UNIVERSITY OF BIRMINGHAM

PhD Civil Engineering

The Evaluation Using a Life Cycle Approach of Different Types of Road Pavement Surfacing Subjected to Climate Impact

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ABSTRACT

The choice of road surfacing depends on different factors, as each type has its own use and its suitability depends on different circumstances. The pavement surfacing in the road network plays a key role in achieving the design target in changing climate and traffic conditions. However, consideration of the potential impact of future climate change in the calculation of the life-cycle cost analysis is limited. To address this, the study aimed to compare the life-cycle costs of various bound surfaces under future climate change impacts. The objectives include developing a framework for the analysis; calibration of the HDM-4 deterioration model to local conditions; future climate change adjustments to the roughness model for the selected emission scenario; and an assessment of the climate change impact using discreate and continues approaches on selected bound surfaces.

The methodology developed in the research was used to investigate the effect of climate change on five surfacing types used in Ethiopia for three traffic levels in five different climate zones of the country. The developed framework can be applied to evaluate not only the identified surface types, but also to other pavement surfacing alternatives for different scenarios. For the considered climate change periods from 2016 to 2059, the roughness model showed environmental age coeffect adjustment from 1% to 10% to incorporate the climate change effect.

The results revealed that from representative AC sections of high-traffic-volume roads, 100% in the moist and semi-arid and 75% in sub-moist climate zones were economically viable compared to DBST, JPCP and JRCP. The maximum increment in the RUC for these

emission scenarios was obtained for the DBST pavement. At the end of 15 years, the user was expected to be charged the highest additional cost (10,941.06 million ETB/km (£269.68 million/km)) when using DBST roads with routine maintenance to correct the additional deterioration caused by the change in climate under the maximum A2 emission scenario. However, the user may be charged 10,865.66 million ETB/km (£267.83 million /km) for AC, if compound maintenance is applied for the same deterioration caused by the climate change scenario. For the minimum A2 emission scenario, 0.024 million ETB/km and 0.029 million ETB/km (£591.57/km and £714.82/km) maximum additional user costs were obtained for AC and DBST pavements, respectively.

Similarly, from the AC section, 100% for the arid and sub-humid high-traffic-volume roads and 62.5% for the sub-humid medium-traffic-volume roads were also economically feasible with a positive NPV/cost ratio under future climate change. In the moist climate zone for medium-traffic-volume roads, the finding showed that 66.67% of DBST and 100% of Otta-seal sections were resilient to future climate change. The DBST sections were strong enough to resist future climate change and they were more economically suitable than AC for low and medium traffic-volume roads in all climate zones, except in moist and sub-humid zones. In addition to this, the lesser deterioration and RUC for AC JPCP and JRCP observed when continues climate change analysis done for the whole 44 years than the usual one-way approach.

It was concluded that the pavement surfacing selection criteria need to be supplemented with an LCCA, since only 71% of the existing representative road pavement surfaces are resilient to future climate change and also economically viable.

DEDICATION

To Temesgen K/Selasie, Ledeta L/Maryam,
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Thank you for all you have done. I wish I had the words
to express my
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ABBREVIATIONS

AADT – Annual Average Daily Traffic

AC - Asphalt Concrete

ADT – Average Daily Traffic

AMGB – Asphalt Mix Surfacing on Granular Base

AR4 - 4th Assessment Report of the IPCC

AR5 -5th Assessment Report of IPCC

BCR - Benefit Cost Ratio

DBST - Double Surface Treatment

ERA - Ethiopian Road Authority

AC A HT – Asphalt Concrete in Arid Climate Zone with High Traffic Level

AC A LT – Asphalt Concrete in Arid Climate Zone with Low Traffic Level

AC A MT – Asphalt Concrete in Arid Climate Zone with Medium Traffic

AC M HT – Asphalt Concrete in Moist Climate Zone with High Traffic Level

AC M LT – Asphalt Concrete in Moist Climate Zone with Low Traffic Level

AC M MT – Asphalt Concrete in Moist Climate Zone with Medium Traffic

AC SA HT – Asphalt Concrete in Semi-Arid Climate Zone with High Traffic

AC SA LT – Asphalt Concrete in Semi-Arid Climate Zone with Low Traffic

AC SA MT – Asphalt Concrete in Semi-Arid Climate Zone with Mid Traffic

AC SM HT – Asphalt Concrete in sub moist Climate Zone with High Traffic Level

AC SM LT – Asphalt Concrete in Sub-Moist Climate Zone with Low Traffic

AC SM MT – Asphalt Concrete in Sub-Moist Climate Zone with Medium Traffic Level

DBST A HT – Double Surface Treatment in Arid Climate Zone with High Traffic

DBST A LT – Double Surface Treatment in Arid Climate Zone with Low Traffic Level

DBST A MT – Double Surface Treatment in Arid Climate Zone with Medium Traffic

DBST M HT – Asphalt Concrete in Moist Climate Zone with High Traffic Level

DBST M LT – Double Surface Treatment in Moist Climate Zone with Low Traffic Level

DBST M MT – Double Surface Treatment in Moist Climate Zone with Medium Traffic

DBST SA HT – Double Surface Treatment in Semi-Arid Climate Zone with High Traffic

DBST SA LT - Double Surface Treatment in Semi-Arid Climate Zone with Low Traffic level

DBST SA MT – Double Surface Treatment in Semi-Arid Climate Zone with Mid Traffic level

DBST SM HT –Double Surface Treatment in sub moist Climate Zone with High Traffic Level

DBST SM LT –Double Surface Treatment in Sub-Moist Climate Zone with Low Traffic

DBST SM MT –Double Surface Treatment in Sub-Moist Climate Zone with Medium Traffic Level

FYB - First Year Benefit

GCM - Global Circulation Model

GPS - Geographical Positioning System

HDM-4 - Highway Development & Management Software

IPCC - Intergovernmental Panel on Climate Change

IRI - International Roughness Index

IRR - Internal Rate of Return

ITCZ - Intern tropical Convergent Zone

LCC - Life Cycle Cost

LCCA – Life Cycle Cost Analysis

MAT – Mean annual Temperature

Max – Maximum

MEPDG – Mechanistic Empirical Pavement Design Guide

Min – minimum

MMP - Mean Monthly Precipitation

MTR – Average Temperature range

NMA National Metrological Agency

NPV - Net Present Value

r - Discount rate

RAC – Road Agency Cost

RD – Road Deterioration

RMND – Road Network Management Directorate

RSDP - Road Sector Development Program

RUC – Road User Cost

STDB – Surface Treatment on Surfacing on Granular Base

TMI – Thornthwaite Moisture Index

UNDP - United Nations Development Programme

UNEP - United Nations Environmental Programme

UNFCCC - United Nations Framework Convention on Climate Change

WBCKP – World Bank Climate Knowledge Portal

WMO - World Meteorological Organization

SYMBOLS

& - and

Δ – deference / change

£ - Great Britain Pound

CHAPTER ONE - INTRODUCTION

1.1. Background to the Study

In developing countries, it is widely recognised that the construction of new, and the improvement of existing road infrastructure is vital for stimulating economic growth (Arnold, et al., 2018). However, in most developing countries the resources available for the development of new and existing road networks are limited (World Bank , 2018). Further, the construction of new roads can often be at the expense of the maintenance of existing roads, and many regions are experiencing accelerated road deterioration due to the impacts of climate change and increased unforeseen use (Burrow, et al., 2016). Hence there is a need for asset management processes to help ensure that there is value for money, equity and long-term, uninterrupted performance, taking into account limited budgets, minimum performance requirements, multiple design alternatives, and the needs of a variety of stakeholders. These activities should be transparent and based on sound engineering and economic principles, including the consideration of whole-life costs/benefits (Paganin, et al., 2019).

This study is focused on Ethiopia's initiative to develop its road network. It considers the development of a life-cycle approach to assess the suitability of five bound-road surfaces (used in Ethiopia), in given scenarios. It also considers the possible impacts of climate change on road surface performance. Although Ethiopia is the focus of the work, the approach developed is suitable for road networks in developed and developing countries.

1.1.1. Considerations for the Selection of a Bound Surface for a Road Pavement

The bound surface of a road pavement is an integral component of a paved road and is used to obtain a durable, impervious, and skid-resistant road surfacing with acceptable ride quality. Bound pavement surfaces permit relatively safe travel at higher speeds with reduced vehicle operating costs and lower pavement maintenance costs, when compared to unbound roads (Roads Department, 1999). However, there is more than one type of bound road surface. For instance, flexible pavement types commonly use asphalt, or asphalt mixtures, whereas ridged structures often incorporate concrete, potentially with an asphalt running surface.

Different surfaces are appropriate for different applications and will have different costs, requirements and benefits associated with them. Variation might be expected from (Chinowsky, et al., 2015; ERA, 2013; Odoki, 2013): 1) initial costs of construction based on the material used for the pavement surfaces. In general, flexible pavements are less expensive to construct than rigid pavements, but require more frequent maintenance (ERA, 2013). 2) The maintenance costs required to achieve a desired level of pavement standard performance over the life cycle of the road. Proactive maintenance has long-term benefits rather than reactive maintenances (Chinowsky, et al., 2015), however, the availability of the budget limits maintenance standard applicability. 3) Road user costs which include vehicle operating cost (VOC), travel time cost, accident costs, and nonmotorized cost. The VOC and travel time cost are affected by the performance of the pavement and for poor condition pavements, higher VOC and travel time would be spent by the user (Odoki, 2013). 4) Environmental costs are associated with the materials and plant use in the construction and maintenance of road activity, which contribute to increasing greenhouse gas (GHG) emissions and sound noise (e.g. vehicle emissions, fuel consumption, and noise). These four aspects are further explored in section 3.2.1.

1.1.2. Life-cycle Cost Analysis for Road Pavement Surfacing

Life-cycle cost analysis (LCCA) evaluation of a road pavement surfacing involves the consideration of costs and benefits over the projected operational life of the pavement surface. It can be used to compare, in economic terms, the performance of one surfacing type against another, or the benefit of one maintenance standard compared to another for the same surfacing type (Peyman, et al., 2016). Thereby, the LCCA can facilitate the reasonable selection of a road surface type for a given environment. For example, Hamim et al. (2020) used an LCCA method to compare two flexible and rigid pavements, for highways in Bangladesh. Similarly, Wang et al. (2013) used an LCCA to quantify the effect of preservatives on asphalt roads. Whereas Hafizyar and Mosaberpanah (2018), used an LCCA to compare chip seal and HMA overlay treatment alternatives for roads in Afghanistan. However, these studies consider different maintenance alternatives for LCCA comparisons and none of them consider the actual climate change effect.

1.1.3. Deterioration of Bound Pavements and Inherent Uncertainties in Performance Due to Climate Change

Within an LCCA the projection of periodic maintenance strategies and road user costs require the condition of the road section, and therefore its rate of deterioration, to be determined. Bound pavement surfaces deteriorate as a function of both environmental impacts (notably climate) and traffic loading. The relative amount of deterioration due to the two factors depends, to a large extent, on the construction of the road and the amount of traffic using the road (Henning, et al., 2014). For low-volume roads, environment-related damage predominates; whereas for higher volume roads pavement deterioration is predominantly attributed to traffic (Chai, et al., 2014; Rolt , J;TRL , 1995; Stankevich, 2005).

Climate-related studies of road deterioration compare known climate conditions (using historical data sets) and projected climate conditions (using published models). A study showed a decrease in pavement performance due to climate change as compared to the performance without climate change for flexible pavements in the USA (Anne, et al., 2019). Moreover, to resist the projected climate change (from temperature and ground water rise) effect, Knott et al. (2019) increased the pavement thickness for both the hot mix asphalt surfacing and for the base. Hence a new standard for pavement design was introduced due to the different results obtained with and without considering climate change for roads in New Hampshire.

It is accepted that the projection of climate change is inherently difficult and can make conclusive findings problematic. This is illustrated by findings of Qiao et al. (2019), who reviewed 141 climate and flexible pavement related studies/research outputs. They found that the purpose of the analysis, method of analysis, the climate parameters considered and the tool(s) used for analysis in the studies all had an impact on outcomes, hence there is uncertainty around these outputs.

However, there is still considerable merit in attempting to further understand the potential consequences of a changing climate on pavement performance, and a relatively small number of studies have focused on this. For instance, Padmini et al. (2017), investigated the impact of climate change, using projected climate data obtained from different climate models on asphalt concrete (AC) and rigid pavements by comparing pavement distress types. The study found changes in the pavement distress factors due to change in climate, considering different climate projection models, in both (rigid and flexible) pavement types. However, for all climate change modules considered in the analysis showed that both pavement types would be expected to fail prematurely due to changes in temperature, precipitation, or both.

Using projected climate data and pavement design stage standards, Daniel et al. (2014) estimated that maintenance costs could increase by up to 160%. Using a different approach, Chai et al. (2014) estimated an increase of up to 30% in maintenance costs of local roads (i.e. urban and rural traffic volume) in Australia. The World Bank (2010 and 2018) undertook two climate impact resilience assessment studies and found that the predicted impacts of climate change in hazardous/problematic areas in Ethiopia could increase the responsive and reactive average maintenance costs by $15 million and $28 million respectively from 2008 to 2050.

Relatively few studies have been found which have considered the evolving future climate as a parameter to evaluate predicted pavement performance with an LCCA. For example, Qiao (2015 b) considered different climate change parameters (temperature, precipitation, groundwater and sea level) and identified the effect on pavement distress factors. While Chai et al. (2014) considered the effect of climate change through the Thornthwaite moisture index (TMI), which measures the subgrade wetness or dryness using a road roughness model. Their approaches to the problem, the climate projection methods and climate parameters used, were considerably different, although both sets of results suggest that climate change will impact future pavement performance, maintenance requirements and associated costs.

From the above, it is evident that climate change will impact the performance of pavements and maintenance and therefore, the life-cycle cost (LCC) of a pavement surfacing. However, the literature indicates that there are variations in how the researchers consider climate projection models and climate parameters (one or more), and in their methods of calculation to estimate the climate effect. Hence, there is a need for an LCCA that incorporates climate change effects for various climatic regions and pavement surfacing types in a trusted and commonly used tool to provide a consistent approach when addressing the impacts of climate change on the LCCA of road surfaces.

1.2. Situation in Ethiopia

Ethiopia has undergone a large road building and upgrading programme over the last 21 years in order to stimulate economic growth (ERA, 2019). During this period the paved road network expanded from 26,550 km, at the start of the Road Sector Development Programme (RSDP) in 1997 to 126,773 km in 2018. However, despite this initiative the total paved road length (17, 579 km) still accounts for only 13.87% of the total network length. The remainder of the road network is unpaved (Figure 1.1). The Ethiopian Road Authority (ERA) manages Ethiopia's major road network comprising 28,699 km of roads, of which 15,886 km are paved (ERA, 2019). More than 81% of these paved roads are constructed with an AC surfacing. The inclination towards using one type of surfacing has a significant effect on life-cycle costs when considering the largescale network expansion plan of the RSDP.

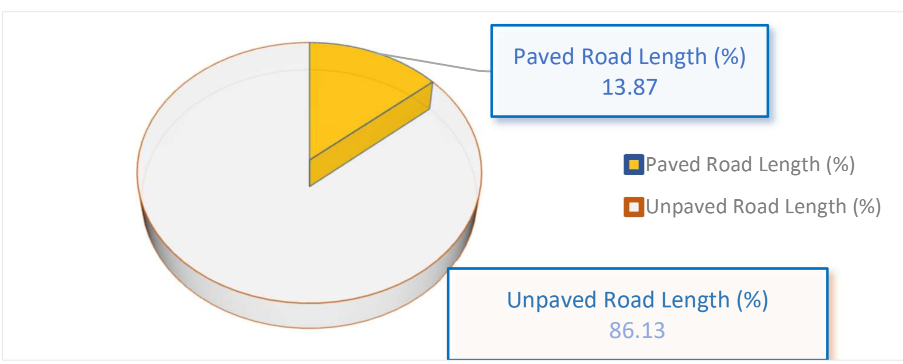

Figure 1.1 Proportion of paved and unpaved road from the total network in Ethiopia

The ERA recognise the need for pavement surfaces to achieve a number of criteria, these include: road surfacing that can increase the life of existing pavements; being resilient to the effects of climate change; and providing affordable, comfortable, safe and economic use. To meet these requirements, the ERA is investigating the use of more resilient surfacing materials than it has used to date. Whilst there are several possible surfacing types which could be used in the ERA's road network, each of them provides different benefits at varying costs (as mentioned previously). It is recognised that the problem of selecting appropriate surfacing options is exacerbated by:

1. the prevailing climate in Ethiopia, which varies widely across the country (Arnold, et al., 2018);
2. the effects of climate change on road deterioration;
3. construction and maintenance budget constraints (despite the large investment programme) (The World Bank, 2018);
4. future changes in traffic levels.

This research, therefore, embraces these challenges by developing an LCCA methodology that is used to evaluate the pavement surfaces currently used by the ERA and which takes into account, current and future levels of traffic, the five different climate zones encountered in Ethiopia and predicted climate change effects (predictions are taken from (McSweeney, et al., 2010.).

1.3. Aim and Objectives

1.3.1. Aim

The aim of this study is to develop a life-cycle approach that can evaluate road pavement surfacing, in economic terms, whilst taking into account the changing impact of climate during the road surface's life.

1.3.2. Objectives

To achieve the aim, the research has the following objectives:

1. Explore LCCA analysis concepts for the comparison of road maintenance strategies and review the literature on the potential impact of climate change on road surfacing performance in general and in the Ethiopian context in particular.
2. Explore and identify suitable tools for LCCA of road pavements which have the capability to account for climate change effects during a life-cycle analysis.
3. Develop a framework which can be used to quantify life-cycle cost components using the selected tool, taking into account climate change impacts.
4. Calibrate the selected tool(s) to represent local conditions in Ethiopia, considering the need to account for future climate change.

5. Assess the use of the tool and the developed framework by comparing, on a discrete and on a continuous life-cycle cost basis, the use of the five pavement surfaces used by the ERA.

1.4. Novelty of the Study

The novelty of this study arises from the development of a life-cycle analysis approach that evaluates the performance of road surfaces in terms of maintenance requirements and road user costs, incorporating changing climate conditions. The approach is tailored and demonstrated for five different road surfacing types which are used by the ERA. As far as the researcher is aware, this is the first time such a methodology has been developed to assess the use of LCCA techniques for different road surfacing types, taking into account the impacts of climate change on pavement structural performance and road user costs. Furthermore, it is the first time that such an approach has been developed and used for the ERA road network and in particular, to assess the five different road surface types within five different climate zones.

1.5. Contribution of the Research

The LCCA in the context of road surfacing, enables the economic selection of these bound surfaces. Therefore, applying the research in practice will enable the selection of road surfaces which are the most economically beneficial to society. Moreover, there is a paucity of LCCAs for road pavement surface studies which consider the impact of climate change, and therefore, this work will be an important contribution to the body of knowledge.

The outcome of the study will be directly used by the ERA to better inform its selection of pavement surfaces using a transparent approach to yield the most economically beneficial. The approach will enable the road sector to develop a road network that uses the most appropriate road surfacing technologies taking into account, resilience to potential changes in environmental loading, available maintenance budgets and road use costs. By so doing the ERA will be able to make best use of its construction and maintenance budgets, thus, benefitting society as a whole. Moreover, the results and the approaches of the research will disseminate through the ERA to different projects in sub-Saharan countries.

This study does not investigate conditions solely related to Ethiopia, and the concepts pioneered herein could be modified to suit the traffic loading, volume, and environmental conditions (and predicted changes) in other countries. Hence, this study provides a means by which this (assessing the suitability of pavement surfacing for long-term performance) can be achieved. Therefore, this study can be taken as a trailblazer for other studies.

1.6. The Structure of the Thesis

The thesis has Seven chapters. These are summarised below.

1. Chapter One introduces the research, describes the aim and objectives of the study and summarises the novelty and contribution of the work.
2. Chapter Two presents: a review of previous research related to life-cycle cost analysis; climate change and road deterioration; tools which are available for the LCCA; and the rational for selecting a tool.
3. Chapter Three describes: the research methodology and describes the selection of the LCCA tool; calibration of the identified LCCA tool; scenarios; adjustments of the tool to account for the impacts of climate change; and LCCA considerations to compare road pavement surfaces.
4. Chapter Four sets out the framework of the LCCA for road pavement surfacing under climate change impact.
5. While Chapter Five presents the findings of the analysis.
6. Chapter Six discusses various aspects of the research.
7. Chapter Seven provides the conclusions and recommendations for further work.

CHAPTER TWO – LIFE CYCLE COST ANALYSIS AND CLIMATE IMPACT

2.1. Introduction

This chapter reviews various literature in order to highlight gaps in considering the climate change effect in life-cycle cost analysis (LCCA) within current knowledge and state-of-the-art practices. This involves pavement surfacing types and their selection requirements, LCCA practices, and climate change impacts on pavement. The chapter also focuses on identifying the current state of knowledge in relation to climate change impact on pavements in Ethiopia.

The chapter organised in six sections including this introduction (section 2.1). Section 2.2 provides pavement surfacing selection requirements followed by the approaches of LCCA in section 2.3. That section covers the components of LCCA, its levels of application and factors that affect it, before discussing the state of practise of LCCA tools. Next, section 2.4 identifies the sources of climate change and summarises them, before presenting the use of these changes in design manuals and policy documents. The section also highlights the current knowledge on climate change impacts, and is then followed by section 2.5 that shows identified gaps in climate change impact studies. Finally, section 2.6 summarises the chapter.

2.2. Pavement Surfacing Selection Factors

The pavement is a part of a durable road structure and it helps the road to stay strong for long time by transferring the wheel load to the subgrade soil. The top part of the pavement is referred to as the pavement surfacing and it is used as a contact media of roads to traffic loads, the environment and climate actions. Depending on the material used there are different road pavement surfaces (Appendix A) and their choice can be affected by different factors.

Table 2.1 presents the common factors used in different pavement design manuals/guides, such as ERA (2013b), Lila (2012), Andrew, et al. (2009), the Roads Department (1999) and others. The final choice of surfacing, however, may be biased to one or more factors depending on the decision makers financial, social, and political considerations or other factors.

Table 2.1 Factors used in the selection of pavement surfacing (source: (ERA, 2013b; Roads Department, 1999))

Factors	Area of consideration
Pavement types	This factor considers the strength and flexural properties of the pavement structure based on the material property and the soil characteristics.
Monetary	Includes initial cost and future cost estimates to identify available funds and life cycle cost.
Riding quality	This factor considers the user comfort and associated cost.
Operational factors	This considers the level of the traffic, surface stresses, geometry, and other similar factors.
Safety	Surface texture, interference with traffic.

Environment considerations	Climate, noise, conservation of material and energy, recycling.
Construction and maintenance strategies	Continuity of cross section, life cycle cost, performance, and planned works for sustaining the service.
Characteristics of available materials	Aggregate, binder and utilising other locally available material.
Social and political factors	Local preference, social and political stability.

The advantage of considering the above factors is to find the most cost-effective solutions. However, the Roads Department (1999) suggested that LCCA should be used for selection of surfacing alternatives, even if the surfacing meets other technical and environmental requirements. This is because the LCCA determines the long-term maintenance needs in terms of quantity of work and its associated costs in order to make decisions (Lila, 2012). The quantity of work considers pavement performance, operational factors, safety and environmental factors. Moreover, the decision process includes risk consideration when there is a limitation in meeting the required maintenance budget. Hence, LCCA uses economic principles and values to better appraise the overall long-term monetary viability of various road investment alternatives (Prasada, et al., 2009).

The LCCA is used to appraise different initial, operational and maintenance cost alternatives at the design phase or after construction (Tighe, et al., 2008). However, an LCCA can be applied for pavement type selection and different reconstruction alternative evaluations, and material selection as well as bid evaluation (Adams &

Kang, 2006). However, Karim (2011), stated that the LCCA is less important for bid evaluations. The state of practice discussed by Peyman et al. (2016) indicated that the practice of using an LCCA differs in different road agencies/authorities found in the USA, Europe and Canada. Their differences lie in the approaches of measuring and combining the costs and effectiveness of each alternative decision and purpose of LCCA use. These differences in one way or another agree with the identified gaps between the state-of-the-art and the state of practice of the LCCA shown by Ozbay et al. (2004). The findings of Ozbay et al. (2004) showed that treatment of uncertainty, timing of future rehabilitation activities and the inclusion of user costs were the major gaps in LCCA use.

However, the practice of the LCCA in developing countries is mostly limited to fulfilling the donors' requirement for funding (Bagui & Ghosh, 2015). For instance, there is no recorded state of practice found for Ethiopia, except some practice in ERA to use LCCAs for international donor-funded projects (like the World Bank). This is because the World Bank requires feasibility studies in terms of LCCAs to make the funds available to the project. However, the current pavement management activities of the ERA have shown improvements towards considering maintenance strategies and LCCAs for government-funded projects.

2.3. LCCA Approaches

2.3.1. Components of LCCA

An LCCA can be defined as a method of analysis to evaluate the whole design life costs considering long-term economic effectiveness between different investment choices (Walls & Smith, 1998). The concept of life-cycle cost analysis integrates sets of components of costs that are related to road construction and discounted future agencies, users and other relevant costs. The method compares these cost components to identify the lowest long-term cost option from the proposed investment alternatives (Peyman, et al., 2016). The cost calculation in discounted present values involves the pre-set standard and quantity of the resources required for the predicted pavement deterioration multiplied by its unit rate. According to Odoki and Kerali (2006), this economic appraisal helps road administration offices to answer the following two questions:

a. How to determine road investment? and
b. What economic returns to expect?

The solution for these questions is provided in the form of pavement performance, and its associated costs. The analysis results are expressed in terms of savings in user cost, environment, maintenance and construction costs as defied by Bennett and Greenwood (2004) as follows:

Road Agency Cost (RAC) – it is a cost incurred to any road administration office and it is the major cost from the LCCA components. It involves costs that are associated with road design and construction, contract administration, pavement maintenance and roadside or off-carriageway activities, and salvage. From the total life-cycle cost (LCC) about 70% to 90% is spent at the initial stage of the road development (Odoki & Kerali, 2006). The remaining 30% to 10% are assigned for maintenance and for the other cost components. The salvage value is deducted from the other costs since it is the remaining value of the road at the end of the analysis period.

Road User Costs (RUC) – this is a cost incurred to the road user by the road in the form of the following four costs.

I. Motorised vehicle operating cost (VOC) - this cost represents the cost that the road user spent for fuel and lubricant consumption, tyre and parts consumption, labour, capital, crew, and overheads.
II. Travel time cost - it is a cost which is associated with passenger travel time cost and cargo holding time cost.
III. Non-motorized transport time and transport cost - this includes costs and time associated with transport means using animals and pedestrian walks.
IV. Accident costs - this cost is characterised by accident costs caused to people and property by three separate groups: fatal cost, injury cost and property damage only cost.

Environmental Effects Cost – this refers to the costs due to environmental hazards caused by emission of GHGS, other toxic gases, and noise. In quantifying the environmental cost some literature, such as the work of Qiao et al. (2015) stated that it is difficult to quantify environmental costs because environmental effects can be cost saving and/or a potential cause for spending money. For example, decreasing driving speed in rainy weather may save money on accident costs but may lengthen travel time and increase operational cost. Therefore, there are options to include/exclude one or more environmental components in LCCA depending on the analysis type.

The above discussions for LCCA in terms of RAC and RUC can be summarised in Figure 2.1. The figure indicates that when the standard of a road in terms of performance increases due to maintenance application, the cost of the RAC, which includes maintenance, construction and agency overheads also increases. However, providing a high standard leads to decreasing vehicle operation costs, thereby decreasing the RUC. The figure also shows how the LCCA identifies the best maintenance intervention in providing improved road standards and the associated components of the total transport cost (TTC). The TTC represents the sum of the RUC and RAC.

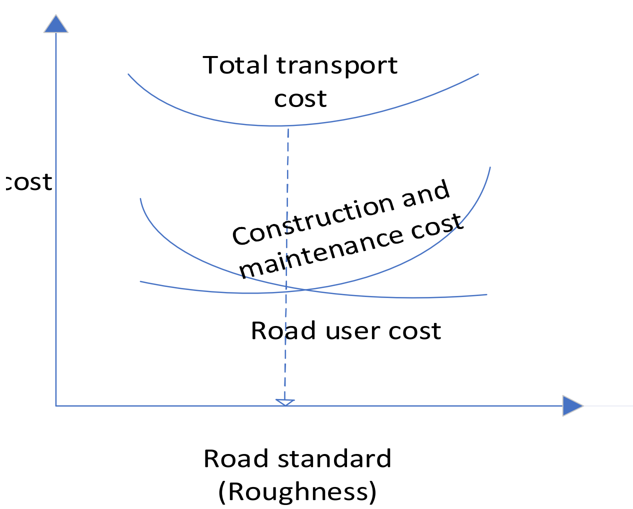

Figure 2. 1 Road standard VS. total transport cost (source: (Odoki & Kerali, 2006))

2.3.2. Levels of Application of LCCA

Some literature (Peyman, et al., 2016; Prasada, et al., 2009; Kerali, et al., 2006) indicates that the outcome of an LCCA is not only to compare one alternative over the other(s), but it is used for: pavement selection (Peyman, et al., 2016); identification of factors that influence cost effectiveness (Prasada, et al., 2009); and the most cost-effective strategy (Kerali, et al., 2006). However, depending on the type of analysis, an LCCA can embrace or neglect financial readiness and strategy concerns (Odoki, et al., 2013). In relation to this, Bennett and Greenwood (2004) revealed that an LCCA can be performed in three (project, programme and strategic) levels as presented in Table 2.2.

Table 2.2 Level of LCCA analysis (source: (Bennett & Greenwood, 2004))

Level of application	Name of the application level	Nature of analysis	Use
I	Project Level Analysis	It is specific, very detailed and involves a very small number of road sections	It gives adequate economic analysis information for decision making. However due to its specificness, the budget will be known, and it does not involve policy considerations.
II	Programme Level Analysis	It involves short to medium term planning for a number of road sections	A set of road sections and road works can be selected, since the funding may be determined with reasonable certainty.
III	Strategic Analysis	It comprises the analysis of the entire road network to determine the type of road works to be applied to maximize economic benefit.	It is possible to search for the combination of investment alternatives provided by the user that optimizes the objective function under a budget constraint.

However, caution is required when considering LCCA approaches due to the different underlying assumptions and cost calculation processes, because some LCCA software excludes the RUC or some of its components (Appendix B). This may occur as a result of quantification difficulty and uncertainty in values associated with user cost components (Peyman, et al., 2016). For instance, the estimation of the accident cost component of the RUC was reported to be difficult for flexible pavements for USA roads (Qiao, et al., 2015). Therefore, the reporter recommended the use of systematic and well-coordinated LCCA tools.

2.3.3. Factors that Affect the LCCA

The LCCA expressed in terms of the three cost components (RAC, RUC and environment, section 2.3.1) uses different procedures to calculate each of them. The estimation of the cost components depends on the pavement type and its conditions; identification methods used; pavement maintenance strategies; and estimation of costs for the RUC and RAC (Santos & Ferreira, 2012). Moreover, the procedures and their outputs are highly dependent on the models used for the analysis, as it involves complex analysis steps (Qiao, et al., 2015).

2.3.3.1. Pavement Surfacing Types Consideration

Pavements in general are broadly classified as either flexible or rigid, based on their load transfer mechanism to the subgrade soil and their constituent material. However, globally, pavements can be sub divided up into 26 types (Appendix A) depending on their surface and base material. Each of these pavement groups has different surfacing types that would be appropriate for different traffic levels, environmental conditions, material availability and economic factors’ considerations.

Burrow et al. (2016) showed that more than 17 surfacing technologies exist for low volume roads in developing countries. This surfacing technologies’ review considers the engineering aspects of the pavement design and material properties; however, there are limitations in implementing these technologies in these countries. The reason for this may be a lack of enough budget, the requirement for construction and/or maintenance and dominating factors used for selecting the pavement surfacing. For instance, the 2013 Ethiopian Road Authority (ERA) manual (ERA, 2013a) involves 14 different types of pavement surfacing (Appendix A). However, the ERA's experience (Figure 2.2) has been mostly limited in the use of asphalt concrete (AC) (ERA, 2012, 2017, 2019).

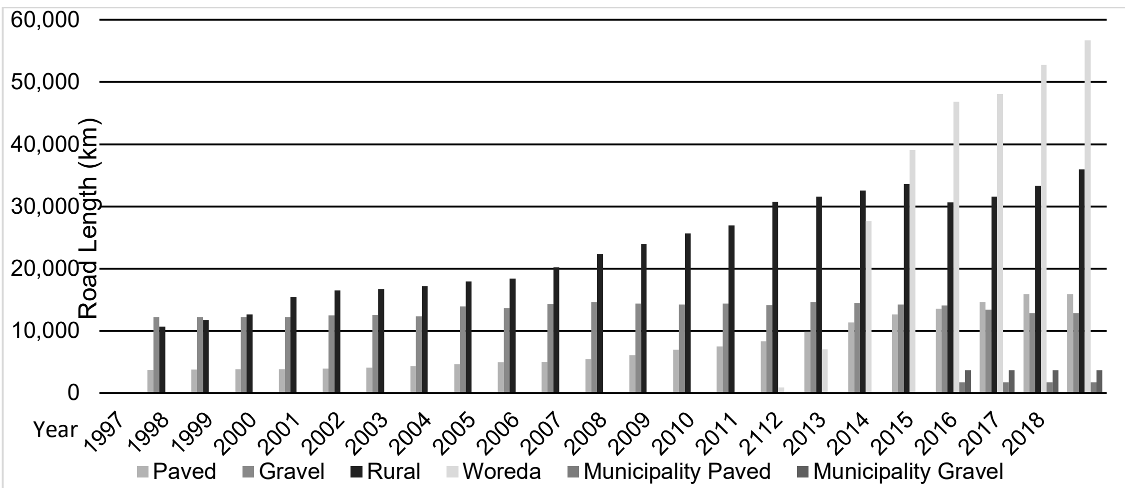

Figure 2.2 Trend of the network development during the 21 years of RSDP (Source: (ERA, 2019)*)*

Roughton (2011), also reported that AC was preferred in ERA even in areas where surface treatments could be sufficient and more suitable. The reason for this includes lack of skilled workmanship and impacts of social/political conditions (Roughton, 2011). Therefore, for the minimum potential demand presented in Table 2.3, comparison of different pavement types using LCCA helps to consider different factors (including climate changes) that can result in efficient budget utilisation.

Table 2.3 Classified Road network in 2018 (Source: (ERA, 2019))

Road category	Paved roads (Km)	unpaved roads (Km)	Total (Km)
ERA	15,886	12,813	28,699
Rural	-	35,985	35,985
Woreda	-	56,732	56,732
Municipality	1,693	3664	5,357
Total (KM)	**17, 579**	**109,194***	

*Potential demand for paving.

2.3.3.2. Pavement Deterioration and Maintenance

According to Transport Research Laboratory (TRL), (1993) and Odoki and Kerali (2006), the road pavement deteriorates due to traffic and climate. Due to traffic and environmental actions pavement deterioration is expressed in terms of different distress factors (Table 2.4). However, considering climate change flexible pavements are affected by rutting, bleeding, potholes, longitudinal and transverse cracking; while rigid pavements suffer from D-cracking, scaling, faulting, pumping curling, corner cracking and punch outs (Kuo, et al., 1991). The distress factors are directly affected by the intervention of maintenance standards (Evdorides, et al., 2012). However, the type, approaches and timing of maintenance and rehabilitation actions can be varied as shown in Figure 2.4. Therefore, the long-term pavement condition depends on the choice of maintenance.

Table 2.4 Description of distress factors (source: (ERA, 2013b; ERA, 2013c; Odoki & Kerali, 2006)))

Distress factors	Descriptions
Cracking	A crack is a discontinuity of the pavement surface and appears as small openings or as fractures. Cracks represent the conditions of the road pavements and can develop to other types of deterioration due to climate, traffic action, environment, or a combination of these factors. Commonly, cracks transmit in to two ways: top-down and bottom-up, by indicating the cause of the cracking. A change in temperature causes thermal tensile stresses, which develop cracking initiation and propagation leading to the asphalt age hardening. In general, there are 4 cracking phenomena:
A) Fatigue cracking	Fatigue cracking is caused by the fatigue failure of the pavement surface or stabilised base under repeated traffic loading (Huang, 2004)
B) Longitudinal cracking	Longitudinal cracking is mostly because of pavement material hardening or shrinkage when the pavement surface experiences low temperatures. The subgrade movements can be associated with moisture (Moffatt and Hassan, 2006).
C) Transverse cracking	Transverse cracking is the same as longitudinal cracking, except that linear crack predominantly develops perpendicular to the pavement centreline.
D) Block cracking	Block cracking is due to a stress induced by change in the daily temperature, and a series of cracks which divide pavements into rectangular pieces.
Ravelling	Ravelling refers to the progressive disintegration of a hot mix asphalt layer from the surface downward because of the dislodgement of aggregate particles.

Pothole	A pothole is a structural failure of the asphalt pavement, which occurs due to moisture in the sublayer and subgrade. Climate, traffic loading and environment conditions contribute to the creation and propagation of a hole. It is obtained from a field survey and often expressed in terms of the number of potholes.
Rutting	Rutting is caused by climate, traffic loading and the environment and appears on the transverse profile of a road surface as a surface depression along the longitudinal wheel path. It is obtained from a field survey and often measured in terms of rut depth (mm).
Roughness	Roughness is an important indicator of road serviceability and riding comfort, found by measuring the longitudinal unevenness of the pavement. Since roughness has an impact on vehicle dynamics, it can affect the dynamic loading that accelerates the deterioration of a pavement. An increase of roughness in a pavement is believed to cause an increase in the road user's cost (Archondo & Faiz, 1994; Bennett & Greenwood, 2003), as well as accidents (Odoki, 2013). It is obtained from a field survey and is often measured in terms of the International Roughness Index (IRI).
Surface texture	This category comprises texture depth and skid resistance.
Faulting	Faulting is a distress that indicates a joint or some cracking contains a variation in height between the right and left sides of the joint or crack. Faulting can be measured as the average fall of all transverse joints of the pavement. It is also considered as the reason to increase roughness in rigid pavements (Odoki & Kerali, 2006).
Spalling	Spalling refers to breaks or cracks of the joint edge that occur up to a distance of 0.6 m from transverse joints (Odoki & Kerali, 2006).

The effect of maintenance choice considered through the performance period of the pavement (Figure 2.4) and the cost of maintenance. Different maintenance alternatives application resulted in different pavement performance conditions. The performance represented by the riding quality/road roughness (Table,2.4). It is obtained from field survey and often measured in terms of International Roughness Index (IRI) and it can be predicted using roughness models (section 3.4). Figure 2.4 indicates that one can decide to use frequent maintenance for a fixed level of performance with less maintenance cost. Or considers long-term performance effect and provide maintenance with higher cost accordingly, or wait until the pavement totally deteriorates and reconstruct afterward (no maintenance intervention). Here the advantage of LCCA is that it considers these options and projected the best alternative for the available maintenance budget. However, when there is a surplus budget for maintenance or when full attention is given to increasing access/network LCCA may not be considered.

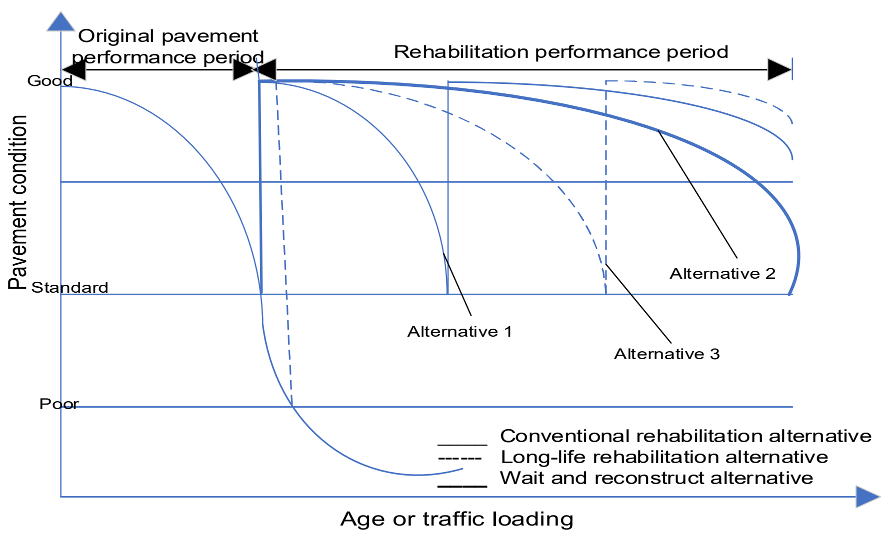

Figure 2.3 Concept of LCCA (source: (California Departement of Transportation , 2010; Prasada, et al., 2009)

2.3.3.3. Economic evaluation consideration and its indicators

An economic comparison of different alternatives includes three major processes (listed a-c below) and requires guides/indicators for the economic analysis results to be interpreted.

a. Discounting the annual costs and benefits streams to a chosen base year
b. Comparing the time stream of costs for each pair of alternatives
c. Calculating the economic indicator

Economic Evaluation Indicators – different indicators such as the benefit/cost ratio (B/C), net present value (NPV), internal rate of return (IRR), first-year benefits (FYB), and equivalent uniform annual cost (EUAC) have been used for economic analysis (Peyman et al., 2016). The choice of the appropriate economic indicator depends on the economic environment, and the level and context in which the analysis is conducted. The first four aforementioned indicators are summarised in Table 2.5 together with a description and associated equations.

Table 2.5 Economic indicators summary (source: (Bennett & Greenwood, 2004))

Indicator	Description	Formula
Net present value (NPV)	It is the sum of the discounted annual net benefit/cost and it converts future cash flow to the present costs, using a discount rate. It is used to compare two alternatives if there is no budget constraint but it cannot be used to compare different road networks/sections. This is because it represents the total cost for different initial costs and road lengths.	$NPV_{(n-o)} = \sum_{y=1}^{y} \frac{NB_{y(n-o)}}{[1+0.01*r]^{(Y-1)}}$ Where: $NB_{y(n-o)}$ = net economic benefit of investment option n to the base option o in year y, r = discount rate (%), y = analysis year (y = 1,2, 3…. y)

	Therefore, greater benefit is obtained from the different investment options relative to the base option.	
Internal Rate of Return (IRR)	It is the discount rate at which the NPV value is zero. The IRR is used as a guide to show if the investment is profitable. A higher IRR than the plan discount rate for an investment indicates that the investment is more profitable and economically justified alternative. However, the IRR cannot provide information about an investment in relation to the size or the cost and/or benefit of the investment.	$\sum_{y=1}^{y}\frac{NB_{y(n-o)}}{[1+0.01*r]^{(Y-1)}}=0$ Where: $NB_{y(n-o)}$ = net economic benefit of investment option n to the base option o in year y, r = discount rate (%), y = analysis year (y = 1,2, 3…. y)
Benefit cost Ratio (BCR)	It is the ratio of the difference between savings and costs. It gives an indication of the profitability of an investment by comparing with the base alternative at a given discount rate. However, similar to the IRR it cannot provide information in relation to the size of the cost and or benefit of the investment.	$BCR_{(n-o)}=\frac{NPV_{(n-o)}}{C_m}+1$ Where: $BCR_{(n-o)}$ = benefit cost ratio of investment option N relative to base option o. $NPV_{(n-o)}$ = discount total net benefit of investment option n relative to base option o. This is the NPV value at discount rate r. C_m = discounted total agency cost of implementing investment option m.
First-year Benefits (FYB)	It is the ratio of the net benefit realized in the first year after construction or improvement work completion to the increase in total capital cost. It is expressed in per cent and provides a rough guide to project timing (that means if the FYB is greater than the discount rate, then the investment should be ok, otherwise it should be delayed	$FYB_{(n-o)}=\frac{100*NB_{y(n-o)}}{\Delta TCC_{(n-o)}}$ Where: $FYB_{(n-o)}$ = first year benefit of investment option n relative to o (%). $NB_{yo(n-o)}$ = net economic benefit of investment option n relative to base option o in year y^o.

	until the discount rate is lesser than the FYB).	Y^o is the year immediately after the last year in which the capital cost for improvement or construction is incurred in option n. $\Delta TCC_{(n-o)}$ – the difference in total capital cost (non-discounted) of investment option n relative to base option o.

Discount rate – the discount rate is an interest rate which is used to convert/discount future costs and benefits in monetary terms to the present cost value. In economic analysis, the real discount rate is always used to exclude the effects of inflation (Philippe & Vijay, 2006). However, Bennett and Greenwood (2004) suggested that economic analysis with different discount rates helps to evaluate comparative pairs of investment options. It can be estimated by subtracting the rate of inflation from a market (nominal) interest rate for government borrowing, which is derived from government bonds.

2.3.4. Review of Documented LCCA Tools

The LCCA tools consist of different modelling methods for pavement deterioration prediction, maintenance strategy development, RUC and RAC estimation and for economic analysis. The type of LCCA is classified based on the modelling approach and functionality (used for pavement performance, cost estimation, and integrated pavement management system (PMS)) (Mizusawa, 2009). The approach of the PMS also differs; from a simple Excel data processing programme to complex and sophisticated software that can consider changes in technology and be applied in different conditions by calibration (Heriberto, et al., 2018).

For the last three decades numerous researchers have developed models to conduct LCCAs. The outputs of this research were used to improve the assumptions and approaches of the LCCA. Ram and Richard (2003) explained the trend of the LCCA tools' improvement for three decades and Table 2.6 summarises the changes made with respect to both deterioration and economic models.

Table 2.6 Changes in deterioration and economic models (source: (Ram & Richard, 2003)

Considered points	From 1970 to 1980	In the period of the 1990s	The first decade of the 21st century
Type of pavement variables to predict	Combined index of several pavement distresses	Predict individual pavement distresses	Predict individual pavement distresses combined using appropriate weights to generate an overall index
Required prediction level	Project level	Project and network level	Project and network level
Type of projection models used	No prediction	Mechanistic, empirical and mixed mechanistic-empirical modes	Employing artificial intelligence (AI) concepts to develop "self-learning" systems
How to consider uncertainties	Not considered	Utilising deterministic and probabilistic* models	Utilising deterministic and probabilistic models
Types of decision models	Expert judgement-based	-	Employing artificial intelligence (AI) concepts to develop "self-learning" systems
Model departure determination	Static decision model	Static and dynamic** decision model	Automatic alerts for model departure
Economic model	Initial construction costs	Life-cycle cost, agency cost and user cost	Expanded database

Prioritization evaluation	Simple measures	Benefit cost ratio, Net present value	Formal optimisation[1]n

2.3.4.1. LCCA models

In general, there are two modelling approaches for an LCCA; namely deterministic and probabilistic approaches. In the deterministic approach input variables of the LCCA are treated as discrete fixed values. However, Peyman et al. (2016) and Philippe and Vijay (2006) indicate that in any engineering analysis that involves prediction, it will inevitably contain some level of uncertainty. These uncertainties can be related to a combination of unknowns associated with data randomness, regional construction variation, human factors, lack of data, unrepresentative (limitation in) models, and others. Therefore, these must be treated through either using risk analysis methods for deterministic models or by using the probabilistic modelling approach.

Sensitivity analysis is the simplest approach for uncertainty assessments (Odoki & Kerali, 2006). Sensitivity analysis is broadly classified as either local or global based on the considered parameter space. Local sensitivity analysis focuses on the sensitivity relation to changes of one parameter value, while other parts remain the same. Whereas a global sensitivity deals with sensitivity with respect to the whole parameter space, and it measures the effects of various input factors on the output of the analysis

[1] * A deterministic model ignores the uncertainty; while a probabilistic model quantifies the uncertainty by estimating probabilities of different future pavement conditions.

(Saltelli, et al., 2000). Moreover, normalisation of sensitivity analysis enables relative comparisons between similar size variations in input parameters.

In addition to this, based on the data used for modelling, models further were subdivided into three categories namely: mechanistic, empirical, and structured empirical models (Morosiuk, et al., 2006). The mechanistic model is based on fundamental theories of material behaviours and it involves lots of data and many parameters to describe the material properties. The advantage of this model type is that it can define different material characteristics, which can be used under different conditions; however, they require data that may be hard to quantify. On the other hand, the empirical model is developed from measured or recorded data trends. The advantage of the empirical model is that it can represent specific local conditions from the recorded data trends but they cannot be used for different conditions. The third model type is structured empirical and it was developed by combining these two (mechanistic and empirical) models (Morosiuk, et al., 2006). This type of model contains experimental and theoretical data to overcome the limitations of the two previous model types, when each is used separately (Heriberto, et al., 2018).

Morosiuk and Riley (2003) explained that the above models could be subdivided into absolute and incremental models, depending on how the effect of time is considered in these models. The models can be counted as absolute models, if the model variables do not account for any change with time. Such models are limited to calculating the average forecasted performance of the pavement; however, they can be used to study the effect of independent variables on a specific point in time. On the other hand, the incremental models estimate variations in pavement conditions from the first stage as a function of those independent factors. Incremental models are preferable in estimating yearly changes and long-term effects of pavement conditions.

Depending on the aim of the model/tool its functionality can be limited to specific analysis or combine different models together to perform the complete analysis with one tool. Pavement performance tools are developed to predict pavement deteriorations of different pavement parameters under various conditions. For this category Mechanistic Empirical Pavement Design Guid (MEPDG) software can be used as an example, since it can only predict performance for different pavement types considering various conditions (Li, et al., 2011; Raul, et al., 2009). Whereas cost estimation tools, may or may not require prediction of pavement performances to estimate the RAC and RUC (Peyman, et al., 2016). For instance, RealCost, and MicroBENCOST, estimate only the costs of the project based on work zone traffic, future maintenance and/or rehabilitation sequencing (Kim, et al., 2015; Geoffrey , et al., 2005). On the other hand, integrated models/tools consist of both the performance and the cost components in one piece of software. For instance, programmes like HERS-ST (Highway Economic Requirement System – State Version) of the USA, ARCH PMS of the UK and the World Bank's HDM-4 perform both steps in one piece of software (Mizusawa, 2009). However, the writer of this thesis has found no journal paper that shows research using HERS-St and ARCH PMS, hence this area is left for future work. The review of the existing LCCA tools is presented in Appendix B.

In addition to this, the choice of models/tool is related to the task at hand, since the inbuilt systems and the associated models, can vary in complexity and focus. For instance, Heriberto et al. (2018) stated that a traditional PMS can be applied for: 1) low traffic; 2) an unlimited maintenance budget; and 3) when focusing only on an increasing network by the construction of new access roads. While large road networks need complex decision methods to preserve the performance. However, AASHTO (2012) recommends that an LCCA should be supported by PM tools.

Therefore, depending on the factors that need to be studied, it is necessary to identify the appropriate PM tool for an LCCA.

2.3.4.2. Assessment of Documented LCCA Tools

The tools listed in Appendix B are similar in that they attempt to consider the whole life-cycle costs of the road pavement. For instance, the costs of construction, maintenance, and for the road user, which include vehicle operation and delay costs. However, they differ in how they attempt to achieve this; that is, in terms of data requirements and adaptability; usage of the deterioration models; the method used to calculate costs; how environmental impacts on road deterioration are considered; and their suitability for the analysis of different road pavement types. Therefore, for this study, attention was given to those PMS tools which were used in climate change and pavement-related analysis.

From Appendix B, three PMS tools, MEPDG, HDM-4 and IPSS are identified as tools that can consider climate changes during pavement performance and its associated cost projections. The MEPDG and HDM-4 tools can provide a prediction of pavements' performance throughout their design life by using the mechanistic empirical pavement design approach. This involves adjusting or calibrating the laboratory-developed pavement performance models to the observed performance measurements from the actual pavements. The advantage of both the MEPDG and the HDM-4 is that they can analyse and project pavement performances for different flexible and rigid pavements. In addition to this, both use input data such as traffic, climate, materials and proposed structure for pavement performance predictions in terms of pavement distresses and ride quality. Moreover, these tools were used in climate impact and pavement performance research such as: "Impact of climate change on pavement structural performance in the United States" by Padmini et al. (2017); "Assessing the impacts of climate change on road infrastructure" by Shao et al. (2017); "Flexible pavements and climate change: impact of climate change on the performance, maintenance, and life-cycle costs of flexible pavements" by Qiao et al. (2015b); "Assessment of the impact of climate change on road maintenance" by Anyala et al. (2011). Section 2.4.4 discusses these works and other climate impact and pavement related research.

On the other hand, the IPSS tool uses works' quantity items and their unit costs as an input to calculate the cost due to climate impact (section 2.7). However, the tool does not provide changes in the road pavement performance due to the climate change impact. The MEPDG and IPSS tools can analyse the impact of both extreme and incremental climatic changes on road infrastructure. However, the HDM-4 tool lacks the consideration of extreme or short-term climate effects. Unlike the other two tools, MEPDG is able to access data directly from the climate projection models. However, the disadvantage of MEPDG is that it cannot perform an LCCA; while HDM-4 and IPSS provide whole-life cost analysis.

The cost analysis approach for HDM-4 and IPSS are very different. The IPSS approach uses a bill of quantities estimation to multiply the estimated climate change damage in terms of different work activities. Due to this, IPSS has a limitation in considering pavement distress parameters and performing the impact of climate in terms of pavement performance (Chinowsky, et al., 2015; Schweikert, et al., 2014). However, the HDM-4 framework is based on a pavement life-cycle analysis concept and used to predict pavement performance, road works' effect, road user effect, and socio-economic as well as environmental impact. The tool can also optimise the available budget for the proposed policy.

The features of HDM-4 include providing three analysis functions at road network, sub-network, or individual segment levels: 1) strategy level to predict pavement deterioration for various funding levels and management strategies at road network level over 5 to 40 years; 2) it has a program level to prepare a multi-year program of projects within resource constraints; 3) it has a project level to analyse costs and benefits of one or more project or investment alternatives (e.g. maintenance, rehabilitation, widening). Moreover, it can analyse different flexible and rigid pavements' (about 26 pavement types defined based on surface and base as presented in Appendix A) material with their input data for traffic, climate, materials, and proposed structure. Another disadvantage of the HDM-4 is that although, due to the mechanistic empirical nature of the models, the tool can be used in different conditions, the processes of model calibrations are very data intensive. Moreover, the software also has a limitation in providing LCCA analysis using a probabilistic approach; thus, it requires further analysis of its output or model adjustments for risks analysis.

Therefore, for this study the World Bank HDM-4 version 2.10 PM tool has better options to analyse the climate change impact by considering modification of models and output analysis approaches.

2.3.4.3. Reported uses of HDM-4

The HDM-4 is the most extensively utilised tool worldwide, and specifically in developing countries. It has been used to evaluate more than 200 projects since 2008, with an estimated total value of more than £35 billion (Bannour, et al., 2015). These include: assessing the costs and benefits of the 8,600-km African North-South Corridor Road network and analysing the £215-million Northern Corridor Transport Improvement Project in East Africa (UKCDR : Building better road networks, 2021).

The HDM-4 mechanistic empirical models must be adjusted to the specific conditions of a location where they are to be applied by adjusting certain calibration factors. Depending on the data used it has three levels of calibration. Level-I calibration uses desk study data; while Level-II uses field survey data; and Level-III uses detailed researched data. Documented calibration practices (Table 2.7) showed different models of HDM-4 calibrated by scholars using various methods and data levels.

Table 2.7 Review on HDM-4 models calibration practices

HDM-4 model type	Calibrated model	Calibrated for	Calibrated factors	Method used for calibration	Reference
pavement deterioration models	flexible pavements	Morocco	structural crack, cracking initiation and propagation	“windows” methodology	Bannour et al., 2015
pavement deterioration models	bituminous pavement	India	roughness age environment, cracking initiation and propagation	HDM-4 manual 7 and “windows” methodology	Bagui and Ghosh, 2015
road user effect		Japan	small passenger cars, medium passenger cars, medium trucks, heavy trucks and heavy buses	comparing parts consumption and labour hours for the VOC relationships and for different gases and emissions’ relationships	Bagui and Ghosh, 2015
emission models		India	operating weight, pavement gradient and vehicle life	sensitivity analysis	Prasad et al., 2013
pavement deterioration progression models	surface treatment	India	cracking, ravelling, edge break and pothole	computer programs in “Visual C” language	Thube and Thube, 2013
pavement deterioration models	surface treatment	Chilean	racking, ravelling, potholing, rut depth, and roughness	“windows” methodology	Herman et al., 2012
fuel consumption model		USA	articulated trucks and medium cars	statistical analysis	Zaabar and Chatti, 2010
road deterioration models	sealed granular and asphalt roads	Australia and New Zealand	cracking, roughness, rutting and deflection	LTPP data	Austroads Technical Report, 2008

road deterioration models	asphalt pavements	Chile	cracks, ravelling, potholes, rutting and roughness	"windows" methodology	Valdes et al., 2006

The use of HDM-4 for LCCA is also reported widely in the academic literature. For example, Koji et al. (2007) revised HDM-4 and discussed points that improve the strategic analysis consideration. Odoki et al. (2013) used HDM-4 adaptation for strategic analysis of UK local roads. Zarabizan et al. (2013) used this tool to conduct technical and economic analysis in generating annual work programmes for pavement maintenance in Malaysia. While Shah et al. (2014) also used HDM-4 for planning pavement maintenance strategies for urban cities; in this case in India, to ensure rational utilisation of limited maintenance funds. Bannour et al. (2015) used HDM-4 to optimise pavement maintenance for Morocco's arterial network. Also in 2015, Koranteng-yorke et al. used HDM-4 to evaluate the life-cycle method of mechanistic-empirical pavement design principles. In 2016 Cutura et al. utilised HDM-4 to establish a road maintenance schedule and capital spending priorities based on various budget scenarios for Bosnia and Herzegovina. All the above-mentioned works confirmed the HDM-4's multi functionality and adjustability.

However, few researchers have used HDM-4 successfully to demonstrate the contribution of the environment and in particular predicted changes in the climate on pavement deterioration. For example, Chai et al (2014) employed HDM-4 for future climate effect analysis on pavement performance by considering climate changes through the Thornthwaite moisture index; which is a measure to show if the subgrade soil is continuously wet or dry. Whilst Anyala et al. (2011) modified an HDM-4 rut model to consider the effects of extreme conditions of climate change. The research modifies the deterministic nature of the rut model to probabilistic to consider extreme and incremental climate changes. However, this approach was not replicated to other distress parameters.

2.3.4.4. Pavement condition measurements in the HDM-4

The prediction of pavement deterioration in the HDM-4 models is related to the design, axle load characteristics, traffic volume, road geometry, and material type used for construction and maintenance activities, construction quality, environmental conditions, and the age of the pavement (Morosiuk et al., 2006). The modelling approach is focused on road distresses. This includes pavement cracking, rutting, ravelling, potholing, and road roughness for flexible pavements; cracking, joint faulting, spalling, failures, serviceability loss and roughness for concrete pavements, and gravel loss on unsealed roads (Odoki and Kerali, 2006). Each of these distresses (Appendix C) are modelled separately in HDM-4, considering various designs and maintenance alternatives.

From the distress factors, roughness represents the pavement performance in the calculation of the LCCA (Odoki, et al., 2013; Archondo & Faiz, 1994) (Appendix C). Odoki (2013) and Archondo and Faiz (1994) stated that this is because roughness indicates the road serviceability and riding comfort impact on vehicle dynamics, since it affects the dynamic loading to accelerate the deterioration of a pavement. Bennett and Greenwood (2004) revealed that an increase in roughness on a pavement can increase the road user's costs. Moreover, according to Sjögren (2003), an increase in roughness can be considered as a cause for accidents.

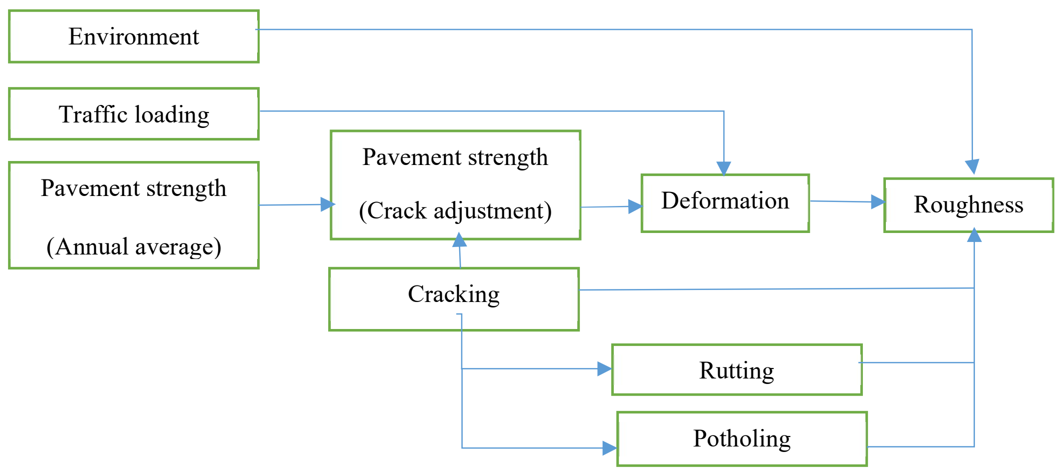

Figure 2.4 The modelling consideration or relation of pavement distress variables to roughness component, source: HDM-4 Manual Volume Four (Odoki & Kerali, 2006)

The HDM-4 version 2 incremental change roughness model for flexible pavements is similar to the HDM-III model used by Bennett and Paterson (2000) (Odoki and Kerali, 2006), but it has some modification in the roughness progression model. The description of the roughness model in HDM-III and its improvement in HDM-4 from Manual Four (Odoki and Kerali, 2006) is summarised in Appendix D. In addition to this, distress factors that are components of roughness are demonstrated in Figure 2.4.

2.3.5. Summary

This section discussed the approaches and consideration of different PMS models and the practice of LCCA. As part of the PM tools, LCCA programmes are used to estimate the costs of road projects and a list of tools was identified from the literatures. Life-cycle costs include costs of construction, maintenance, and road user, which include vehicle operation, accidents, environmental and delay costs. However, the models/tools differ in how they attempt to analyse the life-cycle cost. Therefore, each tool was evaluated based on data requirements and adaptability; usage of the deterioration models and the method used to calculate costs; consideration of environmental/climate impacts on road deterioration; and their suitability for the analysis of different road pavement surfacing types.

Based on the analysis only three tools, MEPDG, HDM-4 and IPSS were able to calculate the climate effect. Thus, MEPDG is identified as a good tool for considering climate change effects for pavement performance analysis, and its results can be expressed in terms of pavement distress factors. However, the section showed that it lacks cost calculations. Although the IPSS tool can consider whole-life costs, its approaches do not include pavement performance analysis. The HDM-4 however, satisfies both conditions but has limitations in considering extreme climate conditions and probabilistic risk analysis approaches. By taking into account model adjustment and additional analysis requirements for the climate change analysis, the HDM-4 PM tool was selected for this study.

Further to this, the section discusses the World Bank HDM-4's multifunctionality and wider acceptance in different research studies. Moreover, a description of the HDM-4 modelling approach, input data requirement calibration, and economic analysis was discussed.

2.4. Climate Change

2.4.1. Cause for Climate Change

Climate change is the change in the average/mean of long-term weather conditions that continues for decades or longer and covers all parts of the earth. The possible causes of the change can be natural or man-made (IPCC, 2007). However, the type and extent of its effect on human-life and the environment varies from place to place. For instance, there may be drought in one part of the world, while flooding occurs in another.

Climate change related reports (IPCC, 2014) have explained that the major climate changes depend on the proportion of the greenhouse gases (GHGs) and their accumulation in the air. Greenhouse gases, plants on the ground, the energy of the sun and atomisers imbalance the power of the climate system (IPCC Working Group III, 2000). Various daily activities, whether natural or man-made, can be the source for GHGs, which include carbon dioxide (CO_2), methane (CH4) and nitrous oxide (N_2O). The IPCC (2007) revealed that the universal intensifications in GHGs are mostly due to fossil fuel use, together with changes in the earth's ground surface use. The report also indicated that the CH_4 accumulation in the air is linked with farming and fossil fuel use, while the rise in the amount of N_2O is related to agronomy.

2.4.2. Reports on future climate

For decades, in order to try to predict future climate changes, different models and assumptions used by various scholars throughout the world were utilised as an input for climate projection models. Internationally, there is a committed group which has formed for gathering and examining such research reports, and this group has detected uncertainties in the climate factors/parameters. The climate factors or parameters include temperature, precipitation, wind. Therefore, for quantifying forthcoming climate change the group provides four climate emission scenarios (IPCC, 2014). These emission scenarios are A1, A2, B1 and B2 and are presented in the Special Report on Emissions Scenarios (SRES) which is summarised in Table 2.8. The SRES utilised different IPCC reports to estimate the upcoming climate change in relation to population growth, economy, technical and demographic conditions. Figure 2.5 shows the possible future climate condition scenarios predicted by the IPCC (2014).

Table 2.8 Climate emission scenarios (Source: (IPCC, 2014))

Climate emission scenario	*Assumption*
A1	This designates the future as being characterised by very quick economic growth, low population growth, and the rapid introduction of innovative and more efficient technologies. It assumes the world population will peak around the 2050s. There are three sub-scenarios under A1 based on energy utilisation, namely A1FI (Fossil fuel), A1T (Non-fossil new energy), and A1B (Balanced century).
A2	It assumes the future as a very heterogeneous world with high population growth. Therefore, the rate of Green House Gas (GHG) emissions was greater when compared with the highest emission scenario of A1 (A1FI). The A2 is lower than that of A1FI until 2020, and

	after 2090, the GHG emissions of the A2 scenario begin to exceed those of the highest A1 scenarios.
B1	Here the future population growth is considered to be lower as compared to A1 and A2 scenarios. It assumes the world population will peak around the 2050s and a decrease in the GHG emissions after 2040.
B2	This assumes the future population growth rate to be intermediate (lower than A2) and population growth lower than A1 and A2 scenarios.

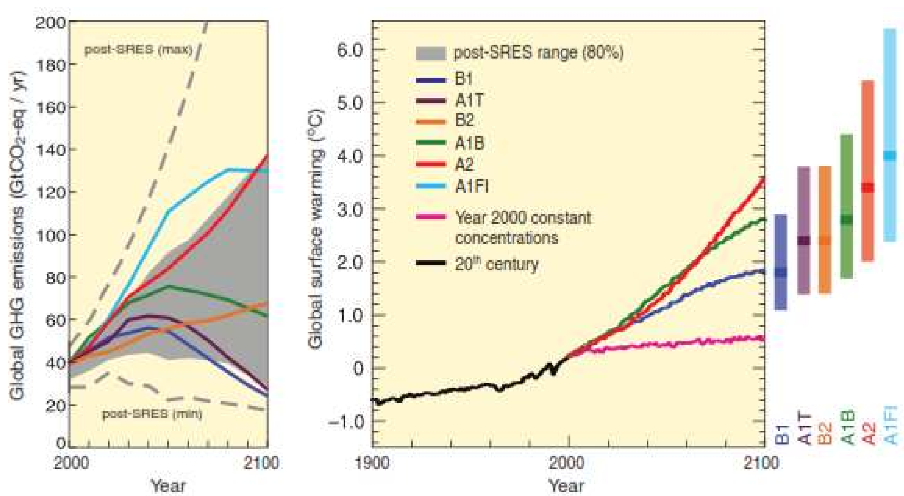

Figure 2.5 Scenarios for emission from 2000 to 2100 (Source: (IPCC, 2014))

2.4.2.1. Sources of Climate Projected Data

Deferent sources of climate data are used for various purposes and some of the research studies take the climate data from agencies where it is directly collected and then they produce their prediction. This type of prediction uses projection models and developed programmes by well-known organisations like the IPCC. Otherwise, researchers use projected data from the literature (such as the World Bank Knowledge Portal, United Nations Development Programme (UNDP) climate change country profile) when there is a limitation in achieving the first approach. For instance,

Appendix I summarises the forthcoming climate prediction of Ethiopia from the United Nations Development Programme (UNDP) climate change country profile (McSweeney, 2010). Although there are climate projections provided by the World Bank Knowledge Portal and the Ethiopian National Metrological Agency, Arnold et al. (2018) recommended the UNDP climate change country profile. In the country profile, the changes in climate are presented in the form of an area-average time, series charts and texts. The charts and texts show the observed climate combined with model-simulated (15-model ensemble) recent and future climates under three SRES emissions' scenarios (A2, A1B, and B1).

In the profile, all projections indicate considerable increases in the frequency of hot days and decreases in the frequency of cold days and nights. A hot day or hot night is classified when the temperature is exceeded by 10% of the days or nights' temperature in the current climate. While a cold day or cold night are those days and nights when the temperature is lower by 10% of the days or nights' temperature in the current climate.

It is also noticeable that the projected changes from different models vary with a range of up to 2.1˚C under a single emissions' scenario. Predictions from different models in the ensemble are approximately consistent in representing rises in annual precipitation in Ethiopia. The report explains that precipitation from October to December in the southern part of the country are responsible for the changes.

2.4.3. Design manuals and climate policy

2.4.3.1. Climate Change Consideration in Pavement Design Manuals

When pavements are designed different variables are taken into consideration. Climate is one important pavement design variable, with its commonly used components such as temperature and precipitation considered in any pavement surfacing designs. The trend of using climate-related inputs for pavement design and cost comparison is mostly limited to historical climate data (Qiao, et al., 2015). This also holds true for the area of study, as the ERA design manual considers historical climate data for design and pavement cost comparisons (ERA, 2013b).

The first design manual which was published in 2002 by ERA was updated in 2013. However, future climate changes were not included in its pavement designs. Only the 2013 version of the Drainage Manual (ERA, 2013d) considered future climate change in order to design drainage structures that could withstand the upcoming flow. Table 2.1 and Table 3.1 in the ERA manual (ERA, 2013d) provide drainage factors, and suggests using an additional design flow allowance of 20% when considering future climate changes. However, the study conducted by the World Bank (2018) reported that this factor was not used often for drainage structure designs. The study was supplemented with a survey on the existing designs and the results revealed that 16.7% of the reviewed designs were reported as using the proposed climate factor of 20%.

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2.4.3.2. *Climate and Environmental Policy*

Since 1997, Ethiopia has approved and used their Environmental Policy document (Environmental Policy document, 1997) which presents the principles that support environmental development. Policies for Ethiopia Environmental Impact Assessment (EIA) were also developed in such a way that they could address wide sectors such as agriculture and transport. The Environmental Protection Authority (EIA) policies (Environmental Protection Authority, 2011) highlight the detection of environmental problems in advance of conducting different parts of project activities. These activities include project planning, public participation, mitigation and environmental management, and capacity building at all administration levels. Considering the major problems frequently facing the country, following experience, most environment programmes focus more towards agricultural sectors. This helps by minimising disaster risk and with capacity building in farming activities, which involves about 80% of the population according to the Ethiopian Central Statistical Agency (2011). In other sectors such as road and transport, Arnold et al. (2018) reported observed gaps in relation to adaptation works to improve environment susceptibilities. Moreover, this study revealed that there is no climate related polices for roads.

2.4.4. Review on climate impact studies

2.4.4.1. *Review on Climate-related Studies in Ethiopia*

To the knowledge of the author, there have been three climate impact and road-related studies conducted by the ERA which can be summarised as follows.

A case study entitled "Make transport climate resilient" for Ethiopia was funded by the World Bank as part of the sub-Saharan initiatives (World Bank, 2010). The study focused on the effect of climate change on transport with methodology comprising the following steps:

- Identification of climate change scenarios for the year 2050, highlighting factors of specific significance for road transport.
- Estimation of the impacts of climate change on road assets and road transport services using existing data for the road infrastructure and climate impact risk assessments.
- Establishment and initial costing adjustment and identification of modification requirements for road related activities.

The study gained the impression that future pavements will be impacted more due to changes in climate, specifically from frequency of precipitation rather than rises in temperature. The approach for the estimation of climate impact considers different road construction stages from site clearing to drainage structure provision. The report identifies heavy flooding conditions and their returning periods for three climate scenarios (A2, A1B and B1) in 2050. The result of the analysis indicates that the cost of construction for new climate resilient roads will increase by one fifth as compared to the cost in 2009, due to extreme climate change. Moreover, if measures are not taken, the costs for road users due to climate-related hazards are expected to increase and may double by 2050.

This estimation suggests that roads in the future will be more expensive. However, the analysis is subject to uncertainties in future annual average daily traffic (AADT), change in risk, and the correlation of risks. Moreover, the analysis is limited and assumes gravel and AC pavements will be constructed in the future. Further to this, the report does not show the climate change effect during the periods when extreme climate conditions were not occurring.

In 2018, for the second time, the World Bank funded a study entitled "Increasing Climate Resiliency of the Ethiopian Road Network". The study focused on the susceptibility of already constructed roads towards future climate effects, and its approach encompasses climate data analysis; selecting suitable approaches for estimation of natural threats, assuming maintenance strategies and preparation of climate susceptibility valuation guidelines. In addition to this, the study was intended to prepare terms of reference for large-level climate susceptibility analysis. The analysis includes identification of the road sections/networks, schedule for activities in reaction to crisis, and preparation of GIS-based climate hazard maps and analysis software.

The study considered ten road segments from different locations that were identified as environmentally problematic areas (e.g. due to flooding and landslides). It looked at the effect of temperature, flooding of culverts and bridges, and landslides on those road sections using the 22 GCM-RCP climate projections. The effect of climate was analysed based on the yearly 7-day maximum historical temperature to fix the criteria for the road binder design. Seven binder categories from 45 ^{o}C to 82 ^{o}C with 6 ^{o}C increments were identified. The concentration of culverts and severe 50-year and 100-year flood events that cause catastrophic damage to bridges were considered for flooding analysis. For landslides, important risk factors within a 50-m buffer zone on the left and right sides of the road sections were considered.

The results indicate that using different input climate projections leads to varied impacts of climate change. According to the World Bank (2018), responsive costs due to temperature on average vary (from \$0 to \$15 million) for the road sections from 2018 to 2050; whereas the relatively highest reactive costs were obtained (\$28 million) in some road sections for the 10th and 90th percentile climate impacts. These results were related to binder ageing, seals rutting, bleeding and flushing due to the temperature rise. Moreover, the findings of the study reported that for 30% of the considered road sections, proactive measures' costs exceeded the reactive costs. For flooding, the highest reactive median total cost (\$25 million) was obtained for culverts on three road sections; while proactive measures' costs were higher than this value in 40% of the road sections. The study indicates that annually, roads which are found in landslide areas will encounter landslides for one day and even up to five days or more for low and moderate risk categories.

The limitation of this study is that it considers only AC pavements on relatively high traffic routes which are located in environmentally hazardous areas. Therefore, other pavement types and AC with different traffic levels and environmental conditions were not investigated. Pavement distress features such as cracks, potholes, and roughness were also not included in the analysis, the cost estimation was done based on activity costs. The activities involve earthwork, subgrade stabilisation, subbase, road base and the gravel-wearing course, bituminous surfacing and road bases, structures and ancillary works. Moreover, the method of the analysis did not show changes in pavement performance and its related costs due to the change in climate.

The third study involved climate risks and acclimatisation for existing and new low-volume rural road infrastructure (Arnold, et al., 2018). The study was funded by UKAid through the Africa Community Access Partnership (AfCAP). It focused on developing country specific guidance for climate resilient low-volume (less than 500 AADT) rural roads.

The study started by developing a guidebook, which was used as a procedure to investigate climate adaptation in low-volume roads and socio-economic related activities. It was focused on the subject of suitable and financially viable approaches. The analysis considered susceptibility and threat valuations, ranking of acclimatisation intrusions and optimisation of resource strength in the context of earth and gravel roads. According to the findings of the study, by 2030 moderate to high-level hazards will be expected on roads in locations with wildfires, flooding and rainfall motivated landslides. It also indicated that due to the long service of the existing bridges (64% in use for more than 30 years), new redesigns that consider climate change are required immediately. In addition to this, the study recommended a review of the current low-volume design manuals to incorporate climate change effects during the design stage. Moreover, the study involved systematised climate hazard information, and activities to develop a policy that precisely states climate change adaptation in ERA activities. However, the study was limited to unpaved rural roads and rural access infrastructures only.

2.4.4.2. *Other Pavement-related Climate Impact Studies*

One of the most detailed studies on the assessment of the effects of climate change impacts and its LCCA was the study conducted by Qiao et al. (2015). It focuses on the effect of climate on performance, maintenance and LCC of flexible pavement. The study involves six road sections from different climate zones in the USA and considered 40 years of pavement life span in the analysis. The researchers used IPCC's MAGICC/SCENGEN programme to forecast climate change, and considered the uncertainties of the predicted climate SRES A1, A1F1, A1B and B1(Table 2.6). The analysis was conducted for high, medium and low emission scenarios for the years 2050 and 2100.

The researchers also considered a sensitivity analysis to deal with uncertainties and estimate the significance of different climate factors. The climate factors used were temperature, precipitation, sea level, wind speed, solar radiation and seasonal temperature. According to Qiao et al. (2015), temperature, precipitation and sea level have significant effects on the pavement distress factors compared to the others.

Using these climate factors and historical and predicted climate data, the performance of the pavement was estimated using the Mechanistic Empirical Pavement Design Guide (MEPDG). After sensitivity analysis, Qiao et al. (2015) found longitudinal cracking, alligator cracking and rutting were more affected by the change in climate than the roughness (Table 2.4). However, the study did not consider the effect of daily, seasonal and annual temperature variation in the prediction of pavement performance. Moreover, during the analysis the increase in the average temperature was considered during an extremely hot and unusual temperature period.

Unlike Qiao et al. (2015), a study made by Chai et al. (2014) showed that climate change represented by the Thornthwaite Moisture Index (TMI) had a significant impact on the roughness for flexible pavements in Australia. The analysis was made using the HDM-III deterioration model by relating the environmental factor (k_{ge}) and the TMI. The disadvantage of this approach is the HDM-III k_{ge} was replaced by the environmental m and environmental calibration factor/environmental age factor (K_{gm}) in HDM-4. Thus, the approach cannot directly use the HDM-4 software for analysis purposes. Similarly, Shao et al. (2017) used the TMI to investigate the impacts of projected climate change on the performance of flexible pavements in Australia. The analysis considers a 100-year climate projection and studies the relationship between the TMI and the average flexible pavement deterioration rates.

The disadvantage of this approach is that it considers only one climate factor, the TMI and doesn't examine the changes in climate zones when a large variation of results occurs in the climate projection. However, the advantage of these two studies is to confirm that HDM-4 models can consider climate change in performance analysis. Further to this, studies made by Chai et al. (2014) found that due to the change in climate there will be a 30% increase in maintenance cost. While Qiao (2015) revealed that climate change may not have an impact on maintenance costs and the LCC, if LCCA maintenance optimisation is applied.

Another study by Padmini et al. (2017) investigated the impacts of climate change on pavement structural performance in the USA. The researchers considered climate predictions from multiple models and different climate regions. Separate analysis for future temperature, precipitation, and both temperature and precipitation together were considered for selected rigid and flexible pavement performance analysis using AASHTOWare Pavement ME software. The 20-year average temperature analysis compares the performance of pavements in terms of distress variables obtained from the projected climate to that of the historical (baseline) climate.

