ADDIS COLLEGE

A FUZZY TOPSIS MODEL APPROACH FOR ROAD MAINTENANCE MANAGEMENT STRATEGY SELECTION: THE CASE OF ADDIS ABABA CITY ROADS AUTHORITY

A THESIS SUBMITTED TO THE PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN CONSTRUCTION TECHNOLOGY AND MANAGEMENT

BY: ADMASU SHIFERAW BEKELE

ADVISOR: DR. BAHIRU BEWKET MITIKIE

SEPTEMBER, 2025

ADDIS ABABA, ETHIOPIA

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DECLARATION AND CONFIRMATION

Declaration

I hereby declare that this thesis paper titled " A FUZZY TOPSIS Model Approach for Road Maintenance Management Strategy Selection: The Case of Addis Ababa City Roads Authority" is my original work. This study has not been submitted for any degree or examination at any other university or institution. All sources of information and data used in this work have been properly acknowledged and referenced.

Student's Name	Signature	Date
Admasu Shiferaw Bekele	_________	___________

Confirmation

The thesis can be submitted for examination with my approval as an advisor.

Advisor's Name	Signature	Date
Dr. Bahiru Bewket Mitikie	_____________	_03 September 2025

ADDIS COLLEGE

SCHOOL OF GRADUATE STUDIES IN

CONSTRUCTION TECHNOLOGY AND MANAGEMENT

This is to certify that the thesis entitled:

“A FUZZY TOPSIS Model Approach for Road Maintenance Management Strategy Selection: The Case of Addis Ababa City Roads Authority”

Submitted to Addis College, in partial fulfillment of the requirements for the degree of Master of Science in Construction Technology and Management, has been carried out by **Admasu Shiferaw Bekele**, under the supervision of **Dr. Bahiru Bewket Mitikie**.

We hereby declare that this thesis is the original work of the candidate and has not been presented for a degree in any other university, and that all sources of materials used for the thesis have been duly acknowledged.

We approve that this thesis meets the required standards and is therefore accepted.

APPROVED BY THE BOARD OF EXAMINATION

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ABSTRACT

Road infrastructure deterioration poses a significant challenge in Addis Ababa, where maintenance strategies are often selected without systematic evaluation, leading to high costs and reduced service life. The objective of this study was to identify the most suitable road maintenance strategy by applying a structured multi-criteria decision-making framework. A quantitative research design with a mixed approach was adopted, combining expert judgment and fuzzy modeling. The sample consisted of 20 purposively selected professionals from the Addis Ababa City Roads Authority (AACRA) and affiliated agencies, chosen for their technical expertise in road design, construction, and maintenance. Primary data were collected through expert questionnaires using linguistic scales, while secondary data were obtained from institutional reports and relevant literature. The Fuzzy TOPSIS method was employed to evaluate three alternative maintenance strategies: Routine, Periodic, and Rehabilitation, against nine criteria: cost-effectiveness, durability, safety improvement, ease of implementation, maintenance frequency, economic impact, life cycle cost, environmental impact, and time efficiency. Results revealed that Periodic Maintenance had the highest Closeness Coefficient (0.617), indicating superior suitability under current conditions, followed by Routine (0.416) and Rehabilitation (0.415). The study concludes that adopting Periodic Maintenance provides a cost-effective and sustainable solution, supporting better decision-making for road asset management.

Keywords: Road maintenance, Research design, Fuzzy TOPSIS, Sample design, Pavement management

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LIST OF ACRONYMS

AACRA ---------------- Addis Ababa City Roads Authority

AASHTO ---------------American Association of State Highway and Transportation Officials

AHP--------------------- Analytic Hierarchy Process

ANP--------------------- Analytic Network Process

BWM -------------------Best-Worst Method

CC----------------------- Closeness Coefficient

CEP---------------------Corporate Environmental Performance

DM ---------------------- Decision-Making

EI------------------------ Extremely Important

FNIS--------------------- Fuzzy Negative Ideal Solution

FPIS--------------------- Fuzzy Positive Ideal Solution

GDP ---------------------Gross Domestic Product

HI----------------------- Highly Important

HMA -------------------- Hot Mix Asphalt

LI------------------------ Low Important

LPFS--------------------- For linguistic Pythagorean fuzzy sets

MACBETH------------- Measuring Attractiveness by a Categorical-Based Evaluation Technique

MCA----------------------multi-criteria Analysis

MCDM------------------ multi-criteria Decision-Making

MI------------------------ Moderately Important

PCI------------------------Pavement Condition Index

PFS----------------------- Pythagorean Fuzzy Sets

TFN---------------------- Triangular Fuzzy Number

TOPSIS-------------------Technique for Order Preference by Similarity to Ideal Solution

VIKOR--------------------VIšekriterijumsko KOmpromisno Rangiranje (Multicriteria Optimization and Compromise Solution)

VLI------------------------- Very Low Important

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

Roads are the foundation of urban growth and are essential for connectivity, transportation, and business. Road infrastructure that is well-maintained promotes economic growth, enhances mobility, and safeguards the public. However, in many cities worldwide, the performance of road networks is being strained by the increasing demand for road infrastructure, financial constraints, and environmental concerns. User safety issues, rising transportation costs, and deteriorating road conditions are often the consequences of these challenges.

Effective road maintenance management has therefore become essential. By strategically planning maintenance activities, cities can extend the service life of roads, reduce repair costs, improve safety, and increase user satisfaction. Yet, road maintenance is inherently complex, involving multiple competing criteria such as cost, durability, safety, environmental impact, and time efficiency. Making the right decisions requires a structured and informed approach.

In this context, sophisticated multi-criteria decision-making (MCDM) techniques are useful, such as the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). Fuzzy TOPSIS helps decision-makers deal with subjectivity and uncertainty by incorporating fuzzy logic into conventional MCDM frameworks, particularly in situations when qualitative assessments or insufficient data are required.

This problem is particularly noticeable in places like Ethiopia's capital, Addis Ababa, where major infrastructure maintenance problems have been brought on by growing traffic, financial constraints, and urbanization. Because of increased safety concerns, deteriorating road quality, and growing transportation expenses, Addis Ababa's roads are performing poorly. A strong, open, and effective framework for maintenance decision-making is necessary to address these problems.

In response to this demand, this study uses the Fuzzy TOPSIS approach to provide a decision-making framework for road repair management in Addis Ababa. The framework compares several factors, such as cost effectiveness, durability, safety, environmental impact, ease of execution, and time efficiency, to evaluate important maintenance options, such as routine maintenance, periodic maintenance, and full rebuilding. Significantly, stakeholder perceptions are also taken into account to ensure that the chosen methods meet the requirements and expectations of the local community.

Within the operational context of the Addis Ababa City Roads Authority (AACRA), the Fuzzy TOPSIS-based approach provides a systematic and objective model for prioritizing and selecting road maintenance strategies. By accommodating multiple criteria and addressing uncertainties, this method enhances the overall effectiveness, transparency, and resource efficiency of road maintenance planning in Addis Ababa.

1.2. Statement of the Problem

Roads are the foundation of any modern city, and in a bustling, fast-growing urban centre like Addis Ababa, they are critical. Every day, thousands of people rely on the city's road network to get to work, transport goods, access healthcare, and connect with the broader economy. However, despite their importance, Addis Ababa's roads are struggling to keep up with the demands placed on them.

The road infrastructure in Addis Ababa plays a vital role in the city's economy and daily life by facilitating the movement of both people and goods. However, the system faces significant challenges due to rapid urbanization, increasing traffic, and inadequate maintenance(AACRA, 2004; World & Bank, 2020). Many roads show visible signs of deterioration, such as potholes, cracks, and uneven surfaces, which not only compromise safety but also raise vehicle operating costs (R. Robinson, Danielson, U., et al., 1998). At the same time, growing concerns about environmental sustainability and road safety highlight the urgent need for maintenance strategies that are both durable and environmentally conscious(AASHTO, 2012; Alawaysheh, Alsyouf, Tahboub, Almahasneh, & Management, 2020a).

The Addis Ababa City Roads Authority (AACRA) is responsible for the construction and upkeep of the city's roads. Yet, due to limited resources, AACRA is forced to prioritize its maintenance efforts, which often results in a shortfall in addressing the growing need for well-maintained roads(AACRA, 2004; Zhang, 2003). Currently, the decision-making process for selecting maintenance strategies is largely subjective and lacks a structured framework. There are no standardized criteria for assessing road conditions, and expert judgments are often ambiguous, further undermining the effectiveness of maintenance planning (Fraser, Hvolby, Tseng, & Management, 2015).

AACRA's existing approach to road maintenance is mostly manual and reactive. This leads to delays in addressing road damage and inefficient use of resources. Without a centralized system to monitor and manage road maintenance activities, it becomes difficult to identify and respond to areas in urgent need of repair. Visual inspections, the primary method used to assess road conditions, are often inconsistent and unreliable (Bosurgi, Pellegrino, Ruggeri, Rustica, & Sollazzo, 2024; R. Robinson, Danielson, U., et al., 1998). The lack of a systematic planning method has resulted in poor allocation of resources and insufficient attention to critical maintenance needs (Gul & Ak, 2021).

Making decisions about road maintenance is inherently complex, involving multiple, often conflicting, factors such as cost-effectiveness, durability, safety, environmental impact, ease of implementation, frequency of maintenance, economic outcomes, life-cycle costs, and time efficiency (Gul & Ak, 2021; Yaohan Liu et al., 2024). Traditional decision-making methods struggle to account for uncertainty and personal bias, often producing less-than-ideal results. The absence of a structured system to weigh these criteria and include stakeholder perspectives only adds to AACRA’s difficulties.

To address these issues, this research proposes the use of the Fuzzy TOPSIS technique. This method incorporates fuzzy logic to manage uncertainty and rank maintenance alternatives more accurately(L. A. Zadeh, 1965). By considering a range of factors from cost and durability to environmental and economic impacts, Fuzzy TOPSIS provides a transparent and systematic framework for making informed maintenance decisions(Ayalew, Meharie, & Worku, 2022). Implementing this approach aims to improve the efficiency, quality, and transparency of AACRA's road maintenance decisions. Ultimately, this research supports AACRA in adopting a comprehensive solution that enhances the sustainability and performance of Addis Ababa’s Road network while tackling its most pressing infrastructure challenges.

The motivation for this research arises from the increasing challenges faced in managing road maintenance in rapidly growing cities like Addis Ababa. As road conditions deteriorate due to rising traffic and limited resources, effective decision-making becomes crucial. Traditional methods often fail to address the uncertainty and complexity involved in selecting maintenance strategies. Therefore, this study adopts the Fuzzy TOPSIS approach to better handle multiple, conflicting criteria and uncertain expert judgments. The aim is to support the Addis Ababa City Roads Authority in prioritizing and selecting optimal road maintenance strategies more effectively.

In summary, the developing infrastructure issue in Addis Ababa is the subject of this study. It is more important than ever to make the appropriate choices about road maintenance because of the increasing traffic and the limited resources. Through the implementation of a methodical, open, and flexible framework, this research aims to assist AACRA in enhancing the effectiveness, sustainability, and general performance of its road maintenance operations.

1.3. Research Objectives

1.3.1. General Objectives

The General Objective of this study is to develop a comprehensive decision-making framework using the Fuzzy TOPSIS method to prioritize road maintenance strategies based on multiple factors for the Addis Ababa City Roads Authority.

1.3.2. Specific Objectives

- To identify the critical factors influencing road maintenance decisions.
- To prioritize the identified factors based on their relative importance.
- To evaluate various road maintenance strategies using the Fuzzy TOPSIS method.
- To determine the most suitable road maintenance strategy for different scenarios based on the evaluation results.

1.4. Research Questions

- What are the critical factors that influence road maintenance decision-making in Addis Ababa?
- How can these factors be prioritized based on their relative importance to road maintenance planning?
- How can the Fuzzy TOPSIS method be applied to evaluate and compare different road maintenance strategies?
- Which road maintenance strategy is the most suitable under different decision-making scenarios in Addis Ababa?

1.5. Significance of the Study

This research has academic and practical policy implications. It provides the Addis Ababa City Roads Authority with a structured, data-driven decision-support tool that helps them prioritize road maintenance plans more effectively from a policy perspective. By combining several factors, including durability, cost-effectiveness, safety, and environmental impact, the framework based on fuzzy TOPSIS provides more transparent, resource-efficient, and sustainable infrastructure planning. This may result in better public funding distribution, more road safety, and longer urban road service life.

Academically, the research contributes to the growing body of knowledge on multi-criteria decision-making (MCDM) in infrastructure management, particularly in the context of developing urban environments. It demonstrates how fuzzy logic can be applied to address uncertainty in complex decision-making processes, and offers a replicable model that can inform future studies and applications in similar contexts both within Ethiopia and internationally.

1.6. Scope of the Study

The scope of this study defines the boundaries of the research in terms of the thematic, spatial, and temporal aspects. It helps to clarify the areas addressed by the research and the limitations that may occur due to these boundaries.

1.6.1. Thematic Scope

The thematic scope of this study presents several notable strengths. By employing a Multi-Criteria Decision-Making (MCDM) framework using the Fuzzy TOPSIS method, the research introduces a structured and objective approach to prioritizing road maintenance strategies. This methodology is particularly valuable as it accounts for the inherent uncertainty and subjectivity in human judgment using fuzzy logic and linguistic variables. Additionally, the inclusion of a wide range of evaluation criteria, such as cost-effectiveness, durability, safety, environmental impact, and life cycle cost, ensures a holistic assessment aligned with the practical needs of urban road asset management. The focus on Addis Ababa further enhances the study's contextual relevance, offering practical insights for decision-makers in the city. However, the study is not without limitations. Its geographic focus may restrict the generalizability of findings to other regions with different infrastructure or socio-economic conditions. Moreover, while fuzzy logic addresses some uncertainty, the reliance on expert input introduces a degree of subjectivity. The model also provides a static evaluation, potentially overlooking dynamic factors such as evolving traffic patterns or policy changes. Lastly, the technical complexity of the Fuzzy TOPSIS method may limit its accessibility to practitioners without specialized training. Despite these constraints, the study makes a valuable contribution by offering a structured, adaptable, and context-sensitive decision-support tool for road maintenance planning.

1.6.2. Spatial Scope

The spatial scope of this study is confined to the road network within Addis Ababa, the capital city of Ethiopia. As a rapidly expanding urban centre, Addis Ababa faces numerous challenges in road maintenance, driven by increasing traffic volumes, diverse environmental conditions, and ongoing urban development.

The Addis Ababa City Roads Authority (AACRA) oversees a total of 7,470.11 kilometres of roads, categorized by pavement type. This includes 3,250.07 km of asphalt roads, 2,647.17 km of cobblestone roads, 792.22 km of gravel roads, 145.41 km of care stone roads, and 635.25 km of earth roads, all typically built to a standard width of seven meters. Among these, asphalt roads make up the largest share, accounting for approximately 43.5% of the city's total road network.

1.6.3. Temporal Scope

The temporal scope outlines the period during which the study is conducted and the data analysed:

Study Period

The temporal scope of this research centres on current road maintenance strategies and decision-making processes. The study takes into account recent developments in maintenance techniques and updated regulations and standards, with a focus on data and practices up to 2024.

The temporal scope of this study encompasses three key timeframes: historical context, current analysis, and future implications. The historical context involves a review of past road maintenance data and strategies to identify trends, challenges, and performance outcomes that have shaped current practices. The current analysis focuses on evaluating the present state of road maintenance, considering stakeholder priorities, operational practices, and real-time decision-making challenges faced by the Addis Ababa City Roads Authority. Finally, the future implications of the study aim to provide informed recommendations for medium to long-term road maintenance planning, taking into account projected traffic growth, budgetary limitations, and anticipated environmental changes.

1.7. Limitations of the Study

This study is subject to several limitations that define the extent and applicability of its findings. First, the research is geographically limited to the jurisdiction of the Addis Ababa City Roads Authority (AACRA) and does not extend to other regional or national road networks in Ethiopia. As such, the findings may not be directly transferable to other cities or contexts without further adaptation.

Second, the study specifically focuses on the maintenance system of asphalt roads within Addis Ababa. Although AACRA manages various types of roads, including cobblestone, gravel, and earth roads, this research does not evaluate maintenance strategies for those other surfaces. The decision to concentrate on asphalt roads is based on their prevalence (accounting for 43.5% of the city's road network) and their critical importance in supporting the city's transportation needs.

Third, the temporal scope is confined to six years, from 2018 to 2024, during which recent trends, policy changes, and technological advancements in road maintenance are analysed. While this timeframe allows for a focused and up-to-date evaluation, it may not capture long-term impacts or emerging innovations beyond 2024.

Additionally, this study does not introduce any new road maintenance techniques beyond those already implemented by the Addis Ababa City Roads Authority (AACRA). Rather, it aims to evaluate and prioritize the existing strategies, periodic maintenance, routine maintenance, and rehabilitation based on a structured decision-making framework to enhance the effectiveness and efficiency of current practices."

Finally, while the study aims to propose a robust and structured decision-making framework using the Fuzzy TOPSIS method, it relies on expert opinions and subjective judgments, which inherently carry uncertainty and potential bias. Despite the use of fuzzy logic to manage this uncertainty, the accuracy of the results still depends on the quality and consistency of the expert input.

Overall, this study strives to offer a comprehensive framework for assessing and prioritizing asphalt road maintenance strategies in Addis Ababa. However, readers should interpret the findings within the context of the study's defined scope and inherent constraints.

1.8. Structure of the Thesis

This thesis is organized into six chapters, each building upon the previous to develop a comprehensive analysis of road maintenance strategy prioritization using the Fuzzy TOPSIS method. Chapter One introduces the study by outlining the background and rationale, defining the research problem, objectives, and questions, and detailing the scope, limitations, and significance of the study. It also presents a brief overview of the thesis structure. Chapter Two provides a detailed literature review, covering the fundamentals of road maintenance management, Multi-Criteria Decision-Making (MCDM) approaches, and the integration of fuzzy logic to handle uncertainty. Particular focus is placed on the Fuzzy TOPSIS method and its application in infrastructure decision-making. The chapter concludes by identifying research gaps that this study addresses. Chapter Three outlines the research methodology, justifying the selection of Fuzzy TOPSIS and detailing each step in the process, including criteria weighting, fuzzy matrix construction, normalization, and the calculation of closeness coefficients. It also explains the data collection method, which relies on expert judgment and linguistic variables, and presents the conceptual framework guiding the analysis. Chapter Four presents the results of the fuzzy analysis, including the construction of the decision matrix, calculation of fuzzy weights, and the ranking of road maintenance strategies based on the closeness to ideal solutions. The findings are displayed in both tabular and graphical formats. Chapter Five summarizes the key findings, identifies the most suitable maintenance strategy for the Addis Ababa City Roads Authority (AACRA), and discusses practical policy implications. It also outlines study limitations and suggests directions for future research, such as the inclusion of predictive models or broader geographic applications. Finally, Chapter Six contains the appendices and supplementary materials, including raw data tables, expert questionnaires, fuzzy conversion tables (TFNs), Excel analysis tools, and supporting diagrams such as the conceptual framework of the Fuzzy TOPSIS model

1.9. Definition of Key Terms

To ensure clarity and consistency throughout this study, the following key terms are defined as used in the context of this research. Road Maintenance Strategies refer to the planned interventions and techniques applied to preserve or restore road infrastructure performance. Multi-Criteria Decision-Making (MCDM) is a structured approach used to evaluate and prioritize multiple conflicting criteria in complex decision environments. Fuzzy Logic is a mathematical method for handling uncertainty and imprecise information, allowing expert judgments to be expressed through linguistic variables. Fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a specific MCDM method that incorporates fuzzy logic to rank alternatives based on their closeness to an ideal solution. Expert Judgment involves input from knowledgeable professionals used to assign weights and evaluate criteria where precise data may be lacking. Decision Criteria are the factors or attributes (e.g., cost-effectiveness, safety, environmental impact) used to assess and compare alternative strategies. FPIS (Fuzzy Positive Ideal Solution) and FNIS (Fuzzy Negative Ideal Solution) represent the best and worst possible levels of performance across all criteria, used as benchmarks in the Fuzzy TOPSIS analysis. These terms are central to the development and application of the decision-support framework proposed in this study.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

This section lays the groundwork for the study by exploring key themes in road maintenance management, multi-criteria decision-making (MCDM) methods, and the incorporation of fuzzy logic into decision-making processes. By examining these areas, it highlights the relevance and necessity of applying the Fuzzy TOPSIS model to improve how maintenance strategies are selected in the context of Addis Ababa's Road infrastructure.

Effective road maintenance is central to sustainable infrastructure management, directly influencing economic productivity, public safety, and environmental sustainability. When roads are poorly maintained, the consequences are widespread: higher vehicle operating costs, increased accident rates, and elevated greenhouse gas emissions due to inefficient traffic flow. The World Bank (2020) estimates that poor road maintenance in low-income countries can cost up to 1–2% of GDP annually, highlighting the urgent need for more effective and strategic maintenance decision-making.

However, identifying the optimal road maintenance approach is not straightforward. Planners must weigh competing and often conflicting factors, such as initial costs, long-term performance, traffic disruption, environmental impact, and political priorities. Traditional decision-making models, such as cost-benefit analysis or standard MCDM approaches, often fall short in addressing the inherent uncertainty and subjectivity in these evaluations. For example, the widely used Analytic Hierarchy Process (AHP) struggles to handle the linguistic ambiguity found in expert judgments, such as expressions like "high priority" or "moderate risk," which are common in pavement condition assessments.

To address these limitations, the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) presents a promising alternative. This method combines fuzzy set theory, introduced by (L. A. Zadeh, 1965), with the classic TOPSIS model developed by (Hwang, Yoon, Hwang, Yoon, & survey, 1981). By translating vague or imprecise linguistic evaluations into fuzzy numbers (e.g., triangular or trapezoidal membership functions), Fuzzy TOPSIS allows for more nuanced and realistic assessments of alternatives. It evaluates each option based on its closeness to an ideal solution and its distance from the least desirable one, offering a systematic and transparent approach to decision-making under uncertainty.

This literature review synthesizes global research on the application of Fuzzy TOPSIS in road maintenance planning, examines how it compares to other MCDM techniques, and identifies key methodological advantages and limitations. In doing so, it also highlights areas where further research is needed, particularly in adapting and applying these methods to the unique challenges faced by cities like Addis Ababa.

2.2. Theoretical Literature Review

The conceptual framework for this study is grounded in decision-making theory, fuzzy logic, multi-criteria decision-making (MCDM) methodologies, and sustainability principles. These theoretical foundations provide the basis for developing a structured and adaptive model for selecting optimal road maintenance strategies in Addis Ababa.

At the core of this framework is the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS), a method that integrates fuzzy set theory with classical TOPSIS to accommodate uncertainty and imprecision in expert judgment. Traditional decision-making tools often fall short when dealing with subjective assessments, especially in infrastructure management, where criteria such as "ease of implementation" or "environmental impact" are not always quantifiable in precise terms. Fuzzy logic, first introduced by (L. A. J. I. Zadeh & control, 1965), addresses this challenge by enabling the use of linguistic variables and fuzzy numbers to express expert opinions more realistically.

The decision-making theory underpinning this study emphasizes rational evaluation and prioritization of alternatives based on multiple conflicting objectives. In the context of road maintenance, this includes balancing factors such as cost-effectiveness, durability, environmental sustainability, safety, and ease of implementation. MCDM methodologies are particularly suited for this task, as they allow for the structured comparison of options across diverse criteria. Among these, Fuzzy TOPSIS stands out due to its ability to capture the vagueness and ambiguity often present in human decision-making.

Additionally, the framework is informed by sustainability principles, recognizing that road maintenance is not only a technical and economic challenge but also an environmental and social one. Sustainable infrastructure management seeks long-term resilience, reduced ecological footprint, and enhanced public welfare, all of which are integrated into the evaluation criteria used in this study.

In summary, this conceptual framework brings together fuzzy logic, MCDM techniques, decision theory, and sustainability thinking to create a robust and adaptable model for road maintenance planning. The use of Fuzzy TOPSIS enables AACRA and similar agencies to make informed, transparent, and balanced decisions despite limited resources and complex urban challenges.

2.2.1. Critical Factors Influencing Road Maintenance Decisions

2.2.1.1. Introduction

Road maintenance management is a cornerstone of sustainable infrastructure development, as the durability and serviceability of transportation networks directly depend on how well maintenance activities are planned, prioritized, and implemented. Roads are vital to national economies, facilitating mobility, trade, and access to essential services; thus, their deterioration has significant social and economic consequences (R. Robinson, U. Danielson, & M. Snaith, 1998a). Poorly maintained roads increase transport and logistics costs, amplify accident risks, exacerbate environmental damage, and place a heavy burden on public budgets through recurrent repairs. Consequently, decisions regarding road maintenance must be informed by multiple critical factors to ensure effective and sustainable interventions.

2.2.1.2. Road Maintenance Strategies

Existing literature classifies road maintenance strategies into four broad categories: routine maintenance, periodic maintenance, rehabilitation, and reconstruction. Routine maintenance, including pothole patching, surface sealing, and drainage cleaning, is essential for preventing minor defects from escalating into costly structural failures (R. Robinson et al., 1998a). Periodic maintenance involves scheduled treatments such as overlays and surface renewals, preserving pavement functionality before significant deterioration occurs(Hwang & Yoon, 1981). Rehabilitation addresses critical pavement damage through structural strengthening, resurfacing, or full-depth repairs, while reconstruction is reserved for pavements that are irreparably compromised. The selection of a strategy is influenced by a complex interplay of factors, including financial resources, technical feasibility, environmental sustainability, and user needs (Alawaysheh, Alsyouf, Tahboub, Almahasneh, & Management, 2020b; Burningham & Stankevich, 2005).

