4 \leq IRI < 6$	Fair
4	$6 \leq IRI < 8$	Poor
5	$IRI \geq 8$	Very Poor

rate, infrastructure safety, and crash history. The pavement deterioration rate is evaluated using the heterogeneity factor estimated by the MMH model to identify these critical sections. Additionally, the safety condition of the sections is assessed using the iRAP star rating and crash history. The findings of the case study are presented below.

Figure 5.5(a) displays the deterioration curve of road sections where the bold red curve is the benchmark deterioration. The road sections located to the left of the benchmark have a heterogeneity factor greater than 1, which means they deteriorate relatively faster. Conversely, road sections with the curves on the right of the benchmark have heterogeneity factor values less than 1 indicating a relatively slower deterioration. Consequently, the road sections on the left have a shorter life expectancy than those on the right. The result showed that the benchmark section has a life expectancy of 6 years, but the life expectancy of road sections varies from 2.4 to 10.7 years.

The degree of variation in deterioration among the road sections can be determined using a heterogeneity factor. Based on this factor, it is found that road sections with heterogeneity factor 1.31 or higher, at the 90th percentile and above, are categorized to a level 1 deterioration rate, $D1$. This value indicates that these road sections experience deterioration at a rate that is 31% faster than the standard benchmark. Road sections with a heterogeneity factor between 1.1 and 1.31, at the 75th to 90th percentile, fall under level 2, $D2$, while those with a factor less than 1.1, below the 75th percentile, experience a level 3 deterioration rate, $D3$. The heterogeneity factor varies from 0.68 to 2.16. The distribution of the heterogeneity factor can be seen in **Figure 5.5(b)**.

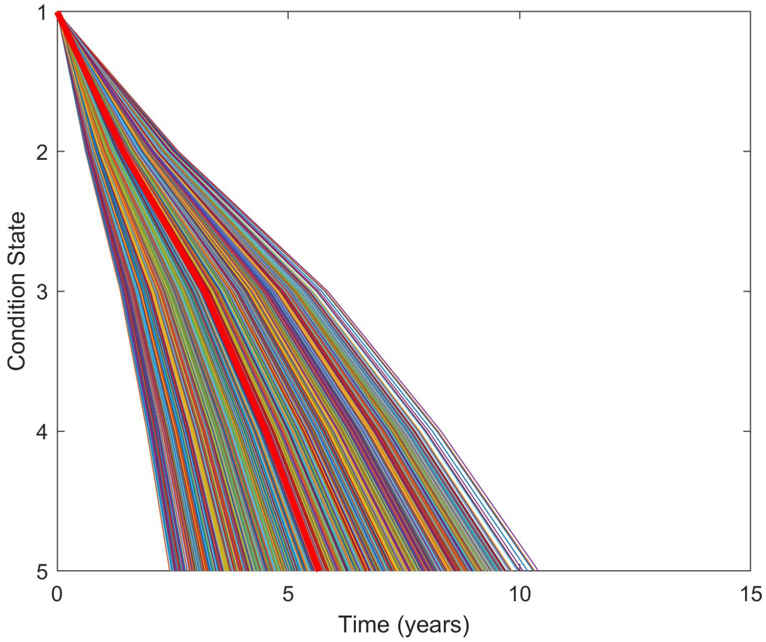
Another important finding from the case study analysis is that most road sections in levels $D1$ and $D2$ have a pavement condition state that is fair or better. For instance, out of the 47.3

km of roads in level 1, $D1$, 37.8 km (80%) have a pavement condition that is fair or better, meaning their IRI value is less than six. Similarly, out of 70.7 km of roads with a level 2 deterioration rate, $D2$, 57 km (81%) have pavement conditions that are fair to better. It is noteworthy that the road section with the slowest deterioration rate (heterogeneity factor of 0.68) and the road section with the fastest deterioration rate (heterogeneity factor of 2.16) both have good pavement conditions with a condition state rank of 2, IRI value ranging from two to four.