Padmini et al. (2017) concluded that regardless of pavement location and climate forecast models, the future climate impact will have a considerable effect on pavement distress parameters. This implies that pavements will be facing greater deterioration and initial failure due to changes in climate. In addition to this, the results reported indicate that for AC pavements rutting rather than fatigue cracks will be highly affected by temperature change; while lesser transverse cracking and higher joint faulting will be induced by climate change on rigid pavements. However, as this study was limited only to the climate effect on pavement distress factors, it does not show the impacts of climate in terms of cost. Moreover, it lacks the examination of climate parameters, except projected temperature and precipitation, as compared to the findings of Qiao et al. (2015) above.

Like Padmini et al. (2017), Meagher et al. (2012) focused on the preparation and use of climate model data sets as input to climate impact analysis. However, Meagher et al. (2012) considered only the projected temperature change to estimate pavement distress parameters (rutting and cracking) for New England's flexible roads. On the other hand, Mndawe et al. (2015) used projected temperature and precipitation data to consider the protracted moisture content in the subgrade soil. The result of the analysis indicated that the projected precipitation causes a negligeable effect on the subgrade soil for roads found in South Africa.

Bizjak et al. (2013) indicated that flexible pavements will exhibit difficulties due to temperature and precipitation rise when looking at a hundred years of projected climate data. The future climate change aspects that were studied were an increase in temperature, rise in precipitation intensity in most areas and a reduction in freeze–thaw cycling on the European road network. Moreover, the MEPDG analysis result showed that surface treatments and unpaved roads will not be suitable in areas where there will be a shorter frozen period. The research, however, lacks an indication of the impact of climate in terms of cost.

To finalise this section, prevailing research works have indicated that climate change will impact the performance, maintenance and LCC of pavement surfacing. However, there are some limitations in the existing literature and Section 2.5 summarises these gaps.

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2.5. Current Gaps on Effects of Climate Change on Pavements

The objective of this literature review was to assess the current knowledge and identify any gaps for future work. Therefore, the review indicated that considerable research work has been conducted in the area of:

I. Identifying future climate changes and utilisation of different climate projection models.
II. Quantifying climate change effects on pavement distress parameters, maintenance alternatives, and costs.
III. Different approaches for climate change risk assessment quantification and adaptations.
IV. Identifying maintenance alternative solutions to future climate changes.

However, the following areas have received only limited attention:

a. There is a paucity of life-cycle analyses of pavement performance which consider road use costs as well as road agency costs. Most studies focus on the latter and estimation of risk costs for extreme climate conditions for a specific year.
b. There is lack of life-cycle cost analyses of road pavement performance under different conditions (traffic and environment) found in Ethiopia.
c. There are no life-cycle cost analysis studies focusing on road surfacing materials and climate change.

d. There are no studies which take into account the potential impact of future climate change (excluding extreme conditions of climate) on pavement performance and its associated LCCA in Ethiopia.

e. The climate pavement related analysis gives different results due to different approaches, uses of climate models, climate projections, pavement parameter consideration and use of analysis tools. Hence, it indicates that this area needs further investigation/study in the future.

2.6. Summary

This chapter reviewed different research works in the area of climate change impact and pavements. The prevailing evidence showed that climate change will impact the performance, maintenance and LCCA of the pavement surfacing. However, the literature indicates that there are variations in consideration of climate projection models, climate parameters, and the approach used to estimate the impact. This has resulted in different analysis outcomes. For instance, for the same climate projection model, the risk analysis of pavement under climate change will not be the same as with extreme climate change conditions. In addition to this, very few studies (Qiao et al., 2015), and (Chai et al., 2014) carried out an LCC due to climate change impact. However, their approaches, uses of climate models and climate projections and analysis tools differ from one another. Therefore, there is a need to further study the area to address the climate change effect in an LCCA.

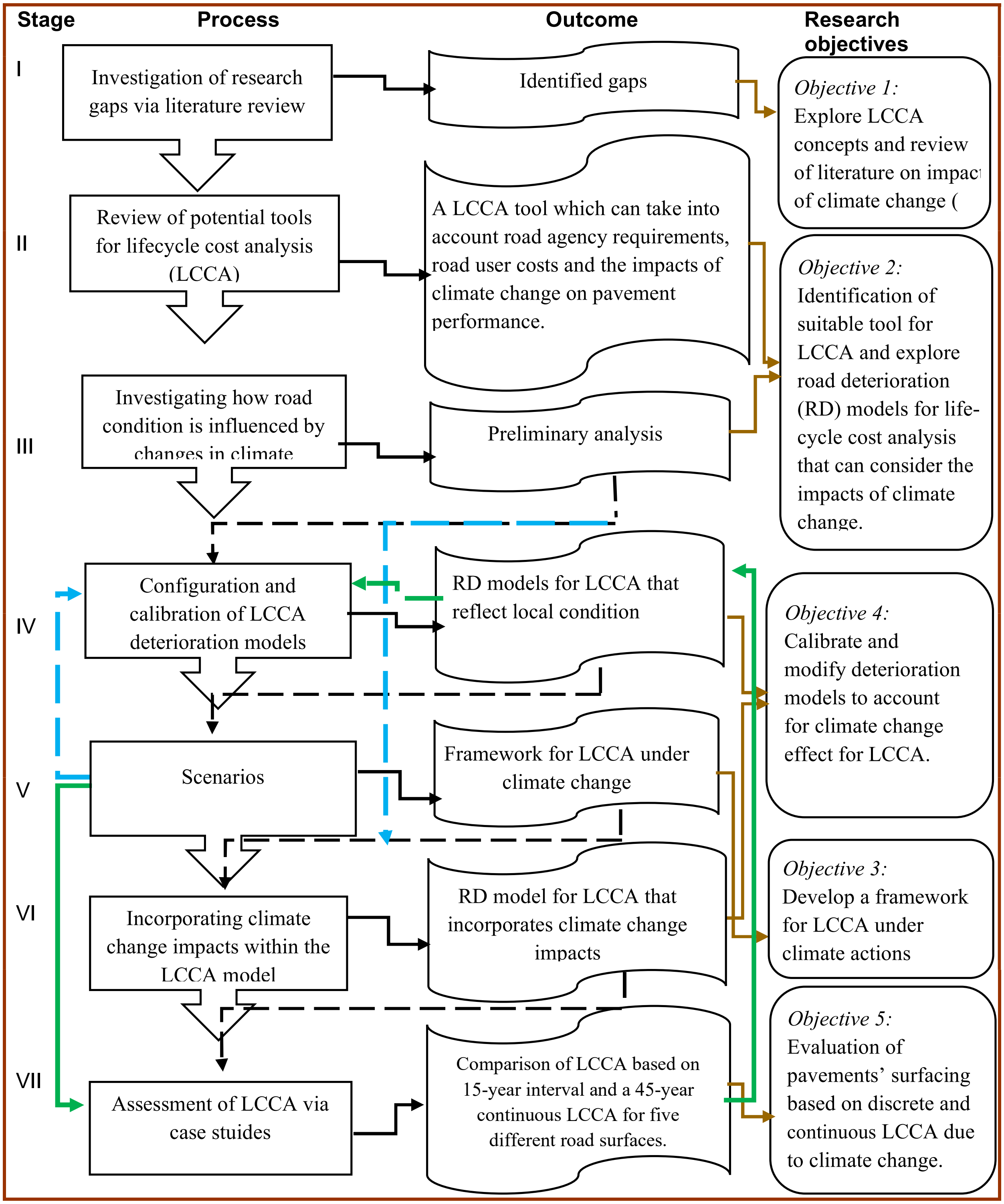
The next chapter, therefore, explores the methodology used to estimate the LCCA of the climate change impacts on different pavement types.

CHAPTER THREE - METHODOLOGY

3.1. Introduction

The aim of this study is to develop an LCCA approach that can be used to appraise the suitability of road pavement surfacing types for use in a variety of environments, taking into account climate change. The developed approach is to be trialled using data from Ethiopia for five different road surfaces, i.e. Asphalt Concrete (AC), double surface treatment (DBST), Otta seal, jointed plain/unreinforced concrete pavement (JPCP), and jointed reinforced concrete pavement (JRCP), carrying three different levels of traffic (high, medium, and low) and five climate zones, i.e. arid, semi-arid, sub moist, moist and sub-humid (section 1.2). The approach requires the selection of a suitable LCCA methodology or tool which can predict road pavement performance over a road's life cycle. Such a tool should enable the consideration of the implications on the LCC and benefits in economic terms, of changes in performance due to climate change.

Five objectives were conceived (section 1.4) to meet the aim of the research. This chapter describes the methodology developed in the research to achieve the objectives and consists of seven stages (see Figure 3.1):



Note: since the research deals with predicted climate conditions, model validation for future condition was not possible.

Figure 3.1 Overarching research methodology

- Stage I reviews previous research on the impact of climate change on road pavement performance and the limitations of the existing LCCA. It was found that different LCCA approaches/model development consideration leads to different outcomes for the same inputs. This is due to underlying assumptions and approaches in considering different parameters/interconnected relationships varying within the modules.
- Stage II identifies candidate LCCA tools and develops a set of criteria to select the most appropriate for the task at hand.
- Stage III provides a preliminary analysis to identify climate change factors for the deterioration model of the selected LCCA tool, which has the potential to account for the effect of climate change.
- Stage IV identifies the methods that can be used to configure and calibrate the road deterioration models of the selected tool to local conditions. These are applied to the environmental conditions found in Ethiopia for the five road surfacing types. The work involves a comparison of the historical deterioration of actual road sections in Ethiopia with that predicted for these sections by the tool. In relation to this, since the research deals with predicted climate conditions, model validation for future condition was not possible.
- Stage V looks at the possible scenarios involved in climate change to develop the LCCA framework of the research.
- Stage VI shows how projected climate change effects can be modelled for the calibrated deterioration models (calibrated in Stage IV).

- Stage VII (and final) stage carries out LCCA to evaluate the five different road surfacing types prevalent in Ethiopia, to identify the most appropriate surfacing types, in economic terms, for the range of traffic and environmental conditions.

The aforementioned stages are described in more detail in the following subsections.

It should be noted that the description of the methodology presented in Figure 3.1 is an overview of the process. The method required for this study was bespoke and was developed by the author; it drew on the literature, the HDM-4 LCCA manual and established an additional computational stage for climate change consideration. The predictions allow for the consideration of the five surfacing types in the five climatic environments under three traffic loads (low, medium and high). The development of this approach was not straightforward, it required iterative steps and feedback loops with reflection and reassessment undertaken between stages. On occasions, a backward step was required in order to develop the method, to ensure it functioned as desired.

3.2. Stage I: Literature Review

Life-cycle cost methods and the implications of climate change on road pavement performance were reviewed in Chapter Two. The review highlighted that there is a need to develop an LCCA methodology that considers the impacts of future climate change on road pavement surfacing performance. The methodology should enable the rational comparison and selection of road pavement surfacing types. Worldwide there is a paucity of such approaches and for Ethiopia no such approach exists.

3.3. Stage II: Review of Potential Tools for Life-cycle Cost Analysis

This study was not carried out to develop a new LCCA tool, therefore, the decision was taken to use an existing package. A review was undertaken on an existing tool for LCCA, and their relative capabilities are summarised in Table 3.1 (please note that descriptions of the tools are provided in section 2.3.4 and Appendix B should the reader wish for more information on these). The comparison was based on data requirements of the tools; deterioration model type and their requirements; the approaches to LCCA; capability of the tool for the analysis of different pavement surface types; and the potential of the tool to take into account possible effects of climate change on road deterioration.

By comparing the capabilities and requirements of the tools with the research objectives, the following criteria were developed to select the tool:

1. Data requirements for the LCCA software may include the pavement condition, the cost of maintenance, traffic data, maintenance type, and others. However, depending on the specific target of the tool, all or some of the data may be considered.

2. Deterioration model characteristics have an impact on the model usage since the applicability of models by adjusting coefficients would cover wide ranges of application compared to that of models developed for specific conditions.
3. Approaches for cost in LCCA calculation also affect the LCCA, since all cost components of an LCCA (RAC, RUC, and environment) may or may not be represented in one tool due to different reasons.
4. Suitability for pavement types is also an important factor; since the use of an LCCA is to show the long-term cost-effectiveness of the pavement surfacing, thus, comparisons of a wide range of pavement types are necessary.
5. Applicability for practical use is important for the tool to be useful for climate change related works.

Comparing the above criteria and the summary information presented in Table 3.1, as well as the descriptions of some of the tools given in the literature review (section 2.3.4.2), it was decided that the World Bank's standard for road investment appraisal, HDM-4, was the most appropriate tool for the task in hand. The capabilities of HDM-4 are described more fully in section 2.3.4.3, but the main reasons it was chosen for the research are its capability to predict pavement performance and provide an LCCA for different pavement types. It appears to be capable of taking into account the impact of climate change over a road pavement's life cycle. It takes into account RUCs using a robust process. It is used to optimise budgets for strategic maintenance, and it is widely used, accepted and readily available worldwide.

However, it should be noted that HDM-4 has some disadvantages, including the deterministic nature of the models (probability assessments cannot be directly analysed), the complex process of model calibration, and the intensive data requirements.

Table 3.1 Summary of documented LCCA tools

Name of the tool	Data requirement				Deterioration model characteristics						Approaches for cost for LCCA calculation									Potential environmental and climate change and for LCCA calculation						Suitability for pavement types and accessibility			
											RAC		RUC							Evaluate									
	Basic pavement related data	Basic cost related data	Work item quantity and unit cost	Hourly traffic distribution and the work-zone duration	Mechanistic	Empirical	Structured/Mechanistic empirical	Deterministic	Probabilistic	Flexible to consider climate change effect	Function of pavement performance	Using other estimation	Pavement performance	Work zone closure duration	Accident	Alternatives can be analysed at a time	LCCA using deterministic	LCCA using probabilistic	Considered design analysis year	Different alternative	Project level	Network level	Performance analysis including extreme conditions	Performance analysis without extreme condition	Vehicle emissions	Flexible	Rigid	Unpaved	Accessibility
Asphalt Pavement Alliance (APA) LCCA		√		√								√		√		4	√	√	N F		√					√			
D-TIMS**	√	√									√										√	√				√			
Evaluation Model (IHEEM)		√														1	√	√	E Y		√					√			
Highway Development and	√	√		√			√	√		√	√		√	√	√	M	√		√	√	√	√		√	√	√	√		√

Management (HDM-4)																													
Highway Economic Require-Ments' System (HERS)	√	√		√				√			√		√	√			√					√				√			
Indiana Highway Economic	√	√		√							√		√	√	√	1		√	√		√				√	√			
Infrastructure Planning Support System (IPSS)			√									√									√		√	√		√			
Life-cycle Cost Analysis Package (LCCOST)																													
MEPDG/S	√			√			√	√	√	√									√	√	√		√	√	√	√	√		
OPTIPAV	√	√	√			√							√				√	EY				√			√				
Project Analysis System International (PASI)	√	√		√						√			√	√	√						√				√	√			
Life-cycle Cost Analysis Primer																													
REALCOST				√				√						√	√		√	√			√	√			√	√			
Roads Economic Decision Model (RED)	√			√				√						√ *	√						√							√	√

Note: NF - Not Flexible, EY - Every year, M – many * Traffic growth only, and ** doesn't predict performance

3.4. Stage III: Preliminary Analysis

The HDM-4 is able to consider the performance of both flexible and concrete pavements represented by eight and six general types of modelled pavement distresses, respectively (section 2.3.4.4). These general model forms can be calibrated to represent the behaviour of other, non-standard (marginal materials), pavements. For flexible pavements, the factors which HDM-4 uses to model deterioration and the relative importance of these in determining deterioration, are documented in Volume Five of the HDM-4 series of manuals (Bennett & Paterson, 2000).

The manual shows that the roughness age environment, cracking initiation, and crack propagation are the three most critical/sensitive deterioration model factors (termed herein as critical distress factors). However, from these distress factors, the HDM-4 LCCA models predominantly use road roughness, expressed in terms of the international roughness index (IRI). It represents the performance of the pavement (Odoki, 2013; Archondo & Faiz, 1994). Since roughness has the greatest influence amongst distress types it is used in the calculation of road maintenance and road user costs (Bennett & Greenwood, 2004). Consequently, as this research is concerned with the development/adjustment of an LCCA model that can be used to assess climate change impacts on life-cycle costs of pavement, it was decided to focus on determining how the impacts of climate change could be modelled in HDM-4 through changes to HDM-4's roughness models.

Climate variables, such as: temperature, rainfall, relative humidity/water vapour pressure, solar radiation/sunshine hours, wind speed and direction, and thermal amplitude, are used to categorise a geographical region into a climate zone. Although these climate parameters are considered in HDM-4, the impact of climate on pavement deterioration is reflected through four major parameters, namely temperature, precipitation, the TMI (Thornthwaite Moisture Index) (see section 2.4.4.2), and susceptibility to freeze/thaw (Shao, et al., 2017; Odoki & Kerali, 2006). The values of these parameters can be modified by the user for a particular simulation and thus the impact of climate on deterioration modified accordingly.

Temperature refers to the average annual temperature of the region where the road is located. It is changed directly by the user and indirectly by changing the climate zone in which the road is situated. A climate zone is defined in terms of the mean annual temperature, average temperature ranges, number of days greater than 32ºC, mean monthly precipitation, duration of dry season, moisture index and freeze index (Odoki & Kerali, 2006). The software (HDM-4) does not allow the climate zone to be changed over the period of the analysis.

Each climate zone has an associated environmental factor (m), which is user defined (Morosiuk, et al., 2004). The HDM-4 Manual Five suggests possible ranges of values for different climate zones (Bennett & Paterson, 2000). The recommended range of m values vary for different climate categories from 0.005 in a tropical arid zone to 0.060 in a temperate extended freeze humid zone (Morosiuk, et al., 2004). The m value is used by HDM-4 when calculating rates of pavement deterioration as described below.

In HDM-4's roughness progression model for flexible pavements, given in Equation 3.1 and the components summarised in Table 3.2, roughness progression is a function of a number of factors including the age of the pavement, accumulated traffic, the existing pavement strength, the amounts of cracking, rutting and potholes and a term related to the impact of environment has on roughness ($\mathbf{m}\boldsymbol{K_{gm}}\,\boldsymbol{RI_a}$)(termed herein as the roughness age environmental factor). Of these factors, pavement strength and the roughness age environmental effect have user adjustable calibration coefficients related to the environment (i.e. K_{gm} and K_{ge}); K_{gm} and K_{ge} are both roughness age environment calibration coefficients for Level II and I respectively (Appendix D). The research used these calibration factors together with the climate input parameters to consider the local simulation as well as to adjust the model for future climate change conditions. The process of how this was achieved is presented in section 3.5.3.1 and section 3.5.3.2.

$$\Delta \mathrm{RI} = \boldsymbol{K_{gs} a_o} \,\mathbf{exp}\big(\boldsymbol{mK_{gm}\, AGE3}\big)(\mathbf{1} + \boldsymbol{SNPK_b})^{-\mathbf{5}}\, \boldsymbol{YE4} + \boldsymbol{K_{gc} a_o \Delta ACRA} + \boldsymbol{K_{gr} a_o \Delta RDS} + \boldsymbol{K_{gp}\, a_o}\, (\boldsymbol{a_1} - \boldsymbol{FM})\big\lfloor \boldsymbol{NPT_{bu}^{a2}} - \boldsymbol{NPT_{a}^{a2}} \big\rfloor + \mathbf{m}\boldsymbol{K_{gm}\, RI_a} \quad \text{.........Equation 3.1}$$

Table 3.2 The HDM-4 improved distress models for roughness (source: (Bennett & Paterson, 2000)

Roughness model component	HDM-4 Models	Calibration coefficient	Description
a. Structural	$\Delta \mathrm{RI}_s = K_{gs} a_o \exp(m K_{gm}\ AGE3)(1 + SNPK_b)^{-5}$ Where, $\mathrm{SNPK}_b = MAX[(SNP_a - dSNPK), 1.5]$ and $\mathrm{Dsnpk} = \mathrm{K_{snpk}}\ a_o \{\min(a_1, ACX_a)\ HSN$ $MAX\ [MIN(ACX_a - PACX, a_2), 0]\ HSOLD\}$	K_{gs}	The structural component of roughness relates to the deformation in the pavement materials under the shear stresses imposed by traffic loading. And it considers the effect of climate by including the seasonal and drainage effect.
b. **Cracking**	$\Delta \mathrm{RI}_c = K_{gc} a_o \Delta ACRA$	K_{gc}	It is related to the initial time of cracking and considers the quality of the material used for surfacing.
c. **Rutting**	$\Delta \mathrm{RI}_r = K_{gr} a_o \Delta RDS$	K_{gr}	It is a function of standard deviation of rut depth.
d. **Potholing**	$\Delta \mathrm{RI}_p = K_{gp}\ a_o\ (a_1 - FM)\lfloor NPT_{bu}^{a2} - NPT_a^{a2} \rfloor$	K_{gp}	Represents the effect of different sizes and frequencies of potholes.
e. **Environmental age**	$\Delta \mathrm{RI}_e = \mathrm{m} * K_{gm}\ RI_a$	K_{gm}	The roughness component represents the change in roughness due to temperature, moisture fluctuations and foundation movement.

Where:

ΔRI_s = incremental change in roughness due to structural deterioration during the analysis year (IRI m/km)

dSNPK = reduction in the adjusted structural number of the pavement due to cracking

$SNPK_b$ = adjusted structural number of the pavement due to cracking at the end of the analysis year

SNP_a = adjusted structural number of pavements at the start of the analysis year

ACX_a = area of indexed cracking at the start of the analysis year (% of total carriageway area)

PACX = area of previous indexed cracking in the old surfacing (% of total carriageway area): that is, 0.62 (PCRA) + 0.39 (PCRW)

HSNEW = thickness of the most recent surfacing layers (mm)

HSOLD = total thickness of previous underlying surfacing layers (mm)

AGE3 = pavement age since last overlay (rehabilitation), reconstruction or new construction (years)

YE4 = annual number of equivalent standard axles (millions/lane)

ΔRI_c = incremental change in roughness due to cracking the analysis year (IRI m/km)

ΔACRA = incremental change in area of total cracking during the analysis year (% of total carriageway area)

ΔRI_r = incremental change in roughness due to rutting during the analysis year (IRI m/km)

ΔRDS = incremental change in standard deviation of rut depth during the analysis year (mm) (RDS_b – RDS_a)

FM = freedom to manoeuvre

ΔRI_p = incremental change in roughness due to potholing during the analysis year (IRI m/km)

NPT_{bu} = number of potholes per km at the end of the analysis year as seen by the road user

ΔRI_e = incremental change in roughness due to the environment during the analysis year (IRI m/km)

RI_a = roughness of the pavement at the start of the analysis year (IRI m/km)

m = environmental coefficient

RI_b = roughness of the pavement at the end of the analysis year (IRI m/km)

a_o = upper limit of pavement roughness, specified by the user (default = 16IRI m/km)

a1 = default coefficient values for roughness component

K_{gs} = calibration factor for structural component of roughness

K_{ge} = calibration factor for environmental age factor for calibration Level I

K_{gm} = calibration factor for environmental age factor for calibration Level II

K_{snpk} = calibration factor for SNPK

K_{gc} = calibration factor for cracking component of roughness

K_{gr} = calibration factor for rutting component

Unlike its models for flexible pavements, HDM-4's rigid pavements' distress models do not have user adjustable calibration coefficients related to the environment, to consider the climate change conditions.

To provide further insight into how climate change effects might be considered within an HDM-4 analysis, the HDM-4 predicted incremental roughness progression using a range of m values was compared for four arbitrarily selected road sections. These sections are serving a high traffic with AC pavement in ERA road network (Appendix F) and they are in the range of good pavement conditions.

$$K_{ge} = m_{eff}/0.023 \quad \text{............ Equation 3.2}$$

Where:

$$m_{eff} = m\ K_m \quad \text{............ Equation 3.3}$$

With reference to Equations 3.2 and 3.3, changes of climate were considered using six different roughness age environmental factors (K_{ge}), i.e. 0.25, 0.50, 1.00, 2.00, 4.00 and 8.00 as suggested by Odoki and Kerali, (2006); where 1.00 is the default value and represents the condition from dry (K_{ge} = 0.25) to cold (K_{ge} 8.00). The period of analysis was 15 years and during this time it was assumed that only routine/minimum maintenance would occur. The differences in the roughness values shows the change in pavement condition with respect to the change in K_{ge}. A positive change in pavement condition (ΔRI) represents an increase in pavement deterioration; while a negative change show slowing down of the deterioration as compared to the default condition, where K_{ge} = 1.

For each analysis, the sensitivity of a change in road condition with respect to a change in climate (indirectly via K_{ge}) was calculated using Equation 3.4 (Odoki, et al., 2006).

$$\textbf{Sensitivity} = \frac{\left(\frac{\Delta RI}{RI}\right)}{\left(\frac{\Delta Kge}{Kge}\right)} \text{ ....Equation 3.4}$$

where:

RI = pavement roughness value in terms of IRI (m/km)

ΔRI = change in roughness compared to the initial/default condition

ΔK_{ge} = calibration factor for change in the roughness environmental age factor for level I

The results of the analysis, shown in Figure 3.2, indicate that in HDM-4 a change in climate zone (m value) can indeed affect a change in road roughness in terms of IRI. As can be seen from Figure 3-2, in general, the higher the m value (and therefore K_{ge}), i.e. the wetter the climate, the greater the increase in pavement deterioration in terms of average IRI. For example, making the climate wet by increasing K_{ge} by 100% yields an increase from 0.87 to 1.29 % in road deterioration; whereas decreasing K_{ge} (i.e. making the climate drier) by 50% results in a 0.43% decrease.

The changes in deterioration however, are not a linear function of the change in K_{ge}. Rather the rate of change increases with increased K_{ge} and thus, the greatest changes occur in extreme climate conditions. Such changes are not the case for this study. For values where K_{ge} is between 0.50 and 2.00, as would be expected in Ethiopia, small changes in average roughness are apparent in Figure 3.2. Moreover, the change in pavement deterioration depends on the initial roughness values, since the road sections have similar surfacing and different traffic levels (Appendix F). For instance, pavement in good condition (section A-s, with roughness 2.91 IRI m/km) showed relatively less sensitivity to the change in climate expressed by K_{ge}.

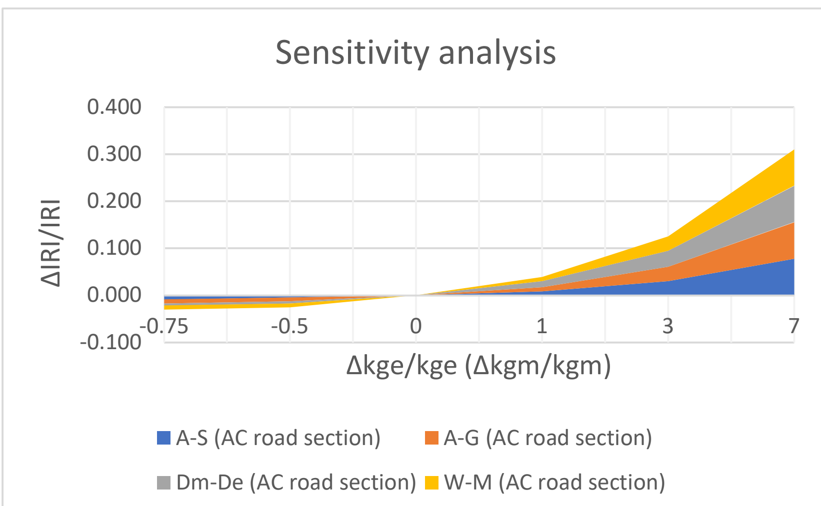


Figure 3.2 The sensitivity of distress factors to changes in K_{ge}

The following sections show how appropriate roughness environmental age factor (K_{ge} and K_{gm}) values were calculated for the current climate zones considered for Ethiopia; how the values were adjusted for pavement type (i.e. calibration); and how the values were adjusted during an LCCA to model a changing climate during the period of analysis.

3.5. Stage IV: HDM-4 Configuration and Calibration

As mentioned in section 2.3.4, HDM-4 consists of various complex models, which have default settings and coefficients that can be configured and calibrated to fit their use to a variety of situations and conditions. The HDM-4 configuration refers to the process of customising settings and standards to reflect the conditions at hand. Then again, calibration is used to increase the accuracy of the predictions/projections of the models. The calibration and configuration processes adopted for this research are described below.

3.5.1. Representative road sections

A representative section is a modelled section of road, which is used to represent all other road sections in a network with similar or homogeneous characteristics. These characteristics are defined by parameters such as surfacing type, road class, pavement condition, strength, and traffic flow (Odoki & Kerali, 2006). Therefore, instead of analysing every single actual road section in a road network, an analysis is only performed on representative sections and the results are scaled up to represent the whole network. In this study, the pavement surfacing, traffic level, road condition in terms of roughness, and climate zone were used to identify the possible road network matrix.

3.5.1.1. Considered Surfacing Types

The matrix of the combinations of representative sections developed for this research is given in Table 3.5 (section 3.6) and the pavement surfaces under consideration are:

1. Asphalt Concrete (AC): - it is classified as flexible pavement surfacing and it is the most widely used in the ERA federal road network. It is made up of materials which have a continuous distribution of aggregate particle sizes. The aggregates are designed to get the maximum particle density after compaction by allowing adequate space for the bitumen (Roads Department, 1999; ERA, 2013a).

2. Double Surface Treatment (DBST): - this is a thin bituminous pavement surfacing type that is constructed by adding additional bituminous and single smaller sized chippings on single surface dressing. This type can be used for surfacing newly constructed roads, depending on the expected traffic level, and is also used for maintenance of existing roads (Roads Department, 1999; ERA, 2013a). In this research however, this type of pavement surfacing was considered as a new construction for low and medium traffic level roads, since the ERA used it as surfacing for this stage of construction.

3. Otta Seal: - is also classified as a thin bituminous surfacing, and its unique character relies on using a relatively wide range of graded aggregate sizes, including marginal materials. Similar to the DBST surfacing, it is considered in this study as a new

construction surfacing, and the ERA research trial section was used to represent it (Roads Department, 1999; ERA, 2013a).

4. Jointed Plane Concrete Pavements (JPCP): - this is classified as rigid pavement and consists of plain slabs made of concrete that are cast in place and the joints are used to divide the slabs into bays. Since it does not have reinforcement, the short dimensions of the bays protect the slabs from cracks due to shrinkage during the concrete curing progression (Odoki & Kerali, 2006; ERA, 2013b).

5. Jointed Reinforced Concrete Pavements (JRCP): - this type of rigid pavement contains reinforcement in cast-in-place concrete slabs, and its areas are divided into bays using joint separation. The bays are relatively longer than JPCP due to the presence of the reinforcement to protect the slabs from cracks. Both concrete types considered in this section were from the ERA trial section (Odoki & Kerali, 2006; ERA, 2013b).

3.5.1.2. Data

The various types of data required for the analysis (Appendix G) were predominantly provided by ERA. Most of the required road condition data were derived from commissioned road condition surveys and were available in consultant reports (DANA, 2018; HITCON Engineering, 2018; Araya & Chali, 2018). For the economic analysis the discount rate data were taken from the National Bank of Ethiopia and are mentioned in section 3.5.1.

Appendix G summarises the sources of the input data used for the strategic HDM-4 analysis.

3.5.2. Configuration

For this study the following parameters were configured to represent the actual standards of roads:

a) **Vehicle fleet:** this input data is vehicle data which concerns the types and categories of vehicles that use the studied road network. The information includes vehicle operating characteristics and costs, passenger and freight time costs, as well as the cost of fuel and lubricants (Stannard, et al., 2006). Input data associated with vehicle operating costs (VOC) and total traffic costs (TTC) for the study area were taken from HITCON (2018) and are presented in Appendix K.

b) **Traffic flow pattern**: the data concerns the various levels of traffic and traffic delays experienced in the network at different hours of the day, days of the week and years (Odoki and Kerali, 2006). For this research the required data was obtained from ERA for the years 2012 to 2016 (ERA, 2017g). The ERA traffic data collection/count bases the seasonal variation of traffic on the assumption that the highest congestion occurs during the harvesting season. Therefore, for the study area the flow pattern on the road network has been estimated by considering the average seasonal data.

c) **Speed flow**: refers to the speed of vehicles travelling along a road section (Bennett and Greenwood, 2004). For this study, the selection of speed flow types was based on the actual capacity of the selected representative road sections as shown in Table 3.3.

Table 3.3 Speed flow patterns (source: HITCON Engineering, 2018)

Speed flow type	Criteria
Single Lane Road	for all single lane roads
Intermediate Road	for all two-lane roads if the carriageway width of the road is less than 5.6m
Two Lane Road	for all two-lane roads if the carriageway width of the road is between 5.6m and 8m
Two Lane Wide	for all two-lane roads if the carriageway width of the road is greater than 8m.
Four Lane Road	adopted for all four lane roads

d) **Traffic growth rates** – these have been inferred from historical records of vehicle–km of traffic in the whole network. The traffic flow data were collected from ERA and the annual percentage increase in the traffic growth was calculated using Equation 6.1 according to Odoki and Kerali (2006). By using more than 5 years traffic data the annual traffic growth rates were calculated leading to the following: 1. Articulated Truck - 5.26 %, 2. Heavy truck 6.52%, 3. Medium truck 5.57%, 4. Light trucks 5.79%, 5. Large bus 3.71%, 6. Small Bus 7.38%, 7. 4WD 4.01% and 8. Car 1.32%.

Furthermore, Araya and Chali (2018) reported a 38% variation in the ADT value for the Otta seal section from traffic count made twice only with about six-month differences. Therefore, the AADT for this research was estimated by taking the average of the two ADT counts multiplied by a 90% seasonal factor of 0.9.

e) **Roadside and non-roadside friction**: for modelling traffic flows and their effects on VOC (section 2.3.1), HDM-4 uses roadside friction (XFRI) and non-motorised transport factors (XNMT) (Bennett and Greenwood, 2004). The XFRI is related to the pavement width and road class; while XNMT is associated with non-motorised transport. For this research, a value of 0.6 XFRI was chosen for the surface treatment, since the noise created by it is more than that of the AC surface. Also 1.0 XNMT for the AC was applied (Kerali, et al., 2006).

f) **Economic costs**: a conversion factor is used within HDM-4 for the RUC calculation (section 2.3.1) to change the financial costs to economic costs and to represent the 'time value of money' (Odoki and Kerali, 2006). To this end, the financial costs of maintenance and improvement work activities were converted to economic costs using a conversion factor discount rate.

g) **Discount rate:** HDM-4 uses a discount rate to calculate various measures of economic performance, such as the NPV, as part of its LCCA. The discount rate is the rough difference between the interest and inflation rates and it indicates the real value of money over time (Peyman, et al., 2016). For the condition of Ethiopia, an official fixed rate is not yet set, hence the chosen rate is based on information provided by the National

Bank of Ethiopia (NBE) and given in Table 3.4. The table shows the saving deposits and lending interest, in per cent per annum from 2015 to 2018. For the purposes of this research, a discount rate of 12.25% was used. However, research carried out by the World Bank in several developing countries has suggested that an 8% discount rate can be suitable (Bannour, et al., 2021).

Table 3.4 Saving deposits and lending interest in per cent per annum (source: (National, Bank of Ethiopia : 2017/18 Annual report, 2018)

Particulars	2015	2016	2017	2018
	June	June	June	June
Minimum saving deposit rate set by NBE	5.00	5.00	5.00	7.00
Lending interest rate				
Minimum	7.50	7.50	7.50	7.00
Maximum	16.25	17.00	17.25	20.00
Average	**11.25**	**12.00**	**12.25**	**13.00**

h) **Unit construction and maintenance costs**: HDM-4 uses unit construction and maintenance costs together with predicted deterioration rates and specified road maintenance standards to determine road agency costs. The unit construction and maintenance costs used in the analysis are presented in section 4.2.1.

i) **Traffic accidents:** this is the data for the number of vehicles' accidents and the associated damage. The HDM-4 estimates the changes in the rates of traffic accident from traffic accident data, to estimate the RUCs (Bennett and Greenwood, 2004). The estimated accident rates are associated with any specified changes to the design of a road section determined using algorithms which consider a number of factors such as widening, pavement type and others (Bennett and Greenwood, 2004). Since the available traffic accident data varies significantly, the country wide average data reported by Debela (2019) was adopted in this study. The data used for the analysis is presented in Appendix J.

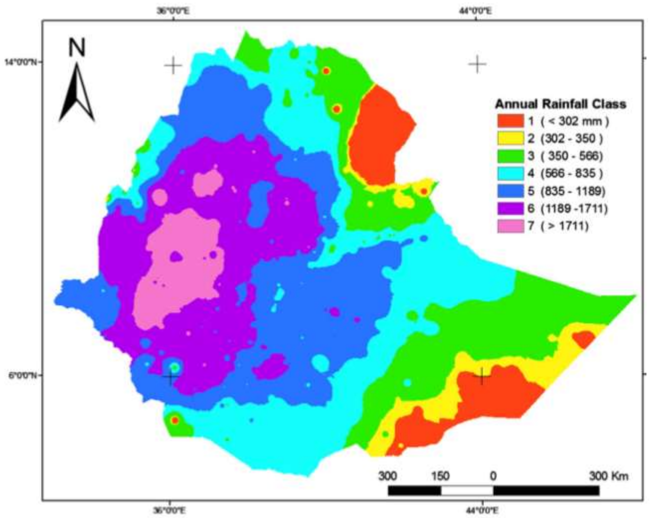
j) **Climate zone:** as mentioned above in section 3.4 a climate zone in HDM-4 refers to a region where similar average climate conditions exist. For this study, climate zoning was determined according to a procedure developed by (Belete, et al. (2013) that is based on elevation; since elevation in Ethiopia has been found to have a direct relationship to temperature, precipitation, and soil moisture.

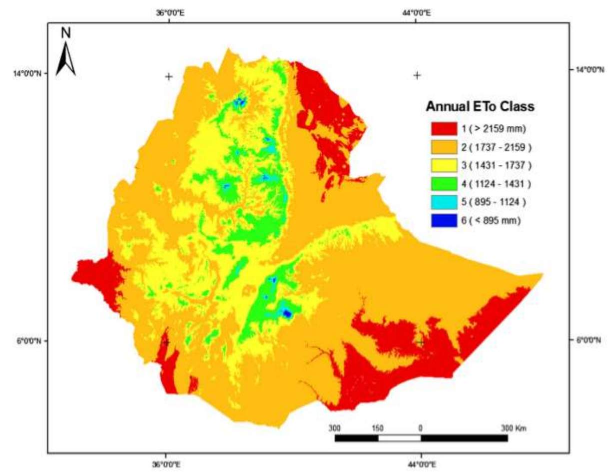
Accordingly, the five climate zones described below consider the area where the large ERA road network exists. Figure 3.3 shows the mean annual rainfall, evapotranspiration (ETo) and Köppen climate classification for Ethiopia and the ERA road network.

1. Arid climate zones – are zones with an annual rainfall less than 302 mm and a temperature greater than 27.5°C.
2. Semi-arid climate zones – are areas with an annual rainfall between 302 mm and 350 mm and a temperature between 27.5°C and 21°C.
3. Sub-moist climate zones – include areas with a range of rainfall varying from 350 mm to 566 mm and a temperature from 21°C to 16°C.
4. Moist climate zones – cover areas with range of rainfall varying from 566 mm to 835 mm and a temperature from 16°C to 11°C.

5. Sub-humid climate zones – cover areas with a range of rainfall varying from 835 mm to 1189 mm and a temperature from 11°C to 7.2°C

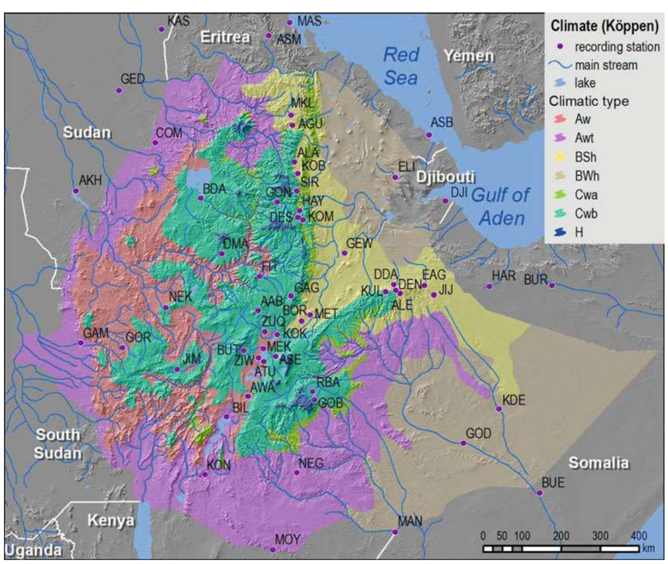
Appendix H compares the parameters defined in HDM-4 for each climate zone with the definitions for Ethiopia given by Belete et al. (2013).





a) Mean annual rainfall

b) Mean annual evapotranspiration (ETo)



c. Map of the Köppen climate classification

Figure 3.3 mean annual rainfall (a); evapotranspiration (ETO) (b); and the Köppen climate classification (c) of Ethiopia, source: (Belete, et al., 2013) and (Massimiliano, et al., 2015)

3.5.3. Calibration

Calibration refers to the process of adjusting the HDM-4 mechanistic-empirical model parameter coefficients to represent the local conditions. The overall calibration process followed the guidance provided in the HDM-4 Manual Five (Bennett and Paterson, 2000). The manual provides detailed procedures for three levels (Level I, II, and III; mentioned in section 2.3.4.3) of calibration for the deterioration models, depending on the perceived reliability of the data used for calibration. The data requirement varies for each level, for instance: for Level I desk data is required; for Level II historical data is required, and for Level III the use of detailed site investigation data is required.

In this study, the level of calibration achieved was, according to the availability of data (Appendix K). For some representative sections, historical data were available and these were therefore calibrated to Level II; whilst for other sections, it was only possible to achieve Level I. Using these calibration factors wouldn't affect the pavement evaluation process or results, since the analysis considers climate changes as a factor and it compares the change in different climate periods as compared to the baseline condition.

The three critical distress factors are roughness environment age, crack initiation, and crack propagation (see section 3.4). Sensitive projections are expected from the critical distress factors since they have high impact elasticity (Bennett & Paterson, 2000). Therefore, calibration factors need to be calculated for these distress factors. These factors are K_{ge}, K_{ci}, k_{cp}, K_{gm} and k_{gp} in Equation 3.1. The following section presents the methods used for calibration.

3.5.3.1. Level I Distress Model Calibration for Flexible Pavements

As mentioned above, Level I calibration was used for the road sections for which only limited historical data was available (Appendix I). According to the HDM-4 User Guidelines (Bennett and Paterson, 2000), Level I calibration requires only configuration data to calibrate the program. Following the recommendations provided by Bennett and Greenwood (2004), for the HDM-4 Level I calibration, default values were used in the main, but some calibration of the critical distress factors was felt prudent. The processes undertaken to achieve this are described below.

- **Roughness-age-environment calibration factor (K_{ge})** – is used in HDM-4 to match the roughness progression model to observed roughness data (Bennett and Paterson, 2000). The process of determining K_{ge} is given in detail in HDM-4 Manual Five (Bennett and Paterson 2000), and is presented schematically in Figure 3.4 and summarised as follows.

K_{ge} is determined using Equations 3.2 and 3.3 below, as given in the HDM-4 Manual Volume Five ((Bennett & Paterson, 2000)). In Equation 3.3, the effective environmental factor (m_{eff}) is determined from the environmental factor (m), which is appropriate for the climate zone of the representative road section being considered (section 3.4).

The environment coefficient modifying factor for highway construction and drainage effects, K_m, is used to account for the material and drainage quality with engineering standards. It is obtained from the HDM-4 Manual Volume Five (Bennett & Paterson, 2000). A range of possible K_m values can be found in Table 6.4 of the Manual, as a function of material quality, and drainage effect, for freezing and non-freezing areas. For the purpose of this study, K_m was determined as 1 for a non-freezing area; which is considering the materials are as per the engineering standard and adequate drainage and formation for local precipitation presents with moderate maintenance condition.

$$K_{ge} = \frac{m_{eff}}{0.023} \text{ .... Equation 3.2}$$

Where:

$$m_{eff} = m\, K_m \text{ .... Equation 3.3}$$

- **Cracking initiation adjustment factor (K_{ci})** - is used in HDM-4 to adjust the default time for the flexible pavement structural crack initiation to that for the representative road section being considered. The time for initiation of structural cracks, *ICA*, is defined in HDM-4 using Equation 3.5 (Bennett & Paterson, 2000). The approach used to obtain K_{ci} for this research was as suggested by Bagui and Ghosh (2015) and is summarised in Figure 3.4. Bagui and Ghosh (2015) used two approaches for crack initiation adjustment factor determination. The first considers various CDS values, which is the construction defects indicator for bituminous surfaces, to compare with the HDM-4 run output. The second method involves estimation of crack initiation time and iterative processes. This method is employed in this research, since it is used when there is a limitation in the recorded crack initiation time data.

The method adopted involves estimating a plausible range of crack initiation times, obtained by observation or expert opinion, from similar road pavements. The range of K_{ci} values obtained is then subdivided and the resulting value is compared with the default K_{ci} values given in the HDM-4 Manual Five (Bennett and Paterson, 2000), to obtain the appropriate one for the representative section being considered.

$$ICA = K_{cia}\left\{CDS^2\, a_O\, exp\left[a_1 SNP + a_2\left(\frac{YE4}{SNP^2}\right)\right] + CRT\right\} \text{............. Equation 3.5}$$

Where: ICA is the time to initiation of all structural cracks (years); CDS is the construction defects' indicator for bituminous surfaces; YE4 is the annual number of equivalent standard axles (millions/lane); SNP is the average annual adjusted structural number of the pavement; HSNEW is the thickness of the most recent surface (mm); PCRW is the area of all cracking before latest reseal or overlay (% of the total cracking area); CRT is crack retardation time caused by maintenance (years), and it is the model's coefficients.

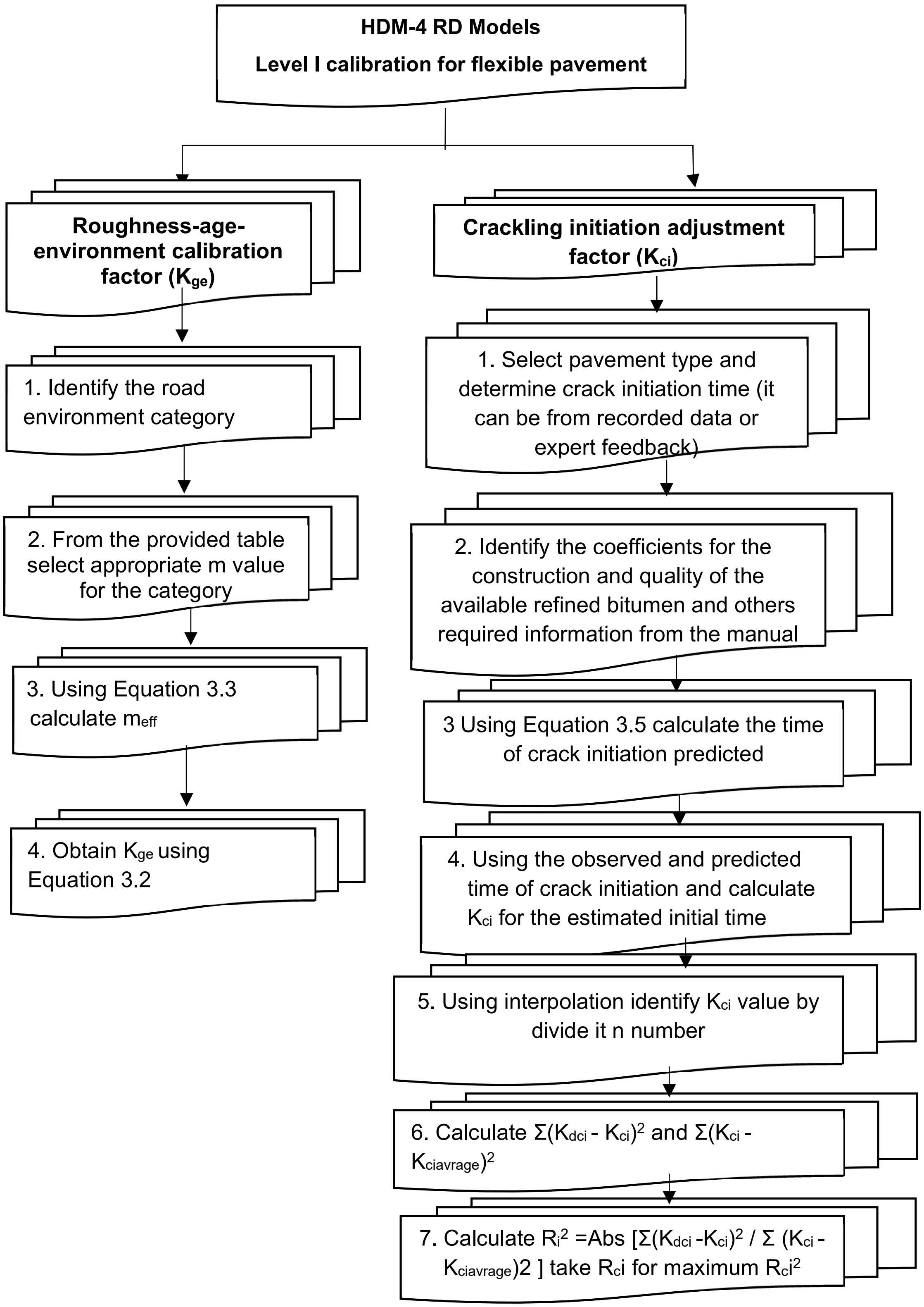


Figure 3.4 Procedure for Level I calibration (flexible pavement)

Due to the lack of documented historical data for the crack initiation time of the road sections studied in this work, expert opinion was obtained from experienced pavement engineers from the ERA who had observed the deterioration of the ERA's road network. They estimated that the crack initiation time after construction was between 4 and 5 years for AC surfacing, depending on the traffic and local condition of the road. For surface treatment pavements, the crack initiation time was estimated to be 3 to 4 years, depending on the traffic condition and local condition of the site after construction. The calculation considers each year separately and uses interpolations, the details are presented in Appendix K.

- **Cracking progression factor (K_{cp}) -** the cracking progression factor (K_{cp}) was determined using Equation 3.6, below, as recommended in HDM-4 Manual Five (Bennett & Paterson, 2000).

$$K_{cp} = \frac{1}{K_{ci}} \quad \text{............ Equation 3.6}$$

- **Rutting, ravelling and pothole adjustment factors (K_{pr}), (K_{pv}), and (K_{ph}) -** the HDM-4 economic models are relatively insensitive to rutting, ravelling, and pothole calibration factors, according to Bennett and Paterson (2004). Therefore, the default values (i.e. K_{pr} = K_{pv} = K_{ph} = 1) were used in this research in accordance with recommendations provided in the HDM-4 Manual Five (Bennett and Paterson, 2000).

3.5.3.2. Level II Distress Model Calibration for Flexible Pavements

The distress models which were calibrated to level II were the same three critical distress factors with calibration factors K_{ci}, K_{cp}, K_{gm} and K_{gp}.

Data required for calibration

According to the HDM-4 User Guidelines (Bennett & Paterson, 2000), Level-II calibration requires at least four to five years of historical pavement distress data. For instance, for a Level-II calibrated roughness progression model, the calibration of the coefficient (K_{gp}) (Bennett & Paterson, 2000) requires at least four years of roughness data taken from different pavement segments of the road section. Further, in the event of missing data, a variety of interpolation and extrapolation techniques are recommended by Bennett and Greenwood (2004) to generate data.

For the representative road sections used for this research, condition data were obtained from ERA's Alemgena Road Network Management Directorate (ARNMD). The pavement condition data obtained included traffic, distress parameters and maintenance status, pavement character and costs. These were obtained from yearly visual condition surveys undertaken from 2012/13 to 2015 and annual machine surveys undertaken in 2012/13, 2015/16 and 2017/18. The details are presented in Appendix K.

Roughness model

The Level II calibration process for the roughness model (Equation 3.1) involved determining the coefficients of critical distress. The procedures adopted in this research for each calibration coefficient used historical data (obtained as above) and repeated iterative calculations following Bennett and Paterson, (2000) and Bennett and Greenwood (2004), and is summarised below.

a) **Environmental coefficient (m)** K_{gm} is given as a function of m and to calibrate K_{gm} to local conditions Equations 3.7 and 3.8 provided by Bennett and Paterson (2000), were used to obtain adjusted m values. These were then used in Equation 3.1 to provide values for K_{gm}.

$$\boldsymbol{m} = \frac{ln[1.02RI_t - 0.143RDS_t - 0.0068ACRX_t - 0.056APAT_t] - ln\left[RI_o + \frac{135NE4_t}{(1+SNP)^5}\right]}{AGE3} \text{ ………….. Equation 3.7}$$

$$\boldsymbol{m} = \frac{ln[RI_t] - ln\left[RI_o + \frac{263NE4_t}{(1+SNP)^5}\right]}{AGE3} \text{ ………….. Equation 3.8}$$

Where: AGE3 = the age since the last overlay, reconstruction or construction whichever is the most recent, but excluding surface treatments

RI_t = roughness at AGE3 years after construction

RI_o = roughness when new

$NE4_t$ = cumulative axle loading since construction

SNP = Pavement structural number

RDS_t = standard deviation of rut depth at AGE3

$ACRX_t$ = area of indexed cracking at AGE3

$APAT_t$ = area of patching at AGE3

b) **Crack initiation calibration (K_{ci})** – the method proposed by Bennett and Paterson (2000) was used to calibrate the crack initiation and involves determining K_{ci} using Equation 3.9.

$$K_{ci} = \frac{mean\ OTCI}{mean\ PTCI} \quad \text{……….. Equation 3.9}$$

Where the $RMSE = SQRT\left\{mean\ \left[\left(OTCI_j - PTCI_J\right)^2\right]_{j=1,..n}\right\}$ ………….. Equation 3.10

RMSE: root mean square error

OTCI: observed time to crack initiation for the road pavement section

PTCI: time to crack initiation for the road section, predicted by using HDM-4 models

For this research, OTCI was determined using an expert opinion as described in section 3.5.3.1. and the sample calculation procedure is presented in Appendix K.

c) **Crack progression (K_{cp})** – the Bennett and Paterson (2000) recommendation to use the reciprocal of K_{ci}, that is $K_{cp} = 1/K_{ci}$, is applied in this research.

d) **Roughness components (K_{gm})** - since it was not possible to obtain the initial roughness (RI_o) data for all road sections, an alternative method suggested by Henning et al. (2006) was used to determine appropriate values for K_{gs}, K_{gr}, and K_{gm}. Henning et al.'s (2006) approach is similar to that given in the HDM-4 Manual Five (Bennett & Paterson, 2000) and the former provides a hint on how it can be done through an example, where initial roughness was not given to obtain the calibration factors. This approach assumed that due to routine maintenance application cracking and potholing do not contribute to roughness.

The approach, summarised in Figure 3.5, is based on obtaining convergent *m* values via an iterative process that compares m values obtained using Equation 3.8 and via regression analysis. For the selected *m* value calculate the structural roughness distress components and perform multiple regression analysis to obtain K_{gs}, K_{gr}, and K_{gm} (Figure 3.5). For the average roughness calculation, the relationship given by Equation 3.11 is used; but only $K_{gs,}$ $K_{gr,}$ and K_{gm} has a relation with m, therefore, the iteration process considers these two factors. Examples of the calculation of the calibration factors using the field data collected are presented in Appendix K.

$$\Delta \mathrm{RI} = \boldsymbol{K_{gs} a_o \exp\left(m K_{gm}\, AGE3\right)\left(1 + SNPK_b\right)^{-5} YE4} \;+\; \boldsymbol{K_{gr} a_o \Delta RDS} \;+\;+\; \mathbf{m}\boldsymbol{K_{gm}\, RI_a}$$

………Equation 3.21

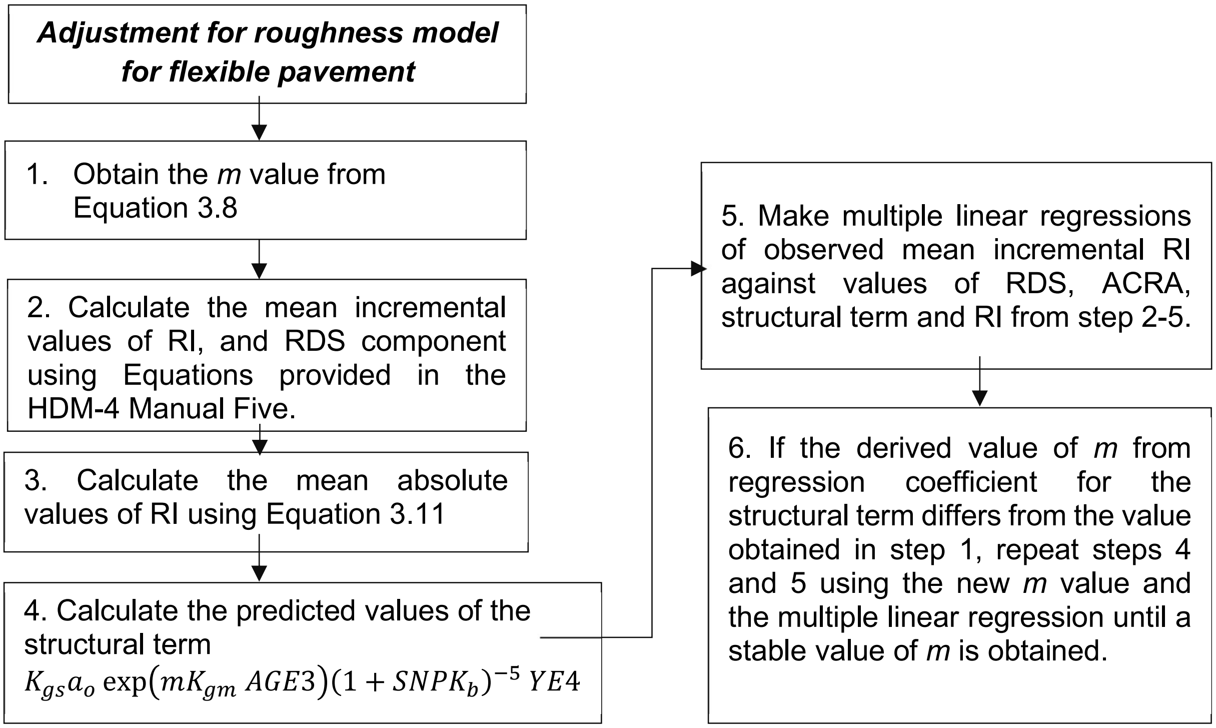


Figure 3.5 The adopted procedure for roughness components' calibration for flexible pavement in HDM-4 (Bennett & Paterson, 2000; Henning, et al., 2006)

3.5.3.3. Road Deterioration (RD) Model Calibration for Rigid Pavements

The type of rigid pavement roughness models provided in HDM-4 are either absolute or incremental (as explained in section C3 in Part C of HDM-4 Manual Four (Odoki & Kerali, 2006)). The rigid pavement roughness distress models vary depending on the type of concrete pavement.

The roughness models for jointed plain/unreinforced concrete pavements (JPCP) and jointed reinforced concrete pavement (JRCP) used in HDM-4 are given by Equations 3.12 to 3.18 below (Odoki & Kerali, 2006). However, the calibration process required to determine the calibration factors Kjp_r, Kjp_s and Kjr_r in the equations is not provided by the HDM-4 manuals, as the introduction of the associated deterioration models is relatively recent compared to the flexible pavement models. Therefore, the approach to calibration of the rigid pavement deterioration models used in this research was based on a study by Stannard et al. (2006) and chilina study.

$$RI = Kjp_r * (RI_o + 2.6098 * TFAULT + 1.8407 * SPALL + 2.2802x10^{-6} * TCRACKS^3) \text{ ……………. Equation 3.12}$$

$$\Delta RI = 0.00265(\Delta TFAULT) + 0.0291(\Delta SPALL) + 4.51x10^{-7}(TCRACKS)^2 (\Delta TCRACKS) \text{ ……………… Equation 3.13}$$

Where:

$$TFAULT = \frac{FAULTx\ 5280}{JTSPACE} \text{ ………. Equation 3.14}$$

$$TCRACKS = \frac{PCRACK*5280}{JTSPACE*100} \text{ …….. Equation 3.15}$$

$$SPALL = Kjp_s * AGE^2 * JTSPACE * 10^{-6} * [549.9 - 895.7 * (LIQSEAL + PREFSEAL) + 1.11 * DAYS90^3 + 375 * DWLCOR + (29.01 - 27.6 * LIQSEAL) * FI - (28.59 * PREFSEAL + 27.09 * SILSEAL) * FI] \text{ …… Equation 3.16}$$

For jointed reinforced concrete pavement

$$RI_t = Kjr_r * \left[-log_e\left(\frac{0.2*PSR_t}{0.0043}\right)\right] \text{ …….. Equation 3.17}$$

$$PSR = -0.00845\ (TFAULT)^{-0.5}(\Delta TFAULT) - 0.112(SPALL)^{-0.75}(\Delta SPALL) - 16$$

$$\mathbf{734 * 10^{-5}}\ (\boldsymbol{TCRACK})(\Delta \boldsymbol{TCRACK})$$ …….. Equation 3.18

The approach suggested by Stannard et al. (2006) is summarised in Figure 3.6 to determine the appropriate values for K_{jpr}, K_{jps} and K_{jrr}. The approach involves multiple-linear-regression analysis, which was used to adjust the calibration factors for the average incremental roughness model. The predicted roughness values were calculated using Equations 3.12 and 3.18 for the observed cracking, faulting, and spalling and calibrated by using recorded data. Examples of the calculation using the field data collected are presented in Appendix K.

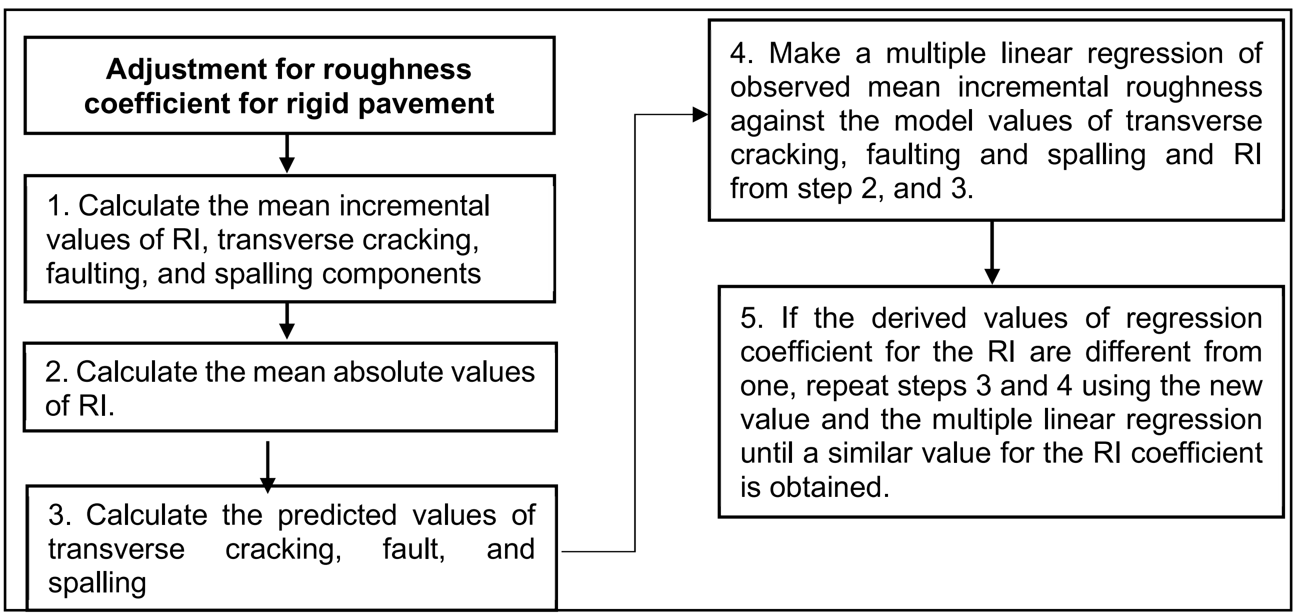


Figure 3.6 The adopted procedure for rigid pavement calibration for jointed plane concrete pavement (Stannard, et al., 2006).

3.6. Stage V: The Scenarios Modelled

3.6.1. Representative road sections

As mentioned in section 3.5.1, an HDM-4 analysis is performed on homogeneous road sections which are representative of the range of conditions and environments of the actual road network under consideration. For the purposes of this research, it was decided to use the variables of road surfacing type, climatic zone, and traffic loading (see section 3.1) to establish the representative homogenous road sections. The thickness of the pavement and the pavement condition were taken into account for each section of the pavement; however, to limit the number of variables, they are not considered to be one of the road network matrix classification criteria.

This research aimed to demonstrate the developed LCCA approach for the range of conditions found in Ethiopia's paved road network. Currently, Ethiopia uses five different pavement surface types (i.e. AC, DBST, Otta seal, JPCP, and JRCP) in five climate zones, namely arid (A), semi-arid (SA), sub-moist (SM), moist (M) and sub-humid (SH) (section 3.5.2). The range of traffic levels using different paved roads in Ethiopia's road network ranges from 30 AADT to more than 10,000 AADT. For the purposes of the research, it was felt that three traffic levels could be used to categorise these into low (LT, less than 500 AADT), medium (MT, from 501 to 3000 AADT), and high (HT, greater than 3000 AADT) traffic levels.

The combinations of pavement types, climate zones and traffic levels would produce a 5 x 5 x 3 matrix of representative road sections and hence give 75 variations. However, looking at actual ERA data, there were 73 representative road sections to consider. Currently, Ethiopia has AC pavements carrying high, medium and low traffic levels; while DBST serves as surfacing for medium and low trafficked roads. The ERA is also piloting sections of Otta seal and rigid pavements (JPCP, and JRCP) carrying medium and high traffic levels. Further, in Ethiopia there are no high traffic DBST roads in arid regions, nor low traffic DBST roads in semi-arid regions. Therefore, after amalgamating actual road sections into representative sections, the study considered 25 possible combinations of road surface type, climate zone and traffic levels. The resulting road network matrix is presented in Table 3.5.

As mentioned above, the data were collected from 73 representative road sections across Ethiopia to represent each possible combination. The total lengths of the representative sections is 2,562 km, which is 16% of ERA's 15,886-km paved road network and are summarised in the matrix shown in Table 3.5. From Table 3.5 it can be seen that the representative sections to be analysed in the research consist of: 1,626 km asphalt concrete (AC); 935 km double surface treatment (DBST); 1.5 km Otta seal; 0.5 km jointed plain/unreinforced concrete pavement (JPCP); and 0.5 km jointed reinforced concrete pavement (JRCP). The 73 representative road sections within the road network matrix represent 8.9% from the total paved and 16.1% from the ERA paved road length. These were subsequently considered in the LCCA, using HDM-4 strategic analysis (section 2.3.2) during the main phase of analysis (as reported in Chapter Five).

Table 3.5 Road network matrix for representative road sections

No.	Representative road section category (surface type, climate and traffic level)	No. of represent ative road sections	Length of actual road sections [km] [1]						Length of actual road section [km]
			RS1	RS2	RS3	RS4	RS5	RS6	
1	AC A HT	3	2.1	2.1	37. 7				41.9
2	AC A MT	4	23.3	2	12.2	22.3			37.5
3	AC A LT	3	34	59	189				282.0
4	AC M HT	5	13.5	4.7	55.5	5.4	50.3		73.7
5	AC M MT	4	55	25	58	14			138.0
6	AC M LT	3	67	48	53				168.0
7	AC S-A HT	6	98	25.3	40	92.9	17.9	30	163.3
8	AC S-A MT	6	53	70	62	18	34.2	42	185.0
9	AC S-A LT	4	48	36.6	3.9	59.5			88.5
10	AC S-M HT	5	18.8	12.7	44.6	44.2	6.3		76.1
11	AC S-M MT	4	55	21	60	106			136.0
12	AC S-M LT	6	66	80	90	26	42.5	94	236.0
13	DBST A MT	3	20.6	76	48				144.6
14	DBST A LT	3	165	34	60.4				259.4
15	DBST M HT	1	43.8						43.8
16	DBST M MT	1	46						46.0
17	DBST M LT	1	44.6						44.6
18	DBST S-A HT	1	54.8						54.8
19	DBST S-A MT	1	49						49.0
20	DBST S--M HT	1	76.8						76.8
21	DBST S-M MT	3	68	17	54				139.0
22	DBST S-M LT	2	8	69					77.0
23	Otta seal M MT	1							1.0
24	JP S-A HT	1	0.5						0.5
25	JR S-A HT	1	0.5						0.5
	TOTAL	***73***							***2562.0***

[1]Road length represents the total length of the road section.

3.6.2. Climate Considerations

For the research, historical, current and future climate data were required and the processes involved in obtaining these and the sources used are summarised in Figure 3.7. Appendix I presents the climate data that was used in this research.

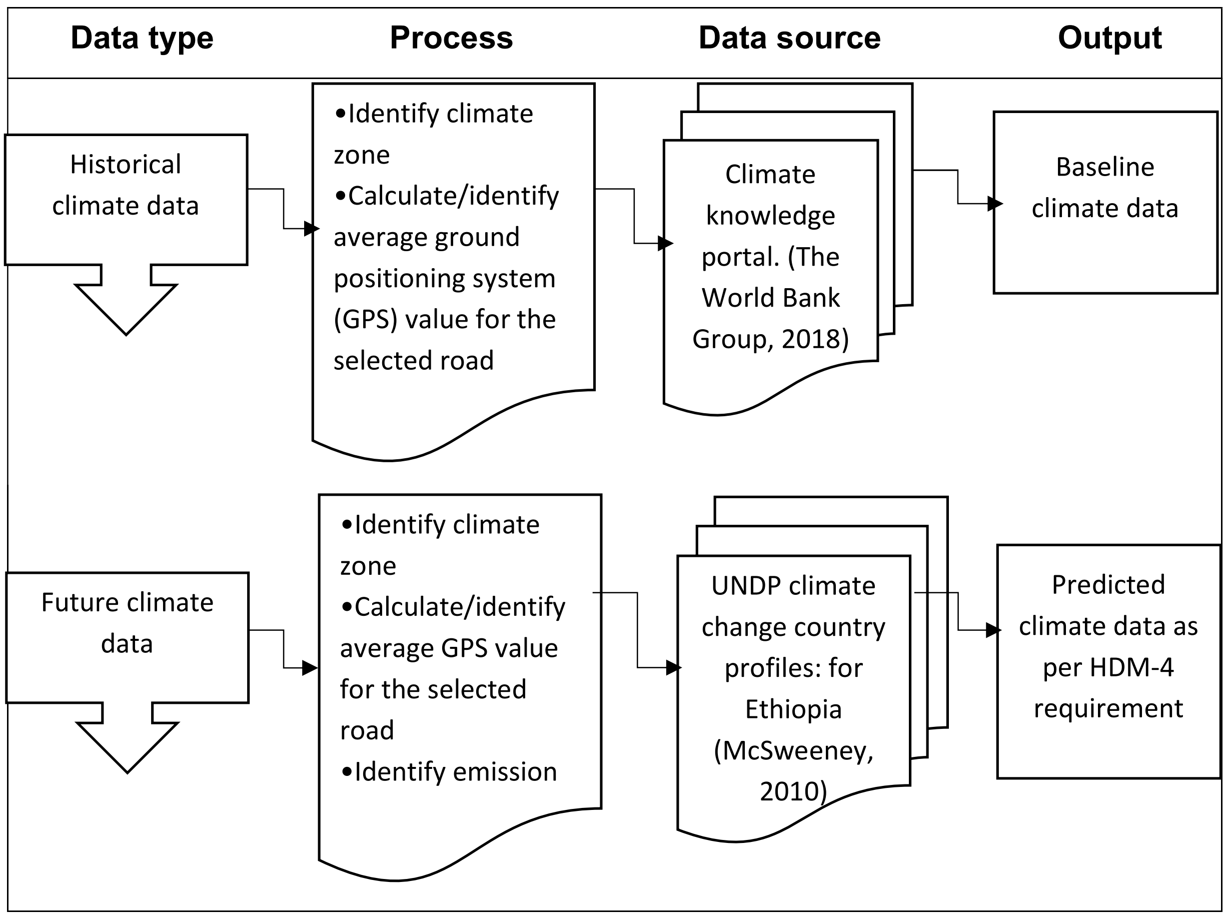


Figure 3.7 Climate data sources

Current and historical climate data were collected from the World Bank Climate Knowledge Portal (WBCKP) (The World Bank Group, 2018). The GPS co-ordinates of the selected road sections were used to determine the data to be extracted. To identify a road section's climate zone and select appropriate data from the WBCKP an average GPS value of the road was used to identify the closest gridded climate data. This data was used as a baseline for the HDM-4 network level analysis. As climate change projections are linked to emission scenarios (see section 2.4.2), it was necessary to select at least one relevant future climate which could be pertinent to Ethiopia. This is described in section 3.6.3 below.

Based on the recommendations of Arnold et al. (2018) the UNDP climate change country profile report (McSweeney, 2010) was used as the source of projected climate change data (section2.4.2.1). McSweeney (2010) provides a projected change from the 1970-1999 average climate for the future for each 10-year period in terms of multiple climate parameters as a function of SRES (section 2.4.2) scenarios (McSweeney, 2010).

3.6.3. Emission scenario selection

In Chapter Two possible emission scenarios, which are utilised by climate projection researchers to estimate the world's future climate, were presented. The scenarios are based on different assumptions associated with factors which might contribute to changes in emission levels, for example levels of future population growth, energy sources utilized and the use of technology (section 2.4.1).

From the review carried out in Chapter Two, the following are pertinent to the study area and are of interest to this research:

1. The population of Ethiopia is expected to increase by about 1.6% in total between 2012 and 2032 and thereafter by up to 2.1% until 2050 (Alemayehu & Yihunie, 2014).

2. As a result of the increase in population an increase in energy demand would occur which would potentially lead to the use of different energy sources to satisfy the demand. Baseem and Pawan (2017) for instance, showed that the availability of electricity power in the country was only 26% in 2014 and was projected to increase up to 60% by 2040, requiring the utilisation of diverse energy sources. These sources could include wind, geothermal, diesel, wood, and hydroelectric power.

For this study, the upper and lower climate projection changes predicted for the A2 emission scenarios were used to demonstrate the developed LCCA approach. In selecting a climate emission scenario for demonstration purposes, the above facts/points are taken into consideration and correspond to the base assumption of each emission scenario reported in SRES. The IPCC (2014) provided the assumption for each emission scenario as presented in Table 2.8 in section 2.4.2 and for the selected A2 emission scenario as follows:

- A2 emission scenario assumes the future as a heterogeneous world with high population growth.

- The GHG emissions ($GtCO_2$-eq/yr.) projection for the A2 emission scenario is less than A1 (A1FI), which has the highest global GHG emissions (see Figure 2.6, section 2.4.2).
- A1 (A1FI) and A2 emission scenarios have a relatively similar global surface warming projection until 2060. After 2060 the A2 scenario results have the greatest degree of global warming amongst all scenarios (Figure 2.6).

3.6.4. Vehicle Operating Costs

The calibration of HDM-4's VOC model (section 2.3.1) utilised a previous study conducted for the ERA by HITCON Engineering (2018).

3.7. Stage VI: Adjustment of the Roughness Model to Account for Climate Change Effect

The HDM-4 can take into account the impacts of climate change in two ways: 1) by adjusting environmental associated calibration factors to alter appropriately the rates of deterioration predicted by HDM-4's deterioration models; and/or 2) by introducing probabilistic function(s), as described in section 2.3.4. For the reasons discussed in section 3.3 it was decided to focus on the former approach.

Since the environmental age component of HDM-4's roughness model is used to capture climate effects (see section 3.4), it is hypothesised that the roughness environment age coefficient (K_{gm}) associated with the roughness model could be adjusted to represent a particular region and a different climate condition. As mentioned above, an economic analysis could be broken down into consecutive periods of time, and a different K_{gm}, carefully selected, to represent the effects of a changing climate over the entire period of the economic analysis. The procedure would be similar to the calibration process of the flexible roughness model but applied for the climate change condition and all other factors are kept constant. The approach may have some similarity to Shao et al.'s (2017) approach but has a number of differences as described in the following.

1) **Considering climate parameters** - Shao et al. (2017) used one climate parameter, i.e. the TMI (Thornthwaite Moisture Index), to represent the change in climate but in this study the impact of climate change will be considered through all climate parameters concurrently. The TMI represents only one potential way in which the climate can affect road pavement performance. However, other aspects associated with the climate are also important and include changes in rainfall, temperature, groundwater and the number of hot /cold days (Odoki, et al., 2006).

2) **Method used to consider climate change** – the study conducted by Shao et al. (2017) developed a relationship between the roughness model and the TMI. However, this research tries to find a relationship between *m and* K_{ge}, K_{gs}, and K_{gm} within HDM-4, which could affect pavement performance (section 3.4). The advantage of this

approach is that the effect of all climate parameters can be considered in the roughness deterioration model, as mentioned above.

To this end, the process developed in this research, for each period of climate to be modelled, is summarised in Figure 3.7 and described below.

1. For each new climate, regression analysis, was used to determine a new model modification coefficient (i.e. K_{gm}). This was achieved using the SPSS program to do the statistical analysis associated with regression analysis, and used as the tool for climate related research like in the case of Shao et al. (2017) and John et al. 2015.
2. By means of multiple linear regression analysis, the coefficients of the distress factors in the roughness model were determined. Then, using the quadratic regression analysis, it was seen whether any secondary effects existed or not due to the climate change effect on the other parameters such as rutting, cracking and potholes. Also, a logarithm approach was used to check if the climate change effect can be better explained in a log function.
3. The accuracy of the fitted regression model is checked by computing its R^2 statistic. The R^2 is the ratio of the variance of the models without taking into account climate change and the variance of the predicted model (i.e. those that take into account climate change). The closer the value of R^2 to 1 the better the precision of the regression model. However, this process or calculation is valid only for those roughness components found to be statistically significant; which means the statistical significance of each roughness component and the change in the roughness model as a whole should be assessed first in order to use the R^2 value.

The roughness model adjustment process involves prediction of distress parameters under the “do minimum” maintenance conditions for five climate periods. The reason for using the “do minimum” maintenance alternatives option was to see the impact of climate change on the roughness model, considering the actual routine ERA maintenance practice.

Figure 3.8 shows the process of adjustment for the climate change effect for the locally calibrated roughness models through the process presented in Figures 3.4 and 3.5.