2.2.1.3. Cost-Effectiveness

Cost-effectiveness is a key determinant in maintenance decision-making. Lifecycle cost analysis (LCCA) evaluates all direct and indirect costs over the pavement's lifespan, including construction, periodic maintenance, user costs from delays or accidents, and eventual reconstruction (Hwang & Yoon, 1981). While routine maintenance may seem costly if performed frequently, it often delays major rehabilitation or reconstruction, producing net savings over the pavement's service life. Conversely, neglecting early preventive actions can accelerate deterioration and result in exponentially higher future costs. Thus, cost-effectiveness is dynamic, depending on the timing, frequency, and quality of maintenance interventions.

2.2.1.4. Technical Feasibility

Technical feasibility is another crucial factor. The appropriateness of a maintenance strategy depends on existing road conditions, available materials, equipment, and construction technologies (F. Wang, Zhang, & Machemehl, 2003). For instance, while hot-mix asphalt overlays may be highly effective, they may be impractical in remote areas lacking asphalt plants. Similarly, advanced reconstruction techniques may be unsuitable in developing countries with limited technical capacity. Maintenance strategies must therefore balance technical soundness with contextual realities, ensuring effective implementation within prevailing resource and infrastructure constraints.

2.2.1.5. Safety Considerations

Safety is integral to road maintenance decisions. Well-maintained roads reduce accident risks by mitigating hazards such as potholes, cracks, rutting, and poor drainage (R. Robinson et al., 1998a). Maintenance interventions should also minimize short-term risks during construction, avoiding unsafe work zones and prolonged traffic diversions. Ultimately, strategies must improve long-term road safety while ensuring minimal disruption to road users during execution.

2.2.1.6. Environmental Impacts

The environmental dimension of road maintenance has gained importance as societies seek to minimize the infrastructure's ecological footprint. Maintenance strategies vary in environmental impact; routine actions like crack sealing generally have low ecological implications, whereas large-scale rehabilitation or reconstruction can generate significant emissions and resource consumption (Alawaysheh et al., 2020b). Moreover, smooth pavement surfaces reduce vehicle fuel consumption and emissions, highlighting the indirect environmental benefits of timely maintenance. Sustainable strategies must, therefore, optimize technical and economic performance while mitigating environmental harm.

2.2.1.7. User Satisfaction

User satisfaction is another critical determinant. Maintenance decisions directly affect travel time, comfort, vehicle operating costs, and overall commuter experience (Burningham & Stankevich, 2005). Roads with frequent defects or prolonged maintenance activities can generate significant frustration and economic loss for users. Incorporating user perspectives into maintenance planning enhances public acceptance and supports long-term infrastructure management goals, aligning with principles of transparency, accountability, and responsiveness.

2.2.1.8. Climatic and Traffic Conditions

Climatic and traffic conditions further influence maintenance decision-making. Roads in areas with extreme weather, such as heavy rainfall, freeze-thaw cycles, or high temperatures, deteriorate more quickly and require tailored interventions (Motlagh, Parsakhoo, Najafi, Mohammadi, & Engineering, 2024). Similarly, traffic volume and load characteristics affect strategy selection; high-traffic urban roads with heavy trucks demand more frequent interventions than low-volume rural roads. Ignoring these factors can lead to premature pavement failures, undermining cost-effectiveness and sustainability.

2.2.1.9. Integrated Decision-Making Framework

In practice, road maintenance decision-making requires balancing multiple, sometimes competing, factors: economic, technical, environmental, safety-related, and user-centred. A strategy that maximizes cost savings may compromise user satisfaction, while environmentally friendly interventions may entail higher initial costs. Therefore, a holistic, multi-dimensional approach that integrates all these factors is essential for sustainable and effective road maintenance management.

2.2.2. Prioritization of Road Maintenance Factors

The process of prioritizing factors in road maintenance is a crucial element in infrastructure management, as it determines which strategies are adopted, how resources are allocated, and what long-term impacts can be achieved in terms of sustainability and economic growth. Since road agencies often face financial constraints and competing demands, the ability to rank maintenance factors systematically provides the foundation for rational and evidence-based decision-making (Burningham & Stankevich, 2005). Without structured prioritization, road maintenance often becomes reactive rather than preventive, leading to higher lifecycle costs and more rapid deterioration of assets (Haas & Hudson, 2015). Therefore, the application of systematic prioritization frameworks, especially those grounded in decision science, has been increasingly emphasized in both developed and developing countries (F. Wang et al., 2003).

2.2.2.1. Importance of Prioritization in Road Maintenance

Prioritization is not merely a technical exercise but also a socio-economic necessity. Roads are subject to varying levels of traffic, climatic conditions, and environmental stressors, which create heterogeneity in maintenance needs. For example, high-traffic corridors may require immediate intervention due to safety risks, while rural roads may be deprioritized despite their social importance (R. Robinson et al., 1998a). Given these competing demands, prioritization frameworks ensure that decision-making aligns with overarching goals such as maximizing economic return, ensuring road safety, and promoting equitable accessibility (Haas, Hudson, & Zaniewski, 1994). By integrating multiple perspectives, economic, technical, social, and environmental, road agencies can balance short-term operational needs with long-term sustainability (Alawaysheh et al., 2020b).

2.2.2.2. Multi-Criteria Decision-Making (MCDM) Approaches

Multi-Criteria Decision-Making (MCDM) provides a systematic way of evaluating and ranking competing factors under uncertainty. Traditional cost-benefit analysis, while useful in assessing direct financial implications, often fails to incorporate qualitative and subjective dimensions such as user satisfaction or environmental impact (Triantaphyllou, 2000). MCDM methods address this gap by allowing the integration of both quantitative and qualitative criteria into the decision-making framework. Techniques such as the Analytic Hierarchy Process (AHP), Best-Worst Method (BWM), Grey Relational Analysis (GRA), and Multi-Attribute Utility Theory (MAUT) have been widely applied to infrastructure decision-making because they accommodate complexity and subjectivity (Saaty, 1980). The adoption of these methods reflects the shift in road maintenance management from deterministic approaches to more flexible and inclusive frameworks.

2.2.2.3. Analytic Hierarchy Process (AHP) and Its Applications

The Analytic Hierarchy Process (AHP), developed by (Saaty, 1980), remains one of the most widely applied MCDM techniques in infrastructure management. AHP decomposes complex decision problems into a hierarchical structure of criteria and sub-criteria, enabling decision-makers to compare elements pairwise. In road maintenance, AHP has been extensively used to weigh the relative importance of cost, safety, environmental impact, and technical feasibility (Khichad, Vishwakarma, Gaur, Sain, & Technology, 2024). However, one major limitation of AHP lies in its reliance on exact numerical comparisons, which often fail to capture the uncertainty inherent in human judgment. To address this, extensions such as Fuzzy AHP have been developed, incorporating fuzzy set theory to better accommodate imprecise assessments (Chang, 1996). Studies in transportation have shown that Fuzzy AHP provides more reliable and consistent prioritization compared to classical AHP, especially when expert opinions are subjective and linguistically expressed (Wen, Liao, Zavadskas, Antuchevičienė, & Management, 2021).

2.2.2.4. Best-Worst Method (BWM) and Comparative Advantages

The Best-Worst Method (BWM) is a more recent MCDM technique introduced by (Rezaei, 2015) that reduces the number of pairwise comparisons required compared to AHP. This makes BWM particularly attractive for infrastructure projects involving large numbers of criteria, as it enhances consistency while lowering the cognitive burden on experts. In the context of road maintenance, BWM has been applied to prioritize safety, cost, and durability factors more efficiently than traditional approaches (Mohammed Abdelkader et al., 2023). Furthermore, hybrid models that combine BWM with other ranking methods, such as VIKOR or TOPSIS, have been found to produce more robust outcomes in evaluating maintenance alternatives (Hasan, Jaber, & Research, 2024). Compared to AHP, BWM's advantage lies in its efficiency and reduced subjectivity, although it is still relatively less explored in road management literature.

2.2.2.5. Fuzzy Logic in Prioritization

The integration of fuzzy logic into prioritization frameworks represents a major advancement in handling uncertainty in road maintenance decision-making. Since maintenance decisions often rely on expert opinions that are vague or qualitative, fuzzy set theory, introduced by (L. A. J. I. Zadeh & control, 1965), provides a mathematical basis for expressing linguistic judgments such as "high cost," "moderate durability," or "low environmental impact." In practice, fuzzy logic has been combined with AHP, BWM, and TOPSIS to improve the reliability of prioritization outcomes (Kahraman, Cebeci, & Ulukan, 2003). For example, fuzzy AHP allows experts to use triangular fuzzy numbers instead of precise ratios, thereby capturing the imprecision of real-world assessments. Similarly, fuzzy TOPSIS has been applied to rank road maintenance strategies under uncertainty, showing higher stakeholder satisfaction compared to crisp methods. Thus, fuzzy logic enhances the adaptability of prioritization frameworks to complex and uncertain environments.

2.2.2.6. Alternative MCDM Methods

Beyond AHP, BWM, and fuzzy-based approaches, several other MCDM methods have been applied in road infrastructure prioritization. Grey Relational Analysis (GRA) is particularly effective in situations with incomplete or uncertain data, making it suitable for developing countries where information availability is limited (Julong, 1989). MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) provides another alternative by converting qualitative judgments into numerical scales for transparent decision-making (DE CORTE, VANSNICK, & Making, 2012). Additionally, hybrid approaches such as AHP–TOPSIS, AHP–ELECTRE, and FBWM–VIKOR have been developed to combine the strengths of weighting and ranking methods, thereby producing more consistent and defensible prioritizations (Sayadinia, Beheshtinia, &

Management, 2021). Each method carries its own advantages and limitations, underscoring the need for context-specific selection.

2.2.2.7. Case Studies Across Countries

Several empirical studies highlight the global relevance of prioritization frameworks in road maintenance. In Ethiopia, (Ayalew et al., 2022) applied a hybrid fuzzy AHP–TOPSIS model to evaluate alternatives such as pothole patching, crack sealing, and overlays, with periodic maintenance emerging as the most effective strategy. In Turkey, the application of fuzzy TOPSIS reduced decision-making time by 20% compared to AHP while improving stakeholder consensus (Yuan Liu et al., 2021). Similarly, in India, Gupta and Jha (2019) demonstrated the usefulness of BWM in prioritizing maintenance projects for urban roads, showing higher consistency in judgments compared to AHP. These cases illustrate how prioritization is not a one-size-fits-all process but must be adapted to specific environmental, financial, and institutional contexts.

2.2.2.8. Governance and Policy Implications

The prioritization of road maintenance factors also has significant governance and policy implications. Transparent decision-making frameworks enhance accountability and reduce the influence of political bias in resource allocation (Heggie & Vickers, 1998). Furthermore, prioritization tools help align road agency objectives with broader policy goals such as sustainable urban mobility, climate change adaptation, and regional equity (Bank, 2018). By adopting scientifically grounded prioritization methods, road authorities can justify budget allocations to stakeholders and secure international funding for infrastructure projects. Thus, the use of prioritization is not merely technical but also political, shaping the legitimacy and effectiveness of public institutions.

2.2.3. Evaluation of Road Maintenance Strategies Using Fuzzy TOPSIS

2.2.3.1. Introduction

Evaluating road maintenance strategies is an essential component of infrastructure management, as transportation agencies must decide how to allocate limited resources among competing maintenance needs. Traditional approaches to strategy evaluation often rely on deterministic cost-benefit analysis, which tends to oversimplify decision contexts characterized by uncertainty and subjective judgments. To address these limitations, decision-making techniques that integrate fuzzy set theory and multi-criteria decision-making (MCDM) have gained prominence. Among these, the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) has been widely applied due to its flexibility, transparency, and robustness in handling complex and uncertain evaluations (Kahraman et al., 2003).

2.2.3.2. Theoretical Foundation of Fuzzy TOPSIS

TOPSIS was first introduced by (Hwang et al., 1981) as a method to rank alternatives based on their relative closeness to an ideal solution. The central concept is that the most suitable alternative should have the shortest distance from a Positive Ideal Solution (PIS) and the farthest distance from a Negative Ideal Solution (NIS). While classical TOPSIS is effective in deterministic contexts, it faces limitations when inputs are vague or subjective. To overcome this, fuzzy set theory, pioneered by (L. A. J. I. Zadeh & control, 1965), is integrated with TOPSIS to create Fuzzy TOPSIS, enabling decision-makers to use linguistic variables such as "high," "low," or "moderate," which are represented mathematically through fuzzy numbers like triangular or trapezoidal membership functions (Chen & systems, 2000).

By blending the strengths of fuzzy logic and the classical TOPSIS approach, Fuzzy TOPSIS allows evaluators to incorporate human judgment and uncertainty, making it highly relevant for infrastructure decision-making contexts where precise data is often unavailable.

2.2.3.3. Advantages of Fuzzy TOPSIS in Road Maintenance Evaluation

Fuzzy TOPSIS has emerged as a preferred methodology in road maintenance because of several key advantages. First, it provides transparency by offering a clear ranking of alternatives, based on the calculated closeness coefficient (CC) between each strategy and the ideal solution (Behzadian, Otaghsara, Yazdani, & Ignatius, 2012). Second, it demonstrates robustness by effectively capturing the uncertainty inherent in expert opinions and qualitative data. Third, it exhibits flexibility, as it can accommodate both quantitative measures, such as cost and service life, as well as qualitative dimensions such as user satisfaction and environmental sustainability.

Additionally, Fuzzy TOPSIS is computationally straightforward compared to other hybrid MCDM methods such as AHP-TOPSIS or ELECTRE, which may require more complex pairwise comparisons. Its ability to process linguistic judgments while still producing numerical rankings enhances its practicality in policy environments where decisions must be justified in both qualitative and quantitative terms (Yuan Liu et al., 2021).

2.2.3.4. Operational Mechanics of Fuzzy TOPSIS

The application of Fuzzy TOPSIS to road maintenance typically follows several structured steps. First, decision criteria are identified, such as cost, safety, durability, environmental impact, and social acceptability (Burningham & Stankevich, 2005). Each criterion is assigned a weight, often using methods such as Fuzzy AHP, to reflect relative importance (Kahraman et al., 2003; Saaty, 1980).

Next, expert opinions are collected using linguistic variables, which are then converted into fuzzy numbers, typically triangular fuzzy numbers (TFNs). The fuzzy decision matrix is constructed, and the criteria are normalized to ensure comparability. The PIS and NIS are then determined based on the fuzzy weighted normalized decision matrix. Distances between each alternative and both the PIS and NIS are computed using fuzzy distance measures, and finally, a closeness coefficient (CC) is calculated for each strategy. The alternative with the highest CC is ranked as the most suitable maintenance strategy (Y.-M. Wang & Elhag, 2006).

This systematic procedure ensures that both quantitative data and subjective expert knowledge are rigorously incorporated into the decision-making process.

2.2.3.5. Applications of Fuzzy TOPSIS in Infrastructure Management

Fuzzy TOPSIS has been applied in various contexts around the world to evaluate and rank road maintenance strategies. In Ethiopia, for example, (Ayalew et al., 2022) developed a hybrid Fuzzy AHP–Fuzzy TOPSIS framework to evaluate strategies such as pothole patching, crack sealing, overlays, and reconstruction. Their findings revealed that periodic maintenance was the most effective strategy, balancing cost efficiency and long-term pavement durability. Similarly, in Turkey, (Yuan Liu et al., 2021) reported that the use of Fuzzy TOPSIS reduced decision-making time by nearly 20% compared to classical AHP while improving consensus among stakeholders.

Other studies have applied Fuzzy TOPSIS to prioritize pavement maintenance projects in India, where traffic congestion and limited budgets complicate decision-making. Researchers found that the method enabled policymakers to incorporate socio-economic impacts into the ranking of alternatives, ensuring that user satisfaction and safety were not overshadowed by purely financial considerations (Kumar, 2005).

2.2.3.6. Integration with Other MCDM Techniques

While Fuzzy TOPSIS is powerful as a stand-alone method, it is often integrated with other MCDM techniques to enhance accuracy and consistency. For instance, weights for decision criteria can be derived using Fuzzy AHP or the Best-Worst Method (BWM) before applying TOPSIS for ranking (Masoumi, Hadji Molana, Javadi, & Azizi, 2022). Similarly, hybrid models such as Fuzzy TOPSIS–VIKOR have been proposed to capture different perspectives on compromise solutions, particularly in situations where multiple stakeholders must reach consensus (Sayadinia et al., 2021).

These hybrid approaches provide greater reliability by reducing biases associated with a single method, and they have been shown to produce more robust recommendations in contexts characterized by conflicting objectives.

2.2.3.7. Limitations of Fuzzy TOPSIS

Despite its many strengths, Fuzzy TOPSIS is not without limitations. One challenge lies in the subjectivity of assigning membership functions to linguistic variables, which can introduce biases depending on the expert backgrounds (Behzadian et al., 2012). Additionally, while the method handles small to medium-scale decision problems effectively, it can become computationally intensive for very large-scale applications involving hundreds of criteria and alternatives. Another limitation is that it assumes decision criteria are independent, which may not hold in real-world contexts where factors such as cost, durability, and environmental impact are interrelated (Y.-M. Wang & Elhag, 2006).

Nevertheless, these challenges can often be mitigated through careful methodological design, expert calibration, and the use of hybrid approaches.

2.2.4. Determining the Most Suitable Road Maintenance Strategy

2.2.4.1. Introduction

Determining the most suitable road maintenance strategy is one of the most crucial aspects of infrastructure asset management. While identifying critical factors and prioritizing them provides the foundation for decision-making, the final step involves selecting strategies that best align with contextual realities such as climate, traffic conditions, economic resources, and sustainability requirements. According to (Burningham & Stankevich, 2005)Maintenance strategies must be tailored to the socio-economic environment in which roads operate, as a “one-size-fits-all” approach often leads to resource wastage and inefficiencies. Therefore, decision-making tools such as Fuzzy TOPSIS, Fuzzy AHP, and other multi-criteria methods are increasingly used to assess, compare, and recommend the most suitable strategies.

2.2.4.2. The Role of Closeness Coefficient in Strategy Selection

The Closeness Coefficient (CC), derived from the Fuzzy TOPSIS methodology, serves as a key metric for ranking alternatives by measuring how close each option is to the Positive Ideal Solution (PIS) and how far it is from the Negative Ideal Solution (NIS) (Chen & systems, 2000; Hwang et al., 1981). In the context of road maintenance, CC enables decision-makers to simultaneously evaluate multiple maintenance strategies under uncertainty, considering both qualitative and quantitative criteria such as cost, technical feasibility, safety, environmental impact, and user satisfaction. A higher CC value indicates that a particular strategy is more aligned with the desired objectives and prevailing operational conditions. Empirical studies in Ethiopia by (Ayalew et al., 2022) demonstrate that periodic maintenance often ranks higher than routine maintenance or rehabilitation in terms of overall suitability, as it balances long-term pavement durability with cost efficiency, particularly for roads experiencing moderate traffic volumes and climatic conditions. The CC thus provides a systematic, data-driven basis for prioritizing road interventions, reducing reliance on purely subjective judgments.

2.2.4.3. Scenario-Specific Strategies

The optimal road maintenance strategy is highly dependent on the unique environmental, traffic, and socio-economic conditions surrounding a road network. Decision-makers must account for factors such as climatic severity, traffic intensity, funding availability, and user expectations when selecting interventions. For instance, high-traffic urban roads may require more frequent and intensive maintenance, while rural low-traffic roads may remain serviceable with less frequent interventions. Scenario-specific analyses ensure that maintenance strategies are tailored to contextual needs rather than applying generic solutions, thereby improving both cost-effectiveness and user satisfaction (Haas & Hudson, 2015).

2.2.4.4. Preventive Maintenance in Moderate Climates

Preventive maintenance, including crack sealing, surface treatments, and minor patching, is particularly effective in Mediterranean, temperate, and other moderate climates where pavements experience gradual wear and tear. These interventions aim to address minor distresses before they escalate into major structural failures, thereby extending the pavement's service life and reducing lifecycle costs (Motlagh et al., 2024). By implementing preventive measures at the right time, road agencies can minimize costly rehabilitation needs and disruptions to traffic. Moreover, preventive strategies contribute to smoother road surfaces, enhancing user safety and comfort while reducing vehicle operating costs.

2.2.4.5. Rehabilitation in Wet and Humid Environments

In regions characterized by high rainfall and sub-humid climates, water infiltration accelerates pavement deterioration, leading to potholes, rutting, and weakening of underlying structural layers. Rehabilitation strategies, such as overlays, structural strengthening, and full-depth repairs, are preferred in such environments because they address both surface and sub-surface damage (Zhang, 2003). While rehabilitation interventions are more capital-intensive than routine or preventive maintenance, they provide longer-lasting performance and reduce the frequency of recurring repairs. By focusing on foundational integrity, these strategies mitigate the compounded effects of moisture, heavy traffic, and climatic stressors, ensuring that road networks remain functional and safe over extended periods.

2.2.4.6. Low-Budget Short-Term Fixes in Semi-Arid Climates

In resource-constrained environments, particularly in semi-arid regions characterized by extreme temperature fluctuations, limited rainfall, and occasional heavy storms, road agencies often face significant challenges in maintaining pavement performance. Due to financial limitations, the focus frequently shifts to low-budget, short-term interventions, such as pothole patching, localized surface repairs, and temporary sealing of cracks. These measures, while not necessarily cost-efficient over the pavement lifecycle, serve the critical purpose of maintaining basic road functionality and ensuring minimum levels of serviceability for road users (Cabana, Liautaud, & Faiz, 1999; Motlagh et al., 2024).

Short-term fixes are typically reactive rather than preventive, addressing visible defects that could disrupt traffic flow or cause accidents. Although they may temporarily restore usability, such interventions often fail to address underlying structural issues, resulting in faster pavement deterioration over time. Consequently, these strategies can lead to repeated maintenance cycles and higher cumulative costs if not complemented by long-term planning and preventive maintenance measures. Semi-arid climates exacerbate these challenges, as high daytime temperatures, intense UV exposure, and large diurnal temperature swings accelerate pavement cracking, rutting, and surface disintegration(Haas & Hudson, 2015).

Despite their limitations, low-budget short-term strategies remain essential in contexts where funding is insufficient for comprehensive rehabilitation or reconstruction. By prioritizing immediate road usability, agencies can maintain access for communities, facilitate local economic activity, and prevent complete network failure while planning for more sustainable long-term interventions. Thus, understanding the trade-offs between short-term fixes and long-term maintenance investments is crucial for effective road management in semi-arid regions

2.2.4.7. High-Traffic vs. Low-Traffic Roads

Traffic volume is one of the most critical factors influencing the selection and prioritization of road maintenance strategies. High-traffic corridors, such as major highways, urban arterials, and commercial routes, are subjected to heavy loads, frequent braking, and turning movements, which accelerate pavement deterioration. Consequently, these roads require more frequent inspections, preventive maintenance, and timely rehabilitation interventions to ensure safety, maintain service levels, and minimize user disruptions. Neglecting maintenance on high-traffic roads can lead to accelerated structural failures, increased accident rates, and higher vehicle operating costs for road users(R. Robinson, Danielson, U., et al., 1998; Zhang, 2003).

In contrast, low-traffic roads, typically rural roads, feeder routes, or roads in sparsely populated areas, experience less structural stress and can remain serviceable with less frequent maintenance interventions. Although these roads may not justify intensive preventive measures due to lower economic returns, targeted maintenance strategies can still optimize lifecycle costs and extend pavement longevity. Studies highlight that maintenance prioritization should account not only for current traffic levels but also projected traffic growth, vehicle type composition, and seasonal variations, ensuring that interventions are appropriate for both current and anticipated demand (Hwang et al., 1981; Motlagh et al., 2024).

Balancing maintenance across high- and low-traffic roads is essential for equitable resource allocation. While high-traffic roads often dominate funding and planning, the inclusion of low-traffic routes in strategic maintenance programs ensures accessibility, economic inclusivity, and long-term sustainability of the transportation network. Therefore, traffic volume serves not only as a technical criterion but also as a key factor in broader infrastructure management and planning decisions.

2.2.4.8. Integration of Sustainability Dimensions

Modern road maintenance strategies are increasingly evaluated through a multi-dimensional lens that encompasses economic, environmental, and social considerations. While cost-effectiveness remains a critical factor, decision-makers now recognize that long-term sustainability necessitates a balance among these three pillars.

Economic Sustainability

Economically, maintenance strategies must optimize the use of limited public resources, minimize lifecycle costs, and ensure that interventions provide maximum value over the pavement’s service life. This involves selecting maintenance practices that not only extend the lifespan of road infrastructure but also offer the best return on investment. For instance, preventive maintenance approaches can be more cost-effective in the long run compared to corrective measures, as they address issues before they escalate into more significant problems.

Environmental Sustainability

Environmentally, strategies are assessed for their impact on natural resources, emissions, waste generation, and overall ecological footprint. Techniques that reduce material consumption, improve energy efficiency during construction and maintenance, and minimize emissions are preferred, as they contribute to mitigating climate change and conserving resources. (Alawaysheh et al., 2020a) emphasize the importance of integrating environmental criteria into maintenance practices, highlighting that preventive maintenance is advantageous when considering waste and noise pollution as environmental selection criteria.

Social Sustainability

Socially, road maintenance interventions must consider the needs, safety, and satisfaction of road users and local communities. This includes minimizing traffic disruptions, reducing accident risks, and ensuring equitable access to transportation networks.(R. Robinson, Danielson, U., et al., 1998) discuss the broader impacts of road maintenance on communities, noting that well-maintained roads can lead to improved accessibility and quality of life for residents.

Integrating these three dimensions, such that economic, environmental, and social, ensures that road maintenance decisions are not only technically sound but also socially responsible and environmentally conscious. This holistic approach aligns with global principles of sustainable infrastructure management and supports the development of resilient transportation systems that meet the needs of current and future generations.