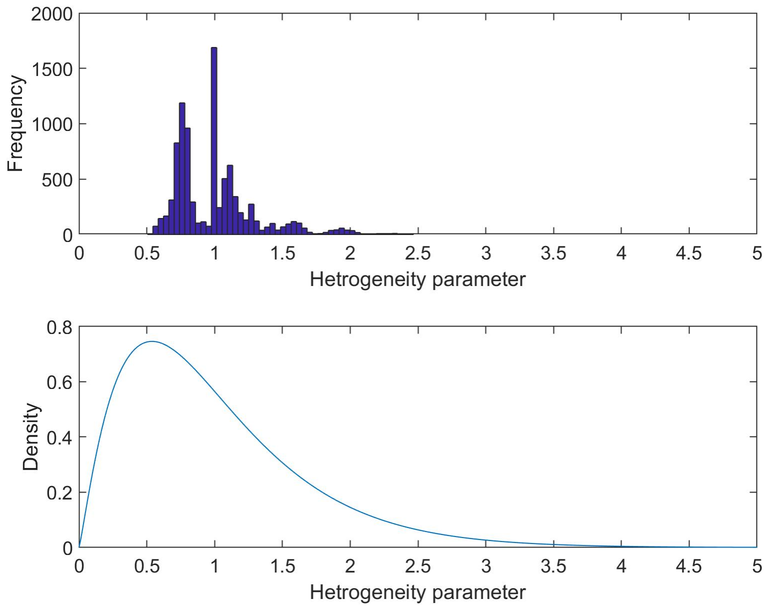
The iRAP star rating protocol is utilized to evaluate the safety of the infrastructure for different groups of road users. Addis Ababa has a road network that is relatively safe for people traveling in vehicles, with only 26% of sections being unsafe and receiving a rating of 1 or 2 stars. However, the network is much riskier for pedestrians, with 61% of the network receiving a 1 or 2-star rating for this group. The road network is also unsafe for bicyclists following pedestrians, with 52% of road sections being unsafe, while it is comparatively safer for motorcyclists, with only 40% being unsafe. Even though the network is relatively safe for some road users, there is still significant safety risk for all users. Therefore, the infrastructure safety level of each road section is represented by the minimum star rating among the four user groups to account for all road users' safety risks. As a result, the network has 343.4 km (73%) of unsafe road sections.

The crash data of 467, which happened in the three years period, were obtained from TMA. Among these, 86% were fatal crashes, 10% resulted in serious injuries, and 4% caused minor injuries. Of all the crashes, 288 occurred on roads with a 1 or 2-star safety rating, 94.4% of them resulting in fatal and serious injuries. On the other hand, 179 crashes occurred on safer roads with 3-star or higher safety ratings.

According to **Table 5.3**, $CLASSI$ roads make up 43.2% of the road network, which is equivalent to 204.1 km. $CLASSI$ roads can be further categorized into $CLASSI(A)$, $CLASSI(B)$, and $CLASSI(C)$, with level vectors of $(1, 1, 1)$, $(1, 2, 1)$, and $(1, 3, 1)$, respectively. The length of these subcategories is 15.5 km (3.3%), 15.5 km (3.3%), and 16.3 km (3.4%), respectively. $CLASSI$ roads also include $CLASSI(D)$ and $CLASSI(E)$, which have level vectors of $(2, 1, 2)$ and $(3, 1, 3)$, respectively. These roads cover 24.6 km (5.2%) and 132.2 km (28%), respectively. In addition, $CLASSII$ roads make up 37.4% of the road network, equivalent



(a) Pavement deterioration curves.



(b) Dispersion of pavement deterioration rates as expressed by heterogeneity factor's histogram and gamma distribution.

Figure 5.5: Heterogeneous deterioration among pavement sections.

Table 5.3: Critical road sections' proportion in the road network

CLASS		Length (km)	Percentage (%)
CLASS I	A	15.5	3.3
	B	15.5	3.3
	C	16.3	3.4
	D	24.6	5.2
	E	132.2	28
	Total	**204.1**	**43.2**
CLASS II	A	25.3	5.4
	B	20.8	4.4
	C	130.3	27.6
	Total	**176.4**	**37.4**
CLASS III		**92**	**19.5**

to 176.4 km. The least critical category of roads, $CLASSIII$, makes up 19.5% of the road sections, equivalent to 92 km. The map in **Figure 5.6** presents the distribution of critical sections in the road network.

5.4 Discussion

The case study results show that it is crucial to consider the deterioration rate and infrastructure safety factors to assess pavement performance and safety proactively. Additionally, analyzing crash history can assist in identifying the root causes of crashes. The results also show the advantages of using a hierarchical decision matrix approach when resources are limited. This section focuses on discussing the findings of the case study.