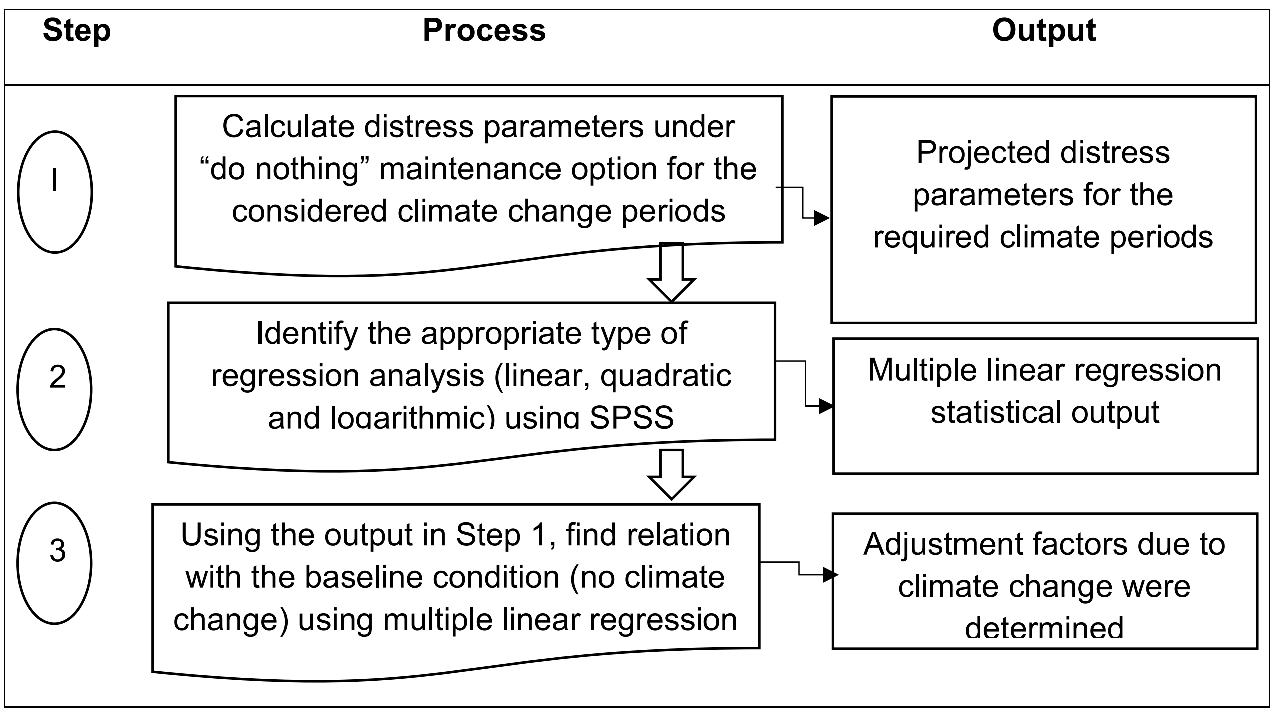


Figure 3.8 Climate adjustment factor calculation processes

3.8. LCCA

In order to better understand the engineering and economic performance of the five pavement surfacing materials under the effects of climate change, and under various traffic levels, two modelling approaches were adopted:

1. The first approach sought to investigate the impact of climate change, by comparing a series of discrete life-cycle analysis periods for each of five climate zones for the baseline and four future climate periods.

2. The second approach was to try to incorporate climate change within a single life-cycle period of analysis of 44 years.

The approaches are described further below.

3.8.1. Approach 1

Flexible pavements are planned to serve the expected traffic load over a period of 10 to 20 years, depending on their function (typically 20 years for trunk and link roads, 15 years for main access roads, and 10 years for feeder and local roads) (ERA, 2013). Rigid pavements are also designed to last more than 40 years. For the purposes of this research, an average period of 15 years was used for the flexible pavement life-cycle analyses in this approach. Such a period of time was felt reasonable as the intention of this aspect of the study was to investigate the effect of climate change alone in terms of changes to the LCC. An LCCA for each representative road section in Table 3.4 was conducted for five future climate change periods i.e. for 2016 (baseline), from 2017 to 2029, from 2030 to 2039, from 2040 to 2049, and from 2050 to 2059. These climate change periods were according to the climate projection of McSweeney (2010).

In summary, in this approach each LCCA was carried out for 15 years for the flexible road pavements and 15 and 40 years for the rigid ones. Five LCCAs were conducted for each road section, i.e. one to represent each climate change period including the baseline. Each analysis, for economic purposes, started in 2016, and used the same input factors/configuration (i.e. traffic levels, initial road condition etc. applicable to 2016). However, the pavement deterioration models for each of the four analyses were calibrated, using the procedures described above, according to the climate change period considered. In addition to this, the investment scenarios (maintenance standards) presented in section 4.2.1 were also modelled. Figure 3.9 depicts the approach conceptually.

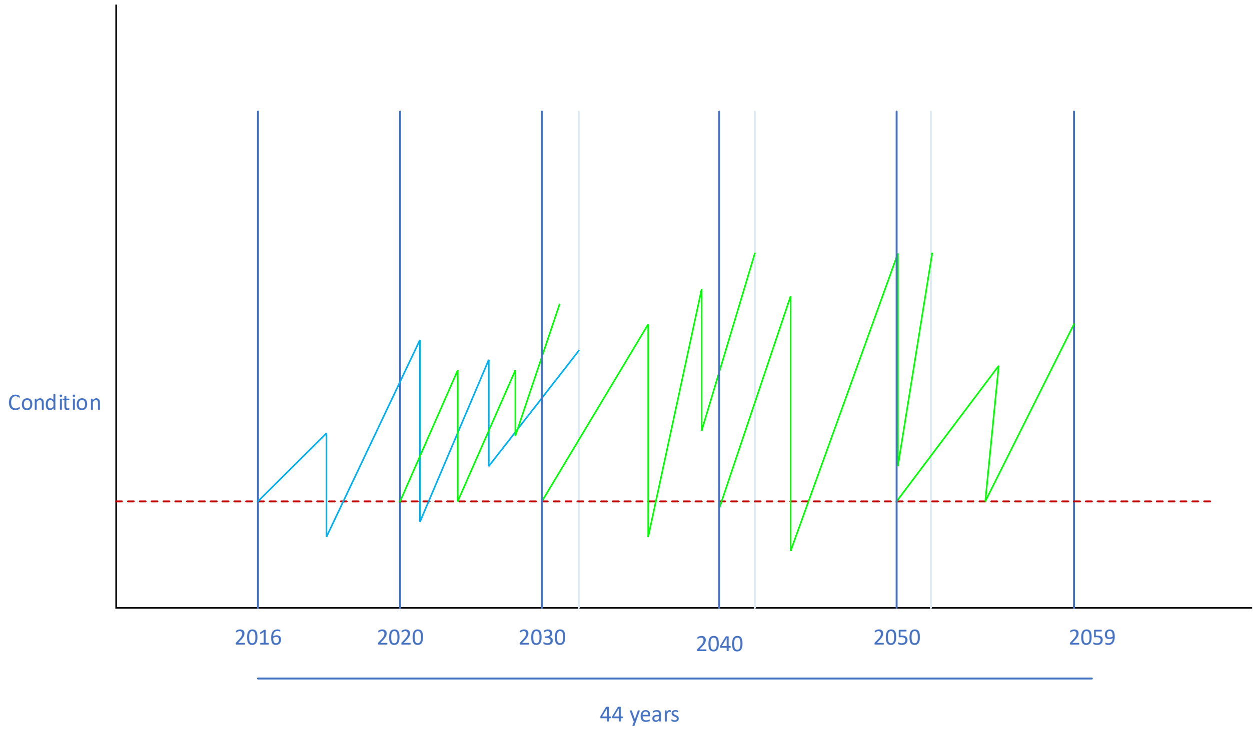


Figure 3.9 LCCA procedure for climate change only assessment

Figure 3.9 indicate that the baseline condition analysis result in blue and the analysis results that considers different climate periods in green. In order to identify the impact of climate change alone, approach 1 was used to compare each of the analysis result due to different climate change to that of the baseline. For this approach, 15-year LCCA period, same traffic growth rate and pavement related factors except for the climate input data and climate related model factors were used.

3.8.2. Approach 2

For the five-pavement surfacing representative road sections shown in Table 3.5 an economic analysis was performed for a period of 44 years. In each case the 44-year analysis period was broken down into one 4-year, and four, 10-year consecutive periods of time (or stages) to try to replicate the effects of climate change within a complete life-cycle; namely, 2016-2019; 2020-2029; 2030-2039; 2040-2049; and 2050-2059 (i.e. climate change was modelled crudely as changing five times during the 44 year period). To this end, the HDM-4 input parameters, which can affect road deterioration, were adjusted for each 10-year period using the methodology described in section 3.7 and the pertinent HDM-4 output parameters (e.g. pavement condition, age, traffic, pavement thickness and surfacing type) from the previous 4- or 10-year period.

Similar to approach 1, the investment scenarios (maintenance standards) presented in section 4.2.1 were considered for the LCCA.

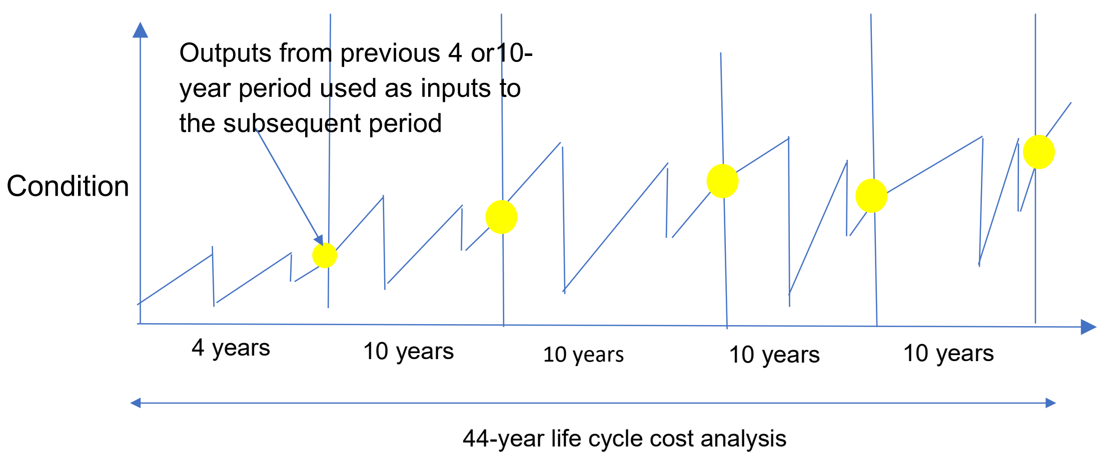


Figure 3.10 LCCA 44 years calculation processes

Figure 3.10 shows that the LCCA considers the effects of climate change every 10-year except for the first analysis period (where 4 years considered). This approach helps to see the climate change effect as continuous bases. That means the pavement condition and the traffic data consider the output of the first LCCA result as an initial condition to perform the next consecutive ten years LCCA. The yellow circle in Figure 3.10 indicates that the output of the analysis used as a starting / initial value for the next analysis. However, the input of the climate data and climate related model factors were changed for each climate change periods. The result of the LCCA therefore, is a cumulative effect of traffic growth (the growth rate is similar to approach 1) and climate change together for the entire periods.

For both applications for the purposes of reporting the economic analysis, the NPV value method was used since it can convert the future cash flow to the present costs using a discount rate. The NPV is a function of the size (i.e. cost) of a project, larger projects tend to have larger NPVs. Moreover, unlike the other economic indicators for the long-term effectiveness analysis, the NPV/cost and NPV/road-length value were used to compare and rank the alternative investment scenarios (see section 2.3.3.3). This condition helps the research analysis since it is required to identify the best surface type. However, the calculation of NPV/cost ration for approach 1 and 2 are different. The discounted RAC and RUC values can be directly obtained from the HDM-4 analysis for approach 1; while for approach 2, it was calculated on an Excel spreadsheet using the identified discount rate.

3.9. Summary

This chapter discussed the methodology used in this study, which consists of eight major stages.

Stage-I summarised the most pertinent findings of the literature review; while Stage-II briefly described the potential tools available for the LCCA and identified HDM-4 as the most appropriate tool for the research.

Stage-III reported a preliminary analysis which was carried out to better understand how the climate change impacts could be reflected in HDM-4 via its distress models. In particular, the analysis suggested that HDM-4's roughness model could be adjusted to consider climate change effects through the use of the roughness model's roughness environment age coefficient (k_{gm}).

Stage-IV discussed the configuration and calibration of the HDM-4 roughness model for local conditions in Ethiopia. Considering the availability of historical data, two levels of calibration were used. Level I calibration is used for road sections which lack sufficient historical data for a higher order calibration; while Level II calibration will be conducted for those sections where four or more years of historical data is available. Extrapolation and interpolation were used in accordance with recommendations provided in the HDM-4 guide document where the data was observed.

Stage-V considers the existing conditions and identifies possible scenarios to be included for the development of the framework for the defined road network matrixes. Stage-VI described and explained how the calibrated HDM-4 roughness model could be adjusted to account for the effect of climate change. The proposed process involves with the use of multiple linear regression analysis in order to identify the climate adjustment factor. Finally, Stage-VII outlined the basic elements of the economic analysis to be carried out using the proposed approach and identified the NPV/cost ratio as the most appropriate method of comparing different investment strategies.

The next chapter describes the analytical framework of the research.

CHAPTER FOUR - FRAMEWORK

4.1. Introduction

This chapter presents the framework that can be applied to determine the impact of the climate change effect on pavement performances and its associated LCCA on different pavement surfacing. The framework, developed to address the third objective of this research described in section 1.3.2., is presented in three sections (including this introduction) within this chapter. Section 4.2. discusses the five components of the framework, while section 4.3. summarises the chapter. The framework was developed to consider changing environmental conditions in tropical areas, attributed to climate change, which could impact upon the performance of different pavement surfacing and the associated LCCA. The framework however, can be applied to any pavement surfacing located in different climate zones using different climate emission scenarios, as long as the pavement surfacing can be defined in the HDM-4.

4.2. Components of the framework

The framework is designed to show how a projected pavement performance and its related costs can be obtained by considering climate change projection data from Ethiopia. The components of the framework, therefore, encompass activities and requirements of the HDM-4 software and include additional inputs to model climate change effects. A flowchart of the developed framework for measuring pavement performance and related LCC due to future climate change scenarios using HDM-4 is depicted in Figure 4.1.

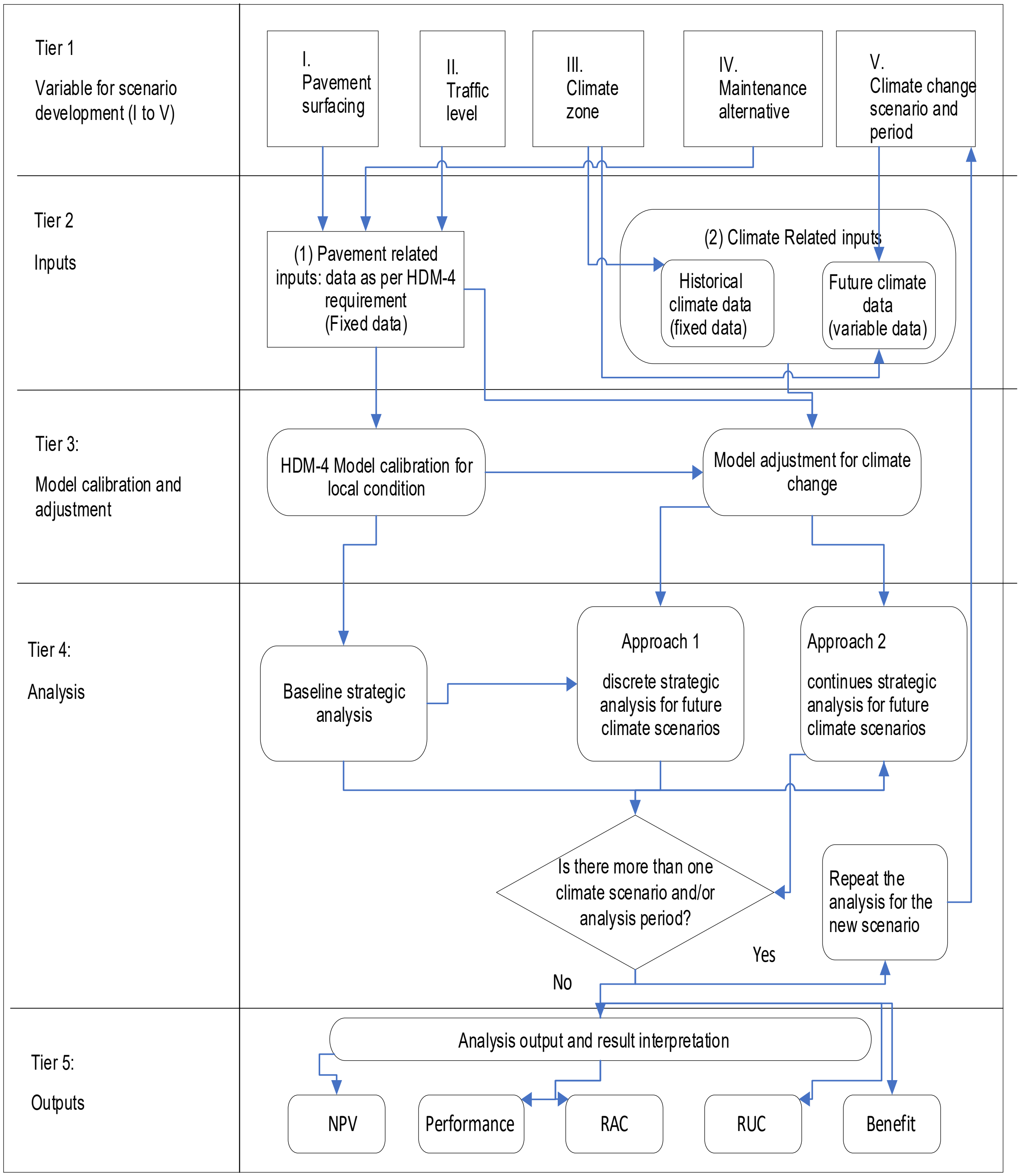


Figure 4.1 The proposed five-tier framework for evaluation of different pavement surfacing based on an LCCA, under future climate change impact

The framework has five tiers as shown in Figure 4.1. The first tier focuses on the possible variables to develop different scenarios, while the second tier considers the type of input data in relation to their use. The third tier involves the adjustment of the deterioration model to simulate the local and future conditions, and is followed by the three types of analysis in the fourth tier. The final tier presents the evaluation of the LCCA and the economic assessment of the pavement types. Each of the components or tiers of the framework are discussed in the following subsections.

4.2.1. Scenarios

This study deals with five different pavement surfacing types, five climate zones, three traffic levels, two maintenance alternatives, and five climate change conditions/periods. These variables are combined to create different scenarios. The variables can have significant effects on the pavement's performance, as well as on the required budget in order to provide the expected levels of service throughout the pavement's design life. The five variables (I to V) in Tier 1 of the framework (Figure 4.1) are briefly considered below.

Variables for Scenario I. Pavement Surfacing

The HDM-4 distress models (previously considered in section 3.4.) used for performance prediction are based on the surfacing and base material characteristics. The performance of each material under different conditions may vary. To consider this variation in using the HDM-4 software, the program has established 26 classifications of pavement type based on surfacing and base material (Appendix A). For this study, five pavement surfacing types were considered and these are: asphalt concrete on granular base (ACGB); double surface treatment on granular base (BD STGB); Otta seal (Otta seal STGB); jointed plain/unreinforced concrete pavement (JPCP); and jointed reinforced concrete pavement (JRCP) from the ERA network. However, for the LCCA approach 2, the surface, base, sub-base material and the thickness of surfacing may vary based on the analysis result, because approach 2 uses the first ten years analysis' output as an input for the next ten years' analysis (section 3.8.2.). Therefore, the framework (Figure 4.1) has the potential to be applied to other kinds of surfacing, which can be represented by the HDM-4 models. Once the pavement structure has been configured in HDM-4, the associated deterioration model can be defined by coefficient adjustment and/or by adjusting other factors as previously discussed. In addition to this, the calibration process as described above is used to accommodate changes in pavement material and environmental conditions.

The selected flexible pavement representative sections had a range of pavement thickness of 500 mm-700 mm and 200 mm-400 mm for AC and DBST pavement types, respectively. For Otta seal, JPCP and JRCP pavements the range of the thicknesses were 300 mm - 630 mm, 250 mm and 500 mm respectively (ERA, 2013b, 2013c; HITCON Engineering, 2018). The materials' properties for the five pavement types considered in this study were taken from ERA Road Asset Directorate (ERA, 2013f, 2012). The materials, and their properties, for the five pavement types are presented in Appendix K.

Variables for Scenario II. Traffic Level

Traffic is a significant variable in pavement design and performance evaluation, as various traffic levels influence the pavement condition differently. The traffic levels are expressed in terms of the AADT and the five components of traffic considered in HDM-4 are discussed in Appendix I. These traffic components include traffic composition, traffic volume, traffic growth rate, traffic flow pattern, and equivalent standard axle load factors (ESALF).

Variables for Scenario III. Climate Zone

The environment and climate conditions that a road pavement will be exposed to during its operational life dictate the type(s) of pavement surfacing that would/would not be suitable. Hence, environment and climate conditions dictate the material properties that should be used in the HDM-4 modelling process (Odoki & Kerali, 2006). For example, pavement surfacing material that is suitable for arid climate zones may not be suitable or economical for wetter climate zones.

The HDM-4 software includes road pavement models that incorporate different base and surfacing materials (section 2.3.4.2.). It is also able to model different climate zones and requires a variety of input variables to this end (see section 3.4.). By providing appropriate input values for the associated variables, it is possible to represent the historical and projected future climate for each climate zone. To model the effect of climate on road deterioration and also its economic impacts, a separate analysis for each climate zone and the projected future climate for the considered representative road sections was carried out. For example, for all representative road sections that were initially in the arid climate zone separate analyses were performed for each of the five climate periods considered.

Variables for Scenario IV. Maintenance Alternatives

According to Odoki and Kerali (2006), maintenance activities are considered as road works that aim to preserve and/or improve the pavement condition as it deteriorates overtime. Pavement deterioration is a function of a number of factors (see section 2.3.3.2.), including: (1) usage, i.e. traffic and increase in traffic as time passes; (2) environmental/climate conditions; and (3) the physical nature of the pavement structure, that is geometry and pavement structure (including adjacent lanes and road features), neighbouring land use and topography affect the rate of deterioration. The HDM-4 model is able to account for these factors when addressing pavement deterioration and maintenance requirements, as described in section 2.3.4.3. For this research, maintenance and improvement activities that were used were hieratically structured by category, class, and type as maintenance scenarios and presented in Figure 4.2.

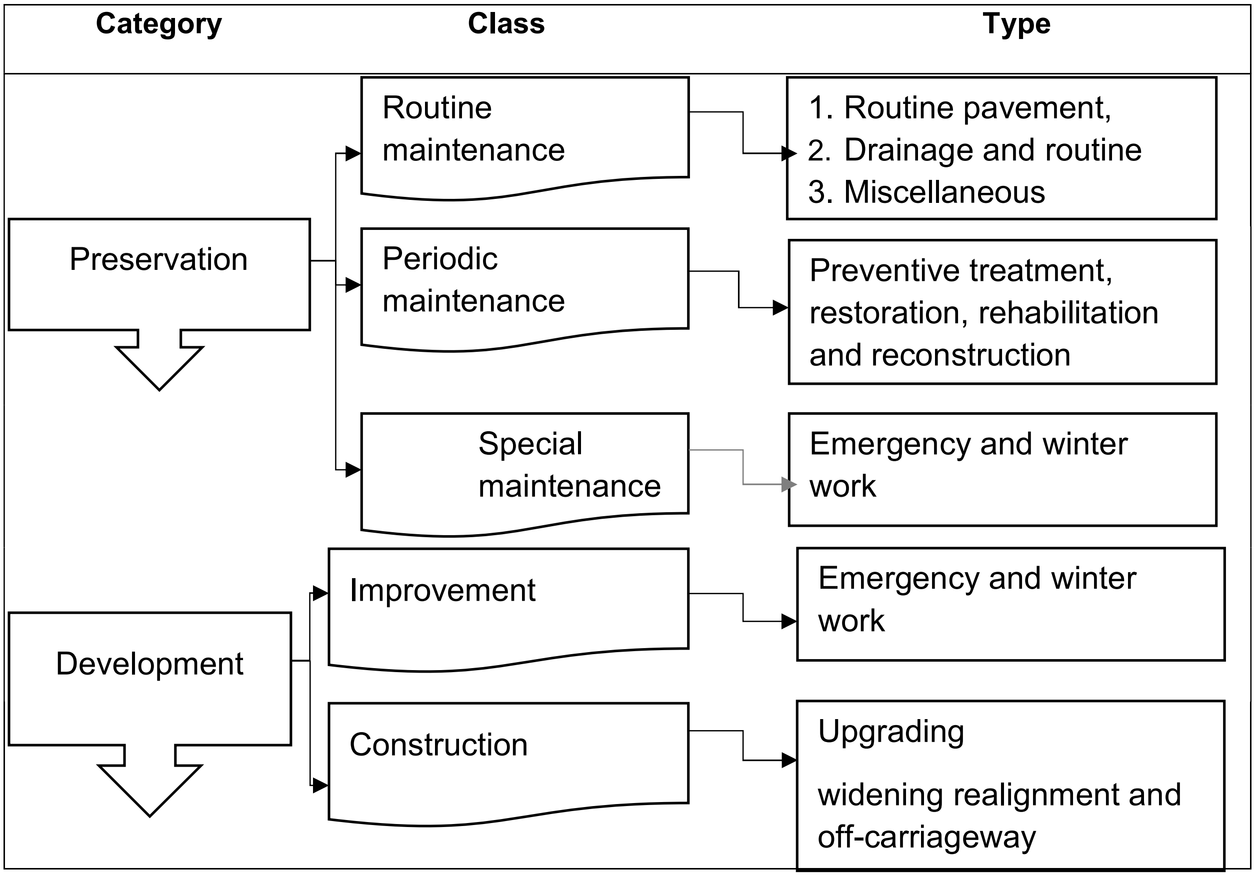


Figure 4.2 Maintenance and improvement category, classes and types

In this study, maintenance scenarios were established based on routine and periodic (i.e. condition-based) maintenance activities. The standards applied in this research were based on those criterions used by ERA (ERA, 2013b; HITCON Engineering , 2018). These standards consider different construction methods for asphalt concrete and surface treatments for flexible pavements, and routine maintenance for rigid pavements. The long-term maintenance options for this study are presented as compound maintenance, which consists of a set of different maintenance activities; an example of this is shown in Table 4.1.

Table 4.1 Maintenance Standard (source: (HITCON Engineering, 2018))

	Standard	Description	Intervention Level	Financial Cost [ETB]	Economical Cost [*ETB]	Units
Flexible Pavement	**1 Base Alternative Bituminous**	**Routine and Recurrent Activities**				
		Patching damage	Potholes > = 10 No/km	**1108.80**	1042.27	per m^2
				1331.96	1252.04	per m^2
		Crack sealing	Edge break > 5m^2/km	**349.02**	328.08	per m^2
			Wide structural cracking > = 1%			
		Drainage cleaning	DF >3			
		Miscellaneous activities	Every year	**7,325.81**	6886.26	Per km/year
	2 Base Alternative for Surface-Treatment	**Routine and Recurrent Activities**				
		Patching damage	Potholes > = 10 No/km, Wide structural cracking > = 3%	**202.50**	1042.27	per m^2
		Crack sealing	Rut depth mean > = 10 mm or	**70.00**		per m^2
		Drainage cleaning	Edge break > 0 m^2/km Total carriageway cracked > = 2% DF > 3	**7,000.00**		per km
		Miscellaneous activities	Every year	**46,750.00**	6886.26	Per km/year
	3. Compound Standard	**Preventive Maintenance Surface Dressing**				
		Overlay 15 mm	total carriageway cracked > = 2%, < = 10 and 2 < = wide structural cracking > = 7,	**87.00**		per m^2
		Overlay 25 mm	IRI < = 4 and ESAL< = 4 and Rut depth mean < =10 mm	**145.00**		per m^2
		Bituminous Overlays Structural				
		Overlay 50 mm	4 < = Roughness IRI > = 6.5, 7% < = Wide Structural cracking > =, 15% and	**450.00**	135.42	per m^2

		Overlay 100 mm	Rut depth mean < = 5 mm 4 < = Roughness IRI > = 6.5, 7% < = Wide Structural cracking > =, 15% and 5 mm % < = Rut depth mean < = 20 mm	**700.00**	203.12	per m^2
		Bituminous Rehabilitation Reconstruction 50 mm	Roughness > = 6.5 IRI or Rut depth mean > = 20 mm	**19,000,000.00**	676.80	per km
		Reconstruction 100 mm	Roughness > = 5.5 IRI and Wide Structural cracking > = 10%	**24,000,000.00**	1861.00	per m
		Improvement Bituminous Widening + Reconstruction 10 cm	Two-way AADT > = 15,000 veh/day and Cumulative ESAL > = 16.5 MESAL/lane	**40,000,000.00**	2685.58	per km
Rigid Pavement	**Base Alternative Bituminous**	**Routine Activities** Drainage cleaning Miscellaneous activities	Every year	**7,325.81**	6886.26	Per km/year
		Sealing	Interval>=7, <=10 Years	**494.95**	410.87	Per m^2
		Spalling	Spalling >=10%	117.71	97.84	Per m
		Deep spalling	Spalling >=10%, <= 20%	235.44	195.30	Per m
		Thine overlay 50mm	Cumulative ESAL < = 1 MESAL/lane and Deteriorated cracks >= 5 no/km and Failures >= 2 no/km	494.94	410.87	Per m^2
		Overlay 100 mm	Cumulative ESAL >= 1, <= MESAL/lane and Deteriorated cracks >= 10 no/km and Failures >= 2 no/km	770.13	639.42	Per m^2

Variables for Scenario V. Climate Change Scenarios and Periods

This study utilises the long-term weather condition projection of the UNDP climate change country profile for Ethiopia as discussed in section 2.4.2.1 (see also Appendix I) (McSweeney, et al., 2010). The projection breaks down the predicted future climate into ten-year intervals for the four emission scenarios A1, A2, B1 and B2 (IPCC, 2007 and McSweeney, et al., 2010). Furthermore, three projections are provided for all emission scenarios to represent low, medium, and high greenhouse gas (GHG) emission possibilities, to take into account the uncertainties in the projection. In this study, the A2 emission scenario with its associated low and high emission projections were used as discussed in section 3.6.2.

4.2.2. Model Input

Tier 2 of the framework (Figure 4.1) indicates how these scenarios can be represented in the HDM-4. The approach used the existing HDM-4 input data set-up and then imported additional inputs to facilitate the projected impact of climate change in the LCCA analysis. A separate analysis as well as continuous approaches were chosen to take into account different periods of climate change for the defined road matrices (section 3.8).

To input the data into the framework, the five variables for scenario development (described in stage one of the framework) were arranged into two broad input categories

(Figure 4.3: Tier 2: Inputs): (1) pavement data and (2) climate related data. The pavement related data, which includes road condition and inventory data (section 3.5), were considered as fixed/unchanged data during the analysis. Conversely, at this level of the framework, the climate variables' input data were allowed to vary to represent the potential change over the ten years' climate period for each of the selected analyses (Tier 1: Scenario V).

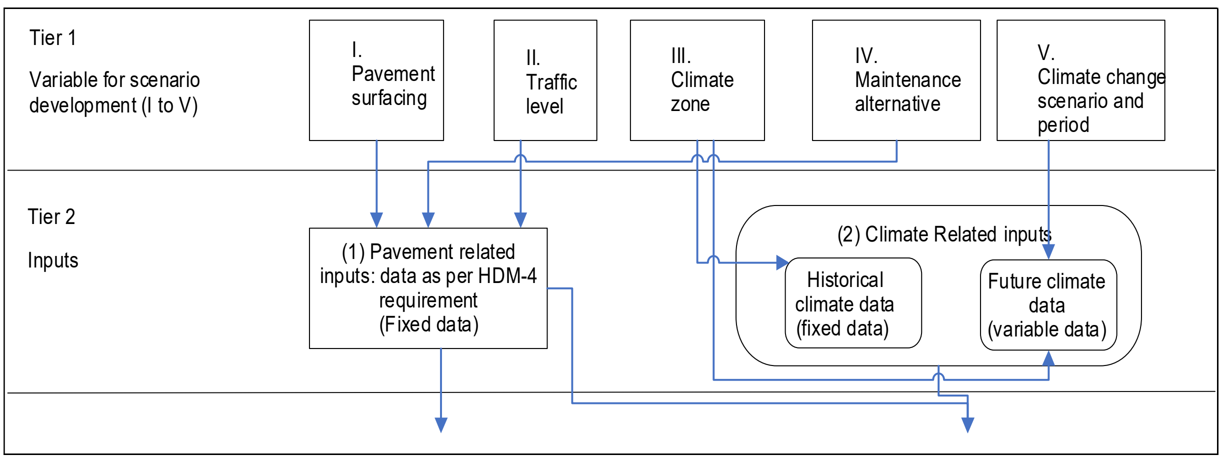


Figure 4.3 Section scenarios and input categories for the identified scenarios in Tier 1 and Tier 2

4.2.3. Model Calibration and Model Adjustment for Climate Change

Tier 3 of the framework considers the outputs from simulation of the HDM-4 generic model (Input 1) to the suggested changes due to local and future climate conditions (Input 2). The initial stage is to set up and calculate (to calibrate it) the default HDM-4 model; this provides a baseline to allow consideration of subsequent changes with the changing climate. Calibration enables simulation of the local condition for the developed road matrixes using the selected climate zone, traffic level, and pavement surfacing. The procedure to obtain the calibration factors, for each case, is explained in section 3.5.3.

The calibrated model is then used to consider the historical climate input data as part of the wider simulation process. Once complete, the calibrated roughness model needs further adjustment to incorporate projected changes in climate (Figure 4.4). The modification is represented through the roughness environment age model coefficient, which signifies the future pavement condition for different climate change scenarios and periods for the LCCA. The procedure explained in section 3.7 was used for calculating the adjustment coefficient.

Various climate change analyses can be undertaken, using different K_{gm} model coefficients, to provide a spectrum of outputs that relate to projected changes in climate. In section 3.4, this variation was shown by changing different values to represent cold to hot cases for the roughness environment age coefficient (K_{gm}) and environmental factor (m). This will provide a better understanding of the potential impacts of climate change on the requirements to manage an operational pavement; hence, improving risk-based analysis as part of a decision-support tool.

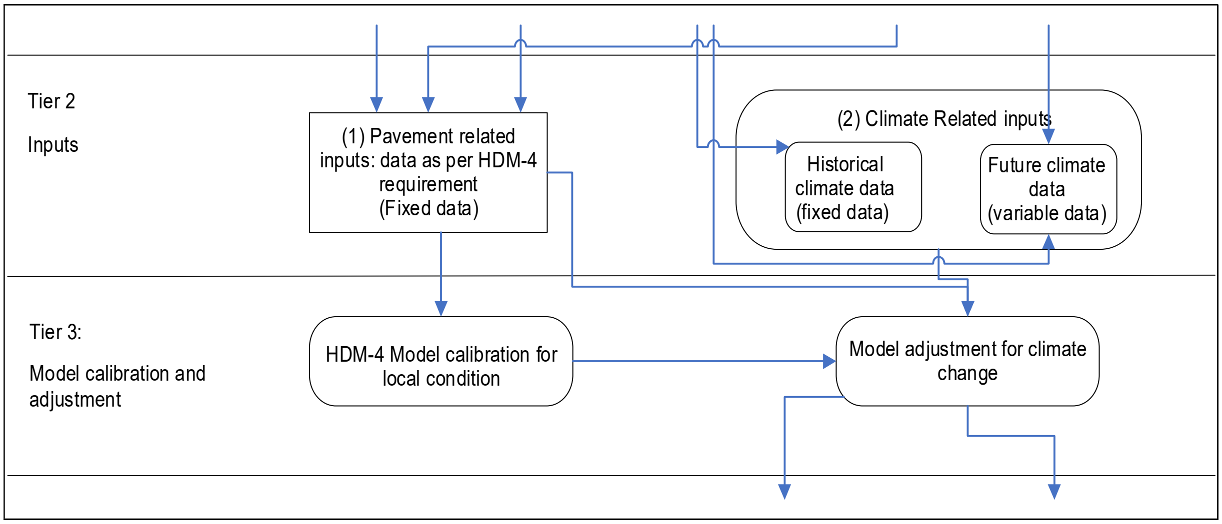


Figure 4.4 Input categories for the identified scenarios and model calibration and adjustment in Tier 2 and Tier 3

4.2.4. Analysis

The HDM-4 has three analyses levels, based on the level of detailed information provided; namely, project, program, and strategic (section 2.3.2). The project level is for a detailed economic assessment for one project; whereas the program level is used for annual work programme preparation. The strategic level, however, considers network analysis for long-term planning and was therefore used in this research to assess the potential impacts of long-term climate change on pavement performance and the LCCA (see section 2.7).

By repeating the analysis process and changing the parameters associated with the climate change scenarios and the analysis period, the potential climate change impacts were considered. The baseline analysis takes into account historical climate data with a locally calibrated model; whereas the other two LCCA approaches take into account climate change and future climate data with modified models. As mentioned in section 3.8, approach 1 compares the performance of the representative road sections under each of the climate change periods considered above. The initial conditions and input data, other than that associated with the climate, are kept constant. Approach 2, on the other hand, uses a continuous analysis to consider the commutative effects of traffic and climate change over the life-cycle period considered. Figure 4.5 depicts this process.

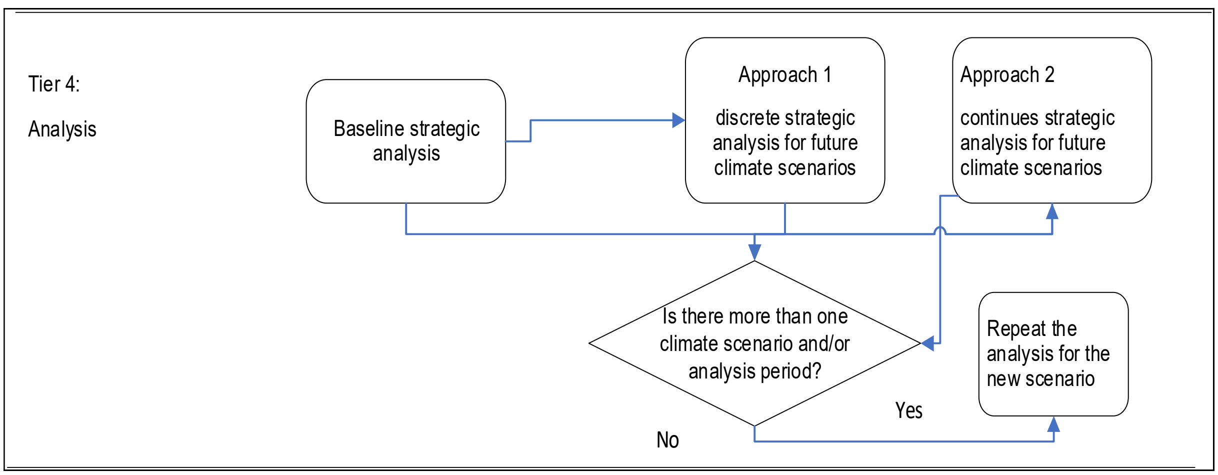


Figure 4.5 Analysis procedures for different scenarios in Tier 4

4.2.5. Output Interpretation and Presentation

The strategic analysis outputs, described above, for each combination of surfacing type, traffic level, maintenance strategy, climate zone, and future predicted climate are presented using a number of charts and tables. Approach 1 compares the difference between historical and predicted future climate analysis results, to interpret the analysis results in terms of the climate change effect alone. Approach 2 considers the cumulative effects of traffic and climate over a longer time period (44 years) for each of the analysis results. The results of the economic evaluation are presented in terms of NPV/cost ratio, pavement performance, RAC and RUC, for each case (Figure 4.6).

The NPV/cost ratio economic evaluation is used to identify the most appropriate type of pavement surface for each combination of traffic level and environment for both LCCA approaches. In contrast, the analysis of the road pavement performance for Approach 1 provides an insight into the physical effect of climate on the pavement surface. Also, the RAC metric forecasts the costs for anticipated maintenance and improvement projects that would be required as a result of climate change. Similarly, the RUC metric identifies the costs for the road users as a result of the climate change effect. The cost benefit analysis attempts to show the total transportation cost while taking changing conditions into account. However, for approach 2 the pavement performance, RAC and RUC are determined based on a cumulative or long term (44 years) of both climate and traffic actions together.

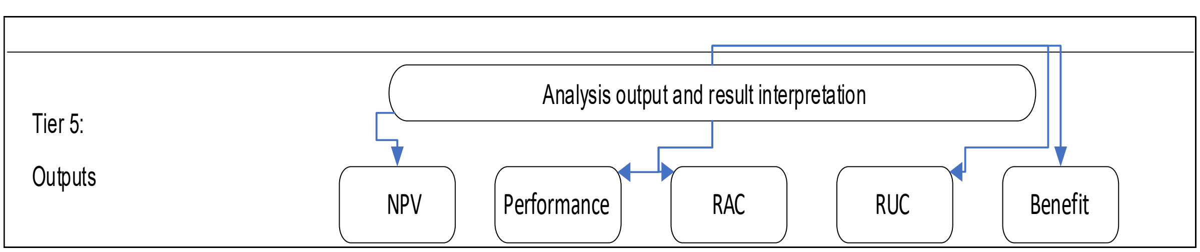


Figure 4.6 Analysis output and interpretation (Tier 5)

4.3. Summary

This chapter presents a five-tiered framework for assessing the impact of climate change on the LCC for various pavement surfacing using the HDM-4. The framework's first tier involved identifying those parameters using two or more scenarios. Following that, the second tier focused on categorising the input data based on the HDM-4 set-up, as pavement-related and climate-related data categories. The third tier included the simulation of the HDM-4 model to local conditions, followed by model adjustment for the selected climate changes. Climate change evaluations performed as strategic level analysis to determine the LCCA are found in the fourth tier. The expected analysis output presentations in terms of key results were indicated in the framework's fifth tier.

The next chapter presents the results of the analysis using this five-tiered framework.

CHAPTER FIVE - RESULTS

5.1. Introduction

This chapter presents the findings of the analyses which were conducted to address objectives four and five of the research stated in section 1.3.2. The chapter has five sections including this introduction (section 5.1). Section 5.2 of this chapter provides the HDM-4 road deterioration model calibration results. The results of the roughness model coefficients' adjustment for the considered climate change periods are presented in section 5.3. Then section 5.4 deals with the LCCA and presents the results using graphical means, and it also describes and discusses the economic analyses in terms of a variety of economic metrics, including NPV/cost ratio, RAC, RUC, and cost benefit. The engineering-related performances over the lifetime of the road pavements considered are also assessed in this section. Finally, section 5.5 summarises the chapter.

5.2. Calibration and Climate Adjustment Factors

As discussed in section 3.5.3 the calibration of the HDM-4 critical distress models was required in this research in order to replicate as accurately as possible the deterioration of the selected representative road sections. Following the application of the methodology described in section 3.5.3, Tables 5.1 and 5.2 present the calibration factors obtained for the flexible and rigid representative sections respectively. As shown in the tables, in some cases because of the lack of availability of data, mentioned in section 3.5.3, some of the calibrations had to be undertaken at Level 1.

Table 5.2 Calibration factor for each representative road section

Representative road sections							
Climate zone	Pavement type	Traffic level	Crack initiation K_{ci}	Crack progression K_{cp}	Rut depth progression K_{rp}	Roughness age environmental coefficient (K_{gm} /K_{ge})	Roughness progression factor K_{gp}
Arid	AC*	High	0.6	1.667	1.000	0.22	1.00
	AC*	Medium	0.6	1.667	1.00	0.22	1.00
	AC*	Low	0.6	1.667	1.00	0.22	1.00
	DBST *	High	0.6	1.667	1.00	0.22	1.00
	DBST *	Medium	0.6	1.667	1.00	0.22	1.00
	DBST *	Low	0.6	1.667	1.00	0.22	1.00
Semi-Arid	AC	High	3.96	0.25	0.12	0.17	1.90
	AC*	Medium	0.6	1.667	1.00	0.43	1.00
	AC	Low	0.67	1.5	0.19	2.84	1.88
	DBST	High	0.67	1.48	0.07	5.05	1.88
	DBST*	Medium	0.8	1.25	1.00	0.43	1.00
	DBST*	Low	0.8	1.25	1.00	0.43	1.00
Sub-Moist	AC	High	2.21	0.45	0.01	1.9	1.91
	AC*	Medium	1.1	0.91	1.00	0.43	1.00
	AC*	Low	1.1	0.91	1.00	0.43	1.00
	DBST	High	2.37	0.42	0.10	2.11	1.90
	DBST	Medium	2.2	0.45	0.29	1.15	1.91
	DBST	Low	0.38	2.57	0.38	4.37	1.88
Moist	AC*	High	1.1	0.91	1.00	0.87	1.00
	AC*	Medium	1.1	0.91	1.00	0.87	1.00

	AC*	Low	1.1	0.91	1.00	0.87	1.00
	DBST	High	2.4	0.42	0.13	2.52	1.90
	DBST	Medium	1.85	0.54	0.39	2.24	1.90
	DBST*	Low	1.1	0.91	1.00	0.87	1.00
	Otta seal*	Medium	0.9	1.11	1.00	0.45	1.00
Sub-Humid	AC*	High	1.1	0.91	1.00	0.87	1.00
	AC*	Medium	1.1	0.91	1.00	0.87	1.00
	AC*	Low	1.1	0.91	1.00	0.87	1.00
	DBST	High	2.4	0.42	0.13	2.52	1.90
	DBST	Medium	1.85	0.54	0.39	2.24	1.90
	DBST*	Low	1.1	0.91	1.00	0.87	1.00

Note 1. * Represents level I calibration carried out due to lack of sufficient data to carry out a level 2 calibration.

Table 5.2 Rigid pavement calibration (sub-humid climate zone)

Pavement type	**Traffic level**	**Calibration adjustment factor for**			
		Cracking	Faulting	Spalling	Roughness
JPCP	High	0.763	0.987	1.043	0.956
JRCP	High	-	0.793	0.703	0.930

5.3. Roughness Model Adjustment for Future Climate

As mentioned in section 3.7, the impact of climate change over time on pavement performance was modelled by adjusting the values of the global HDM-4 climate parameters (e.g. temperature, precipitation, TMI (Thornthwaite Moisture Index)) and also through recalibrating/adjusting the climate-related parameter (K_{gm}) in the roughness (RI) models for each representative road section. The values of the global HDM-4 climate parameters used for the analysis are shown in Appendix I.

The results of the linear regression analysis have showed that the environment component of the roughness has been consistently statistically significant ($p<0.05$), which means K_{gm} can express the climate change (Appendix K). As far as the climate-related parameter (K_{gm}) of the roughness deterioration model is concerned, Tables 5.3-5.7 show the values determined, using the methodology described in section 3.7, for the representative road sections in the five different climate zones considered (namely arid, semi-arid, sub-moist, moist and sub-humid) and for each of the climate periods (namely 2017-2029, 2030-2039, 2040-2049 and 2050-2059). As far as the arid climate is concerned, it was found that almost no adjustment was needed (< 1%) to the coefficient for the AC representative road sections for all traffic levels and all climate periods. Similarly, the coefficients for the DBST representative road sections also showed little adjustment (~ 2%) was required for all traffic levels and climate periods, with very slight increases of K_{gm} with traffic and time. This is to be expected because the arid climate has little rainfall.

Table 5.3 Climate adjustment factor (K_{gm}) for the arid climate zone

Period	AC						DBST			
	High traffic		Mid traffic		Low Traffic		Mid traffic		Low Traffic	
	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.
2020-29	1.000	1.001	1.000	1.000	1.002	1.002	1.001	1.000	1.008	.992
2030-39	1.000	.999	1.000	1.000	.999	.998	1.000	.999	.997	.992
2040-49	.999	1.001	1.000	1.000	.994	1.002	.998	1.001	.980	.980
2050-59	1.000	.998	1.000	1.000	1.007	.998	1.002	1.000	1.022	1.022

Note: sce. stands for climate emission scenario

Similar results were obtained for the representative road sections in the semi-arid climate category (Table 5.4). For both AC and DBST surfacing K_{gm} required adjusting by less than 2.5%, with very slight increases with increased traffic and time. Again, this is to be expected since not much precipitation is anticipated in the semi-arid region and the structural component of the K_{gm} will not be affected much by the traffic for AC low-volume roads.

Table 5.4 Climate adjustment factor for semi-arid climate zone

Period	AC						DBST			
	High traffic		Mid traffic		Low Traffic		Mid traffic		Low Traffic	
	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.
2020-29	1.001	1.000	.957	.997	.979	.999	.981	.999	.981	.999
2030-39	1.000	1.000	.968	.998	.988	.999	.986	.999	.986	.999
2040-49	1.001	1.002	.951	1.002	.981	1.001	.978	1.001	.978	1.001
2050-59	1.000	1.000	.944	.997	.979	.999	.975	.998	.975	.998

Note: sce. stands for climate emission scenario

In the sub-moist climate zone (Table 5.5), DBST surfacing K_{gm} required adjusting by less than 9.8%, for low traffic roads. The result is expected in this climatic zone since the climate change increases the moisture fluctuation in the sub-grade soil, hence the structural component of the roughness is affected.

Table 5.5 Climate adjustment factor for sub-moist climate zone

Period	AC						DBST			
	High traffic		Mid traffic		Low Traffic		Mid Traffic		Low Traffic	
	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.
2020-29	.999	.996	.993	1.003	.991	1.004	.999	1.000	1.028	1.000
2030-39	1.000	.996	.998	1.000	.997	1.000	1.000	1.000	1.020	1.015
2040-49	1.000	.996	.996	1.009	.995	.994	1.000	.999	1.013	1.098
2050-59	1.000	.996	1.009	0.993	1.010	.993	1.001	.999	1.063	1.098

Note: sce. stands for climate emission scenario

Table 5.6 shows the results obtained for the representative road sections in the moist climate zone. The result show that for low and medium traffic levels K_{gm} varies between 0.979 to 1.075 (i.e. about 10%) for AC representative road sections; between 0.995 and 1.015 for DBST (i.e. about 2%); and between1.000 and 1.006 for Otta seal (i.e. < 1%). The result for the high-traffic-volume road is expected, since due to the traffic load, its pavement is relatively strong and thicker to withstand the changes in climate. However, this is not the case for the medium and low-traffic-volume representative roads. Therefore, the fluctuation in projected precipitation (i.e. for the 1st climate period projected to be in the range of 38.98 mm to 37.60 mm, for the 2nd from 39.70 mm to 32.48 mm, for the 3rd from 37.57 mm - 36.38 mm, for the 4th from 34.19 mm - 35.09 mm, and for the 5th from 33.58 mm - 43.30 mm (Appendix I)) directly reflected on the k_{gm} as indicated in Table 5.6.

Table 5.6 Climate adjustment factor for moist climate zone

Period	AC						DBST						Otta-Seal	
	High traffic		Mid traffic		Low Traffic		High traffic		Mid Traffic		Low Traffic		Mid Traffic	
	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.
2020-29	1.000	1.002	.999	1.034	1.000	1.071	1.000	1.009	1.000	1.005	1.000	1.014	1.000	1.006
2030-39	1.000	1.002	.989	1.035	.990	1.074	.998	1.009	1.000	1.005	.998	1.015	1.000	1.006
2040-49	.999	1.002	.989	1.029	.979	1.064	.997	1.008	.999	1.005	.995	1.012	1.001	1.006
2050-59	1.000	1.002	1.006	1.030	1.009	1.064	1.001	1.008	1.000	1.005	1.001	1.012	1.000	1.006

Note: sce. stands for climate emission scenario

For the sub-humid climate zone, it was found that almost no adjustment was needed (< 1%) to the K_{gm} for the AC and DBST representative road sections for all traffic levels and all climate periods (Table 5.7). This is to be expected since the moisture content of the sub-grade soil is not affected by the fluctuation in projected precipitation as it is a wet zone.

Table 5.7 Climate adjustment factor for sub-humid climate zone

Period	AC						DBST	
	High traffic		Mid traffic		Low Traffic		Low traffic	
	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.	Max A2 sce.	Min A2 sce.
2020-29	1.000	1.000	1.000	.999	1.000	.996	1.000	.998
2030-39	1.000	1.000	1.001	1.001	1.007	1.002	1.003	1.002
2040-49	1.000	1.000	1.000	.999	1.000	.996	.999	.997
2050-59	1.000	1.000	1.004	.997	1.019	1.000	1.010	.999

Note: sce. stands for climate emission scenario

5.4. LCCA Results

Two approaches were used for the LCCA analysis as described in section 3.8. The first approach tried to compare five different climatic periods via a series of 15-year analysis periods. For the first approach, all HDM-4 input parameters, apart from those related to the different climate periods, were kept constant. The LCCA consisted of comparing compound maintenance alternatives with the do-minimum case (i.e. routine maintenance) (see section 4.2.1). The second approach evaluated road pavement and economic performance over a 44-year period consisting of five consecutive periods in time. During each period of time the parameters in the HDM-4 relating to climate were modified and the outputs from a preceding period of analysis were used as the inputs to the subsequent analysis (including for example traffic levels and pavement condition). For the second scenario the LCCA analysis involved comparing the minimum maintenance with the pre-set maintenance alternatives as described in section 3.8.2. The representative road sections considered were from the predefined road network matrices in Table 3.5 for each predefined representative road section category. The results of both of the approaches are presented below and discussed in detail in section 6.3.2 of the discussion chapter.

5.4.1. Approach 1

Pavement performance and therefore the results of any LCC are a function of the climate (see section 3.4). The following sections describe the results of the LCCA for the medium- and high-volume traffic AC, DBST, Otta seal, JPCP and JRCP representative road sections in moist and semi-arid climate zones. The results of the analysis for the other climate zones (arid, sub-moist and sub-humid) are summarised in Table 5.8 and section 5.4.3.

5.4.1.1. Moist Climate Zone with Medium Traffic Levels

5.4.1.1.1. Evaluation Based on NPV/Cost Ratio

As shown in Table 5.8, from the considered three pavement types (namely AC, DBST and Otta seal), two of the DBST representative road sections in the DBST M MT showed the highest NPV/cost ratios (namely B51-2 and B51-2a respectively) under the maintenance regime described in 4.2.1. While from the DBST representative road section (B51-3) it has been observed that it is not economically feasible for the actual traffic and climate conditions. The Otta seal pavement and two AC pavement representative road sections (A3-5 and A2-9) were shown to be economically feasible (i.e. NPV/cost ≥ 1). From the representative road sections, 50% of AC, 66.7% of DBST and 100% of Otta seal representative road sections can be considered to be economically viable (Figure 5.1).

The results were expected since only donor-funded projects are required to utilise a LCCA approach for selecting road pavement type. However, more than 60% (ERA, 2019) of the road projects were constructed by the government and the analysis indicated the lack of LCCA for these projects.

Figure 5.1 shows that the value of NPV/cost ratio for the analysed flexible pavement representative road sections varied from 2.32 to 3.55 and from14.34 to 23.85 for AC and DBST pavements respectively, depending on the climate change period, traffic level and the initial climate zone. It was found that the Otta seal pavement was economically viable with a positive NPV/cost ratio (10.87 to 11.91) for all climate periods considered.

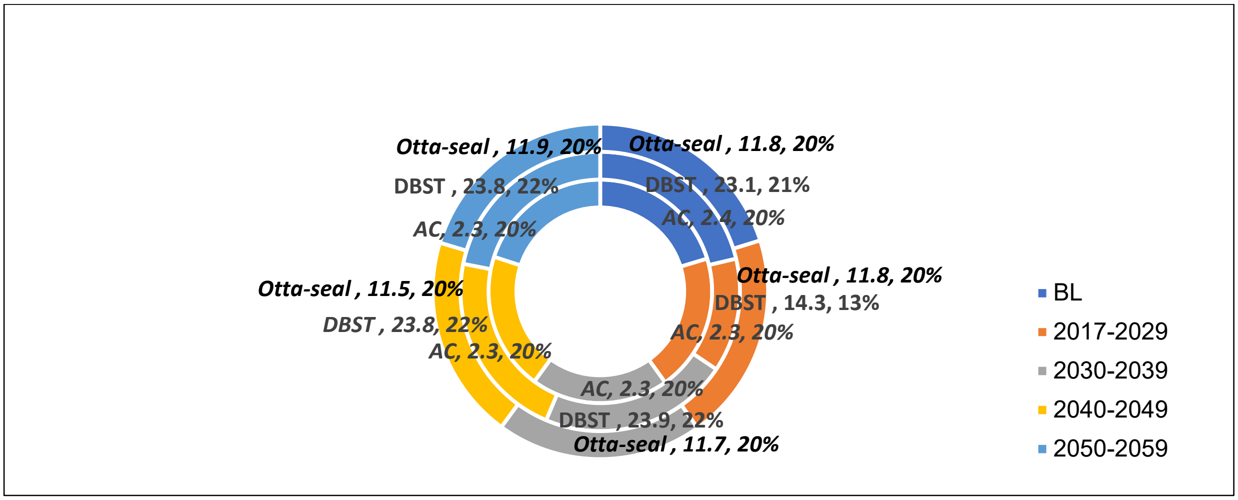


Figure 5.1 NPV/Cost ratio for AC, DBST and Otta seal representative road sections in the moist climate zone

Table 5.8 NPV/cost ratio results by climate zone

Climate zone	Representative road category for the representative road section	Pavement	NPV/cost ratio	For the climate zone
Arid high	AC A HT	AC only	1.38 to 0.69	This zone has 42.86% AC and 100% DBST positive NPV/cost ratio values
Arid low traffic	AC A MT DBST A MT	DBST	From the analysed representative road section 66.67 % of AC and 100% of DBST pavements have positive NPV /cost ratios. The maximum NPV /cost ratio obtained 3.76 to 2.79 for DBST, which is followed by 1.97 to 1.90 and 0.15 for AC.	
Arid mid traffic	AC A MT DBST A MT	AC	25% has positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 0.24 to 0.25 for AC followed by 0.13 for DBST.	

Moist low traffic	AC M LT DBST M LT	DBST	100% of AC and 100% of DBST pavements have positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 3.70 to 3.5 for DBST, which is followed by 0.41 to 0.40 for AC.	This zone has 84.62% AC and 83.33% DBST positive NPV value
Moist mid	AC M MT DBST M MT	DBST, Otta seal	50% of AC, 66.67% of DBST and 100% Otta seal pavements have positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 23.97 to 23.1 for DBST, followed by 12.42 to 12.00 for Otta seal and 3.3 to 2.32 AC.	
Moist high	AC M HT DBST M HT	AC	100% AC and DBST has positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 23.853 to 17.40 for AC followed by 11.21 to 11.40 for DBST.	
Semi-arid low traffic	AC S-A LT	DBST	66.66% of AC and 100% of DBST pavements have positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 1.453 to	This zone has 62.5% AC and

			1.448 for DBST, followed by 0.69 to0.55 for AC.	50% DBST positive NPV/cost ratio values 100% and 25% zero NPV/cost ratio values obtained for rigid and DBS pavements respectively
Semi-arid mid	AC S-AMT DBST S-A MT	DBST	33.33% of AC and 100% of DBST pavements have positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 10.45 to 10.36 for DBST, followed by 2.43 to 2.39 for AC.	
Semi-arid high	AC S-A HT DBST S-A HT JPCP S-A HT JRCP S-A HT	AC	100% positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 24.25 to 22.9 for AC and zero for DBST. In addition to this, zero NPV value obtained for the two rigid pavements.	
Sub-humid low traffic	AC S-H LT DBST S-H LT	DBST	100% of AC and 100% of DBST pavements have positive NPV/cost ratio value. The maximum NPV/cost ratio obtained was 4.13 to	This zone has 75% AC and

			4.08 for DBST, followed by 0.72 to 0.69 for AC.	100% DBST positive NPV/cost ratio value
Sub-humid mid	AC S-H MT DBST S-H MT	AC only	has positive NPV/cost ratio value. The maximum NPV/cost ratio obtained was 5.78 to 5.72, 62.5% for AC	
Sub-humid high	AC S-H HT DBST S-H HT	AC only	100% positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 19.5 to 19.42 for AC	
Sub-moist low traffic	AC S-M LT DBST S-M LT	DBST	100% of AC and DBST pavements have positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 10.03 to 9.86 for DBST, followed by 0.69 to 0.55 for AC.	This zone has 77.78% AC and 50% DBST positive NPV/cost ratio value
Sub-moist mid	AC S-M MT DBST S-M MT	DBST	66.67% of AC and 100% of DBST pavements have positive NPV/cost ratio value. The maximum NPV/cost ratio obtained 5.00 to 5.56 for DBST, followed by 4.01 and 0.2 for AC (2).	

Sub-moist high	AC S-M HT DBST S-M HT	AC	75% positive and zero NPV/cost ratio value for AC and DBST respectively. The maximum NPV/cost ratio obtained 24.25 to 22.9 for AC.

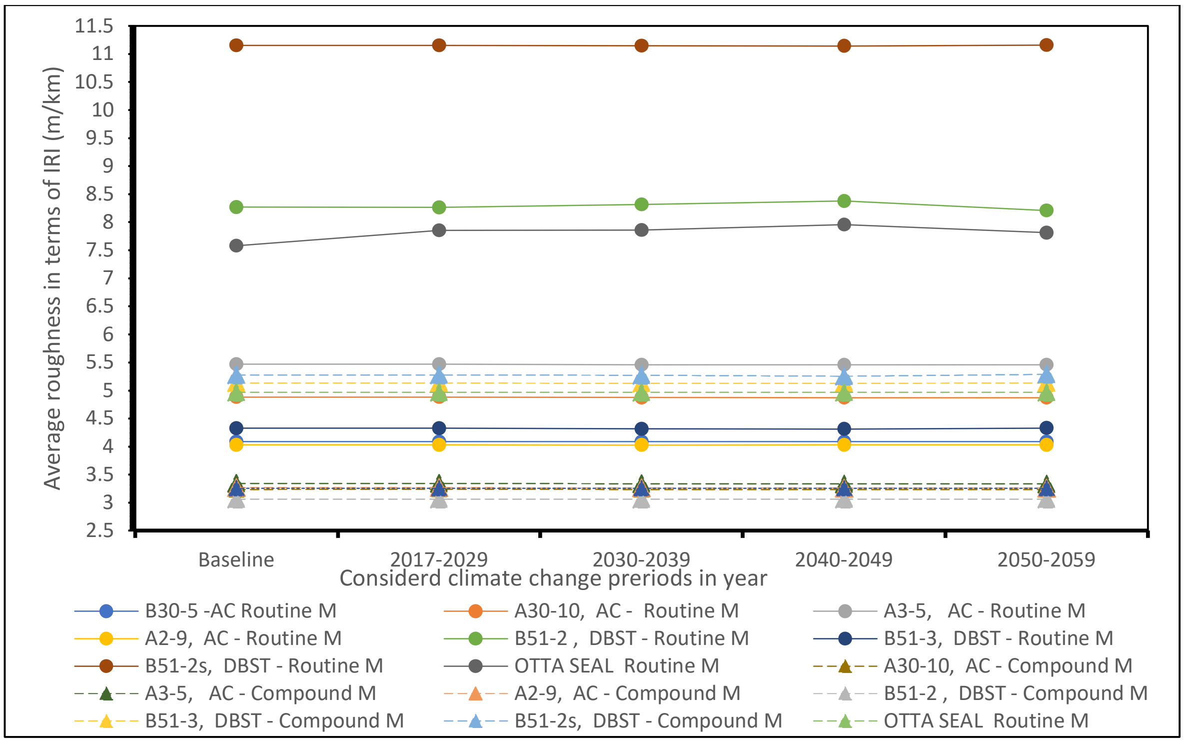
5.4.1.1.2. Pavement Performance

In order to compare the predicted performance, in terms of deterioration of DBST, Otta seal and AC pavements, a total of eight road sections were selected from the ERA road network (from AC M MT, DBST M MT, and Otta seal) with initial pavement conditions which fall in the range of good to fair. For the purpose of this research, a pavement in good condition was considered to be one with a value of between 1.0 m/km and 3.5 m/km, and one in a fair condition was considered to have an IRI value of between 3. 5 m/km and 5.5 m/km (HITCON Engineering, 2018).

The analysis was conducted for the four climate periods mentioned in section 3.8 and compared a zero-maintenance scenario, with routine maintenance (i.e. patching damaged, crack sealing, drainage cleaning, miscellaneous activities) and a compound maintenance standard (i.e. preventive maintenance surface dressing, bituminous overlays structural, bituminous rehabilitation), under 100%, 85% and 60% unconstrained budget.

A road section by road section comparison is given in Figures 5.2 to 5.3. These Figures show the average roughness for each of the five climate periods, for the representative road sections carrying medium traffic levels. Figure 5.2 shows the roughness levels when the high emissions' scenario was used to calculate climate change inputs; and Figure 5.3 shows the same when the low emissions' scenario was used. The main findings from the figures are as follows:

1. The average roughness value for similar traffic growth for 15 years of analysis but with different climate change showed small changes in roughness for the three road pavement surfaces namely AC, DBST and Otta seal in the moist climate zone.
2. The average roughness trend showed a small increment due to the climate change effect, even though routine maintenance was applied to all (AC, DBST and Otta seal) the representative road sections.
3. The average roughness trend shows that applying proper maintenance will control the effect of climate for all representative sections (Figures 5.2 and 5.3)



Note: M is for maintenance

Figure 5.2 The trend of average roughness for moist climate zone with mid-traffic level considering maximum A2 emission scenario vs. climate change periods

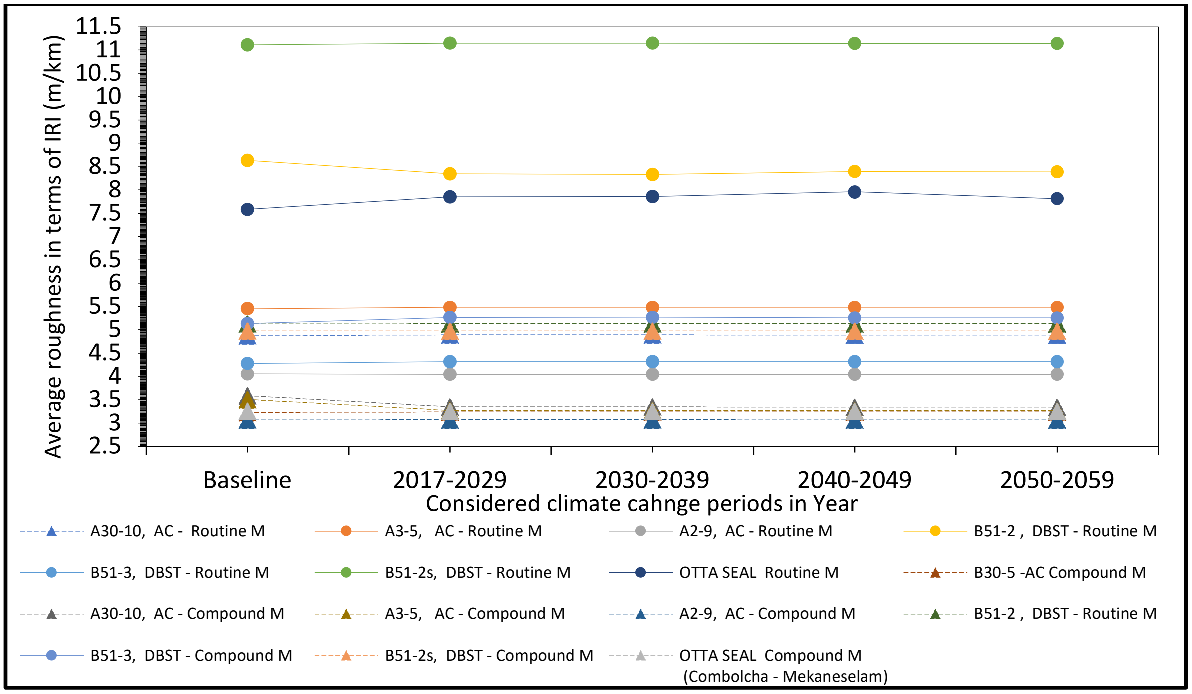
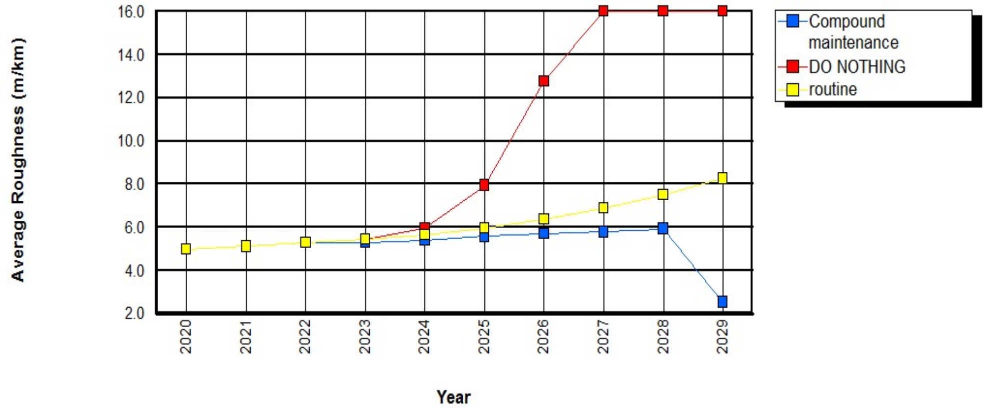
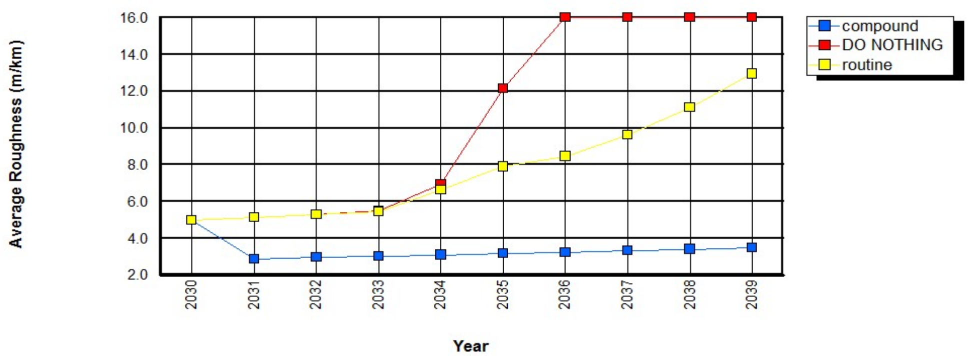


Figure 5.3 The trend of average roughness for moist climate zone with mid-traffic level considering minimum A2 emission scenario vs. climate change periods

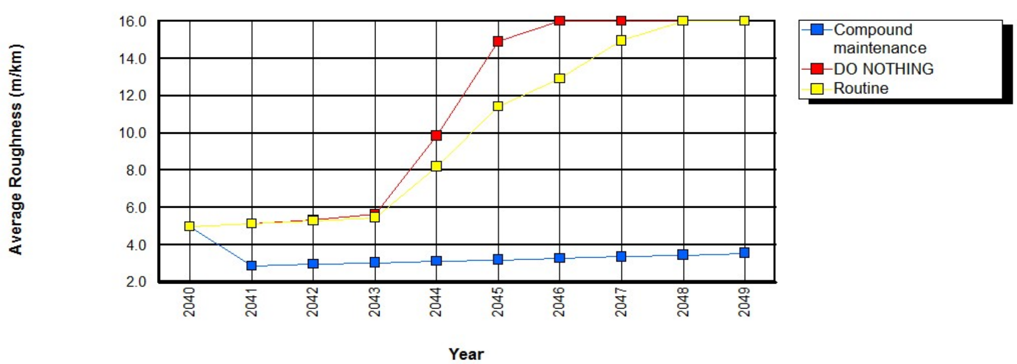
In order to demonstrate roughness progression in detail, a typical HDM-4 output showing roughness progression over time for an Otta seal road section initially in fair condition, under the minimum A2 emission scenario, and initially in the moist climate zone is shown in Figure 5.4.



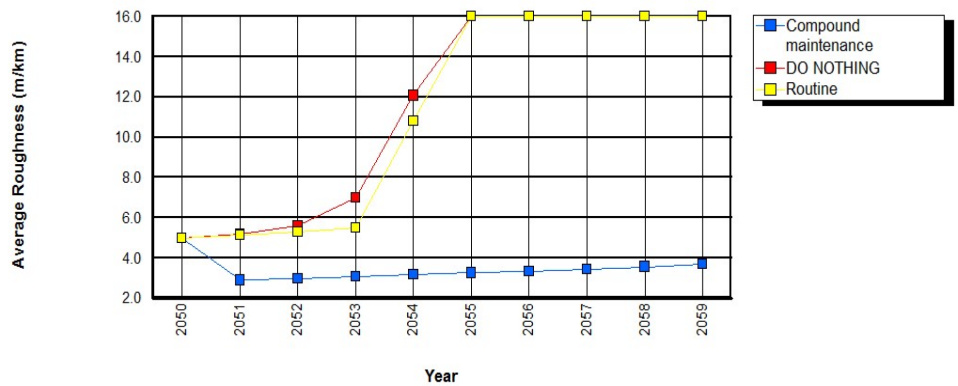
a) For 2020-2029 climate period



b) For 2030 to 2039 climate period



c) For 2040 to 2049 climate period



d) For 2050 – 2059 climate period

Figure 5.4 Typical HDM-4 roughness analysis section output (sample from Otta seal section)

The following main findings can be drawn from Figure 5.4 (a to d).

(i) The effect of climate change on the deterioration of the Otta seal pavement can be seen by comparing the roughness progression for the scenarios without maintenance (i.e. red line, do-nothing case). For the climate period 2020-2029 the roughness increases from 5 m/km to 16 m/km (the maximum) in the seventh years of the first 10 years' analysis. For the period 2030 – 2039 it increased from 5 m/km to 16 m/km in the sixth year of the second 10 years' analysis. For the period 2040 – 2049 it increased from 5 m/km to 16 m/km in the sixth year of the third 10 years' analysis; and for the period 2050 – 2059, it increased from 5 m/km to 16 m/km in the fifth year of the fourth 10 years' analysis. It is therefore evident that climate change appears to increase the rates of roughness progression.

(ii) For all five climate periods routine maintenance slows the rate of deterioration. For the climate period 2020-2029 the roughness increases 5 m/km to 8.4 m/km (the maximum) in 10 years. For the period 2030-2039 it increased from 5 m/km to 13 m/km in the next 10 years. For the period 2040-2049 it increased from 5 m/km to 16 m/km in the ninth year of the third 10 years' analysis; and for 2050-2059 it increased from 5 m/km to 16 m/km in the fifth year of the fourth 10 years' analysis. Nevertheless, it is apparent that despite routine maintenance the impact of climate change on road deterioration is still evident.

(iii) The selected compound maintenance standards are effective in maintaining the road condition to a good to fair condition for the duration of the analysis. For all periods considered, the initial roughness (5 m/km) changed gradually to 3.5 at the end of the 10 years' period of analysis. However, this required significant road agency cost which increased for each of the climate periods analysed (see section 5.4.1.1.3).

Figures 5.5 and 5.6 show the performance of four AC, three DBST and one Otta-seal representative road sections for high and low A2 emission scenarios, respectively. In both figures the effects of routine and compound maintenance standards are shown and comparison is made between the change in average roughness with respect to the baseline average roughness (rather than in absolute roughness terms) for the five climate periods.

From Figure 5.5 it can be seen that the Otta-seal sections show greater predicted changes in roughness compared to the DBST and AC sections, although the average changes in all cases are very small. The maximum average predicted roughness change with respect to the baseline period for Otta seal varies from -0.087 IRI m/km to 0.378 IRI m/km, and for the DBST from -0.007 m/km to 0.137 m/km for the 2040 to 2049 climate period.

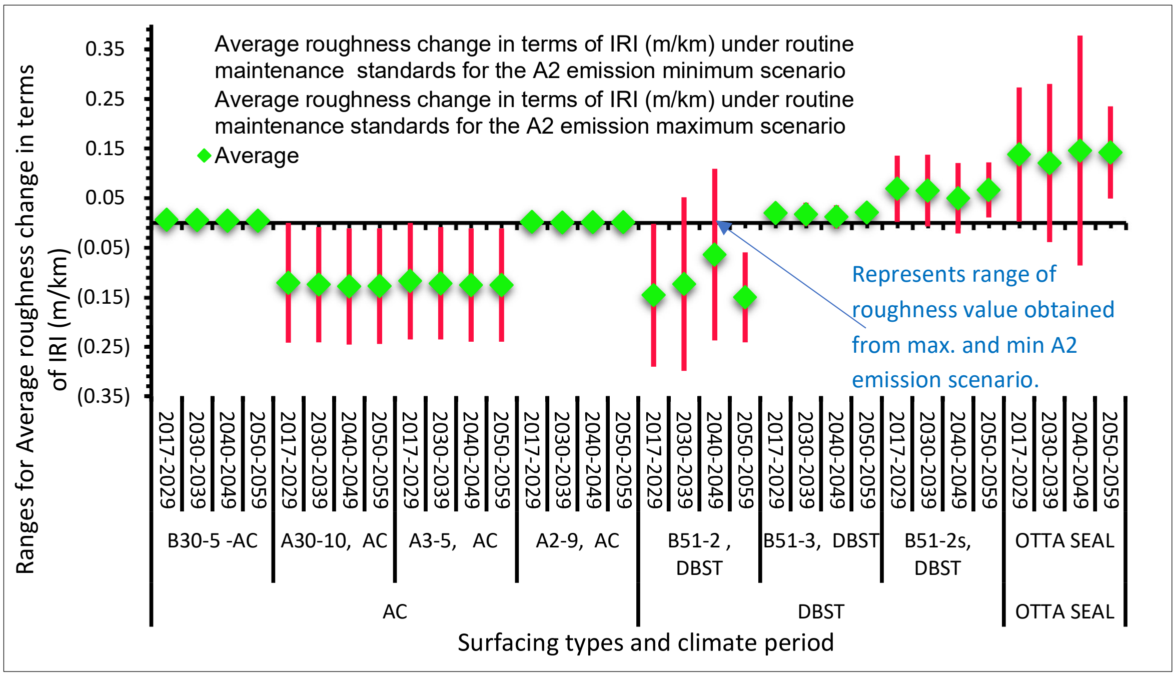


Figure 5.5 Ranges for change in average roughness for the case where routine maintenance was applied

From Figure 5.6 it may be seen that maintenance application controls the climate change effect. One of the DBST sections (B51-3) showed the change in the average roughness deterioration increased up to 0.036 IRI m/km, while zero and negative changes were observed for all other pavements.