2.2.4.9. Integration of Economic, Environmental, and Social Dimensions

Modern road maintenance strategies must balance economic efficiency, environmental sustainability, and social benefits. From an economic perspective, strategies should minimize lifecycle costs while ensuring long-term durability and functionality. Environmental considerations have become increasingly critical, as road maintenance activities can generate significant ecological impacts, including emissions from asphalt production, energy consumption, and potential water contamination from construction runoff (Alawaysheh et al., 2020a). Social benefits are equally important: well-maintained roads reduce accident risks, travel times, and vehicle operating costs, while improving ride comfort and public satisfaction (Burningham & Stankevich, 2005). The Fuzzy TOPSIS approach is particularly advantageous in this context, as it allows decision-makers to quantify and balance these competing priorities under uncertain and subjective conditions, incorporating both qualitative judgments and quantitative data to identify the most suitable maintenance strategy (Yuan Liu et al., 2021).

2.2.4.10. Applications of Strategy Determination

Empirical applications of strategy determination demonstrate the importance of contextual adaptation. In Ethiopia, (Ayalew et al., 2022) showed that periodic maintenance interventions such as overlays and surface resealing were generally the most appropriate approach. This selection was driven by the need for cost-effective solutions that maximize pavement life while operating within limited financial resources. Similarly, in Turkey, (Yuan Liu et al., 2021) applied Fuzzy TOPSIS to evaluate urban and rural road networks and found that rehabilitation strategies achieved higher closeness coefficients for urban high-traffic areas, whereas preventive strategies were more effective for low-traffic rural roads. These results underscore the significance of tailoring maintenance strategies to specific traffic patterns, environmental conditions, and budget constraints.

Globally, hybrid decision-making approaches such as Fuzzy AHP–TOPSIS have been increasingly adopted to integrate expert knowledge, traffic data, and climatic variables into maintenance planning. Such approaches enhance the transparency, robustness, and defensibility of maintenance decisions, allowing agencies to justify strategy selection and optimize resource allocation while considering economic, environmental, and social dimensions simultaneously.

2.3. Empirical Literature Review

2.3.1. Introduction

Road maintenance management is a vital component of infrastructure sustainability, directly affecting transportation safety, operational efficiency, and long-term economic performance. As road networks age and traffic volumes increase, selecting effective maintenance strategies becomes increasingly complex and critical. These decisions must balance multiple, often conflicting, criteria such as cost, environmental impact, technical feasibility, safety, and user satisfaction.

To navigate this complexity, fuzzy multi-criteria decision-making (MCDM) methods have gained prominence. Among them, the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) stands out for its ability to incorporate both quantitative and qualitative factors while effectively managing uncertainty and linguistic imprecision, common features of expert-based evaluations in road infrastructure projects.

This empirical literature review provides a comprehensive synthesis of recent studies that apply Fuzzy TOPSIS in the context of road maintenance management. It explores how these models have been operationalized across various case studies, including national highway agencies, urban maintenance programs, and resource-constrained environments.

2.3.2. Critical Factors Influencing Road Maintenance Decisions

Road maintenance management is a central element of infrastructure sustainability, with direct impacts on safety, economic efficiency, and service quality. Empirical studies have explored the critical factors influencing maintenance decisions by analysing real-world road networks, maintenance data, and expert evaluations.

Cost-effectiveness and lifecycle cost have been repeatedly highlighted in empirical studies as major determinants of maintenance strategy selection. For instance, (Ayalew et al., 2022) evaluated Ethiopian Roads Authority (ERA) maintenance projects, comparing routine, periodic, and rehabilitation strategies. Their analysis, based on real budget and maintenance data, showed that periodic maintenance offered the best balance between cost, durability, and resource allocation. Similarly,(Motlagh et al., 2024) used lifecycle cost analysis across Iranian highways and concluded that strategies optimized for LCCA consistently reduced long-term expenditures while maintaining service levels.

Technical feasibility also drives practical maintenance decisions. (Cabana et al., 1999; Zhang, 2003) highlighted that local road conditions, pavement material characteristics, and available machinery determine which interventions are operationally viable. In a case study in Turkey, (Yuan Liu et al., 2021) demonstrated that even cost-effective strategies like preventive crack sealing were often infeasible on heavily trafficked or structurally compromised roads, underlining the importance of empirical assessment of technical feasibility.

Safety improvements form another empirically validated factor. (R. Robinson, Danielson, U., et al., 1998) analyzed accident reports in U.S. state highways and found a strong correlation between timely pothole repair and reduced crash frequency. A similar study in Kenya by(Ouma, Opudo, & Nyambenya, 2015) integrated pavement distress data with accident statistics, showing that maintenance prioritization targeting high-risk sections effectively minimized accident rates.

Environmental impact is increasingly recognized in road maintenance decision-making. (Alawaysheh et al., 2020b) examined municipal maintenance programs in Jordan and quantified carbon emissions and energy consumption for various strategies, concluding that environmentally informed interventions (e.g., micro-surfacing instead of full overlays) reduced emissions while maintaining service quality.

User satisfaction and operational impact are also critical. (Burningham & Stankevich, 2005) surveyed commuters in urban networks, linking traffic delays and ride comfort with maintenance scheduling priorities. Empirical findings revealed that strategies minimizing disruption, even at slightly higher costs, improved public satisfaction and perceived road quality.

Climatic and traffic conditions have been validated as key drivers in maintenance decisions. (Motlagh et al., 2024; Zhang, 2003) provided evidence from Iran and China, showing that weather extremes, rainfall, and heavy traffic load accelerated pavement deterioration and influenced the choice of preventive versus corrective strategies.

2.3.2.1. Collective Insights from Empirical Studies

Empirical studies across diverse countries, including Ethiopia, Kenya, Iran, Turkey, and the United States, consistently highlight that road maintenance decision-making is inherently multi-dimensional. Research indicates that effective maintenance planning requires integrating technical, economic, environmental, and social considerations rather than relying on a single criterion. Data-driven approaches, which utilize traffic counts, pavement condition indices (PCI), accident statistics, and environmental impact measures, have been shown to improve the effectiveness, cost-efficiency, and safety of road networks (Ayalew et al., 2022; Yuan Liu et al., 2021; Motlagh et al., 2024; Ouma et al., 2015) For instance, studies in Ethiopia demonstrated that prioritizing maintenance activities based on PCI and traffic load allowed authorities to allocate limited resources more strategically, reducing overall rehabilitation costs while maintaining service levels. Similarly, research in Kenya and Turkey revealed that integrating environmental and safety metrics alongside traditional cost-based evaluations led to maintenance strategies that were both sustainable and socially acceptable. These findings collectively underscore the importance of combining multiple data sources and expert judgments to inform maintenance decisions, providing a foundation for multi-criteria decision-making methods such as Fuzzy TOPSIS.

2.3.3. Prioritizing the Identified Factors

2.3.3.1. Importance of Factor Prioritization

Prioritizing critical factors in road maintenance is essential for guiding decision-makers toward interventions that have the greatest impact on pavement performance, safety, and cost-effectiveness. By focusing resources and planning efforts on the most influential criteria, authorities can improve the overall effectiveness and sustainability of maintenance strategies. Traditional prioritization methods, such as simple weighted scoring, often struggle to handle uncertainty and subjective judgments inherent in expert assessments. As (Seiti, Hafezalkotob, & Engineering, 2019) note, such methods may produce inconsistent or biased results, particularly when multiple decision-makers provide differing opinions under ambiguous conditions.

2.3.3.2. Fuzzy TOPSIS for Prioritization

To address these limitations, fuzzy TOPSIS has been widely adopted for factor prioritization in infrastructure management. The method allows qualitative expert judgments to be expressed using linguistic scales such as “high,” “medium,” or “low,” which are then converted into triangular fuzzy numbers for quantitative analysis. This approach captures the inherent uncertainty in human evaluations, ensuring that subjective opinions are systematically accounted for in the prioritization process(Ouma et al., 2015).For instance, critical factors such as safety significance, environmental impact, structural durability, and traffic load can be assessed across multiple experts, enabling a more reliable ranking that reflects both consensus and variability in expert perception.

2.3.3.3. Empirical Evidence

Empirical studies validate the robustness and effectiveness of fuzzy TOPSIS in factor prioritization. (Baykasoğlu & Gölcük, 2015) demonstrated that fuzzy prioritization reduces bias in expert judgment and ensures consistency in the relative importance of factors across different evaluators. Their study highlighted that maintenance cost, pavement distress, and traffic volume consistently ranked as top factors when analyzed through fuzzy TOPSIS, confirming the method’s applicability in practical road maintenance planning. These results underscore that integrating fuzzy logic into multi-criteria decision-making improves both the reliability and transparency of prioritization, ultimately supporting more informed and effective maintenance strategy selection.

2.3.4. Evaluating Road Maintenance Strategies Using Fuzzy TOPSIS

2.3.4.1. Maintenance Strategy Types

Empirical research classifies road maintenance strategies into routine, periodic, preventive, and rehabilitation interventions, each differing in scope, cost implications, and impact on pavement performance (Ayalew et al., 2022). Routine maintenance typically addresses minor defects, such as potholes, surface cracks, and drainage issues, aiming to prevent small problems from escalating into structural failures. Periodic maintenance involves scheduled interventions, such as overlays or surface renewals, which preserve pavement functionality before severe deterioration occurs. Preventive strategies focus on early intervention measures like crack sealing and thin surface treatments that extend pavement life and reduce long-term costs. Rehabilitation strategies, in contrast, address substantial structural damage through strengthening, resurfacing, or full-depth reconstruction, ensuring road usability under high traffic or harsh environmental conditions. The choice among these strategies requires careful consideration of technical feasibility, budget constraints, and long-term performance objectives.

2.3.4.2. Multi-Criteria Evaluation

Fuzzy TOPSIS provides a structured framework for evaluating these maintenance strategies against multiple, often conflicting criteria. By incorporating both qualitative and quantitative factors, the method allows decision-makers to systematically compare strategies under uncertainty.(Akram, Kahraman, & Zahid, 2021) demonstrated the application of spherical fuzzy TOPSIS to assess maintenance alternatives across key criteria such as technical feasibility, cost-effectiveness, safety, and environmental impact. The approach converts expert linguistic judgments into fuzzy numbers, enabling a more nuanced and comprehensive ranking of strategies than conventional deterministic methods. This multi-criteria evaluation ensures that selected interventions not only optimize road performance but also align with broader sustainability and safety objectives.

2.3.4.3. Empirical Applications

Several empirical studies highlight the practical effectiveness of fuzzy TOPSIS in road maintenance decision-making. (Xu et al., 2024) applied the method to preventive maintenance planning for asphalt pavements, integrating factors such as traffic load, Pavement Condition Index (PCI), and environmental conditions to identify the most suitable interventions for varying pavement states. Similarly,(Moazami, Behbahani, & Muniandy, 2011) utilized fuzzy TOPSIS for urban road rehabilitation prioritization, demonstrating improved resource allocation and more effective scheduling of maintenance activities compared to traditional methods. These studies collectively show that fuzzy TOPSIS supports evidence-based, context-specific decision-making, providing road authorities with a reliable tool to optimize maintenance strategies while considering technical, economic, and environmental factors.

2.3.5. Determining the Most Suitable Maintenance Strategy for Different Scenarios

2.3.5.1. Scenario-Specific Evaluation

Scenario-specific evaluation enables road authorities to identify the most appropriate maintenance strategies by considering the unique characteristics and operational conditions of each road segment. This approach takes into account factors such as traffic volume, pavement condition, climatic conditions, and budget availability, ensuring that interventions are contextually relevant and cost-effective (Yaohan Liu et al., 2024). For instance, high-traffic urban corridors may require frequent preventive and periodic maintenance to minimize disruptions and maintain user safety, whereas low-traffic rural roads can be effectively managed through less intensive routine maintenance. Similarly, regions with wet or humid climates may necessitate rehabilitation-focused interventions to address water-induced pavement deterioration, while semi-arid areas may rely more on short-term fixes to maintain minimal serviceability under resource constraints. By evaluating maintenance strategies within specific scenarios, road agencies can optimize resource allocation, reduce lifecycle costs, and extend pavement service life, while ensuring that safety, environmental sustainability, and user satisfaction are adequately addressed. Scenario-specific evaluation thus provides a structured framework for translating multi-criteria decision-making outputs, such as those derived from Fuzzy TOPSIS, into practical, actionable maintenance plans.

2.3.5.2. Case Examples

The selection of maintenance strategies varies according to traffic intensity, road hierarchy, and operational importance. For high-traffic and critical routes, rehabilitation strategies such as overlays or full-depth reconstruction are often prioritized because they enhance long-term durability, reduce recurrent maintenance costs, and improve road safety for heavy user flows. Conversely, low-traffic secondary or rural roads can often be maintained effectively through preventive interventions, including crack sealing and surface treatments, which extend pavement service life at a lower cost while maintaining acceptable performance levels. These distinctions highlight the importance of tailoring maintenance strategies to specific road conditions rather than applying uniform solutions across all network types.

2.3.5.3. Fuzzy TOPSIS Contributions

Fuzzy TOPSIS significantly enhances the decision-making process by enabling the ranking of maintenance alternatives under conditions of uncertainty. This method allows decision-makers to incorporate expert judgments and multiple weighted criteria, including technical, economic, environmental, and social factors, into a structured evaluation framework. (Ouma et al., 2015) demonstrated that fuzzy evaluation produces solutions that are context-specific and reflective of the nuanced trade-offs inherent in infrastructure management. Furthermore, (Xu et al., 2024) incorporated Pavement Condition Index (PCI) thresholds within the fuzzy TOPSIS framework to determine the optimal timing for maintenance interventions, ensuring that resources are allocated efficiently and that treatments are implemented when they are most cost-effective. Together, these contributions illustrate how fuzzy TOPSIS supports informed, evidence-based decisions for road maintenance prioritization in diverse scenarios.

2.4. Policy Guidelines and Strategic Implementation

A sustainable and efficient road maintenance system is crucial for Ethiopia to ensure safe transportation, reduce operational costs, and prolong the lifespan of road infrastructure. The policy framework should emphasize data-driven decision-making, whereby a robust Pavement Management System (PMS) is utilized to collect and analyze real-time road condition data, traffic volumes, and environmental factors to inform maintenance decisions. Critical factors influencing maintenance, such as traffic intensity, pavement condition, and environmental impact, should be systematically identified using methods like the Fuzzy Analytical Hierarchy Process (AHP), which effectively captures expert judgments under uncertainty(Ouma et al., 2015). Once these factors are identified, maintenance activities must be prioritized using the Fuzzy TOPSIS method, allowing decision-makers to rank tasks based on their closeness to an ideal solution, thereby ensuring that limited resources are allocated to interventions with the greatest impact on road safety, service quality, and cost-effectiveness (Ayalew et al., 2022).

The strategic implementation of road maintenance should focus on optimizing resources, ensuring that the highest-priority maintenance tasks are addressed within the available budget. Incorporating stakeholder engagement is also essential, as local communities, maintenance personnel, and government authorities bring diverse perspectives and expertise that enhance the effectiveness, transparency, and acceptability of maintenance plans. Regular monitoring and evaluation of maintenance activities should be institutionalized to track performance, assess adherence to budgets and schedules, and measure improvements in road conditions. This process facilitates continuous improvement, as feedback from completed projects can inform updates to the PMS, refine prioritization criteria, and adjust strategies to better respond to evolving road infrastructure challenges. Sustainability must remain central to both policy and strategy, promoting environmentally friendly practices and long-term benefits while balancing economic constraints.

Overall, by integrating fuzzy multi-criteria decision-making approaches such as Fuzzy AHP and Fuzzy TOPSIS into road maintenance policy and strategy, Ethiopia can adopt a systematic, transparent, and data-driven approach to managing road infrastructure. This not only improves decision-making quality but also ensures that maintenance interventions are socially acceptable, economically efficient, and technically sound, ultimately contributing to a safer, more resilient, and sustainable road network.

2.5. Best Experiences and Lessons Learned

Several international and regional studies provide valuable insights into the application of fuzzy-based multi-criteria decision-making models for road maintenance prioritization. In Ethiopia (Ayalew et al., 2022) developed a road maintenance management strategy evaluation model for the Ethiopian Roads Authority by integrating Fuzzy AHP and Fuzzy TOPSIS. Their model incorporated a hierarchical structure of decision criteria, including cost-effectiveness, durability, safety improvement, environmental impact, ease of implementation, maintenance frequency, economic impact, life cycle cost, and time efficiency. The analysis compared routine, periodic, and rehabilitation maintenance alternatives, ultimately identifying rehabilitation maintenance as the optimal choice due to its long-term durability and safety benefits, despite its higher initial cost.

In Kenya (Ouma et al., 2015) applied both Fuzzy AHP and Fuzzy TOPSIS to prioritize pavement maintenance functions across road sections. Expert input on pavement distress types such as cracking, potholes, ravelling, and patching was used to evaluate strategies based on objectives like road safety, surface preservation, operational status, and aesthetics. Alternatives included thin hot mix asphalt (HMA) overlays, resurfacing, slurry seals, cape seal, micro surfacing, and fog seal. While both methods produced the same top three alternatives (HMA overlays, resurfacing, and slurry seals), Fuzzy TOPSIS aligned more closely with manual priority rankings, whereas Fuzzy AHP showed a tendency to overestimate.

In China (Yaohan Liu et al., 2024) introduced an AHP–TOPSIS framework for selecting preventive maintenance strategies for national trunk highways. The evaluation criteria included service functionality, pavement performance, economic benefits, and environmental impact. Among several alternatives such as ultra-thin overlays, micro surfacing, and chip seals, ultra-thin overlay emerged as the most effective solution, offering a balanced outcome between performance enhancement and life cycle cost management.

In Iran (Y.-M. Wang & Elhag, 2006) applied a more advanced version of the Fuzzy TOPSIS model, based on α-level sets and nonlinear programming, to bridge risk assessment. Their study demonstrated that this enhanced fuzzy approach provided superior accuracy in ranking high-risk scenarios compared to earlier fuzzy models, effectively handling imprecision in expert judgment. The methodology proved particularly useful in urban road and bridge maintenance planning, showcasing the potential for more nuanced decision-making under uncertainty.

2.6. Conceptual Framework

The conceptual framework for the study is presented in Figure 1

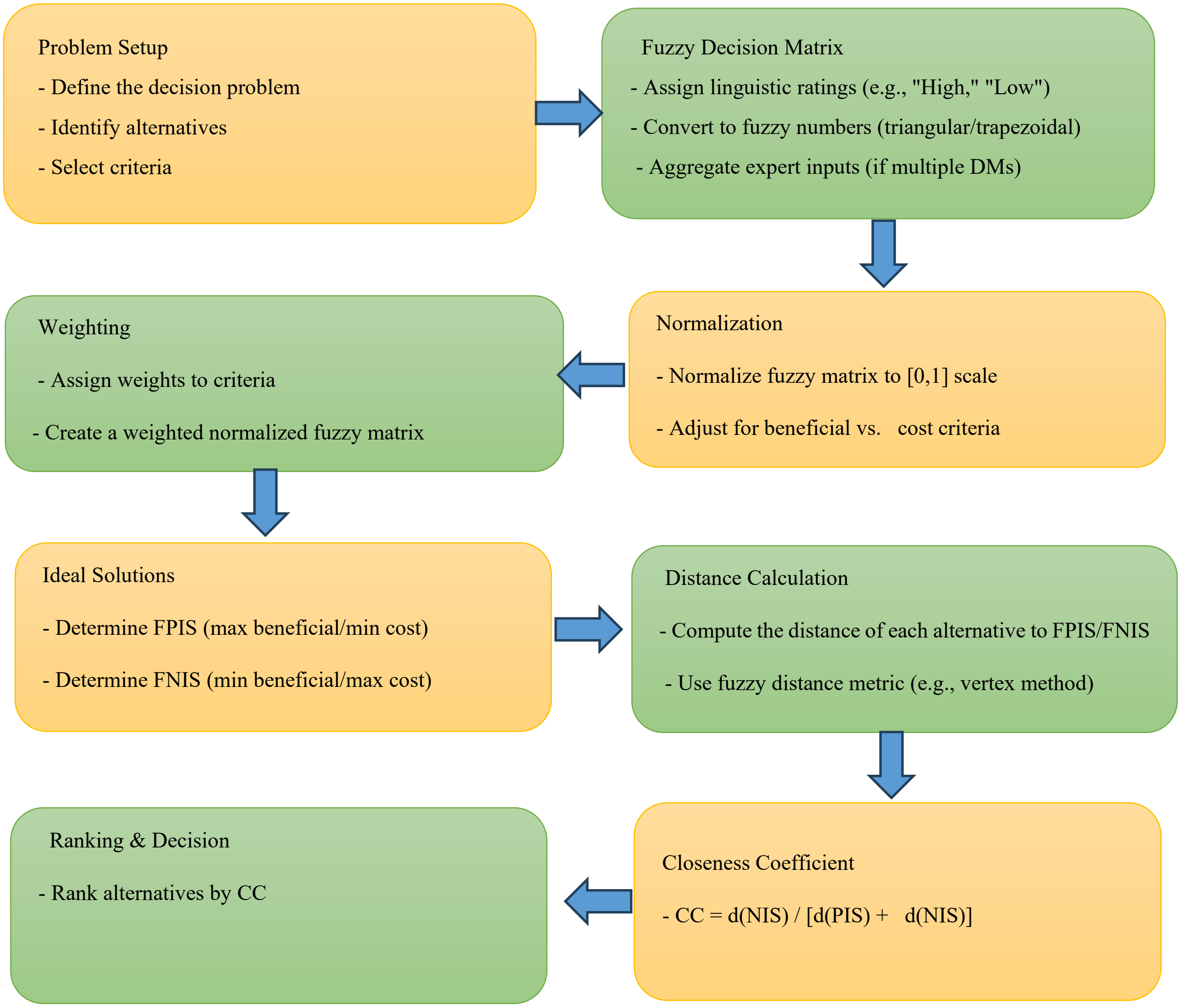

Figure 1. The conceptual framework for the study

2.7. Research gap

Despite the growing adoption of fuzzy multi-criteria decision-making methods, such as Fuzzy TOPSIS, in road maintenance management, several critical research gaps persist. First, although numerous studies have sought to identify factors influencing road maintenance decisions, there is a lack of comprehensive empirical evidence on the relative significance of these factors in diverse contexts, particularly in developing countries like Ethiopia (Ayalew et al., 2022). Localized factors such as road user behaviour, environmental conditions, and budgetary constraints are often overlooked, limiting the applicability of generic models. Second, while prioritization of maintenance factors has been addressed using fuzzy methods, most research emphasizes theoretical model performance without sufficient validation through field data or stakeholder input. This creates a gap in understanding how prioritization translates into practical, cost-effective maintenance strategies (Ouma et al., 2015).

Third, although Fuzzy TOPSIS has proven effective in evaluating various road maintenance strategies, few studies have systematically compared multiple strategies under different operational scenarios to determine context-specific suitability. In particular, the integration of preventive, routine, and rehabilitation maintenance strategies with dynamic road conditions, traffic patterns, and resource limitations remains underexplored (Xu et al., 2024). Moreover, stakeholder involvement spanning government authorities, maintenance managers, pavement experts, and local communities is often inadequately incorporated into existing models. This omission reduces the social legitimacy and sustainability of maintenance decisions, as the preferences and risk perceptions of stakeholders are critical for prioritizing interventions and ensuring long-term adoption(Li, Ng, & Skitmore, 2013).

Finally, most studies focus on short-term optimization of maintenance activities, with insufficient attention to long-term lifecycle performance, cost-effectiveness, and environmental impacts. The lack of longitudinal studies means that maintenance strategies may appear optimal in theory but fail to maximize infrastructure longevity or minimize costs and environmental harm over time (Ayalew et al., 2022). Addressing these gaps by integrating empirical data, stakeholder perspectives, and multi-scenario evaluations will contribute to the development of a robust, context-sensitive, and sustainable framework for road maintenance decision-making, which aligns with the objectives of identifying critical factors, prioritizing them, evaluating strategies using Fuzzy TOPSIS, and determining the most suitable maintenance interventions for varied conditions.

Despite significant progress in developing prioritization methods, certain gaps remain. First, most studies focus on technical and economic factors, while social and equity considerations receive less attention. Second, while fuzzy logic improves the handling of uncertainty, it also introduces computational complexity that may hinder its adoption in low-capacity agencies (Xu et al., 2024). Finally, the majority of case studies are concentrated in Asia and Africa, with limited research from Latin America and smaller developing economies. Addressing these gaps requires further research into context-specific prioritization frameworks that integrate social, environmental, and governance dimensions alongside traditional cost and safety considerations.

CHAPTER THREE

3. RESEARCH METHODOLOGY

3.1. Introduction

This chapter presents the methodological framework used to conduct the study. It outlines the processes involved in data collection, analysis, and model development that support the selection of optimal road maintenance strategies. The research employs a combination of qualitative and quantitative methods under a multi-criteria decision-making (MCDM) approach, with a particular focus on the Fuzzy TOPSIS model.

Given the complexity of infrastructure decisions characterized by multiple, and often conflicting, criteria and subjective expert judgments, the methodology adopted in this study is designed to address uncertainty, imprecision, and vagueness inherent in real-world decision-making. The use of fuzzy logic allows the incorporation of linguistic variables and expert-based assessments into a structured and mathematically robust decision-making framework.

This chapter begins by describing the study area and the rationale for its selection, followed by the research design and approach. It then identifies the target population, outlines the sampling strategy, and presents the tools and techniques used for data collection. The chapter also details the analytical procedures employed to calculate fuzzy weights and rank the alternative strategies. Lastly, issues of validity, reliability, ethical considerations, and research limitations are addressed to ensure the transparency and credibility of the research process.

3.2. Description of the Study

This study is focused on evaluating and selecting appropriate road maintenance strategies using a fuzzy multi-criteria decision-making model. The study is specifically applied to the case of the Addis Ababa City Roads Authority (AACRA), which is responsible for managing the planning and execution of road maintenance activities in the capital. The study considers expert-based assessments and integrates both qualitative and quantitative data to support structured decision-making.