It is a common practice to consider a highly deteriorated pavement as a critical sections and prioritization based on the level of deterioration for maintenance and repair. This approach follows corrective action than preventive. However, identifying critical road sections based on the deterioration rate allows early detection of sections with a relatively faster deterioration trend. The difference in deterioration rate among road sections is inevitable due to their heterogeneity. Consequently, the expected lifespan of the pavement network ranges from 2.4 to 10.7 years, with an average of 6 years. The variation in the lifespan is reflected in the heterogeneity factor, which

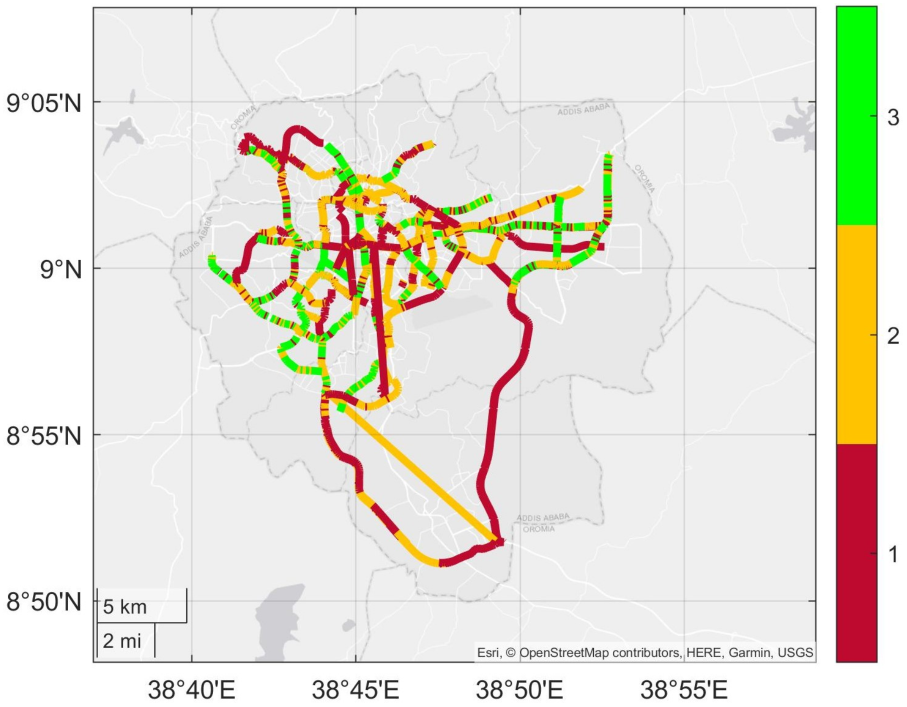


Figure 5.6: Critical Sections road network map.

ranges from 0.68 to 2.16. This means that some sections deteriorate much faster than others, with rates that are more than twice the average. The case study results support the importance of using the deterioration rate to identify critical sections, considering the heterogeneity property, instead of relying on prioritization based on the level of deterioration.

If critical sections are identified based on pavement condition ranks, pavements with "very poor" and "poor" conditions would be given the highest priority since they are highly deteriorated. However, while evaluating the network using the deterioration rate only 20% of the road sections in the level 1 ($D1$) category are in the highly deteriorated state, whereas 80% are in "fair" or better conditions. Similarly, 81% of level 2 ($D2$) pavement sections are in fair and better condition. These results indicate that even if the pavement condition of the road sections is relatively good, they are deteriorating at an alarming rate. In other words, these sections can potentially reach the worst condition in a relatively short time if no action is taken. Therefore, early identification of sections with high deterioration speed can benefit road authorities to investigate the reason and take timely actions.

Moreover, the result showed that pavements with the fastest and the slowest deterioration rate were in the same pavement condition. Despite having a similar "good" condition, these sections had life expectancies of 2.4 and 10.7 years, respectively. This emphasizes the importance of using a deterioration rate to identify critical sections. If these two sections had been evaluated only based on their current pavement condition states they would receive the same level of attention. However, considering their deterioration rates, the section with the highest rate requires the most attention, while the other requires the least. Therefore, utilizing a deterioration rate helps to account for the variation in deterioration among the road sections due to heterogeneity, regardless of their current condition.

The case study results of the safety analysis revealed a correlation between the infrastructure safety level and crashes. It was found that the majority of crashes, specifically 61.7%, occurred on unsafe road sections. These crashes also resulted in fatal or serious injuries 94.4% of the time, which is consistent with an earlier study [31]. Therefore, this emphasizes the need for actions to improve the infrastructure safety of roads with 1 or 2-star safety ratings. Even if other factors contribute to crashes, enhancing the road infrastructure's safety can reduce the severity of crashes. The remaining 38.3% of crashes occur on road sections with safe infrastructure conditions. Therefore, it is essential to investigate these incidents to determine their underlying causes and develop appropriate safety policies and regulations.