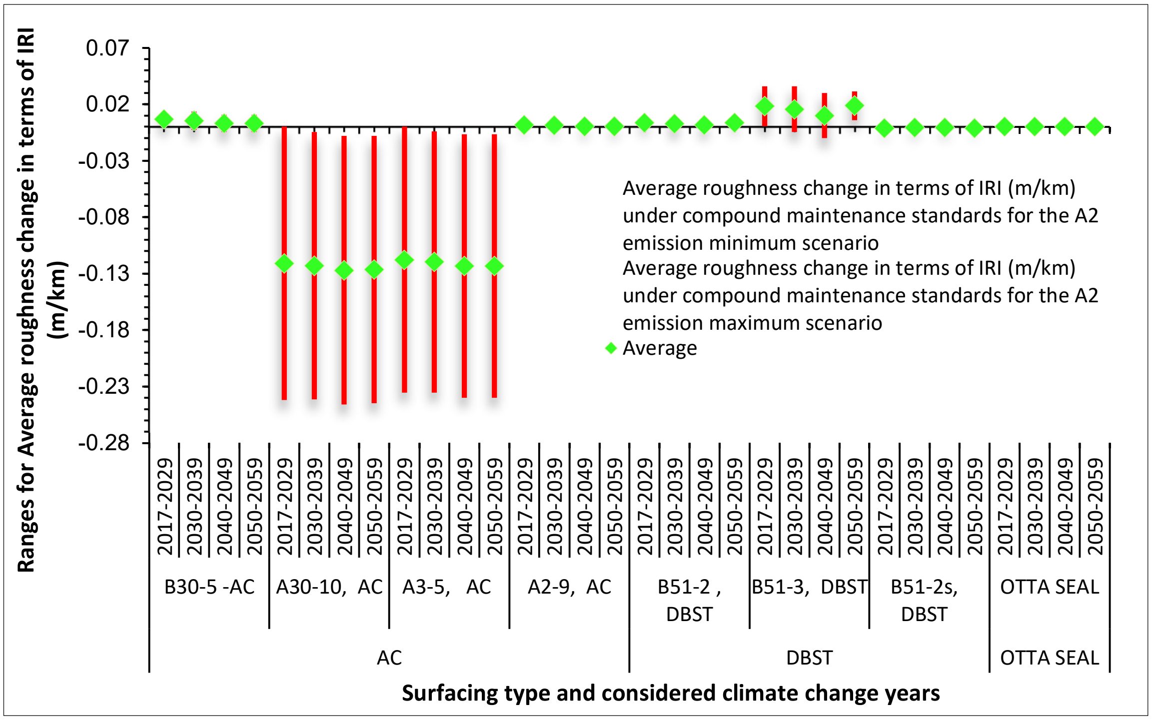


Figure 5.6 Ranges for change in average roughness for the compound maintenance standard

In order to assess the impacts of climate change on road deterioration an analysis was undertaken of the change compared to the baseline (without climate change) in average performance for the maximum and minimum A2 emission scenarios, when compound and routine maintenance standards were applied (see Table 4.1). It should be noted that change in this case means the difference between the pavement performance obtained by using the current practice with current climate condition, to that of the pavement performance obtained by a different climate period consideration. Figures 5.7 and 5.8 present the results for representative road sections initially in the moist climate zone, carrying medium levels of traffic. The results for the other sections are presented in Appendix L. Figure 5.7 shows that Otta seal had the highest change in average deterioration, with changes in IRI values compared to the baseline ranging from 0.23 m/km to 0.4 m/km from the period 2017 to 2059 when routine maintenance is applied under the routine maintenance option. Under similar conditions, the change in average deterioration was lower for DBST (0.122 m/km to 0.137 m/km IRI values respectively). Small changes in deterioration were observed for one of the AC pavements (i.e. section A30-5); while the others did not show any change in deterioration associated with a change in climate.

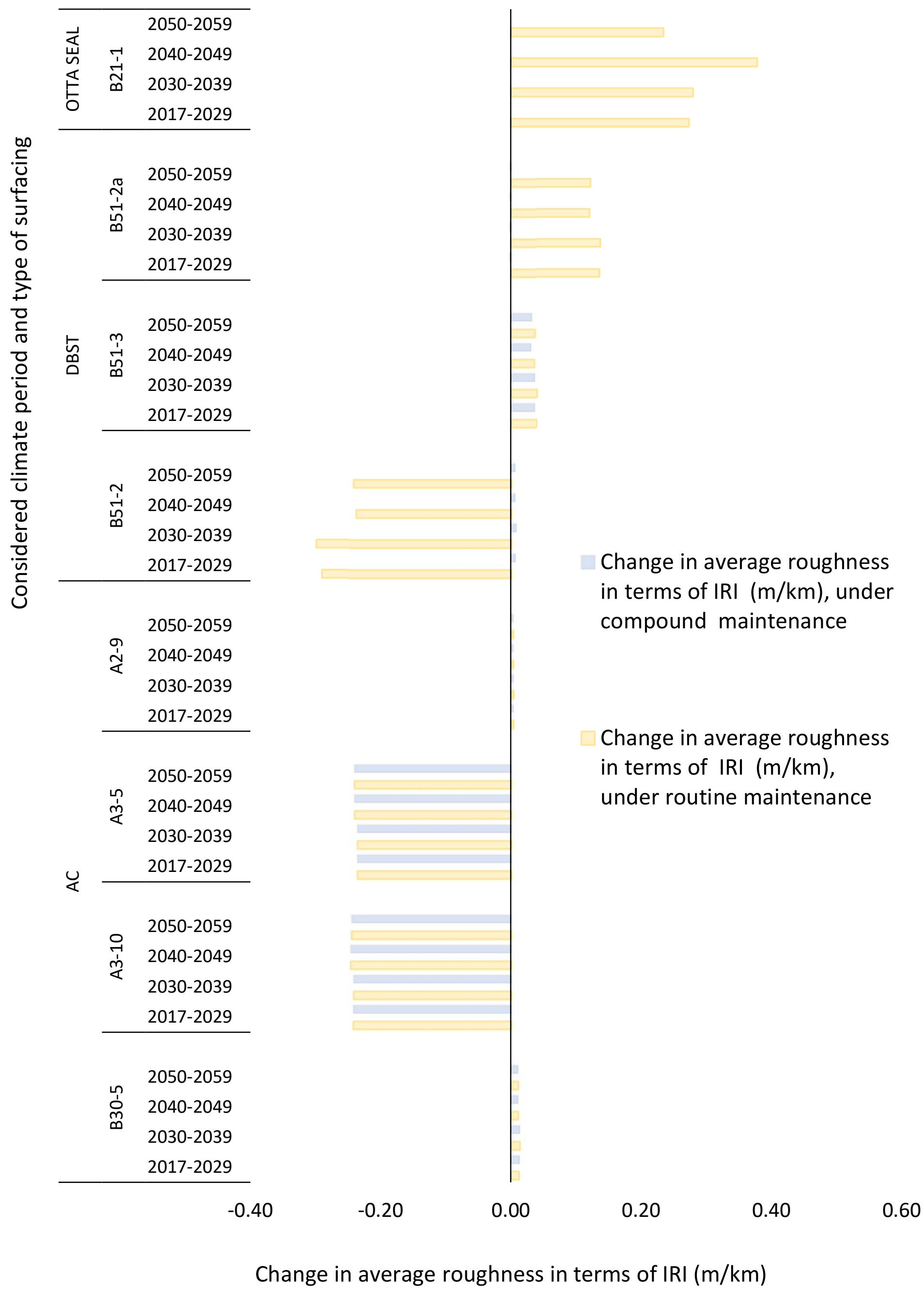


Figure 5.7 Change in pavement performance under minimum A2 emission scenario

(Change refers to roughness value obtained by current climate analysis (base condition) compared to the roughness value obtained from climate change analysis)

Similarly, Figure 5.8 shows the change in average performance under the maximum A2 emission scenario. High and medium changes in average deterioration were obtained for DBST and Otta-seal pavement surfacing, (changes in IRI values ranged from 0 m/km to 0.11 m/km and 0 m/km to 0.05 m/km, respectively), during the 2017-2059 period when routine maintenance was applied. Conversely, AC pavement surfaces were found to be resilient to the change under this climate category with 0 m/km IRI values, provided routine maintenance was undertaken. Moreover, only a slight change in IRI values due to the compound maintenance strategy, considering maximum and minimum A2 emission scenarios, was found for the AC and DBST pavements (0.00 to 0.006 m/km and 0.00 to 0.036 m/km).

The maximum difference in performance for the maximum and minimum A2 emission scenarios ranged from 0.05 m/km to 0.38 m/km, 0.11 m/km to 0.14 m/km and 0 m/km to 0.01 m/km for Otta-seal, DBST and AC pavements, respectively; where the maximum difference in performance is defined as the maximum difference between the baseline average roughness value obtained by using current climate, and that of the average roughness value due to climate change.

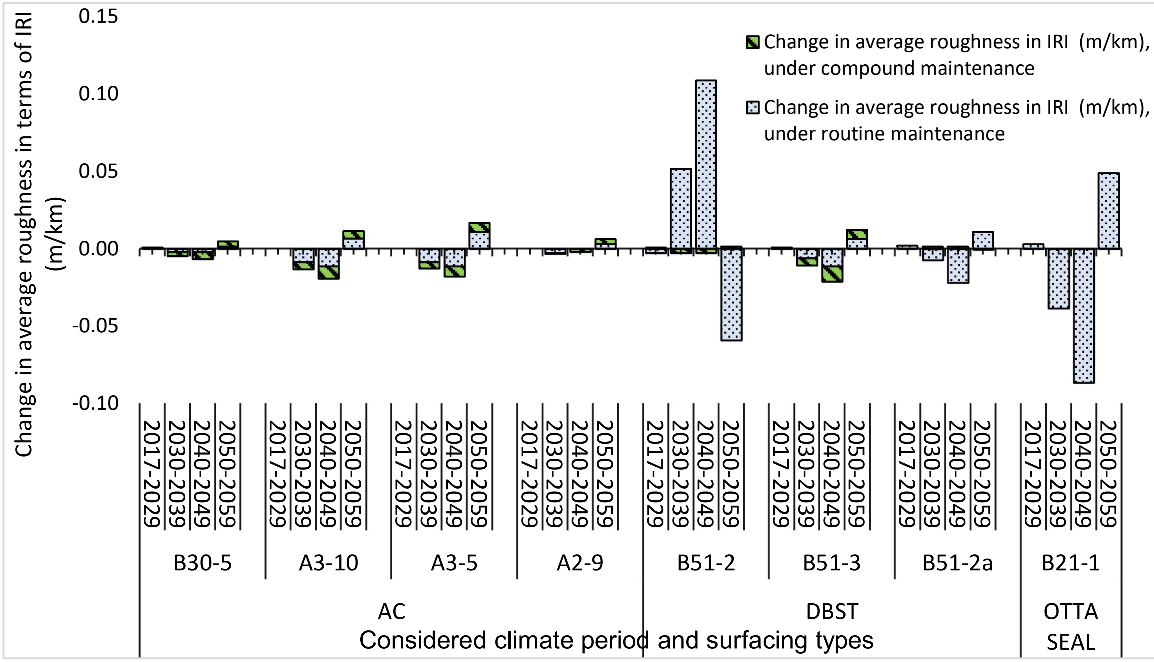


Figure 5.8 Change in pavement performance under maximum A2 emission scenario

5.4.1.1.3. Road Agency Costs (RAC)

The highest RACs were associated with AC pavements due to climate change for both maintenance alternatives; whereas the lowest RAC was obtained for the Otta-seal section for similar conditions. Moreover, the agency will not be affected by the additional deterioration caused by climate change for maximum and minimum A2 emission scenarios in AC and DBST pavement types. That means the RAC for the baseline condition with the current climate and for different climate change considerations for the three pavements were the same. However, for the Otta-seal pavement the road agency would need to allocate additional budget to take into account the impacts of climate change, if the road agency wanted to utilise the same maintenance approaches (Figure 5.9).

The highest RAC due to routine maintenance was obtained for the AC pavements and the range was from 0.436 million Ethiopian Birr (ETB)/km to 0.444 million ETB/km (£10,746.88/km to £10,944.07/km) for the max. and min. A2 emission scenario. Whereas the lowest RAC range (0.017 million ETB/km to 0.356 million ETB/km (£419.03/km to £8,774.98/km)) was obtained for the Otta-seal section and for DBST the range of costs was 0.355 million ETB/km to 0.367 million ETB/km (£8,750.33/km to £9,046.12/km).

In the case of applying ERA's usual compound maintenance standards, the road agency would be required to spend the highest amount for AC pavement sections with the discounted cost values ranging from 0.542 to 7.903 million ETB/km (£13,359.66/km to ₤194,799.59/km) for the max. and min. A2 emission scenario. While for DBST and Otta-Seal representative road sections, the associated costs would be 0.879 million ETB/km to 4.978 million ETB/km (₤21,666.31/km to ₤122,701.81/km) and 0.055 million ETB/km to 1.170 million ETB/km (₤1,355.68/km to ₤28,839.11/km), respectively for the max. and min. A2 emission scenario. These values related to the maximum difference for the representative road section performance for maximum and minimum A2 emission scenarios, which was in the range of 0.05 m/km to 0.38 m/km, 0.11 m/km to 0.14 m/km, and 0 m/km to 0.01 m/km for Otta seal, DBST and AC pavements, respectively.

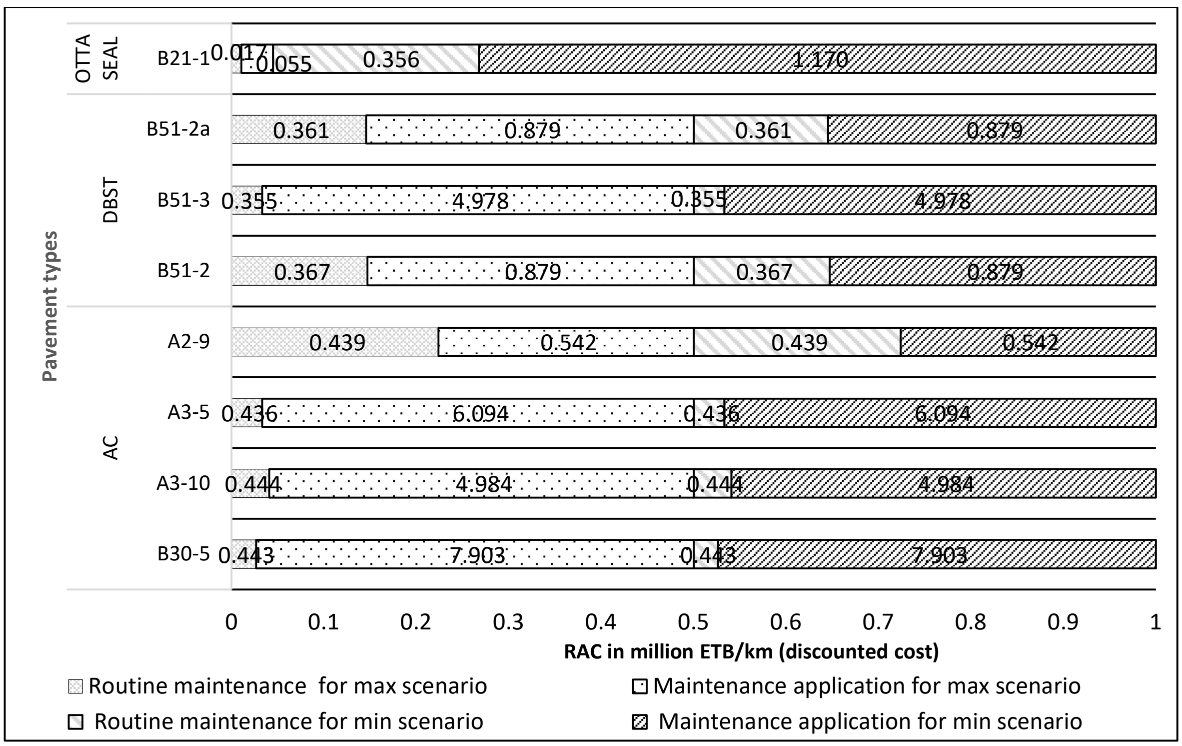


Figure 5.9 Comparison of RAC for different climate and maintenance scenarios

An analysis was carried out to investigate the climate change associated cost impacts when different maintenance standards were applied, and for budgets of 60%, 85% and

100% of the unconstrained budget. The maintenance alternatives considered were renewal, rehabilitation, reconstruction, compound and routine maintenance (see Table 4.1). Similar results were observed for the representative road sections for different budget scenarios, and therefore for demonstration purposes a typical result for an Otta seal representative road section is presented in Figure 5.10. This Figure shows the results of optimisation analysis (which provides the best economical alternatives by comparing different maintenance alternatives for the specified budget) in terms of the present value of the agency cost, increase in agency cost, and decrease in user cost for the climate periods. The maximum present value of the agency cost and increase in agency cost was obtained for the renewal alternative 408.47 million ETB (£10,067,968.56) and 407.89 million ETB (£10,053,672.72) for the period of 2050-2059. Moreover, the compound maintenance showed a minimum present value of the agency cost, and an increase in the agency cost of all other maintenance alternatives.

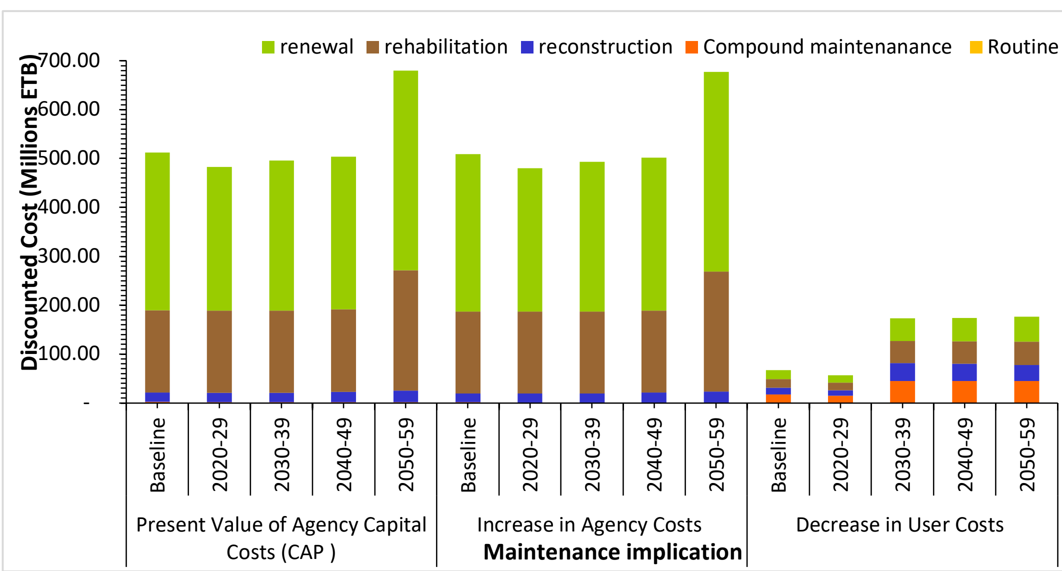


Figure 5.10 Comparison of different maintenance alternatives for Otta seal

Figure 5.11 shows comparison results using an increased in agency cost for AC, DBST, and Otta-seal surfacing after maintenance optimisation. As expected, the renewal alternative showed the maximum increase in agency cost with respect to routine, compound, rehabilitation and reconstruction, i.e. of 18,378,78 million ETB (£453.00 million) for the DBST representative road section for the period of 2020-2029. Whereas for the AC surfaced road section, the maximum increase in agency cost with respect to renewal was 6168.41 million ETB (£152.04 million) (in the period of 2050-2059). For the same maintenance alternative, the Otta-seal surfacing showed the smallest increment in agency cost (i.e. 407.89 million ETB (£10.05 million)).

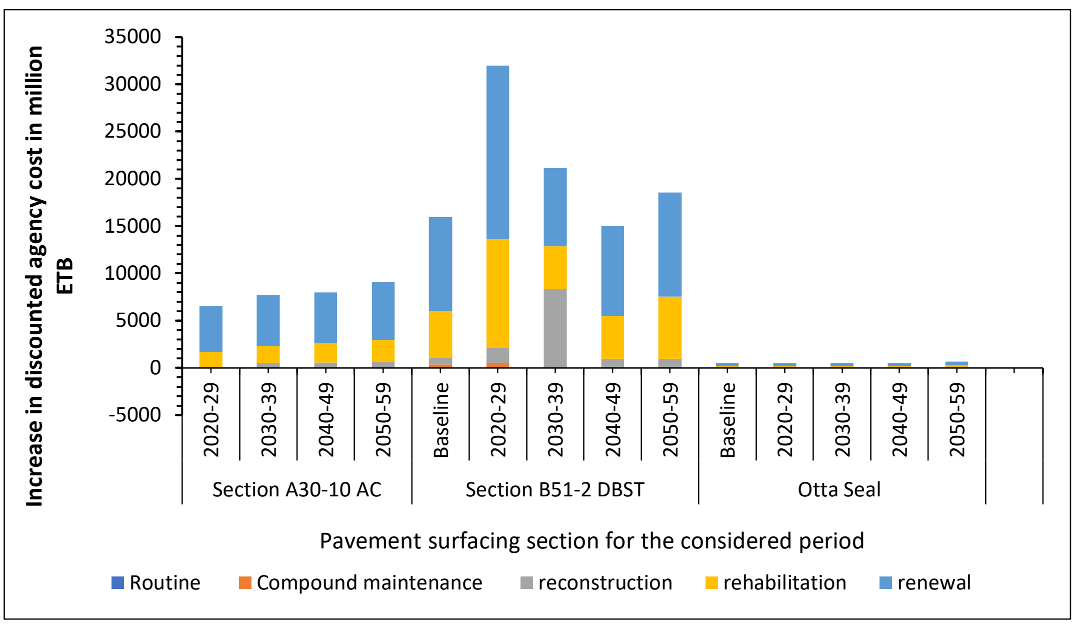


Figure 5.11 Comparison by increase in discounted agency costs

5.4.1.1.4. Road User Costs (RUC)

Unlike the RAC, the RUC showed some variation with the change of average roughness which resulted from change of climate. The lowest additional cost for the road user was obtained for the Otta-seal road representative section under compound maintenance application in both climate scenarios as shown in Figures 5.12 and 5.13. However, for the routine maintenance option, road user costs are highest for DBST surfaced roads (Figure 5.12).

Figure 5.12 also shows that the lowest additional road user cost due to climate change was for the Otta-Seal pavement section. The range for the change in road user cost was obtained by comparing discounted RUC climate change results with that of the baseline (current/without climate change). The cost for the user was found to be in the range of 0.00 ETB/km to 0.01 million ETB/km (£0/km to £246.49/km) for routine maintenance for the maximum A2 scenario. For DBST pavements under similar scenarios, the user costs rise from 0 ETB/km to 0.13 million ETB/km (£0/km to £3,204.35/km) in the representative road sections as compared to the baseline (current/without climate change). The result showed an increase in the RUC for AC and DBST road sections in similar emission scenarios when the compound maintenance standard was applied. The increased costs were in the range of 0 ETB/km to 0.14 million ETB/km (£0/km to £3,450.83/km) for AC and from 0 ETB/km to 0.05 million ETB/km (£0/km to £1232.44/km), for DBST. These increased costs are obtained by comparing the climate change result of RUC to the baseline (current/without climate change) and the results are associated with the change in average roughness; which ranged from 0.05 m/km to 0.38 m/km, 0.11 m/km to 0.14 m/km and 0 m/km to 0.01 m/km for Otta-seal, DBST and AC pavements for the maximum and minimum A2 emission scenarios (section 5.4.1.2).

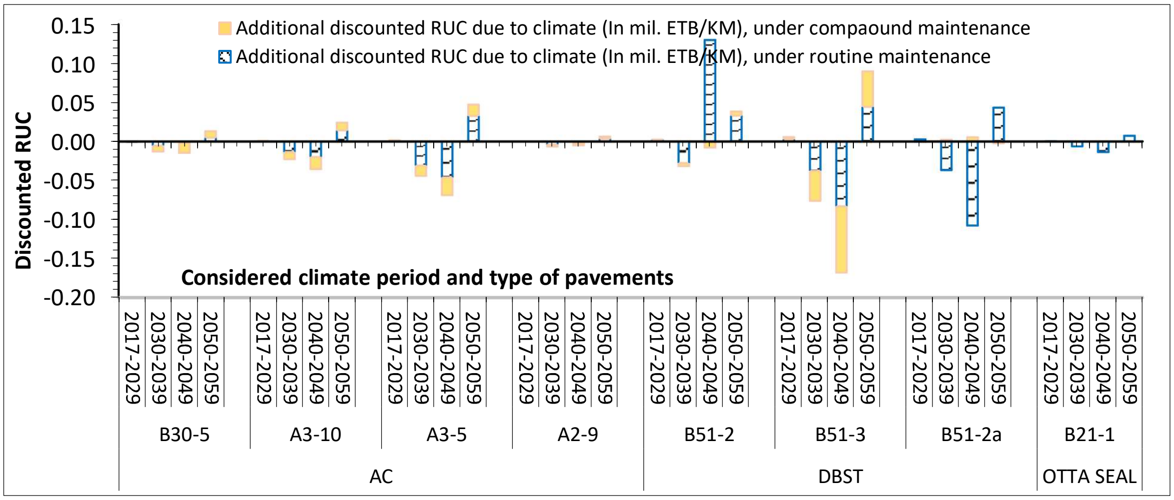


Figure 5.12 Assessment of discounted RUC due to future climate under max A2 emission scenario

The results of the analysis under the minimum A2 emission scenario are shown in Figure 5.13. The maximum incremental (the positive difference between the climate change result of discounted RUC to the baseline (current without climate change)) user cost occurs for the routine maintenance alternative for DBST surfacing. This cost ranges from 0 ETB/km to 1.57 million ETB/km (£0/km to £38,698.64/km). Similarly, for Otta-seal and the AC surfaced sections the values obtained were between 0.74 ETB/km and 0.896 million ETB/km (£18,240.01/km to £22,085.21/km) and between 0 ETB/km and 0.03 million ETB/km (£0/km to £739.46/km)) respectively.

When applying the more rigorous schedule of compound maintenance, the maximum and medium additional (the positive difference between the climate change result of discounted RUC to the baseline (current/without climate change)) road user costs were in the range of 0 ETB/km to 0.03 ETB/km (£0 /km to £739.46 /km) for AC, and 0.02 ETB/km to 0.30 ETB/km (£492.98/km to £7,394.64/km) for DBST pavements respectively. There was no additional (with respect to baseline (current/without climate change)) road user cost for the Otta-seal section for the compound maintenance alternative application.

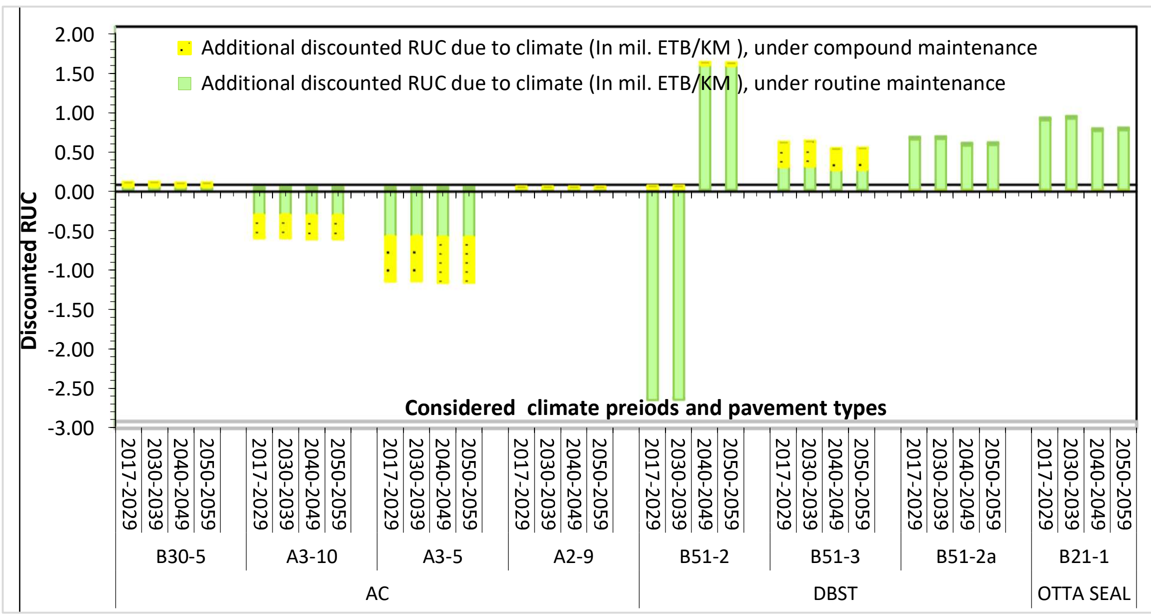


Figure 5.13 Assessment of discounted RUC due to future climate under min A2 emission scenario

5.4.1.1.5. The Total Net Benefit Analysis Measurement

For each representative road segment, the total net benefit analysis was calculated (Figure 5.14 and 5.15) for both maximum and minimum A2 emission scenarios. For evaluation purposes, the total net benefit cost is normalised against the length of each road-segment. The results show that the maximum net benefit was between 20.96

million ETB/km and 21.02 million ETB/km (£516,639.18/km to £518,118.11/km) for DBST; between 13.57 million ETB/km and 13.91million ETB/km (£334,484.43/km to £342,865.03/km) for the Otta-seal section; and between 1.99 million ETB/km and 2.02 million ETB/km (£49,051.14/km to £49,790.61/km) for the AC sections.

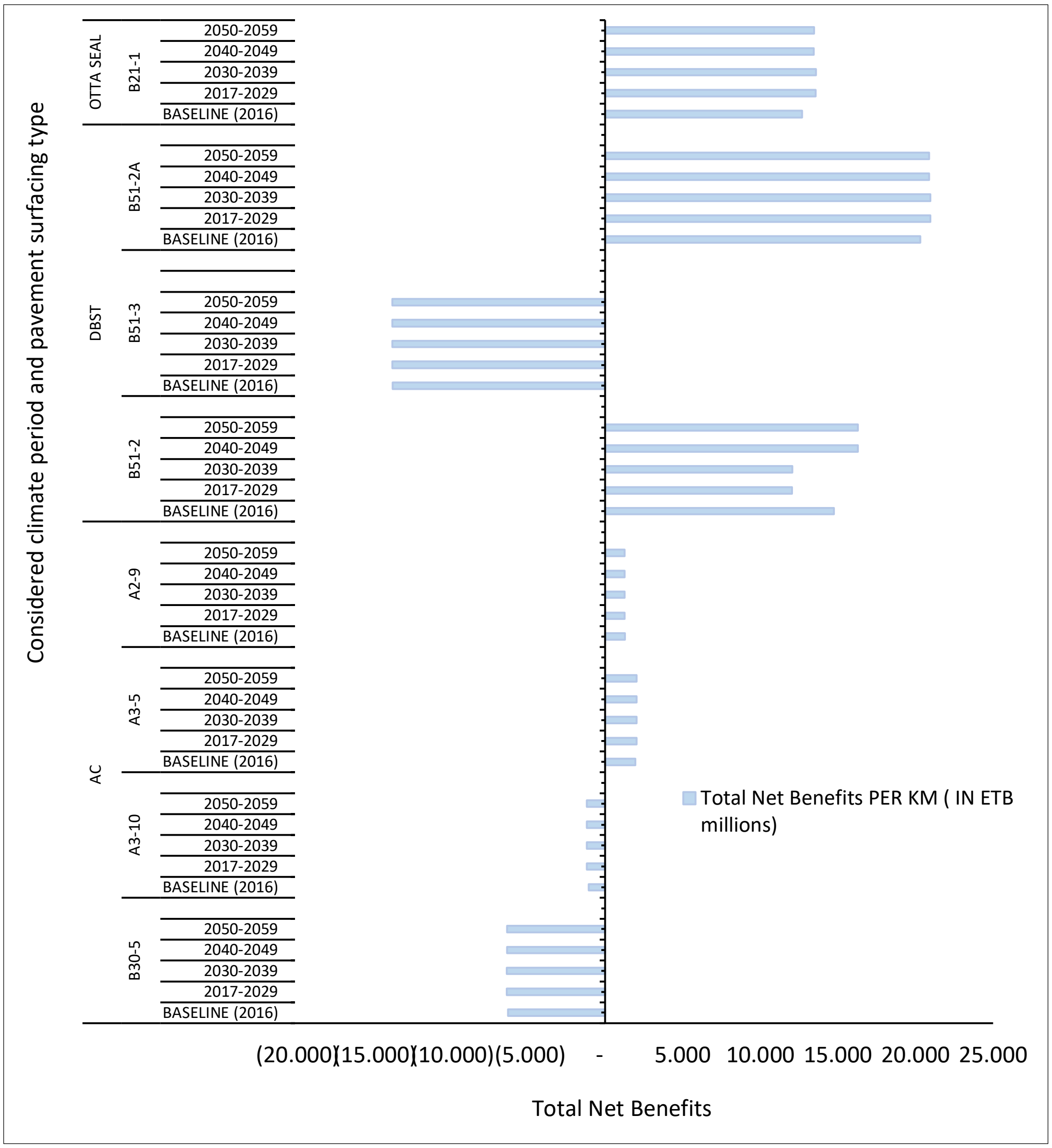


Figure 5.14 Total net benefit maximum A2 emission scenario

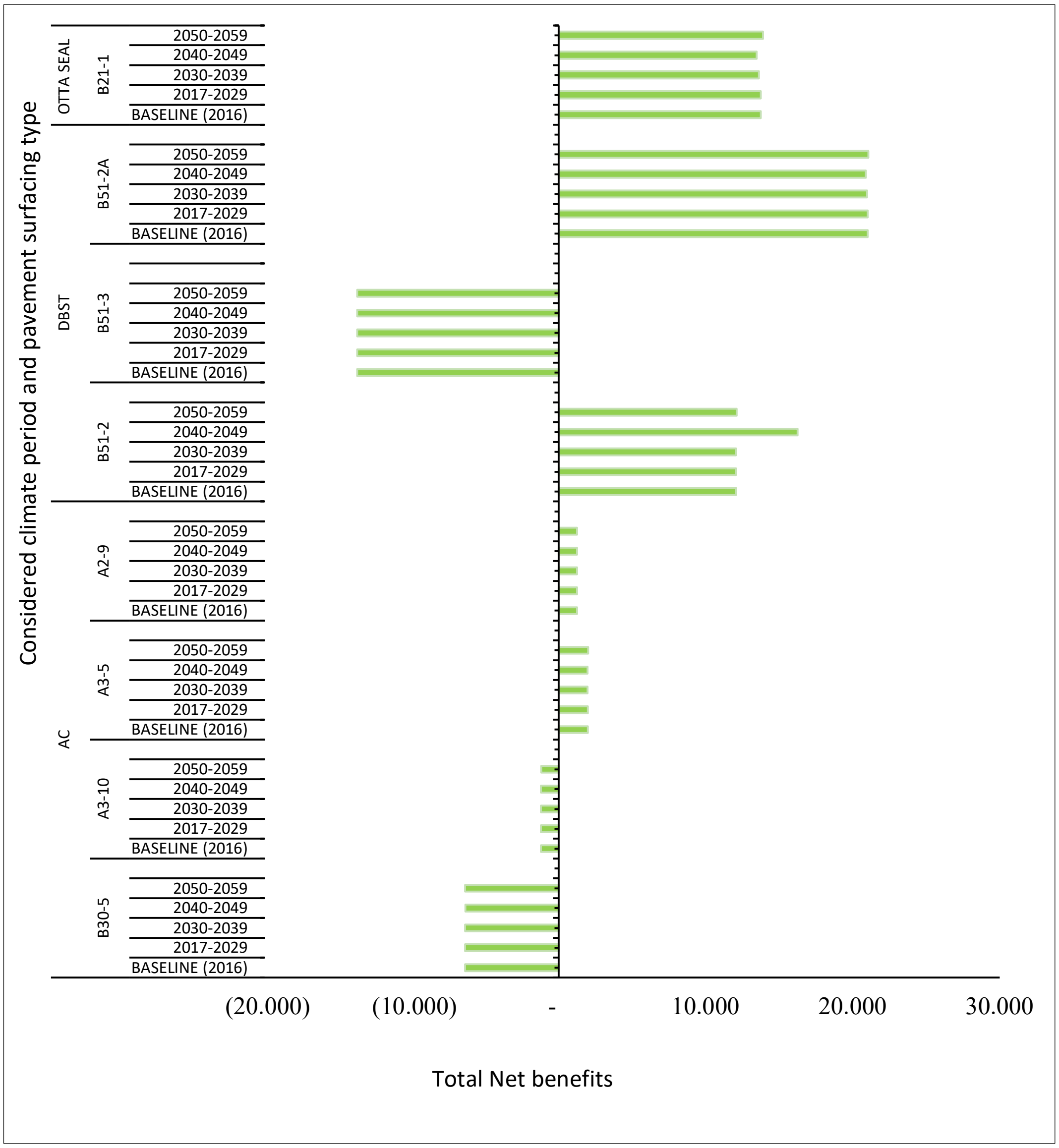


Figure 5.15 Total net benefit minimum A2 emission scenario

5.4.1.2. Semi-Arid Climate Zone with High Traffic Levels

5.4.1.3.1. NPV/Cost Ratio

The analysis revealed that AC pavements carrying high traffic levels will be more climate resilient and economically suitable and have higher NPV/cost ratios than DBST, JRCP and JPCP road sections. The NPV/cost ratios determined showed a small difference between the maximum and minimum A2 emission scenarios in the semi-arid climate zone. The NPV/cost ratio for the AC pavement surfacing sections varied between from 22.901 and 24.288, and between 5.822 to 5.842 for both road sections; whereas a zero NPV/cost ratio was obtained for DBST and the rigid pavements (Figure 5.16).

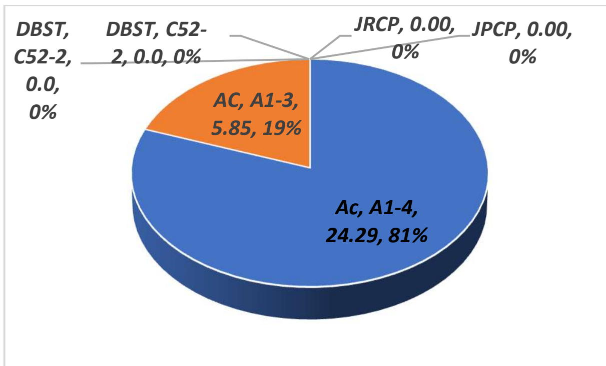


Figure 5.16 NPV/cost ratio for AC and DBST pavements in the semi-arid climate zone

5.4.1.3.2. Pavement Performance

Two road sections were used to represent the AC and the DBST surfacing with a pavement condition in the range of good to fair. The effect of climate change on AC and DBST surfacing induced up to 0.003 IRI m/km additional to the baseline (with no climate change) condition's average deterioration under both routine and compound maintenance alternatives by considering 15 years of analysis (see Figure 5.17 and Figure 5.18). On the other hand, for both rigid pavement sections there was no change in pavement deterioration during the four-climate periods (Figure 5.19).

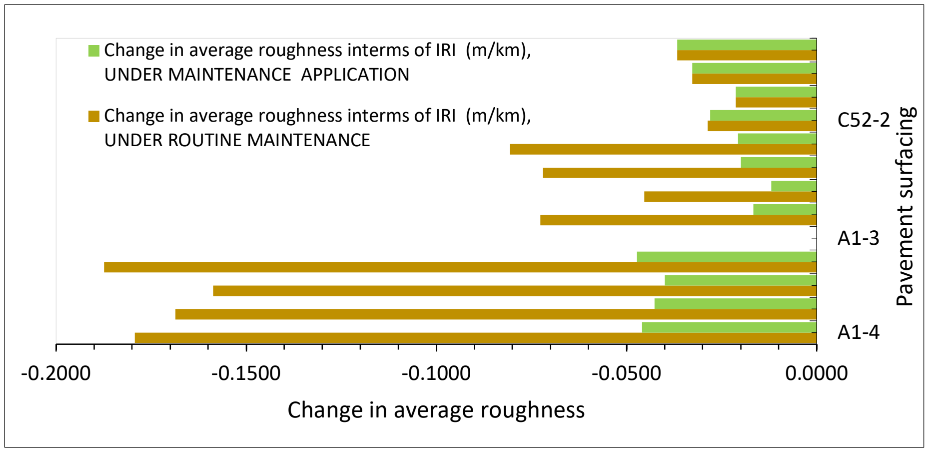


Figure 5.17 Additional pavement deterioration due to climate change for both maintenance applications under A2 emission scenario

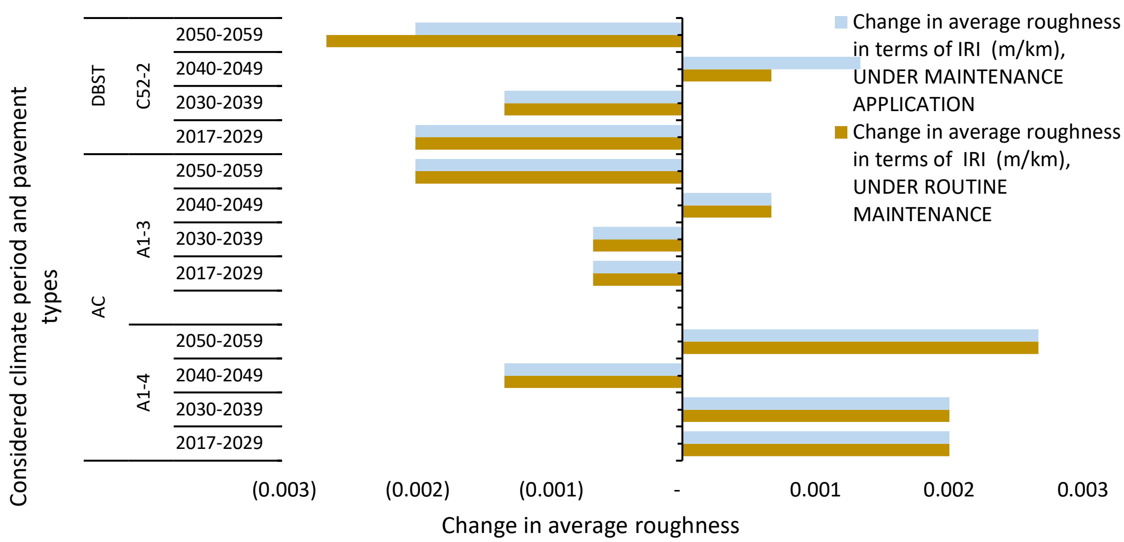


Figure 5.18 Change in average performance due to climate change for both maintenance applications under minimum A2 emission scenario

Figure 5.19 shows that the spalled joints in JPCP and cracking in JRCP have relatively higher changes due to traffic and climate action compared to the other distress parameters. The average roughness of the representative section changed from IRI

2.23 m/km to 3.19 m/km for JPCP and from IRI 2.20 m/km to 2.37 m/km for JRCP during the 15 years of analysis.

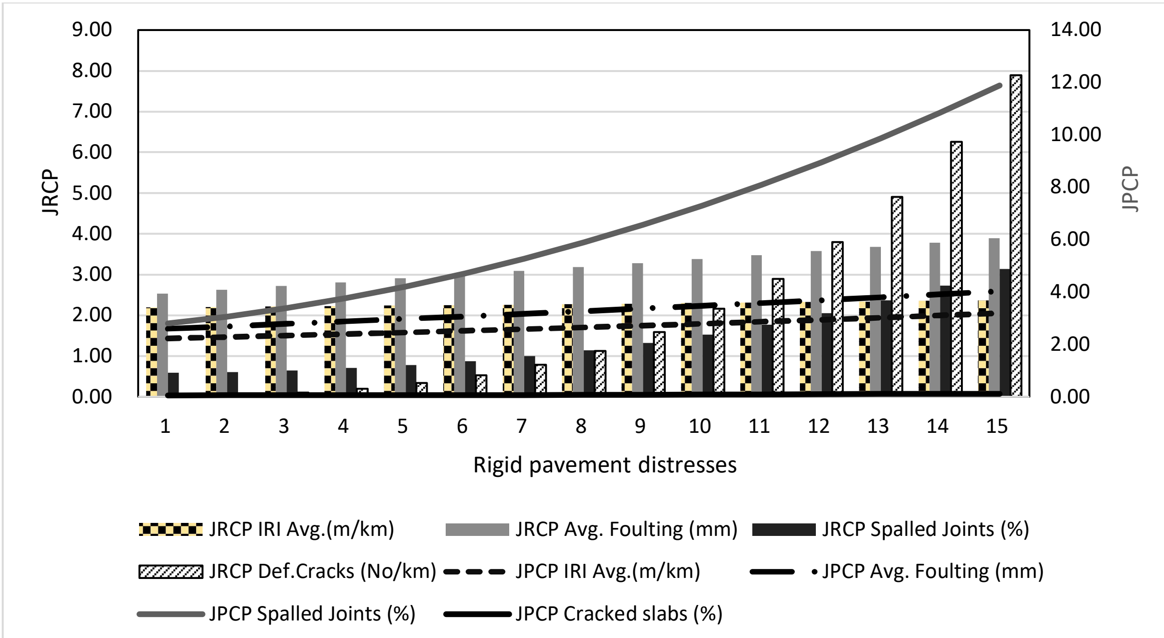


Figure 5.19 Distresses on JRCP AND JPCP pavements

5.4.1.3.3. Road Agency Costs

There was no additional agency cost observed due to the climate change projected from the A2 emission scenarios for both the routine and compound maintenance standards. The discounted RAC analysis results are shown in Figure 5.20. The agency would need to spend the most on the AC pavement sections from 0.441million ETB/km to 0.447 million ETB/km (£10,870.13/km to £ 11,018.02/km) as compared to DBST and rigid pavements' routine maintenance. This is associated with the 0.003 IRI m/km additional (compared to the baseline (without climate change)) average deterioration due to climate change under both maintenance options. Furthermore, for the analysis

15-year period, 0.313 million ETB/km (₤7,715.08/km) additional (with respect to the baseline (with no climate change)) RAC would occur for the DBST sections; while the result showed no increment in road agency costs would be required for JRCP and JPCP sections due to climate change.

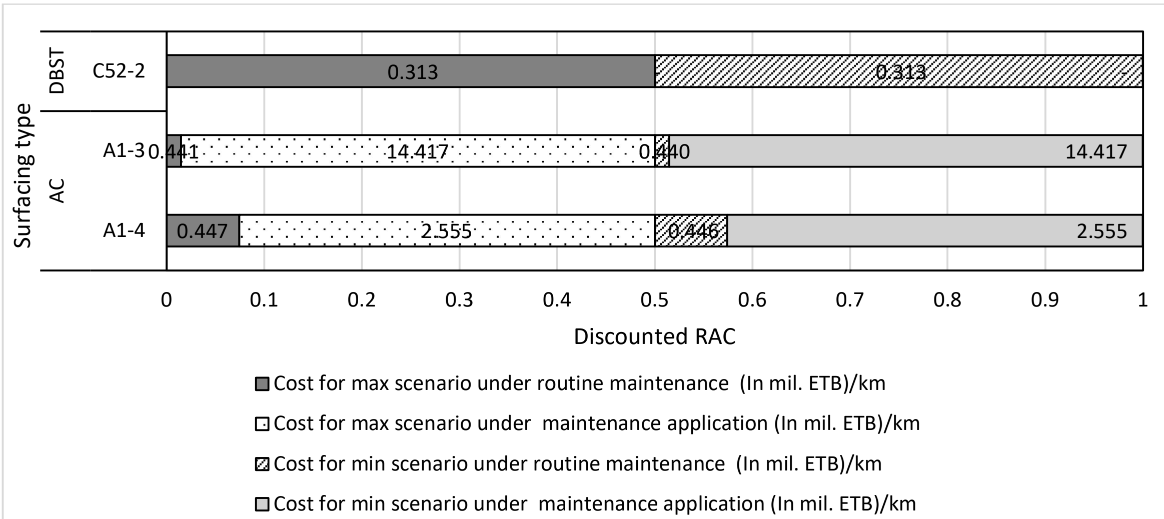


Figure 5.20 Discounted RAC for AC and DBST pavement surfacing under climate change

5.4.1.3.4. Road User Costs

There were no additional road user costs for the AC pavement sections under routine and compound maintenance alternatives for the maximum A2 emission scenarios, as presented in Figure 5.21. The maximum increment in discounted RUC for these emission scenarios was obtained for the DBST pavement sections. The total 15 years' highest additional (with respect to the baseline (with no climate change)) discounted road user cost (10,941.06 million ETB/km (₤269.68 million/km)) occurs on the DBST road sections with routine maintenance under the maximum A2 emission scenario.

However, the user may spend 10,865.66 million ETB/km (£267.83 million/km), if the compound maintenance standard is applied (Figure 5.22).

For the minimum A2 emission scenario, 0.024 million ETB/km and 0.029 million ETB/km (£591.57/km and £714.82/km) maximum additional discounted road user costs were obtained for the AC and DBST pavement sections, respectively.

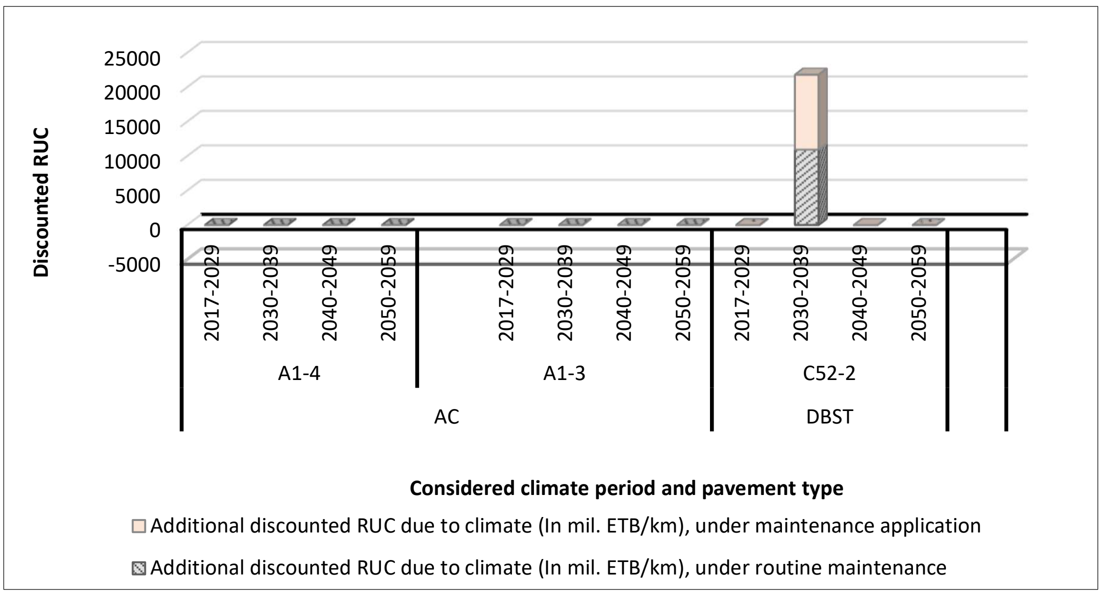


Figure 5.21 Additional discounted RUC due to climate change under maximum A2 emission scenario

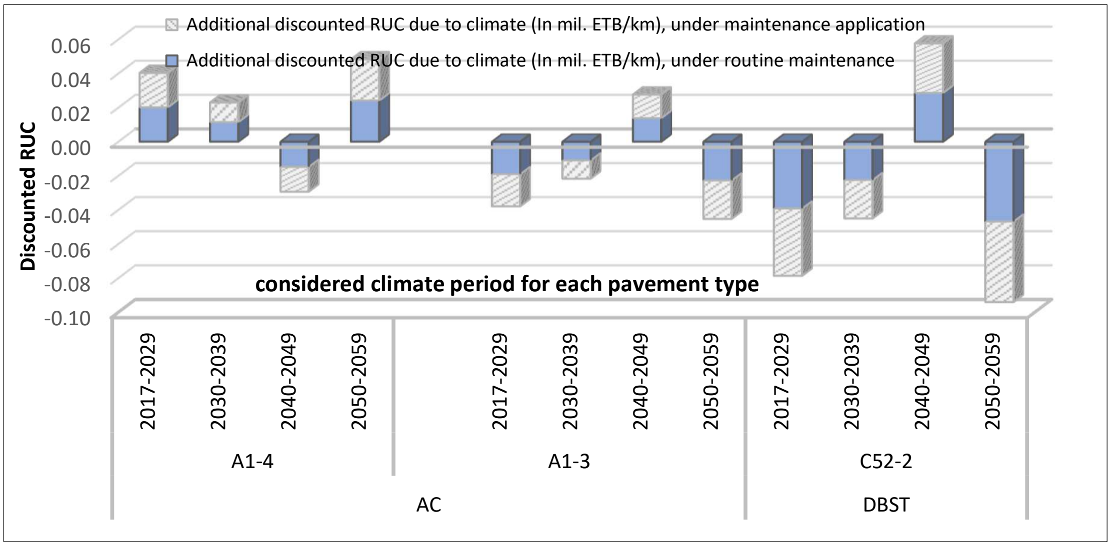


Figure 5.22 Additional discounted RUC due to climate change under A2 emission scenario

The trend of RUC for JRCP and JPCP pavements increased with deterioration as shown in Figure 5.23. The range of discounted RUC for JRCP varied from 1830.24 million ETB/km to 643.103 million ETB/km (£45.11 million/km and £15.85 million/km) within 15 years; whereas, for the JPCP road section discounted road user costs are between 1019.22 million ETB/km and 435.56 million ETB/km (£25.12 million/km and £10.74 million/km).

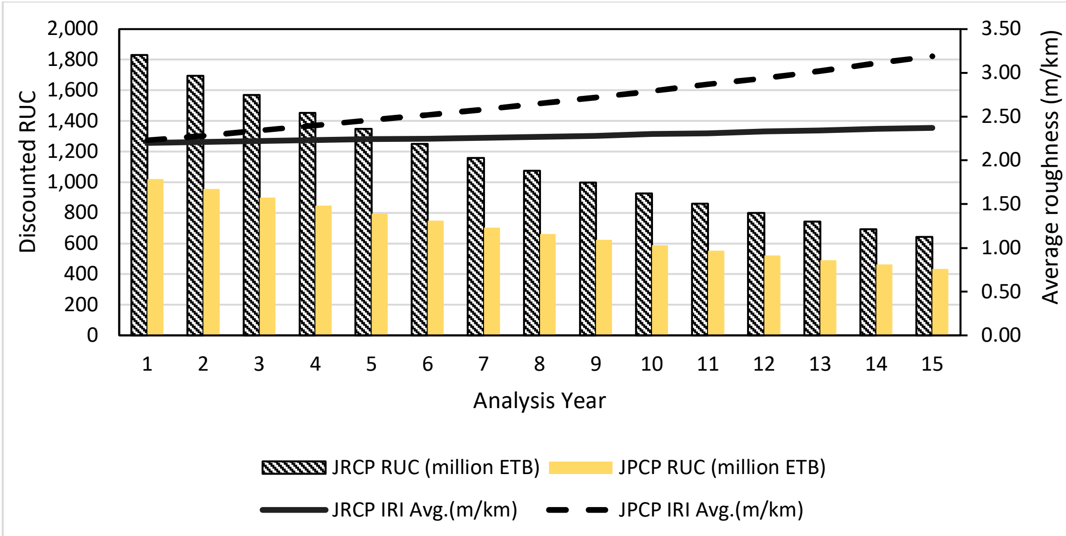


Figure 5.23 Discounted RUC for JRCP and JPCP pavements for A2 emission scenario

5.4.1.3. LCC Analysis Results for Arid, Sub-moist and Sub-humid Climate Zones

The remaining climate zones have one (AC) or two (AC and DBST) for their road network matrix. The results of the analysis of the arid, sub-moist and sub-humid climate zones are presented in Appendix L. This sub-section briefly summarises the results of representative road sections for the three climate zones as follows:

5.4.1.3.1. Arid Climate Zone with Medium Traffic Levels

5.4.1.3.2.1. NPV/Cost Ratio

The LCCA result indicated that three out of four AC representative road sections in this climate category were not economically feasible, while the DBST representative road section was suitable for long-term LCC effectiveness. The three AC representative road sections in the Arid medium traffic category were found not to be economically feasible with a negative NPV/cost ratio (-5.1 for C35d, -0.97 for C34b, and -0.68 for C11-1b). However, the remaining AC representative road section (C34c) and the BDST section on Itang-Jicawo km48 to124 road were identified as economically feasible with positive 0.25 and 0.19 NPV/Cost ratio respectively. The result indicated that in AC A MT traffic influence on the long-term economic effectiveness was not considered when providing AC pavement surfacing.

5.4.1.3.2.2. Pavement Performance

A slight incremental change in pavement deterioration (in terms of IRI) due to the climate change was obtained in this climate category. Effect of climate change on the deterioration of the AC and DBST pavements was found by comparing the roughness progression with the baseline for routine and maintenance application (i.e. Blue, Green, Orang, and Gray lines of Figure 5.24). The maximum additional deterioration due to climate change was found to be 0.007 IRI(m/km) for C34b and C11-1b and 0.005 IRI(m/km) for Itang-Jicawo road sections under routine and compound maintenance application. Moreover, there was no additional deterioration caused by the climate change effect considering the A2 emission scenario for C35d, AC representative road section, under maintenance application. This result revealed that when climate change become drier in Arid region, the distress effect on the subgrade soil would be minimum and controlled by maintenance application.

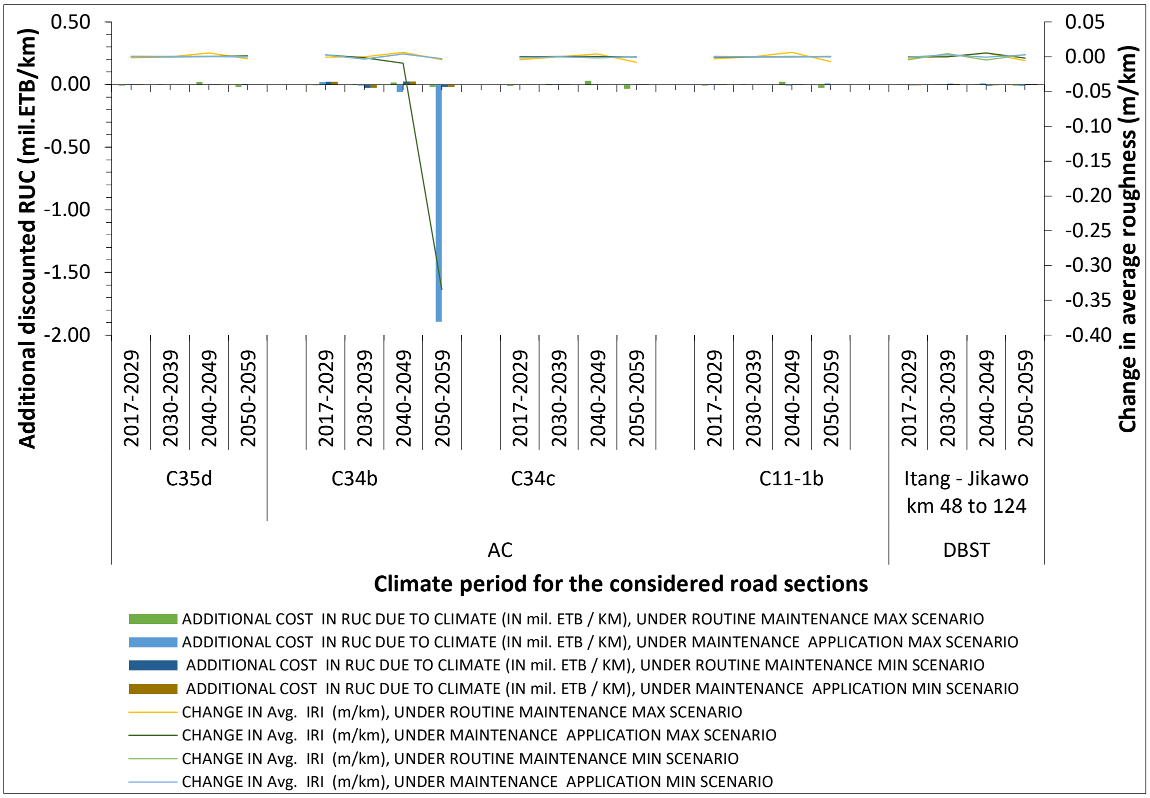


Figure 5.24 Change in pavement performance and Discounted RUC for AC and DBST pavements surfacing for A2 emission scenario

5.4.1.3.2.3. Road Agency Costs

Figure 5.25 shows that the highest RAC are associated with C35d and C34b AC representative road sections subject to both routine and the compound maintenance standards (0.31 million ETB/km to 11.18 million ETB/km (£7,644.04/km to £27,5678.53/km)) for the A2 emission scenario. Whereas, the lowest RAC ranges between (0.35 million ETB/km to 6.02 million ETB/km (£8,630.37/km to £148,442.29/km)) was required for the Itang-Jikawo DBST road section when routine and compound maintenance standards were used.

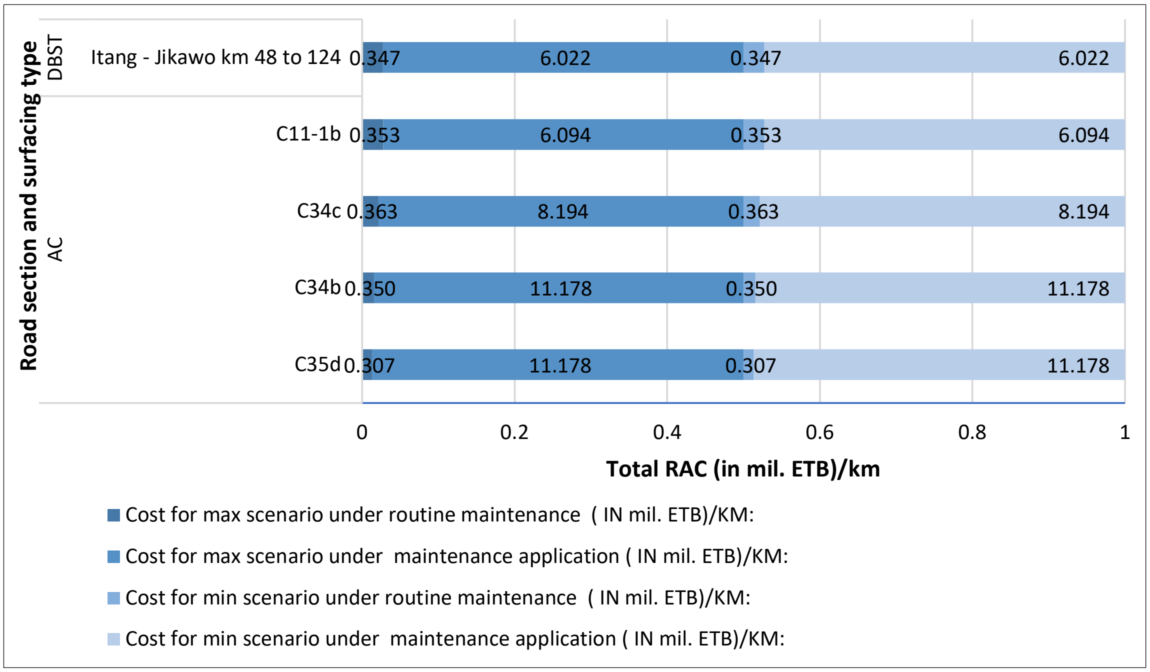


Figure 5.25 Discounted RAC for AC and DBST pavement surfacing under climate change

5.4.1.3.2.4. Road User Costs

A maximum additional discounted user cost was obtained for the AC representative road sections as compared to the DBST. This maximum added RUC (from -0.020 million ETB/km to 0.032 million ETB/km (£-493.16/km to £789.06/km)) found for the C34c AC road section when it was subject to routine maintenance (Figure 5.24). When the effect of applying periodic maintenance in accordance with the compound maintenance standard was considered, the road user costs changed from -1.891 million ETB/km to 0.026 million ETB/km (£-46,628.63/km to £641.11/km) when compared to the baseline condition. The negative result obtained when the RUC due to climate change is less than the RUC of the base line condition. Similarly, higher incremental user costs, which is the difference between RUC due to climate change and baseline condition, from -0.008 million ETB/km to 0.007 million ETB/km (₤-197.27/km to ₤172.61/km) and from -0.01 million ETB/km to 0.01 million ETB/km (₤-246.58/km to ₤246.58/km) are predicted for the Itang-Jikawo DBST road sections when respectively routine and compound maintenance standards were considered.

5.4.1.3.2. Sub-Moist Climate Zone with Medium Traffic Levels

5.4.1.3.3.1. NPV/Cost Ratio

100% DBST and 67% of the AC pavements representative sections were found to be economically feasible in the Sub-moist medium traffic category. The LCCA showed 5.4 NPV/cost ratio for the B51-2, DBST road section, and 3.62 and 1.73 NPV/cost ratio for the AC representative road sections for the A2 emission scenario. However, from the AC representative road section A2-3 was found to be economically unsuitable with -0.69 NPV/Cost ratio. The result showed that the AC representative road section A2-3 was economically unsuitable with negative NPV/Cost ratio, meaning that the benefit become less as compared to the cost of maintenance and construction, for both routine and compound maintenance application. These NPV/cost ratio results indicate that in such climate condition the traffic and climate change effects should be considered in the selection of a suitable pavement surfacing type and the associated maintenance strategy.

5.4.1.3.3.2. Pavement Performance

No change in deterioration compared to the baseline condition were obtained for 67% of the AC representative road sections due to the climate change effect. However, the maximum change of 0.41 IRI (m/km) was obtained for B51-2, DBST pavement, under routine maintenance application and A2 emission scenario compared to baseline condition. Moreover, the DBST pavement deteriorated more than the AC pavements when the compound maintenance standards were considered with a change in IRI ranging from -0.001 m/km to 0.057 m/km due to the effect of climate change between 2017 to 2059. The effect of climate change on the deterioration of the AC and DBST pavements when the routine and compound maintenance standards were taken into account are shown in Figure 5.26 (i.e. Blue, Green, Orang and Gray lines). Furthermore, the additional roughness due to climate change ranges from -0.002 m/km to 0.013 m/km and -0.005 m/km to 0.013 m/km for the C34 road section when the application of routine and compound maintenance modelled respectively.

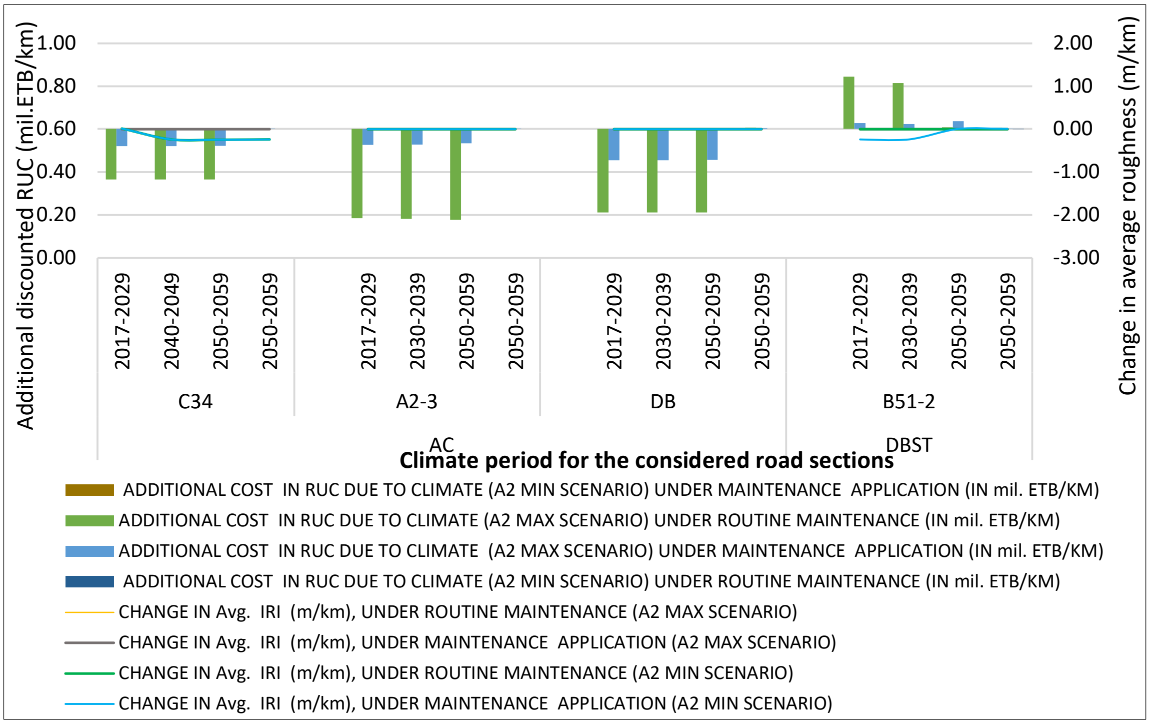


Figure 5.26 Change in pavement performance and Discounted RUC for AC and DBST pavement surfacing for A2 emission scenario

5.4.1.3.3.3. Road Agency Costs

The result of the analysis showed that highest RAC, (0.751 million ETB/km to 4,734 million ETB/km (£18,518.30/km to £116.73 million/km)) was required for the C34, AC representative road section, under compounded maintenance for the A2 emission scenario. Whereas, the lowest RAC (2.075 million ETB/km (£51.17 million/km)) required by the agency was for the DB, AC representative road section. A maximum of 0.36 million ETB/km (£8,876.95/km) was needed for the A2-3, AC road section, for routine maintenance to counter the climate change effect (Figure 5.27). Moreover, RAC 0.313 million ETB/km (£7,718.01/km) and 2.123 million ETB/km (£52.35 million/km) for B51-2, DBST road section, would be essential for the proposed routine and compounded maintenance application from 2017 to 2059.

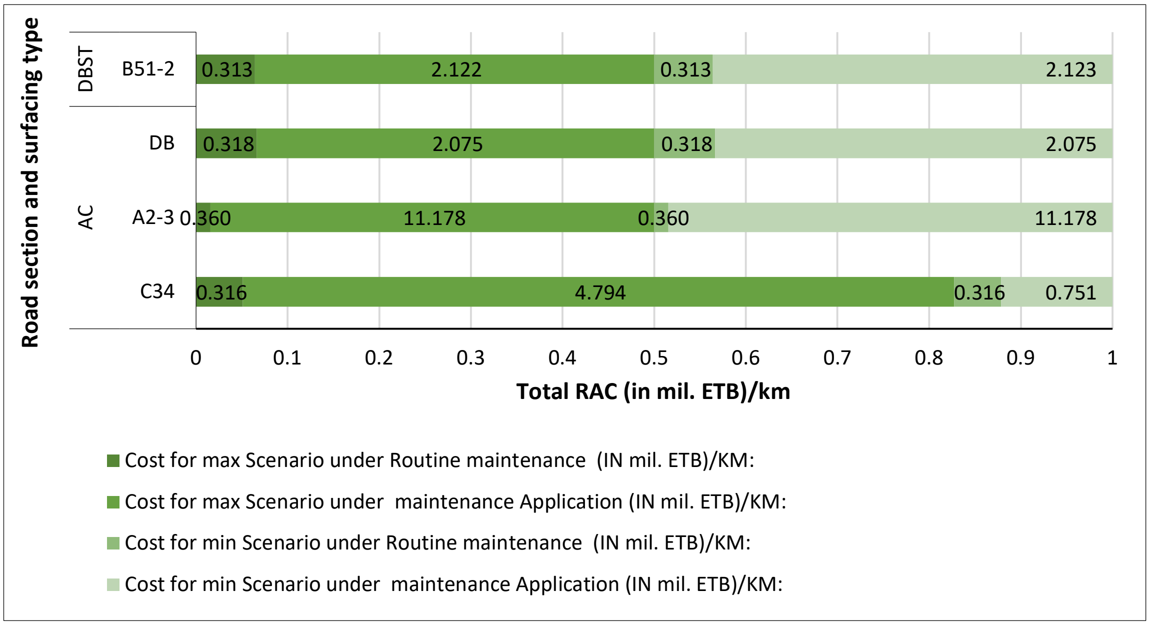


Figure 5.27 Discounted RAC for AC and DBST pavement surfacing under climate change

5.4.1.3.3.4. Road User Costs

The analysis indicated that due to the climate change effect from 2017 to road user costs are higher for B51-2, DBST road section, compared to the AC pavements. The highest additional discounted RUC (1.567 million ETB/km (£38.63 million/km)) was obtained when considering routine maintenance. And similarly, RUC of 0.183 million ETB/km (£4,512.45/km) was obtained when the compound maintenance standards were modelled. The difference in RUCs can be attributed to differences in road roughness. For example, the maximum additional pavement deterioration of 0.41 IRI (m/km), due to the predicted impacts of climate change occurs under the A2 emission scenario for B51_2 (Figure 5.26). The second highest RUCs of 0.033 million ETB/km

(£813.72/km) and 0.140 million ETB/km (£3,452.15/km) occur when each routine and compound maintenance standards are considered respectively for DB road section.

5.4.1.3.3. Sub-humid Climate Zone with High Traffic Levels

5.4.1.3.3.1. NPV/Cost Ratio

The result indicated that all of the representative AC pavements in AC SH HT category were economically feasible. Two of the AC representative road section in sub-humid high traffic category were found to be economically feasible with positive NPV/cost ratio. The values for NPV/cost were 19.42 and 18.22 for A3-1 and A3-1a respectively. However, the remaining AC representative road section (AT) was identified as economically suitable with a maximum NPV/Cost ratio 31.23.

5.4.1.3.3.2. Pavement Performance

Similar changes in the range of roughness, in terms of IRI, were obtained in this climate category for 67% of the considered representative road sections. The change in IRI was due to the climate change under the routine maintenance strategy for the considered climate change periods (Figure 5.28). The additional roughness due to climate change ranges from -0.007 IRI m/km to 0.001 IRI m/km for the three AC representative road sections under the routine maintenance strategy considering the A2 emission scenario. The IRI increased from -0.001 m/km to 0.001 m/km for A3-1 the road section and from -0.001 m/km to 0.005 m/km for the AT and the A3-1a.

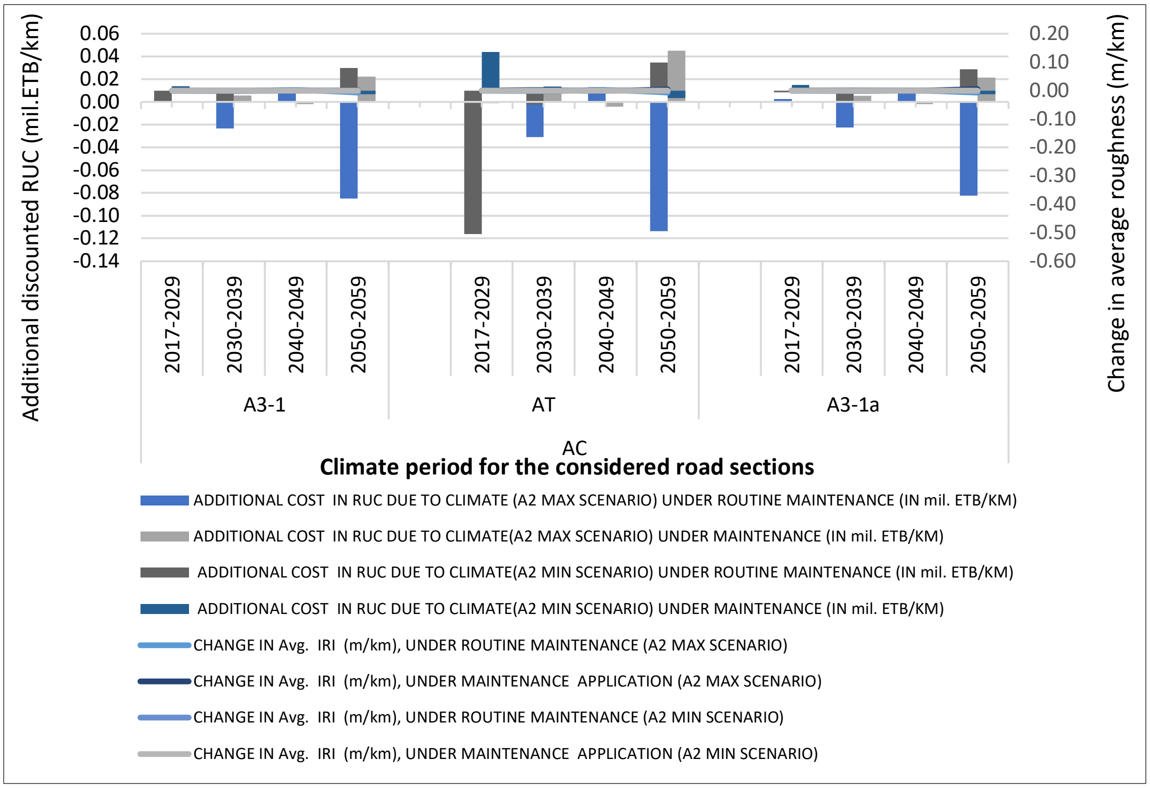


Figure 5.28 Change in pavement performance and Discounted RUC for AC pavements surfacing for A2 emission scenario

5.4.1.3.3.3. Road Agency Costs

The highest RAC was obtained for the AT representative road section under the compounded maintenance strategy (3.73 million ETB/km to 99.49 million ETB/km (£91,975.04/km to £2.45 million/km)) for the A2 emission scenario. Whereas, the lowest RAC (from 3.49 million ETB/km to 0 million ETB/km (£86,057.07/km to £0/km)) was obtained for the A3-1a road section (Figure 5.29). Moreover, for A3-1 the range of costs was 0.457 million ETB/km to 0.451 million ETB/km (£11,268.79/km to £11,120.84/km).