3.3. Research Design and Research Approach

3.3.1. Research Design

The research design for this study adopts a descriptive and analytical framework, aimed at systematically investigating the critical factors influencing road maintenance decisions and evaluating road maintenance strategies. A descriptive design is appropriate because it allows the researcher to identify, describe, and understand the current state of road maintenance practices in the context under study, including technical, economic, environmental, and social dimensions. Additionally, an analytical component is incorporated to assess relationships and prioritize factors using quantitative methods, particularly the Fuzzy TOPSIS technique, which enables a structured evaluation of multiple criteria.

The choice of this design is justified by the complex, multi-dimensional nature of road maintenance decision-making, which involves interacting technical, economic, and social variables. A purely qualitative or experimental approach would not capture the quantitative relationships among the critical factors and the relative performance of different maintenance strategies. By combining descriptive observation with analytical evaluation, this design ensures that the study not only identifies relevant factors but also provides actionable insights into prioritizing and selecting the most suitable strategies for varying road conditions and scenarios.

Moreover, this design supports the integration of empirical data from field surveys, secondary data sources, and expert judgments, thereby increasing the reliability and validity of the findings. It also accommodates the use of decision-making models like Fuzzy TOPSIS, which require numerical inputs and structured analysis, making the design methodologically coherent with the study objectives.

3.3.2. Research Approach

This study employs a mixed-methods research approach, combining quantitative and qualitative methods to achieve a comprehensive understanding of road maintenance decision-making. The quantitative component focuses on measuring and prioritizing the critical factors influencing maintenance decisions through structured surveys, expert assessments, and application of the Fuzzy TOPSIS method. This allows the researcher to objectively evaluate multiple criteria, assign relative weights to factors, and rank maintenance strategies based on their overall performance.

The qualitative component complements the quantitative analysis by providing contextual insights into decision-making processes, including policy constraints, technical feasibility, user satisfaction, and environmental considerations. Interviews with road maintenance experts, practitioners, and stakeholders help to capture experiential knowledge, which may not be fully represented in numerical data alone.

The justification for a mixed-methods approach lies in the complexity of road maintenance management, where decisions are rarely based solely on cost or technical feasibility. A purely quantitative approach could overlook social, environmental, and contextual factors, while a purely qualitative approach would lack the rigor to compare and prioritize strategies objectively. By integrating both methods, the study ensures a holistic analysis that aligns with the four specific objectives: identifying critical factors, prioritizing them, evaluating strategies using Fuzzy TOPSIS, and recommending the most suitable maintenance strategies under different scenarios.

3.4. Target Population

The target population comprises experts and professionals involved in road infrastructure management, planning, and maintenance decision-making, primarily from the Addis Ababa City Roads Authority (AACRA). It includes Senior Civil Engineers, project managers, designers, surveyors, construction foremen, Maintenance Project Coordinators, and Field Supervisors, who provide technical insights, operational perspectives, and knowledge of road deterioration, materials, and costs. Decision-makers and policy advisors are also included to capture strategic, budgetary, and administrative considerations. Additionally, consulting engineers and external experts contribute feasibility assessments and technical evaluations. This diverse group ensures comprehensive coverage of practical, technical, and institutional expertise relevant to road maintenance strategy selection.

3.5. Sample Size Determination and Sampling Technique

3.5.1. Sample Size

The study engaged a total of 20 professionals as participants, selected specifically for their expertise in road maintenance management. These participants included engineers, planners, and managers who have direct experience in designing, implementing, and overseeing maintenance strategies across various road networks. The sample size was carefully considered to provide sufficient diversity of professional perspectives, ensuring that the judgments captured reflect both technical expertise and practical decision-making insights.

In qualitative Multi-Criteria Decision-Making (MCDM) studies, such as those employing the Fuzzy TOPSIS method, the focus is on obtaining in-depth, informed evaluations rather than statistical generalizability. As such, a sample size of 20 is considered adequate and manageable, enabling detailed interaction with participants while ensuring comprehensive coverage of relevant professional viewpoints. A smaller sample allows the researcher to conduct in-depth interviews and expert assessments, improving the reliability and richness of the data collected.

A purposive sampling technique was used to select experts based on their knowledge, qualifications, and experience in road maintenance. The sample size consisted of 20 professionals, deemed adequate for qualitative MCDM analysis and consistent with previous similar research.

3.5.2. Sample Size Determination

The sample size was determined based on both practical considerations and methodological guidelines for qualitative decision-making studies. Existing literature indicates that for MCDM studies that rely on expert judgment, a range of 15 to 30 experts is sufficient to capture diverse perspectives and produce meaningful prioritization of criteria (Hwang et al., 1981; Zhang, 2003).

The rationale for selecting twenty experts was guided by several key considerations. First, expert coverage was essential to ensure that all relevant areas of road maintenance routine, periodic, rehabilitation, and reconstruction were adequately represented, allowing the study to capture a comprehensive range of professional perspectives. Second, data reliability played a crucial role in determining the sample size, as twenty respondents provided sufficient input to mitigate bias from individual opinions while keeping the dataset manageable for qualitative analysis. Finally, feasibility was taken into account, considering logistical constraints such as time, accessibility, and the depth of interaction required for detailed interviews and structured evaluations. The number of participants allowed for meaningful engagement without compromising the quality of insights gathered. By adopting this approach, the study aligns with prior research in infrastructure management and Multi-Criteria Decision-Making (MCDM) studies, where the emphasis is placed on the quality and relevance of expert input rather than on achieving large sample sizes.

3.5.3. Sampling Technique and Justification

This study adopted a purposive (judgmental) sampling technique, selecting participants deliberately based on their qualifications, knowledge, and practical experience in road maintenance decision-making. Purposive sampling is widely recognized in MCDM research because it focuses on individuals who can provide specialized knowledge and informed judgments rather than general population opinions.

The justification for using purposive sampling in this study is grounded in several considerations. Primarily, expertise-centred selection was crucial, as only individuals with hands-on experience in road maintenance strategies, planning, and implementation could reliably identify critical factors and evaluate maintenance alternatives. This approach enhances the relevance and accuracy of the data, ensuring that the information collected is directly applicable to the study objectives and thereby increasing the credibility and validity of the Fuzzy TOPSIS analysis. Additionally, purposive sampling improves efficiency and manageability by targeting a specialized group, enabling the researcher to engage meaningfully with participants and gather high-quality data without excessive resource expenditure. This method also aligns with previous research, as many MCDM studies in civil infrastructure management and road maintenance prioritize expert judgment over random sampling, reflecting the need for informed decision-making rather than probabilistic representation. By employing purposive sampling, the study ensures that the analysis incorporates context-specific expertise, producing findings that are both practical and actionable for policymakers and road agencies seeking to optimize maintenance strategies.

3.6. Data Collection

3.6.1. Data Source/Type

The study employed both primary and secondary data sources to ensure a comprehensive understanding of road maintenance decision-making. Primary data were collected directly from experts in road maintenance, including engineers, planners, and managers, who possess extensive hands-on experience in implementing routine, periodic, rehabilitation, and reconstruction strategies. These participants provided specialized insights into critical factors affecting maintenance decisions and evaluated alternative strategies based on practical knowledge. Secondary data were obtained from existing literature, technical reports, government publications, and prior research studies, which provided contextual and theoretical support for the analysis. Combining primary and secondary data enhances the validity of the findings, as expert opinions are grounded within established theoretical frameworks and documented practices in road infrastructure management.

3.6.2. Data Collection Tool

Data were collected using structured questionnaires, specifically designed to capture expert judgments on critical factors influencing road maintenance and the relative performance of different maintenance strategies. The questionnaire included Likert-scale items and pairwise comparison matrices to facilitate qualitative Multi-Criteria Decision-Making (MCDM) analysis, particularly using the Fuzzy TOPSIS method. The combination of structured questionnaires and semi-structured interviews ensures a balance between standardized data collection for analytical rigor and flexibility for capturing nuanced expert insights.

The primary tool was a structured expert judgment questionnaire, designed based on the Fuzzy TOPSIS framework. Respondents were asked to rate the importance of criteria using predefined linguistic terms (e.g., Very Low Important to Extremely Important) mapped to Triangular Fuzzy Numbers (TFNs).

3.7. Data Analysis

3.7.1. Data Analysis Techniques

The collected data were analysed using the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS), a widely recognized MCDM method suitable for handling both quantitative and qualitative expert judgments. Initially, expert responses were aggregated and converted into fuzzy numbers to capture the inherent uncertainty and subjectivity in human judgment. Each critical factor influencing road maintenance decisions was weighted based on expert evaluation, and maintenance strategies were scored relative to these factors. The Fuzzy TOPSIS technique allows the calculation of a closeness coefficient for each alternative strategy, ranking them based on their proximity to the ideal solution and distance from the negative-ideal solution. This approach provides a systematic and transparent framework for evaluating multiple competing strategies while accommodating the subjective nature of expert input.

The data analysis was conducted using the Fuzzy TOPSIS method, which involved several systematic steps to evaluate and rank road maintenance strategies. Initially, fuzzy pairwise comparison matrices were constructed to capture expert judgments on the relative importance of each critical factor, allowing the incorporation of uncertainty and subjectivity inherent in human evaluation. Next, fuzzy weights for each factor were calculated using the Geometric Mean Method, providing a consistent and balanced measure of their influence on decision-making. Following this, a fuzzy decision matrix was developed for the alternative maintenance strategies, reflecting their performance against the identified factors. The decision matrix was then normalized and weighted, and the fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) were determined to represent the best and worst-case scenarios, respectively. Finally, the closeness coefficient for each alternative was calculated, which quantified how close each strategy was to the ideal solution, and the alternatives were ranked accordingly. This structured approach ensured that the evaluation process accounted for both quantitative and qualitative criteria, resulting in a robust and transparent ranking of road maintenance strategies.

3.7.2. Data Analysis Tools

The analysis was conducted entirely using Microsoft Excel, which served as the primary tool for data organization, normalization, fuzzy number calculations, and implementing the TOPSIS procedure. Excel was employed to construct pairwise comparison matrices, calculate fuzzy weights, develop the fuzzy decision matrix, and perform the steps required to determine the closeness coefficients and final rankings. Its flexibility with formulas, matrix operations, and data visualization functions made it suitable for handling the computational requirements of the Fuzzy TOPSIS method without the need for specialized MCDM software. By relying on Excel, the study demonstrates that robust multi-criteria decision-making analysis can be effectively carried out using widely accessible and practical tools.

3.8. Validity and Reliability

Ensuring the validity and reliability of the research findings is essential to maintaining the scientific rigor and credibility of this study. In the context of decision-making research that integrates expert judgment and fuzzy multi-criteria analysis, specific methodological strategies must be employed to confirm that the results are both accurate (valid) and consistent (reliable).

This section outlines the proactive measures taken to enhance validity, as well as the statistical and procedural techniques used to ensure the reliability of the data collected and analyzed.

3.8.1. Proactive Measures

To ensure content validity, the data collection tools, including the pairwise comparison matrix and fuzzy linguistic rating forms, were developed based on a thorough literature review and existing applications of the Fuzzy TOPSIS method in infrastructure and maintenance studies. These tools were then reviewed and validated by a panel of domain experts, including senior civil engineers and road maintenance planners from AACRA (Addis Ababa City Roads Authority), to ensure that the criteria and linguistic scales were relevant, comprehensible, and applicable to the local context.

These measures helped to ensure that the constructs measured by the research instruments accurately reflected the real-world decision environment of road maintenance management.

3.8.2. Pilot Study

Before full-scale data collection, a pilot study was conducted involving five expert participants. The goal of the pilot study was to test the clarity, consistency, and interpretability of the questionnaires and pairwise comparison formats. Based on the feedback, minor adjustments were made to the phrasing of certain criteria and the alignment of linguistic terms with their corresponding fuzzy scales (Triangular Fuzzy Numbers, TFNs).

The pilot study also helped verify the face validity of the instrument, confirming that the questionnaire appeared, on the surface, to measure what it intended to measure.

3.8.3. Triangulation

To enhance the robustness of the findings, methodological triangulation was employed by integrating multiple sources of input and analysis to cross-validate the outcomes. Expert judgments were first collected in the form of qualitative input using linguistic scales, which allowed the incorporation of professional knowledge and practical experience into the evaluation process. These qualitative insights were then complemented by quantitative modeling through the application of the Fuzzy TOPSIS methodology, which provided a structured and systematic framework for analysing and ranking the identified maintenance strategies. In addition, literature benchmarks were used to compare the relative importance of criteria and strategies, ensuring that the study's results were consistent with established knowledge and practices in road maintenance management. By bringing together expert opinion, quantitative techniques, and evidence from existing studies, triangulation minimized the risk of bias and strengthened the construct validity of the research outcomes, thereby enhancing both the credibility and applicability of the findings.

The study can utilize a multi-method approach, including quantitative and qualitative research, to gather information for its objectives. Quantitative methods were conducted through a questionnaire survey, while a qualitative study was performed through document review. In this paper, a total of 20 decision-making experts were selected as the target population from the Addis Ababa City Roads Authority, consultants, and contractor, as they possess background knowledge regarding the overall design of the road and its construction, from the feasibility stage through to design, construction, completion, and maintenance of the road.

The sample size that can be used for this study was consensus-based MCDM methods called the Experts Panel MCDM methods. According to (Tarei, Thakkar, & Nag, 2018)The number of experts involved in the MCDM methods was based on their subject knowledge, experience, skills, and personal relationships. This study employed convenience sampling as it emphasizes representative samples of individuals who are willing and available to participate in the research.

Primary data were collected through a questionnaire survey and document analysis, while secondary data were gathered from a literature review to compile all relevant information needed to address the research questions. The study's questionnaire was developed using a pairwise comparison matrix analysis with fuzzy scales based on various selection criteria in road maintenance management at the Addis Ababa City Roads Authority.

Table 1. The characteristics of the decision-makers

variables		number	percentage
total number of experts		20	100
gender	male	15	75
	female	5	25
Education Level	Diploma	5	25
	Bachelor's	10	50
	Master's	3	15
	PhD	2	10
Field of Study	Civil Engineering	7	35
	construction foreman	6	30
	designer	2	10
	project manager	3	15
	surveyor	2	10
work experience in years	0-2	1	5
	2-4	2	10
	4-6	3	15
	6-8	6	30
	>8	8	40

The questionnaires were distributed to owners, consultants, and contractors involved in road maintenance projects at the Addis Ababa City Roads Authority. The decision-makers invited to complete the questionnaire had varying years of experience and were selected based on their subject knowledge, experience, and skills. Table 1 summarizes the characteristics of the decision-makers who participated in the survey.

3.9. Ethical Consideration

When conducting an ethical consideration assessment for a study on road maintenance strategies, particularly focusing on the Addis Ababa City Roads Authority, several key ethical considerations should be addressed. Here are some ethical considerations specific to this study

3.9.1. Informed Consent

Ensure that all participants, including employees, contractors, and stakeholders involved in the road maintenance projects, are fully informed about the nature of the study, their involvement, and any potential risks or benefits. Obtain voluntary consent from participants to ensure their willingness to contribute to the research.

3.9.2. Confidentiality and Anonymity

Protect the privacy of participants by safeguarding any personal or sensitive information collected during the study. Ensure that individual participants cannot be identified from the data when reporting findings. This is particularly important when discussing sensitive issues related to road construction and maintenance practices.

3.9.3. Avoiding Harm

Take measures to minimize any potential harm to participants, including employees and stakeholders involved in road maintenance. Ensure that participation in the study does not have negative consequences for individuals or the organization.

3.9.4. Respect for Diversity and Inclusivity

Ensure that the study respects the diversity of the participants and avoids any form of discrimination based on factors such as gender, race, religion, or age. Include diverse perspectives and experiences in the study to ensure inclusivity.

3.10. Fuzzy multi-criteria decision-making model

3.10.1. Introduction to Fuzzy TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a widely used Multi-Criteria Decision-Making (MCDM) method that ranks alternatives according to their distances from an ideal solution. Fuzzy TOPSIS enhances the traditional TOPSIS by integrating fuzzy set theory, enabling decision-makers to manage uncertainty and subjective assessments in criteria evaluations.

3.10.2. Steps in the Fuzzy TOPSIS Method

The Fuzzy TOPSIS method involves a structured process to evaluate alternatives under uncertainty. First, the problem and criteria are defined by identifying the alternatives—such as routine maintenance, periodic maintenance, and full reconstruction—and setting evaluation criteria like cost-effectiveness, durability, safety, environmental impact, ease of implementation, and time efficiency, with appropriate weights assigned to each. Next, a fuzzy decision matrix is constructed, where decision-makers rate each alternative using linguistic variables. These ratings are then converted into Triangular Fuzzy Numbers (TFNs), which capture uncertainty and the imprecision of human judgment in the decision-making process.

Table 2. Linguistic Terms & Corresponding TFNs

Linguistic Term	TFN (Triangular Fuzzy Number)
Very Low Important (VLI)	(1, 2, 3)
Low Important (LI)	(2, 3, 4)
Moderately Important (MI)	(3, 4, 5)
Highly Important (HI)	(4, 5, 6)
Extremely Important (EI)	(5, 6, 7)

Normalize the Fuzzy Decision Matrix

Each value is normalized using the **benefit** or **cost criteria formula**:

- **For Benefit Criteria** (Higher is better)

$$\bar{r}_{ij} = \frac{L_{ij}}{max_i\ u_{ij}}, \frac{m_{ij}}{max_i\ u_{ij}}, \frac{u_{ij}}{max_i\ u_{ij}} \text{ ……… Equation 1}$$

- **For Cost Criteria** (Lower is better):

$$\bar{r}_{ij} = \frac{min_i\ L_{ij}}{u_{ij}}, \frac{min_i\ m_{ij}}{m_{ij}}, \frac{min_i\ u_{ij}}{l_{ij}} \text{………… Equation 2}$$

Construct the Weighted Normalized Fuzzy Decision Matrix

Each normalized value is multiplied by its **criterion weight.** w_j

$$\bar{u}_{ij}=\bar{r}_{ij}*w_j \text{…………………… Equation 3}$$

Determine the Fuzzy Ideal Solutions

Positive Ideal Solution (FPIS)

$$\tilde{A}^{+} = (\max_i l_{ij}, \max_i m_{ij}, \max_i u_{ij}) \text{…….…. Equation 4}$$

Negative Ideal Solution (FNIS)

$$\tilde{A}^- = (\min_i l_{ij}, \min_i m_{ij}, \min_i u_{ij})$$ ………..…. Equation 5

Calculate the Distance to FPIS and FNIS

The distance between a fuzzy number $\tilde{v}_i$ and the ideal solutions is computed using the Euclidean distance formula:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(\frac{(l_{ij}-l_j^+)^2+(m_{ij}-m_j^+)^2+(u_{ij}-u_j^+)^2}{3}\right)}$$

……….….. Equation 6

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(\frac{(l_{ij}-l_j^-)^2+(m_{ij}-m_j^-)^2+(u_{ij}-u_j^-)^2}{3}\right)}$$

Calculate the Closeness Coefficient (CC)

The closeness coefficient determines the ranking

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-}$$ ………………………………………. Equation 7

Where:

- CC_i Is the closeness coefficient of the alternative A_i.
- D_i^- It is the distance from the negative ideal solution.
- D_i^+ It is the distance from the positive ideal solution.

The alternative with the highest CC is the best choice.

CHAPTER FOUR

4. RESULT AND DISCUSSION

4.1. Introduction

This chapter presents the results and discussions derived from the empirical analysis carried out to achieve the objectives of this study. The central aim was to examine the critical factors influencing road maintenance decision-making within the Addis Ababa City Roads Authority (AACRA), to prioritize these factors, and to evaluate the comparative performance of alternative maintenance strategies using the Fuzzy TOPSIS method. The chapter integrates both qualitative insights from expert respondents and quantitative analysis generated through fuzzy multi-criteria decision-making (MCDM) techniques, thereby providing a comprehensive understanding of the issues at hand.

The results are organized according to the four specific objectives of the study. First, the chapter identifies and discusses the major factors that shape maintenance decisions, such as cost-effectiveness, durability, safety, environmental impact, ease of implementation, frequency of maintenance, economic effects, life-cycle costs, and time efficiency. Second, it examines the prioritization of these factors by experts through fuzzy weighting, establishing which considerations carry the greatest influence in practice. Third, the chapter evaluates the three major maintenance strategies, Routine Maintenance, Periodic Maintenance, and Rehabilitation, based on their performance against the identified criteria. Finally, it presents a scenario-based discussion of the most suitable strategies under different operational, financial, and environmental contexts.

By combining expert perspectives with structured fuzzy decision analysis, this chapter not only highlights the trade-offs among competing criteria but also demonstrates how context-sensitive decision-making can guide maintenance planning. The findings provide practical insights for AACRA and similar agencies in developing countries, where limited resources, high demand, and variable climatic conditions make strategic prioritization essential.

4.2. Results and Discussion for Objective One: Critical Factors Influencing Road Maintenance Decisions

The first objective of this study was to identify the critical factors influencing road maintenance decisions within the context of the Addis Ababa City Roads Authority (AACRA). Data were collected from experts and professionals directly engaged in road infrastructure planning, design, supervision, and maintenance activities. A total of 20 purposively selected respondents, comprising senior civil engineers, project managers, foremen, and designers, provided their inputs on the factors they considered most influential in determining road maintenance strategies.

4.2.1. Identified Critical Factors

The responses revealed a convergence around several major categories of factors: cost-effectiveness, durability, safety, environmental impact, ease of implementation, frequency of maintenance, economic outcomes, life-cycle costs, and time efficiency. These findings align with existing theoretical literature (Hwang et al., 1981; Popov, Osokin, & management, 2021; R. Robinson, U. Danielson, & M. S. Snaith, 1998b; R. Robinson, Danielson, U., et al., 1998; Zhang, 2003), suggesting that road maintenance is a multidimensional decision-making problem.

For instance, more than 80% of respondents emphasized cost-effectiveness as a decisive factor. Many participants argued that frequent routine maintenance, though seemingly costly in the short term, prevents larger expenditures on rehabilitation and reconstruction. This perception is supported by lifecycle cost analysis studies (Haas & Hudson, 2015), which stresses that early preventive interventions extend pavement life and reduce future costs.

Similarly, Durability was highlighted by 70% of respondents. Engineers noted that certain interventions, such as asphalt overlays, require specific technologies and materials that are not always readily available in Ethiopia. Thus, while theoretically effective, such methods may be impractical in local contexts, a finding consistent with (Zhang, 2003) who emphasized contextual constraints in strategy selection.

4.2.2. Safety as a Core Driver

Road safety emerged as another dominant theme. Nearly all respondents agreed that defects such as potholes, surface cracks, and drainage failures directly contribute to accidents. This confirms (R. Robinson, Danielson, U., et al., 1998) assertion that pavement condition strongly correlates with accident frequency. Respondents further observed that in Addis Ababa, poor surface conditions contribute to frequent minor accidents and increased vehicle operating costs. Consequently, maintenance decisions are often accelerated when safety concerns are evident, even if budgets are limited.

4.2.3. Environmental and Climatic Considerations

While cost and safety were most frequently cited, respondents also acknowledged the growing importance of environmental sustainability. For example, 45% of respondents noted that reconstruction projects generate large amounts of construction waste and greenhouse gas emissions, while smoother pavements reduce vehicle emissions. These observations resonate with (Alawaysheh et al., 2020a) who highlight the ecological footprint of infrastructure projects.

Climatic conditions were also emphasized. Respondents pointed to the challenges posed by seasonal rainfall and temperature fluctuations in Addis Ababa. Roads often deteriorate quickly during rainy seasons, particularly when drainage systems are poorly maintained. These local insights are consistent with (Motlagh et al., 2024) who argue that climate and traffic loading accelerate pavement deterioration and necessitate tailored maintenance approaches.

4.2.4. User Satisfaction and Institutional Pressures

Another critical factor identified was user satisfaction. Respondents argued that the public's perception of road quality, measured in terms of smoothness, reduced travel time, and fuel consumption, often pressures authorities into prioritizing visible interventions such as pothole patching.

While these interventions may not always be the most cost-effective, they serve political and social functions by maintaining public trust in government agencies. This aligns with(Burningham & Stankevich, 2005) who emphasize the socio-political dimension of road maintenance decisions.

4.2.5. Comparative Analysis with Literature

The factors identified in this study broadly confirm findings from international literature. For example, (Haas & Hudson, 2015) also found cost-effectiveness and technical feasibility to be the most critical determinants. However, one divergence in the Ethiopian context is the relatively higher weight placed on user satisfaction and institutional responsiveness. Unlike in high-income countries, where long-term sustainability often dominates, in Ethiopia, immediate public concerns and budgetary constraints appear to drive many decisions. This highlights the need for context-sensitive frameworks like Fuzzy TOPSIS, which can integrate multiple, and sometimes conflicting, criteria into a coherent decision-making process.

4.2.6. A detailed explanation of each criterion

Table 3Explanation of the criterion

Criterion	Description
Cost-Effectiveness	Measures how well the strategy balances cost with benefits, aiming to get the most improvement per cost.
Durability	How long does the maintenance last before needing repairs or replacement?
Safety Improvement	How much does the strategy improve road safety for all users by reducing hazards and accidents?
Environmental Impact	Considers how eco-friendly the strategy is, including emissions, waste, and the use of sustainable materials.
Ease of Implementation	How practical and simple it is to apply the strategy, including resource availability and minimal disruption.
Maintenance Frequency	How often the road will need maintenance after the intervention; less frequent is better.
Economic Impact	The wider economic effects on the community, such as job creation and business impact.
Life Cycle Cost (LCC)	Total cost of the strategy over its whole life, including all maintenance and replacement costs.
Time Efficiency	How quickly can the maintenance be completed, minimizing disruption and delays for road users?