According to the case study, 43.2% of the network, which is equivalent to 204.1 km, is classified as $CLASSI$ criticality level and requires urgent attention and detailed investigation. However, addressing all critical sections might be difficult in some situations due to resource constraints. In such cases, it is necessary to have a hierarchy of priority within each category as described in the methodology section. For example, an authority may decide to address the critical sections in phases, with the priority given to the first three subclasses of $CLASSI$. In doing so, the critical sections requiring immediate attention can be reduced to 47.3 km from 204.1 km which gallows for the concentration of resources to the 10% of the network that demands the most urgent attention.

5.5 Conclusions

In this chapter, a decision matrix to facilitate a proactive road asset management strategy toward providing safe and effective transportation was proposed. By using the pavement deterioration rate obtained using the MMH model as a basis for detecting road sections with a high rate of deterioration, it is possible to investigate the cause in detail and take prompt action. Similarly, using the iRAP star rating in evaluating infrastructure safety enables the identification of high-risk road sections considering all road user groups, allowing appropriate action to be taken before traffic crashes occur. As demonstrated in the case study, this approach effectively identifies critical road sections in advance, favoring preventive measures over corrective ones and ultimately saving economic and social costs. Moreover, incorporating the crash history into the analysis provides initial insight to investigate the potential causes of traffic crashes, which can be used to inform the development of road safety policies and regulations.

The case study indicates that using the matrix approach is advantageous in making informed decisions when identifying critical sections instead of relying on a single factor. Specifically, this was evident in 132.2 kilometers of road sections categorized as $CLASSI(E)$, where they were deemed a high priority when evaluated using three factors but would be of lower priority if pavement deterioration alone was considered. The study also emphasized the importance of selecting an appropriate performance indicator within the matrix formulation. The results revealed that road sections with the same pavement conditions could be ranked as the most or least critical, up on using deterioration rate as a performance indicator. As a result, the proposed matrix approach provides a comprehensive strategy for identifying critical sections considering relevant factors and their performance indicators.

The suggested approach is applicable at various levels of decision-making. The macro-level decision matrix classifies criticality into three categories at the network level, allowing for an overall evaluation of resource needs. Meanwhile, the micro-level decision matrix divides criticality into nine categories, providing detailed information on required actions. The micro-level decision matrix helps with resource allocation by fine-tuning re-source labeling. This hierarchical approach assists road authorities in planning actions within resource constraints. Furthermore, the approach offers a chance to consider other parts of the road in addition to the pavement that is necessary for the safety of non-motorized road users since the safety evaluation is conducted separately for each group of road users, and the course of action is determined based on the assessment. As a result, the proposed decision matrix can be effectively used to ensure safe and efficient mobility.

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Chapter 6

Conclusions

6.1 Brief Summary

This study is motivated by the purpose of tackling the devastating impact of road traffic crashes at individual, national, and global levels. The burden of these crashes is particularly severe in LICs and MICs, which requires attention from academia and other stakeholders. The increase in the number and severity of traffic crashes has led governments and academia to adopt a new approach, the safe system approach, which views road users, road infrastructure, and vehicles as a system. This research focuses on one component of the safe system approach: road infrastructure. After examining research efforts and analyzing gaps, the need to integrate road safety into the decision-making process for road maintenance was identified as an area that requires further study to realize safer road infrastructure. This study can contribute to making road networks safer by providing road agencies with guidance on integrating safety into maintenance decision-making processes. It can also serve as a reference framework for academia to conduct further research and contribute to sustainable development by reducing the economic and health crises associated with traffic crashes. The first two chapters of the dissertation cover details on the impacts of traffic crashes, the safe system approach, the objective, and literature reviews.

The main purpose of this research is to create a comprehensive framework that systematically incorporates road safety into the decision-making process for road maintenance. To achieve this goal, the study proposes three analytical decision support frameworks that specifically target major decisions in the road maintenance process. These frameworks are designed to meet the three specific objectives of the research for integrating safety into road maintenance. The first framework, discussed in Chapter 3, is aimed at integrating safety considerations into strategic road maintenance decision. The second framework, discussed in Chapter 4, seeks to improve traditional maintenance prioritization methods by including road safety factors. The third framework, presented in Chapter 5, proposes a proactive approach to identify critical road sections while considering road safety. Together, these three frameworks address the specific objectives of the study and collectively contribute to the overall objective of the dissertation, which is to develop a framework that integrates road safety into the road maintenance decision process. By using these analytical frameworks, decision-makers can make informed decisions that prioritize safety, ultimately leading to safer road networks.