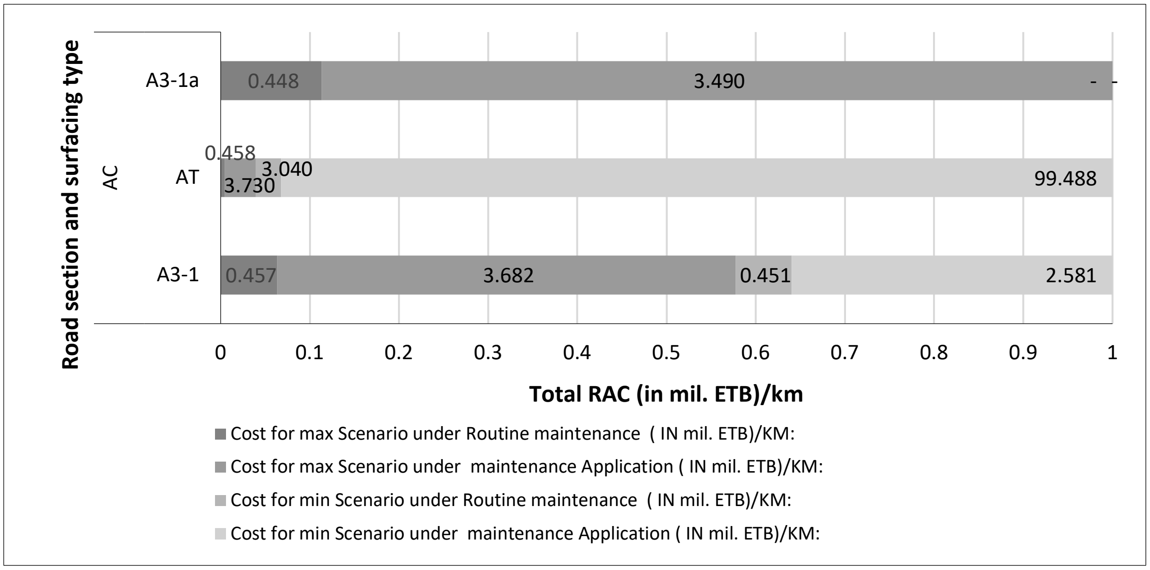


Figure 5.29 Discounted RAC for AC pavement surfacing under climate change

5.4.1.3.3.4. Road User Costs

The maximum change in discounted RUC obtained under the compound maintenance strategy was found for the AT road section i.e -0.026 million ETB/km to 0.135 million ETB/km (£-641.11/km to £3,328.86/km). This result is due to the highest pavement deterioration 0.005 IRI (m/km) caused by the climate change effect (Figure 5.28). For the remaining representative road section under the compound maintenance strategy, change in RUCs due to the modelled impacts of climate change vary from -0.013 million ETB/km to 0.022 million ETB/km (£-320.56/km to £542.48/km). Similarly, a higher discounted RUC (0.098 million ETB/km (£2,416.50/km)) was obtained for the AT section when for the routine maintenance strategy. Moreover, RUC between -0.085 million ETB/km to 0.009 million ETB/km (£-2,095.95/km to £221.92/km) were obtained for the A3-1 representative road section, when the routine maintenance strategy was considered. For similar conditions, changes in RUCs due to the impacts of climate change range between -0.082 million ETB/km to 0.075 million ETB/km (₤-2,021.97/km to ₤1,849.36/km) for the A3-1a road sections.

5.4.1.4. Summary for Approach 1

- Of the representative AC sections carrying high traffic roads, 100% in the moist and semi-arid and 75% in sub-moist climate zones were found to be economically viable (NPV/cost > 0). For these conditions, the AC is the preferred surfacing type compared to DBST and Otta Seal, because the traffic considered in the representative area is high (more than 10,000 AADT). Conversely, for low and medium traffic road sections the DBST and Otta-Seal sections were found to be more economically viable and more resilient to the effects of climate change than the AC sections in all climate zones, except in the moist and sub-humid zones.
- The maximum additional changes in deterioration caused by the climate change projected from the A2 emission scenario were found in the semi-arid and arid regions. The change in average roughness values varied between 1.121m/km and 0.005 m/km and 0.401m/km to -0.335m/km for AC surfacing under routine and standard maintenance alternatives respectively. For DBST representative sections in the sub-moist climate zones, 1.020m/km to -0.133m/km and 3.563m/km to -0.072m/km changes in average roughness were found for routine and compound maintenance alternatives respectively.
- The findings showed that the road agency would not be required to have an additional budget to remedy the deterioration caused by the variation for the

considered climate periods. This is because the optimised maintenance values handle the effect of climate without additional cost.

- The RUC showed a needed additional cost due to the deterioration caused by climate change impact for all representative road sections, except for the AC surfacing for medium traffic in the sub-moist climate region section. The maximum range of the RUC (3.192 million ETB/km and -0.030 million ETB/km (£78678.74/km and £-739.46/km)) occurred for the high traffic AC representative road section in the arid region.
- A comparison of the maximum RUC from all climate regions showed that users will spend less when using DBST surfacing compared with AC road sections, except on roads with low traffic levels.
- In the arid climate zone, the change in climate is computed to require additional RUCs of 0.183 million ETB/km to -0.183 million ETB/km (£4510.72/km to £-4510.72/km) under the routine maintenance standard for high traffic AC surfacing. Under the compound maintenance standard, the cost would be 3.192 million ETB/km to -0.125 million ETB/km (£78678.74/km to £3081.09/km). Under the routine maintenance standard, the additional RUC was found to be between 64.93% and 100% and between 69.39% and 100% higher for DBST than AC road sections for medium and low traffic respectively. Correspondingly, for compound maintenance applications the costs were lower by 45.62% to 100% for medium traffic and higher by 66.23% to 100% for low traffic levels on DBST as compared to AC surfaces.
- In the sub-moist climate zone, for routine maintenance applications, the additional as compared to the baseline (without climate change) RUC for DBST surfaces

were in the range of -34.42% to 41.36% higher than for AC for medium traffic levels. For the same conditions, but for low traffic levels, the additional road user costs for DBST were -87.93% to 88.81% higher than for AC. However, for roads maintained with the compound maintenance standard, the additional road user costs ranged from -71.83% to 56.68% more for DBST surfaced sections compared to AC sections for medium traffic level roads. Moreover, the value of the RUC increased by -25.37% to 14.80% for low traffic DBST surfaced sections compared to AC sections with similar traffic levels.

5.4.2. Approach 2

The primary purpose of the second approach was to demonstrate how climate change could be incorporated within a lengthy economic analysis. To this end a 44-year analysis period was selected and four representative road sections with high traffic levels, i.e. two AC, one JPCP and one JRCP pavements in the semi-arid climate zone were used. For the two flexible pavements four maintenance alternatives were compared, namely routine maintenance, compound maintenance, rehabilitation, reconstruction and renewal; and for the two rigid pavements, three maintenance alternatives were compared, namely routine, spalling and deep spalling. The results of the analysis are presented below.

5.4.2.1. NPV/Cost

For the projected traffic and climate, the two AC pavements were found to have NPV/cost ratios of 5.14 for road section A1-4, and 6.37 for section A1-3; while zero NPV/cost was obtained for the two rigid pavements. These NPV/cost values were achieved due to reconstruction and rehabilitation maintenance alternatives applied during the last analysis period (2050-2059) for sections A1.4 and A1-3 respectively. A lower positive NPV/cost ratio of 0.41 was found for section A1.4 due to rehabilitation and 1.65 for A1-3 for a compound maintenance standard; while a zero NPV/cost ratio was the result for all the other maintenance options considered. A zero NPV/cost ratio was obtained for the JPCP and JRCP pavements under the full-depth repair option; while all other maintenance alternatives for the rigid pavement sections provided negative NPV/cost ratios.

5.4.2.2. Pavement Performance

High average roughness values were observed for the two AC pavements (i.e. A1-3 and A-1.4 road sections) at the end and the start of the ten-year climate change periods after 2019, due to the traffic and climate change effect under the compound maintenance standard. Due to the maintenance application, the maximum average roughness values were found to be less than the 5.0 m/km IRI for both representative road sections (Figure 5.30). Moreover, for this approach the traffic action dominates in determining the pavement performance and it has been observed from Figure 5.30 and Figure 5.31 that the climate change becomes insignificant.

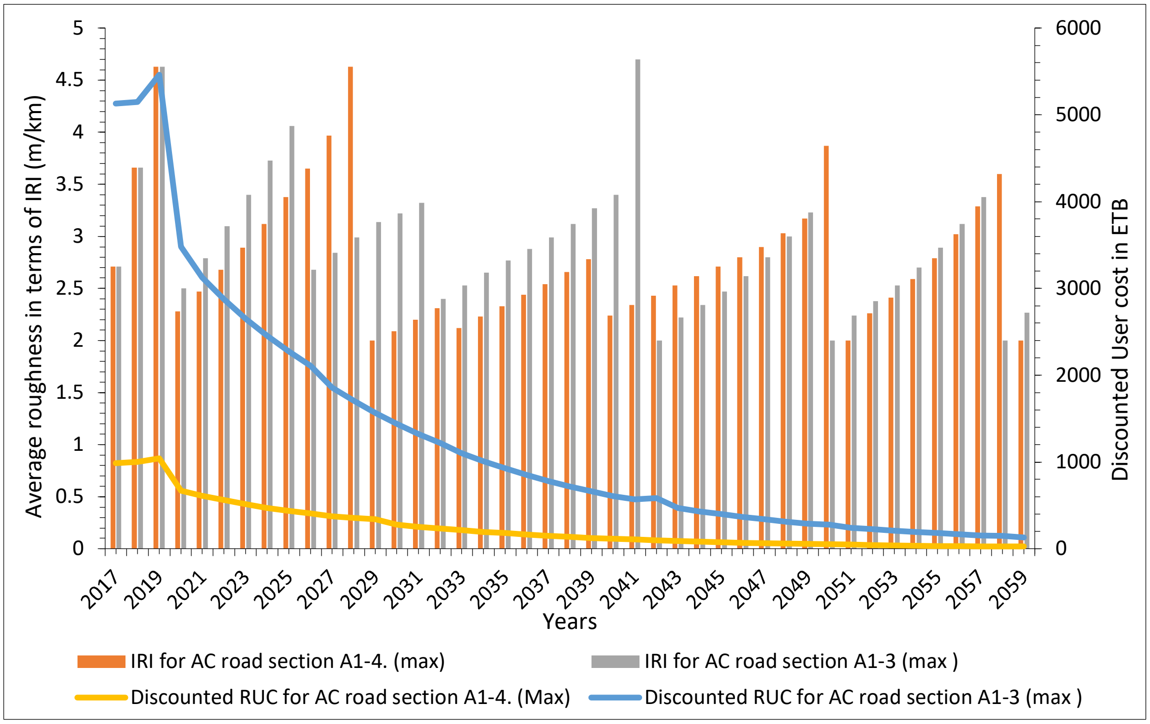


Figure 5.30 Average roughness progression for the A2 maximum climate emission scenario

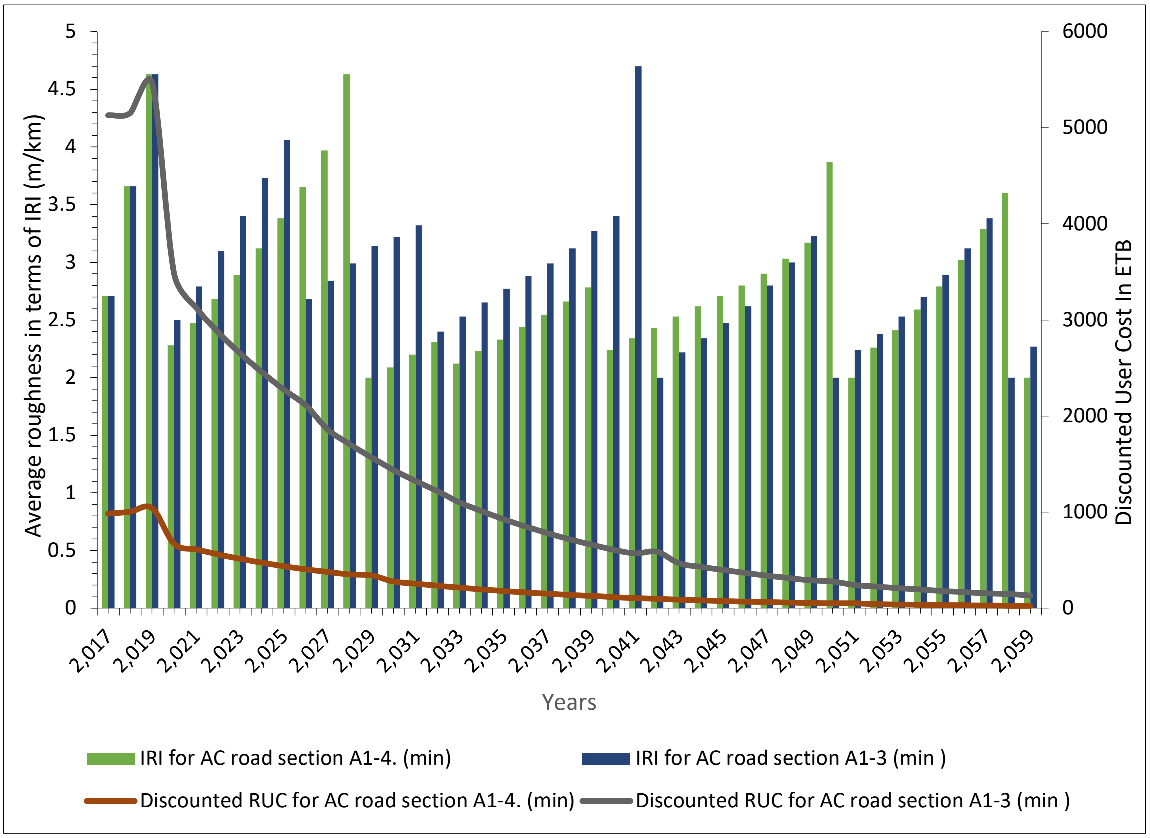


Figure 5.31 Average roughness progression for the A2 minimum climate emission scenario

Figure 5.32 shows the performance of JPCP and JRCP pavements in terms of concrete pavement distress factors for the 44 years of analysis. From the figure it can be seen that the JRCP pavement slab will start to crack (13.6%, which is more than 10%) and lose its pavement surface uniformity due to faulting (with 12.5 mm) by the year 2043 (Figure 5.32). The pavement average annual roughness for 2043 was 5.21 m/km IRI and no spalling has been observed for the same year. The JPCP pavement slab, on the other hand, showed a large amount of faulting (12.97 mm) by 2032.

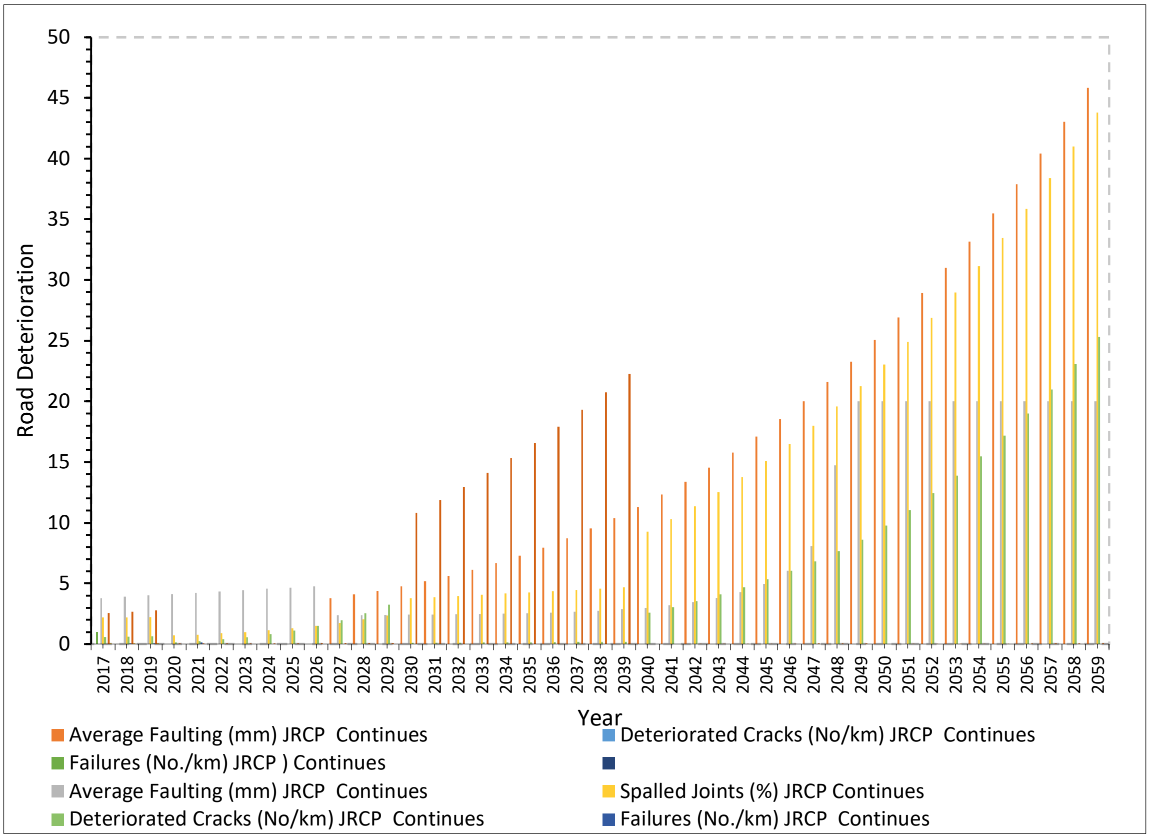


Figure 5.32 Deterioration of a rigid pavement

5.4.2.3. Cost Comparisons

Figures 5.30, 5.31 and 5.33 show also the discounted road user cost and the roughness results for the two AC representative road sections. From these figures it can be seen that the discounted user cost continuously decreases throughout the 44 years as the roughness is kept below 5 m/km IRI due to maintenance application. Higher discounted user costs occur for the AC pavement representative road section A1-3 than for section A1-4 in the semi-arid climate region for high-level traffic roads.

Different maintenance alternatives were considered for each ten-year step-by-step analysis as outlined in section 4.2.1. Then the best investment alternative based on the NPV/cost ratio was selected for the next analysis as an input condition for the next ten years. This is because the roughness change caused by different maintenance alternatives can be controlled through an optimised maintenance application.

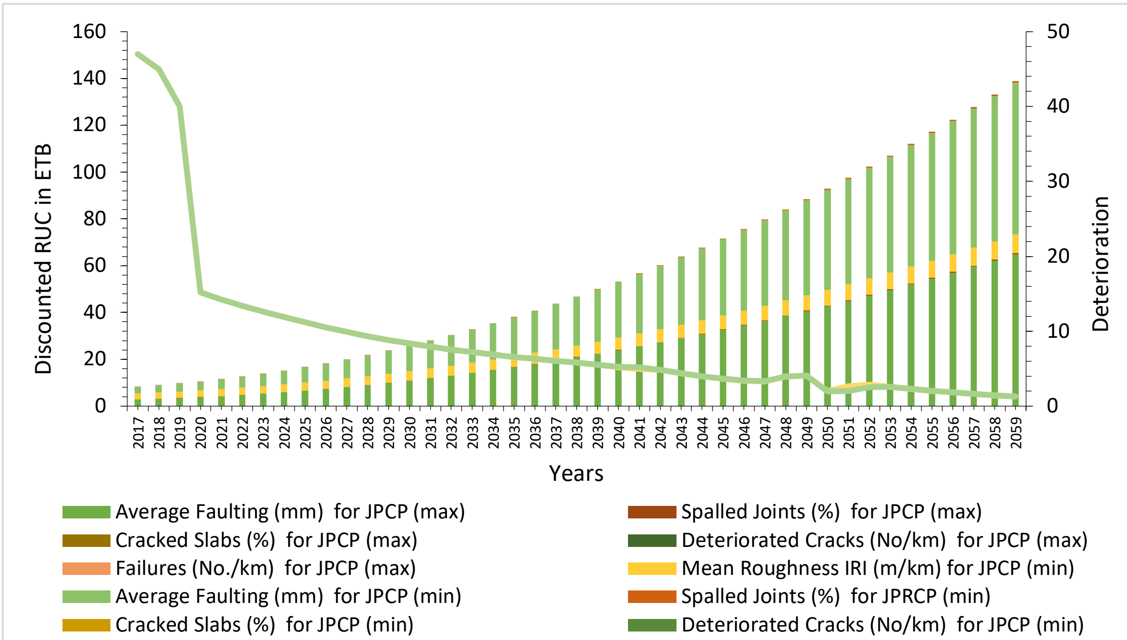


Figure 5.33 Rigid pavement deterioration for A2 maximum and minimum climate emission scenario

5.5. Summary

This chapter presented the findings of the analysis, which aimed to determine the HDM-4 road deterioration model calibration, the roughness model adjustments (to consider four future climate predictions), and evaluate the performance of five pavement types and their LCC.

Level I and II calibrations were used to obtain suitable values of the HDM-4 deterioration model calibration factors for the identified road network matrix in Ethiopian conditions. Moreover, the roughness model coefficient was also adjusted in order to account for the effect of climate change, albeit the modified coefficients for most of the cases were close to one (i.e. the default value).

The LCCA evaluation demonstrated two approaches. The results of the first approach show the relative performance of road sections under baseline conditions and four future climate periods for the A2 emission scenarios, taking into account two maintenance strategies. The LCCA evaluated representative road sections in terms of the discounted RAC, RUC and net benefit. In addition to this, the most suitable pavement for each climate zone was identified by using the NPV/cost ratio and for the representative road section presented in each defined road network matrix. For instance, Otta-seal and DBST surfaces were found to be the suitable options for low and medium traffic level roads in the moist climate zone. The two rigid pavements were found to be the most economically beneficial in the moist and semi-arid climate for roads carrying medium and high traffic levels respectively.

Furthermore, the findings indicated that the change in the average deterioration caused by the predicted change in climate varied by pavement surfacing type, traffic level and climate zone. For instance, for the 15 years' analysis the maximum deterioration obtained was 1.121 m/km for AC in the semi-arid region, 3.565 m/km for DBST in the sub-moist region, and 0.378 m/km for Otta-seal representative road sections in the moist region. The JRCP and JPCP pavements showed no noticeable change in deterioration.

The second LCCA approach demonstrated how climate change impacts could be included within a life-cycle analysis. The approach was demonstrated using AC, JPCP and JRCP representative road sections carrying high traffic in semi-arid areas. The analysis was conducted for 44 years and the projected data were updated for every ten years in order to have continuity with the previous output of the analysis. The results of the analysis showed that the developed approach can consider both projected traffic and climate change effects.

The following chapter discusses the results presented in this chapter.

CHAPTER SIX – DISCUSSION

6.1. Introduction

The development and management of road networks includes design, construction, operation, and maintenance processes; which are (relatively) long-term endeavours that can cause significant capital and operational expense. This cost is shared by the road agency and by the road users over the design life of the pavement network. Growing countries give priority to developing their road networks as a way of stimulating economic growth; although the resources available are unlikely to be sufficient to fund all potential projects. Therefore, those that are constructed must be both value for money and resilient to changes in operational conditions; such changes include an increase in traffic loads and/or climate change.

A LCCA for road infrastructure commonly considers pavement surface/material, traffic, proposed maintenance strategies, and other factors. However, it does not commonly consider how changing environmental conditions, due to climate change, might impact performance. If the climate is expected to change (projected models by the IPCC were used herein), then this could impact the long-term performance of the road and thereby remedial maintenance costs and road user costs. This study has developed a framework to address this, modified an existing LCCA pavement deterioration model within HDM-4 to incorporate predicted climate change impacts, as presented in Chapter Four. This was used to compare the performance of five road surfacing types

(AC, DBST, Otta seal, JPCP, and JRCP) as a function of operating conditions. These include initial and future climates, maintenance scenarios, and traffic.

A number of outcomes arose from this approach and this chapter provides a discussion of these. It considers the findings of the analysis and reviews the framework developed.

6.2. Summary of the Methodology/Framework Developed to Model the Scenarios of the Research

As discussed in section 3.6 the road network matrix was developed to consider the climate change effect on five pavement surface types (AC, DBST, Otta seal, JPCP, and JRCP) in five climate zones, functioning under three traffic levels. To obtain the climate effect the analysis has been done using the ERA maintenance practices and it considers routine maintenance as a “do minimum” maintenance option. This approach disagrees with Shao et al. (2017) since they considered “do nothing” as a minimum maintenance condition to evaluate the climate change effect. Their approach may be valid as maintenance protects pavement surfacing from climate impacts, but doesn’t consider the actual practice and the effect of routine maintenance.

The five climate zone classifications described in section 3.5.1.2 were used in this study to represent varied climate zones where relatively wider ERA road network coverage exists. These classifications also help to study the temperature and precipitation ranges in tropical areas where the groundwater is mostly found more than three metres below the ground. HDM-4 models the local climate via climate zones that are classified based on temperature and precipitation ranges. These ranges, however, have considerable overlaps and may lead to similar results for different zones. For instance, the HDM-4 climate zone classification considers semi-aired and sub moist climate zones in one semi-arid climate region by providing larger temperature and precipitation ranges. Similarly, moist and sub humid climate zones were included in sub humid HDM-4 climate zone. To limit the effect on the analysis result each of the five climate regions treated separately with their climate characteristics. However, for level I calibration similar environmental coeffects (as proposed by the manual (Bennett & Paterson, 2000)) were used for these climate zones found in one HDM-4 climate region.

In the study, the long-term impact of climate change was investigated in the LCCA. The short-term climate impact that refers to extreme weather events like flooding and drought was not considered. These impacts are discussed in two World Bank climate adaptation and risk assessment studies described in section 2.4.4.1.

The research used the A2 climate emission scenario for demonstration purposes as discussed in section 3.6.2. However, in the future, the other emission scenarios can be considered by applying the developed framework. The framework was developed for this particular research but it can be applied for any climate impact analysis using

HDM-4 software, because it consists of the HDM-4 LCCA approaches as well as model modification to account for climate change, which is added on this approach.

6.3. Discussion of Model Outcomes: Deterioration Model for Local Calibration and Climate Adjustments.

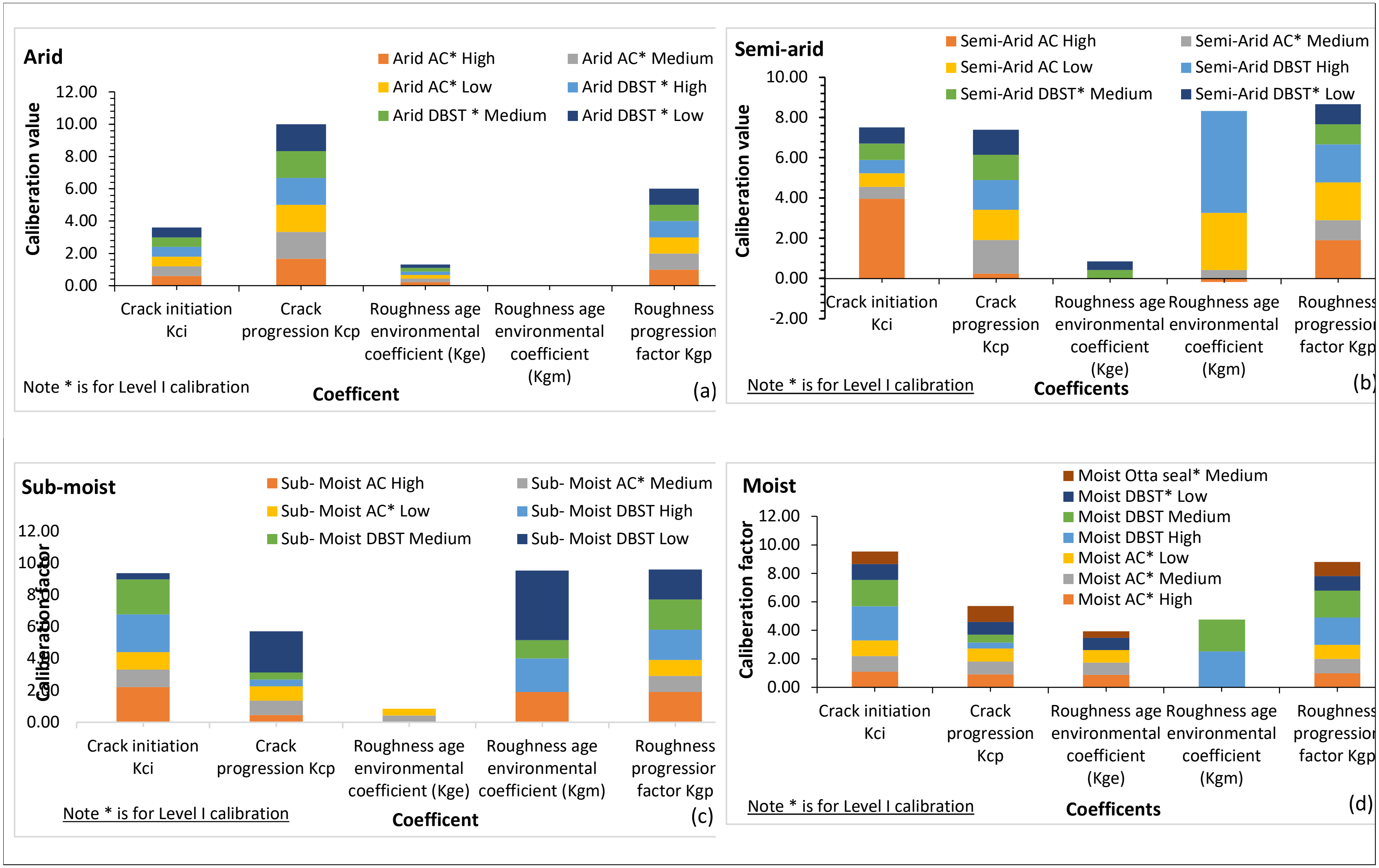
To use the HDM-4 software, the generic models of the software were modified to consider the local conditions of the research area and they were further adjusted to take into account the predicted climate change. The calibration and climate adjustment findings and processes are discussed separately below.

6.3.1. Local calibration

The implications of calibration are discussed as follows:

1. Based on the available data, Level I and Level II calibration factors were obtained for pavement distress parameters classified in first and second impact elasticity groups (section 3.5.2). The higher impact elasticity classes were chosen because pavement distress parameters with higher elasticity (in first and second classes) could result in more sensitive model prediction. Therefore, calibration factors for crack initiation (K_{ci}), crack progression (K_{cp}), roughness environmental factor (k_{ge}), and roughness environmental age calibration factor (K_{gm}) were considered. The roughness environmental factor (k_{ge}) for Level I calibration and roughness environmental age calibration factor (K_{gm}) for Level II were used to represent different climate changes in the analysis.

Level II calibration was carried out for AC surfacing in semi-arid regions for high and low traffic; in the semi-arid region for high traffic; and in sub-moist regions for high traffic. For DBST surfacing, in semi-arid regions for high traffic; in the sub-moist region for high, medium and low traffic; in the moist region for high and medium traffic and in the sub-humid region for low traffic. For the remaining road networks defined in section 3.7, Level I calibration was calculated and the result is presented in Table 5.1 summarised in Figure 6.1 below.



Arid
Arid AC* High
Arid AC* Medium
Arid AC* Low
Arid DBST * High
Arid DBST * Medium
Arid DBST * Low
Caliberation value
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Crack initiation Kci
Crack progression Kcp
Roughness age environmental coefficient (Kge)
Roughness age environmental coefficient (Kgm)
Roughness progression factor Kgp
Note * is for Level I calibration
Coefficent
(a)
Semi-arid
Semi-Arid AC High
Semi-Arid AC* Medium
Semi-Arid AC Low
Semi-Arid DBST High
Semi-Arid DBST* Medium
Semi-Arid DBST* Low
Caliberation value
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
Crack initiation Kci
Crack progression Kcp
Roughness age environmental coefficient (Kge)
Roughness age environmental coefficient (Kgm)
Roughness progression factor Kgp
Note * is for Level I calibration
Coefficents
(b)
Sub-moist
Sub- Moist AC High
Sub- Moist AC* Medium
Sub- Moist AC* Low
Sub- Moist DBST High
Sub- Moist DBST Medium
Sub- Moist DBST Low
Calibration factor
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Crack initiation Kci
Crack progression Kcp
Roughness age environmental coefficient (Kge)
Roughness age environmental coefficient (Kgm)
Roughness progression factor Kgp
Note * is for Level I calibration
Coefficent
(c)
Moist
Moist Otta seal* Medium
Moist DBST* Low
Moist DBST Medium
Moist DBST High
Moist AC* Low
Moist AC* Medium
Moist AC* High
Caliberation factor
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Crack initiation Kci
Crack progression Kcp
Roughness age environmental coefficient (Kge)
Roughness age environmental coefficient (Kgm)
Roughness progression factor Kgp
Note * is for Level I calibration
Coefficents
(d)

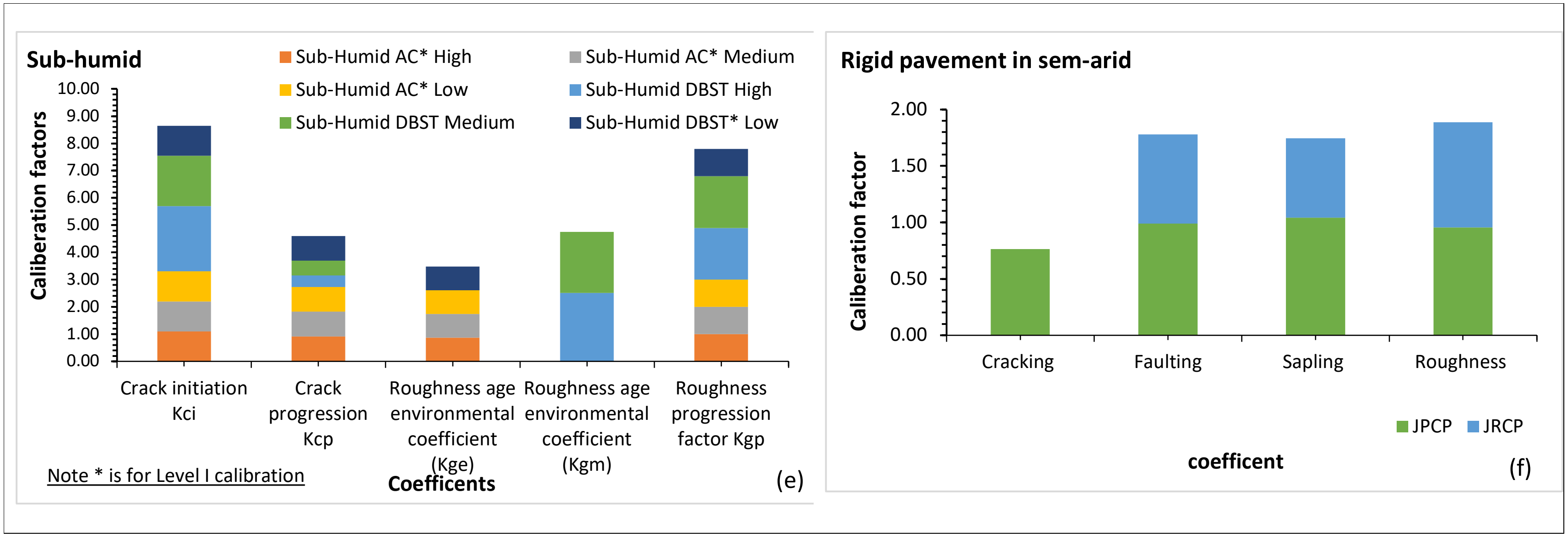


Figure 6.1 Calibration factor vs. distress coefficients

2. The Level I and Level II calibration results in Figure 6.1 were used to represent the local condition of each road network considering the baseline (2016, no climate change) condition. But to account for the climate change, the roughness model further needs to be adjusted for climate change using K_{gm}. The study considers four future climate changes in ten-year intervals from 2020 to 2059; hence, the variation due to these changes should be reflected in the locally calibrated model through four K_{gm} for each climate change period for the LCCA.

3. Using two levels of calibration will barely affect the evaluation results since climate projection data was the main varying parameter used for LCCA assessment comparisons. Each road section representative result compares pavement performance and associated costs for the four climate change periods with that of the output of the baseline climate. This means that all input parameters were similar for the analysis except for the climate input data for each identified road matrix and scenario. This type of comparison approach was used by Padmini et al. (2017) and Daniel et al. (2014) to quantify the climate change output alone. However, their works were focused on the effect of different climate projection models and climate impact on maintenance studies, respectively. Moreover, their research used different tools and has limitations associated with the cost components considered within the LCCA, as explained in section 2.8.

4. The findings of the Level I calibration varied by climate zone. However, similarities within a road representative section categories at different traffic levels and within a climate zone were observed, as presented in Figure 6.1 (detail in the Results

chapter, Table 5.1). This is because the Level I calibration process considers average representative coefficients for the environment, type of construction material, and quality of materials (Bennett and Paterson, 2000).

5. Figure 6.1 (or Table 5.1 in section 5.2) indicates that the difference between Level I calibration and the baseline is less than that between Level II and the baseline. For the crack initiation adjustment, the approach used a comparison between model output and experts' estimation for the crack initiation time. Experts' estimation was used when the initial cracking time was not recorded in the pavement condition records. For such conditions, Bagui and Ghosh (2015) used experts' estimation to calibrate the crack initiation model for Indian state highways.

6. Linear regression analysis was used to establish a relationship between recorded values and HDM-4 estimations, as presented in Figure 6.1(f) (for details see Table 5.2, in section 5.2). There is no established environmental factor to control the climate change effect for the HDM-4 rigid pavement deterioration models, like the (m) factor for flexible pavements. This may be due to its stiffness to resist subgrade.

7. The calculated calibration levels (Level I and II) showed variation from the default model coefficients of HDM-4 for K_{Ci}, K_{cp}, and K_{gm} (Figure 6.1). Therefore, the analysis was made based on the calibration factors, except for the roughness progression calibration factor K_{gp}. For the analysis, K_{gp} was taken as the default value (that is 1)(Bennett & Paterson, 2000). However, for Level II calibration the calculated K_{gp} results were more than 1, which indicated that there is a need for level III calibration.

The third level of calibration requires a detailed field investigation which may take at least five years and was therefore not considered in this work.

6.3.2. Roughness model adjustment for climate effect

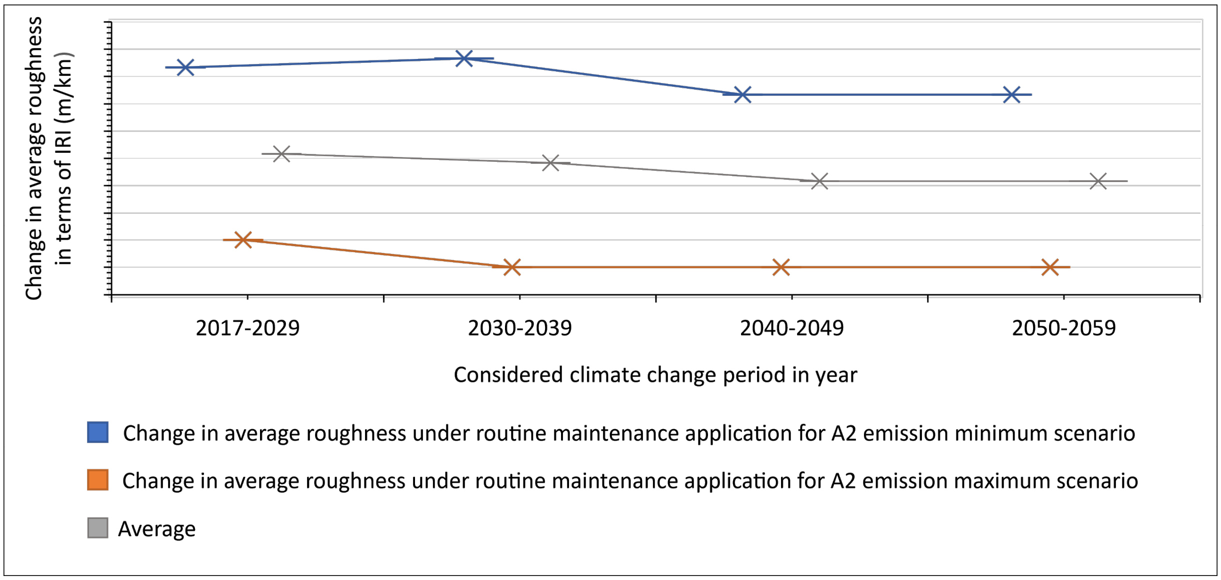
The approach used to modify the deterioration models to account for climate change was described in section 3.7. The preliminary analysis described in section 3.4 confirmed that climate change could be represented by adjusting HDM-4's environmental factor (m), which represents the different climate zones, and an environmental age factor (K_{gm}) within the flexible pavement roughness model. Likewise, Shao et al. 2017 used m and K_{gm} to evaluate performance under climate as described in section 3.7. However, their work was limited to considering only the TMI, which shows continued dryness or wetness of the subgrade soil. Considering one climate variable at a time may help to show the change of behaviour of the pavement surfacing due to that particular parameter. However, in reality, flexible pavements suffer from fluctuations of soil moisture, which is a result of at least two climate parameters, changes in temperature and precipitation. Therefore, in this study changes not only for the TMI but also for all other climate input variables were examined.

The linear and quadratic regression analysis technique, discussed in Appendix K, were used to derive adjustment factors for the roughness model K_{gm}. The linear regression model can estimate the effects of input variables on the model response, while the quadratic regression estimated the effect of input variables and their interactions on model responses. Linear regression is also recommended to calibrate the roughness model (Bennett & Paterson, 2000). However, for model development, there may be other graphical and numerical analysis techniques that could be also utilised, such as tornado charts, spider diagrams, and ranked sensitivity coefficients. These were not considered herein.

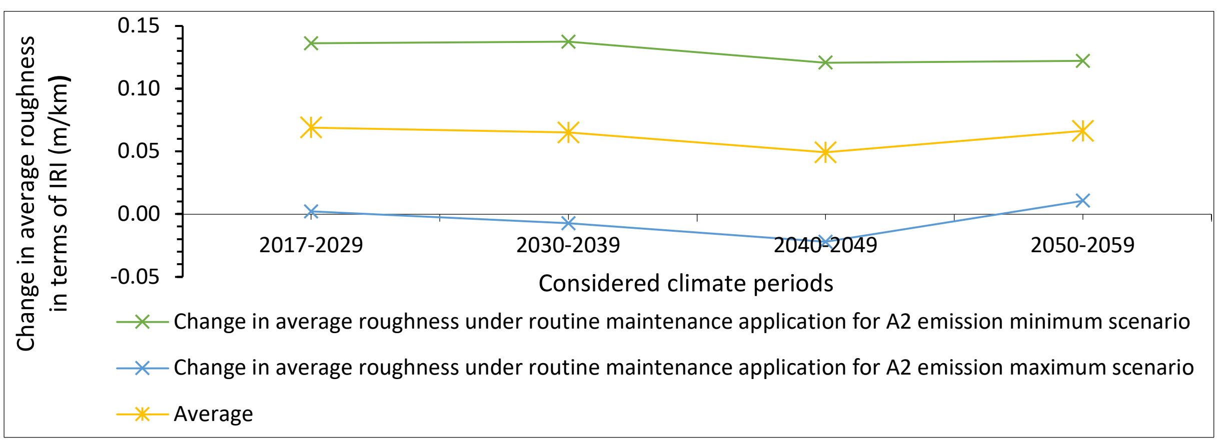
The findings of the analysis indicate that linear regression shows better model adjustment for the roughness model, as compared to the quadratic method (Appendix K). This is because there was no influence of interactions between the roughness components themselves (structural effect, cracking, pothole, rutting, and roughness). The quadratic regression confirms if there is a secondary effect from the interaction between the roughness variables that needs to be incorporated into the relationship. The analysis indicated that there are no secondary effects and this agrees with the model adjustment approach described by (Bennett & Paterson, 2000), where linear regression is proposed for roughness model Level II calibration.

The advantage of this approach is that it helps to perform climate change analysis for different climate periods and surfacing materials for the identified climate zones. The disadvantage is it requires repetition of the procedure for the desired climate change period. This may be a lengthy process depending on the considered climate change.

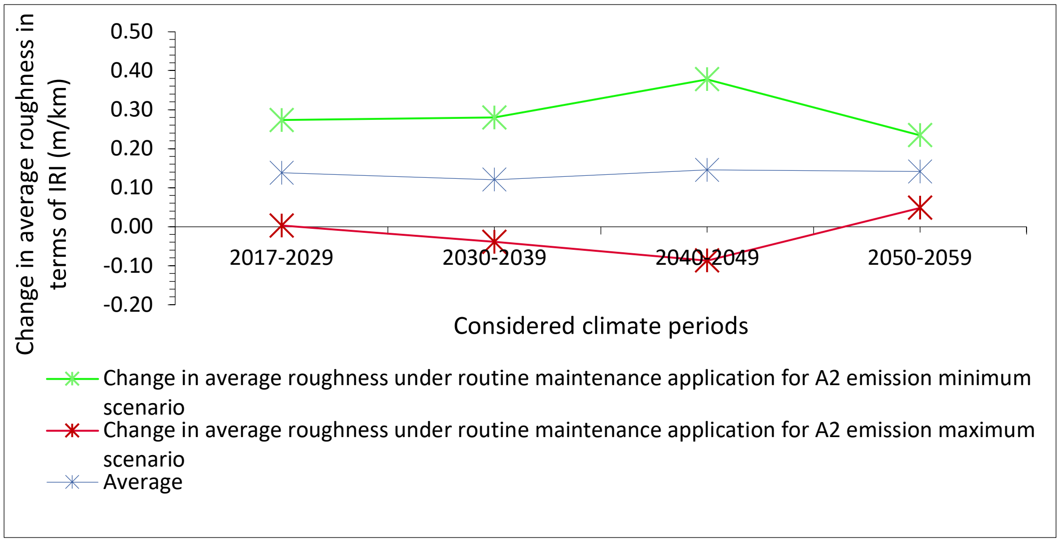
The climate adjustment factors K_{gm} used to consider the climate change effects (increase/decrease) in the road deterioration. The results of the analysis for some of the representative road sections are shown in Figures 6.2a-6.2c. Figure 6.2a indicates how the average road roughness changed with respect to the current climate as a function of K_{gm} for road section B30-5, which is an AC road carrying medium-traffic in a moist climate zone.



a) For road section B30-5 AC medium-traffic road in a moist climate zone



b) For road section B51-2a DBST medium-traffic road in a moist climate zone



c) For road section LTTP 1 Otta seal medium-traffic road in a moist climate zone

Figure 6.2 Change in average roughness due to climate adjustment

Figure 6.2 indicates that due to the 0.999 to 1.005 change in K_{gm} for the climate periods of 2017-2029 to 2050 - 2059, the change in the average roughness was in the range of -0.002 IRI m/km to 0.013 IRI m/km for AC; -0.022 IRI m/km to 0.136 IRI m/km for DBST; and -0.09 IRI m/km to 0.38 IRI m/km for Otta seal. This represents a change in deterioration (compared to the baseline) of up to a 0.43% for AC, 2.47% for DBST and 7.71% for Otta seal increase in the deterioration as compared to the baseline. The negative change in the average roughness retards the deterioration process, hence climate change does not always increase the rate of deterioration.

The result of the analysis indicates that surfacing used for a high-traffic level (that is AC, JRCP, and JPCP) required no climate adjustment modification though the calibrated values of K_{gm} changed in the range of 0.996 to 1.002 from 2017 to 2060. This may relate to the thickness and stiffness of these pavements, since thicker and stiffer surfacing for high-traffic action can resist the climate change effect. On the other hand, for low-traffic levels (AADT < 500) relatively higher ranges in the adjustment coefficient were obtained due to climate change. The value was observed to be varied between surfacing types. For instance, a relatively higher range in the adjustment coefficient was found for DBST surfacing than for AC in sub-moist and moist climate zones, as presented in section 5.3. The values ranged from 0.993 to 1.01 for AC, and 1.00 to 1.115 for DBST in sub-moist climate zones; and from 0.990 to 1.074 for AC, and from 0.995 to 1.015 for DBST for moist climate zones. However, higher K_{gm} values do not always cause a higher change in pavement deterioration, as their effect depends on other factors like the initial condition of the pavement. Table 6.1 shows K_{gm} and the percentage change in average roughness due to climate change from the baseline for low-traffic pavement surfacing. However, the highest change in the average roughness as compared to the baseline was obtained for the semi-arid low-traffic AC pavement (Table 6.1).

Table 6.1 Climate adjustment factor and change in average roughness for low-volume traffic surfacing

Pavement surfacing	*climate change consideration*	*Arid*	*Semi-Arid*	*Sub-moist*	*Moist*	*Sub-humid*
AC	Climate adjustment factor (K_{gm})	0.994–1.007	0.979–1.001	0.991-1.010	0.979 - 1.074	0.996–1.019
	% Incremental Change in average roughness IRI m/km	0.26	38.00	0.25	0.39	0.95
DBST	Climate adjustment factor (K_{gm})	0.980-1.022	0.975-1.001	1.000-1.115	0.995-1.015	1.010-0.997
	% Incremental Change in average roughness IRI m/km (due to climate change only)	0.00	11.49	0.92	2.28	0.43

Validation with actual data might help to increase the accuracies of the model adjustment coefficients. However, for this research, it was not possible to validate the modified coefficients with actual data, since the study considers future climate change conditions. Therefore, the output of the results discussed with two ERA senior engineers (Table 6.2) and the result of the analysis can be acceptable due to the following three major reasons.

Table 6.2 Consulted engineer profile

No.	Qualification	Experience
1	MSC in Engineering	More than 18 years in ERA road asset management
2	MSC in Engineering	More than 15 years in ERA road asset management

1. The change in climate and material property: - the climate change expected every ten years is not high to change the property of bituminous material used for surfacing and as a binder coat
2. Therefore, the change in roughness is likely to be minimal since the martial integrity is not affected by the climate change considered.
3. The maintenance and drainage facility: - routine maintenance provides crack sealing, which block water from entering to the subgrade. This with the good drainage will result in low amounts of pavement surface deterioration. However, the deterioration is likely to be higher in areas where there is a frequent change in subsoil moisture.
4. The ranges of the roughness for pavement condition classification consider the traffic loading which is more significant than climate change. If the effect of climate change alone is measured within the range, it is likely to be insignificant.

6.4. Discussion of Analysis Outcomes: Economic Evaluation, Pavement Performance Analysis, and Cost Components of the LCCA

Two LCCA analysis methods (approach 1 and approach 2) were followed in this research to identify the impact of climate change (section 3.8). The findings of each approaches discussed separately as follows:

6.4.1. LCCA approach 1

6.4.1.1. Economic Appraisal

The NPV value was used to perform the economic analysis to select the best alternative, by considering the sum of the discounted annual net benefit or cost. However, NPV values do not help to compare one option with the other, since it considers the total cost for different initial capital and road section lengths (section 2.3.3.3). To compare and rank the alternatives, comparisons should be made based on NPV/cost or NPV/road-length value. Hence, to evaluate the different pavement surfaces based on LCCA results, the NPV/cost ratio method of economic assessment was used in this research. It is acknowledged that the HDM-4 tool provides a number of alternative methods (internal rate of return (IRR), benefit-cost ratio (BCR), and first-year benefits (FYB)) for economic appraisal, as discussed in section 2.3.3.3.

The NPV/cost ratio involves using a discount rate to change the future cost to a present value. It is acknowledged that using different discount rates may vary the result of the economic analysis, as discussed in section 2.3.3.3. Although, for this study, a single (12.5%) discount rate was used to show the effect of climate change only in the economic analysis. This is because the discount rate is not stable (changes frequently) for growing countries, due to development activities. Therefore, for future work different discount rates, using probability or risk analysis methods, could provide a more informed estimate of the future financial conditions of the study area.

The economic analysis results in terms of NPV/cost ratio comparison for the moist climate zone showed that DBST and Otta seal surfaced pavements were economically viable for low and medium-traffic roads, as compared to AC; with Otta seal proving economically more viable than DBST. Although AC pavements showed better resilience to the climate change effect, the cost of construction and maintenance and the users' cost are higher as compared to the surface treatments considered. The standard and/or simplicity in their construction process (for instance, in aggregate productions and mix preparation) makes the Otta seal and DBST surfacing types less expensive than AC pavement.

The AC sections were more economically feasible than rigid pavement (JRCP and JPCP) for the same traffic level and climate conditions, even though the rigid pavements required lower maintenance costs. This is due to the higher construction cost for the pilot rigid pavements, which is associated with their small road section length (0.5 km each). That means the cost of construction (for example, for machinery and equipment) would be effectively utilised if the length of the trial sections was increased. Therefore, the initial cost has more impact on the NPV/cost ratio in this evaluation than the climate change effect. The summary of the NPV/cost ratio in each climate zone is presented in Table 5.8 in section 5.4.1.

6.4.1.2. Pavement performance analysis that considers climate change effects

The method used to identify the climate change effects on the performance of different surfacing was described in section 3.8. The approach compares the performance of the pavement surfacing in terms of IRI and the results were found to vary by surfacing type, traffic, and climate zone. The effect of climate does not always increase the deterioration rate. In some conditions (e.g. AC SA HT shown in Figure 6.3 below) it reduces the rate of deterioration. These findings agree with those of Anne et al. (2019), which showed a decrease in pavement performance when the effects of climate change are considered compared to without climate change for flexible pavements in the USA.

The findings revealed that for flexible pavements, higher ranges of changes in average roughness value were observed in the sub-moist and moist climate zone from 2050 to 2059. This is because in this period a relative increase in precipitation has been shown, as presented in Appendix I. Also, from 2040 to 2059, an increase in temperature was observed, and together with the TMI values suggests that the subgrade soil is continuously drying out during the considered periods. This resulted in a favourable condition for the arid climate zone as the average roughness decreased, as shown in Figure 6.3. However, this creates moisture fluctuation in other regions which leads to weakening of the strength of the subgrade and increases average roughness. In semi-arid climate zones with low and medium-traffic roads, both climate and traffic contribute to increasing future pavement deterioration, as presented in Appendix L.

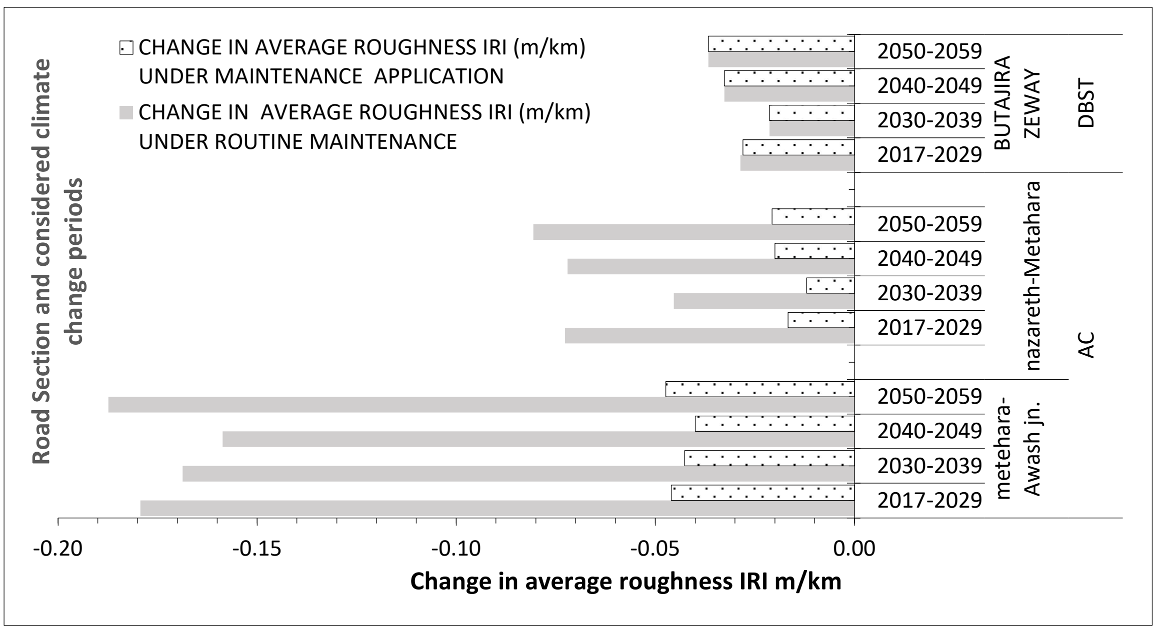


Figure 6.3 Change in average roughness for pavements in a semi-arid climate zone with high traffic for maximum A2 emissions' scenario

Although, the fluctuation in the temperature and precipitation affects the subgrade soil characteristics (such as swell, and water content) for resisting the traffic actions, Mndawe et al. (2015) found that the projected precipitation causes a negligible effect on the subgrade soil for roads found in South Africa. However, Shao et al. (2017) used the TMI change to find the impacts of projected climate change on the performance of flexible pavements in Australia. The result of the analysis showed that decreasing precipitation leads to a decreasing TMI (Appendix I), which will slow flexible pavement deterioration. Hence, climate change analysis is affected more by the climate zones where the roads under consideration are found.

The results also showed that the rigid pavements in general resisted the effects of climate change, with no observed additional pavement deterioration due to climate change as presented in section 5.4.2.2. These could be due to the stiff resistance of the pavement to resist the subgrade reaction due to moisture fluctuation. However, due to temperate change, some cracking might occur.

Hence, this study indicates that climate change effects can vary both due to the variation in climatic zones and the type of pavement surfacing used. This agrees with Padmini et al. (2017), who showed that climate change affected rigid and flexible pavement distress parameters irrespective of climate change prediction models' variation for USA roads. However, their study indicated that rigid pavements are not affected by a change in precipitation. But if the change in temperature alone is considered, it may cause joint faulting and transverse cracking. In the real world, however, both (temperature and precipitation) changes occur simultaneously.

In addition to this, for the same traffic level and climate condition, the AC pavement has more strength and flexibility for traffic and climate actions. The AC surfaced pavements consist of a different structure and material characteristics as compared to surface dressing pavements. This is due to the bitumen and the aggregate mixtures used in AC being very dense, but this is not the case for surface treatments. Surface treatments lose their materials/aggregate from traffic action when the temperature changes in arid and semi-arid climate zones rise. This is because the binder aging, rutting, bleeding, and flushing are affected by the temperature rise, as explained in section 2.4.4.1.

The voids between the aggregate are also higher in DBST pavements due to the single-sized aggregates in each layer, as compared to AC and Otta seal (Figure 6.4). The result also showed that Otta seal resisted the climate change impact better than DBST since Otta seal uses graded aggregate with a range of sizes (from crusher dust to 19 mm). This result disagrees with the findings of Bizjak et al. (2013) since the suitability of surface treatments will not depend only on a shorter frozen period. However, fluctuation in precipitation together with traffic actions makes surface treatments less durable in tropical areas.

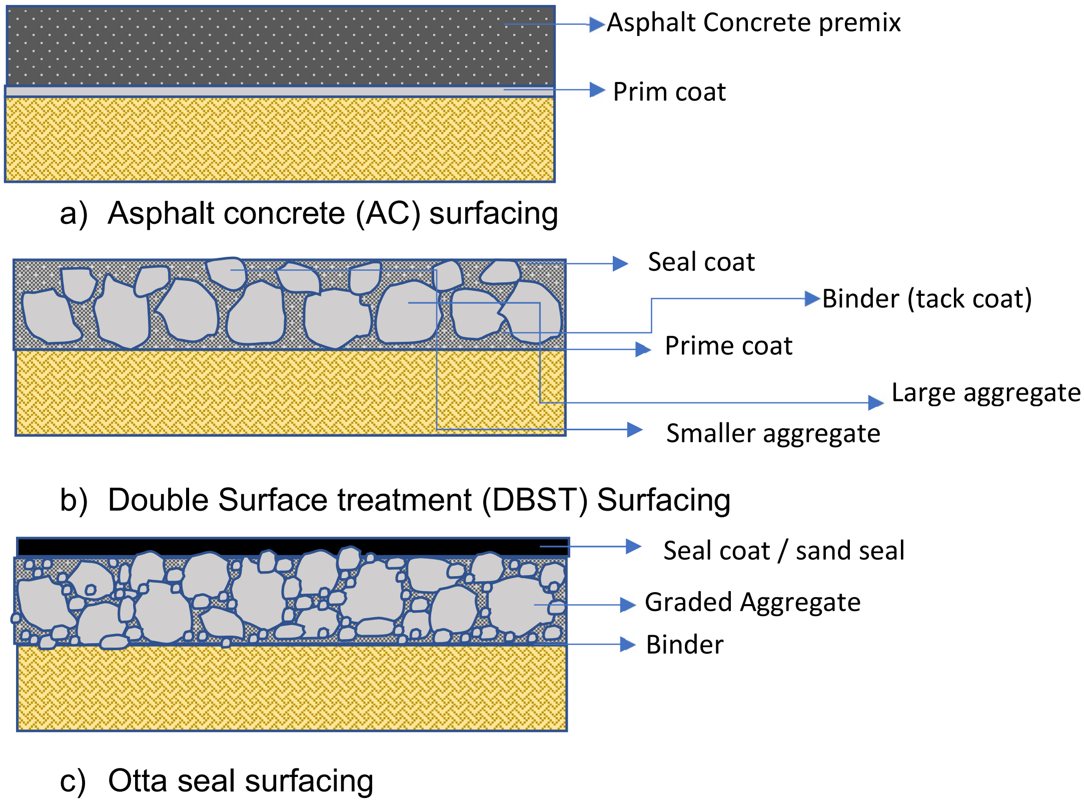


Figure 6.4 Flexible pavement surface section

6.4.1.3. Cost Comparison Analysis to Quantify the Impacts of Climate Change

The cost components of the LCCA, expressed in terms of RAC and RUC are defined in section 2.3. For the LCCA, two maintenance standard alternatives were considered for the analysis, routine and compound maintenance. Routine maintenance was considered the base alternative for the LCCA. Compound maintenance comprised of different maintenance alternatives that were applied as a function of road condition and traffic as described in section 4.2.1.

6.4.1.3.1. Road Agency Cost

The result for the discounted RAC showed no change in maintenance and agency costs for the considered climate change periods. This is because the LCCA analysis using the HDM-4 program selected the best maintenance option from the list in the compound maintenance category. This means the HDM-4 system compares the different maintenance alternatives in the compound maintenance category according to the defined standard and budget scenario (section 4.2.1). The selected maintenance alternative by the tool was based on pre-set specified standards and can handle the impacts of climate change in those periods.

To further investigate this, three additional maintenance alternatives (renewal, reconstruction, and rehabilitation) were separately introduced for the analysis. The results of the optimisation analysis confirmed that the above selection using compound maintenance is valid for the case of 15% and 40% budget constraints. Figure 6.5 shows the results by taking one section from each surfacing type in a moist climate zone with a medium-traffic level as a sample. The figure shows a minimum incremental agency cost observed for compound maintenance compared to the four maintenance alternatives for medium-traffic pavement surfaces in moist climate zones.

Hence, the effect of climate is minimum in influencing maintenance standards as compared to traffic action.

This result disagrees with the findings of Chai et al. (2014) in different climate zone, which show that due to climate change there will be a 30% increase in maintenance costs. On the contrary, the findings of Schweikert et al. (2014) indicate that climate change in sub-tropical areas mostly slows down the deterioration of the pavement. Moreover, the finding of Qiao et al. (2015) also showed that climate change does not have an impact on maintenance costs, if maintenance optimisation is applied. However, these results may not always be true for different climate zones. For instance, Knott et al. (2019) showed that an adjustment to the design process/manual is inevitable, if considering an increase in surfacing and base thicknesses to resist climate change effects.

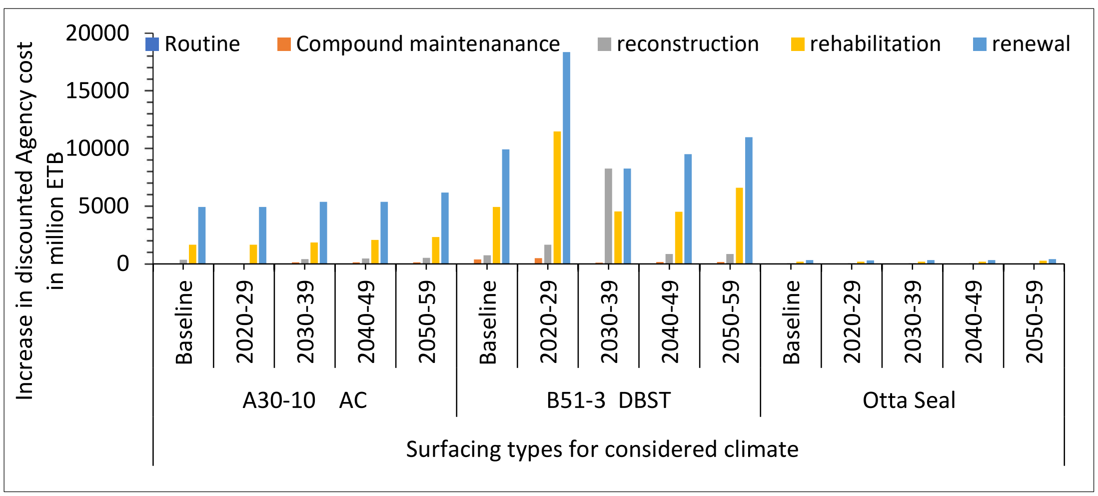


Figure 6.5 Incremental in discounted agency cost for four maintenance alternatives for AC, DBST, and Otta seal in a moist climate zone with medium-traffic level

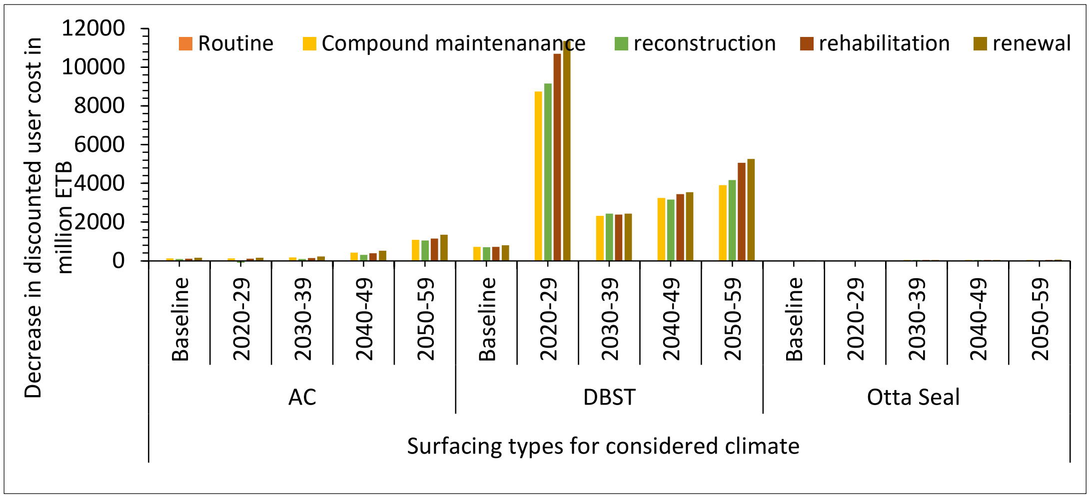


Figure 6.66 Decrease in discounted road users' cost for four maintenance alternatives for AC, DBST, and Otta seal in a moist climate zone with medium-traffic level

6.4.1.3.2. Road User Cost

Figure 6.5 shows a discounted minimum incremental agency cost observed for compound maintenance as compared to the four maintenance alternatives for medium-traffic pavement surfaces in moist climate zones. Moreover, as shown in Figure 6.6 applying the above maintenance standards results in reducing the users' cost in the range of: from 125.12 to 1090.86 million ETB for A30-10 AC; 722.83 to 8739.58 million ETB for B51-3 DBST; and from 45.03 to 15.10 million ETB for Otta seal (Figure 6.6).

The highest ranges of discounted RUC were obtained for the sub-moist, moist and sub-humid climate zones as compared to arid and semi-arid climate zones (section 5.4.1.4, section 5.4.2.4 and Appendix L).

The road user may spend a relatively higher incremental cost in using DBST surfacing type under low and medium-traffic levels in those climate zones as compared to AC as explained in section 5.4.1.4. The reason for this is related to the deterioration of the pavement due to the change in climate, as explained in section 6.4.2. From the components of the RUC, accident costs have shown no variation due to climate changes. However, the majority of change in the RUC has been from the change in VOC caused by the change in deterioration.

Figure 6.7 and Figure 6.8 showed that the road user spent a minimum additional cost due to climate change for AC pavements in a moist climate zone under both routine and compound maintenance applications. While the user spent the highest amount using DBST roads followed by Otta seal.

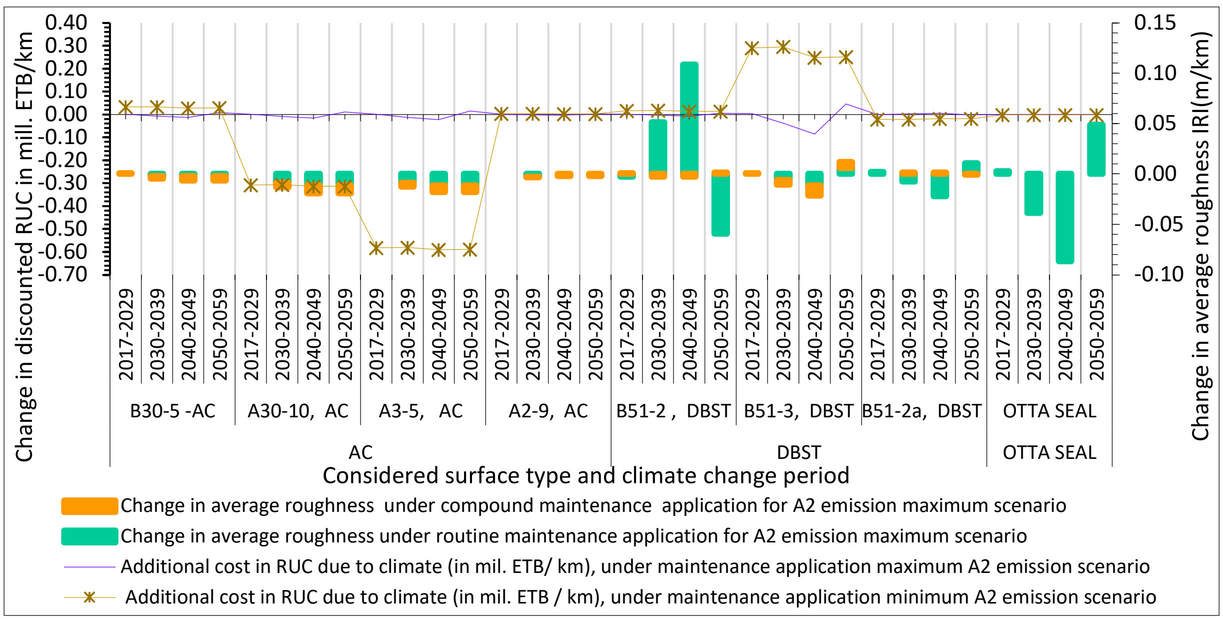


Figure 6.7 Relation between change in average roughness and change in discounted RUC under maintenance application

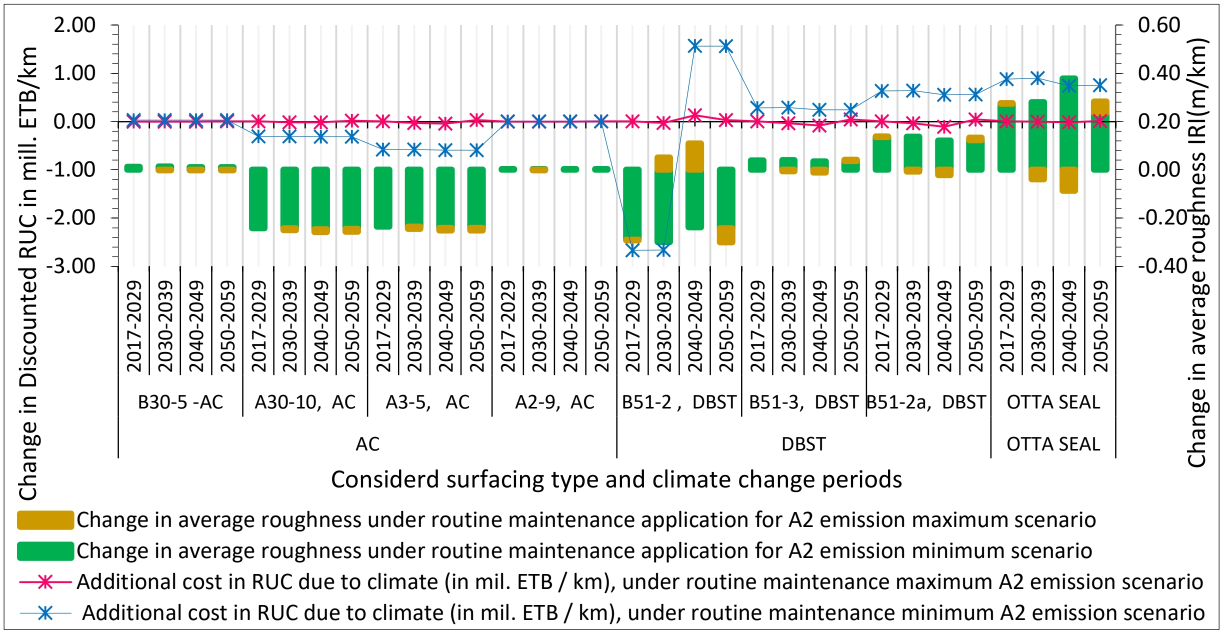


Figure 6.8 Relation between change in average roughness and change in discounted RUC under routine maintenance application

The incremental change in the discounted RUC due to climate change for the rigid pavements was considered for 15 years for comparison purposes with flexible pavements. The findings showed that there was no change in the RUC for the JRCP and JPCP due to climate change, as explained in section 5.4.2. This result did not change when studying 40 years of pavement design life, which is the minimum expected design life for rigid pavement. The discounted RUC for the15 years' analysis is shown in Figure 6.9 and it indicated that most of the cost for the user is from vehicle operation costs.

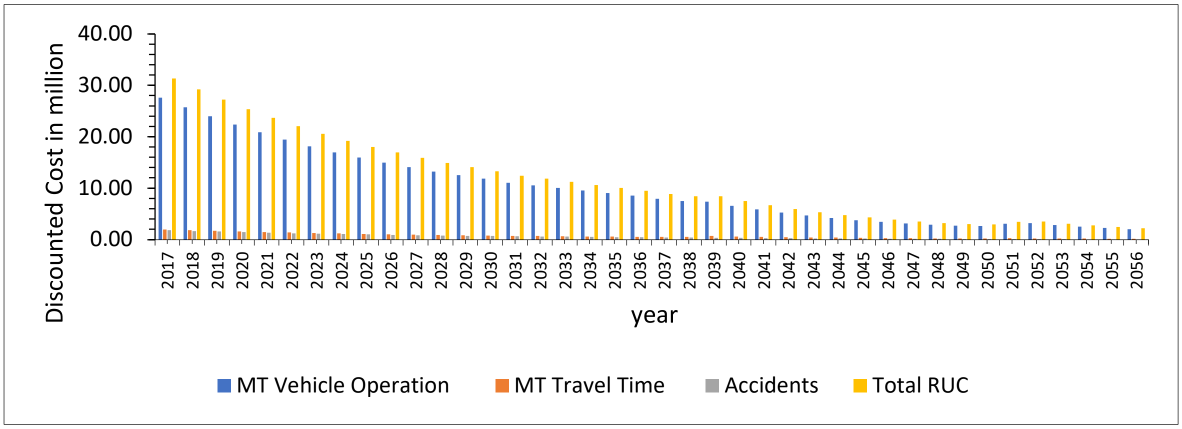


Figure 6.9 Discounted RUC components for rigid pavement

6.4.2. LCCA approach 2

6.4.2.1. Evaluation Based on NPV/Cost Ratio

The second approach of LCCA in this study considers the long term, i.e 44 years, continuous analysis using projected traffic and climate change actions together. For the projected traffic and climate change optimised maintenance alternative was used from the predefined maintenance standard (section 3.4) for each ten years analysis period. The result indicate that application of compound maintenance was the most appropriate for the period 2017 - 2039 and reconstruction from 2040 to 2059 for A1-4. Whereas for A1-3 compound maintenance was feasible for the first two period of analyses and from 2030 to the end and reconstruction was the best alternative (Table 6.3). These results were different from that of approach 1 where compound maintenance alternative was adequate to handle the climate change effect. These investment alternatives for approach 2 mostly address the projected traffic rather since the traffic effect is higher than the climate change effect. On the other hand, zero NPV/cost ratio obtained for the JPCP and JRCP pavements in all cases except where spalling and deep spelling applied (obtained -1.00 NPV/cost ratio).

Table 6.3 NPV/ cost ratio for the considered investment alternatives

Pavement type	Road section	Alternatives	2017-2019	2020-2029	2030-2039	2040-2049	2050-2059
AC	A1-4	Base alternative	0.00	0.00	0.00	0.00	0.00
		Compound maintenance	4.99	-0.279	0.70	6.29	-0.36
		Reconstruction	0.00	0.00	0.00	0.00	0.00
		Rehabilitation	-1.00	-0.88	0.00	-1.04	-0.82
		Renewal	-0.947	-0.93	0.00	-0.98	-0.84
	A1-3	Base alternative	0.00	0.00	0.00	0.00	0.00
		Compound maintenance	12.62	7.11	18.22	0.08	1.13
		Reconstruction	0.00	0.00	0.00	0.00	0.00
		Rehabilitation	-0.93	-0.72	-1.06	-0.84	-0.52
		Renewal	-0.87	-0.83	-0.95	-0.83	-0.67
Concrete	JPCP	Base alternative	0.00	0.00	0.00	0.00	0.00
		Spalling	0.00	0.00	0..00	0..00	-1.00
		Deep spalling	0.00	0.00	-1.00	-1.00	0.00
	JRCP	Base alternative	0.00	0.00	0.00	0.00	0.00

		Spalling	0.00	0.00	0.00	-1.00	-1.00
		Deep spalling	0.00	0.00	0.00	0.00	0.00

6.4.2.2. Pavement Performance Analysis that Considers Climate Change Effects

In addition to this, the results of the analysis showed that the average roughness value become maximum for the years when the previous period ends and the new began for approach 2 analysis. Since traffic is a governing factor in this analysis the type of maintenance used in the analysis may affect the results. Therefore, the maintenance standard defined in section 4.2.1 used for the analysis and the data for the next analysis were taken from the alternative with highest NPV/cost ratio. This helps to consistently select the next analysis input.

Figure 6.10 compares the second approach (approach 2) of the LCCA to the continues one-way analysis results for 44 years. The continues one-way analysis represents the usual HDM-4 LCCA analysis for fixed climate change condition. However, for comparison purpose average projected climate change conditions were taken from 2030 to 2039 period to analyse the whole 44 years. The result shows there is a considerable difference in the prediction of pavement performance as well as the associated road user costs. The RUC in all cases decreased when the time of the analysis increases (Figure 6.10 and

Figure 6.11). This is because the continuous approach uses appropriate maintenance alternatives based on the predefined standard for the deteriorated pavement.