4.3. Results and Discussion for Objective Two: Prioritization of Critical Factors

The second objective of this research was to prioritize the identified critical factors influencing road maintenance decision-making. While Objective One established that factors such as cost-effectiveness, durability, safety, environmental impact, ease of implementation, frequency of maintenance, economic outcomes, life-cycle costs, and time efficiency all play a role, it is necessary to establish their relative importance for decision-making. Without prioritization, road agencies may struggle to allocate resources efficiently, particularly in contexts where budgetary and technical constraints limit the ability to address all needs simultaneously.

4.3.1. Application of Fuzzy TOPSIS for Factor Prioritization

The study employed the Fuzzy TOPSIS method to capture expert judgments and translate qualitative perceptions into quantitative priorities. Respondents rated the relative importance of each factor using linguistic scales such as Very Low Important (VLI), Low Important (LI), Moderately Important (MI), Highly Important (HI), and Extremely Important (EI), which were then converted into triangular fuzzy numbers. This approach helped capture uncertainty and subjectivity in expert judgments, consistent with (Ouma et al., 2015) who note that fuzzy methods reduce bias by allowing experts to express judgments in approximate terms.

The fuzzy pairwise comparison matrices were then aggregated using the geometric mean method, producing fuzzy weights for each factor. Finally, the defuzzification process converted these fuzzy numbers into crisp values, allowing for direct comparison and ranking.

Table 4. Linguistic terms and their numerical intervals for fuzzy TOPSIS

Linguistic Term	TFN (Triangular Fuzzy Number)
Very Low Important (VLI)	(1, 2, 3)
Low Important (LI)	(2, 3, 4)
Moderately Important (MI)	(3, 4, 5)
Highly Important (HI)	(4, 5, 6)
Extremely Important (EI)	(5, 6, 7)

Table 5. Fuzzy weights of the criteria concerning the goal

Criteria	Average Value	Linguistic Term	TFN (Triangular Fuzzy Number)
Cost-Effectiveness	4.756	Extremely Important (EI)	(5,6,7)
Life Cycle Cost	4.731	Extremely Important (EI)	(5,6,7)
Safety	4.656	Highly Important (HI)	(5,6,7)
Durability	4.625	Highly Important (HI)	(5,6,7)
Economic Impact	4.600	Highly Important (HI)	(4,5,6)
Time Efficiency	4.444	Moderately Important (MI)	(3,4,5)
Maintenance Frequency	4.419	Moderately Important (MI)	(3,4,5)
Environmental Impact	4.406	Low Important (LI)	(2,3,4)
Ease of Implementation	4.595	Low Important (LI)	(4,5,6)

4.3.2. Results of Factor Ranking

The results showed that cost-effectiveness emerged as the most highly ranked factor, with an average value of 4.756. This suggests that experts consistently view financial sustainability and lifecycle cost minimization as the most decisive considerations in road maintenance planning.

Safety was the third most influential factor, receiving an average value of 4.656. This highlights the strong recognition among engineers and policymakers that deteriorated roads directly contribute to accidents, higher vehicle operating costs, and loss of life.

Economic Impact ranked fifth, with an average value of 4.6. Respondents emphasized that even when cost-effectiveness and safety demand a particular strategy, the practical availability of equipment, materials, and technical expertise often determines whether the intervention is feasible.

4.3.3. Discussion of Findings

These results reflect the realities of infrastructure management in developing contexts like Ethiopia. The emphasis on cost-effectiveness supports the findings of (Haas & Hudson, 2015), who argue that financial sustainability is central to infrastructure management. Similarly, the prioritization of safety aligns with (R. Robinson, Danielson, U., et al., 1998) who emphasized that surface defects are major contributors to traffic accidents.

Interestingly, the relatively low prioritization of user satisfaction contrasts with studies in high-income countries, where road user experience and comfort are often central to performance evaluation(Burningham & Stankevich, 2005).

This divergence may reflect differences in institutional pressures: while governments in developed nations face strong public accountability for service quality, Ethiopian agencies operate under more severe budgetary constraints, making technical and financial considerations dominant.

The relatively low emphasis on environmental sustainability also highlights the tension between immediate infrastructure needs and long-term ecological concerns. Although recent studies (Alawaysheh et al., 2020a; Xu et al., 2024) stress the importance of environmentally friendly practices. In Ethiopia, such concerns remain secondary to urgent cost and safety priorities.

4.3.4. Comparative Insights from Empirical Studies

The prioritization pattern observed here mirrors findings in similar studies from other developing nations. For example, (Ayalew et al., 2022) found that Ethiopian experts consistently prioritized periodic maintenance strategies because they offer the best balance of cost-effectiveness and safety improvements. Similarly, demonstrated in Bangladesh that financial and technical feasibility dominated decision-making, while user satisfaction was considered relatively less critical.

In contrast, studies from developed contexts (Baykasoğlu & Gölcük, 2015; Yuan Liu et al., 2021) show a more balanced weighting between financial, environmental, and user-oriented factors. This highlights the contextual nature of prioritization: while the Fuzzy TOPSIS method ensures a robust, structured ranking process, the actual weights reflect local realities and institutional priorities.

4.3.5. Implications for Road Maintenance Management

The prioritization of factors has important implications for the Addis Ababa City Roads Authority. By recognizing cost-effectiveness and safety as primary concerns, AACRA can design maintenance programs that focus resources where they will generate the highest impact. However, the relative neglect of environmental and user-related factors suggests a need for policy reform to ensure a more balanced, sustainable approach. For instance, incorporating environmental performance indicators into road maintenance contracts could raise the salience of sustainability, while public consultation mechanisms could elevate user perspectives.

4.4. Results and Discussion for Objective Three: Evaluation of Road Maintenance Strategies Using Fuzzy TOPSIS

The third objective of this study was to evaluate different road maintenance strategies by applying the Fuzzy TOPSIS method. Building on the factor prioritization in Objective Two, this section applies the weights of cost-effectiveness, durability, safety, environmental impact, ease of implementation, frequency of maintenance, economic outcomes, life-cycle costs, and time efficiency to compare the three major road maintenance strategies: Routine Maintenance, Periodic Maintenance, and Rehabilitation.

4.4.1. Construction of the Fuzzy Decision Matrix

Create the fuzzy-decision matrix based on the criteria, then choose the appropriate linguistic variables for the options. The completed questionnaire will start with the building dataset that was acquired. The best workable road maintenance management plan is assessed and selected in this study. The respondents have a variety of linguistic factors used in this study, based on their subjective evaluations. This study uses the average value approach for each evaluator of equal relevance to integrate the fuzzy/vague judgment values of different evaluators regarding the same assessment criteria. The evaluators then used linguistic terms, such as "Very Low Important," "Low Important," "Moderately Important," "Highly Important," and "Extremely Important," to convey their thoughts about each person's rating based on the fuzzy data of the 20 decision experts listed in Table 1.

This stage captured the subjective but structured knowledge of domain experts. Converting linguistic inputs into TFNs allowed the decision-making model to integrate both qualitative insights and numerical analysis, reducing bias and enhancing transparency. This step ensured that the real-world expertise of AACRA engineers and planners was embedded into the strategy evaluation.

4.4.2. Combined Decision Matrix

An essential phase in the Fuzzy TOPSIS technique is the Combined Decision Matrix, especially when there are several experts or decision-makers involved. It is the sum of the individual decision matrices into a single, integrated matrix that expresses everyone's collective assessment.

Table 6. Combined decision matrix

Criteria / Alternative	Routine	Rehabilitation	Periodic
Cost-Effectiveness	(2,4.7,7)	(1,4.25,7)	(1,4.85,7
Durability	(2,4.6,7)	(2,4.8,7)	(3,4.7,7)
Safety	(3,4.7,7)	(2,4.85,7)	(2,4.7,7)
Environmental Impact	(2,4.85,7)	(2,4.55,7)	(2,5.2,7)
Ease of Implementation	(2,4.75,7)	(2,4.75,7)	(3,5.15,7)
Time Efficiency	(3,5.05,7)	(2,5.05,7)	(3,4.6,7)
Maintenance Frequency	(1,4.7,7)	(2,4.7,7)	(2,4.75,7)
Economic Impact	(2,4.8,7)	(2,4.65,7)	(2,4.7,7)
Life Cycle Cost	(2,4.9,7)	(2,4.75,7)	(2,4.9,7)

This table aggregates expert evaluations of the three road maintenance alternatives, Routine, Periodic, and Rehabilitation, across the nine criteria. Each value in the table is a TFN representing the collective perception of how well each strategy performs for each criterion.

For example, Periodic Maintenance scored highly in Durability (3, 4.7, 7) and Ease of Implementation (3, 5.15, 7), showing expert agreement on its technical feasibility and effectiveness.

Routine Maintenance had lower scores in criteria like Durability (2, 4.6, 7), indicating a lesser perceived long-term benefit.

This matrix reflects raw expert judgment before normalization

4.4.3. Normalize the fuzzy decision matrix

The Normalized Fuzzy Decision Matrix represents a crucial stage in the Fuzzy TOPSIS process, as it ensures that all evaluation criteria are expressed on a comparable scale, regardless of their original measurement units. This step eliminates bias caused by differing scales and allows decision-makers to evaluate alternatives fairly. The normalization process was performed using Equations (1) and (2), which adjust benefit-oriented criteria (where higher values are better) and cost-oriented criteria (where lower values are preferred) differently. The resulting normalized fuzzy values for each alternative are presented in Table 7.

Table 7. Normalized Fuzzy Decision Matrix for Road Maintenance Alternatives

Criteria / Alternative	Routine	Rehabilitation	Periodic
Cost-Effectiveness	(0.5,0.21,0.14)	(1,0.24,0.14)	(1,0.21,0.14)
Durability	(0.29,0.66,1)	(0.29,0.69,1)	(0.43,0.67,1)
Safety	(0.43,0.67,1)	(0.29,0.69,1)	(0.29,0.67,1)
Environmental Impact	(0.29,0.69,1)	(0.29,0.65,1)	(0.29,0.74,1)
Ease of Implementation	(0.29,0.68,1)	(0.29,0.68,1)	(0.43,0.74,1)
Time Efficiency	(0.43,0.72,1)	(0.29,0.72,1)	(0.43,0.66,1)
Maintenance Frequency	(1,0.21,0.14)	(0.5,0.21,0.14)	(0.5,0.21,0.14)
Economic Impact	(0.29,0.69,1)	(0.29,0.66,1)	(0.29,0.67,1)
Life Cycle Cost	(0.5,0.2,0.14)	(0.5,0.21,0.14)	(0.5,0.2,0.14)

The normalization produces fuzzy numbers that lie within the range of 0 to 1, reflecting the degree of satisfaction with respect to each criterion. For example, under Durability, the fuzzy value for Periodic Maintenance is (0.43, 0.67, 1), which is noticeably higher than those for Routine (0.29, 0.66, 1) and Rehabilitation (0.29, 0.69, 1). This indicates that periodic interventions are perceived by experts as more durable in extending pavement life compared to the other alternatives.

Similarly, in terms of Environmental Impact, Periodic Maintenance again shows stronger performance with normalized values of (0.29, 0.74, 1). This suggests that while all three strategies contribute to environmental considerations, periodic interventions strike a better balance between sustainability and effectiveness. This is particularly relevant in the Ethiopian context, where reducing emissions from reconstruction activities and minimizing resource wastage are critical priorities.

For Safety Improvement, Routine Maintenance scores (0.43, 0.67, 1), slightly higher than Rehabilitation and Periodic. This result is intuitive, as routine interventions such as patching potholes and repainting road markings directly contribute to road user safety on a day-to-day basis, even if they do not significantly extend structural durability.

On the other hand, cost-related criteria such as Cost Effectiveness, Maintenance Frequency, and Life Cycle Cost show that Routine Maintenance often receives relatively higher normalized values. For instance, Routine Maintenance scores (1, 0.21, 0.14) in Maintenance Frequency, meaning it requires frequent but less resource-intensive interventions. This aligns with the reality that routine works are less expensive per intervention but demands consistent allocation of resources. In contrast, Rehabilitation, with values like (0.5, 0.21, 0.14), is less frequent but far more resource-demanding, which shifts the balance toward higher upfront costs but longer intervals between interventions.

In terms of Ease of Implementation and Time Efficiency, Periodic Maintenance again demonstrates an advantage with values of (0.43, 0.74, 1) and (0.43, 0.66, 1) respectively. This reflects the perception that periodic works, such as overlays, are easier to organize and execute in a predictable timeframe, unlike rehabilitation which requires extensive planning, machinery, and capital investment.

From a holistic perspective, the normalized decision matrix reveals clear patterns in the comparative performance of the three maintenance strategies. Routine Maintenance demonstrates strength in cost-related and short-term safety aspects, as it provides immediate solutions such as pothole patching and surface sealing at relatively low cost while directly reducing accident risks. Periodic Maintenance, on the other hand, emerges as the most balanced strategy, excelling in durability, environmental sustainability, and ease of implementation. Its ability to extend pavement life through scheduled interventions such as overlays and resealing makes it both practical and resource-efficient, while its comparatively lower environmental footprint underscores its sustainability advantage. Rehabilitation, though resource-intensive, remains critical for long-term service restoration, particularly in cases of severe structural failure. However, it underperforms in cost-effectiveness and implementation ease due to high capital requirements, longer execution times, and greater disruption to road users. Taken together, these findings suggest that while each strategy has its niche, Periodic Maintenance offers the most comprehensive benefits across multiple criteria, Routine Maintenance provides short-term efficiency, and Rehabilitation should be reserved for contexts of advanced deterioration where other interventions are insufficient.

Thus, the normalization process provides a structured way of visualizing trade-offs among the three strategies. It highlights that Periodic Maintenance offers the most balanced performance across multiple criteria, while Routine Maintenance remains essential for immediate safety and cost control. Rehabilitation, although resource-intensive, is indispensable in cases of severe deterioration. This balanced understanding sets the foundation for the subsequent steps of Fuzzy TOPSIS, where weighted aggregation and closeness coefficients are applied to determine the optimal strategy.

4.4.4. Compute the Weighted Normalized FUZZY Decision Matrix

The computation of the Weighted Normalized Fuzzy Decision Matrix represents a critical advancement in the Fuzzy TOPSIS process, as it integrates two essential dimensions: the normalized performance scores of each alternative and the relative importance (weights) of the evaluation criteria. This ensures that alternatives are not only compared based on their normalized outcomes but also adjusted according to the priority attached to each criterion by experts. In practice, this means that a strategy performing well on a criterion deemed highly important, such as durability or safety, will have a stronger impact on the final ranking than performance on a less significant criterion.

Table 8. Weighted Normalized Fuzzy Decision Matrix

Criteria / Alternative	Routine	Rehabilitation	Periodic
Cost-Effectiveness	(2.5,1.28,1)	(5,1.41,1)	(5,1.24,1)
Durability	(1.43,3.94,7)	(1.43,4.11,7)	(2.14,4.03,7)
Safety	(2.14,4.03,7)	(1.43,4.16,7)	(1.43,4.03,7)
Environmental Impact	(0.57,2.08,4)	(0.57,1.95,4)	(0.57,2.23,4)
Ease of Implementation	(1.14,3.39,6)	(1.14,3.39,6)	(1.71,3.68,6)
Time Efficiency	(1.29,2.89,5)	(0.86,2.89,5)	(1.29,2.63,5)
Maintenance Frequency	(3,0.85,0.71)	(1.5,0.85,0.71)	(1.5,0.84,0.71)
Economic Impact	(1.14,3.43,6)	(1.14,3.32,6)	(1.14,3.36,6)
Life Cycle Cost	(2.5,1.22,1)	(2.5,1.26,1)	(2.5,1.22,1)

In Table 8, the normalized fuzzy ratings of each alternative are multiplied by the corresponding fuzzy weights derived from Table 5, yielding a set of weighted fuzzy numbers that more accurately reflect the interplay between performance and priority. For instance, Periodic Maintenance emerges as the leading strategy in criteria with high importance, such as Durability (2.14, 4.03, 7) and Ease of Implementation (1.71, 3.68, 6). This reinforces its role as a balanced approach that is not only technically sound but also practical and sustainable in implementation. Conversely, Rehabilitation performs best in Cost-Effectiveness (5, 1.41, 1), but because this criterion carries lower weight compared to durability or environmental impact, its advantage here does not compensate for its weaker scores in other critical areas. Similarly, Routine Maintenance demonstrates relatively strong performance in Maintenance Frequency (3, 0.85, 0.71), indicating its usefulness for immediate and repetitive interventions, but its limited contribution to long-term durability reduces its comparative standing.

The value of this weighted approach lies in its ability to merge subjective expert judgment (criteria importance) with objective performance data, producing a composite representation of each strategy's overall suitability. By doing so, the Weighted Normalized Fuzzy Decision Matrix enables decision-makers to move beyond raw comparisons and instead prioritize solutions that align with both technical performance and strategic priorities. Ultimately, this step confirms that while each maintenance alternative has strengths in specific areas, Periodic Maintenance consistently gains higher weighted scores across the most influential criteria, making it the most robust choice for sustainable and cost-efficient road maintenance planning.

4.4.5. Determination of Positive and Negative Ideal Solutions

The determination of the Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS) represent a pivotal stage in the Fuzzy TOPSIS methodology, as it establishes the benchmark reference points against which all alternatives are evaluated. The FPIS corresponds to the "best possible" performance across all criteria, representing maximum benefits or minimum costs, while the FNIS represents the "worst possible" performance, corresponding to the least desirable outcomes. These reference points are extracted directly from the Weighted Normalized Fuzzy Decision Matrix, using the maximum and minimum values of the fuzzy numbers associated with each criterion.

Table 9. Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS)

Criteria / Ideal Solution	FPIS	FNIS
Cost-Effectiveness	(5,1.41,1)	(2.5,1.24,1)
Durability	(2.14,4.11,7)	(1.43,3.94,7)
Safety	(2.14,4.16,7)	(1.43,4.03,7)
Environmental Impact	(0.57,2.23,4)	(0.57,1.95,4)
Ease of Implementation	(1.71,3.68,6)	(1.14,3.39,6)
Time Efficiency	(1.29,2.89,5)	(0.86,2.63,5)
Maintenance Frequency	(3,0.85,0.710	(1.5,0.84,0.71)
Economic Impact	(1.14,3.43,6)	(1.14,3.32,6)
Life Cycle Cost	(2.5,1.26,1)	(2.5,1.22,1)

In this study, Equations (4) and (5) were applied to compute FPIS and FNIS values. The final results are summarized in Table 9, which presents the positive ideal and the negative ideal solutions for all nine evaluation criteria. For instance, in the case of Cost-Effectiveness, the FPIS value of (5, 1.41, 1) indicates the highest desirable score under this criterion, while the FNIS value (2.5, 1.24, 1) marks the least favourable level. Similarly, for Durability, the FPIS (2.14, 4.11, 7) represents the longest possible pavement life, while the FNIS (1.43, 3.94, 7) captures the weakest outcome. In the case of Environmental Impact, the FPIS (0.57, 2.23, 4) reflects a sustainable performance threshold, whereas the FNIS (0.57, 1.95, 4) corresponds to a less desirable scenario with higher ecological risks.

The inclusion of FPIS and FNIS provides the basis for the subsequent step of calculating the distance of each alternative from both the positive ideal solution and the negative ideal solution. This is essential because the final ranking of alternatives is not determined solely by their absolute performance but by their relative closeness to the “best” and “worst” possible conditions. Thus, alternatives such as Periodic Maintenance, which consistently approach the FPIS values in durability, environmental impact, and ease of implementation, are more likely to achieve higher rankings. On the other hand, strategies like Routine Maintenance, although performing strongly in cost-related aspects, tend to fall closer to the FNIS in long-term sustainability criteria, which limits their overall standing.

4.4.5.1. Result Interpretation

The analysis of FPIS and FNIS values reveals several important patterns

Periodic Maintenance emerges as the closest to the FPIS in multiple high-weight criteria, particularly durability (2.14, 4.11, 7) and ease of implementation (1.71, 3.68, 6). This confirms its role as the most balanced and sustainable strategy across both technical and practical dimensions.

Rehabilitation is strongly aligned with the FPIS in cost-effectiveness, scoring (5, 1.41, 1). However, its lower values in environmental impact and implementation efficiency pull it closer to FNIS in those areas, highlighting its limitations in scenarios where sustainability and practicality are emphasized.

Routine Maintenance aligns closely with FNIS in durability and environmental sustainability, demonstrating that although it provides short-term cost advantages, it is less effective for long-term performance. Its proximity to FNIS values such as durability (1.43, 3.94, 7) emphasizes its shortcomings in resilience.

4.4.5.2. Conclusion

The computation of FPIS and FNIS provides a robust foundation for the comparative evaluation of road maintenance strategies. By defining the best-case (FPIS) and worst-case (FNIS) scenarios for each criterion, the analysis enables decision-makers to assess not only how well an alternative performs, but how far it deviates from optimal conditions. This ensures a more nuanced understanding of trade-offs across criteria.

The findings clearly indicate that Periodic Maintenance consistently aligns more closely with the FPIS across critical dimensions, reinforcing its status as the most effective long-term strategy under the studied conditions. Rehabilitation remains a suitable option for cases requiring immediate service restoration, particularly in high-traffic corridors where cost-effectiveness and safety are paramount. Meanwhile, Routine Maintenance provides short-term functionality but aligns too closely with FNIS in durability and environmental factors to serve as a sustainable solution on its own.

Overall, the FPIS/FNIS analysis strengthens the conclusion that Periodic Maintenance should be prioritized as the core strategy for road network management, while Routine and Rehabilitation strategies can serve as complementary measures in specific contexts.

4.4.6. Calculate the Distance to FPIS and FNIS

After identifying the Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS), the analysis measures how far each alternative lies from these two reference points. Following Equation (6), distances were computed on the **weighted, normalized triangular fuzzy numbers** using the standard vertex distance for TFNs (i.e., a Euclidean-type metric applied to the (l, m,u) components). For each criterion, this yielded two crisp distances per alternative:

- Di+: distance to FPIS (smaller is better), and
- Di−: distance to FNIS (larger is better).

Tables 10 and 11 present these distances criterion-by-criterion. Because distances are derived from the **weighted** decision matrix, they already internalize both the performance of each alternative and the priority (weight) of each criterion.

Table 10. Distance of Each Alternative to FPIS

Criteria / Alternative	Routine	Rehabilitation	Periodic
Cost-Effectiveness	2.504	0.000	0.175
Durability	0.735	0.714	0.086
Safety	0.129	0.714	0.726
Environmental Impact	0.150	0.279	0.000
Ease of Implementation	0.639	0.639	0.000
Time Efficiency	0.000	0.429	0.257
Maintenance Frequency	0.000	1.500	1.500
Economic Impact	0.000	0.107	0.071
Life Cycle Cost	0.039	0.000	0.039

Table 11. Distance of Each Alternative to FNIS

Criteria / Ideal Solution	Routine	Rehabilitation	Periodic
Cost-Effectiveness	0.039	2.506	2.500
Durability	0.000	0.171	0.719
Safety	0.714	0.129	0.000
Environmental Impact	0.129	0.000	0.279
Ease of Implementation	0.000	0.000	0.639
Time Efficiency	0.500	0.257	0.429
Maintenance Frequency	1.500	0.009	0.000
Economic Impact	0.107	0.000	0.036
Life Cycle Cost	0.000	0.039	0.000

4.4.6.1. What the FPIS/FNIS Distances Show

Periodic maintenance consistently approaches the ideal on durability, environment, and implementation practicality.

In Table 10, Periodic records the smallest FPIS distances for Durability (0.086), Environmental Impact (0.000), and Ease of Implementation (0.000). In Table 11, the corresponding FNIS distances are largest for Durability (0.719) and Environmental Impact (0.279), confirming that Periodic is not only closest to the best case but also farthest from the worst case for these high-priority attributes. This supports the earlier finding that Periodic is the most balanced, long-horizon strategy where asset longevity and sustainability matter most.

Routine maintenance excels in short-term operability and safety but lags in structural longevity and economics.

Routine shows FPIS distance = 0.000 for Time Efficiency, indicating it meets the ideal on speed of delivery. It also has the smallest FPIS distance for Safety (0.129) and the largest FNIS distance for Safety (0.714), meaning Routine provides the best immediate safety improvements among the three. However, Routine is farther from FPIS in Durability (0.735) and weak on economics in this dataset, e.g., Cost-Effectiveness shows a large FPIS distance (2.504) and a very small FNIS distance (0.039). This pattern fits the operational reality: routine works well for rapid, short-cycle fixes and hazard removal, but it does not deliver strong structural gains or economic efficiency over the life cycle.

Rehabilitation aligns with ideal values on the cost side, but it is penalized on speed and frequency.

Rehabilitation records FPIS distance = 0.000 for Cost-Effectiveness and Life Cycle Cost, and correspondingly very large FNIS distances (2.506 and 0.039, respectively, in Table 11, where larger is better). This says the cost profile of Rehabilitation (when major defects exist) can be optimal in the weighted framework used. Yet, Rehabilitation is penalized for Time Efficiency (FPIS distance 0.429) and Maintenance Frequency (FPIS distance 1.500), reflecting longer construction windows and the disruption associated with heavy works. In other words, where budgets can support major interventions and corridor criticality warrants structural restoration, Rehabilitation performs economically, but it is not the “fast and light” option.

The criterion-by-criterion analysis provides deeper insight into the comparative strengths and weaknesses of each road maintenance strategy, reinforcing their distinct functional roles. In terms of Durability, Periodic maintenance emerges as the closest to the ideal solution (FPIS = 0.086; FNIS = 0.719), highlighting its superior ability to extend pavement life. For Environmental Impact, Periodic again demonstrates its advantage, aligning exactly with the ideal (FPIS = 0.000) while maintaining a safe distance from the worst-case outcome (FNIS = 0.279). A similar trend is observed in Ease of Implementation, where Periodic once again meets the ideal (FPIS = 0.000), while Routine and Rehabilitation are less favourable with equal but higher distances (0.639). When considering Safety, Routine maintenance performs best (FPIS = 0.129; FNIS = 0.714), reflecting its capacity to address immediate safety hazards, though Periodic performs the weakest under this specific criterion (FPIS = 0.726; FNIS = 0.000).