The analytical methods presented were empirically illustrated with data from Addis Ababa, Ethiopia, to assess their practicality and compare them with the conventional maintenance decision-making practices. These frameworks provide a comprehensive approach to maintenance decision-making, covering strategic decisions, prioritization, and identifying critical sections for detailed monitoring and early action. The issues aimed to address in each framework, the formulation of the analytical frameworks, and the outcomes of their empirical analysis were discussed in their respective chapters.

6.2 Conclusions

This study encompasses both academic contributions and practical applications. On the academic front, the research sought to advance the theoretical understanding of road safety and road network maintenance management. This is achieved by developing an innovative safety-oriented framework, paving the way for further exploration and refinement within the academic community.

Simultaneously, the study was equally dedicated to practical implications, aiming to create a framework that road agencies and policymakers could readily implement. Given the limitations in resources, especially in the LICs and MICs, the study considered models and approaches that are effective and easy to implement and automate. Doing so makes the framework more accessible and usable, even for agencies with limited technical expertise or funding.

One of the significant advantages of the proposed framework is its potential impact on policymaking. By incorporating data-driven insights, policymakers can make well-informed decisions when formulating road safety policies and efficient decision-making concerning road network level of service. This approach ensures that policy decisions are based on evidence rather than solely on intuition or historical practices. The study emphasizes the importance of involving road agencies in implementing the proposed framework. These organizations are vital stakeholders responsible for the actual execution of policies and projects. By actively using the framework, road agencies can make optimal decisions regarding budget allocation, maintenance strategies, and project selection, resulting in more efficient and effective road management. The inclusion of a preventive maintenance scheme and emphasis on traffic safety not only have potential cost-saving implications but also offer the opportunity to save lives and bolster national economies.

In summary, this study offers a comprehensive framework that, when embraced and effectively implemented by policymakers and road agencies, can lead to transformative changes in road safety, road maintenance practices, and resource allocation. By providing practical and data-driven solutions, this research aims to make a real difference in how road networks are managed and maintained, benefiting societies and economies. This framework's successful implementation and seamless adaptation depend on policymakers and road agencies embracing and utilizing it to maximize its effectiveness. Some brief concluding points on the significance of the framework are highlighted as follows:

1. The proposed maintenance decision support framework enhances the conventional single-objective road maintenance planning practice, especially in LICs and MICs, by integrating road safety.

2. The analytical models used to create the framework are highly customizable to specific traffic characteristics, resource constraints, and the overall situation of the road agency.

3. The framework can address challenges specific to LICs and MICs, such as a lack of data on road pavement and crashes.

4. The analytical framework favors preventive measures over corrective ones, ultimately saving economic and social costs.

5. The case study results indicated that the proposed safety-integrated approach enhances road user safety by significantly reducing fatality and serious injury compared to the conventional approach.

6. The proposed approach considers the safety of non-motorized road users, making the maintenance decision-making process more inclusive than conventional practices.

7. By incorporating crash history into the analysis, the framework can provide insight into the causes of traffic crashes, informing the development of road safety policies and regulations.

8. The framework is designed for hierarchical decision-making, making it suitable for micro and macro-level road maintenance decisions.

6.3 Further Research

The analytical model used in developing the framework for road safety analysis follows a deterministic approach. However, the risk associated with the deterioration of road infrastructure features is a stochastic process that worsens with time. Similarly, safety countermeasures are assumed to perform perfectly during their design life, but their effectiveness decreases over time. Thus, exploring the stochastic effects of the deterioration of road infrastructure features and safety countermeasures on the overall safety of road sections is an interesting area for further research.

Selecting safety countermeasures is a subjective process that allows decision-makers to choose possible countermeasures within available resources such as finances and expertise. However, selecting optimal countermeasure sets from a vast array of options is not guaranteed. Therefore, further research is needed to optimize countermeasure choices to make effective and objective decisions.

Future research could also evaluate the efficiency and effectiveness of implementing the proposed framework compared to the reactive approach under different circumstances. Additionally, identifying the main factors responsible for the heterogeneity of pavement sections, particularly those with high deterioration rates, could be a valuable area of investigation.