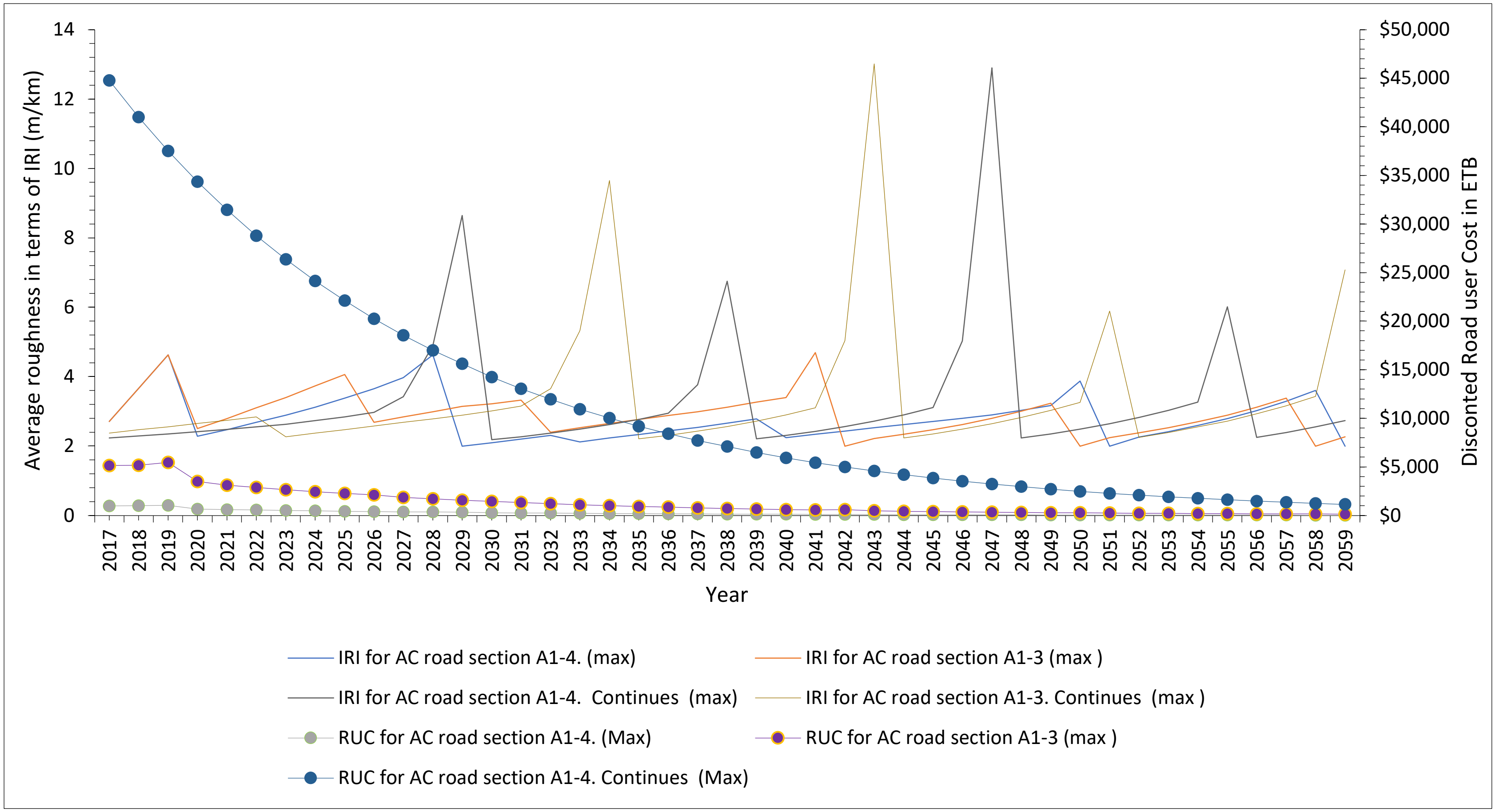


Figure 6.10 continues long-term average roughness and Discounted RUC comparisons for AC SA HT

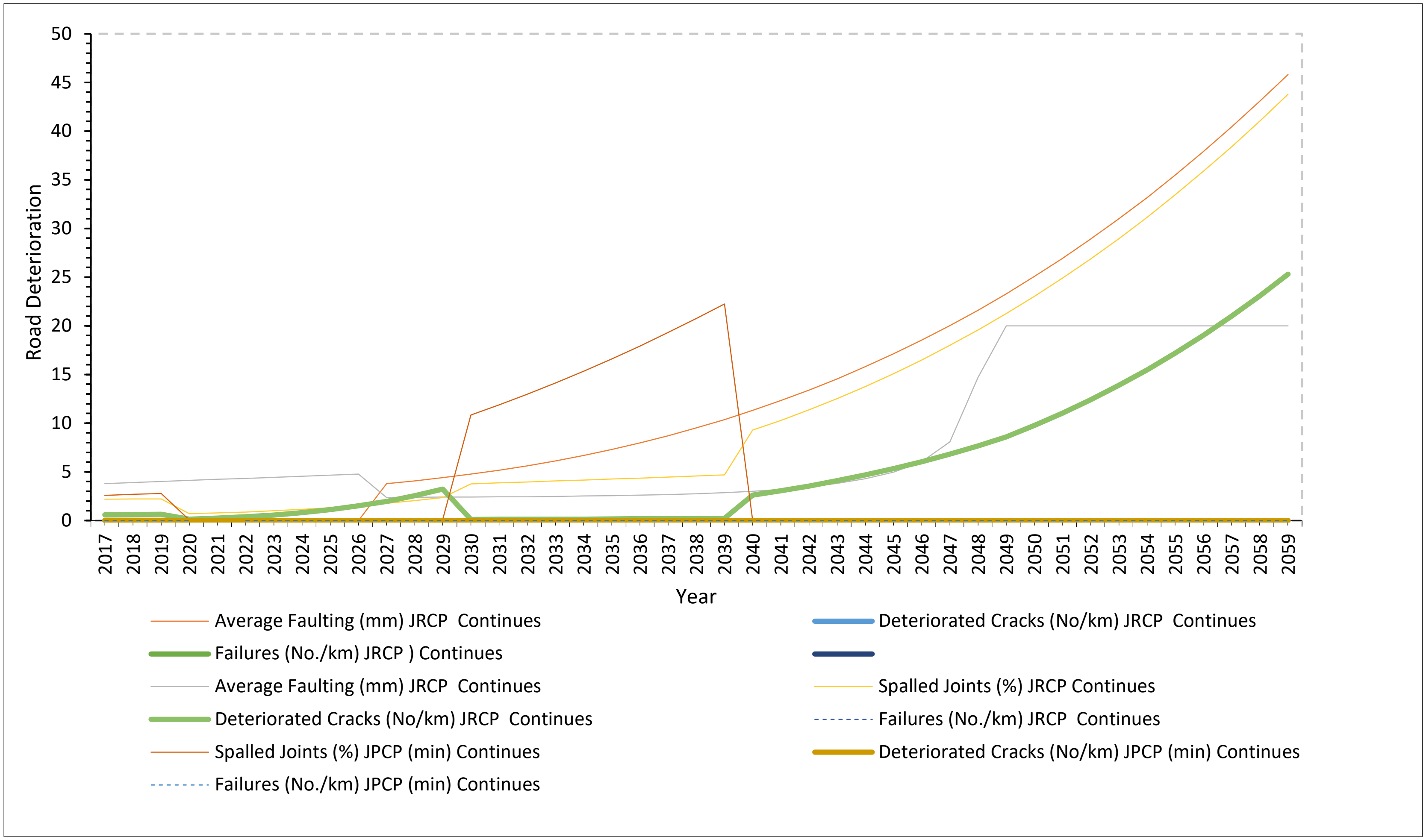


Figure 6.11 Continues long-term average roughness Comparisons for rigid pavements

Approach 2 might be more accurate if climate data of a greater frequent such as every 5 years were used instead of the ten years interval. However, for this study the climate data from McSweeney et al. (2010) were available and this provides climate projections for 10-year intervals.

Moreover, the projected traffic also growing and may reach the capacity of the road section and required additional lane for the increase traffic. This requires to see additional factors such as the time the widening required and the LCCA period of analysis to compare. Therefore, it is suggested that the more frequent climate change analysis and lane widening for the projected traffic are left for future work.

6.5. Value of the Research

The developed framework can facilitate the evaluation of different pavement surfaces under various climate change scenarios using an economic tool, such as HDM-4. By so doing, the developed approach can be used by decision-makers to select climate-resilient and cost-effective surfaces, for new build projects and maintenance regimes for current roads to cater for different future environmental and traffic conditions.

The lack of consideration of climate change effects on pavement surfacing selection and design in current LCCA practices is arguable, because the climate change effect is subjected to different variables which lead to changing environmental conditions that could result in slowing or accelerating the deterioration of the bound surface layer. The most significant variables include: the considered climate change period; climate models and scenarios used; the climate zone where the road is found; the material of the pavement; and the method of analysis. Hence, the approaches used provide a better understanding on the reflection of the costs that would be expected during the life of the pavement surfacing for decision makers.

The next chapter presents the conclusion of this study.

CHAPTER SEVEN - CONCLUSION AND RECOMMENDATIONS

7.1. Introduction

This research aimed to develop a life-cycle approach that can appraise different types of road pavement surfaces in economic terms, considering the impact of climate change on the road surfaces' deterioration. To achieve this aim, five specific objectives were identified. This chapter concludes the study by providing a summary of the main findings with respect to these aims and objectives. Moreover, the chapter presents the contributions and importance of the research, and also its limitations as well as future research areas.

7.2. Accomplished Work

The study has achieved the objectives of the research as follows:

1. The literature was reviewed in the area of LCCA analysis and climate change impacts on road surfacing performance in general and in the Ethiopian context in particular (thus meeting objective 1 of the research).
2. From the literature HDM-4 was identified as a suitable tool for carrying out LCCA taking into account climate change impacts during a road pavement's life cycle (therefore objective two of the research achieved).

3. A framework has been developed to quantify life-cycle cost components using HDM-4 or a similar tool, and taking into account climate change impacts (thus objective 3 of the research was met).
4. HDM-4 was calibrated to represent local conditions in Ethiopia. In addition to this, a number of models in HDM-4 were adjusted further to consider climate change (objective 4 for the research achieved).
5. The developed approach was used to assess AC, DBST, Otta seal, JPCP, and JRCP surface types by considering only climate change effects via a series of discrete 15-year analyses and over a longer continuous life cycle of 44 years (objective 5 of the research achieved).

7.3. Conclusions

From the research the following key conclusions were drawn:

- An LCCA approach was developed which can be used to compare the economic viability of different pavement surface types, taking into account the low, medium and high traffic and long-term impacts of climate change on pavement deterioration.

- Climate change effects can vary both due to the variation in climatic zones and the type of pavement surfacing used.

- For Ethiopian conditions, AC pavements were found to be more economically feasible for high level traffic in all considered climate zones, as compared to DBST, Otta seal, JPCP and JRCP pavements.

7.4. Findings

The key findings of this study are presented as follows:

7.4.1. Literature review

- The literature review indicated that an LCCA can be successfully used to appraise different road investments through economic principles and values by changing different parameters of investment options.
- The impacts of climate change on the road pavement deterioration can be influenced by the location of the road, the purpose of the analysis, the method of analysis, the climate parameters considered and the tool used for the analysis.
- There is a lack of life-cycle cost analyses of pavement performance which consider the climate change effects on road user costs as well as on road agency costs.
- Few studies were identified which take into account the potential impact of future climate change (excluding extreme conditions of climate) on pavement performance and its associated LCCA but none for Ethiopia.

7.4.2. Tools of the LCCA

- A number of potentially suitable LCCA tools were identified. They varied in terms of their data requirements and adaptability; in how the deterioration models consider different pavement surfaces and structural material properties; in the method used to calculate life-cycle costs; and in their consideration of environmental/climate impacts on road deterioration.
- The HDM-4 is widely used for the long-term economic evaluation of road infrastructure projects. It was found to be suitable for analysing climate change impacts since its software takes climate change during a road’s life cycle into account.

7.4.3. Framework for climate change analysis using HDM-4

- The developed framework enables the rational comparison and selection of road pavement surfacing types subject to climate change by considering the LCCA procedures.

7.4.4. The HDM-4 deterioration model modification

- The HDM-4 roughness model was successfully calibrated to level I and level II using data collected from Ethiopia’s road network to simulate the actual conditions.

- The roughness model was also successfully adjusted to future climate change and for flexible pavements it was found to be affected by up to 10% by the climate change projected to occur between 2017 to 2059.
- The analysis showed that JRCP and JPCP pavement types were unaffected by the change in climate, and hence, no adjustment to the pavement deterioration model coefficients was needed.

7.4.5. Evaluation of the selected pavement surfacing based on the LCCA

- Findings of approach 1
    1. From representative AC sections with high-volume-traffic roads: 100% in moist and semi-arid, and 75% in sub-moist climate zones were economically viable (NPV/cost > 0). For these conditions, AC is the preferred surfacing type in comparison to DBST, Otta seal, JPCP and JRCP. While the DBST and Otta-seal sections were economically viable and more resilient to climate change than AC for low- and medium-volume-traffic roads in all climate zones except in sub-humid zones.
    2. The maximum additional average roughness deterioration caused by climate change was found to vary from 0.005 m/km ΔIRI to 1.121 m/km ΔIRI for AC low-volume-traffic roads under routine maintenance in the semi-arid region for the period of 2017 to 2029. Similarly, the maximum average change of deterioration caused by climate change for DBST and Otta-seal surfacing was found in sub-moist and moist climate zones. The average change in roughness in terms of IRI values was obtained in the range of 3.563 m/km to -0.072 m/km and 0.378

m/km to 0.0 m/km for the compound maintenance standard and routine maintenance application respectively. The negative value for the change in roughness indicates that the effect of climate change is predicated to slow down the deterioration. That means the change in climate will not always deteriorate the road pavement.

3. The performance of the two rigid pavement representative road sections was found to be not affected by climate change.
4. The findings of the research showed no change from the baseline value of RAC in different climate change periods for all sections in each road network. These RAC results confirm that the use of appropriate maintenance can limit/control the deterioration of pavements due to climate change.
5. Additional RUCs due to the climate change impacts were found for all representative road sections, except for AC surfacing for medium-volume-traffic in the sub-moist climate region.
6. A comparison of maximum RUC from all climate regions showed that DBST surfacing induces lower user costs compared to the AC, except for roads carrying low levels of traffic.

- Findings of approach 2

  1 In the long-term approach the pavement deteriorated due to both climate change and traffic action, but the climate change effect is controlled by the traffic.

2. Higher NPV/cost ratios were found for AC pavements as compared to the JPCP and JRCP in the semi-arid climate zone.

7.5. Recommendations for Further Research

As mentioned above, the objectives of the research have been achieved using the available data and the HDM-4 software. However, it is recognised that there are limitations to the research associated with data availability and considering uncertainty factors. The following further research areas are suggested to address some of these limitations:

- In the NPV/cost ratio calculation, a single discount rate was used assuming that there will be a constant economic condition. However, the rate can vary over time. Therefore, additional research could be undertaken to consider the effect of different discount rates on the LCCA. This could be achieved by using a risk analysis approach that may vary from simple sensitivity analysis to complex model modification.

- The impact of climate on road surfacing deterioration can be considered both directly and indirectly in the HDM-4. The direct consideration is carried out by changing climate input parameters such as temperature, precipitation, TMI and number of cold days. In contrast, the effects of ground water, wind, and percentage of sunny days are not inputs into HDM-4. Rather, these are indirectly considered via the TMI through evapotranspiration calculations. Climate can indirectly affect traffic levels through demographic changes. In this research however, only the direct climate change effects were considered due to lack of available data. Therefore, further research is required to show the effect of demographic changes on pavement surfacing due to climate change.

- The research considered only the climate predictions resulting from the McSweeney (2010) climate projection model considering the A2 emission scenario. However, future research could compare different climate projection models and emission scenarios.
- The research considers the available ten years of climate data; however, the use of more frequent climate change data may provide more accurate results and should be considered in any further research.
- The road construction and maintenance activities that involves carbon emissions due to vehicle and machinery use, and quarry site protection (to make it environmentally friendly) have impact on climate change. However, the contribution to impacts of climate change due to the process of road construction and maintenance was not addressed in this research and could therefore be a future avenue of research.

Recommendation for HDM-4

- There are different methods reported in the literature to classify climate zones. The approach used by HDM-4 uses temperature and precipitation ranges to classify a climate zone. However, the ranges of temperature and precipitation have overlaps between climate zones. This may lead to similar results for different climate zones analysis. Therefore, it is recommended that in any future updates of HDM-4, climate zone classification methods that are in accordance with standard international practice, are made available to the user.

- HDM-4 allows some climate related data to use within an analysis. However, HDM-4 does not provide output that compares the effect of one climate change period against another. For instance, baseline/current climate condition related to different climate change period conditions. Therefore, climate change related analysis requires further analysis to obtain climate change impact alone using a spreadsheet. Accordingly, future updates of HDM-4 could improve the user friendliness of the software by incorporating modules that automate the use of data from climate change prediction models (such as models developed by IPCC).

Recommendation for ERA

- The potential impact of climate change should be considered in the design, construction, and maintenance phases of road pavements. Climate change effects can be addressed by preventative and reactive measures. In this regard, the ERA design manual needs to be reviewed in order to account for the effect of climate change since the current manual lacks such considerations.
- The LCCA showed that about 71% of the representative road sections of the ERA road network are resilient to climate change and economically viable when

assessed according to predicted changes in IRI and LCCA. To improve this statistic further, it is recommended that ERA improves its pavement type selection process. This is particularly important given that the majority (86 %) of the total road network of the country is unpaved. This means sooner or later there will be a large demand for paving unpaved roads depending on their traffic growth and the importance of the road from different perspectives social, economic, or political. If ERA, the nation's lead road authority, adopts the LCCA approach advocated in this research to identify appropriate road surface types, then regional road agencies could also be encouraged to utilise a similar approach when addressing their needs to upgrade unpaved roads.

- When considering new pavement types, ERA should construct the associated trial sections as part of an ongoing road construction project, so that the trial sections are adjacent to the road construction project. Further the construction of trial sections could usefully be included within the contract let to construction companies for the construction project. This would help to get a better estimation of the cost of construction for new types of road pavements and would require the contractor to be responsible for any modifications to plant and equipment required for the trial sections.

- Depending on the predicted traffic level and the expected impacts of climate change there is a need to reconsider the design life of existing road pavement types and their appropriate maintenance strategies. The choice of appropriate road surfacing types has a direct effect on the country's economic growth since roads stimulate development and poverty reduction. Consequently, it is recommended that ERA utilises a LCCA approach, that accounts for the future impact of climate change for both the selection of road pavement types and associated maintenance strategies. Such policies can be implemented by changing ERA's design standards as mentioned above.

7.6. Applications of the Developed Approach

- The major practical application of the developed approach is that the resulting framework can be used by road agencies to evaluate the life-cycle performance of any pavement surfacing types, provided they can be matched to the pre-established surfacing and base materials available in the HDM-4.
- The framework can be used for any other emission scenarios and/or climate projection models for climate change impact analysis using HDM-4.
- The calibrated and adjusted models, as well as the outcome of the study, will assist the ERA in pavement selection and in implementing sensible maintenance budgets to utilise the limited resources effectively. These can be achieved through improving ERA's pavement design manual so that designs take into account the predicted effect of climate change. A LCCA procedure is provided therein that informs the pavement selection processes.

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Appendix A - Pavement surfacing types

Concepts of Pavement Type Classification in HDM-4

Depending on their response in transferring traffic loads to the subgrade soil pavements are usually classified in two major types as flexible and rigid (Section 2.2.1). This variation is considered in predictive models and is highly dependent on the details of pavement parameters. Therefore, the HDM-4 uses a systematic classification of pavements based on definition and materials used for road surfacing and road base types (Table 1A). Due to this classification the tool potentially can be used for about 26 pavement types. Detailed information is given in the HDM-4 Manual Four and Six (Odoki & Kerali, 2006; Morosiuk, et al., 2004), Table 1A and Figure 1A below summarises these pavement categories.

Table 1A HDM-4 classification of pavement (source: HDM-4 Manual Four)

Name	Description
Bituminous surfacing: -	further divided into Asphalt mix (AM) and Surface treatment (ST) with base material;
Concrete surfacing: -	has three types as jointed plain (JP), jointed reinforced (JR), and continuously reinforced (CR) with base material
Block Surfacing: -	has three divisions Concrete block (CB), brick (BR) and set stone (SS) with base material
Unpaved: -	sub divided into gravel (GR), earth (EA) and sand (SA)

The HDM-4 pavement classifications have influence on the structure and the default value of coefficients of prediction model for certain distress. However, roughness models are dependent on different distresses rather than the pavement influence (Morosiuk, et al. 2006).

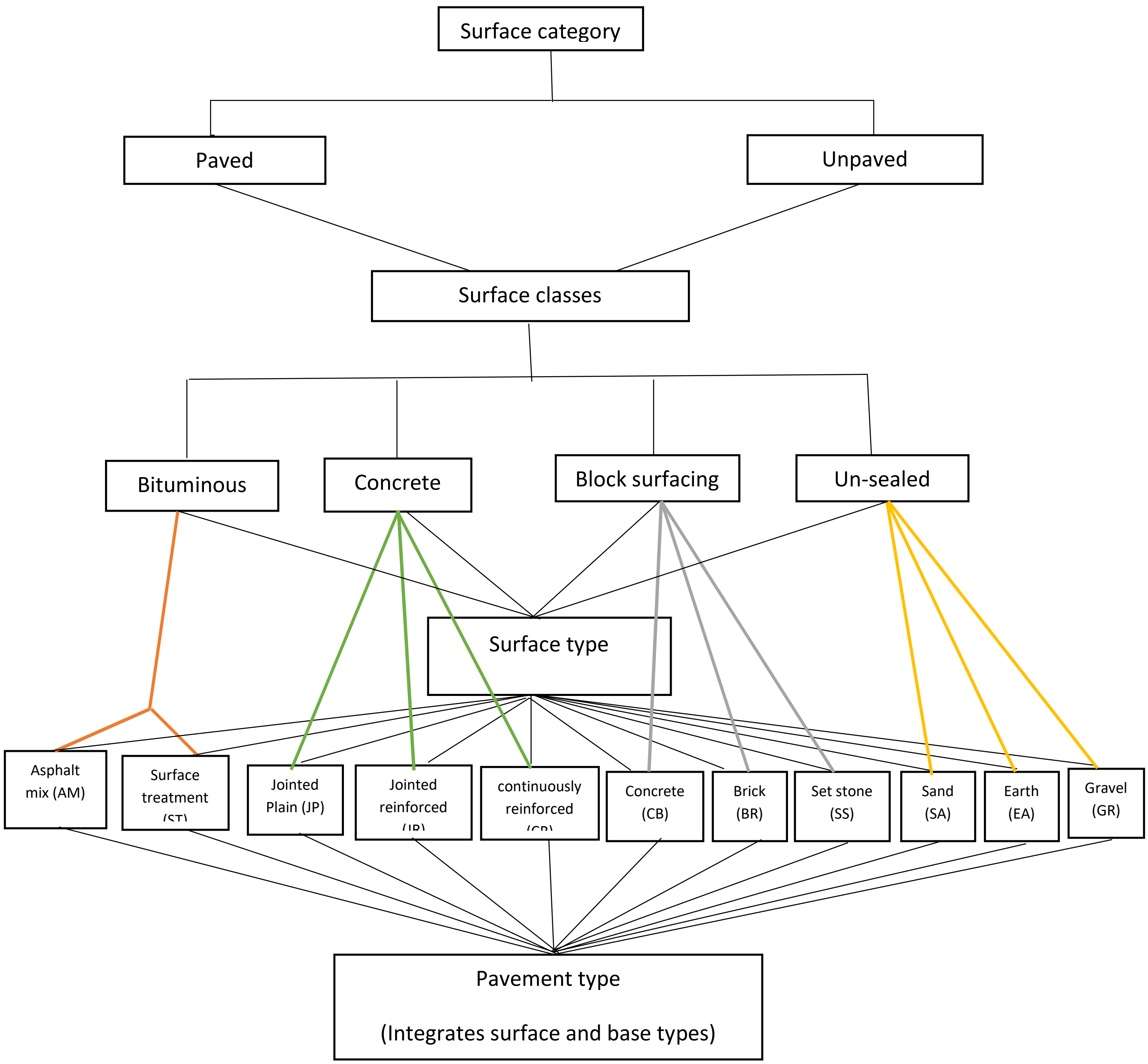


Figure 1A HDM-4 systematic classification of pavements (Odoki & Kerali, 2006))

2. Pavements surfacing types in Ethiopian Road Authority pavement design manual (ERA, 2013a)

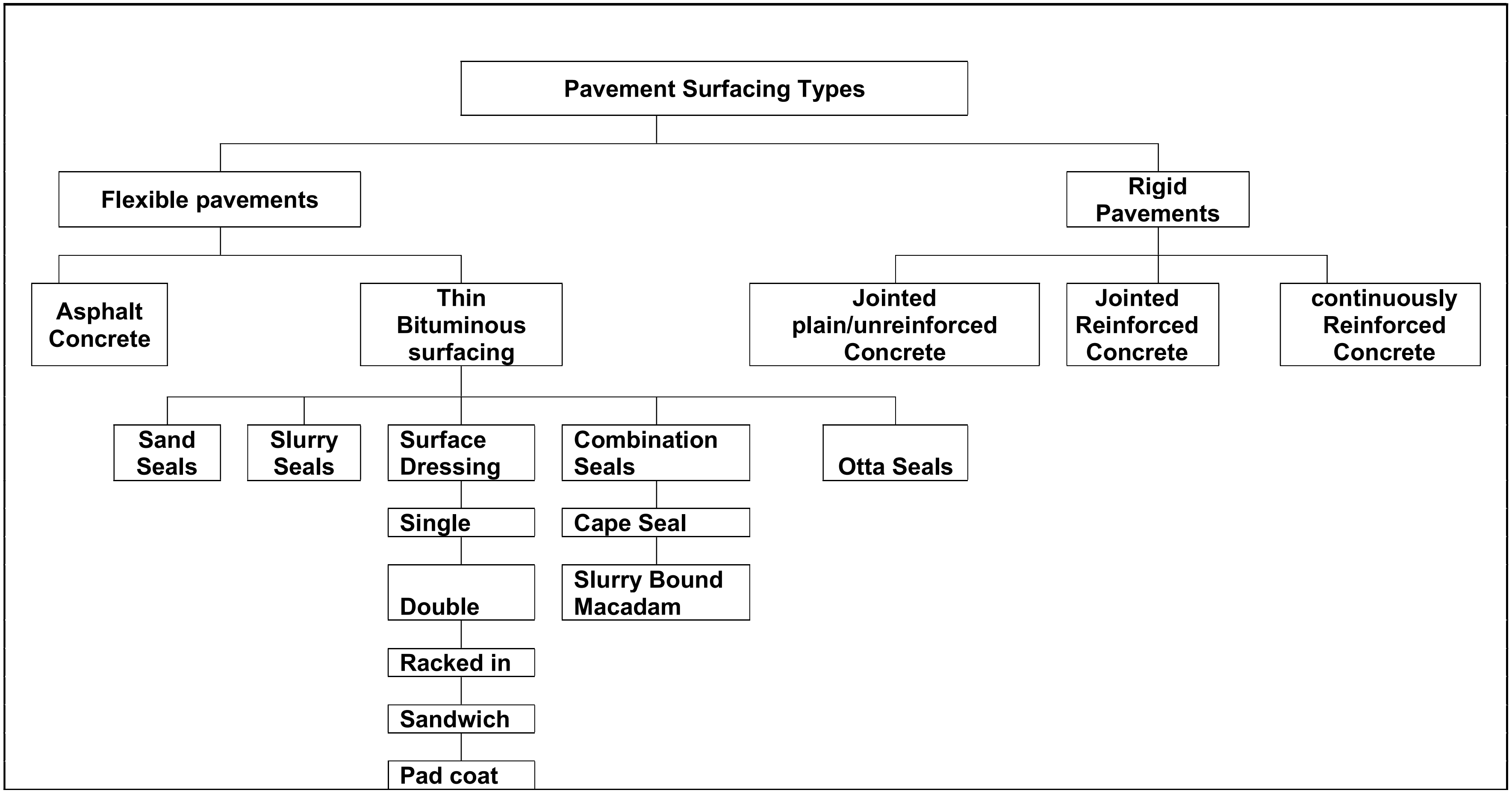


Figure 2 A Pavement surfacing types included in ERA design manual (ERA, 2013b)

Appendix B - Tools

Appendix B Tools

Table 2A- Currently used models and PMS tools

No.	Type of PMS	Brief description	Advantage/disadvantage	Source
1	Asphalt Pavement Alliance (APA) LCCA	APA is LCCA software which is developed using a Microsoft Excel spreadsheet. The software uses work-zone duration and the hourly traffic to estimate the LCCA. Moreover, it considers the initial construction cost, rehabilitation, user cost and salvage value for the LCCA. It calculates the NPV of different pavement alternatives using either deterministic or probabilistic analysis.	The advantage of the tool is that the model performs work-zone user costs' computation and optimises work-zone timing to minimise user costs based on the hourly traffic distribution and the work-zone duration. It can be used for more complex projects on the basis of Federal Highway Administration best practice. The disadvantage of the tool is that it makes no provision for the user to apply the present policies for rehabilitation and maintenance strategies.	Peyman, et al., 2016
2	D-TIMS	D-TIMS is a tool which was developed to calculate life-cycle cost estimates. It considers the initial construction cost, rehabilitation, and user cost for the LCCA. It also uses pavement condition values to set the maintenance and rehabilitation strategies.	The advantage of D-TIMS is that it helps to make pavement investment decisions at a network and project level, by providing recommendations for the treatment of specific distresses. The software also has built-in constraints to schedule treatments.	Peyman, et al., 2016; Geoffrey, et al., 2005

			However, neither the tool nor the pavement performance prediction considers the environment and climate change effect.	
3	Highway Development and Management (HDM-4)	It is a system for analysis of road management and alternative investment. Its framework is based on the pavement life-cycle analysis concept and is used to predict pavement performance, road works' effect, road user effect, and socio-economic as well as environmental impact. The tool can optimise the available budget for the proposed policy. The tool was developed using structured, empirical, deterministic models and measures the pavement performance's driven quality by the international roughness index (IRI).	The advantages of the HDM-4 are that it provides three analysis functions at: 1) strategy level to predict pavement deterioration for various funding levels and management strategies for the road network, sub-network, or individual segment level, over 5 to 40 years; 2) program level to prepare a multi-year program of projects within resource constraints; 3) project level to analyse costs and benefits of one or more projects or investment alternatives (e.g. maintenance, rehabilitation, widening). Moreover, it can analyse different flexible and rigid pavements with traffic, conditions, climate, materials, and proposed structure input data. Although, the mechanistic, empirical nature of the models allows the tool to be used in different conditions, the processes of model calibrations are very data intensive. The software also has limitations in providing an LCCA using a	Odoki and Kerali, 2006; Morosiuk, et al., 2006

			probabilistic approach; thus, it requires further analysis of its output or model adjustments for risks' analysis. The software is used by different researchers to achieve the objectives of various studies including climate change impact analysis.	
4	Highway Economic Requirements System (HERS)	HERS is an LCCA tool which brings together the knowledge of engineering and applied microeconomics to estimate the investment of road projects. The software compares the calculated benefits with initial costs. The benefit calculation includes the reduction in user costs, maintenance costs, and emissions.	The advantage of the tool is that it can predict the performance of the pavement and set the required standard to optimise the order of implementation of the pavement improvements based on the estimated cost. The disadvantage of this tool is that it carries out a comparison for network level analysis only and it does not include climate change analysis for performance prediction.	(Jiang, et al., 2013b)
5	Indiana Highway Economic Evaluation Model (IHEEM)	The IHEEM is an economic analysis model used for road projects. The tool uses traffic volume, existing and proposed road and bridge characteristics and existing road agency cost items as an input to perform economic analysis. The model calculates agency costs and user benefits for each year,	The advantage of IHEEM is that with a basic input data requirement, it can provide deterministic and probabilistic economic analysis. However, the software is limited to cost calculation only. The tool neither carries out pavement performance analysis nor considers	(Jiang, et al., 2013a)

		using a modified internal rate of return (MIRR), internal rate of return, net present value (NPV) and benefit cost ratio (BCR) for the whole analysis period. The model can also be used to conduct risk analysis with the probabilistic analysis approach.	environment and climate change conditions. Moreover, it can analyse only project level appraisals, since it is programmed to evaluate one project at a time.	
6	Infrastructure Planning Support System (IPSS)	The IPSS is a program developed for calculating the whole-life cost of road infrastructure due to climate change impact. The tool uses the quantity of work for reactive and proactive approaches to calculate the cost due to climate impact.	The advantage of IPSS is it can analyse the impact of both extreme and incremental climatic changes on road infrastructure. However, the tool does not provide changes in terms of road pavement performance and other pavement distress parameters due to the climate change impact.	Schinowsky, et al., 2015
7	Life-Cycle Cost Analysis Package (LCCOST)	The LCCOST is an LCCA software package which is developed to estimate pavement life-cycle costs for a specific period. It considers the initial cost of construction, multiple rehabilitation actions throughout the design life, and user delay at work zones during initial construction and subsequent rehabilitation activities.	The advantage of LCCOST is it includes yearly routine maintenance application and salvage value of the pavement and of the individual materials that make up the layers. However, the tool neither considers the performance of the pavement nor the environment and climate change effect.	Peyman, et al., 2016; Geoffrey, et al., 2005

8	MEPDG/S	It is a pavement performance predicting tool that uses a mechanistic-empirical pavement design approach to provide a projection of pavement performance throughout its design life. This entails adjusting or calibrating laboratory-developed pavement performance models to actual pavement performance measurements.	The advantages of MEPDG are: 1) it can analyse and predict pavement performances for different flexible and rigid pavements; 2) it can analyse input data for traffic, climate, materials and proposed structure; 3) It can provide performance projections in terms of pavement distresses and ride quality. Moreover, the tool was used in climate impact and pavement performance research. However, the disadvantage of the tool is it cannot perform an LCCA since it requires a separate program/tool to calculate the LCC.	(Padmini , et al., 2017); (Qiao, et al., 2015); (Li, et al., 2011)
9	OPTIPAV	It is an empirical-based LCCA system built with deterministic optimisation models. It is a modification of the GENETIPAV-D program that predicts the future quality of pavements by means of the pavement performance model of the AASHTO flexible pavement design method. The pavement's quality is expressed in terms of the present serviceability index (PSI). The objective of the tool is to minimise total road costs, which consist of the cost of	The advantage of using OPTIPAV are: a) it requires basic data (such as traffic, discount rate, pavement width and length, subgrade class, number of years for the analysis period, maintenance and rehabilitation activities with their unit costs). b) It provides the optimal pavement structure, predicted annual pavement quality, construction, schedule and cost for maintenance and rehabilitation works and pavement salvage value.	Santos and Ferreira, 2012

		construction, maintenance, rehabilitation works and pavement salvage value.	The disadvantages of OPTIPAV are: a) since the model is empirical the analysis is based on measured or recorded data, which represents specific local conditions of Greek or Portugal; b) the tool cannot consider any environment effect in the LCCA; C) it is used for flexible pavements only.	
10	Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE)	It is a pavement construction decision support and project-level life-cycle assessment tool based on Microsoft Excel workbooks. It is used to track specific performance indicators in order to incorporate environmental factors into the PM decision-making process. In terms of emissions and hazardous outputs, it focuses on primary and secondary construction materials. The tool was developed to determine the total environmental performance of the pavement and its construction material process, which includes production, hauling, erection hauling to landfill, recycling planted.	The advantage of PaLATE is that it can consider the environmental impact due to the pavement and its material production and construction process. In addition to this, it can assess the materials and their processes in relation to potential human toxicity, cancer and causes other than cancer. Furthermore, the result of the analysis can be used for an LCCA for road investment. However, the disadvantage of the tool is that it doesn’t evaluate the performance of the pavement under different maintenance strategies to calculate the LCCA. Furthermore, few studies, such as (Nathman et al., 2009), use the tool for	(Nathman, et al., 2009)

			environmental analysis, and the impact of climate change is not directly addressed in this tool.	
11	Project Analysis System International (PASI)	PASI is a model which was developed for the whole-life costing of different pavement system options in a varied range of environments and countries. The model was adapted from the UK's Scheme Analysis System (SAS) (Philippe and Vijay, 2006).	The advantage of the tool is that it can calculate user costs due to increased delays and accidents in the presence of traffic management. However, the disadvantages of the tool include: 1) it considers only high-performance surfacing for the economical assessment; and 2) it is limited to calculating the effect of fuel consumption and environment for the whole-life cost analysis. Moreover, its use was limited to a specific project.	(Peyman, et al., 2016), (Philippe and Vijay, 2006), (Geoffrey , et al., 2005)
12	REALCOST	It is a Microsoft Excel-based LCCA software package which can calculate life-cycle values that include RAC and RUC for road projects' construction and rehabilitation. It was developed by the FHWA in the USA to automate FHWA's methodology. This tool can perform an LCCA in either a deterministic or a probabilistic form. The software can be used as a tool for pavement selection in	The advantage of the tool is its capability to calculate the RUC due to work-zone closure duration. It is simple and flexible to use, as well as being supported by the FHWA for technical support for the user. However, the tool's life-cycle value output cannot be used for comparing different alternatives to obtain the best option in decision-making, because it cannot predict the RAC or service life	Prasada, et al., 2009

		accordance with Federal Highway Administration best practice methods.	for road projects. Therefore, research projects, such as (Lee, et al., 2018), (Kim, et al., 2015) and (Lee, et al., 2011) used it with another program to perform an LCCA.	
13	Roads Economic Decision Model (RED)	RED is a program which uses a serious of Excel workbooks to perform an economic evaluation of road investment and maintenance alternatives. It is developed for unpaved roads with a consideration of: 1) uncertainties in the traffic, road condition and maintenance plan availability; 2) roads may not be all-weather; 3) the service level and associated user costs; 4) the potential to influence economic development; and 5) beneficiaries other than road users.	The advantages of the tool include its models can compute the benefits according to normal, generated and diverted traffic as a function of a reduction in VOC, time costs and safety benefits. However, its use is limited to low-value unpaved roads only and it does not involve climate change consideration.	World Bank, 2001

Appendix C –

Road Distress Factors in HDM-4

Table 3A Key Road distress factors considered as variables in HDM-4 Deterioration models, (Source: HDM-4 Manual Four (Odoki & Kerali, 2006))

key variables	***For flexible pavements***	***For rigid pavement***
Pavement structural characteristics	Measures pavement strength, layer thickness, material types construction quality and subgrade stiffness.	Measures the pavement strength, slab thickness, material types and properties, amount of reinforced steel, the presence of tied concerted shoulders and widened outside lanes and subgrade stiffness.
Road condition	Includes the surfacing and deformation distresses, surface textures and side drainages.	Deals with pavement defects and side drainage
Pavement history	Referred to pavement age and related to works carried out on the pavement (previous maintenance, rehabilitation, and construction)	Include pavement age and the year of previous major maintenance and construction works carried out on the pavement.
Road geometry	Includes carriageway and shoulder widths, vertical alignment.	Carriageway and shoulder widths.
Environment	Involves mean monthly precipitation, mean annual precipitation, freezing index, Thornthwaite moisture index, temperature range, and number of days with temperature greater than 32^{o}C (90^{o}F)	Comprises of the mean annual precipitation, freezing index, Thornthwaite moisture index, temperature range, and number of days with temperature greater than 32^{o}C (90^{o}F).
Traffic	The flow of all vehicle axles (YAX), flow of equivalent standard axle loads (ESAL), both the flow of heavy commercial vehicle per lane per day (QCV), the number of equivalent light vehicles passes per year (NELV).	The annual flow of equivalent standard axle loads (ESAL) and the cumulative equivalent standard axel loads (NE4).

Appendix D –

Model improvement in HDM-4 from HDM-III

Appendix D Model improvement in HDM-4 from HDM-III

Table 4A Description of HDM-III incremental model and its improvement in HDM-4 v.2 (source HDM-4 Manual Four and Six)

Incremental Roughness model components	**Incremental Roughness model description in HDMIII**	**Incremental Roughness model improvement in HDM-4 V.2**
1) Structural deformation	- Considers the pavement martials strength against the environmental and traffic effect. Moreover, the traffic action has impact on the rutting property of flexible pavement that in turn affect the incremental change of roughness (ΔIRI). Therefore, the rutting part defined as standard variation of the rut depth included in this component	- Considers the adjusted structural number as proposed by Parkman C.C, et al. (1997) as a replacement for modified structural number, which characterizes the pavement strength in HDMIII. In addition to this, the new model takes into account the reduction of the pavement structural strength due to the effect of surfacing and underlying bituminous cracking. - There is no difference in incremental roughness from HDMIII modelling due to rutting.
Surface destress	The surfacing defects like cracking and potholes created in the surface or base of the road pavement are categorized under this group and have influence in the roughness model.	The construction quality indicator considered as an input variable and applied in cracking, ravelling and potholing prediction models. - The HDM-4 potholing model component advancement comprises of a) the maintenance

	The construction quality indicator used as a construction quality code for cracking and ravelling models	frequency of pavement patching according to Morosiuk and Riley (2001), b) the progression of pothole patching reflects the time for patching potholes based on its policy factors according to PIARC (2004), and c) the number of leans of a section of roads according to Morosiuk (2003). There is no difference in incremental roughness from HDMIII modelling due to cracking.
Environment factors	-Roughness model has two coefficients to consider the effect of climate. The first coefficient is calibration factor for roughness progression (K_{gp}) while the second factor is the environmental calibration coefficient (K_{ge}). The environmental coefficient (m) of the HDM is taken from the data used to develop the roughness model. Bennett and Paterson, (2000), provides different m values which varied between 0.005 to 0.23 for those climate categories expressed in the section 3.5.2. However, for the model of ΔIRI without traffic action, the m value used as 0.023 as a base to represents the modelling source data (Brazilian) climate condition	the modified environmental coefficient m according to PIARCE varies from 0.005 to 0.060 for different climate classification the details presented above

Appendix E –

Climate Change Information Summary

Appendix E –Climate Change Information Summary

1. Summarised historical trends of temperature and precipitation from1960 to 2006 in the country.

Ethiopia is found in the Horn of Africa at latitudes of 4 to 15°N, and has a varying climate in different locations of the country. According to McSweeney (2010) the south eastern and north eastern lowland regions can be classified as typical tropical climate, while the central highland regions of the country are much cooler. The mean annual temperatures are around 15oC – 20°C in the high-altitude regions, 25°C – 30°C in the lowlands and up to 50°C in Afar depression. Table 5A presents the summarised historical trends of temperature and precipitation from1960 to 2006 in the country.

Table 5A Summarised historical temperature and precipitation for Ethiopia (Source: (McSweeney, 2010))

a) Temperature		Precipitation	
Mean annual temperature increased by	1.3˚C	From 1960 to 2006 there is not a statistically significant trend in observed mean rainfall in any season	-
average rate of temperature increase	0.28˚C per decade	In 1980s JAS rainfall decreases and observed recovery in the 1990s and 2000s.	-
most rapid rate temperature increase	0.32˚C per decade, In JAS	Insufficient daily rainfall records available to identify trends in daily rainfall variability.	-
the average number of 'hot' days per year	increased by 73 (1960 – 2003)		
the average number of 'hot' days per month	increased by 9.9, in JJA (1960 – 2003)		

The average number of 'cold 'days per year	decreased by 21 (1960 – 2003)		
most rapid rate cold 'days per month	decreased by 2.3 SON days		
average number of 'cold' nights per year	decreased by 41		
most rapid rate of nights per month	decreased by 3.7 in JJA		

2. summarises the forthcoming climate prediction of Ethiopia from the United Nations Development Programme (UNDP) climate change country profile (McSweeney, 2010)

Table 6A Climate projection (Source: (McSweeney, 2010.))

Climate parameters	***Future climate changes***
Temperature	The mean annual temperature is projected to increase by in the range from 1.1 ˚C to 3.1˚C and from 1.5 to 5.1˚C by the 2060s and 2090s respectively
Frequency of days and nights	By the 2060s and 2090s the annually projections indicate that 'hot' days (temperature exceed by 10% from the current condition) will occur on 19-40% and 26-69% of days respectively. In July, August, and September days that are considered 'hot' for their period are projected to rise most rapidly from 38 to 93% of days by the 2090s

	Nights that are considered 'hot' for the annual climate of 1970-99 are projected to increase more quickly that hot days, occurring on 29-66% and 34-87% of nights by the 2060s and 2090s respectively. Nights that are considered 'hot' for their season are projected to increase the most rapidly in July, August, and September, occurring on 53-99% of nights in these months by the 2090s.
Precipitation	October, November, and December monthly precipitation are anticipated to change by 10 to +70% as an average over the whole of country. Comparative rises in these months' precipitation are largest in the driest, eastern most parts of the country. Predictions of variation in the rainy seasons April, May, and June and July, August and September which affect larger portions of Ethiopia are more mixed, but tend towards slight increases in the south west and deceases in the north east. The models in the ensemble are broadly consistent in indicating increases in the proportion of total rainfall that falls in 'heavy' events, with annual changes ranging from -1 to +18%. The largest increases are seen from July to December rainfall. The models in the ensemble are broadly consistent in indicating increases in the magnitude of 1- and 5-day rainfall maxima. The annual increases arise largely due to increases in October, November, and December.

Appendix F - **Preliminary Analysis data**

Appendix F Preliminary Analysis data

Tabel 7A Data for sample analysis

	Name	Length (km)	Traffic (AADT)	IRI	Wide St. Crack%	No. pothole (no/km)	Mean rut depth (mm)
A-S	Sec-1	31.83	1213	3.0	0.05	0.8	3.36
A-G	Sec-2	12.70	1087	3.7	1.72	12	3.84
D-D	Sec-3	51.90	1633	4.0	2.0	5.0	8.00
M-W	Sec-3	80.00	903	3.2	0.65	1.0	4.6

Appendix G –

Summarises for the Sources of the Input Data Used for the Strategic HDM-4 Analysis.

Appendix G Summarises for the Sources of the Input Data Used for the Strategic HDM-4 Analysis.

Table 8A - Data type and source

Data group	Data type	Intended use	Sources
Vehicle fleet	1) Vehicle physical and loading characteristics, utilization and service life, performance characteristics such as driving power and braking power, and unit costs of vehicle resources;	For user cost estimation	(ERA : Traffic Count Anual Report, 2017g), and (HITCON Engineering PLC, 2018)
Traffic data	2) Composition, volumes and growth rates	Pavement performance prediction, work effect and User Cost estimation	(ERA : Traffic Count Anual Report, 2017g), and (HITCON Engineering PLC, 2018)
Configuration data	3) Pavement surface type, base type, new and previous surface thickness, reconstruction & rehabilitation year, surfacing year and construction defect indicator 4) Traffic distribution, road capacity, and 5) Climate zones	Pavement performance prediction, work effect, road agency and user cost estimation	(RAMD : Anual Report, 2017), (RNMDS : Anual Report, 2017), (DANA, 2018),and (HITCON Engineering PLC, 2018)

Visual pavement distress data	6) All cracks, no of potholes, rut depth, ravelling, roughness, texture depth, skid resistance and area of edge wear.	Pavement performance prediction, work effect, road agency and user cost estimation	(RAMD : Anual Report, 2017), (RNMDS : Anual Report, 2017), (DANA, 2018),and (HITCON Engineering PLC, 2018)
Structural pavement condition data	7) Structural no or FWD deflection bowl or Benkelman beam deflection, 8) Relative compaction and Subgrade CBR	Pavement performance prediction	(RAMD : Anual Report, 2017), (RNMDS : Anual Report, 2017), and (HITCON Engineering PLC, 2018)
Drainage	Drainage type and condition	Pavement performance prediction and work effect,	(McSweeney, 2010), (RNMDS : Anual Report, 2017) and (HITCON Engineering PLC, 2018)
Environmental / climate data	Rainfall and temperature	Pavement performance prediction and work effect,	McSweeney, 2010 and (The World Bank Group, 2018)
Maintenance & improvement intervention	9) Maintenance & improvement intervention types, 10) Cost of each maintenance & improvement intervention types	work effect, road agency and user cost estimation	(RNMDS : Anual Report, 2017) and (HITCON Engineering PLC, 2018)
Road safety data	11) Unite cost for different road traffic accident type	User cost estimation	A study conducted on road traffic Accident in Ethiopia, (Debela , 2019)
Economic analysis parameters	12) Discount rate and base year	LCCA	(National, Bank of Ethiopia : 2017/18 Annual report, 2018)

Appendix H - **Climate Zone**

Table 9A Climate zones Source: (Belete, et al., 2013; Odoki & Kerali, 2006)

Moisture Classification					Temperature classification			
Moisture Classification	Description	Ethiopian condition	HDM-4 reference		Classification	Description	Temperature range (°C)	
		Annual rainfall Ethiopian (mm)	Thornthwaite moisture index	Annual precipitation HDM-4 (mm)			Ethiopian condition	HDM-4
Arid	Very low rain fall, high evaporation	< 302	-100 to -61	< 300	Arid / Tropical	Warm temperatures in small range	>27.5	20 to 35
Semi-arid	Low rain fall	302 to 350	-60 to -21	300 to 800	Semi-arid / sub - tropical -hot	High day cool night temperatures, hot-cold seasons	27.5 to 21	-5 to 45
Sub-moist		350 to 566			Sub-moist		21 to 16	
Moist		566 to 835			Moist		16 to 11	
Sub – humid	Moderate rainfall, or strongly seasonal rainfall	835 to 1189	-20 to +19	800 to 1600	Sub – humid / sub-tropical cool	Moderate day temperatures, cool winters	11 to 7.2	-10 to 30
Humid	Moderate warm seasonal rainfall	1189 to 1711	+20 to +100	1500 to 3000	Humid / temperate – cool	Warm summer, shallow winter freeze	<7.5	-20 to 25
Per – humid	High rainfall, or very many wet-surface days.	> 1711	>100	> 2400	Per – humid / temperate - freeze	Cool summer, deep winter freeze		-40 to 20

Note: - 1. The mean monthly precipitation (MMP) is used in the modelling of bituminous pavement deterioration and unsealed road deterioration and it is expressed in mm/month.

2. Thornthwaite moisture index – indicates how wet or dry is a given climatic zone.

Appendix I

Collected DATA

1. The Study Area

The study used data from parts of the Ethiopian Road Authority (ERA) road network which is shown in figure3A. The study area covers different parts of the country to be representative of Ethiopia's nine different climate zones (see figure 4A). The study involves impacts of climate on the evaluation of the performance and LCCA of currently used pavement surfacing types. The road sections were identified by their surfacing types and traffic levels.

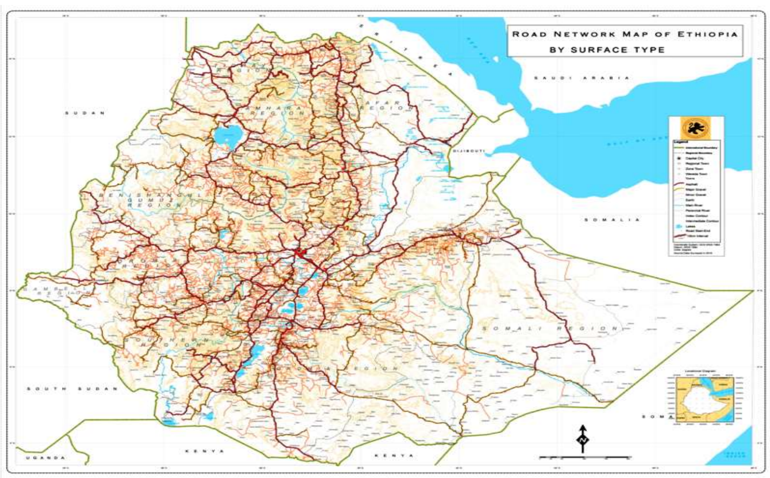
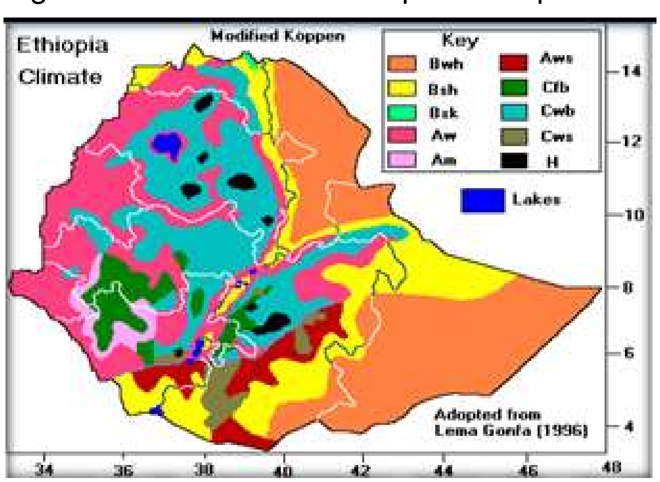


Figure 3A Road network map of Ethiopia surface type.



Bwh: - Hot arid climate
Bsh: - Hot semi-arid climate
Bsk: - cool semi-arid climate
Aw: - Tropical rainy climate
Am: -Tropical rain forest climate
Cwb: - warm temperate rainy climate I (dry months in winter)
Cfb: - warm temperate rainy climate II (all months having some rainfall)
Aws: - Tropical climate (criteria for both summer and winter dry is met)
Cws: - Warm temperate climate (criteria for both winter and summer dry are met) and
H: - highland climate.

Figure 4A Climate Zone of Ethiopia (Source: Lemma Gonfa, 1996)

1.1. Data Description and Processing

The type of data required for the HDM-4 calibration and the LCCA comparison were identified in Chapter 4 and are: Vehicle fleet, Traffic, Configuration data, Visual pavement distresses, Structural pavement condition, Drainage, Environmental / climate, Maintenance, Road safety and Economic analysis parameters. The data collection methods and related processes are discussed below.

1.1.1. Vehicle Fleet

Vehicle fleet data contains information about the types and categories of vehicle types using the analysed network. Table 10A and Table 11A below summarise the vehicle fleet and VOC data used in the study. The information has been obtained from HITCON Engineering PLC (2018).

In accordance with HDM-4 requirements, the costs were expressed in economic terms determined from financial market prices. Usually, these economic costs were determined from the financial costs using standard conversion factors recommended in the Ethiopian Ministry of Finance Publication “National Economic Parameters and Conversion Factors for Ethiopia”.

1.1.3. Traffic data

Traffic characteristic is directly related to the development of the national economy of a country and it is classified as one of the significant factor or reason for pavement deterioration. It also affects the cost of the users. For the HDM-4 analysis the total traffic in terms of traffic composition, volume, growth rate and flow pattern were collected from ERA and has-been used for the selected pavement sections. The subsequent sections discuss each of this.

Table 10A Vehicle Fleet Characteristics (source: (HITCON Engineering PLC, 2018))

	Cars	Utilities	Small Buses	Large Buses	Small Trucks	Medium Trucks	Heavy Trucks	Trucks & Trailers
Passenger Car Space Equivalent	1	1	1.5	2.5	1.5	2.5	2.5	3.75
No. of wheels	4	4	4	6	4	6	10	22
No. of axles	2	2	2	2	2	2	3	6
Tyre type	Radial-ply	Bias-ply	Radial-ply	Bias-ply	Bias-ply	Bias-ply	Bias-ply	Bias-ply
Base no. of recaps	1.3	1.3	1.3	2.4	1.3	2.4	2.4	3.6
Retread costs (%)	15%	15%	15%	15%	15%	15%	15%	15%
Annual km	15,000	20,000	80,000	45,500	55,000	70,000	75,000	60,500
Annual working hours	500	600	2,000	2,000	1,000	2,500	3,000	2,000
Average life (years)	13	13	15	15	10	15	15	15
Private use (%)	85%	20%	15%	0%	0%	0%	0%	0%
Passengers (no.)	4	6	20	45	2	2	2	2
Work related passenger trips (%)	15%	80%	85%	100%	100%	100%	100%	100%
Operating Weight (ton)	1.2	1.6	4.5	15	5.5	9	30	50
ESALF	-	0.1	0.3	1.5	1	2.5	4.5	6.5

Table 11A Summary of VOC and travel time costs input data- (Economic unit prices in ETB) (source: (HITCON Engineering PLC, 2018))

	Cars	Utilities	Small Buses	Large Buses	Small Trucks	Medium Trucks	Heavy Trucks	Trucks & Trailers
New Vehicle Price	484,403	1,052,276	1,026,056	1,874,111	886,011	1,063,746	2,314,391	4,952,124
Replacement tyre	1,609	1,856	3,467	5,991	4,277	7,082	8,019	10,696
Fuel (per litre)	16.26	17.90	17.90	17.90	17.90	17.90	17.90	17.90
Lubricant oil (per litre)	56.40	56.40	56.40	56.40	56.40	56.40	56.40	56.40
Maintenance labour cost (ETB/hour)	20.78	20.78	20.78	20.78	20.78	20.78	20.78	20.78
Crew wages (ETB/ hour)	-	-	17.02	48.01	18.63	25.08	35.83	46.58
Annual Overheads	5,553.93	10,032.91	12,236.56	19,474.59	13,186.11	64,181.93	101,262.48	141,041.16
Annual interest (%)	10	10	10	10	10	10	10	10
Passenger working time (per hour)	19.13	19.13	2.90	2.90	-	-	-	-
Passenger Non-work time (per hour)	6.7	6.7	1.0	1.0	-	-	-	-
Cargo costs (per hour)	-	-	-	-	1.36	4.03	7.72	15.23

1.1.3. Traffic Composition

Odoki and Kerali, (2006) explained that the traffic composition used for the calculation of predicting pavement deterioration, estimation of VOC, travel time, vehicle emission, energy use and Economic analysis. It represents the proportion of different vehicle types that use the road. For this study the vehicle classification in Table 12A used for the analysis.

Table 12A Vehicle Classification (source: (HITCON Engineering PLC, 2018))

Classification	Description
I. Passenger Vehicles	
Car	Car & Taxi
Land Rover	Land Rover, Jeep, Station Wagon, Land Cruiser
Small Bus	Up to 27 passenger seats
Large Bus	More than 27 passenger seats
II. Freight Vehicles	
Small Truck	Up to 3.5-ton load
Medium Truck	3.6-to-7.5-ton load
Heavy Truck & Tankers	7.6-to-12-ton load
Truck–Trailer & Tanker	Above 12-ton load

1.1.4. Traffic Volume

Information on traffic volume and composition is collected through road traffic counting. For the HDM-4 analysis traffic volume is expressed in terms of Annual Average Daily Traffic (AADT) computed from Average Daily Traffic (ADT) adjusted using seasonal variation factors. The EAR traffic seasons represent high, medium and low agricultural related economic activity seasons of the year. Average Seasonal Daily Traffic (ASDT) is computed for each count station. The three seasonal counts are then averaged to get the Average Annual Daily Traffic (AADT).

1.1.5. Traffic growth rate

Traffic growth rates have been inferred from historical records of vehicle–km of traffic in the whole network. The traffic flow data were collected from ERA and the annual percentage increase in the traffic growth was calculated using Equation 6.1 according to Odoki and Kerali (2006). by using more than 5 years traffic data the annual traffic growth rate calculated to result: 1. For Articulated Truck - 5.26 %, 2. Heavy truck 6.52%, 3. Medium truck 5.57%, 4. Light trucks 5.79%, 5. Large bus 3.71%, 6. Small Bus 7.38%, 7. 4WD 4.01% and 8. Car 1.32%.

Since it is difficult to get refined detailed traffic data for each road network matrix, for strategic analysis the data above used as a country average traffic road growth per year. It can be applied for each road matrix on top of their actual traffic data count for the year 2016. Furthermore, for the case of Otta seal section the traffic count made twice only with about six-month differences. The record showed a 38% variation in the ADT value (Araya & Chali, 2018). Therefore, the AADT for this section in this research is estimated by taking the average of the two ADT counts and multiplied by 90% seasonal factor.

Diverted and generated traffic were not considered for this comparison analysis in order to have a consistent traffic influence on the pavement deterioration in different traffic levels.

1.1.6. Equivalent Standard Axle Load Factors (ESALF)

For the study area the axle load factors have been derived from ERA design manual (2013) as shown in Table 13A.

Table 13A Equivalent standard axle load (source: (ERA, 2013))

It. No.	VEHICLE	Equivalency Factor Used
1	Cars	0
2	LGV	0.1
3	Bus Small	0.3
4	Bus Large	1.5
5	Small Truck	1
6	Medium Truck	2.5
7	Heavy Truck	4.5
8	Truck & Trailer	6.5

1.1.7. Configuration data

This data group used to make up the HDM-4 models and consists of pavement surface type, base type, new and surface thickness before overlay, reconstruction & rehabilitation year, surfacing year, construction defect indicator, traffic distribution, road capacity, and climate zones.

1.1.8. Pavement structure and strength input data

The pavement structure and strength are factors that determines the condition of the pavements. In the HDM-4 manual four and six it is considered in terms of the adjusted structural Number (SNP). The data collected from ERA were directly used since the pavement surface deflection data measured by falling weight deflectometer (FWD) and Benkelman Beam (BB).

1.1.9. Pavement conditions input data

a) Data source

Pavement condition data consists of Visual pavement condition that include all cracks, no of potholes, rut depth, ravelling, roughness, texture depth, skid resistance and area of edge wear. The data was collected from ERA. The pavement condition for strategic analysis used survey conducted in 2016 and consists of visual distresses through a vehicle base inspection and manual measurement. Vehicle mounted rougho meter (Laser Profilometer), MERLIN and Falling-Weight Deflecto meter were used during data collection (HITCON Engineering PLC, 2018). In addition to this, historical pavement condition data used for HDM-4 deterioration model calibration. as discussed in section 4.6.

For historical data the ERA has been collecting federal road pavement condition and inventory data from all over the country through the ten RNMDs. The historical data collected from six RNMD compiled and studied thoroughly to analyse for completeness and only one RNMD data set screened out for the calibration calculation. The reasons for the other sections not to be included were lack of having 5 years historical condition data, have only one year machine collected condition data or less. Also, those have gaps in the quantity when compared to the actual bill of quantity and maintenance intervention implementation report were excluded. Table 14A and 15A presents the summarized calibration condition input data.

a) Drainage data

Similar to the above, the drainage data for the study was collected from ERA.

Table 14A Summarized Calibration Data for Flexible pavement (ERA, 2012)

Road Section	Pavement type	Climate Zone	Year	No. of Sections	Length (km)	Total Length (km)	Traffic (AADT)	Construction Year	Term maintenance year	IRI (m/KM)	Wide Structural Cracks (%)	Number of Potholes (No / KM)	Edge Break Area (m2 / KM)	Mean Rut Depth (mm)
C52-2	Double Surface Treatment	Sub-moist	2013	5	10.26	51.49	779	2012		3.00	0.00	0.06	2.87	0.42
			2014				943			3.04	0.02	0.20	5.65	1.95
			2015				988			3.07	0.03	0.38	6.22	2.81
			2016				887			5.10	0.00	0.51	6.68	3.18
B51-1	Double Surface Treatment	Moist	2013	5	15	40.29	4554	2005	2016	2.97	0.05	0.15	0.63	0.34
			2014				6424			3.02	0.11	0.27	0.69	0.66
			2015				8470			3.04	0.29	1.09	0.71	0.66
			2016				10704			5.50	1.86	1.26	1.16	5.42
B51-1a	Double Surface Treatment	Moist	2013	5	15	45.52	4554	2005	2016	2.98	0.06	0.14	0.05	0.26
			2014				6424			3.03	2.16	26.20	19.89	4.14
			2015				8470			3.02	1.74	26.20	19.89	4.14
			2016				10704			5.10	0.59	0.00	0.00	6.13
B51-2a	Double Surface Treatment	Moist	2013	5	15	46.23	1596	2010		2.98	0.02	0.02	0.29	1.62
			2014				1633			3.00	0.04	0.03	0.70	2.26
			2015				1761			3.05	0.09	0.06	0.98	3.95

			2016				1906			5.50	0.15	0.02	1.69	5.04
A7-1	Asphalt Concrete	Semi-Arid	2013	11	12.5	56	8683	2004	2011	2.62	0.14	0.02	0.00	0.19
			2014				5448			2.64	0.19	0.03	0.00	0.26
			2015				6313			3.77	1.03	0.16	0.00	5.14
			2016				9200			3.80	22.49	0.39	30.94	7.61
A2-4	Asphalt Concrete	Semi-Arid	2013	5	15	47.63	2187	2007		2.60	0.04	0.01	0.01	0.11
			2014				2689			2.68	0.36	0.02	0.02	0.46
			2015				2124			2.69	1.55	0.04	0.05	0.50
			2016				1668			2.93	2.28	0.13	0.00	3.89
A1-2	Asphalt Concrete	Semi-Arid	2013	4	10.6	13.9	10116	2004	2011	2.59	0.02	0.01	0.01	0.19
			2014				11706			2.66	0.06	0.04	0.07	1.77
			2015				12854			2.69	0.08	0.05	0.20	2.19
			2016				14386			3.00	4.84	0.00	0.00	4.89
A1-4	Asphalt Concrete	Semi-Arid	2013	3	9.5	37.02	6563	2004	2011	2.62	0.03	0.08	0.27	0.19
			2014				7595			2.83	0.21	0.43	0.15	1.09
			2015				8340			2.94	0.30	0.62	0.22	1.56
			2016				9334			3.26	1.72	0.85	0.35	3.54

Table 15A Summarized Calibration and input data for rigid pavement (ERA, 2017; ERA, 2013f)

Road Section	Pavement type	Climate Zone	Year	No. of Sections	Slab Length (m)	Total Length (km)	Traffic (msa)	Construction Year	Slab thickness (mm)	Sub grad CBR (%)	Faulting (mm)	Spalling (%)	Cracking in slab area (%)
A1-3	JPCP	Sub-moist	2017	5	5	0.5	200	2013	320	15	2.90	2.14	0.11
			2018								3.06	2.34	0.13
			2019								3.18	2.57	0.13
			2020								3.60	2.83	0.13
A1-3	JRCP	Moist	2017	5	25	0.5	200	2013	250	15	2.00	0.00	0.00
			2018								2.11	0.43	0.00
			2019								2.67	0.50	0.00
			2020								3.22	0.57	0.00

1.1.10. Climate data

Data Source - For the study the historical as well as the predicted climate data were collected from the world Bank Climate Knowledge Portal (The World Bank Group, 2018). Also, UNDP climate change country profile (McSweeney, 2010) used for projected climate change data. The following sections describe the historical and future climates of the study area.

Historical climate

The climate data from the World Bank Group (2018), extracted based on GPS co-ordinate of the selected road sections. To categories road sections in specific climate zone an average GPS value of the selected sites were used to identify the closest gridded climate data. This data (Table 16A) used as baseline for the HDM-4 network level analysis. Figure 5A Shows a sample of representation of temperature and rainfall data for the selected location in the World Bank climate knowledge portal. It summarizes the historical monthly temperature and precipitation data presented based on each month of average year from 1901 – 2015.

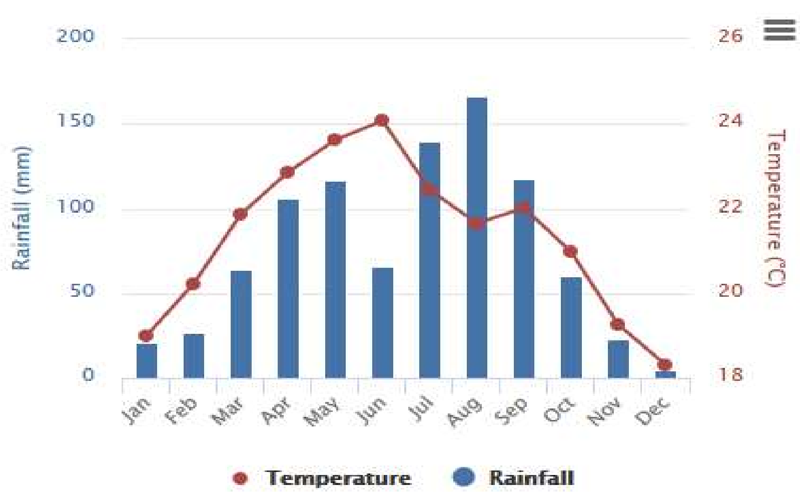


Figure 5A Sample for Historical Average Temperature and Rainfall (source: (The World Bank Group, 2018))

From the data source historical Mean Monthly Precipitation (MMP) was calculated by taking the average of monthly precipitation data from January to December from 1901-2015. Similar approaches used for Mean Annual Temperature (MAT) using the average of monthly temperature data. While for Average Temperature Range (MTR), the calculation includes identification of the average maximum monthly temperature and minimum monthly temperature of 12 months from 1901-2015. Then the difference between maximum and minimum monthly temperature from 1901-2015 was calculated and averaged to get the final range of mean monthly temperature. The historical Thornthwaite moisture index (TMI) calculation involves historical precipitation and evapotranspiration based on Sun (2015) and Karunarathne et al. (2016).

Table 16A Baseline Climate Data (source: (The World Bank Group, 2018))

Year	Climate Classification of the selected roads	Mean Annual Temperature (MAT) in °C	average monthly temperature range (MTR) in °C	Thornthwaite moisture index (TMI)	mean monthly precipitation (MMP) mm
Baseline	Arid	27.08	7.85	-83.36	24.16
	Semi-arid	19.64	4.43	-49.28	74.97
	Sub-moist	15.60	3.30	-28.91	106.27
	Moist / hummed	16.17	3.68	-18.95	109.56

Future climate

The climate data from the UNDP climate change country profile (McSweeney, 2010) extracted based on GPS co-ordinate of the selected road sections. The predicted change in climate parameters is for 10-year periods in the future under each SRES scenario McSweeney (2010). Each grid box, gives the ensemble median value in the centre and ensemble maximum and minimum values in the upper and lower corners respectively (see Appendix B). Climate parameter values are anomalies relative to the mean climate of 1970-1999.

The grids were significantly utilized to read climate data values from the country profile for each climate zones that represents the road sections with average GPS value. The projected climate parameters were obtained for SRES A2, B1 and A1B scenarios. The maximum and minimum projected climate parameters for SRES A2 scenario presented in the subsequent sub-sections and the selection of this scenario.

Temperature

The projected mean monthly temperature and mean temperature range for the five previously identified climate zone provided in Table 17A and Table 18A respectively. The ten-year based projected temperature from 2019 to 2059 shows a fluctuated increment in different climate zones, therefore, change in climate will not be constant in the future. In addition to this, the different trained observed for projected mean monthly temperature for A2 maximum and minimum emission scenario presented in Figure 6A.

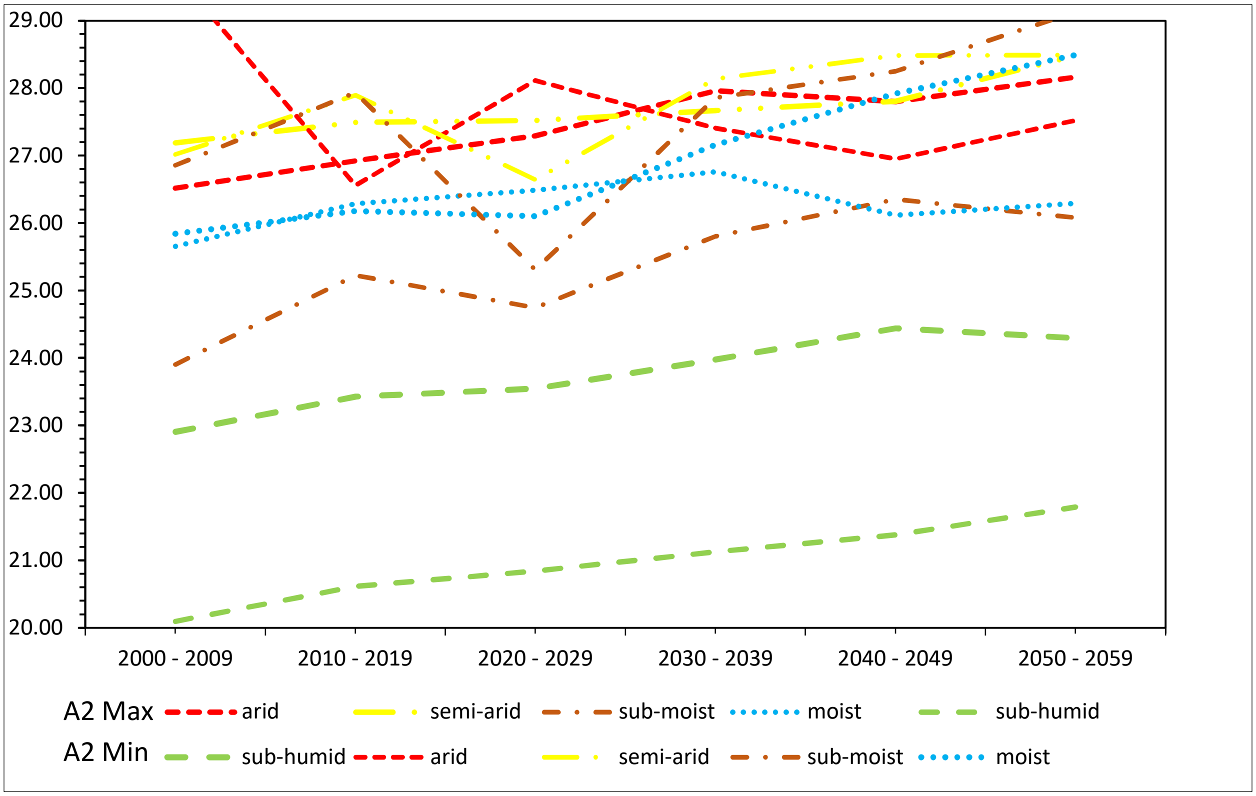


Figure 6A Trend of projected temperature (ºC) vs year for max and min A2 emission scenarios

Precipitation

Similar to the temperature change the mean monthly projected precipitation will have no constant incremental change, while higher precipitation values for 2059 maximum A2 emission scenario shown in different climate zones. Table 19A shows the projected Mean Monthly Precipitation.

Thornthwaite Moisture Index

To know if a given place will be continually wet or dry, or if it is wet in a given season and dry in another. The Thornthwaite moisture index (TMI) in the table 20A indicate that there will be continues dry climate condition until 2059.

Moreover, data related to the hot-day frequency, hot-night frequency, cold-day frequency and cold-night frequency were taken using similar approaches.

1.1.11. Maintenance and improvement intervention

The analytical framework of HDM-4 is based on the concept of pavement life cycle analysis, which is typically 15 to 40 years depending on the pavement type. HDM-4 predicts the life cycle pavement performance and the resulting user costs under specified maintenance and/or road improvement scenarios. The agency and user costs (i.e., RAC and RUC, respectively) are determined by first predicting physical quantities of resource consumption and then multiplying these by the corresponding unit costs. Two or more options comprising different road maintenance and/or improvement works should be specified for each candidate road section with one option designated as the base case (usually representing minimal routine maintenance). The benefits derived from implementation of other options are calculated over a specified analysis period by comparing the predicted economic cost streams in each year against that for the respective year of the base case option.

Therefore, the maintenance and improvement options were considered from the experience of ERA and proposed maintenance alternatives by HITCON Engineering PLC (2018). The routine maintenance activities considered for the analysis is that all possible routine maintenance works provided by the ERA district offices in yearly bases. This presented in Table 4.1 and “do-nothing” and minimum maintenance option used for calibration and model adjustment purpose. However, for the strategic analysis the maintenance and improvement alternatives with the associated cost taken from HITCON Engineering PLC (2018) report.

Table 17A Mean Monthly Temperature (ºC)

	A2 MIN						**A2 MAX**				
YEAR	arid	semi-arid	sub-moist	moist	sub-humid		arid	semi-arid	sub-moist	moist	sub-humid
2010 - 2019	26.92	27.49	25.22	26.29	20.61		26.56	27.90	27.94	26.18	23.43
2020 - 2029	27.29	27.52	24.75	26.49	20.84		28.11	26.65	25.31	26.10	23.55
2030 - 2039	27.96	27.67	25.81	26.76	21.13		27.41	28.14	27.86	27.16	23.98
2040 - 2049	27.80	27.81	26.35	26.12	21.38		26.95	28.48	28.25	27.92	24.44
2050 - 2059	28.16	28.48	26.08	26.29	21.79		27.52	28.49	29.13	28.49	24.30

Table 18A Mean Rang of Temperature

	A2 MIN						**A2 MAX**				
YEAR	arid	semi-arid	sub-moist	moist	sub-humid		arid	semi-arid	sub-moist	moist	sub-humid
2010 - 2019	3.2	4.0	3.2	3.8	3.4		1.9	2.8	2.4	3.8	3.9
2020 - 2029	3.3	2.2	3.1	3.4	2.0		3.2	5.7	3.6	3.2	3.0
2030 - 2039	4.7	3.6	3.7	4.0	3.1		4.3	4.1	4.5	4.0	3.6
2040 - 2049	3.9	3.6	5.4	4.6	3.0		2.6	8.2	4.4	4.4	4.7
2050 - 2059	6.0	3.2	4.0	2.7	3.4		5.1	4.7	6.2	6.1	5.3

Table 19A Mean Monthly Precipitation

A2 MIN							A2 MAX				
YEAR	arid	semi-arid	sub-moist	moist	sub-humid		arid	semi-arid	sub-moist	moist	sub-humid
2010 - 2019	14.24	27.90	38.98	58.02	88.05		21.47	36.60	37.60	58.45	95.59
2020 - 2029	15.46	27.34	39.70	55.56	87.00		22.52	28.27	32.48	58.60	95.44
2030 - 2039	12.86	27.58	37.57	55.89	88.92		21.09	27.30	36.38	56.42	96.97
2040 - 2049	15.61	28.31	34.19	53.31	86.55		18.31	26.85	35.09	53.90	95.10
2050 - 2059	13.17	27.23	33.58	53.48	83.25		25.00	25.61	43.30	60.81	100.80

Table 20A Thornthwaite Moisture Index (TMI)

	A2 Min						**A2 Max**				
YEAR	arid	semi-arid	sub moist	moist	sub-humid		arid	semi-arid	sub moist	moist	sub-humid
2010 - 2019	-76.49	-59.20	-51.57	-41.07	-19.98		-81.52	-58.35	-52.01	-40.41	-16.07
2020 - 2029	-75.44	-59.11	-50.76	-40.89	-19.06		-80.21	-58.91	-53.35	-39.57	-14.61
2030 - 2039	-73.67	-58.59	-50.74	-39.64	-18.23		-79.22	-58.66	-51.19	-39.40	-13.99
2040 - 2049	-75.50	-57.87	-51.22	-39.65	-17.96		-77.32	-58.24	-50.86	-38.83	-13.32
2050 - 2059	-73.84	-57.51	-50.57	-38.29	-16.97		-81.78	-57.96	-46.39	-34.63	-6.85

Appendix J - **Road safety data**

The HDM-4 model for calculating road use cost comprises road safety data among other parameters. Therefore, the software requires to define a serious of accident classes for accident rates considering the road and traffic attributes (see HDM-4 manual Four-part E). Each of the accident rates expressed by fatal, injury and damage only cases in terms of total number of accidents per 100 million vehicle-kilometres.

For the case study, the country wide accident rates were based on the research report since accident cost did no developed for the country (Debela, 2019). The analysis tried to cover the traffic accident trained for eleven years (from 2007/08 to 2014/18). According to Debela (2019), during these years around 291,577 road traffic accidents occurred in 912,956km road network coverage and 681,000 motorized vehicles were registered in Ethiopia. Table 21A below Presents the yearly accident and its associated costs.