Regarding Time Efficiency, Routine is again the most favourable (FPIS = 0.000), followed by Periodic (0.257) and Rehabilitation as the slowest (0.429). For Cost-Effectiveness and Life Cycle Cost, Rehabilitation stands out as the most optimal (FPIS = 0.000), supported by Periodic, which remains relatively close in cost-effectiveness (FPIS = 0.175) and equal to Routine in life cycle cost (0.039). Finally, for Maintenance Frequency, Routine aligns directly with the ideal target (FPIS = 0.000), while the FNIS distances of Rehabilitation (0.009) and Periodic (0.000) suggest differing managerial preferences, with Routine positioned as the most practical in terms of meeting desired maintenance frequency levels. This criterion-based interpretation underscores how each strategy aligns with particular objectives, demonstrating that Routine excels in short-term safety and responsiveness, Periodic dominates in durability, environmental sustainability, and ease of implementation, while Rehabilitation is most effective for cost and long-term structural restoration.

4.4.6.2. Interpretation: What This Means for Decision-Making

Taken together, the distances portray distinct strategy profiles

Periodic is the strategic, sustainability-leaning choice closest to the ideal on durability, environment, and ease of implementation. When extending service life and minimizing ecological impacts are priorities (with acceptable work windows), Periodic should dominate.

Routine is the tactical, operations-first choice closest to the ideal on safety and time efficiency. It is appropriate for fast hazard mitigation, commuter-facing improvements, and short disruptions, but it does not deliver strong structural or economic outcomes in this weighting scheme.

Rehabilitation is the capital-intensive restoration choice economically ideal in this dataset for cost-effectiveness and life-cycle cost when major distress exists, but slower to deliver and more disruptive, with weaker scores on implementation practicality and on safety compared to Routine.

These findings mirror standard asset management logic: use Routine for immediate safety and serviceability, Periodic to preserve and stretch asset life under budget constraints and sustainability targets, and Rehabilitation when condition thresholds or strategic importance justify deep structural intervention.

4.4.7. Calculation of Closeness Coefficients (CC)

The final step of the Fuzzy TOPSIS procedure is the computation and interpretation of the Closeness Coefficient (CC), which distils the entire multi-criteria, fuzzy evaluation into a single comparative score for each alternative. Using the standard TOPSIS formula

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

WhereD_i^+ is the aggregated distance of the alternative from the Fuzzy Positive Ideal Solution and D_i^- is the aggregated distance from the Fuzzy Negative Ideal Solution, CC values were calculated for the three maintenance options.

Table 12 Closeness Coefficient (CC) and Final Ranking of Alternatives

Alternative	FPIS	FNIS	CC	Rank
ROUTINE	4.194	2.989	0.416	2
REHABILITATION	4.382	3.111	0.415	3
PERODIC	2.853	4.601	0.617	1

The results and final ranking appear in Table 12: Periodic maintenance achieves the highest CC (0.617) and is therefore the top-ranked option; Routine maintenance follows (CC = 0.416, rank 2); Rehabilitation scores slightly lower (CC = 0.415, rank 3).

The closeness coefficient (CC) measures the relative closeness of each strategy to the FPIS and its distance from the FNIS. Higher CC values indicate better performance.

These CC values synthesise every earlier computational step, normalization, weighting, and the FPIS/FNIS distance computations into a single measure of relative desirability. The clear leader, Periodic Maintenance, scores highest because it consistently minimizes distance to the positive ideal on the most influential criteria (notably durability, environmental impact, and ease of implementation) while remaining acceptably distant from the negative ideal. In practical terms, this means periodic interventions (e.g., resurfacing, thin overlays, resealing) deliver the best balance of lifecycle performance, environmental benefit, and implementability for the road network conditions and expert judgments used in this study.

Routine Maintenance ranks second because it performs strongly on short-term, user-facing criteria such as time efficiency and immediate safety improvement; its CC demonstrates that while routine works are effective for rapid hazard removal and short-term serviceability, they do not score as highly across the long-term, high-weight criteria that drive overall strategic value. Rehabilitation, despite showing favourable cost-related and life-cycle metrics in specific calculations, ranks third because its relative weaknesses on implementation ease, time efficiency, and some sustainability criteria reduce its overall closeness to the ideal under the chosen weights and expert assessments.

Two practical observations arise from the CC results. First, the gap between Routine (0.416) and Rehabilitation (0.415) is extremely small, indicating that ranking between these two alternatives is sensitive to weight choice and expert judgment; a modest change in criterion weights or additional expert input could reverse their order. This points to the value of conducting sensitivity analysis and stakeholder validation before enshrining any single ranking as policy. Second, the substantially higher CC for Periodic Maintenance (0.617) provides robust justification for prioritizing periodic measures as the core maintenance Strategy for Addis Ababa's Road network, complemented by routine interventions for immediate safety and targeted rehabilitation for critically deteriorated corridors.

In conclusion, the Closeness Coefficient results consolidate the study's empirical and fuzzy-MCDM analyses into a clear recommendation: institutionalize Periodic Maintenance as the principal strategy for routine network stewardship, retain Routine Maintenance as the operational tool for short-term safety and rapid response, and apply Rehabilitation selectively when structural failure or corridor criticality justifies the higher cost and longer works. Before final adoption, the study recommends performing sensitivity tests on criterion weights, expanding expert sampling where possible, and integrating these CC outcomes into a Pavement Management System for periodic re-evaluation as conditions, budgets, and policy priorities change.

4.5. Results and Discussion for Objective Four: Determining the Most Suitable Strategy under Different Scenarios

The final objective of this research was to determine the most suitable road maintenance strategy under different contextual scenarios using the results derived from the Fuzzy TOPSIS method. By integrating multiple criteria, including cost-effectiveness, durability, safety improvement, ease of implementation, maintenance frequency, economic impact, life cycle cost, environmental impact, and time efficiency, the study evaluated how each alternative performs under varying road conditions, budgetary environments, and traffic patterns. The use of Fuzzy TOPSIS allowed the research to capture uncertainty in expert judgments and reflect the nuanced trade-offs among strategies.

4.5.1. Scenario-Based Evaluation of Alternatives

The results of the closeness coefficient analysis clearly indicate that Periodic Maintenance is the most suitable strategy overall, achieving the highest CC value of 0.617, followed by Routine Maintenance (0.416) and Rehabilitation (0.415). However, the most appropriate strategy is not uniform across all road contexts; instead, the decision depends heavily on the prevailing conditions, such as traffic volume, climate, budget constraints, and pavement deterioration levels. This confirms the findings of (Ayalew et al., 2022) That maintenance decision-making must remain adaptive and scenario-specific.

High-Traffic, Critical Corridors

For urban arterial roads and highways that carry significant daily traffic volumes, the results suggest that Rehabilitation becomes the preferred option despite its lower overall CC ranking. This is because rehabilitation measures (e.g., overlays, structural strengthening, and full-depth repairs) directly address severe pavement failures, restore long-term structural capacity, and improve safety under high loading conditions. Although rehabilitation is costlier and more difficult to implement (as shown by its higher distances to FPIS in ease of implementation and time efficiency), its ability to sustain performance under heavy loads justifies its use in these critical scenarios. This aligns with(Yuan Liu et al., 2021) who demonstrated that rehabilitation strategies perform better in dense urban environments where failure risks are high.

Moderate-Traffic Roads with Stable Budgets

The study's fuzzy ranking highlights Periodic Maintenance as the optimal choice in these conditions. Periodic measures such as overlays, surface resealing, and crack treatments scored highest in durability (FPIS 0.086; FNIS 0.719) and environmental sustainability (FPIS 0.000; FNIS 0.279), making them highly effective in extending service life and reducing the need for costly rehabilitation later. For road authorities with stable but not excessive budgets, periodic maintenance provides the best trade-off between lifecycle cost and performance. This finding is consistent with Motlagh (Motlagh et al., 2024), who showed that preventive strategies substantially reduce total life-cycle costs in moderate climates.

Low-Traffic, Rural Roads

In rural and secondary road networks where traffic demand is minimal, the results show that Routine Maintenance remains adequate. Routine strategies (e.g., pothole patching, drainage clearing, surface sealing) performed best in time efficiency (FPIS 0.000) and safety responsiveness (FPIS 0.129), ensuring that low-volume roads remain serviceable without excessive resource allocation. Since rehabilitation in such areas is neither cost-effective nor urgently necessary, road agencies can adopt routine interventions as a cost-saving measure while maintaining basic safety and connectivity.

Budget-Constrained Environments

When financial resources are severely constrained, the analysis indicates that Routine Maintenance again becomes more practical. Its relatively low implementation cost and speed of execution allow authorities to maintain minimum road functionality across wide networks, even though it does not guarantee long-term durability. This mirrors global practices documented by(Burningham & Stankevich, 2005), who found that developing countries often prioritize routine patching strategies during budget shortages.

Climate-Specific Scenarios

Climate conditions also play a critical role in strategy selection. In semi-arid regions with extreme temperature fluctuations, agencies often resort to short-term fixes such as pothole patching despite their low cost-efficiency in the long term(Cabana et al., 1999). Conversely, in humid and wet environments where water infiltration accelerates pavement damage, Rehabilitation becomes more effective since it addresses foundational weaknesses. Meanwhile, in moderate climates, Periodic Maintenance ensures the best life-cycle performance, as confirmed by (Motlagh et al., 2024).

4.5.2. Discussion and Synthesis

The scenario-specific evaluation underscores that no single strategy is universally optimal; instead, the most suitable approach depends on the context of application. Periodic maintenance, which emerged as the top-ranked strategy overall, is particularly effective in stable budget, moderate-traffic, and moderate-climate conditions because it balances durability, cost, and environmental sustainability. Routine maintenance is most appropriate in low-traffic and budget-constrained contexts, ensuring short-term usability and safety despite limited durability benefits. Rehabilitation, although ranked lowest in the aggregate fuzzy evaluation, plays a critical role in high-traffic corridors and deteriorated pavements, where long-term structural restoration and safety enhancement outweigh its cost and implementation challenges.

These findings validate the broader literature in pavement management. For instance, emphasized the importance of adaptive prioritization frameworks that allow decision-makers to allocate limited resources where they generate the highest impact. Similarly, (Ayalew et al., 2022) confirmed that Ethiopian road networks benefit most from periodic maintenance in balancing life-cycle performance and cost-effectiveness.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study examined the persistent problem of ineffective road maintenance strategy selection in Addis Ababa, where reactive interventions have led to premature pavement deterioration, escalating life-cycle costs, and inefficient use of limited resources. Using the Fuzzy TOPSIS multi-criteria decision-making method, three strategies Routine Maintenance, Periodic Maintenance, and Rehabilitation, were evaluated against nine key criteria: cost-effectiveness, durability, safety, environmental impact, ease of implementation, maintenance frequency, economic impact, life-cycle cost, and time efficiency.

The analysis discovered that Periodic Maintenance is the most suitable strategy, offering the best balance between durability, cost efficiency, and sustainability. It emerged as the top-ranked option with the highest closeness coefficient, confirming its capacity to extend pavement life and reduce future rehabilitation needs. Routine Maintenance was found to be effective for short-term safety improvements and rapid interventions, but its limited durability and frequent recurrence reduce its long-term value. Rehabilitation, while necessary for severely deteriorated pavements and critical corridors, ranked lowest overall because of its high cost, complexity, and disruption during implementation.

The findings highlight the need for Addis Ababa City Roads Authority to adopt a systematic, evidence-based decision framework rather than relying on ad hoc or reactive measures. Incorporating multi-criteria approaches such as Fuzzy TOPSIS ensures that financial, technical, environmental, and social factors are all considered in a balanced way.

In conclusion, the study recommends that Periodic Maintenance be institutionalized as the core strategy for Addis Ababa’s Road network, complemented by Routine Maintenance for immediate safety and Rehabilitation for advanced structural failures. Shifting to this structured decision-making process will improve resource allocation, enhance road durability, and contribute to safer and more sustainable urban mobility.

5.2. Recommendations

5.2.1. Recommendations from this Study

Based on the results, the study recommends institutionalizing a decision-support system within the Addis Ababa City Roads Authority (AACRA) to ensure that road maintenance strategies are selected using multi-criteria evaluation methods such as Fuzzy TOPSIS. This would reduce reliance on ad hoc or politically driven decisions and improve cost efficiency. Additionally, greater stakeholder engagement is needed, involving engineers, supervisors, contractors, and road users in the planning and prioritization process. To address financial limitations, innovative approaches such as public-private partnerships (PPPs) and performance-based contracting should be explored, ensuring sustainable funding for periodic and preventive maintenance. Finally, AACRA should invest in capacity building and digital monitoring tools to strengthen technical expertise and enable real-time assessment of road conditions for better maintenance planning.

5.2.2. Recommendations for Further Study

While this research provided valuable insights into strategy prioritization, further studies should focus on integrating climate resilience factors into maintenance decision-making, as changing weather conditions significantly affect pavement performance. Additionally, future research could expand the analysis by considering regional variations within Ethiopia to account for differences in soil type, rainfall, and traffic conditions. Another avenue for exploration is the use of hybrid MCDM methods that combine Fuzzy TOPSIS with other approaches like AHP, BWM, or Grey Systems to provide results that are even more robust. Finally, future studies should also assess the long-term socioeconomic impacts of different maintenance strategies, particularly their effects on urban mobility, trade, and community well-being.

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7. Appendix

Appendix I

Survey Questionnaires

A Road Maintenance Management Strategy Selection by Fuzzy TOPSIS model: The case of Addis Ababa City Roads Authority

Dear respondent, this survey aims to obtain the necessary data for the partial fulfillment of an MSc thesis in Construction Technology and Management at Addis College of Postgraduates. The main objective of the study is to assess and prioritize road maintenance management strategies using the fuzzy TOPSIS model by the Addis Ababa City Roads Authority (AACRA).

Therefore, you are kindly requested to contribute to my research study by filling out this questionnaire and providing accurate information about the study's quality. The respondent's name, as well as that of the firm you represent, will be kept private, and all information gathered from the survey will be utilized solely for academic purposes.

I appreciate the time and effort you took to respond to the questionnaires. Please contact me at the addresses listed below if you have any questions.

Admasu Shiferaw, a postgraduate student at Addis College of Postgraduate Studies, COTM student, Class of 2015 E.C.

Email: abdibekeleadmasu@gmail.com

Mobile Number: +251 921740915 or +251 946662320

Composition of the Questionnaire

This questionnaire is designed to assess and prioritize road maintenance management strategies using the fuzzy TOPSIS model. It includes structured questions divided into four parts: demographic information, pairwise comparison of criteria, challenges and contextual factors, and open-ended responses. The design captures quantitative and qualitative data essential for the model's implementation.

Part 1: Demographic Information

1. Gender

☐ Male

☐ Female

2. Educational Qualification

☐ Doctorate

☐ Masters

☐ Bachelor

☐ Diploma

☐ Other

3. Position

☐ Director

☐ Team Leader

☐ Lead Civil Engineer

☐ Senior Civil Engineer

☐ Civil Engineer

☐ Junior Civil Engineer

☐ Material Inspector

☐ Construction Forman

4. Experience in Years

☐0 - 2

☐2 - 4

☐4 - 6

☐6 - 8

☐> 10

5. Age Group

☐20 - 25

☐25 - 30

☐30 - 35

☐35 - 40

☐40 - 45

☐45 - 50

☐> 50

6. Which sector do you currently work in?

☐Government Agency

☐Private Sector

☐Academia/Research

☐Non-Governmental Organization (NGO)

☐Other

7. Have you previously participated in multi-criteria decision-making (e.g., AHP, Fuzzy TOPSIS) for infrastructure projects?

☐Yes

☐No

8. How familiar are you with different road maintenance strategies?

☐Very Familiar

☐Somewhat Familiar

☐Neutral

☐Not Very Familiar

☐Not Familiar at All

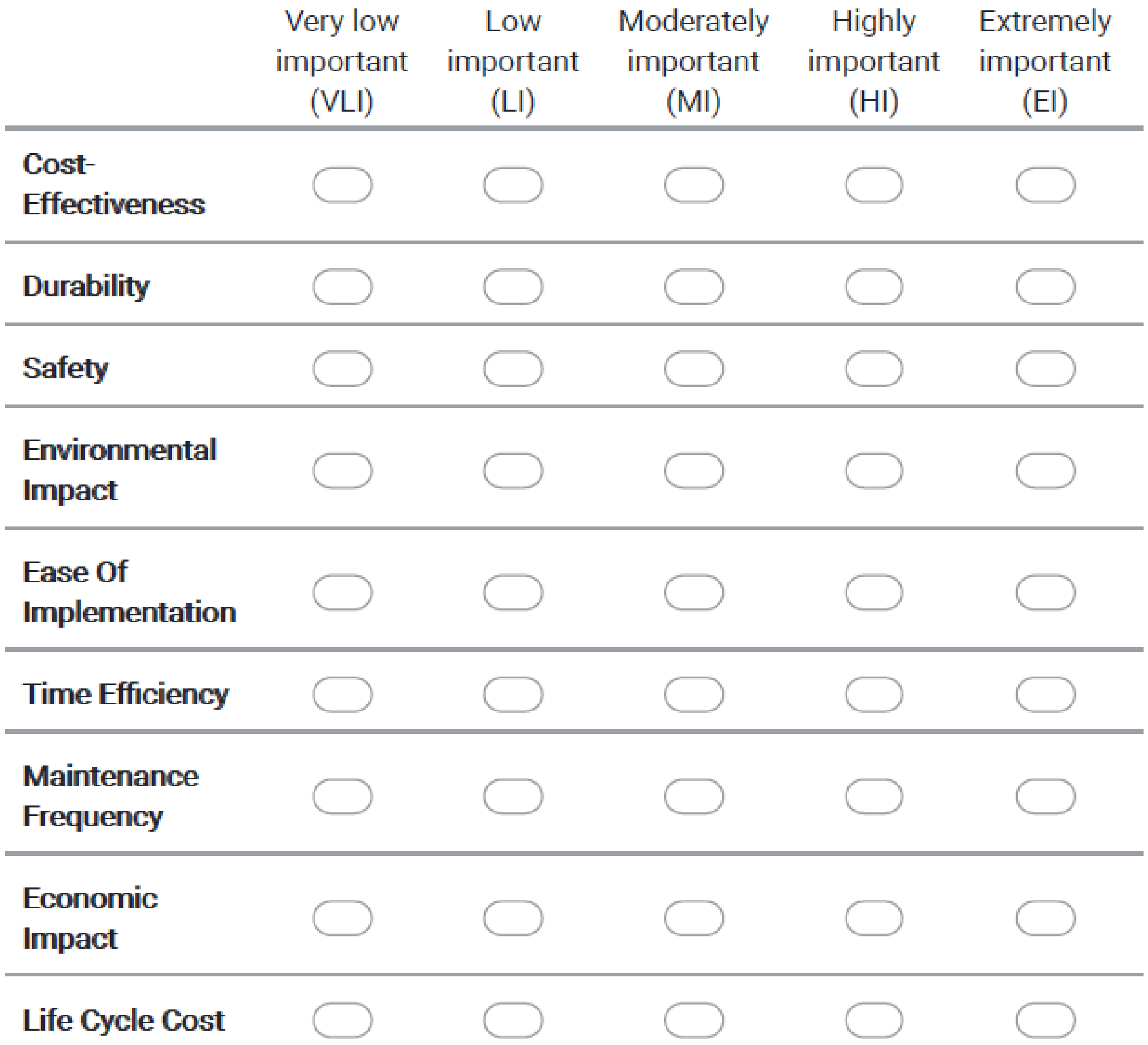
9. Have you worked on any of the following road maintenance strategies? (Check all that apply.)

☐Routine Maintenance

☐Periodic Maintenance

☐Rehabilitation (Full Reconstruction)

10. In your opinion, what are the most critical factors when selecting a road maintenance strategy?



	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Cost-Effectiveness	○	○	○	○	○
Durability	○	○	○	○	○
Safety	○	○	○	○	○
Environmental Impact	○	○	○	○	○
Ease Of Implementation	○	○	○	○	○
Time Efficiency	○	○	○	○	○
Maintenance Frequency	○	○	○	○	○
Economic Impact	○	○	○	○	○
Life Cycle Cost	○	○	○	○	○

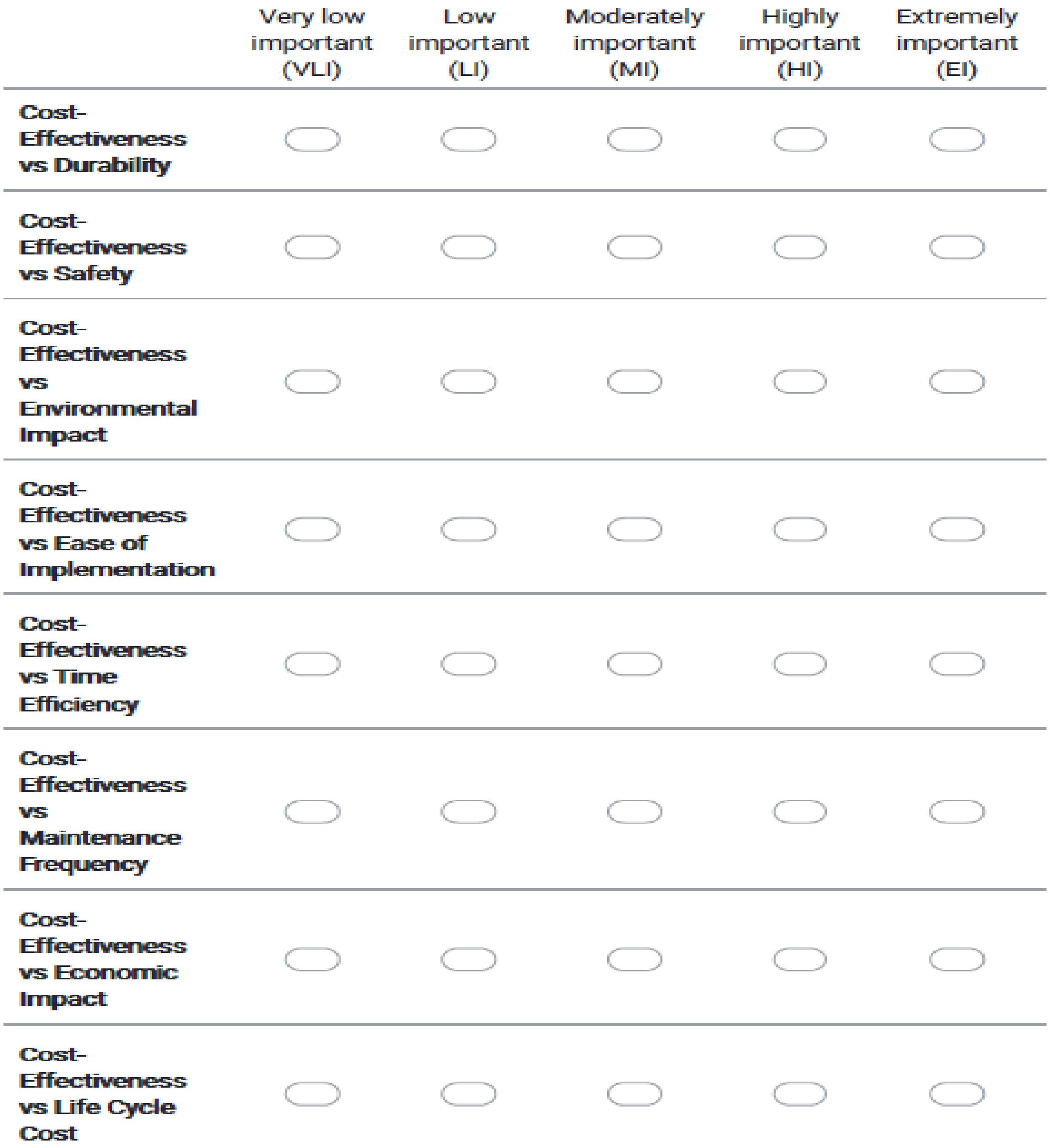
Part 2: Pairwise Comparisons

Pairwise Comparison for Road Maintenance Strategy Selection Using Fuzzy TOPSIS

- Very low important (VLI)
- Low important (LI)
- Moderately important (MI)
- Highly important (HI)
- Extremely important (EI)