Table 21A- Traffic Accident and Its Associated Cost (Debela , 2019)

	Accident in number				**Accident in cost**				
Year	Fatality	Serious Injuries	Light Injuries	Property Damage	Fatality	Serious Injuries	Light Injuries	Property Damage	Total
2007/08	1,802	2,156	2,123	9,005	394.10	261.95	94.58	124.00	874.63
2008/09	2,211	2,276	2,221	8,987	537.27	307.26	109.94	137.50	1,091.97
2009/10	2,600	3,494	4,275	7,098.	702.00	524.10	235.13	120.67	1,581.89
2010/11	2,541	3,545	4,570	12,130	754.68	584.93	276.49	226.83	1,842.92
2011/12	3,132	4,333	4,932	8,444	1,023.22	786.44	328.23	173.69	2,311.58
2012/13	3,362	5,042	6,316	9,117	1,208.20	1,006.64	462.36	206.29	2,883.49
2013/14	3,331	6,039	5,888	13,181	1,316.77	1,326.26	474.13	328.07	3,445.23
2014/15	4,352	5,918	6,508	15,639	1,892.41	1,429.65	576.47	428.18	4,326.71
2015/16	3,847	6,886	7,071	17,977	1,840.10	1,829.85	688.97	541.41	4,900.32
2016/17	4,500	7,288	7,308	19,132	2,367.69	2,130.34	783.27	633.81	5,915.11
2017/18	5,118	7,754	7,775	20,353	2,962.14	2,493.21	916.65	741.68	7,113.68
Total	**36,796**	**54,731**	**58,987**	**141,063**	**14,998.59**	**2,680.61**	**,946.21**	**3,662.12**	**36,287.53**

Appendix K HDM-4 calibration and model adjustment

MODEL CALIBRATION AND CLIMATE CHANGE ADJUSTMENT

1.Introduction

The purpose of calibrating the HDM-4 models to local conditions is to obtain a model that represents local conditions in terms of material behaviour, climate zones, pavement types, traffic and other conditions. As mentioned in the previous section 2.3.4.4, much of the calibration is associated with modifying calibration factors (i.e. “k” values) for the HDM-4 deterioration models, and this is usually obtained by applying a modification to the relevant HDM-4 model coefficient that best matches the recorded data with that of the model’s predictions. For this study, to obtain the road deterioration model calibration factors, different types of procedures suggested in the HDM-4 Manual Volume Five (Bennett and Paterson, 2000) were used. The required adjustments to the HDM-4 models, which take into account the effects of climate change, are different from the usual calibration required for the models and represent some of the innovation of this research. There are however, some similarities to the usual procedure (i.e. the use of regression analysis) to calculate the modification coefficients.

The calibration of the HDM-4 models for the purpose of this work has been presented in section 3.5.3. The subsequent sections of this chapter focus on the process of model calibration and the adjustments required to take into account the effects of climate change during the period of analysis.

The data used for model calibration were selected based on the available historical data (see Appendix I).

2. HDM-4 Roughness Model for Flexible Pavements

2.1 Level I - HDM-4 Model Calibration

As mentioned previously, the process of Level I HDM-4 roughness model calibration involves the selection of factor coefficients from a number of tables in the HDM-4 Manual Five (Bennett & Paterson, 2000). The selection is mainly based on the environment, type of material used for the construction, and the quality of the material. Furthermore, the calibration takes into account an adjustment for critical distress factors with sensitivity levels I, II, and III (section 3.5.3). These sensitivity classifications are determined by impact elasticity; the greater the elasticity, the more sensitive the model predictions (Bennett & Paterson, 2000).

For the purposes of this work, the adjustment for critical distress parameter factors pavement environment coefficient (k_{gm}), crack initiation (k_{ci}) and crack progression (k_{cp}) (section 3.5.3) calibration factors required to calculate roughness progression using Equations 3.3 to 3.6, were calculated using selected values given in Tables 7.3 and 7.4 of the HDM-4 Manual Five (Bennett & Paterson, 2000), as described below. For crack progression, a reciprocal of the crack initiation value was used as recommended in the HDM-4 manual.

For the other distress models in HDM-4 (i.e. potholing, ravelling, rutting), for this study the default values as proposed by the HDM-4 Manual Four (Odoki & Kerali, 2006) were used. These default values for these models were used because of the limitation in historical data and they are not critical distress parameters since their sensitivity level is greater than three. This means the pavement deterioration projection model is not sensitive to these distress parameters (Bennett & Paterson, 2000).

2.1.1 Adjustment for Roughness- environmental Age-coefficient (K_{ge})

The prevailing environmental conditions, the quality of the road construction which is related to the bituminous quality, and the standard of the drainage of the representative road sections were taken into account to calculate the Level I calibration for the roughness-age-environmental coefficient (K_{ge}) required by Equations 3.3 and 3.4 (see section 3.5.3.1). The process of determining K_{ge} involves selecting appropriate m and K_m values for the relevant climate zone using Table 7.3 and Table 7.4 provided in Bennett and Paterson, (2000). The process used in this work to calculate K_{ge} for the five climate zones in which the representative road sections used in the analysis lie is demonstrated by means of an example below. Chapter Six presents the results of the calculations for each representative road section.

Example calculation for an arid climate zone

Representative road section A1-8 from AC A HT

1. For the purpose of this demonstration an arid climate zone was considered for this level.
2. From Table 7.3 in the HDM-4 Manual Five, the environmental coefficient was obtained and m = 0.005.

To obtain the modifying factor of the environment coefficient for road construction and drainage effects from Table 7.4 of the Manual, Bennett and Paterson (2000) provide K_m as a function of material quality, and drainage effect, for freezing and non-freezing areas. Therefore, material quality: normal; drainage: adequate; maintenance: moderate; and formation for local moisture: non-freezing area taken to read the value for $K_{m.}$ Thus, it is equal to 1.

K_m =1.00

3. Using Equation 3.4 calculate m_{eff} as follows

$$m_{eff} = m\,K_m = 0.005*1.00 = 0.005$$

4. Using Equation 3.3 calculate K_{ge}

$$K_{ge} = \frac{m_{effca}}{0.023} = \frac{0.005}{0.023} = 0.22$$

2.1.2. Adjustment for Crack Initiation

I) Cracking initiation adjustment factor (K_{ci})

The method for calibration of the crack initiation factor is summarised in Figure 3.4 and is described in section 3.5.3.1. The process described in Figure 3.4 follows a number of steps and was used Bagui and Ghosh (2015) approach. These steps are replicated below in an example to make it easier to follow the approach.

Example calculation

Selection of pavement type and estimated crack initiation times

The representative road section had the following measured and observed (Bennett & Paterson, 2000) features:

Climate zone – Semi-Arid

Pavement type considered – AC

Estimated crack initiation time – 4 to 5 years CBR – 15%

Binder course – 100 mm

Base course – 300 mm

Subbase course – 450 mm

Surfacing thickness – 50 mm

Prepared subgrade – 600 mm

Since the time for crack initiation is not recorded by ERA for its road sections, expert advice was used to estimate the calibration factor for crack initiation (section 3.5.3.1). Using this process, crack initiation was estimated to vary between 4 to 5 years for AC and 3 to 4 for surface treated pavements. A sample calculation is presented below to show how K_{ci} was obtained. This method was used to calculate K_{ci} for the representative section. The results are presented in Chapter Six.

As above, the crack initiation times for the representative road section were estimated to be between 4 and 5 years.

Obtain the construction and quality coefficients of the available refined bituminous

Equation 3.5 requires three "*a*" model coefficient to be determine the crack initiation time and uses Table 3.4 in the HDM-4 Manual Volume Five (Morosiuk, et al., 2004), which provides a list of values for the coefficients as a function of a number of pavement constructions. The values of "*a*" used in this research are given in Table 22A.

$$ICA = K_{cia}\left\{CDS^2\, a_O\, exp\left[a_1 SNP + a_2\left(\frac{YE4}{SNP^2}\right)\right] + CRT\right\} \text{...... copy of Eq. 3. 5}$$

With reference to Equation 3.5, the following parameters were determined for the representative road section described by this example.

Coefficients a_0, a_1, and a_2

The value of the coefficients a_0, a_1, and a_2 were obtained from Table B3-4 of HDM-4, Manual Five (Morosiuk, et al., 2004) and presented in Table 1 below.

Table 22A Values of a0, a1, and a2 for Equation 2 ((Morosiuk, et al., 2004))

Pavement type	Surface material	HSOLD	a0	a1	a2
AMGB	all	0	4.21	0.14	-17.1
	All except CM	>0	4.21	0.14	-17.1
	CM	>0	13.2	0	-20.1
STGB	All	0	13.2	0	-20.7
	All except CM	>0	13.2	0	-20.7
	CM	>0	13.2	0	-20.7

The annual number of equivalent axle loads (MSA/lane) (YE4)

For the representative road section used in this example, YE4 (the annual number of equivalent axle load in MSA/Lane) = 4.5

Crack retardation time caused by maintenance (CRT)

The Cracking Retardation Time (CRT) was calculated using Equation 3

$$CRT = Min[CRT_{bw} + \frac{CRM}{YXK}, \frac{CRTMAX}{YXK}, 8\,] \qquad \text{Equation 3}$$

Where YXK is the maximum of (YAX, 0.1); CRT/CRT_{aw} is the cracking retardation time after works, in years; CRT_{bw} is cracking retardation time before works, in years;

CRM is the change in CRT due to preventive treatment; CRTMAX is the maximum limit of CRT; and YAX=YE4 is annual number of equivalent axle load in MSA/Lane.

Values for CRM and CRTMAX were obtained from Table B13-5 of HDM-4, Manual Six (Morosiuk, et al., 2004). The values of relevance to this study are shown in Table 23A.

Values of CRT_{bw} are considered as 0 for the representative road section used in this example.

Table 23A Factors for crack retardation time after preventive treatment

Pavement type	**Surface material**	**Representative Section**	**HSOLD**	**Rejuvenation**		**Fog Seal**	
				CRM	CRTMAX	CRM	CRTMAX
AMGB	all	Section on AC SA HT	0	1.5	3.0	0.8	1.6
	All except CM		>0	1.5	3.0	0.8	1.6
	CM		>0	0.75	1.5	0.4	1.6
STGB	All		0	3.0	6.0	1.6	3.2
	All		>0	1.5	3.0	0.8	1.6

With reference to the above and Equation3, the CRT obtained for the example is

$$CRT = Min[CRT_{bw} + \frac{CRM}{YXK}, \frac{CRTMAX}{YXK}, 8\,]$$

$$= Min[0 + \frac{1.5}{4.5}, \frac{5}{4.5}, 8\,]$$

= 0.33

The average annual adjusted structural number of the pavement (SNP)

For the example representative road section Equations B2.26 to 28, which are given in Section B-2 of HDM-4 Manual Six were utilised to calculate the SNP value using three steps to calculate the three "*a*" coefficients *a1, a2* and *a3*. For the representative road section E values were used: 1700 MPa AC, 200 MPa, for the base and 100 MPa and using Equations B2.26 to 28, a was calculated as follows:

$$a_1 = 0.412log_{10}\left(\frac{E_1}{1000}\right) + 0.246 = 0.412log_{10}\left(\frac{1700}{1000}\right) + 0.246 = 0.34$$

$$a_2 = 0.249log_{10}E_2 - 0.439 = 0.249log_{10}(200) - 0.439 = 0.134$$

$$a_3 = 0.229log_{10}E_3 - 0.348 = 0.229log_{10}E_3 - 0.348 = 0.106$$

Calculation for the structural number for the subgrade (SNSG)

$$SNSG = 3.5[log_{10}(CBR)\ ] - 0.85\{log_{10}(CBR)\}^2 - 1.43 \ldots\ldots\text{. . Equation 4}$$

$$= 3.5[log_{10}(15)] - 0.85\{log_{10}(15)\}^2 - 1.43 = 1.51$$

Calculation for SNP_{dry}:

$$SNP_{dry} = [((50 + 40) * 0.34) + (450 * 0.134) + (600 * 0.106)]/32 + 1.51 = 4.54$$

For the example representative road section therefore SNP_{dry} was decreased by 0.23 due to the presence of 0.5% cracks (section 3.5.3). This resulted in a reduced structural number of 4.31.

Then Kci was obtained: 1.163 and 0.930 for estimated crack initiation times of 4 and 5 years respectively.

As described in section 3.5.3.1 in order to get a single K_{ci} value, these values were interpolated through the possible K_{ci} ranges of value (0.1 to 20). To make the interpolation divide the range in numbers, from the interpolation results take the K_{ci} value for where the maximum R^2 value is obtained. For this example, it is 0.926 and repeat the process to get a more refined value. For the example, the next iteration resulted in 0.877, and 0.874 for the final k_{ci} value.

II) Crack Progression adjustment factor (K_{cp})

As described in section 3.5.3.1, Equation 3.6 was used to calculate the crack progression adjustment factor. The K_{ci} was the same for all representative road sections in the same road network matrix (i.e. 0.87 calculated as above) and therefore Kcp was determined as.

$$K_{cp} = \frac{1}{K_{ci}} = \frac{1}{0.87} = 1.15$$

3. Level II HDM-4 Pavement Distress Model Calibration

The intention of Level II calibration is to use field survey data to adjust the coefficients of road distress models (Bennett & Paterson, 2000). For Level II cracking initiation adjustment, the approach described in section.2.1.1 was used to calibrate the cracking initiation model to local conditions. However, for the roughness distress component a method proposed by Henning et al. (2006) was used. Therefore, the subsequent sections discuss the analysis of the calibration processes.

3.1 Adjustment for roughness coefficients (K_{gm})

The process used for the adjustment of the roughness calibration coefficients (K_{gs}, K_{gc}, K_{gr} K_{gp}, K_{gm}) follows the procedure specified in section 3.5.3.2. The calibration process involves calculating the mean and incremental values of each distress factor over the duration of the analysis period. Linear regression analysis was applied to determine the relation between the first and the last applicable survey and errors obtained by differencing the observed and predicted values. Bennett and Paterson (2000), and Henning et al. (2006) describe the adjustment procedure for the environmental coefficient *m*. The procedure can be broken down as shown in section 3.5.3.2:

Example

To illustrate the above procedure an example calculation for the adjustment of the roughness model K_{gm} calibration coefficients is presented below.

1. The observed data, presented in Table 24A for the asphalt concrete in a semi-arid climate zone with high traffic (AC SA HT) representative road section (constructed

in 2002), was used. The outputs for each step and iteration of the example are given in Table 7.

Table.24A Observed data for the representative road network (source: Ethiopian Road Authority (ERA)/ ERA RAMD and ARNMD)

Year	`Traffic in AADT	Roughness IRI	All Structural Cracks (%)	Number of Potholes (No / KM)	Edge Break Area (m2 / KM)	Rutting Mean Rut Depth (mm)
2013	4,529	2.50	0.320	7.14	13.01	1.41
2014	5,241	2.58	0.558	9.84	15.08	1.58
2015	5,755	2.59	0.984	11.81	18.10	1.89
2016	6,441	2.76	1.412	12.28	18.10	2.56

2. For the climate zone of the representative section, m = 0.01 from Table 7.4 in the HDM-4 Manual Five (Bennett & Paterson, 2000).
3. For the structural component of the roughness, calculate using the Equation provided in Table 3.2 for a structure part. The m value and the annual number of equivalent standard axles (millions/lane) are also used to calculate the structural roughness component. The reduced structural component can be calculated using the equation provided in the HDM-4 manual section C2 part 3.
4. Determine the coefficients of Equation 5 to find the new m value. Regression analysis used to obtain the value of m.

$$RI = K_{gs} a_o \exp(mK_{gm}\, AGE3)(1 + SNPK_b)^{-5}\, YE4 \; + \; K_{gr} a_o \Delta RDS + mK_{gm}\, RI_a$$

………Equation 5

5. Then check if the new m value is similar to the previous one. If there is a difference, using the new m value, calculate the structural component of the roughness to repeat the whole process to find the new m.
6. This will be repeated until a close value for m is found.

For the example analysis, using initial m =0.003 the above procedure was iterated five times and stopped when the calculated m value became constant. Using an Excel spreadsheet outputs from the analysis are presented in Table 25A.

. *Table 25A Calculation Summary*

$SNPK_b$	**YE4**	**1st iteration for m=0.01**			**2nd iteration for m=0.022**			**----**	**5th iteration for m=0.003**		
		K_{gs}	K_{gm}	ΔIRI	K_{gs}	K_{gm}	ΔIRI	----	K_{gs}	K_{gm}	ΔIRI
3.33	3.29	1.00	0.94	0.32	0.194	0.941	0.07	----	1.88	0.118	0.53
3.28	3.49	1.00	0.94	0.34	0.194	0.941	0.08	----	1.88	0.118	0.57
3.20	3.71	1.00	0.94	0.37	0.194	0.941	0.08	----	1.88	0.118	0.62
3.07	3.95	1.00	0.94	0.40	0.194	0.941	0.09	----	1.88	0.118	0.67

As shown in Table 25A for an adjusted structural component of the roughness factor (K_{gs}) of 1.88 should be used and similarly an environmental-age component of roughness (K_{gm}) of 0.118 should be used.

Roughness progression calibration factor (K_{gp})

In order to determined K_{gp}, the procedure described by Bennett and Paterson (2000) was used. This involves comparing the incremental observed and predicted roughness values for a road section.

Table 26A Incremental observed and predicted roughness

ΔORI_t	**ΔPRI_t**	**OT_t**	**MORI**	**RESRI**
0.00	0.31	3	2.50	0.31
0.08	0.34	4	2.54	0.26
0.01	0.40	5	2.56	0.39
0.17	0.47	6	2.61	0.30

Where:

ORI_t = the observed roughness RI at the time t (in year) observation;

PRI_t = the predicted roughness RI at the time t (in year) observation;

OT_t = the corresponding time in years of the t observation.

MORI =Sum (ORI_1: ORIn)/n

RESRIj = $\Delta(PRIj_t - \Delta ORIj_t)$

Following the procedure, a linear regression analysis was performed to establish a relationship between RESRI and MORI assuming a zero intercept. For the data shown in Table 26A of the representative road section (R^2 =0.978 with a gradient (ƊRESRI/ƊMORI) = 0.123. Therefore (K_{gp}) is calculated as follows.

$$K_{gp} = 1 + b\ldots\ldots\ldots$$

$$= 1 + 0.123$$

$$\underline{\underline{= \mathbf{1.123}}}$$

4. Model Calibration for HDM-4 Rigid Pavements

The HDM-4 Manual Five (Bennett & Paterson, 2000) provides a procedure for the calibration of flexible pavements, however, it does not provide the same for rigid pavements. Therefore, the effect of climate on rigid pavement deterioration is considered through a number of parameters including the freezing index (FI), mean monthly precipitation (MMP), number of days with temperature greater than 32 °C (DAYS90) and moisture index (MT), see (Odoki & Kerali, 2006). However, as can be seen from Equations 3.15 to 3.20 not all of the parameters are present in all of the rigid pavement distress models, i.e. there is no common climate parameter for rigid pavement models (like the m value for the flexible pavement distress models) that represents environmental effects.

Consequently, as described in section 3.5.3.3, the calibration process suggested by Stannard et al. (2006), based on regression analysis that relates the observed and predicted values (from Equation 3.15 to 3.20) was used.

Example

To illustrate the above procedure an example calculation for the calibration of the faulting model for JPCP provided in the HDM-4 Manual Volume Four (Odoki & Kerali, 2006) is presented below. The observed data, presented in Table 27A for the representative road section (constructed in semi-arid region), was used for the example.

Accordingly, the section is not in a freezing zone; thus, the base of the rigid pavement's sections was not stabilised and the widths have not been widened. The representative section is 0.5 m in length and there are no side drainage facilities as the road was constructed on an embankment. This leads to a Cd value of 1.25 according to the procedure described by AASHO (AASHTO, 2012).

Table 27A Faulting coefficient adjustment calculation summary

Year	NE4	Observed faulting	1st Predicted faulting	2nd Predicted faulting
2016	3.31	2.78	2.78	2.78
2017	3.50	2.88	2.88	2.88
2018	3.70	2.99	2.97	2.99
2019	3.9	3.1	3.07	3.09
2020	4.13	3.21	3.26	3.19

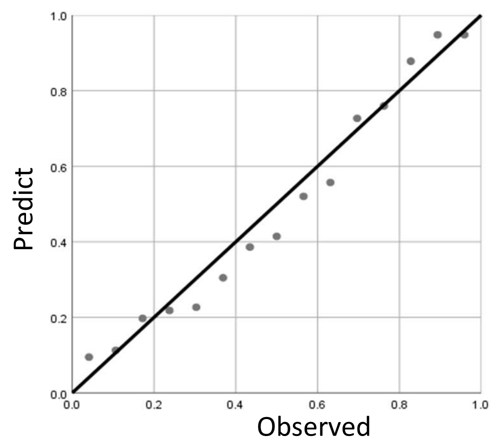


Figure 7A Observed and predicted faulting

Using a similar approach, the coefficients of distress of the other representative road sections were calculated.

5. Model Adjustment for Climate Change

5.1 Data Used for Model Coefficient Modification

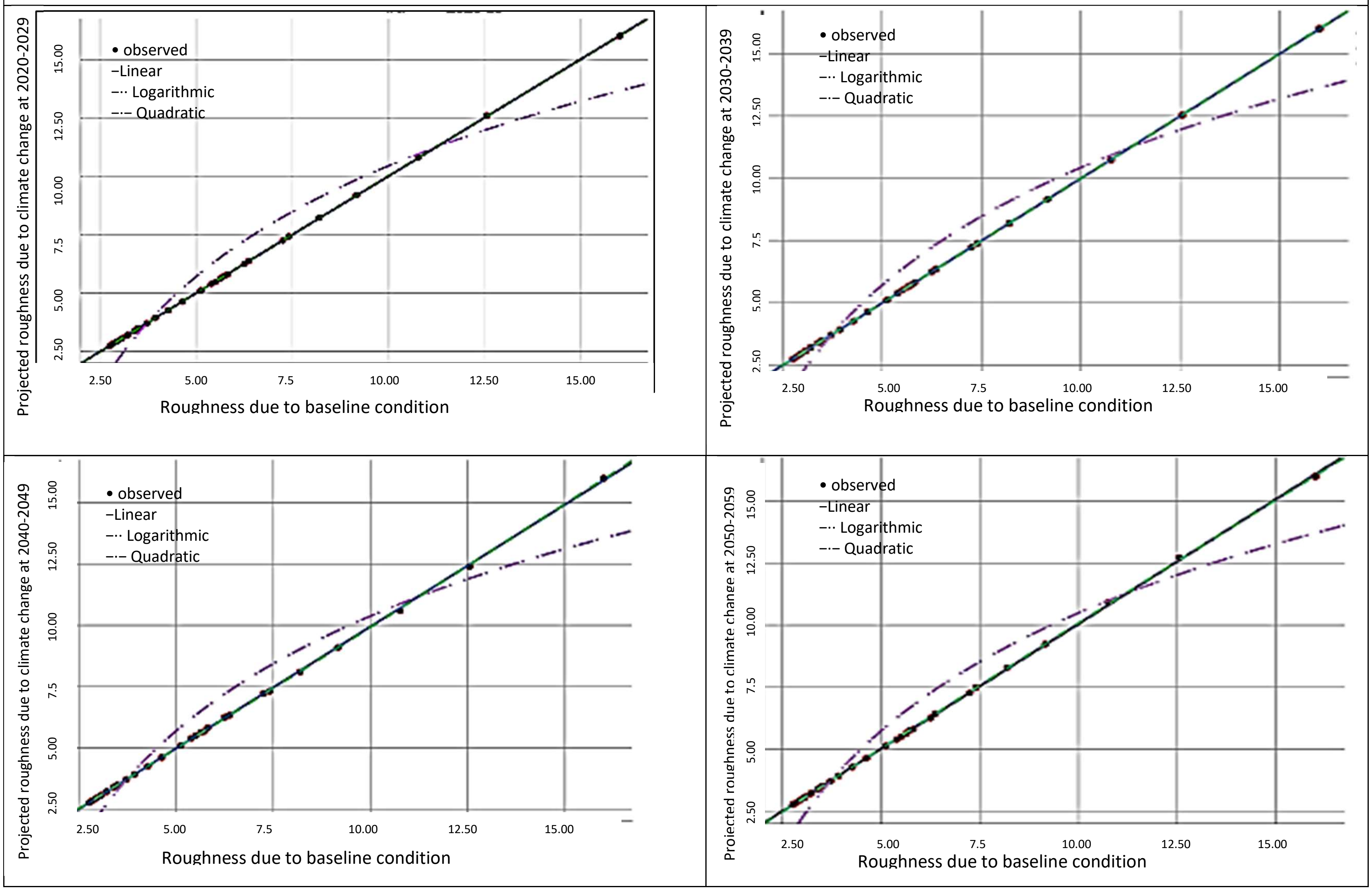
As discussed in section 3.6, the economic analysis has been broken down into five, 10-year steps. For each step, the climate associated parameters in the HDM-4 models are modified to reflect a changing climate over the entire 50-year period of analysis.

5.2 Pavement Roughness Progression Relationships – with and without climate change

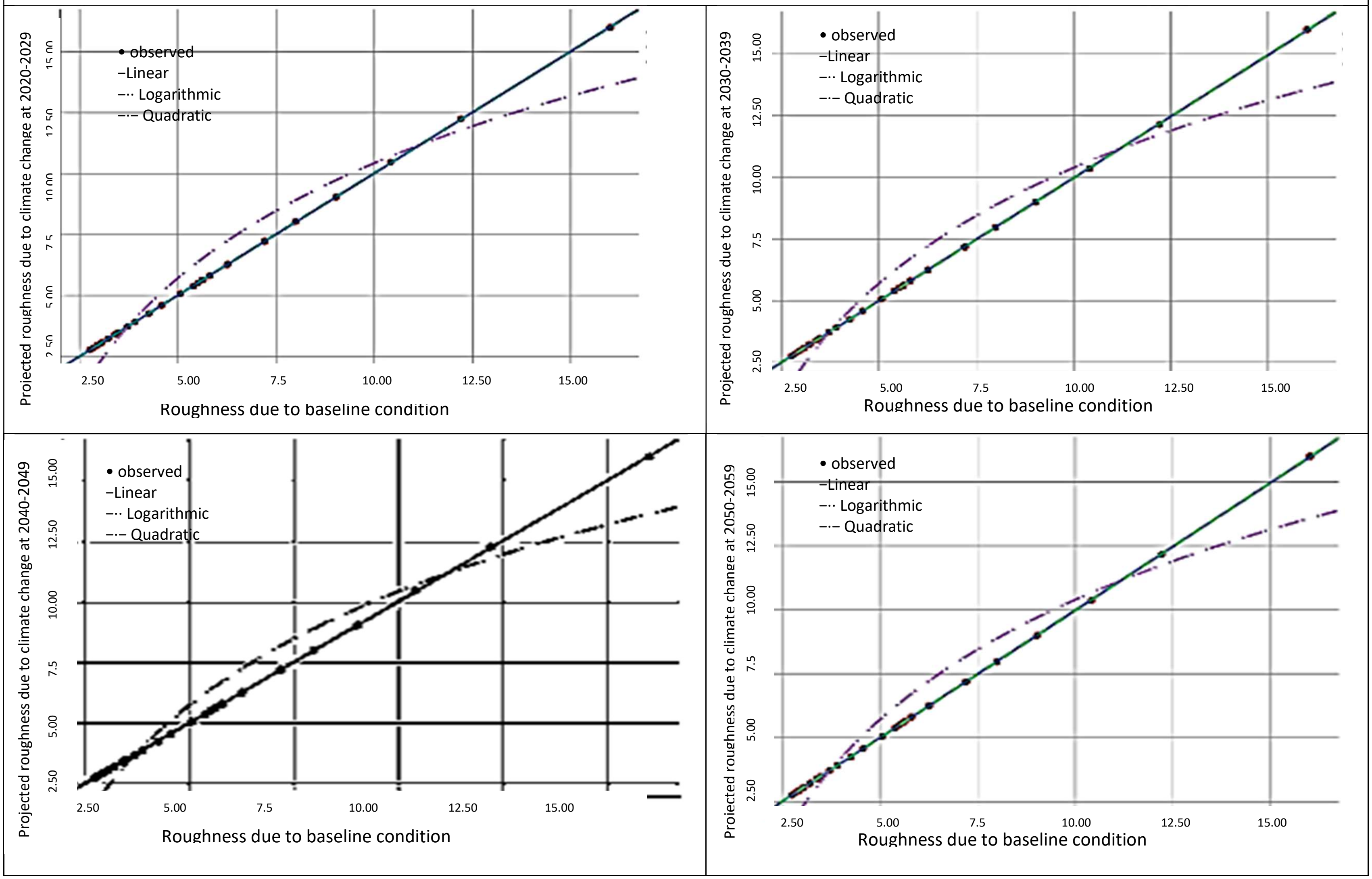
In order to decide what type of relationship can best describe the roughness in the current climate and roughness due to different projected climates the variables are plotted on scatter charts.

Figures.8A (1-4) show typical plots for the asphalt concrete pavement in an arid climate zone with low, medium and high traffic level representative road sections. From the plots it can be seen that the relationship between the predicted roughness considering climate change and the roughness without climate change was best represented by a linear relation.

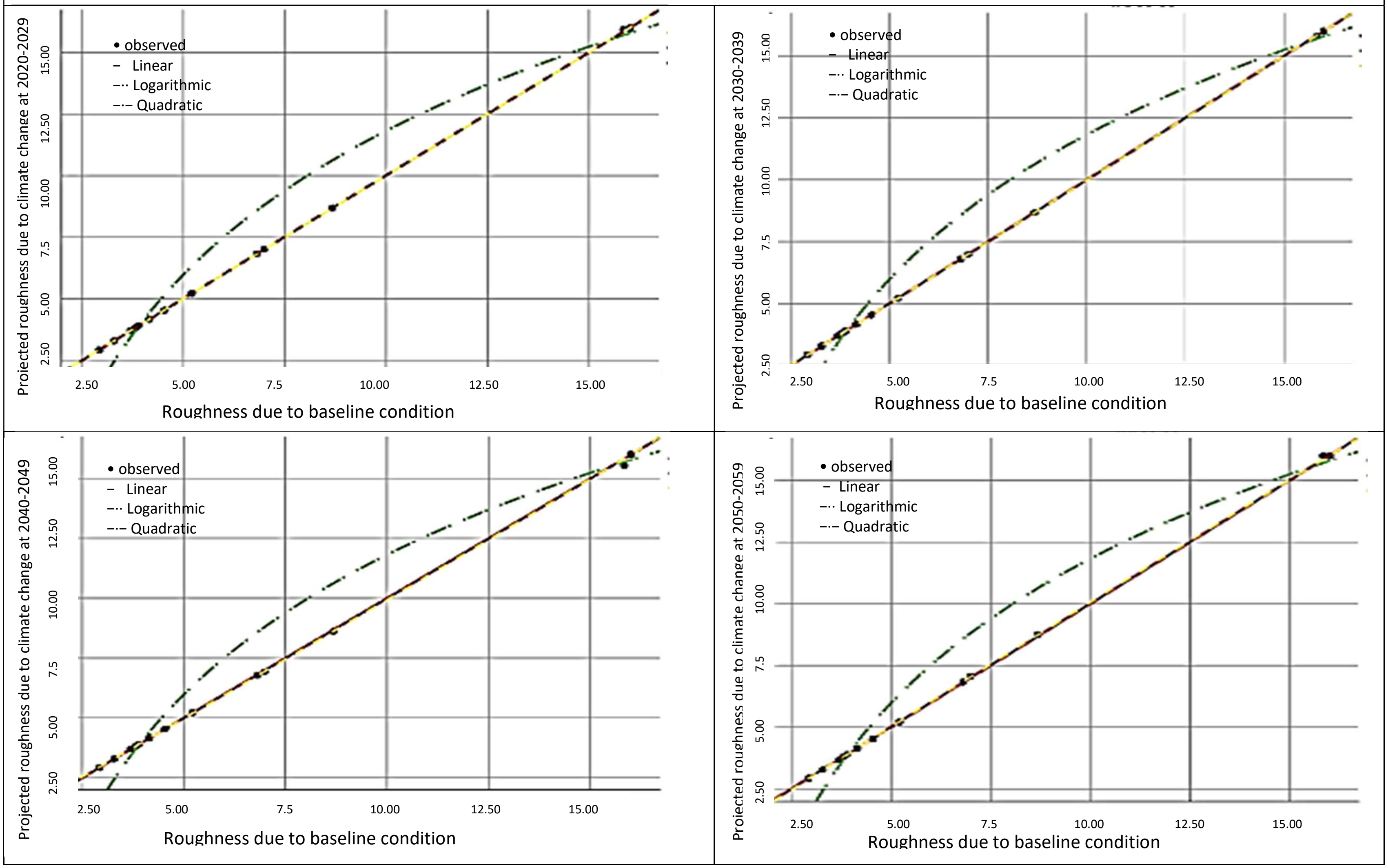
1. AC in arid climate zone with low traffic maximum emission scenario



2. AC in arid climate zone with low traffic minimum emission scenario



3. AC in arid climate zone with high traffic maximum emission scenario



4. AC in arid climate zone with high traffic min emission scenario

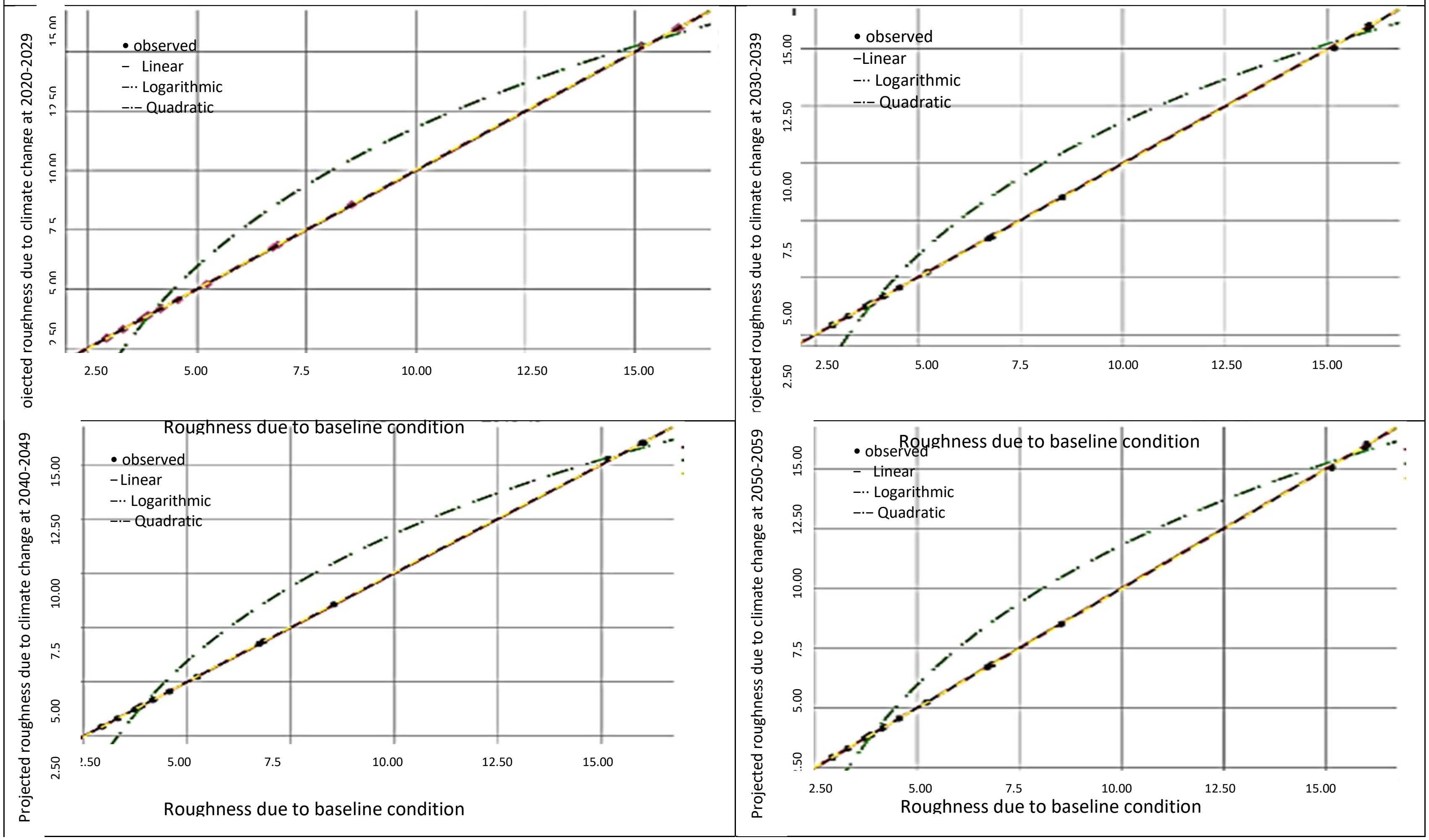


Figure 8A Predicted roughness taking into account changing impacts vs predicted roughness without considering climate change

5.3 Regression Coefficients for Roughness Component

In order to see the climate change effect on the roughness model, the calculation of the importance of each roughness component is independent from the rest of the investigated components. A statistical hypothesis test was used in order to test the linear relation between the roughness components. The null hypothesis H_0 that states the roughness component regression coefficient (B_s, B_{cr}, B_{rut} and B_e) are zero at uncertainty level 90%, was checked against the alternative hypothesis H_1, which is the regression coefficient B_s, B_{cr}, B_{rut}, and B_e are not zero. As a sample, Table 28A indicates that the above hypothesis satisfies B_s, B_{cr}, B_{rut}, and B_e, except for B_{cr} in the max. scenario in the period 2020-2029 for an AC pavement in the moist climate category. In both scenarios the model shows a very good level of model prediction with R value equals 1 and 0.999. In addition to this, Table 29A indicates a typical result, which shows that unlike other factors, only the environment component of the roughness is consistently significant ($p<0.05$) due to climate change.

Table 28A Summary table for regression coefficient of AC pavement with mid-traffic level in the moist climate category due to climate change

		2020 - 2029						2030 - 2039						2040 - 2049						2050 - 2059					
		Unstandardised Coefficients				95.0% Confidence Interval for B		Unstandardised Coefficients				95.0% Confidence Interval for B		Unstandardised Coefficients				95.0% Confidence Interval for B		Unstandardised Coefficients				95.0% Confidence Interval for B	
		B	Std. Error	t	Sig./ p	Lower Bound	Upper Bound	B	Std. Error	t	Sig/p	Lower Bound	Upper Bound	B	Std. Error	t	Sig/p	Lower Bound	Upper Bound	B	Std. Error	t	Sig/p	Lower Bound	Upper Bound
Max scenario	Con.	-.008	.026	-.320	.751	-.061	.045	.059	.023	2.542	.016	.012	.105	.129	.050	2.554	.015	.026	.231	-.072	.026	-2.731	.010	-.126	-.018
	IRIs	4.148	22.205	.187	.853	-40.93	49.227	76.321	19.579	3.898	.000	36.573	116.068	171.147	42.853	3.994	.000	84.151	258.142	- 93.748	22.388	-4.187	.000	-139.20	- 48.298
	IRIc	.000	.000	-1.083	.286	-.001	.000	.000	.000	-.566	.575	-.001	.000	.000	.001	-.455	.652	-.002	.001	.000	.000	.370	.714	-.001	.001
	IRIrut	.007	.007	.920	.364	-.008	.021	-.002	.006	-.358	.722	-.015	.011	-.004	.014	-.291	.773	-.032	.024	.003	.007	.454	.652	-.011	.018
	IRIo	.998	.007	152.404	.000	.985	1.012	.976	.006	169.040	.000	.965	.988	.947	.013	74.873	.000	.921	.972	1.029	.007	155.794	.000	1.016	1.042
Min scenario	Con.	-.381	.187	-2.036	.049	-.761	-.001	-.386	.191	-2.024	.051	-.773	.001	-.326	.160	-2.033	.050	-.651	.000	-.331	.162	-2.043	.049	-.660	-.002
	IRIs	-600.64	189.07	-3.177	.003	-984.5	-216.8	-611.0	192.65	-3.172	.003	-1002.	-219.89	-513.55	161.91	-3.172	.003	-842.2	-184.86	- 521.35	163.81	-3.183	.003	-853.90	- 188.81
	IRIc	.003	.002	1.444	.158	-.001	.008	.003	.002	1.453	.155	-.001	.008	.003	.002	1.456	.154	-.001	.007	.003	.002	1.450	.156	-.001	.007
	IRIrut	.017	.053	.329	.744	-.090	.124	.017	.054	.313	.756	-.092	.126	.015	.045	.330	.743	-.077	.107	.015	.046	.337	.738	-.077	.108
	IRIo	1.155	.050	23.216	.000	1.054	1.256	1.158	.051	22.838	.000	1.055	1.260	1.132	.043	26.581	.000	1.046	1.219	1.134	.043	26.320	.000	1.047	1.222

Table 29A Check for coefficient significances for AC pavement in moist climate

Network matrix name	ΔIRI factors	Coefficient significance							
		Max scenario				Min scenario			
		2020 - 2029	2030 - 2039	2040 - 2049	2050 - 2059	2020 - 2029	2030 - 2039	2040 - 2049	2050 - 2059
AC M HT	Con.	x	√	√	√	√	√	√	√
	IRIs	x	x	x	x	x	x	x	x
	IRIc	x	x	x	x	x	x	x	x
	IRIrut	x	√	√	√	√	√	√	√
	IRIo	√	√	√	√	√	√	√	√
AC M LT	Con.	x	x	x	√	√	√	√	√
	IRIs	x	x	√	x	x	x	x	x
	IRIc	x	x	x	√	x	x	x	x
	IRIrut	x	x	x	x	√	x	√	√
	IRIo	√	√	√	√	√	√	√	√
AC M MT	Con.	x	√	√	√	√	x	x	√
	IRIs	x	√	√	√	√	√	√	√
	IRIc	x	x	x	x	x	x	x	x
	IRIrut	x	x	x	x	x	x	x	x
	IRIo	√	√	√	√	√	√	√	√

Where:

√ – represents the parameter is significant in determination of ΔIRI

x – represents the parameter is not significant in determination of ΔIRI

Moreover, the validation of the importance of the environmental roughness component independently from the rest was checked for the linear relation using original, transformed quadratic and logarithmic data. The null hypothesis H_0 that states the roughness environmental component regression coefficient for B_e is zero at uncertainty level 95% was checked against the alternative hypothesis H_1 (i.e. that the regression coefficient B_e is not zero).

As an example, Table 30A below indicates that for the linear regression, the above hypothesis did not satisfy B_e, for a change in climate input data. Therefore, the environment component of the roughness is affected by climate change.

Table 30A Statistical analysis result for the coefficient of AC SA MT under A2 maximum climate change scenario between 2020 and 2029

Model		Unstandardised Coefficients		t	Sig./ P	95.0% Confidence Interval for B	
		B	Std. Error			Lower Bound	Upper Bound
1	(Constant)	.181	.014	13.241	.000	.153	.209
	IRIo	.957	.002	411.646	.000	.952	.962
2	(Constant)	.041	.030	1.373	.181	-.020	.101
	IRIo	1.003	.009	107.210	.000	.984	1.023
	IRIosqu	-.003	.001	-5.048	.000	-.004	-.002
3	(Constant)	-.167	.075	-2.221	.035	-.322	-.012
	IRIo	.802	.069	11.620	.000	.660	.944

	IRIosqu	.004	.002	1.571	.128	-.001	.009
	logIRIo	1.508	.513	2.942	.007	.454	2.562

5.4 Model Quality Check

Similar to the definition of significance of the regression coefficients, the significance or quality of the entire model can be checked using summary statistics. This includes mean, variance, standard deviation, coefficient of variation, covariance, correlation, and analysis of variance table. The sum of residuals along with degrees of freedom are shown together to compute the p value of the F-distribution.

Table 31A shows a typical model check for analysis result. It indicates adding quadratic and logarithmic value of initial roughness resulted in no improvement from the linear regression as the R^2 change is zero. Also, it is statistically significant with F values 25.480 and 8.654, for 1 and 27, 1 and 26 degrees of freedom with p values 0.000 and 0.007 respectively.

Although the quadratic fitting curve has shown similar characteristics with the linear one, adding a quadratic and logarithmic effect resulted in increasing zero capacity for the linear model.

Table 31A Type model check analysis result

Model	R Square	Adjusted R Square	Change Statistics				
			R Square Change	F Change	df1	df2	Sig. F Change
1	1.000	1.000	1.000	169452.063	1	28	.000
2	1.000	1.000	.000	25.480	1	27	.000
3	1.000	1.000	.000	8.654	1	26	.007

Where:

1 - represents linear relation between Constant, IRI_o & ΔIRI

2 - represents quadratic relation between Constant, IRI_o, IRI_{osqur} & ΔIRI

3 - represents quadratic relation between Constant, IRIo, IRI_{osqur}, $logIRI_o$ & ΔIRI between IRI_o

5.5 Model coefficient for the identified climate periods

For the linear model expressed by $b_1IRI_o + c$ the following results were obtained from the regression analysis. Table 32A provides a sample for the summary statistics of the estimated model coefficient for the environmental component of the roughness in an arid climate for a low-level traffic condition. Similarly, for the remaining road matrix, the results are presented in the results chapter (Chapter Six).

Table 32A Model check and estimate of regression coefficient of ΔIRI for asphalt concrete in an arid climate zone for low traffic level (AC A LT)

	Period	Model quality					Coefficients			
		R^2	Adj. R^2	Changed R^2	F change	Sig /p	b_1	c	t	Sig /p
Max. scenario	2020- 29	1.00	1.00	1.00	1905530.350	.000	**1.002**	- .006	138.409 1380.49	.000 .285
	2030- 39	1.00	1.00	1.00	10328019.237	.000	**.999**	.001	3213.724 .549	.000 .588
	2040- 49	1.00	1.00	1.00	239680.727	.000	**.994**	.014	489.572 .875	.000 .389
	2050- 59	1.00	1.00	1.00	194900.640	.000	**1.007**	- .014	441.476 -.901	.000 .375
Min. scenario	2020- 29	1.00	1.00	1.00	1639236.828	.000	**1.002**	- .003	1280.327 -.606	.000 .550
	2030- 39	1.00	1.00	1.00	1346860.264	.000	**.998**	.004	1160.543 .649	.000 .522
	2040- 49	1.00	1.00	1.00	1449901.196	.000	**1.002**	- .014	1204.118 .710	.000 .484
	2050- 59	1.00	1.00	1.00	2257068.684	.000	**.998**	.003	1502.354 .616	.000 .543

5.6 Summary

The generic pavement material distress models inherent in the HDM-4 software need to be calibrated to local conditions by modifying the model coefficients. Chapter Three introduced the calibration process to be carried out in this research, for both the flexible and the rigid pavement distress models. Whilst Chapter Four showed how the use and calibration of the models ties in with the overall research framework. This chapter, by means of a number of examples and using data collected for some of the representative road sections selected for the research, shows explicitly how the calibration process was carried out. For flexible pavements the calibration processes were associated with determining appropriate values for K_{ge}, K_{ci}, K_{cp}, K_{gm} and k_{gp}, in the roughness progression distress model. Similarly, for the two types of rigid pavements considered in this research (i.e. JPCP and JRCP) the calibration process was demonstrated for the faulting model using the JPCP representative road section. The approach used was based on that suggested by Stannard et al. (2006) and used regression analysis.

Appendix L - **Analysis Results**

Appendix L Analysis Results

1. Change in average roughness due to climate change for maximum A2 emission scenarios

<u>For Arid Climate Region</u>

1.1. CLIMATE ZONE: ARID, TRAFFIC LEVEL: HT

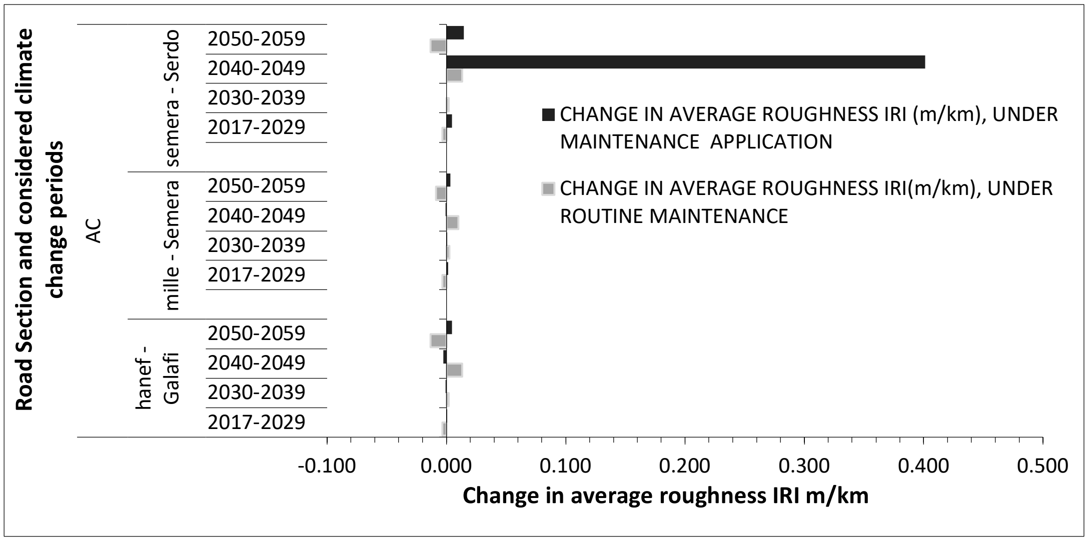


Figure 1 change in average roughness for pavements in Arid climate zone with high traffic

1.2. CLIMATE ZONE: ARID TRAFFIC LEVEL: LT

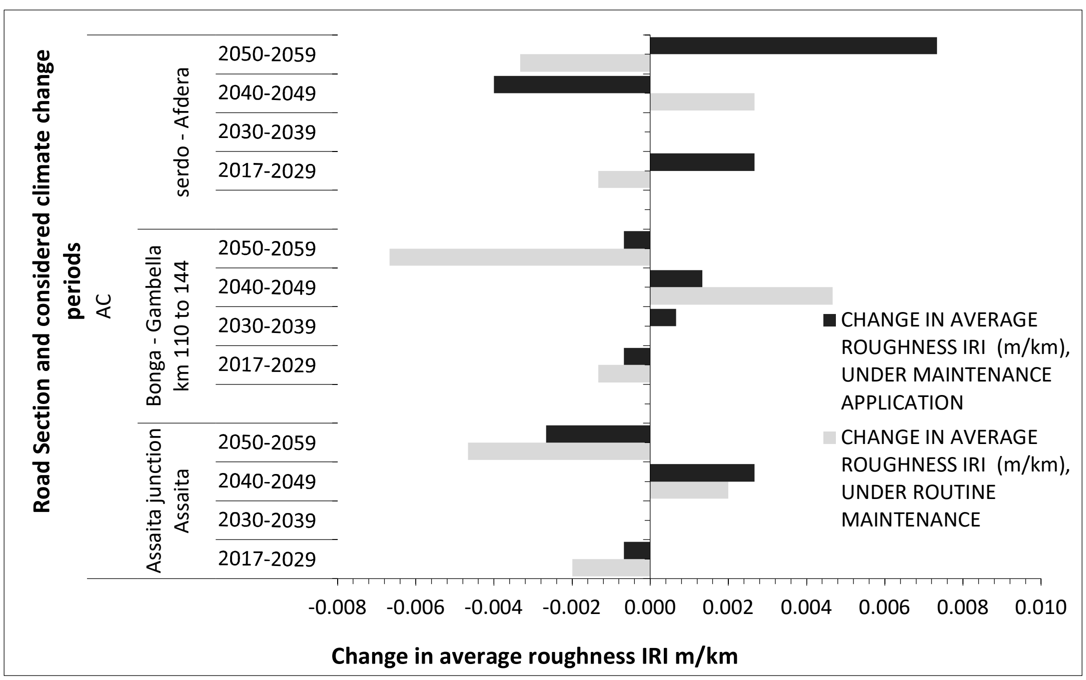


Figure 2 change in average roughness for pavements in Arid climate zone with low traffic

1.3. CLIMATE ZONE: ARID TRAFFIC LEVEL: MT

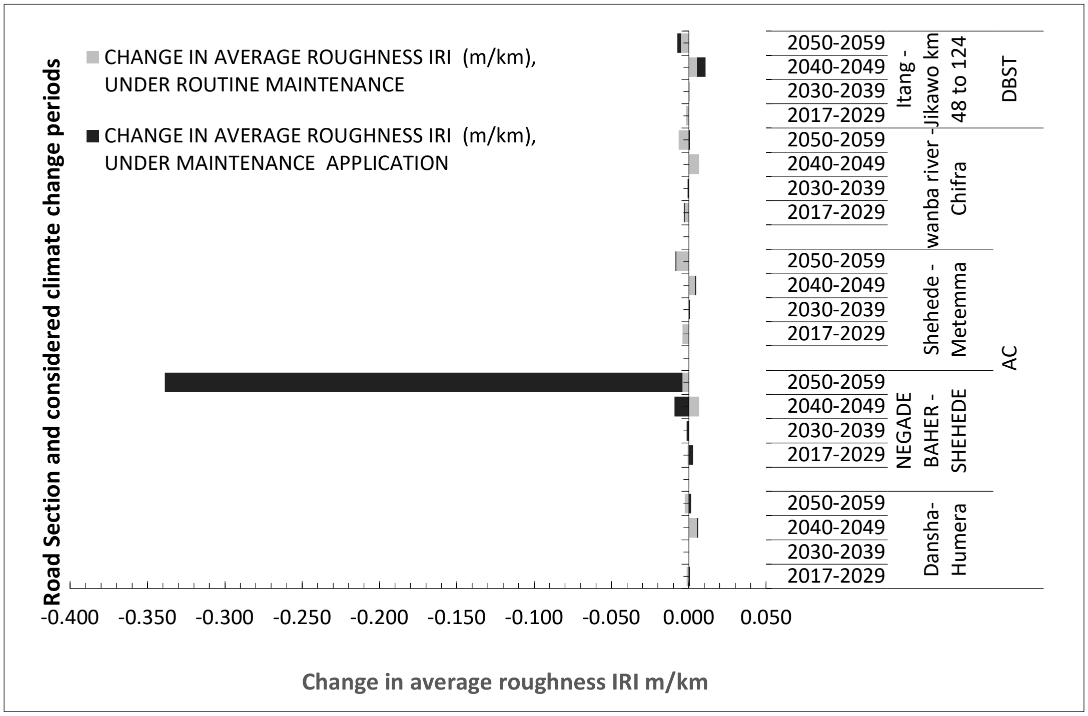


Figure 3 change in average roughness for pavements in Arid climate zone with medium *traffic*

For Semi-Arid Climate Region

1.4. CLIMATE ZONE: SEMI-ARID TRAFFIC LEVEL: HT

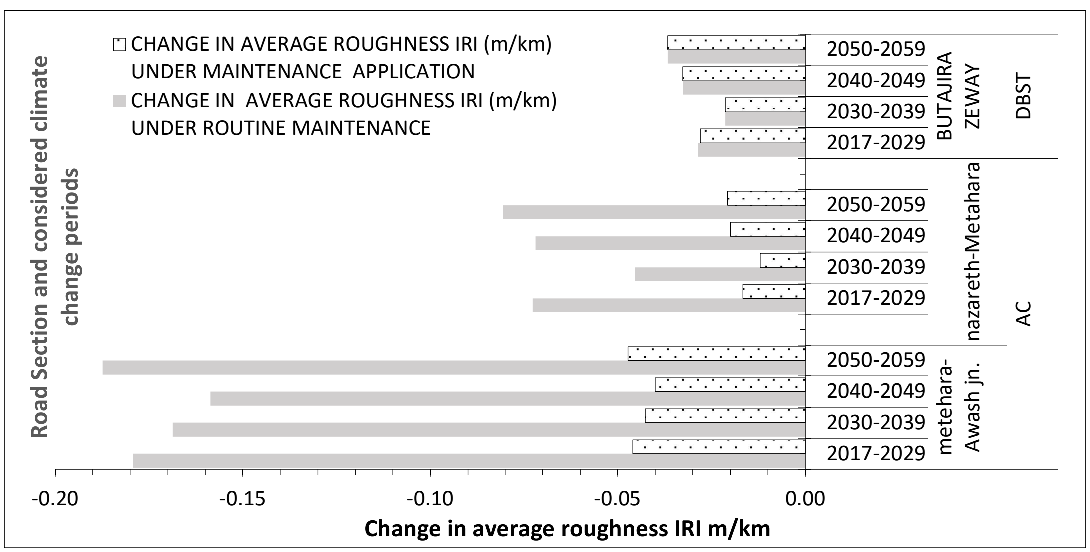


Figure 4 change in average roughness for pavements in a semi-arid climate zone with high traffic

1.5. CLIMATE ZONE: SEMI-ARID TRAFFIC LEVEL: LT

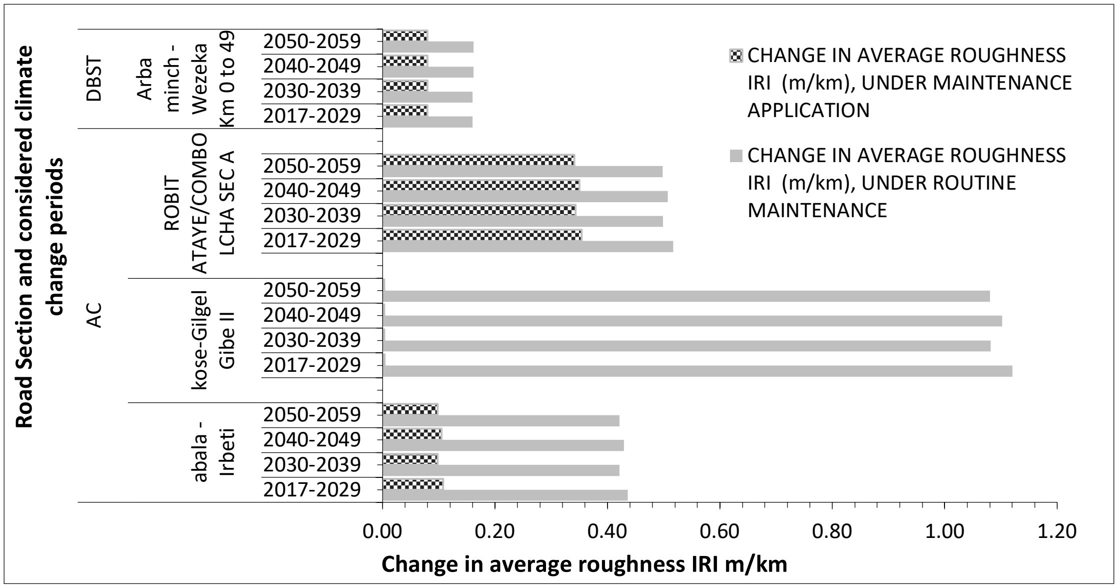


Figure 5 change in average roughness for pavements in a semi-arid climate zone with low traffic

1.6. CLIMATE ZONE: SEMI-ARID TRAFFIC LEVEL: MT

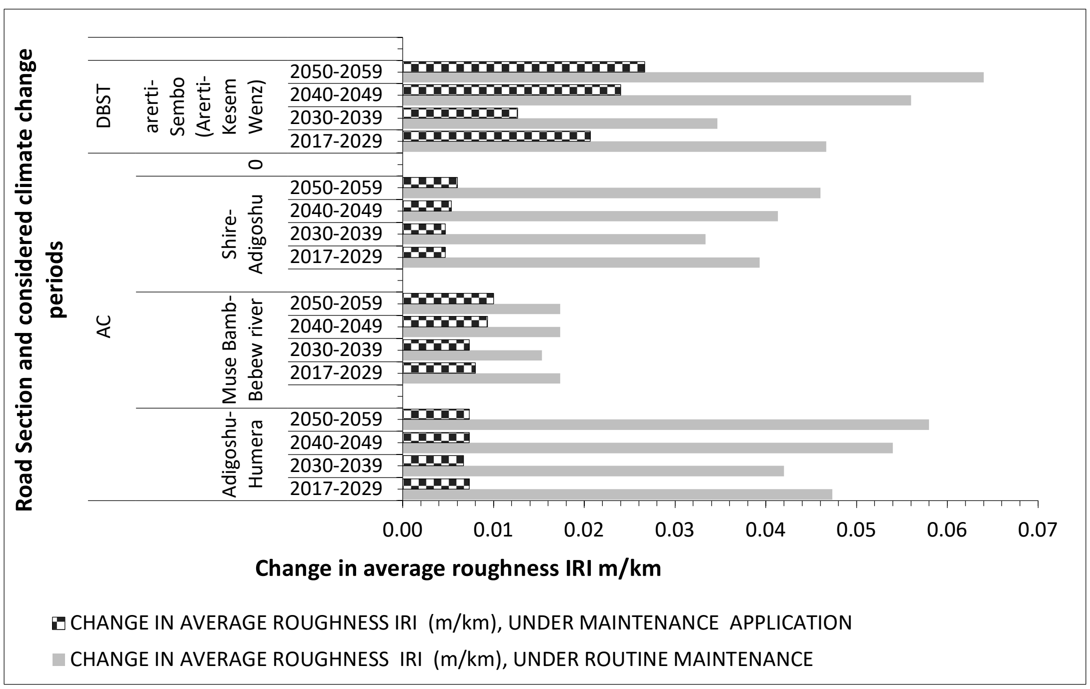


Figure 6 change in average roughness for pavements in a semi-arid climate zone with medium traffic

For Sub-Moist Climate Region

1.7. CLIMATE ZONE: SUB-MOIST TRAFFIC LEVEL: HT

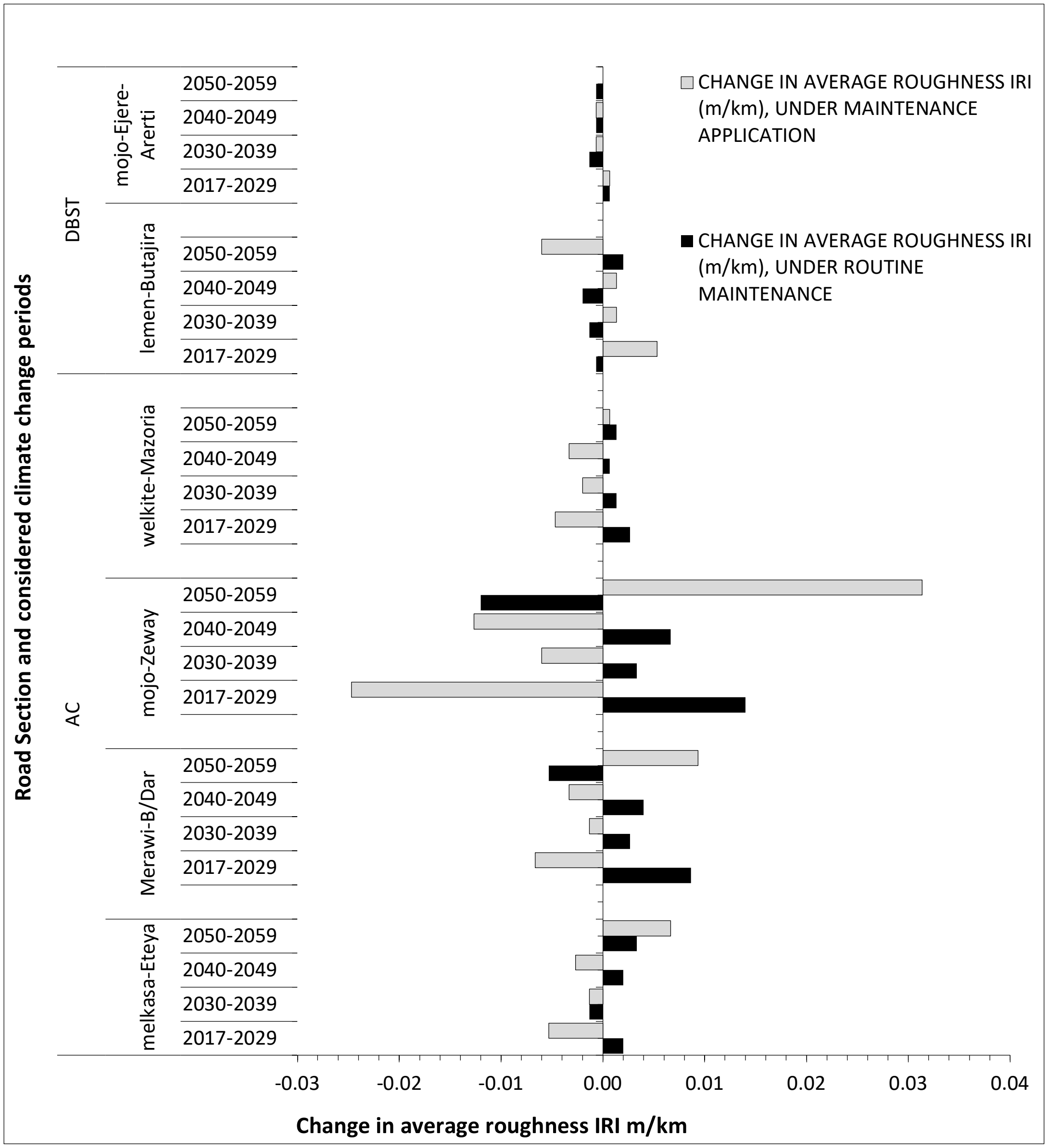


Figure 7 change in average roughness for pavements in a sub-moist climate zone with high traffic

1.8. CLIMATE ZONE: SUB-MOIST TRAFFIC LEVEL: LT

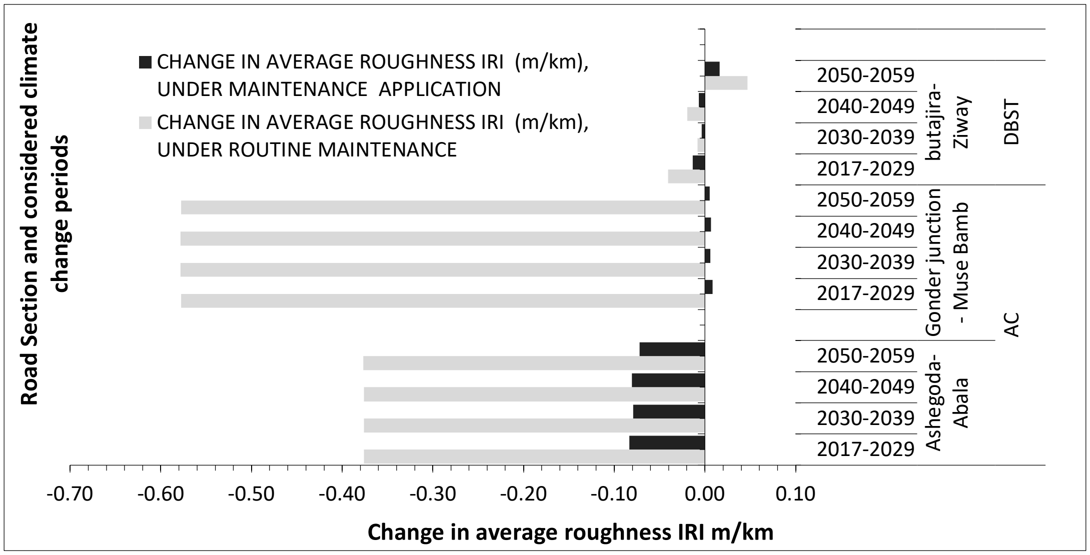


Figure 8 change in average roughness for pavements in a sub-moist climate zone with low traffic

1.9. CLIMATE ZONE: SUB-MOIST TRAFFIC LEVEL: MT

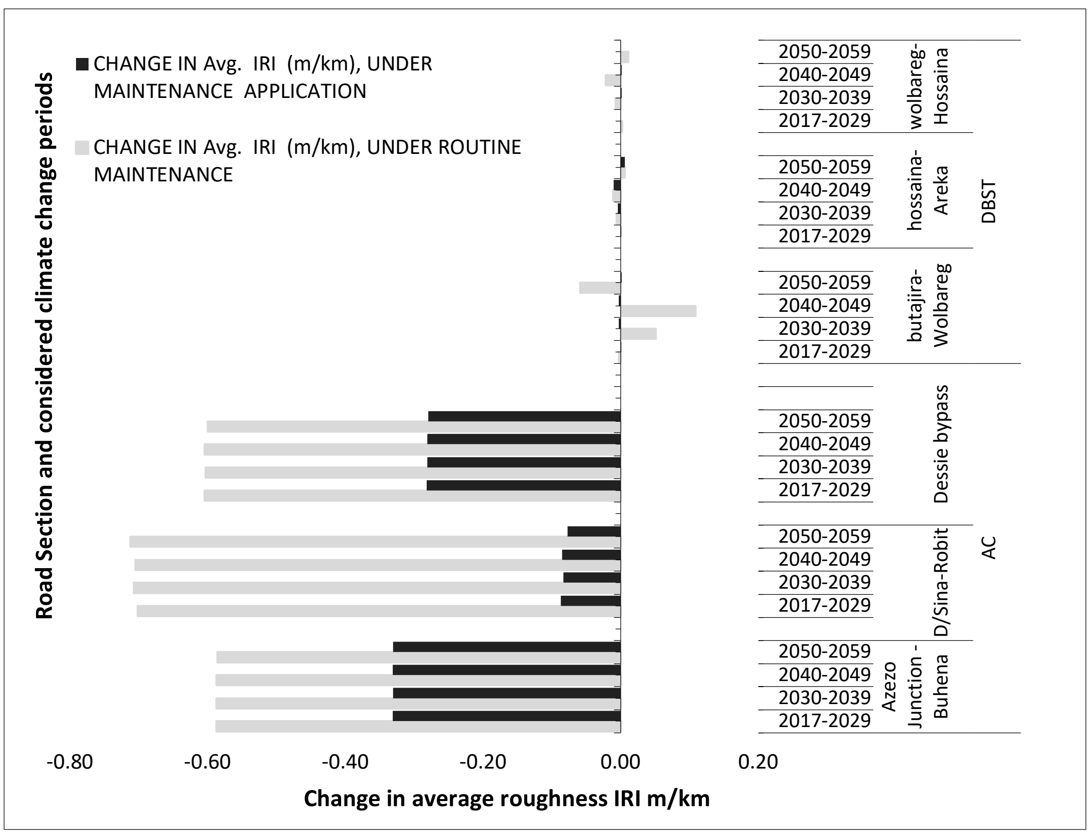


Figure 9 change in average roughness for pavements in a sub-moist climate zone with medium traffic

For Moist Climate Region

1.10. CLIMATE ZONE: MOIST TRAFFIC LEVEL: HT

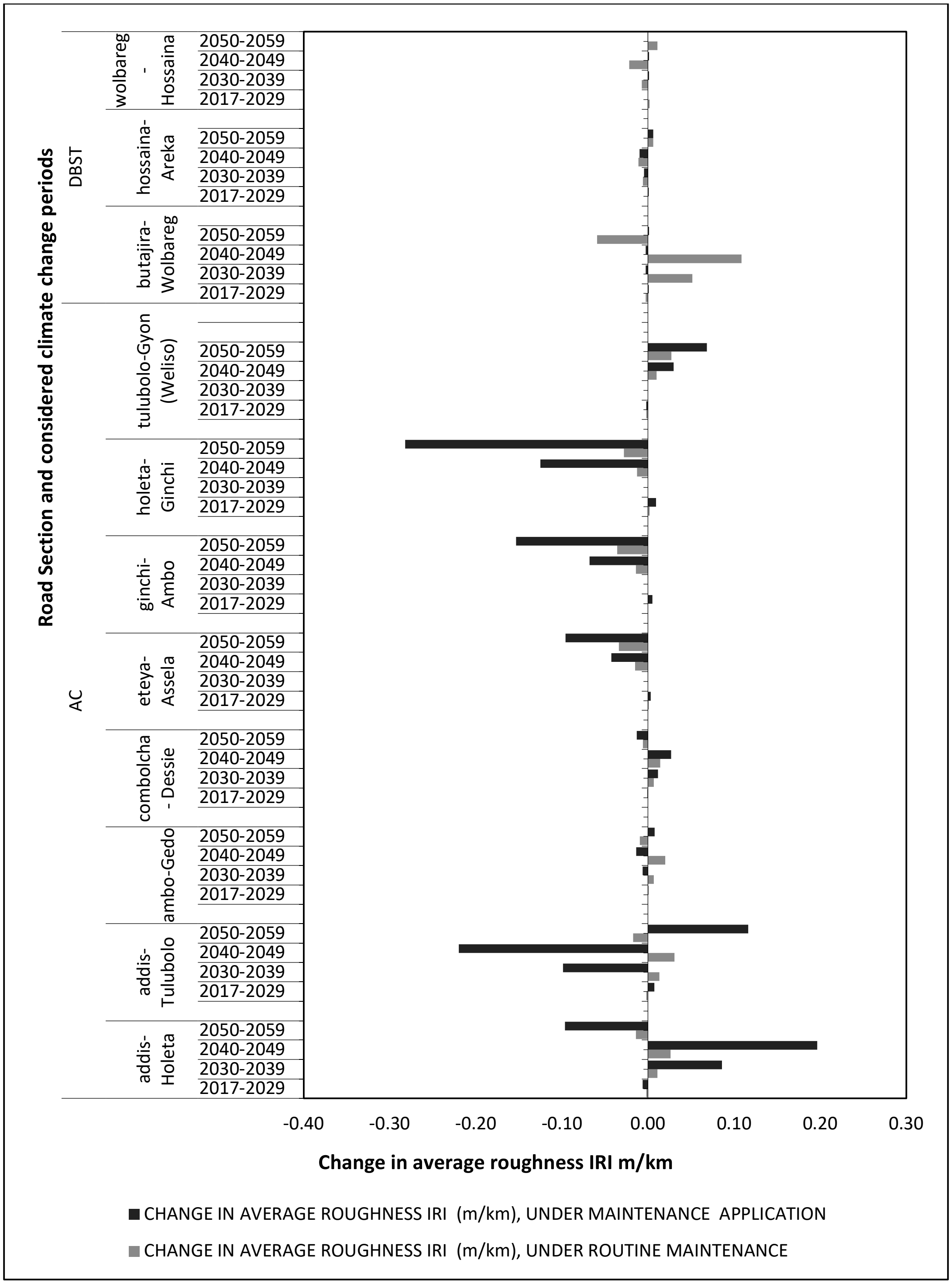


Figure 10 change in average roughness for pavements in a moist climate zone with high traffic

1.11. CLIMATE ZONE: MOIST TRAFFIC LEVEL: LT

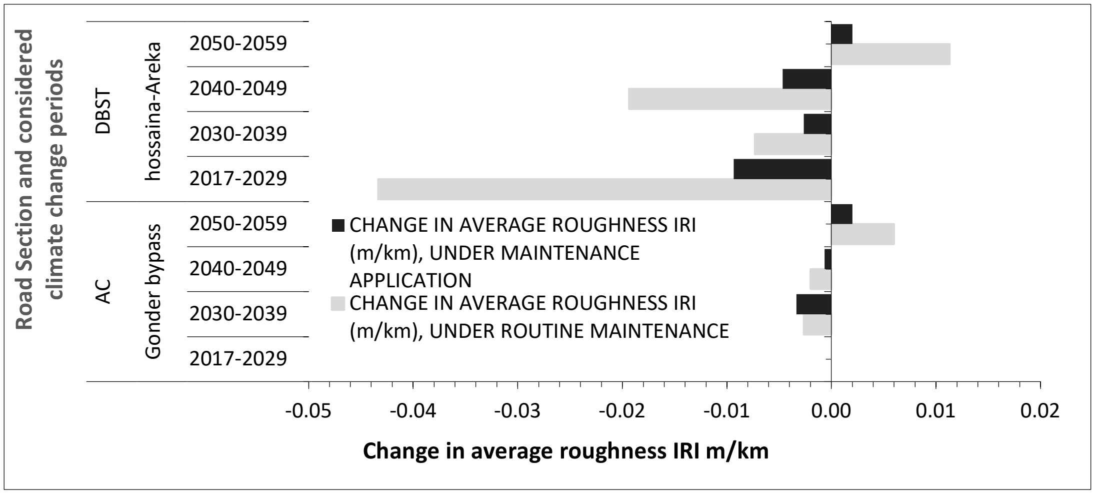


Figure 11 change in average roughness for pavements in a moist climate zone with low traffic

1.12. CLIMATE ZONE: MOIST TRAFFIC LEVEL: MT

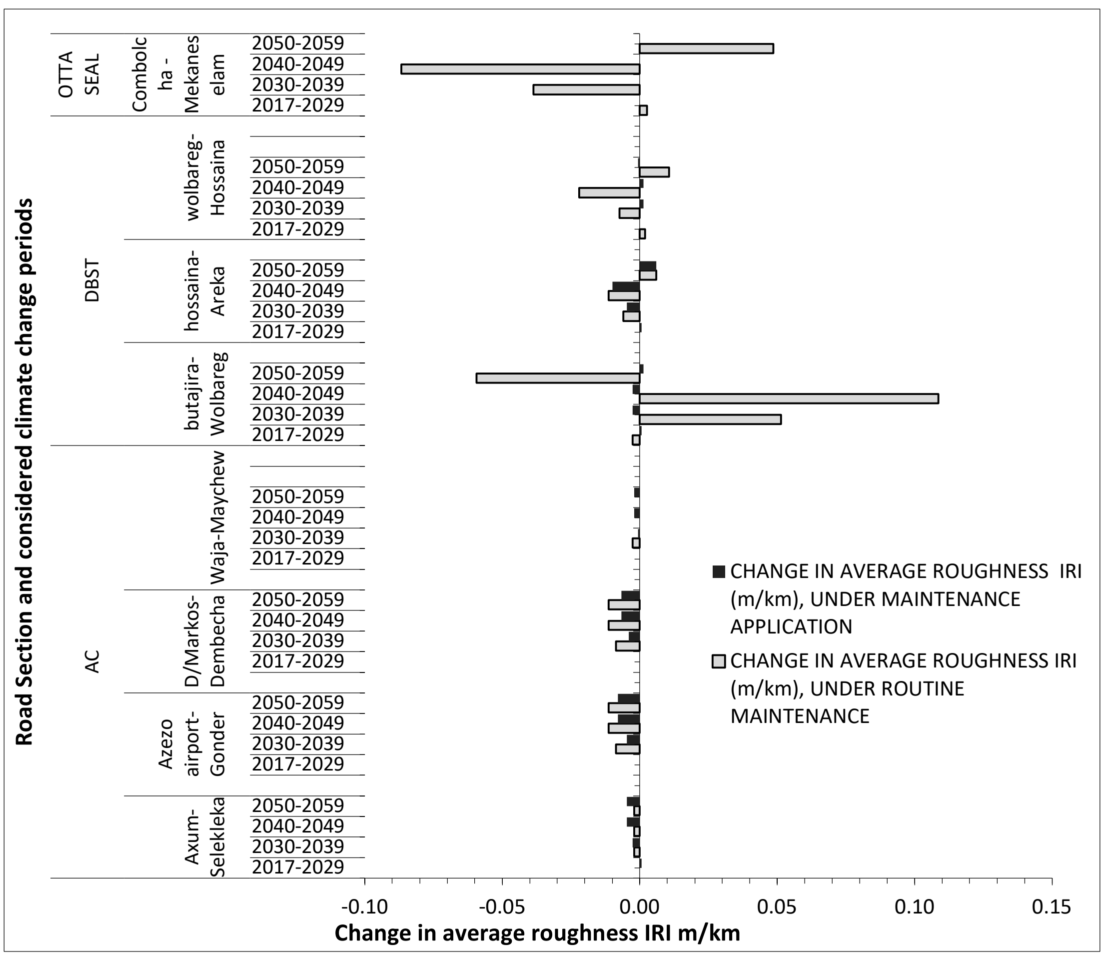


Figure 12 change in average roughness for pavements in a moist climate zone with medium traffic