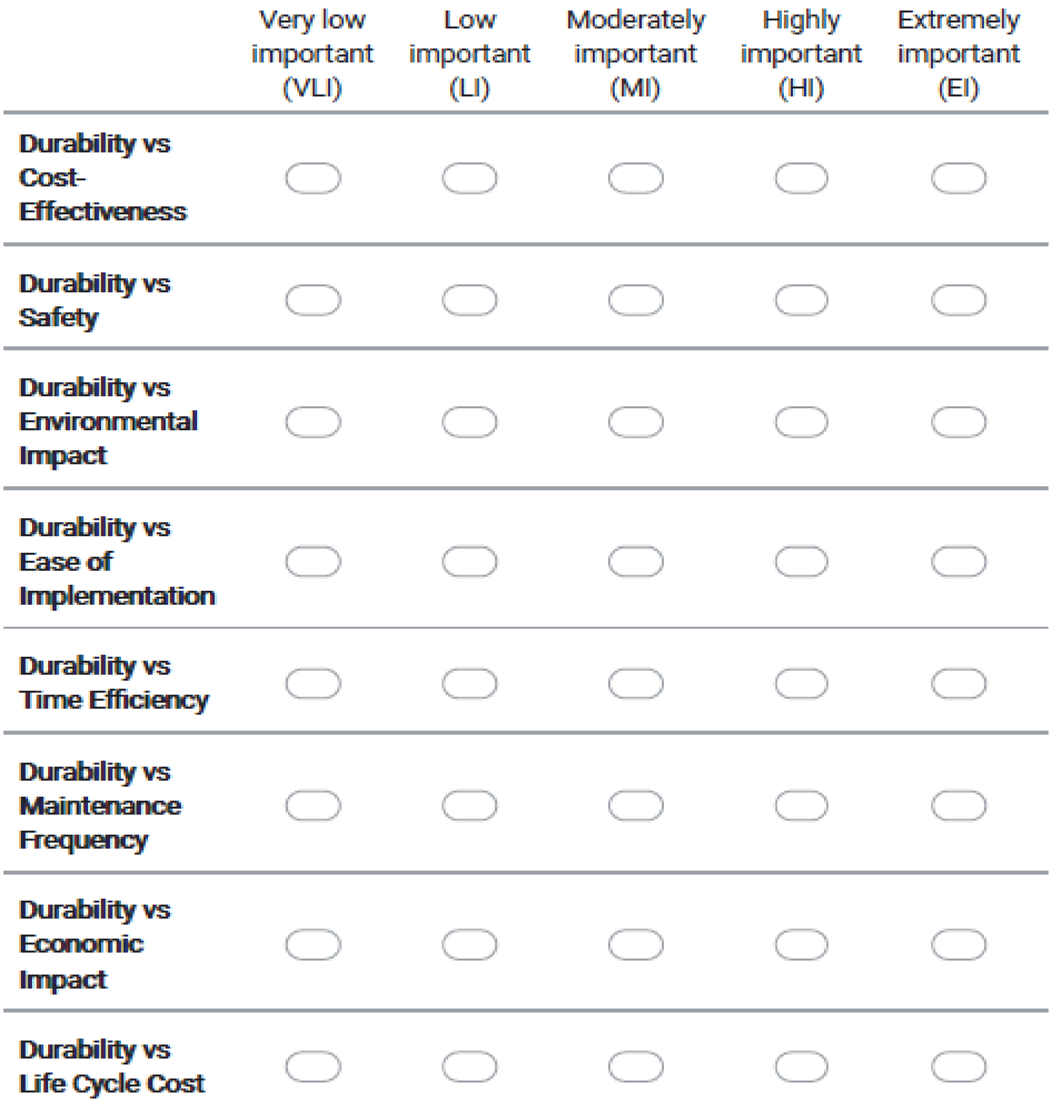
A. Pairwise Comparison of Criteria

1. Cost-Effectiveness compared with other Criteria



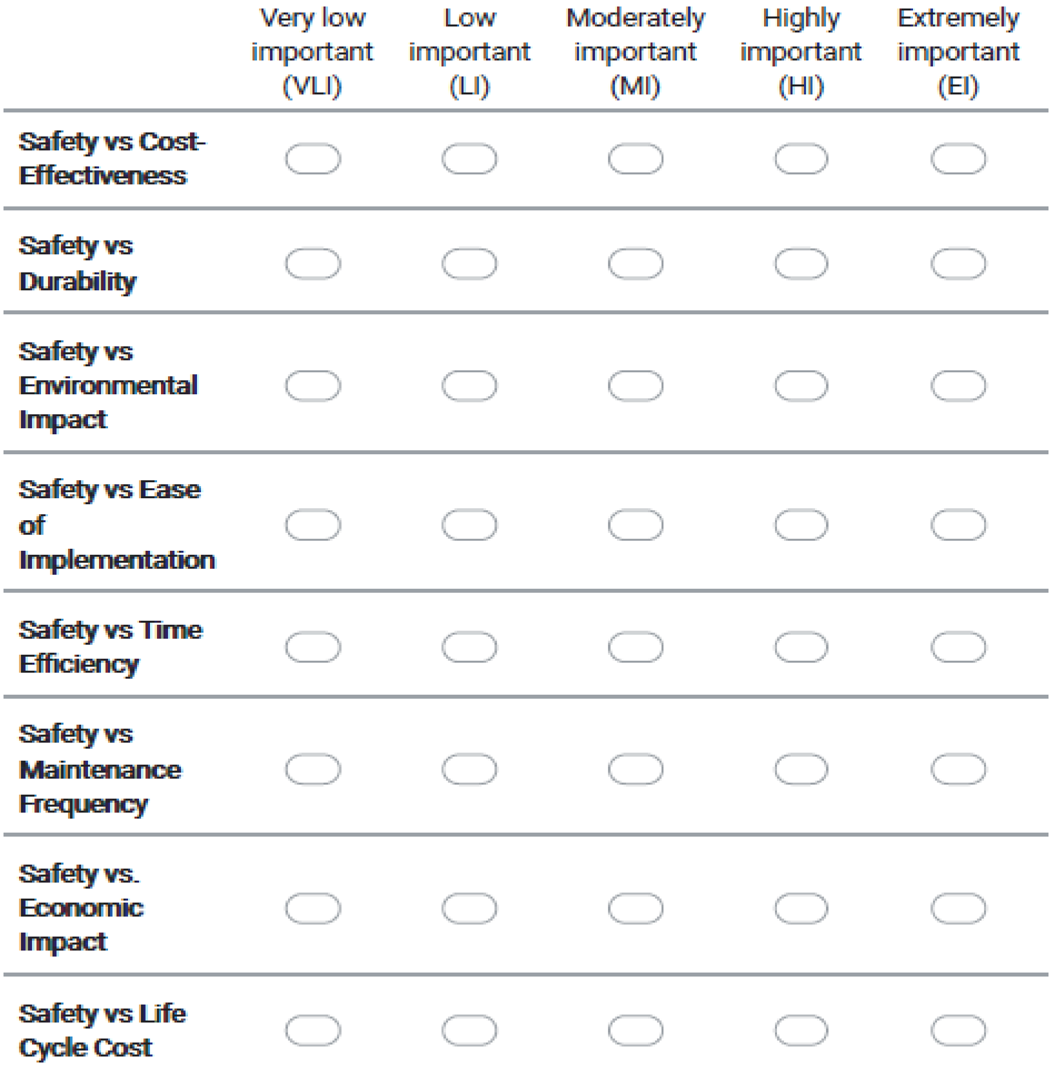
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Cost-Effectiveness vs Durability	○	○	○	○	○
Cost-Effectiveness vs Safety	○	○	○	○	○
Cost-Effectiveness vs Environmental Impact	○	○	○	○	○
Cost-Effectiveness vs Ease of Implementation	○	○	○	○	○
Cost-Effectiveness vs Time Efficiency	○	○	○	○	○
Cost-Effectiveness vs Maintenance Frequency	○	○	○	○	○
Cost-Effectiveness vs Economic Impact	○	○	○	○	○
Cost-Effectiveness vs Life Cycle Cost	○	○	○	○	○

2. Durability compared with other Criteria



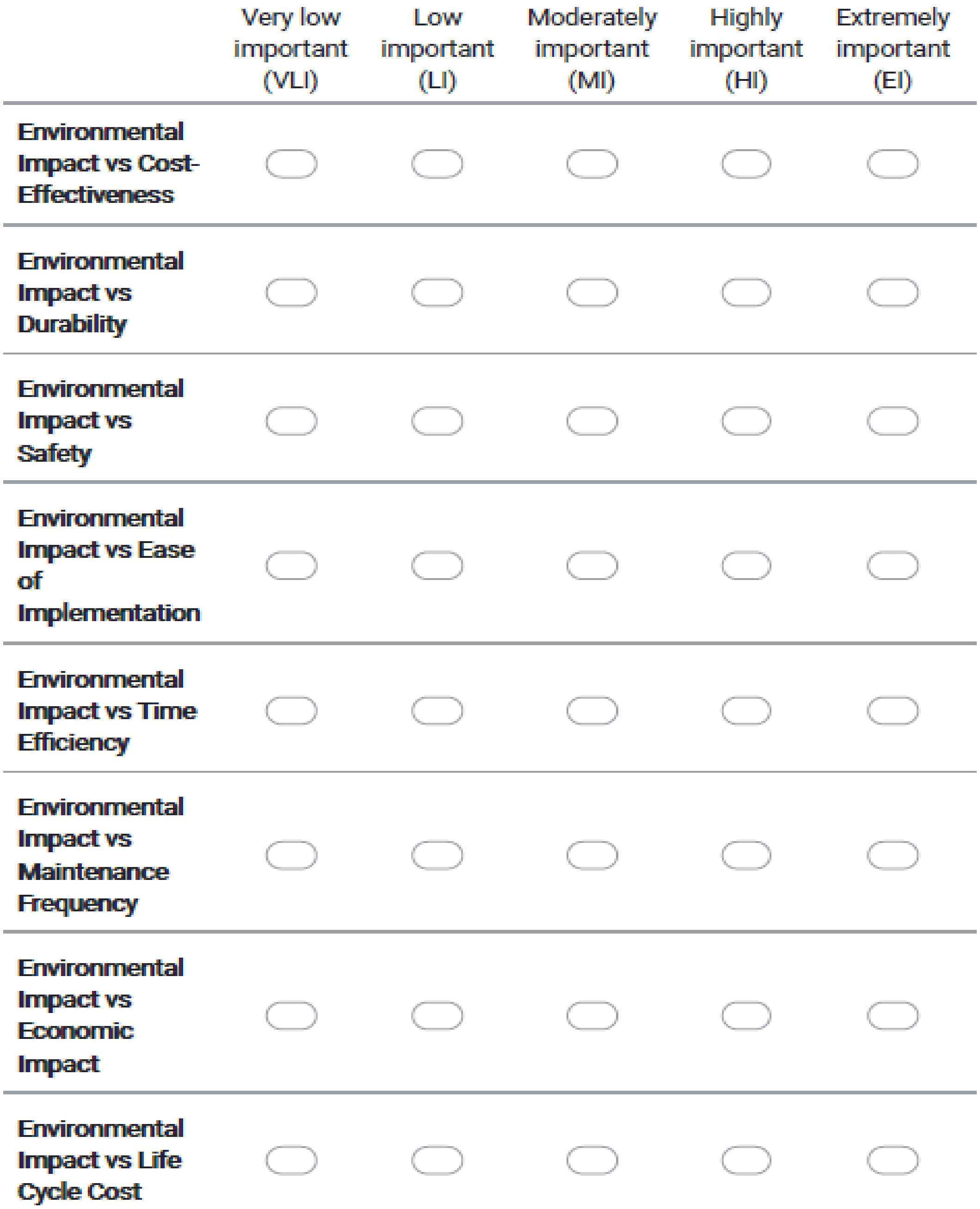
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Durability vs Cost-Effectiveness	○	○	○	○	○
Durability vs Safety	○	○	○	○	○
Durability vs Environmental Impact	○	○	○	○	○
Durability vs Ease of Implementation	○	○	○	○	○
Durability vs Time Efficiency	○	○	○	○	○
Durability vs Maintenance Frequency	○	○	○	○	○
Durability vs Economic Impact	○	○	○	○	○
Durability vs Life Cycle Cost	○	○	○	○	○

3. Safety compared with other Criteria



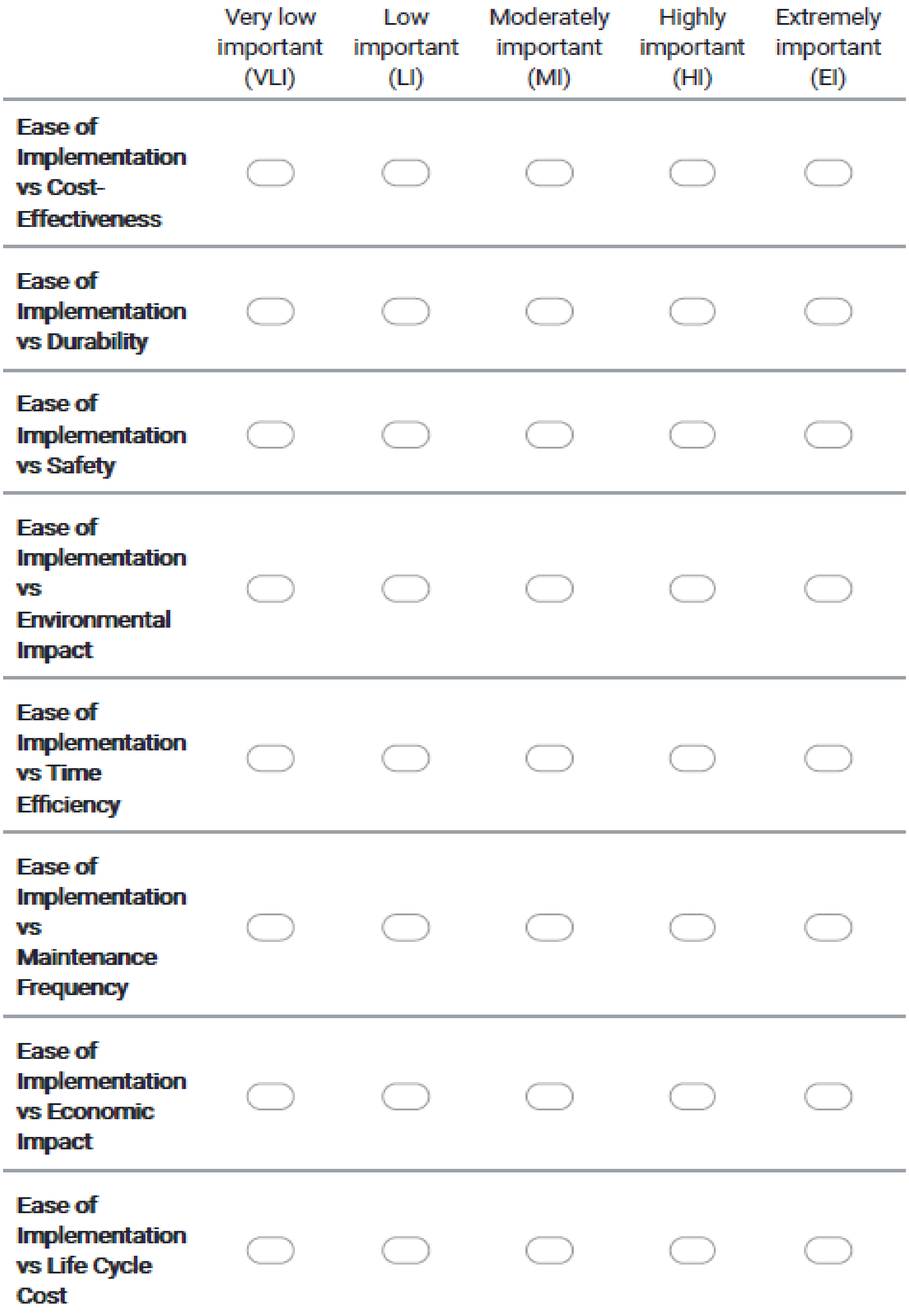
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Safety vs Cost-Effectiveness	○	○	○	○	○
Safety vs Durability	○	○	○	○	○
Safety vs Environmental Impact	○	○	○	○	○
Safety vs Ease of Implementation	○	○	○	○	○
Safety vs Time Efficiency	○	○	○	○	○
Safety vs Maintenance Frequency	○	○	○	○	○
Safety vs. Economic Impact	○	○	○	○	○
Safety vs Life Cycle Cost	○	○	○	○	○

4. Environmental Impact compared with other Criteria



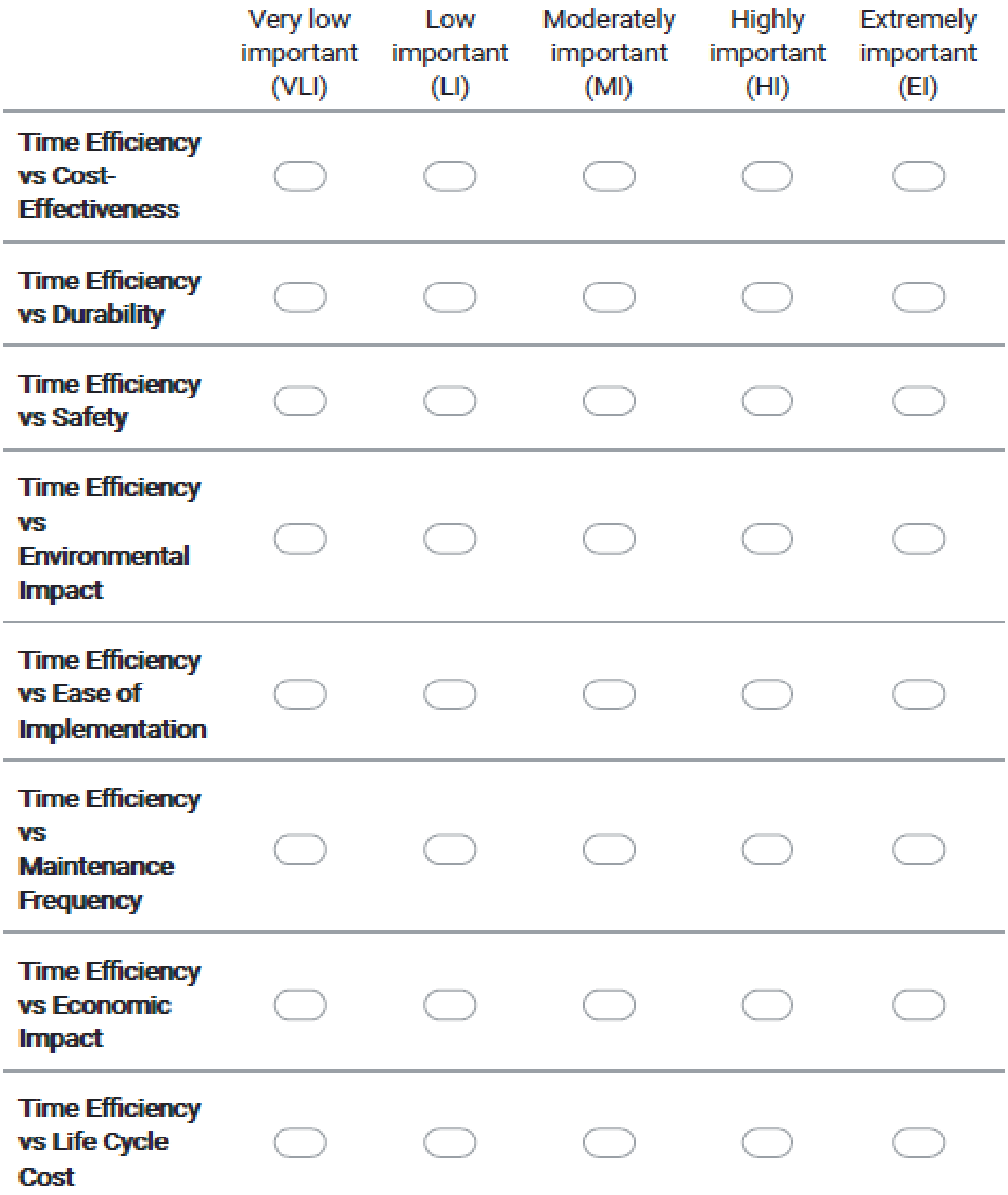
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Environmental Impact vs Cost-Effectiveness	○	○	○	○	○
Environmental Impact vs Durability	○	○	○	○	○
Environmental Impact vs Safety	○	○	○	○	○
Environmental Impact vs Ease of Implementation	○	○	○	○	○
Environmental Impact vs Time Efficiency	○	○	○	○	○
Environmental Impact vs Maintenance Frequency	○	○	○	○	○
Environmental Impact vs Economic Impact	○	○	○	○	○
Environmental Impact vs Life Cycle Cost	○	○	○	○	○

5. Ease of Implementation compared with other Criteria



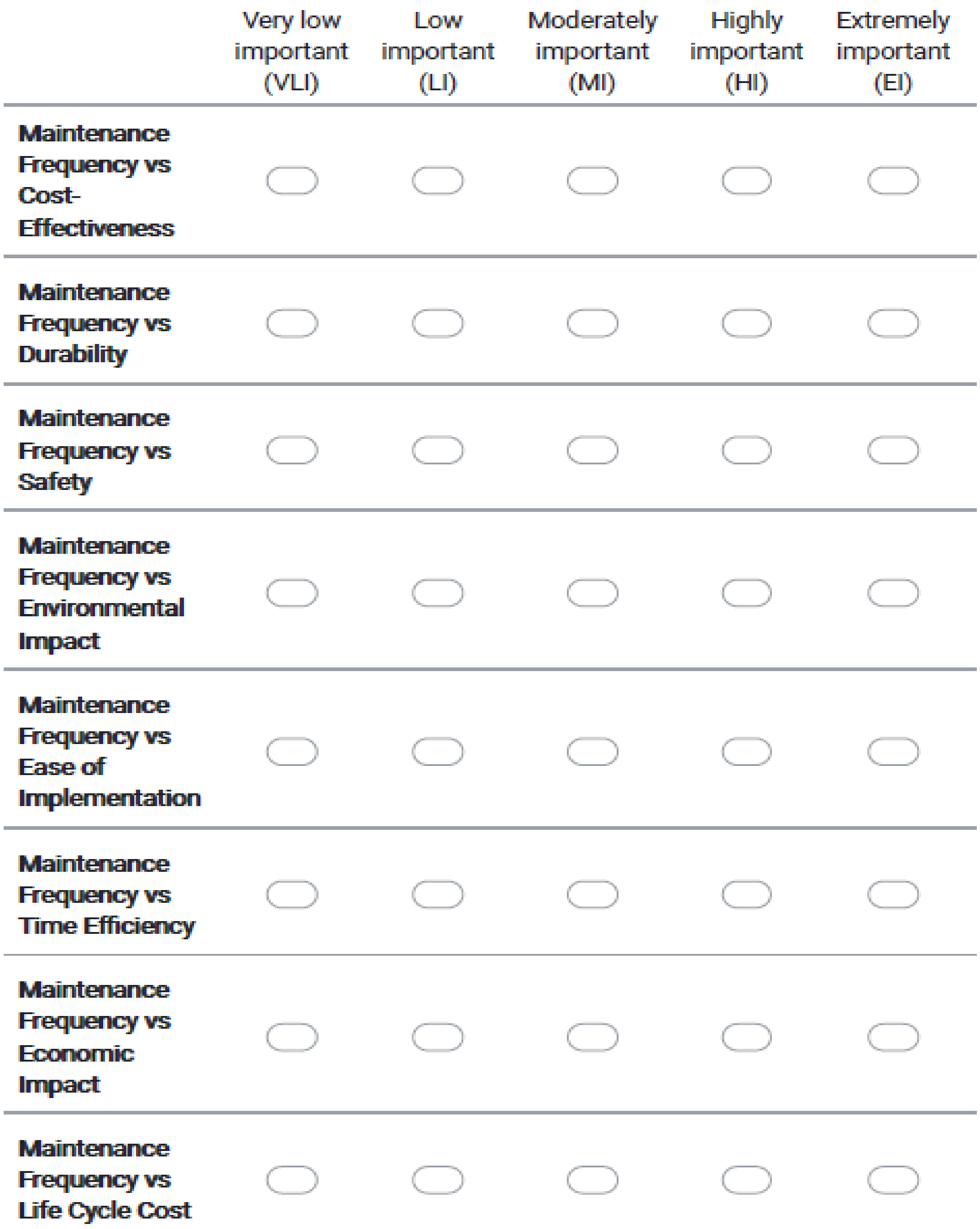
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Ease of Implementation vs Cost-Effectiveness	○	○	○	○	○
Ease of Implementation vs Durability	○	○	○	○	○
Ease of Implementation vs Safety	○	○	○	○	○
Ease of Implementation vs Environmental Impact	○	○	○	○	○
Ease of Implementation vs Time Efficiency	○	○	○	○	○
Ease of Implementation vs Maintenance Frequency	○	○	○	○	○
Ease of Implementation vs Economic Impact	○	○	○	○	○
Ease of Implementation vs Life Cycle Cost	○	○	○	○	○

6. **Time Efficiency compared with other Criteria**



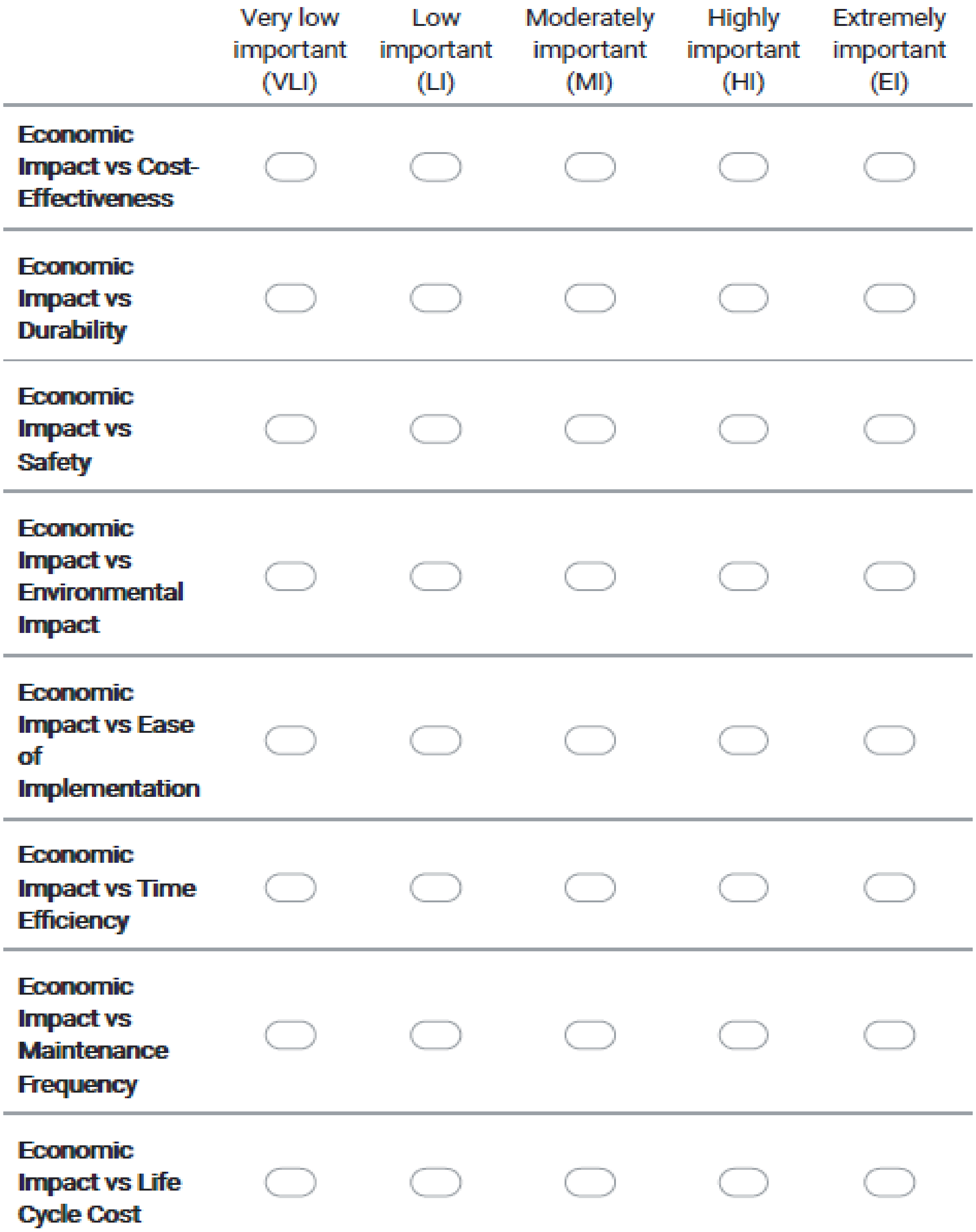
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Time Efficiency vs Cost-Effectiveness	○	○	○	○	○
Time Efficiency vs Durability	○	○	○	○	○
Time Efficiency vs Safety	○	○	○	○	○
Time Efficiency vs Environmental Impact	○	○	○	○	○
Time Efficiency vs Ease of Implementation	○	○	○	○	○
Time Efficiency vs Maintenance Frequency	○	○	○	○	○
Time Efficiency vs Economic Impact	○	○	○	○	○
Time Efficiency vs Life Cycle Cost	○	○	○	○	○

7. Maintenance Frequency compared with other Criteria



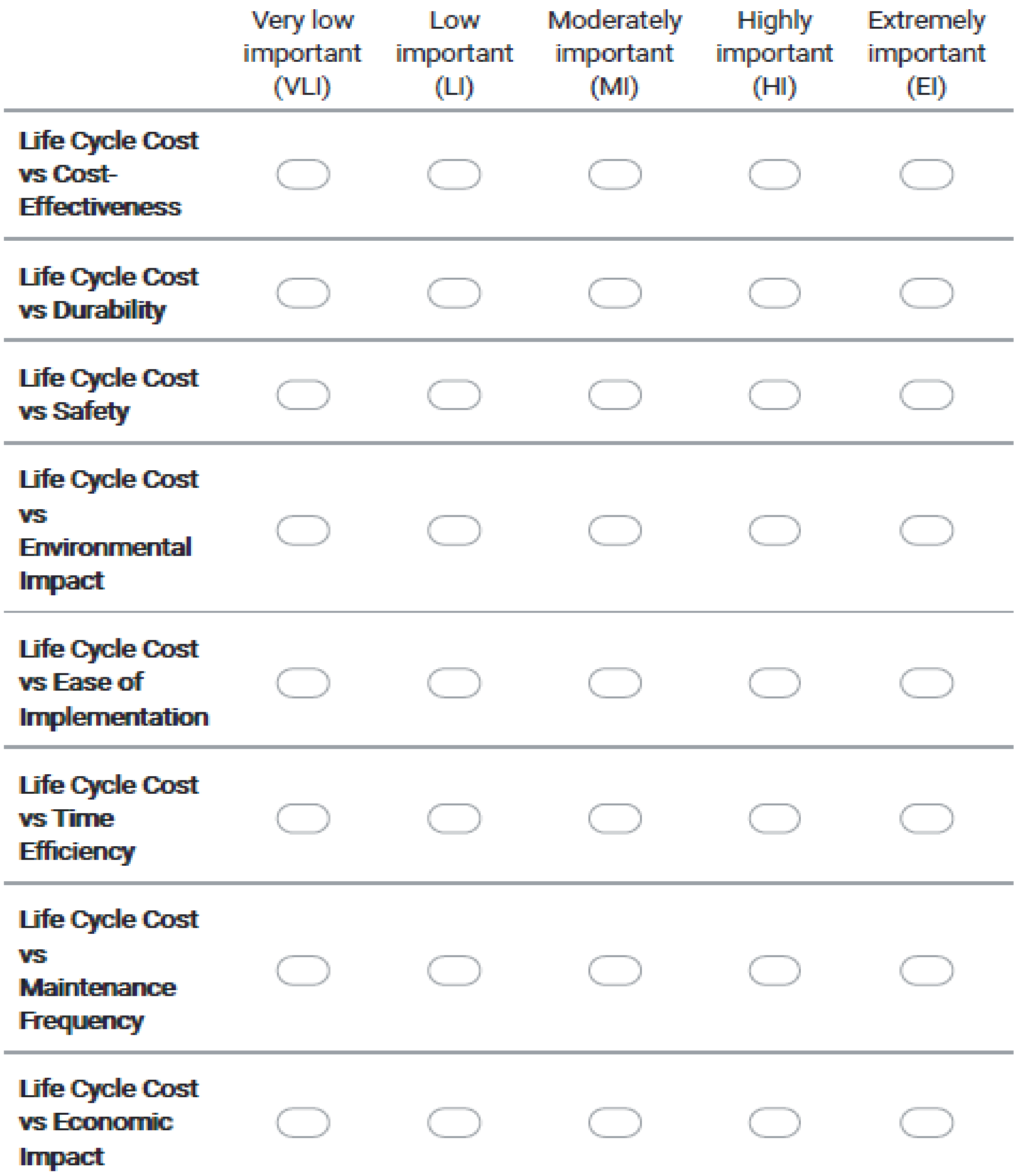
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Maintenance Frequency vs Cost-Effectiveness	○	○	○	○	○
Maintenance Frequency vs Durability	○	○	○	○	○
Maintenance Frequency vs Safety	○	○	○	○	○
Maintenance Frequency vs Environmental Impact	○	○	○	○	○
Maintenance Frequency vs Ease of Implementation	○	○	○	○	○
Maintenance Frequency vs Time Efficiency	○	○	○	○	○
Maintenance Frequency vs Economic Impact	○	○	○	○	○
Maintenance Frequency vs Life Cycle Cost	○	○	○	○	○

8. Economic Impact compared with other Criteria



	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Economic Impact vs Cost-Effectiveness	○	○	○	○	○
Economic Impact vs Durability	○	○	○	○	○
Economic Impact vs Safety	○	○	○	○	○
Economic Impact vs Environmental Impact	○	○	○	○	○
Economic Impact vs Ease of Implementation	○	○	○	○	○
Economic Impact vs Time Efficiency	○	○	○	○	○
Economic Impact vs Maintenance Frequency	○	○	○	○	○
Economic Impact vs Life Cycle Cost	○	○	○	○	○

9. Life Cycle Cost compared with other Criteria



	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Life Cycle Cost vs Cost-Effectiveness	○	○	○	○	○
Life Cycle Cost vs Durability	○	○	○	○	○
Life Cycle Cost vs Safety	○	○	○	○	○
Life Cycle Cost vs Environmental Impact	○	○	○	○	○
Life Cycle Cost vs Ease of Implementation	○	○	○	○	○
Life Cycle Cost vs Time Efficiency	○	○	○	○	○
Life Cycle Cost vs Maintenance Frequency	○	○	○	○	○
Life Cycle Cost vs Economic Impact	○	○	○	○	○

B. Rate each maintenance strategy based on the following criteria:

1. **Very low important (VLI)**
2. **Low important (LI)**
3. **Moderately important (MI)**
4. **Highly important (HI)**
5. **Extremely important (EI)**

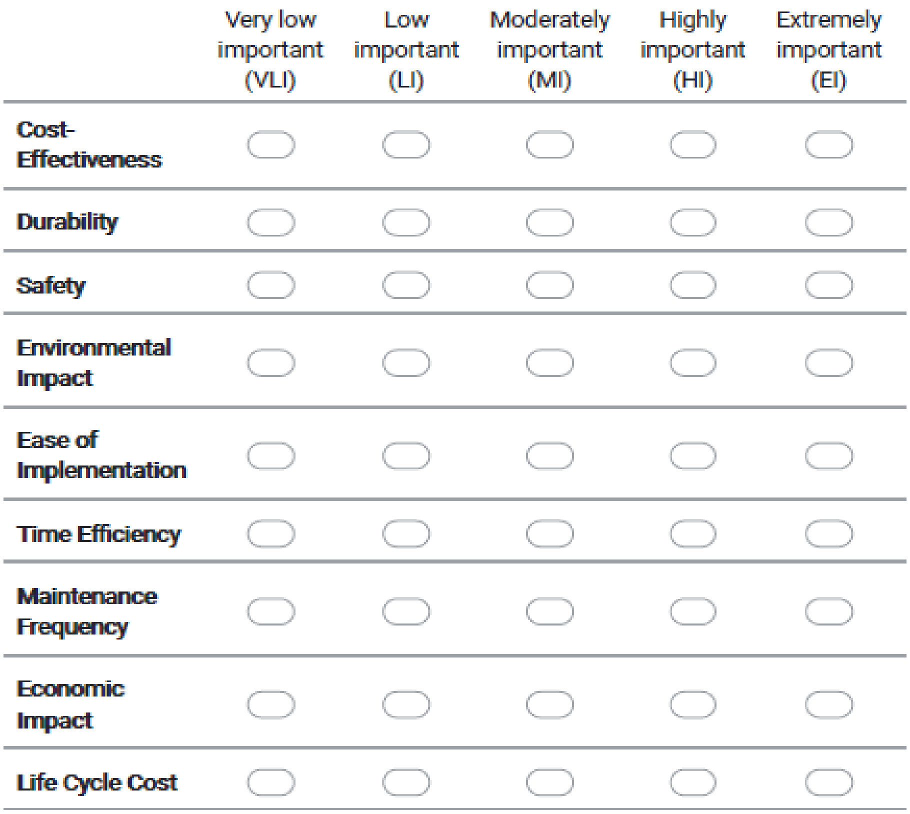
Description About Routine Maintenance, Periodic Maintenance and Rehabilitation

1. **Routine maintenance** refers to the regular and minor maintenance activities performed to keep roads in serviceable condition and to prevent deterioration.

2. Periodic maintenance involves activities aimed at restoring the road's surface and overall structure before significant deterioration occurs. This type of maintenance is done at set intervals to improve or maintain road performance and prevent further damage.

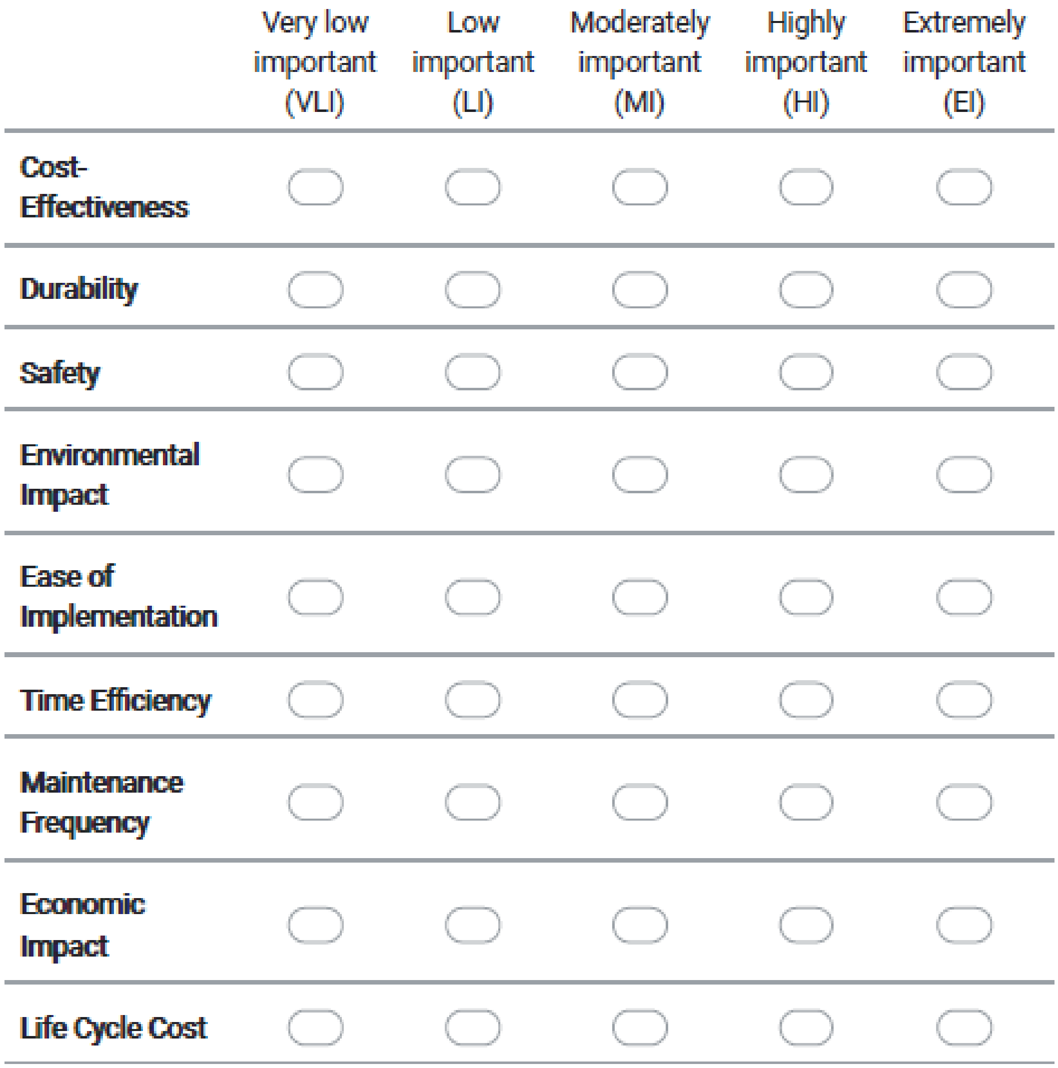
3. Rehabilitation is a major intervention that involves extensive repairs to restore the structural integrity and overall function of a road. It is usually carried out when the road has experienced substantial deterioration or when periodic maintenance has failed to maintain its quality.

1. Rate routine maintenance strategy based on the following criteria:



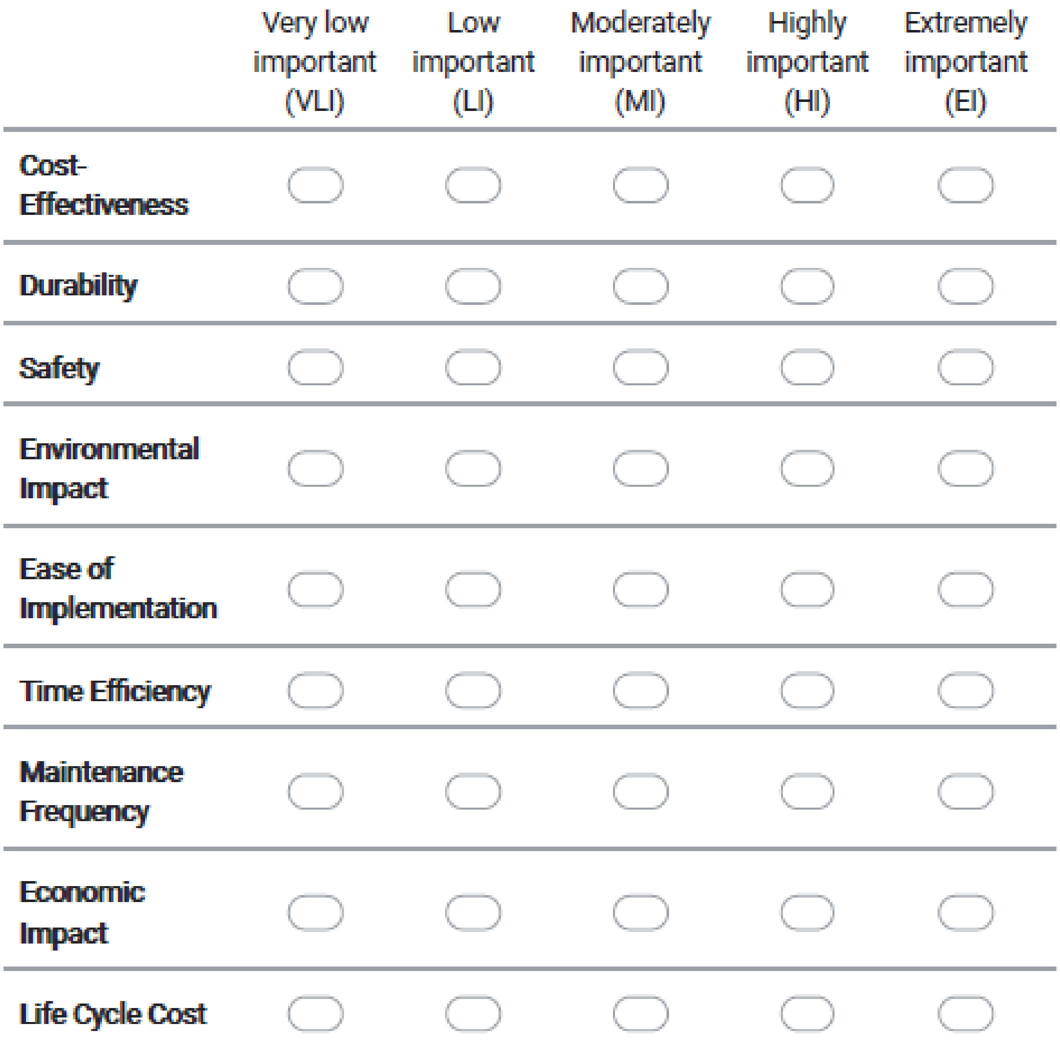
	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Cost-Effectiveness	○	○	○	○	○
Durability	○	○	○	○	○
Safety	○	○	○	○	○
Environmental Impact	○	○	○	○	○
Ease of Implementation	○	○	○	○	○
Time Efficiency	○	○	○	○	○
Maintenance Frequency	○	○	○	○	○
Economic Impact	○	○	○	○	○
Life Cycle Cost	○	○	○	○	○

2. Rate periodic maintenance strategy based on the following criteria:



	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Cost-Effectiveness	○	○	○	○	○
Durability	○	○	○	○	○
Safety	○	○	○	○	○
Environmental Impact	○	○	○	○	○
Ease of Implementation	○	○	○	○	○
Time Efficiency	○	○	○	○	○
Maintenance Frequency	○	○	○	○	○
Economic Impact	○	○	○	○	○
Life Cycle Cost	○	○	○	○	○

3. Rate the rehabilitation maintenance strategy based on the following criteria:



	Very low important (VLI)	Low important (LI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)
Cost-Effectiveness	○	○	○	○	○
Durability	○	○	○	○	○
Safety	○	○	○	○	○
Environmental Impact	○	○	○	○	○
Ease of Implementation	○	○	○	○	○
Time Efficiency	○	○	○	○	○
Maintenance Frequency	○	○	○	○	○
Economic Impact	○	○	○	○	○
Life Cycle Cost	○	○	○	○	○

Part 3: Challenges and Contextual Factors

1. What are the main challenges in road maintenance?

☐ Budget Constraints

☐ Lack of Skilled Labor

☐ Climate Conditions (e.g., heavy rains)

☐ Rapid Urbanization

☐ Inadequate Technology

2. How adequate are current data collection systems for monitoring road conditions in AACRA?

☐ Highly adequate (real-time data, advanced tools)

☐ Moderately adequate (periodic surveys)

☐ Poorly adequate (reactive, manual methods)

☐ No formal system in place

3. How well do AACRA's departments coordinate during maintenance planning and execution?

☐ Seamless coordination (shared goals, integrated workflows)

☐ Moderate coordination (occasional delays)

☐ Poor coordination (siloed operations, conflicting priorities)

☐ No formal coordination mechanism

Part 4: Additional Feedback

1. What do you believe is the most critical factor in choosing road maintenance strategies for Addis Ababa?

____

____

____

2. Are there any other criteria or strategies you think should be considered?

____

____

____

APPENDIX II

CRITERIA / RESPONDANT	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
[Cost-Effectiveness]	Low important (LI)	Highly important (HI)	Extremely important (EI)	Moderately important (MI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Highly important (HI)
[Durability]	Extremely important (EI)	Highly important (HI)	Low important (LI)	Highly important (HI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Moderately important (MI)	Highly important (HI)
[Safety]	Extremely important (EI)	Highly important (HI)	Extremely important (EI)	Highly important (HI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Highly important (HI)	Highly important (HI)
[Environmental Impact]	Low important (LI)	Highly important (HI)	Moderately important (MI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Highly important (HI)	Highly important (HI)	Moderately important (MI)
[Ease of Implementation]	Moderately important (MI)	Highly important (HI)	Highly important (HI)	Moderately important (MI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Highly important (HI)	Extremely important (EI)	Highly important (HI)
[Time Efficiency]	Moderately important (MI)	Highly important (HI)	Extremely important (EI)	Highly important (HI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Moderately important (MI)	Moderately important (MI)
[Maintenance Frequency]	Extremely important (EI)	Moderately important (MI)	Highly important (HI)	Moderately important (MI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Highly important (HI)	Very low important (VLI)	Moderately important (MI)
[Economic Impact]	Low important (LI)	Highly important (HI)	Moderately important (MI)	Highly important (HI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Highly important (HI)	Extremely important (EI)	Highly important (HI)
[Life Cycle Cost]	Moderately important (MI)	Highly important (HI)	Moderately important (MI)	Moderately important (MI)	Extremely important (EI)	Extremely important (EI)	Extremely important (EI)	Highly important (HI)	Highly important (HI)	Moderately important (MI)

APPENDIX III

CRITERIA / RESPONDANT	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
[Cost-Effectiveness]	2,3,4	3,4,5	4,5,6	5,6,7	4,5,6	4,5,6	4,5,6	4,5,6	4,5,6	3,4,5
[Durability]	4,5,6	3,4,5	2,3,4	3,4,5	4,5,6	4,5,6	4,5,6	4,5,6	5,6,7	3,4,5
[Safety]	4,5,6	3,4,5	4,5,6	3,4,5	4,5,6	4,5,6	4,5,6	4,5,6	3,4,5	3,4,5
[Environmental Impact]	2,3,4	3,4,5	5,6,7	4,5,6	4,5,6	4,5,6	4,5,6	3,4,5	3,4,5	5,6,7
[Ease of Implementation]	5,6,7	3,4,5	3,4,5	5,6,7	4,5,6	4,5,6	4,5,6	3,4,5	4,5,6	3,4,5
[Time Efficiency]	5,6,7	3,4,5	4,5,6	3,4,5	4,5,6	4,5,6	4,5,6	4,5,6	5,6,7	5,6,7
[Maintenance Frequency]	4,5,6	5,6,7	3,4,5	5,6,7	4,5,6	4,5,6	4,5,6	3,4,5	1,2,3	5,6,7
[Economic Impact]	2,3,4	3,4,5	5,6,7	3,4,5	4,5,6	4,5,6	4,5,6	3,4,5	4,5,6	3,4,5
[Life Cycle Cost]	5,6,7	3,4,5	5,6,7	5,6,7	4,5,6	4,5,6	4,5,6	3,4,5	3,4,5	5,6,7

APPENDIX IV

CRITERIA / RESPONDANT	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20
[Cost-Effectiveness]	9.76	4.62	1.80	0.00	1.80	1.80	1.80	1.80	1.80	4.62	1.80	4.62	4.62	4.62	1.80	1.80	0.00	1.80	4.62	1.80
[Durability]	4.39	2.19	0.00	2.19	4.39	4.39	4.39	4.39	6.58	2.19	2.19	2.19	6.58	2.19	4.39	4.39	6.58	4.39	2.19	0.00
[Safety]	1.75	0.00	1.75	0.00	1.75	1.75	1.75	1.75	0.00	0.00	0.00	3.51	1.75	0.00	1.75	0.00	3.51	1.75	0.00	1.75
[Environmental Impact]	3.56	1.72	0.00	0.68	0.68	0.68	0.68	1.72	1.72	0.00	0.00	1.72	0.68	3.56	0.68	0.00	0.00	0.68	1.72	0.00
[Ease of Implementation]	4.04	1.35	1.35	4.04	2.69	2.69	2.69	1.35	2.69	1.35	2.69	4.04	2.69	0.00	2.69	1.35	4.04	2.69	1.35	1.35
[Time Efficiency]	2.83	0.00	1.41	0.00	1.41	1.41	1.41	1.41	2.83	2.83	1.41	0.00	0.00	2.83	1.41	2.83	2.83	1.41	0.00	1.41
[Maintenance Frequency]	1.17	0.00	2.97	2.97	1.17	1.17	1.17	2.97	14.53	0.00	2.97	2.97	1.17	2.97	1.17	1.17	0.00	1.17	2.97	2.97
[Economic Impact]	0.00	2.19	6.58	4.27	4.39	4.39	4.39	2.19	4.39	2.19	2.19	2.19	2.19	6.58	4.39	4.39	6.58	4.39	6.58	6.58
[Life Cycle Cost]	0.00	4.62	0.00	0.00	1.80	1.80	1.80	4.62	4.62	0.00	4.62	4.62	0.00	9.76	4.62	1.80	0.00	1.80	4.62	0.00