For Sub-Humid Climate Region

1.13. CLIMATE ZONE CLIMAT: SUB-HUMID TRAFFIC LEVEL: HT

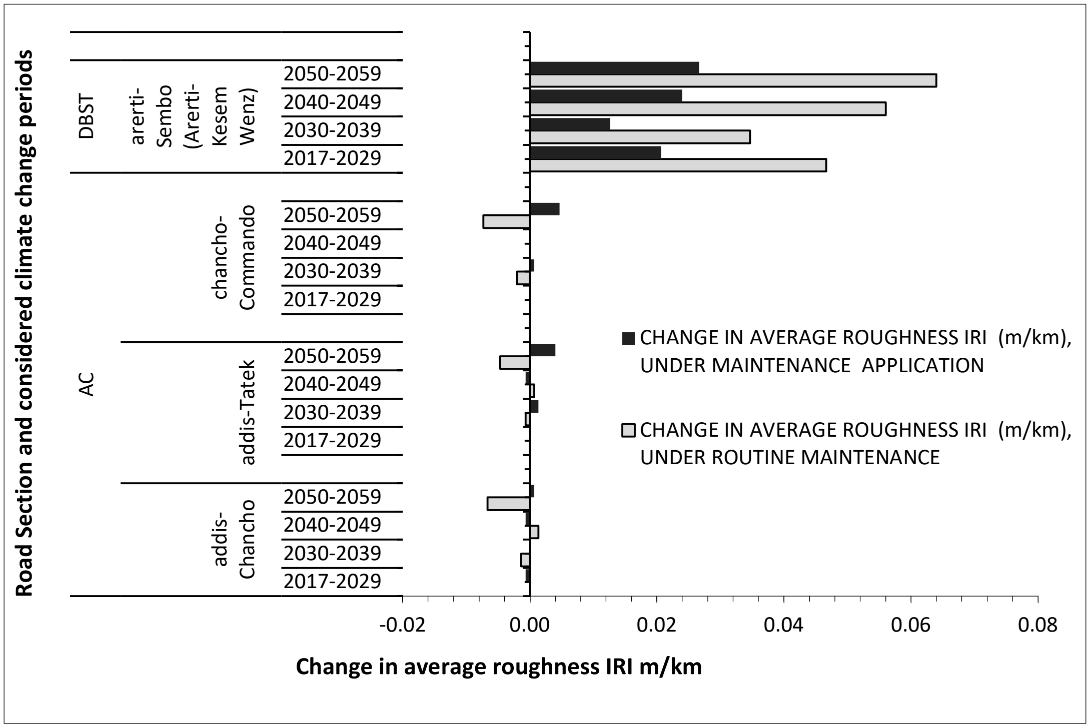


Figure 13 change in average roughness for pavements in a sub-humid climate zone with high traffic

1.14. CLIMATE ZONE CLIMAT: SUB-HUMID TRAFFIC LEVEL: LT

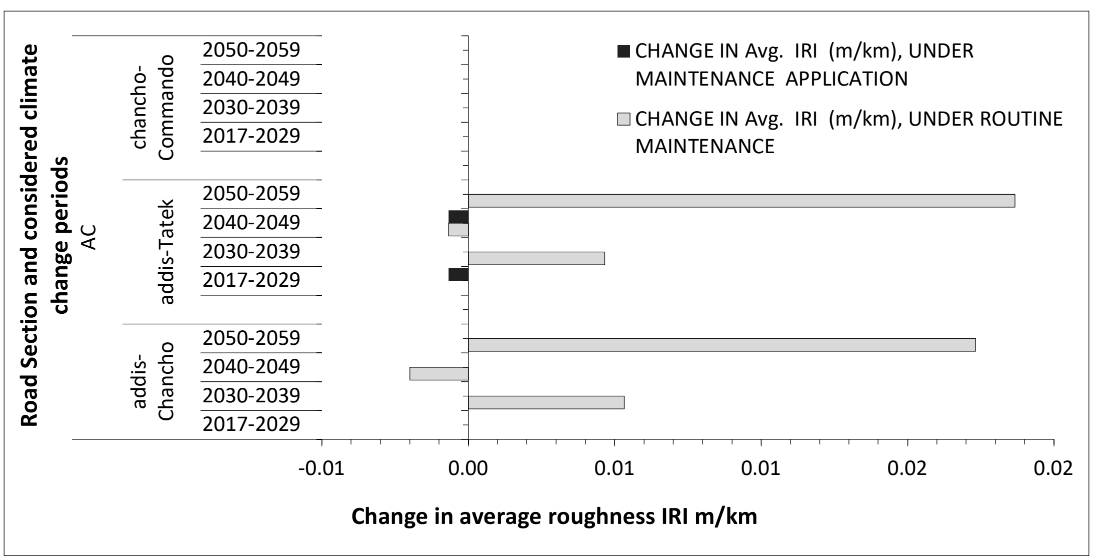


Figure 14 change in average roughness for pavements in a sub-humid climate zone with low traffic

1.15. CLIMATE ZONE: SUB-HUMID TRAFFIC LEVEL: MT

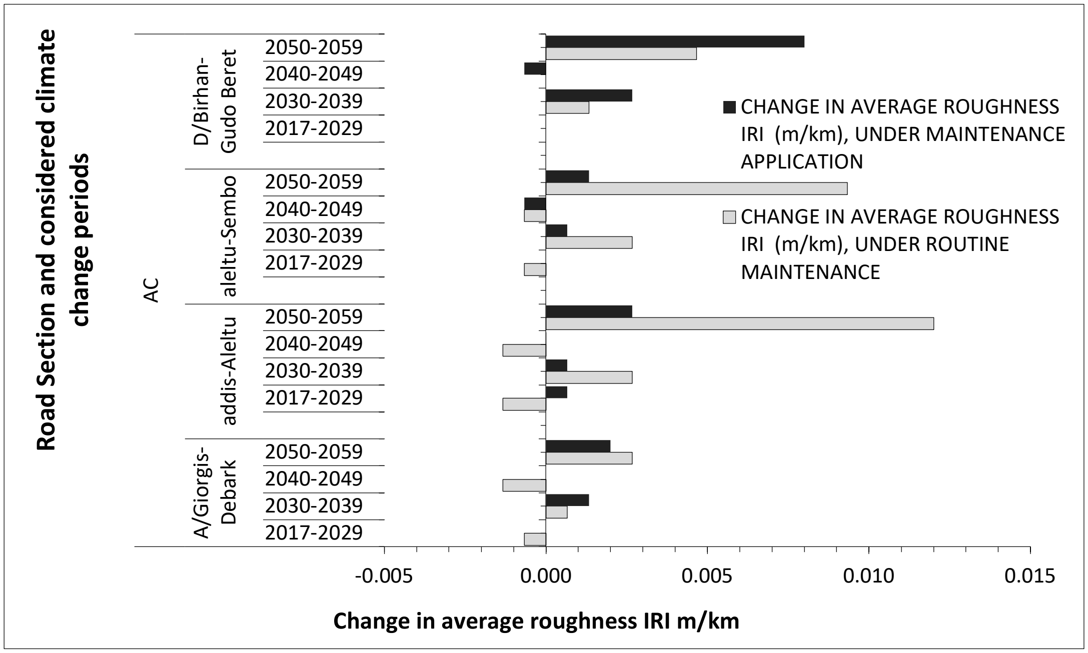


Figure 15 change in average roughness for pavements in a sub-humid climate zone with medium traffic

2.1 Change in average roughness due to climate change for Minimum A2 emission scenarios

For Arid Climate Region

1.16. CLIMATE ZONE: ARID TRAFFIC LEVEL: HT

Figure 16 change in average roughness for pavements in arid climate zone with high traffic

1.17. CLIMATE ZONE: ARID TRAFFIC LEVEL: LT

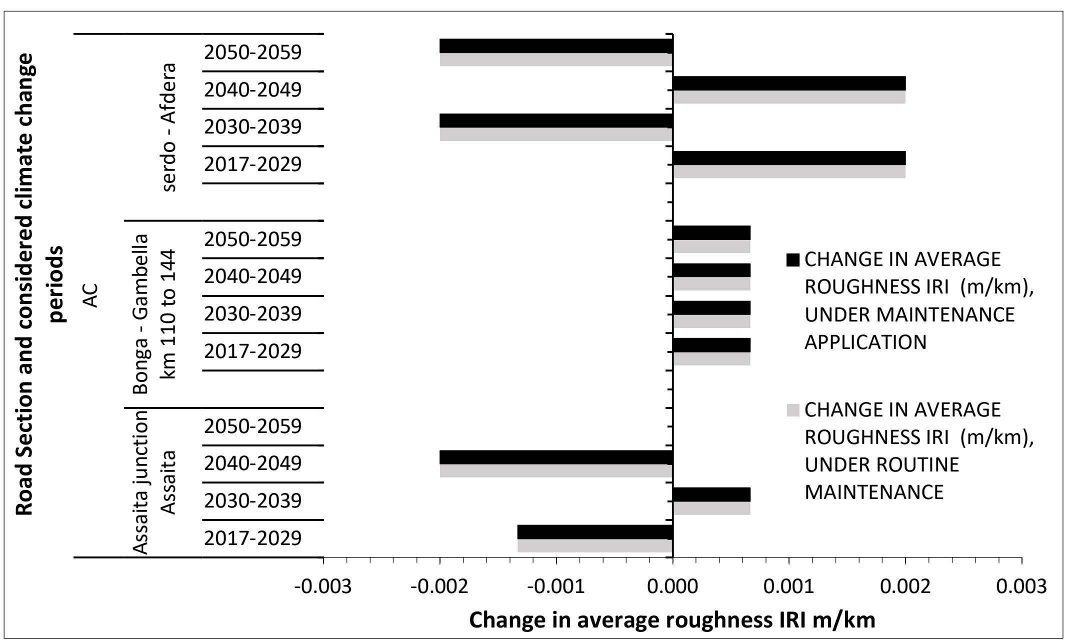


Figure 17 change in average roughness for pavements in arid climate zone with low traffic

1.18. CLIMATE ZONE: ARID TRAFFIC LEVEL: MT

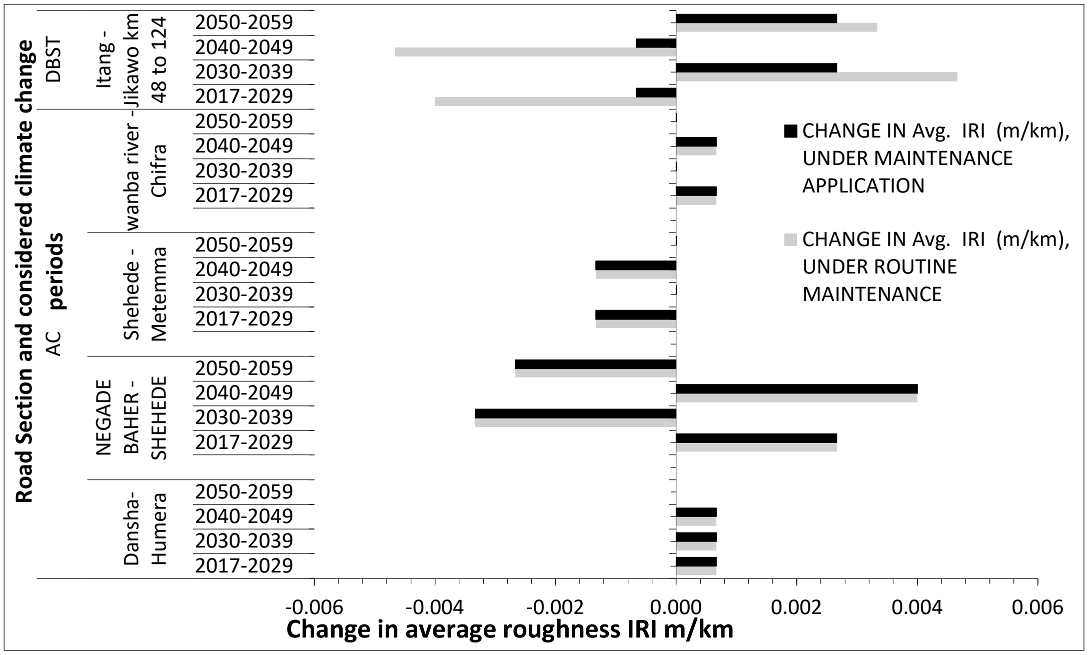


Figure 18 change in average roughness for pavements in arid climate zone with medium traffic

For Semi-Arid Climate Region

1.19. CLIMATE ZONE: SEMI -ARID TRAFFIC LEVEL: HT

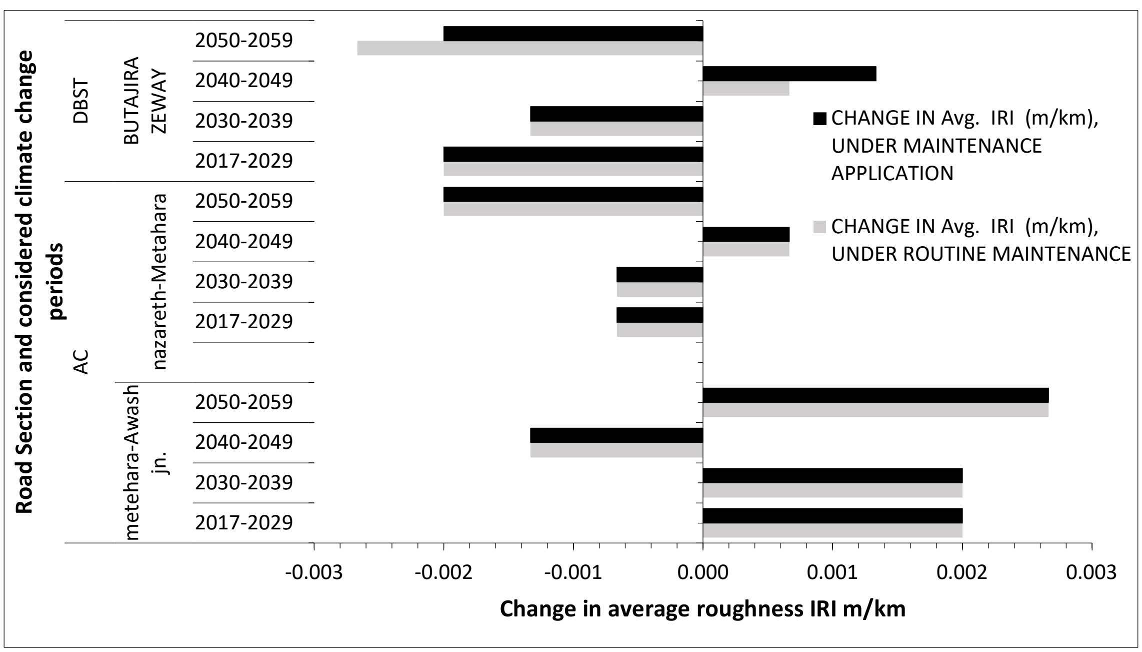


Figure 19 change in average roughness for pavements in a semi-arid climate zone with high traffic

1.20. CLIMATE ZONE: SEMI -ARID TRAFFIC LEVEL: LT

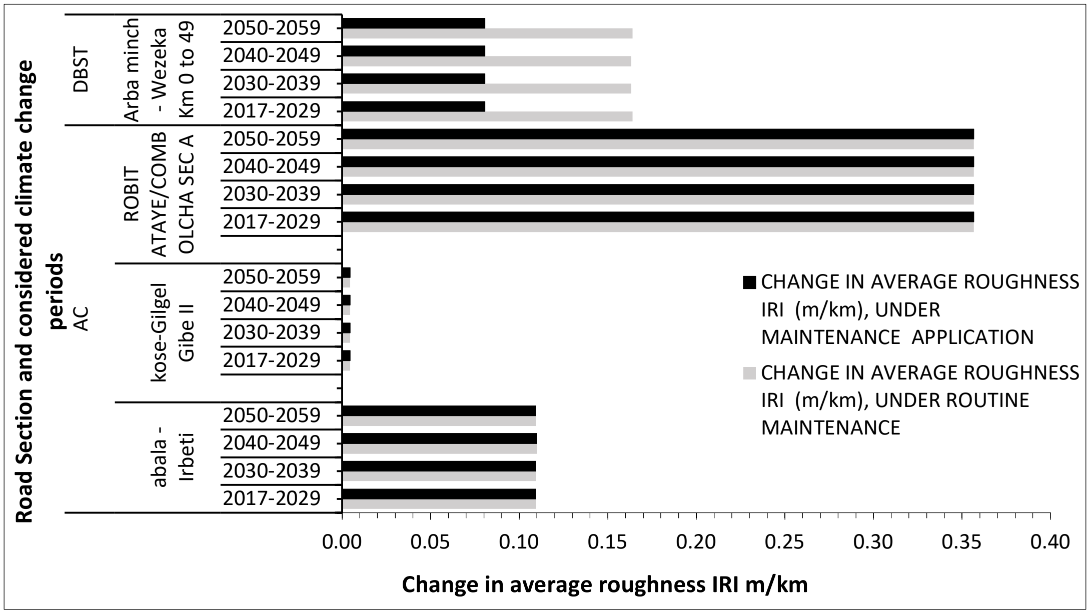


Figure 20 change in average roughness for pavements in a semi-arid climate zone with high traffic

1.21. CLIMATE ZONE: SEMI -ARID TRAFFIC LEVEL: MT

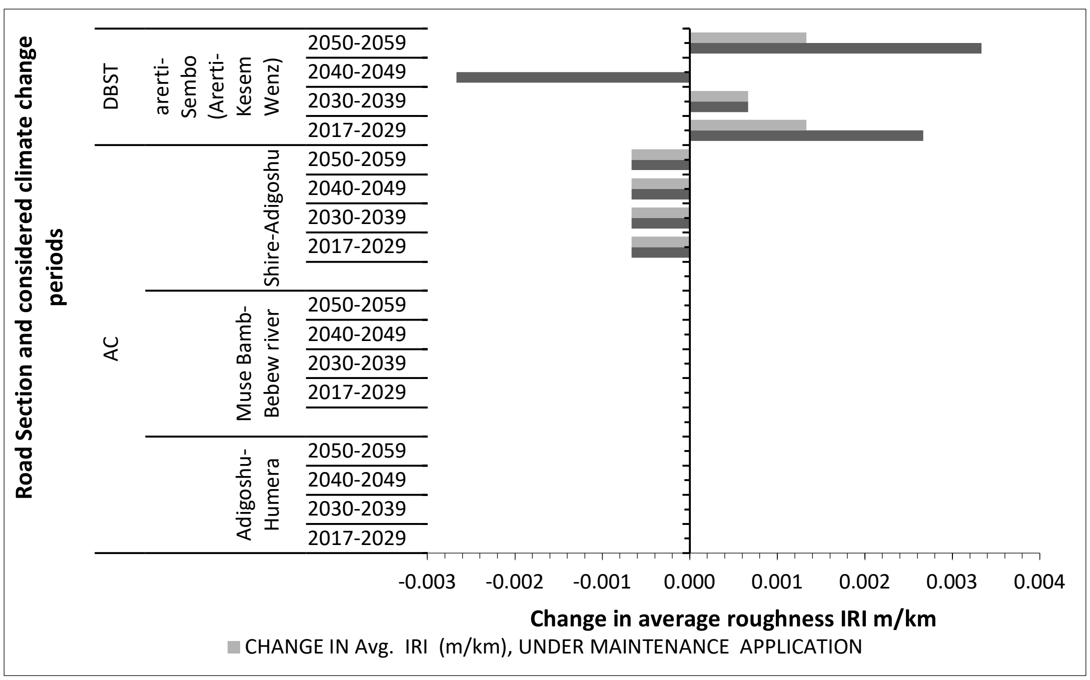


Figure 21 change in average roughness for pavements in a semi-arid climate zone with medium traffic

For Sub-Moist Climate Region

1.22. CLIMATE ZONE: SUB -MOIST TRAFFIC LEVEL: HT

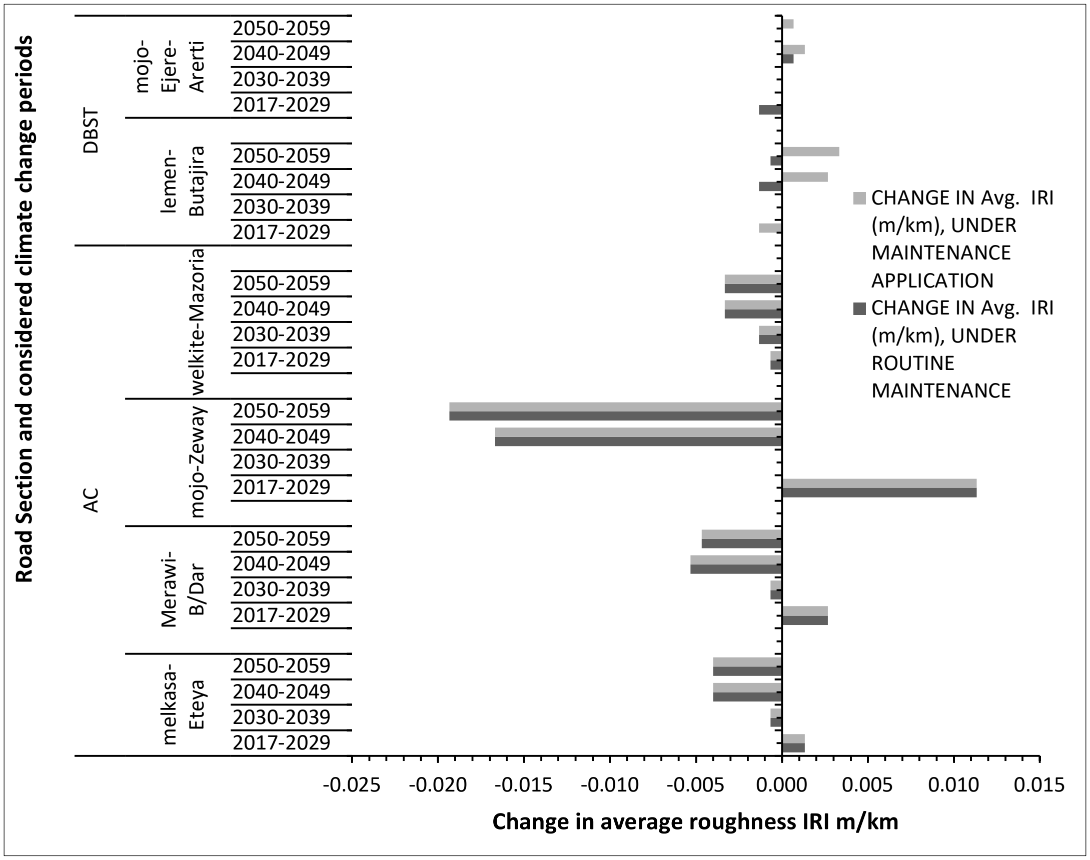


Figure 22 change in average roughness for pavements in a sum moist climate zone with high traffic

1.23. CLIMAT: SUB -MOIST TRAFFIC LEVEL: LT

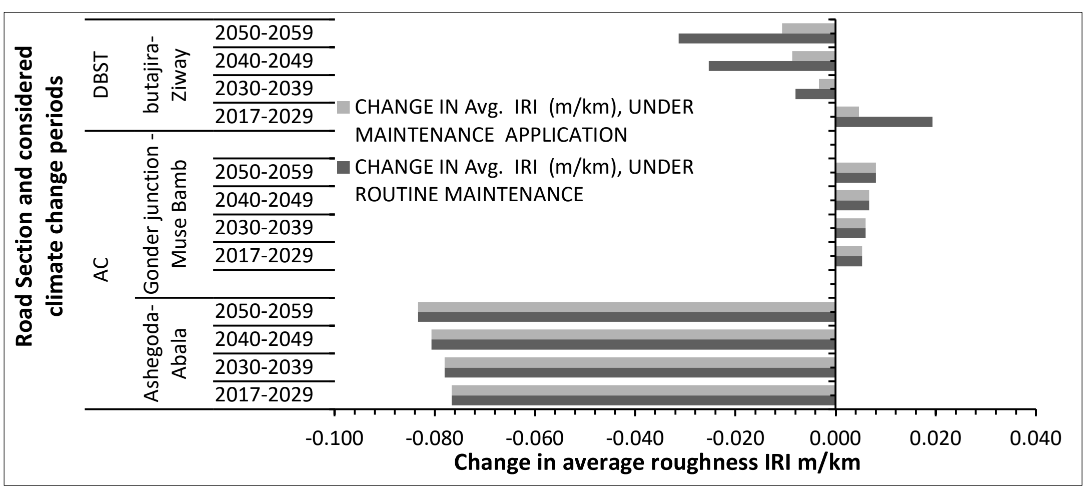


Figure 23 change in average roughness for pavements in a sub moist climate zone with low traffic

CLIMAT: SUB -MOIST TRAFFIC LEVEL: MT

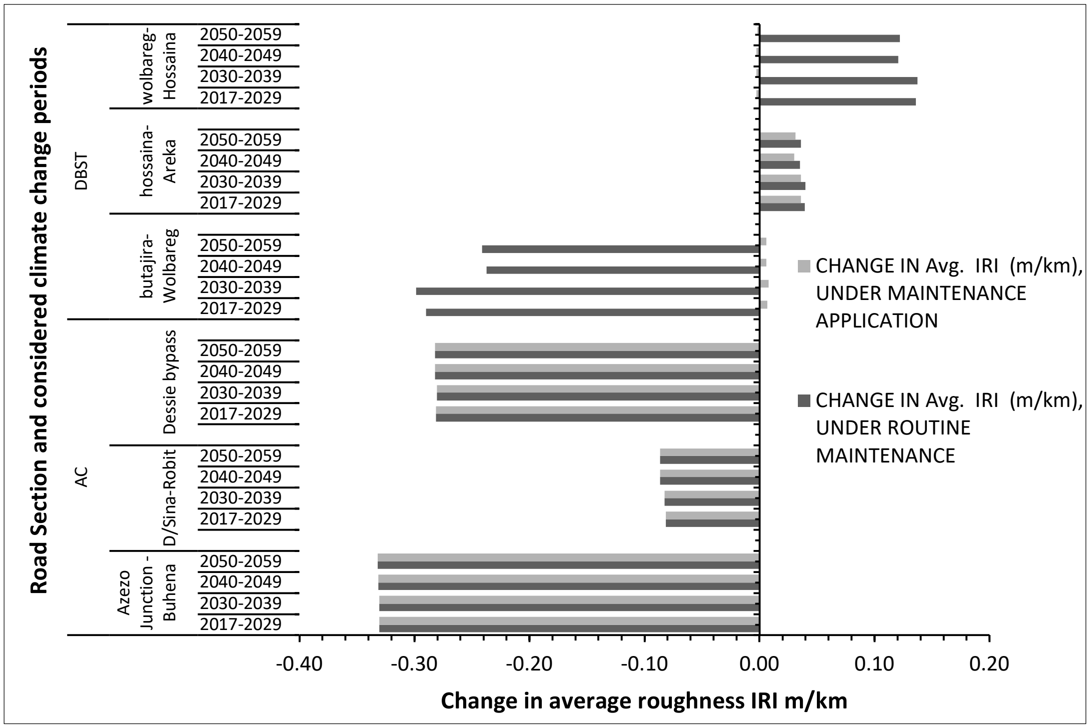


Figure 24 change in average roughness for pavements in a dub moist climate zone with medium traffic

For Moist Climate Region

CLIMAT: MOIST TRAFFIC LEVEL: HT

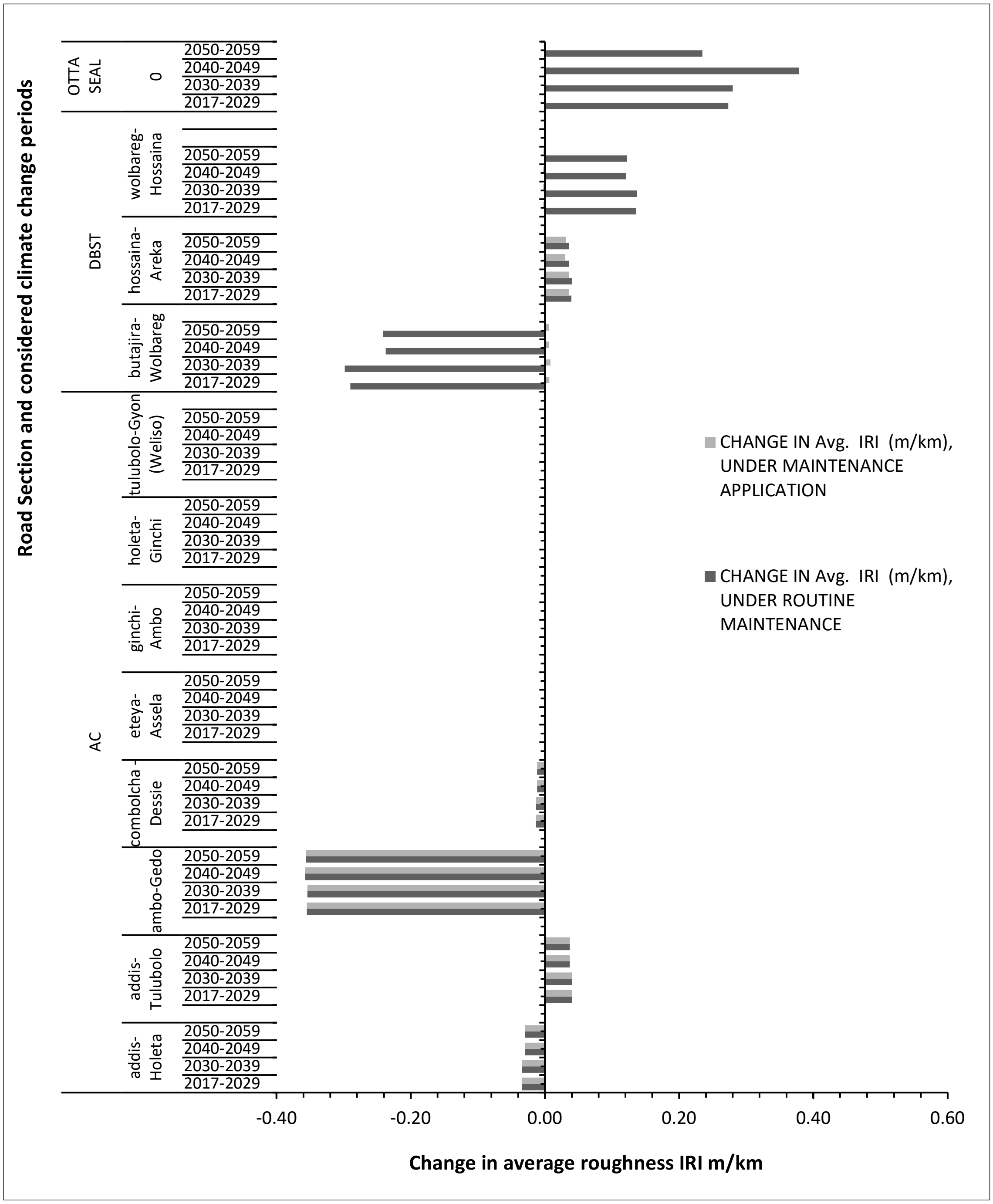


Figure 25 change in average roughness for pavements in a moist climate zone with high traffic

CLIMAT: MOIST TRAFFIC LEVEL: LT

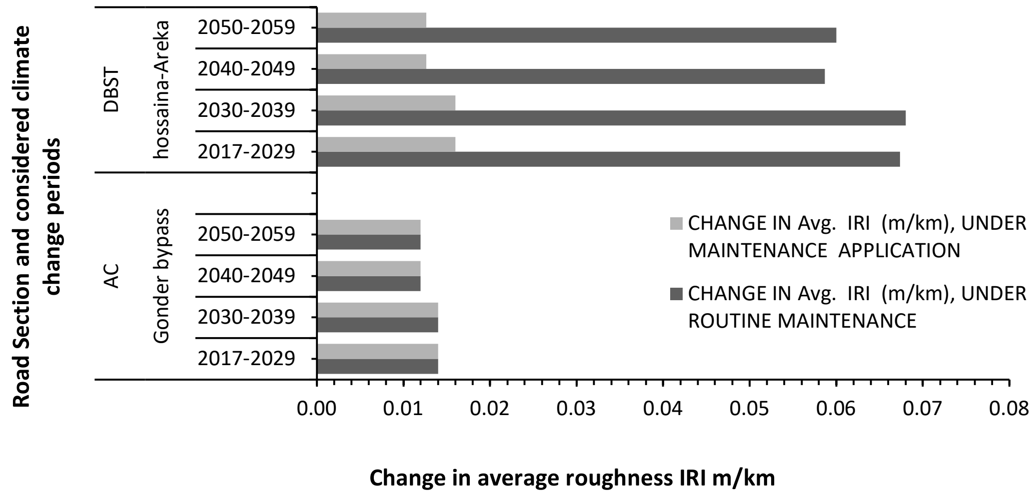


Figure 26 Change in average roughness for pavements in a most climate zone with low traffic

CLIMAT: MOIST TRAFFIC LEVEL: MT

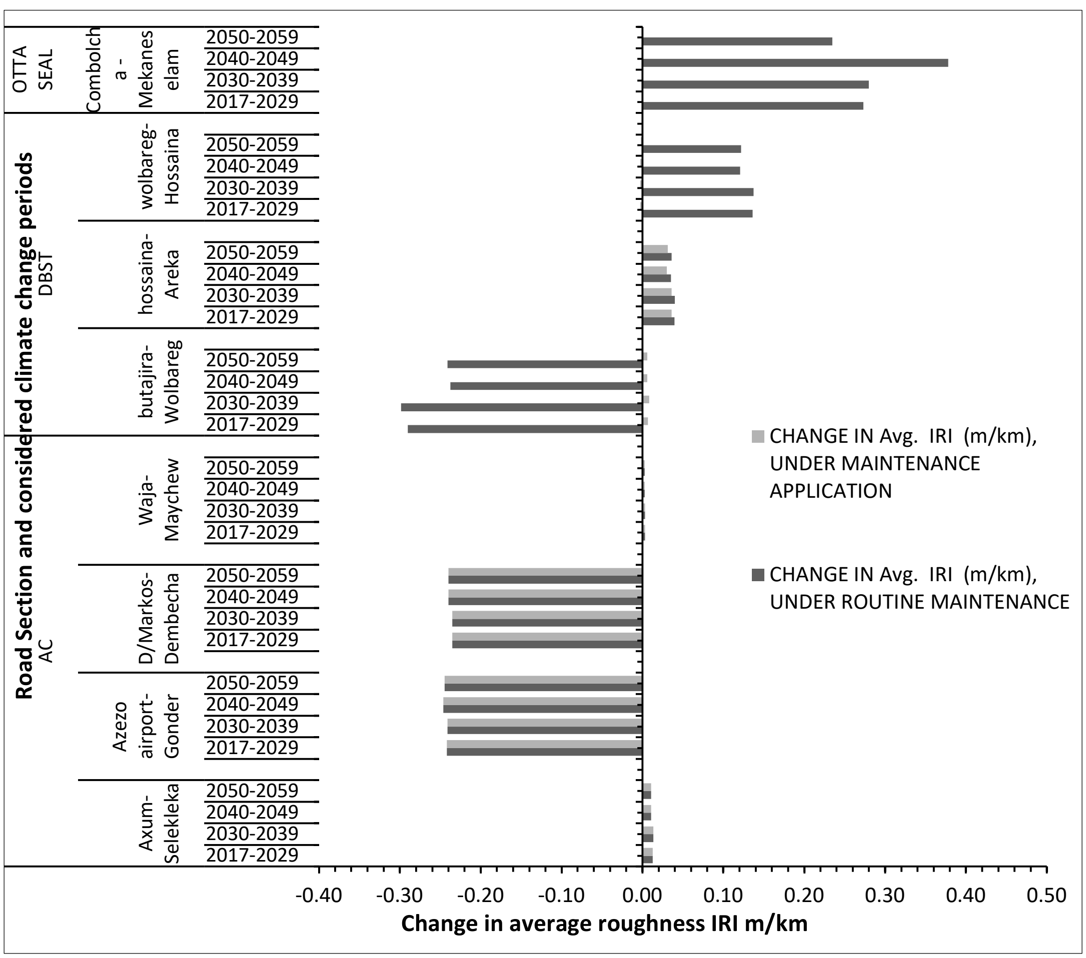


Figure 27 change in average roughness for pavements in a moist climate zone with medium traffic

For Sub-Humid Climate Region

CLIMAT: SUB- HUMID TRAFFIC LEVEL: HT

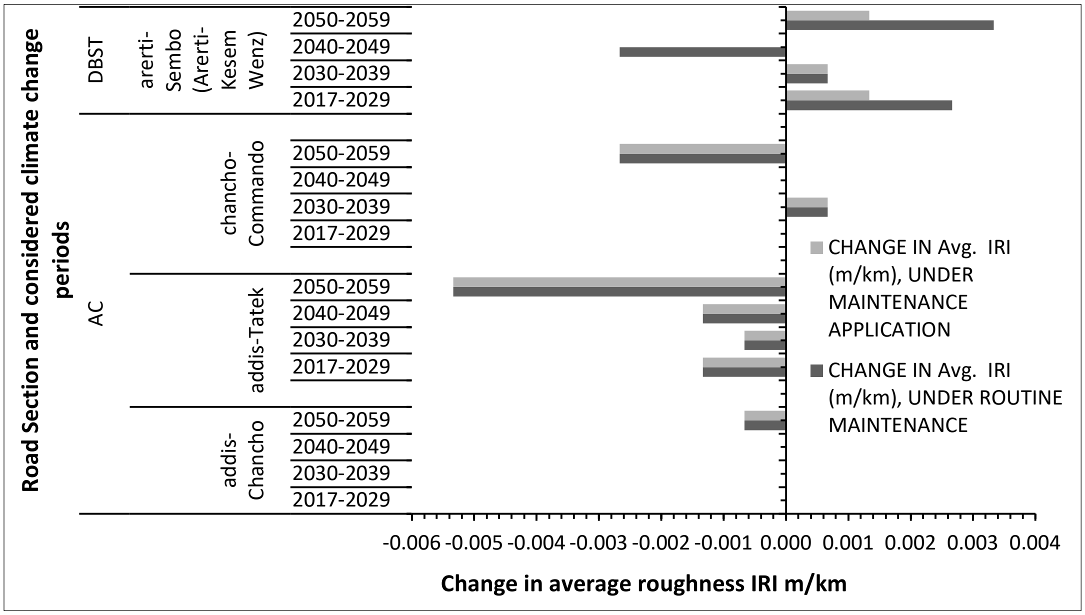


Figure 28 change in average roughness for pavements in a sub-humid climate zone with high traffic

CLIMAT: SUB- HUMID TRAFFIC LEVEL: MT

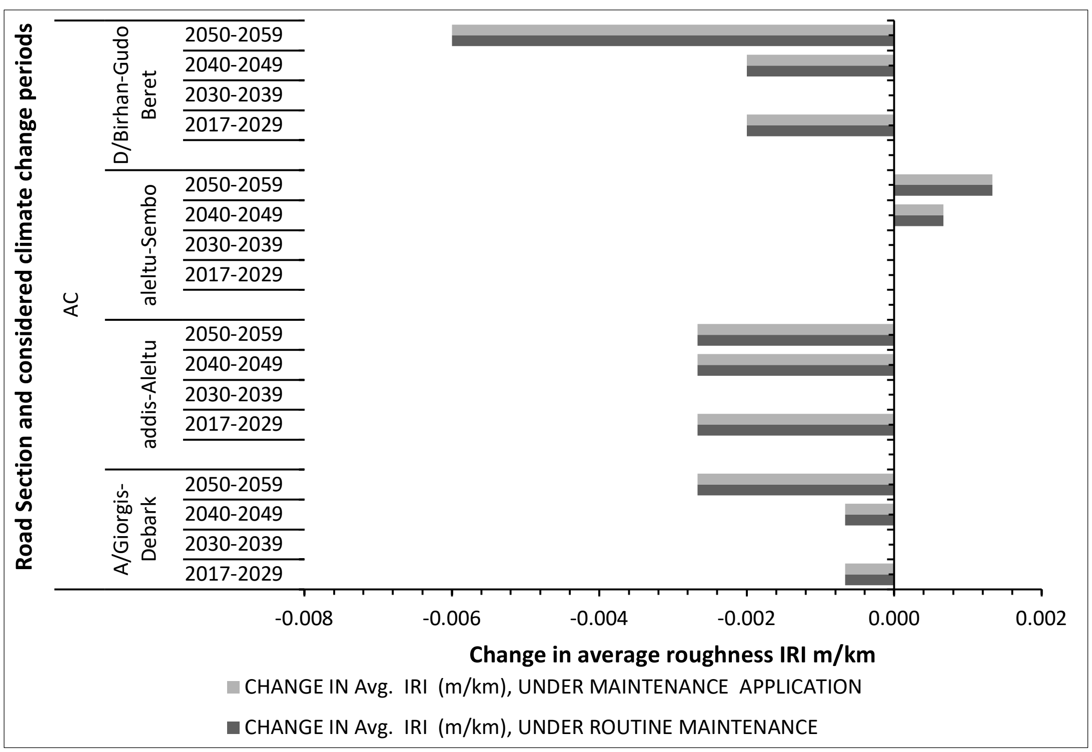


Figure 29 change in average roughness for pavements in a sub humid climate zone with medium traffic

2. Road agency cost

For Arid Climate Region

CLIMAT: ARID TRAFFIC LEVEL: HT

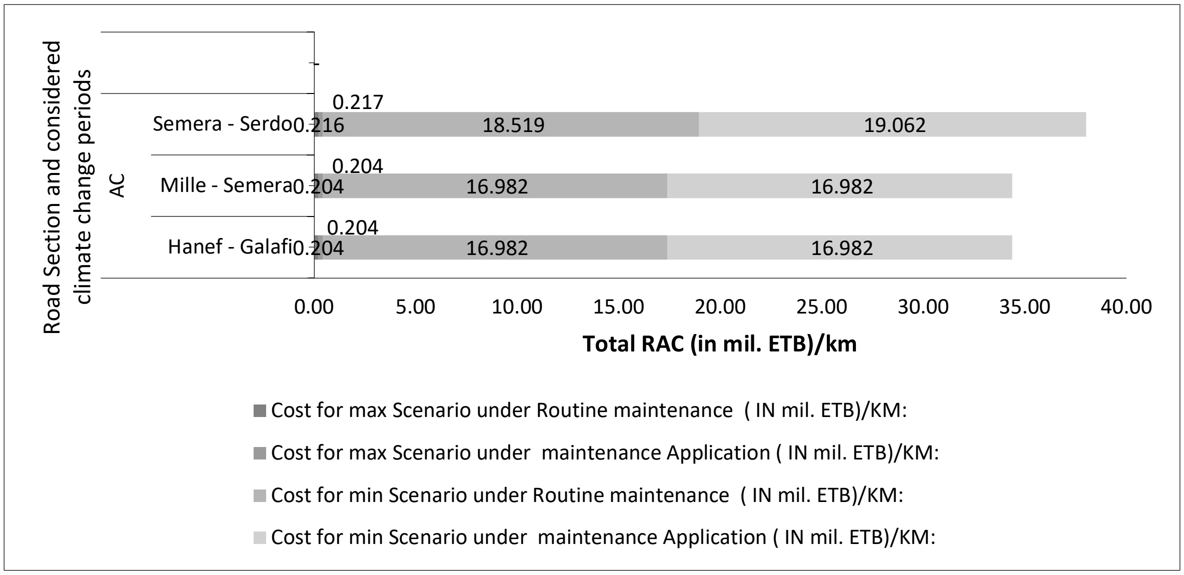


Figure 2.1 additional cost incurred in RAC

CLIMAT: ARID TRAFFIC LEVEL: LT

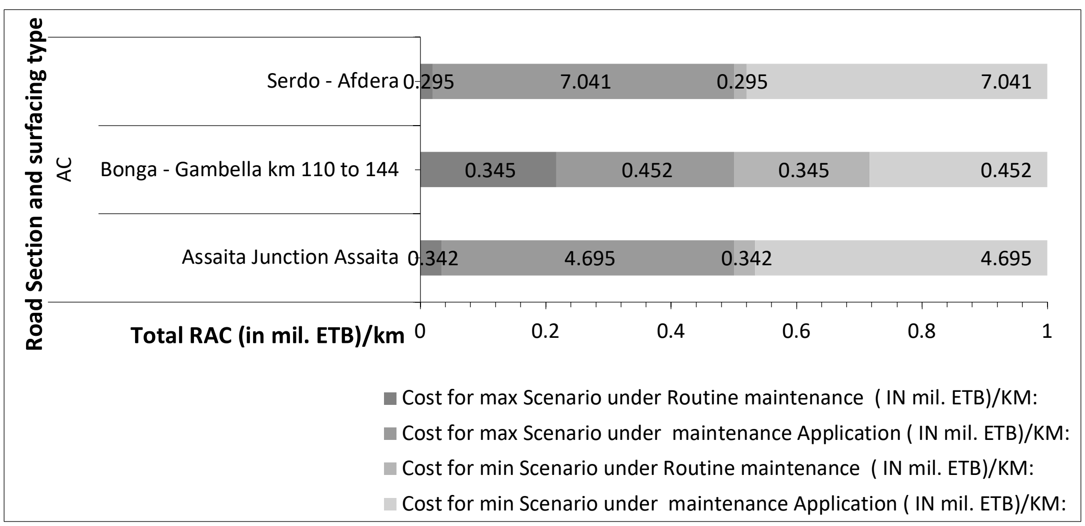


Figure 2.2 additional cost incurred in RAC

CLIMATE: ARID TRAFFIC LEVEL: MT

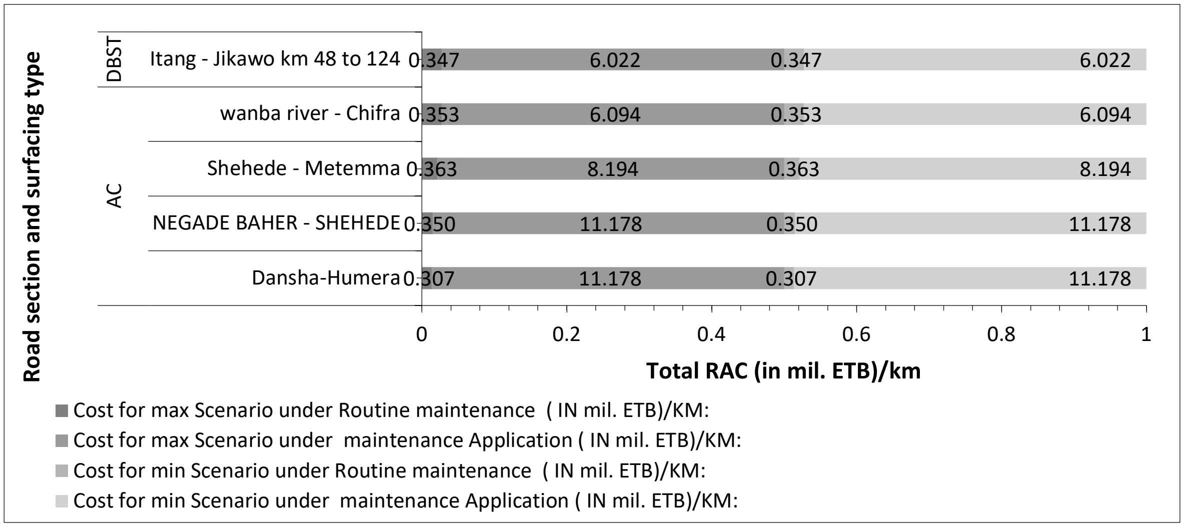


Figure 2.3 additional cost incurred in RAC

For Semi-Arid Climate Region

CLIMAT: SEMI-ARID TRAFFIC LEVEL: HT

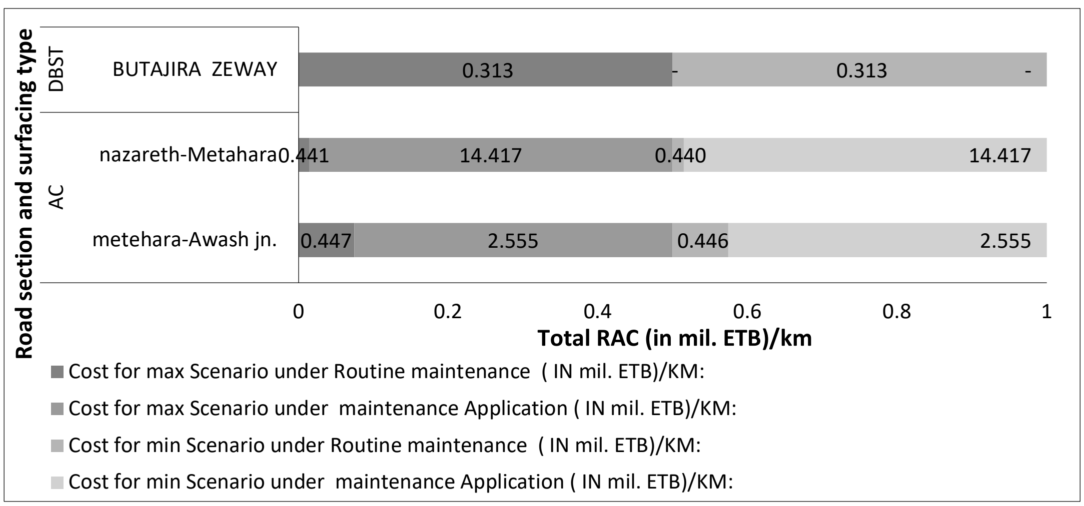


Figure 2.4 additional cost incurred in RAC

CLIMAT: SEMI-ARID TRAFFIC LEVEL: LT

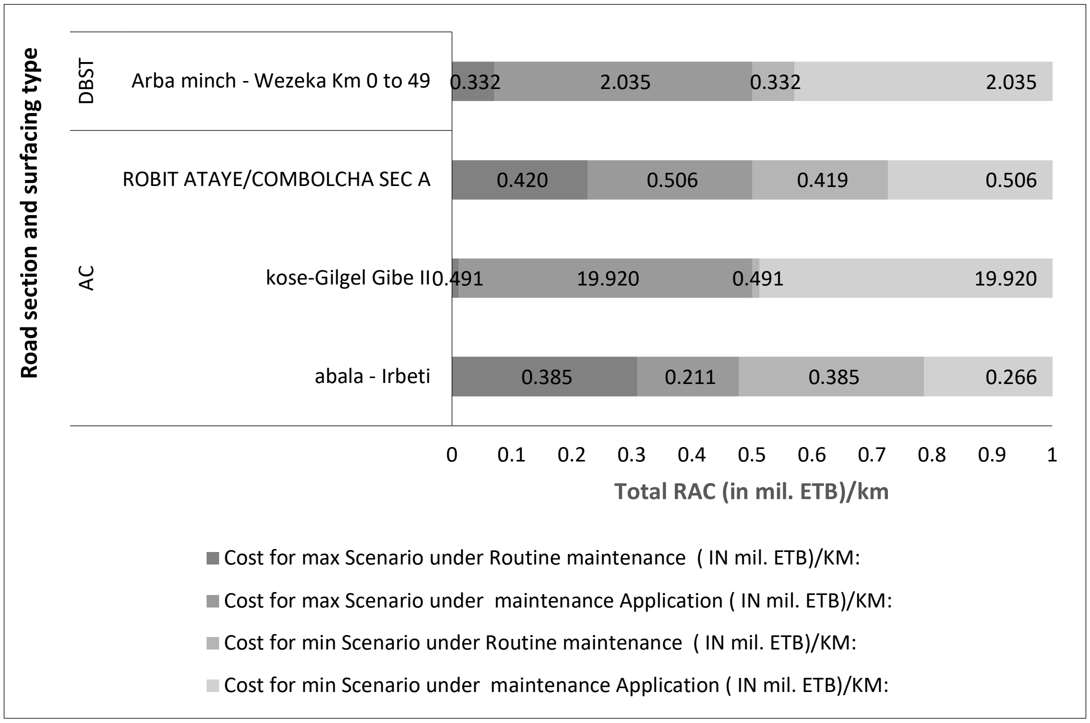


Figure 2.5 additional cost incurred in RAC

CLIMAT: SEMI-ARID TRAFFIC LEVEL: MT

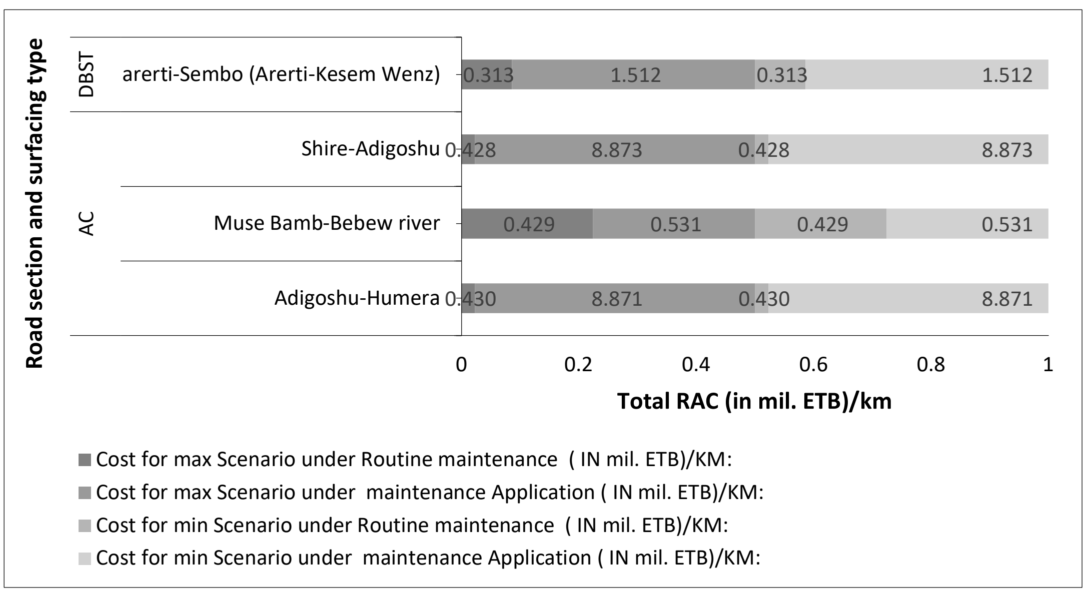


Figure 2.6 additional cost incurred in RAC

For Sub-Moist Climate Region

CLIMAT: SUB-MOIST TRAFFIC LEVEL: HT

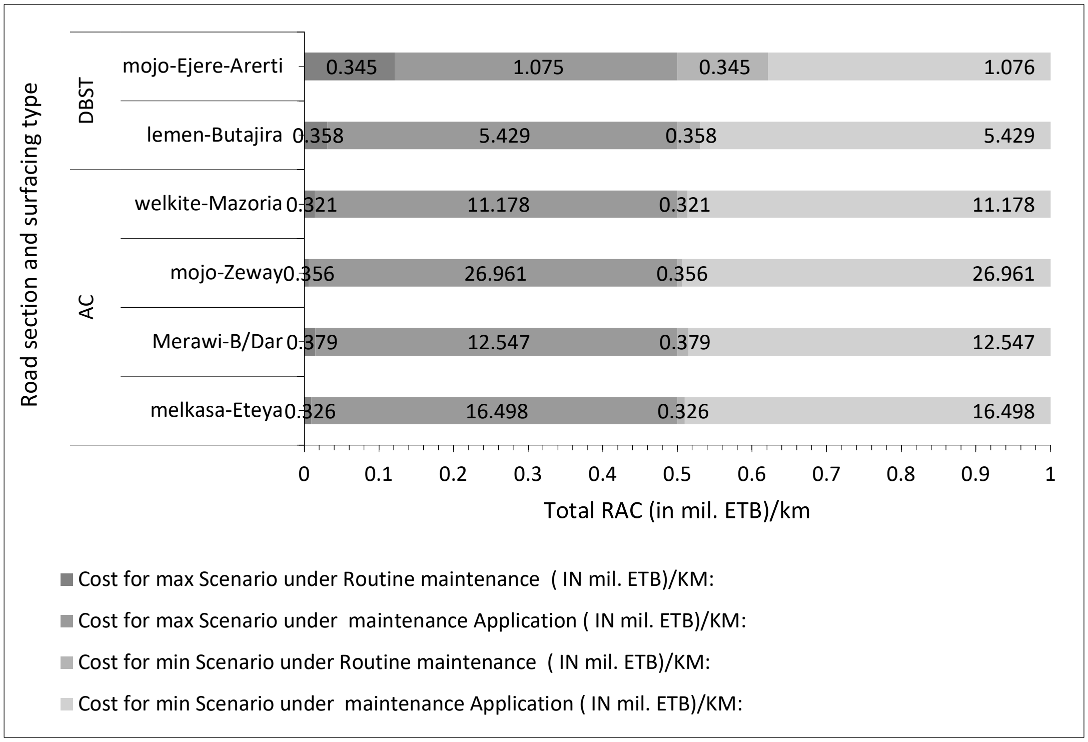


Figure 2.7 additional cost incurred in RAC

CLIMAT: SUB-MOIST TRAFFIC LEVEL: LT

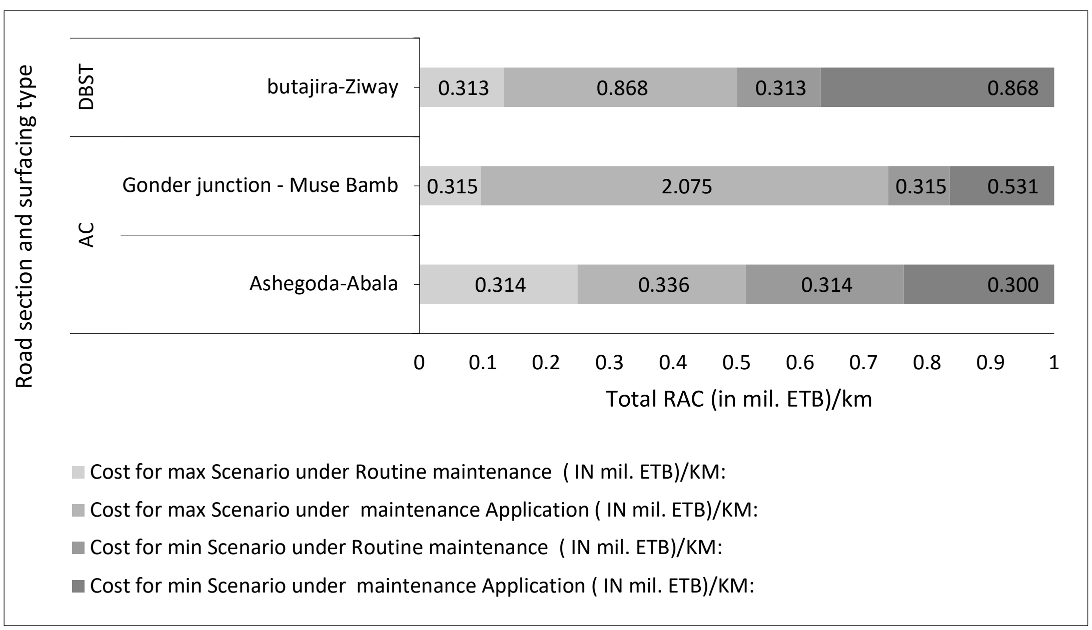


Figure 2.8 additional cost incurred in RAC

CLIMAT: SUB-MOIST TRAFFIC LEVEL: MT

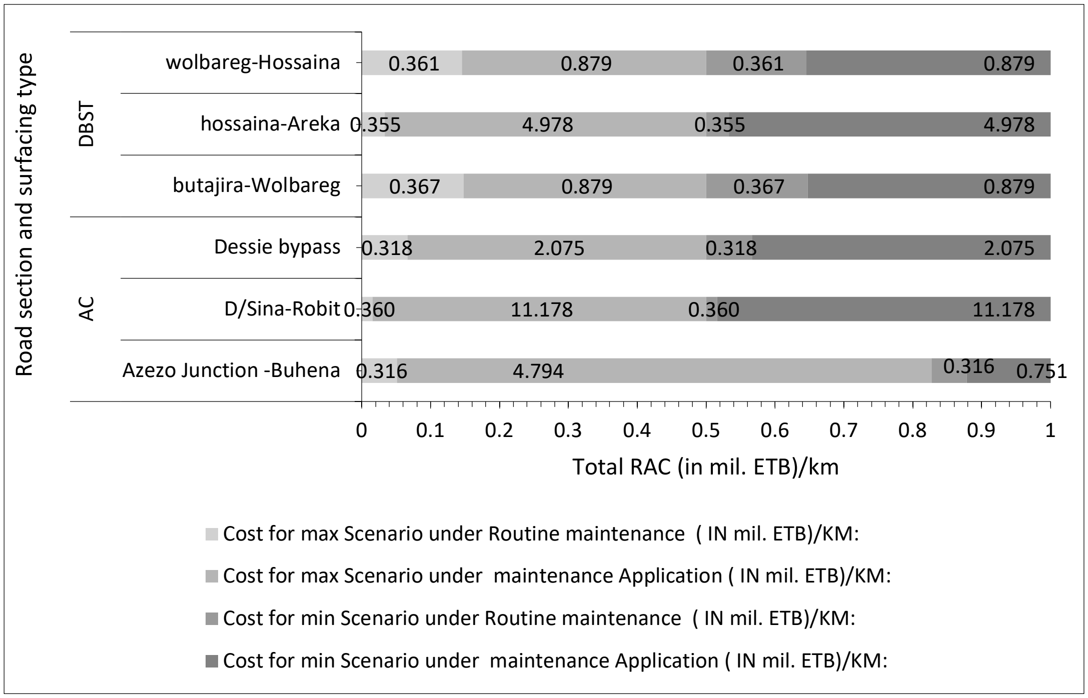


Figure 2.9 additional cost incurred in RAC

For Moist Climate Region

LIMAT: MOIST TRAFFIC LEVEL: HT

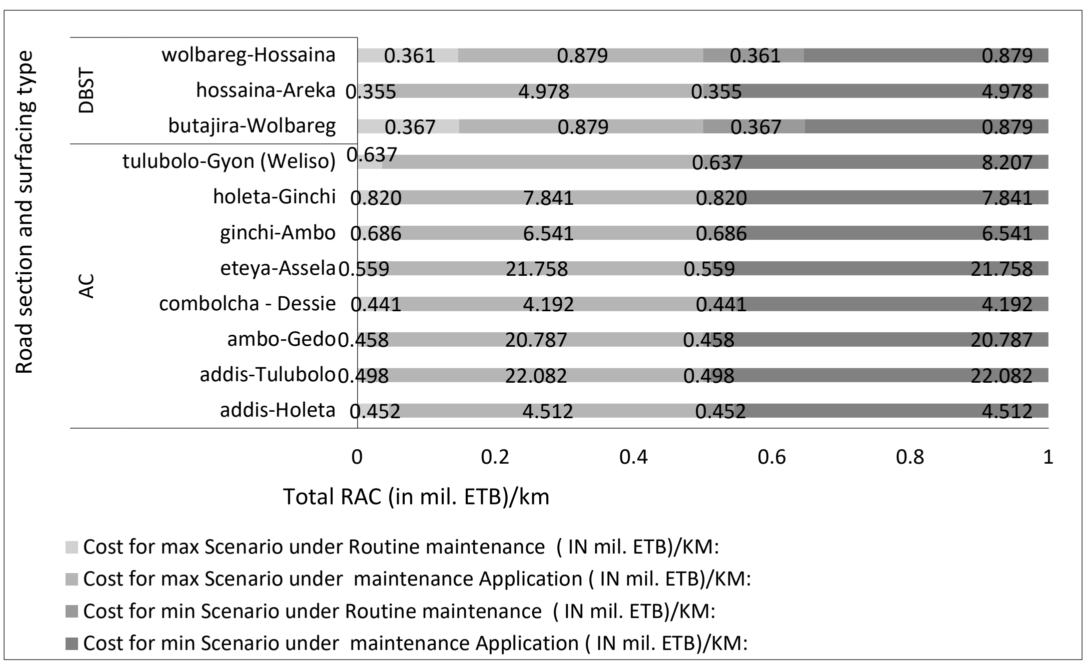


Figure 2.10 additional cost incurred in RAC

CLIMAT: MOIST TRAFFIC LEVEL: LT

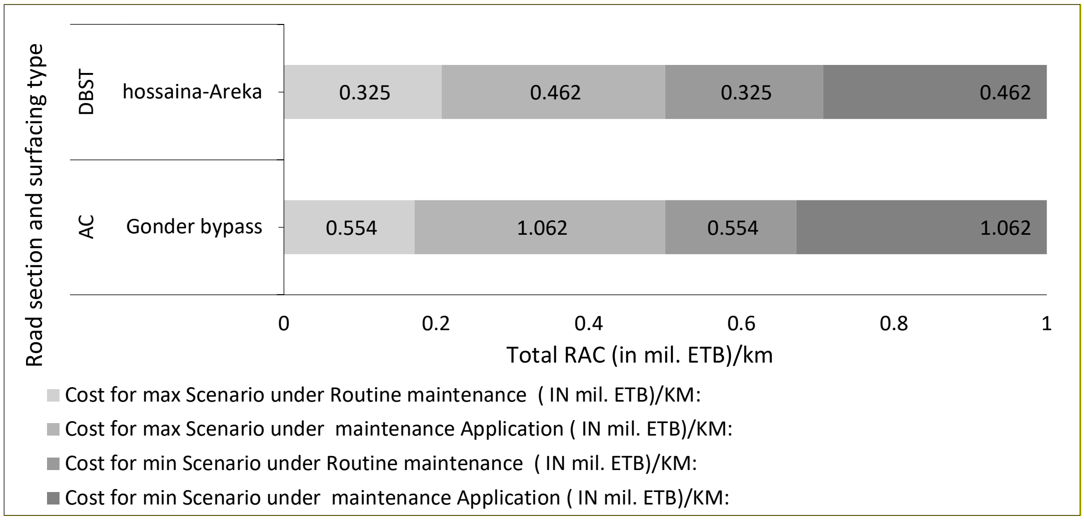


Figure 2.11 additional cost incurred in RAC

CLIMAT: MOIST TRAFFIC LEVEL: MT

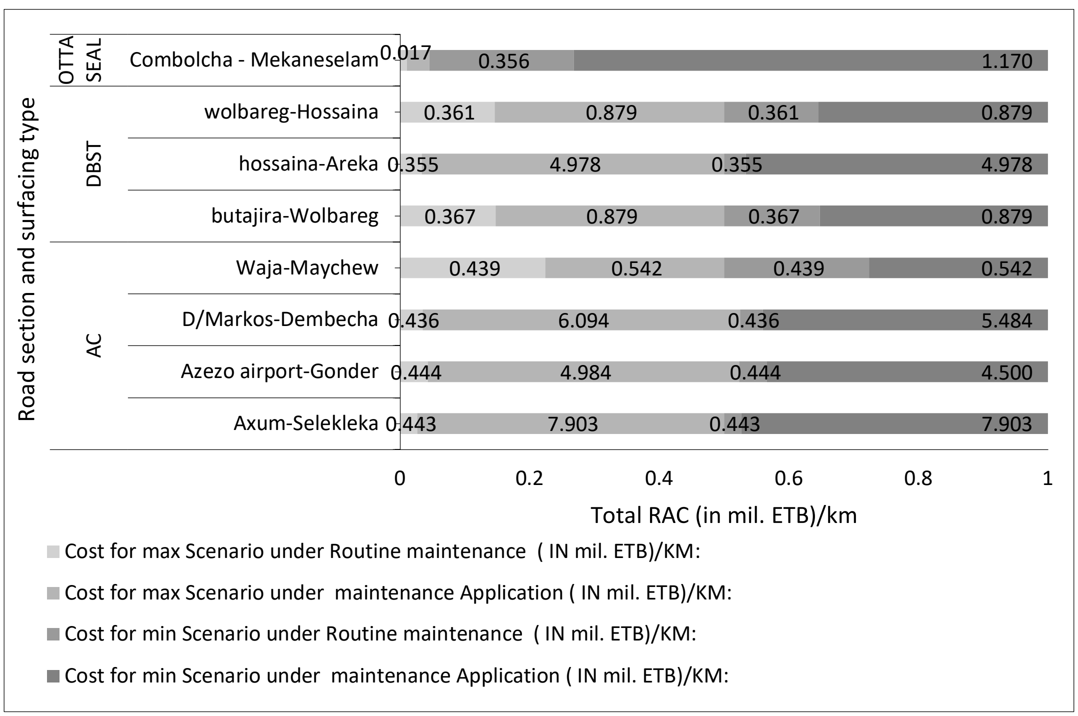


Figure 2.12 additional cost incurred in RAC

For Sub-Humid Climate Region

CLIMAT: SUB-HUMID TRAFFIC LEVEL: HT

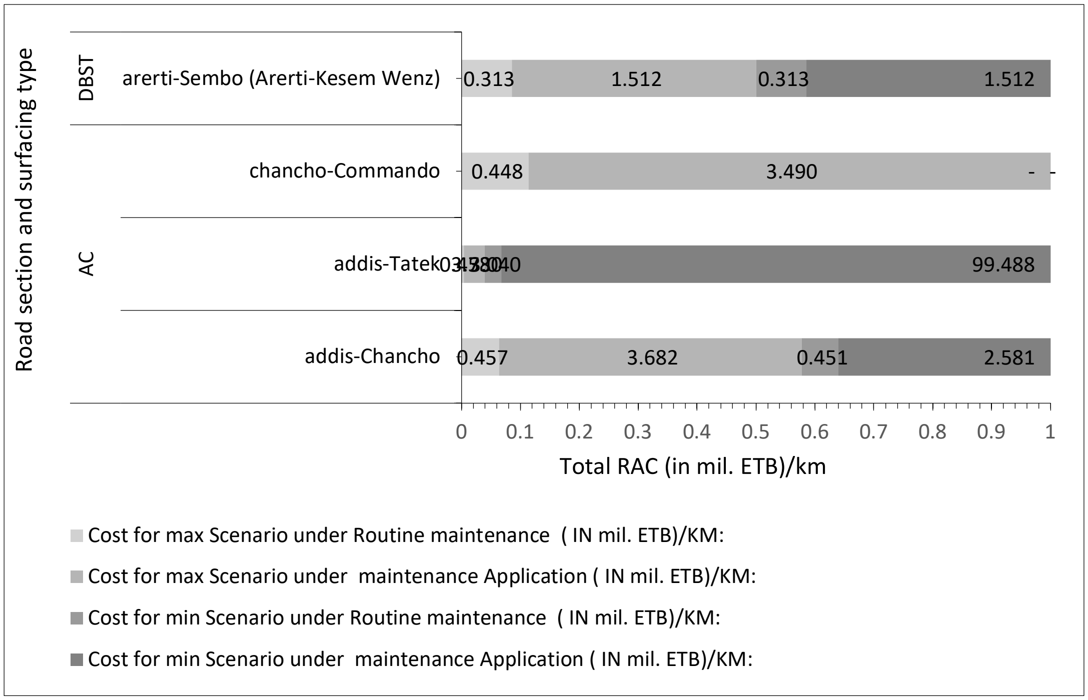


Figure 2.13 additional cost incurred in RAC

CLIMAT: SUB-HUMID TRAFFIC LEVEL: HT

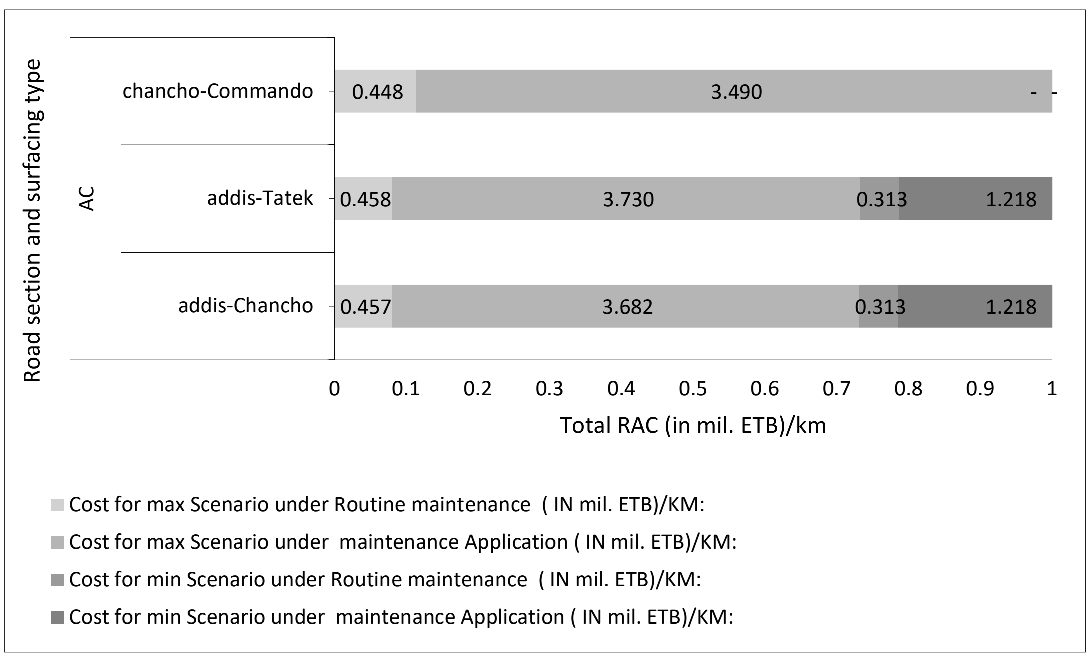


Figure 2.14 additional cost incurred in RAC

CLIMAT: SUB-HUMID TRAFFIC LEVEL: MT

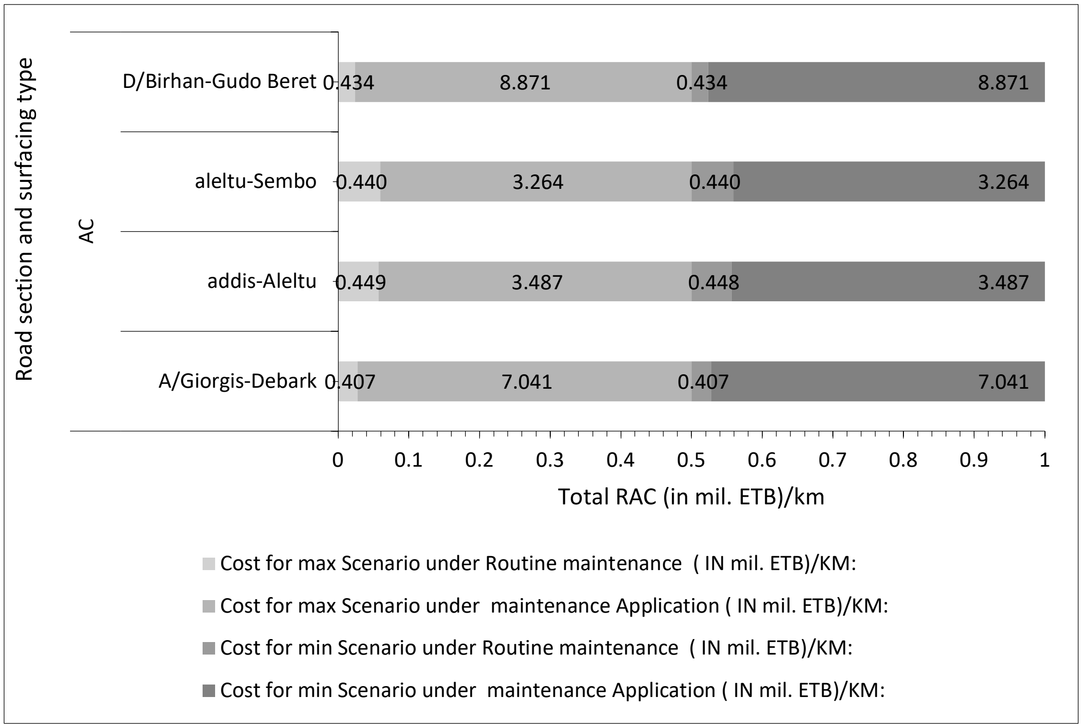


Figure 2.16 additional cost incurred in RAC

3. Road user cost

<u>ADDITIONAL DISCOUNTED COST IN RUC</u>

<u>For Arid Climate Region</u>

CLIMATE : ARID TRAFFIC LEVEL: HT

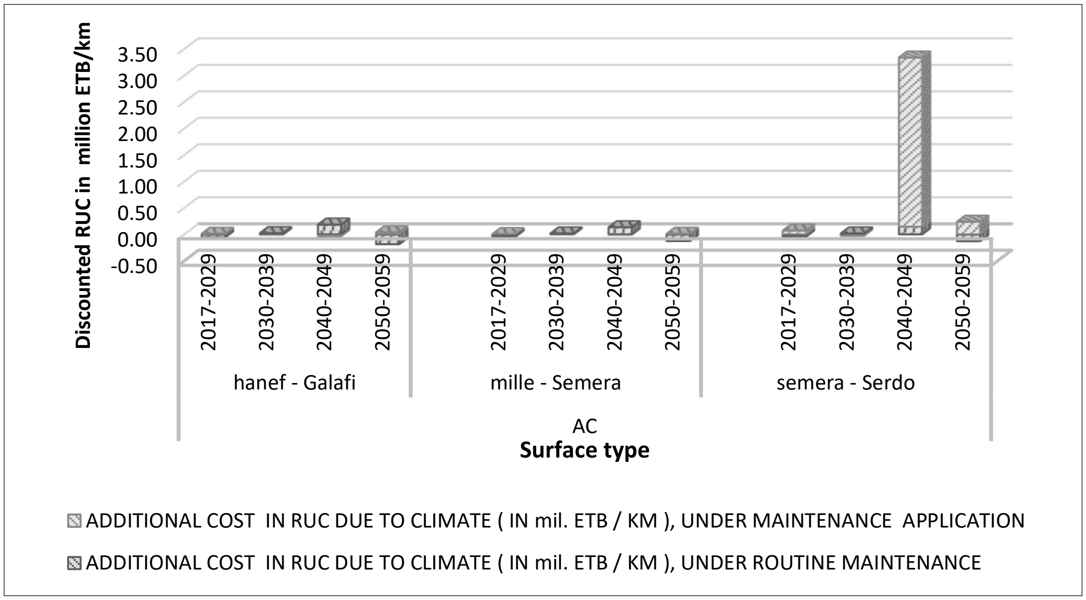


Figure 3.1 additional cost incurred in discounted RUC under max A2-emission senario

<u>ADDITIONAL DISCOUNTED COST IN RUC</u>

CLIMATE : ARID TRAFFIC LEVEL: LT

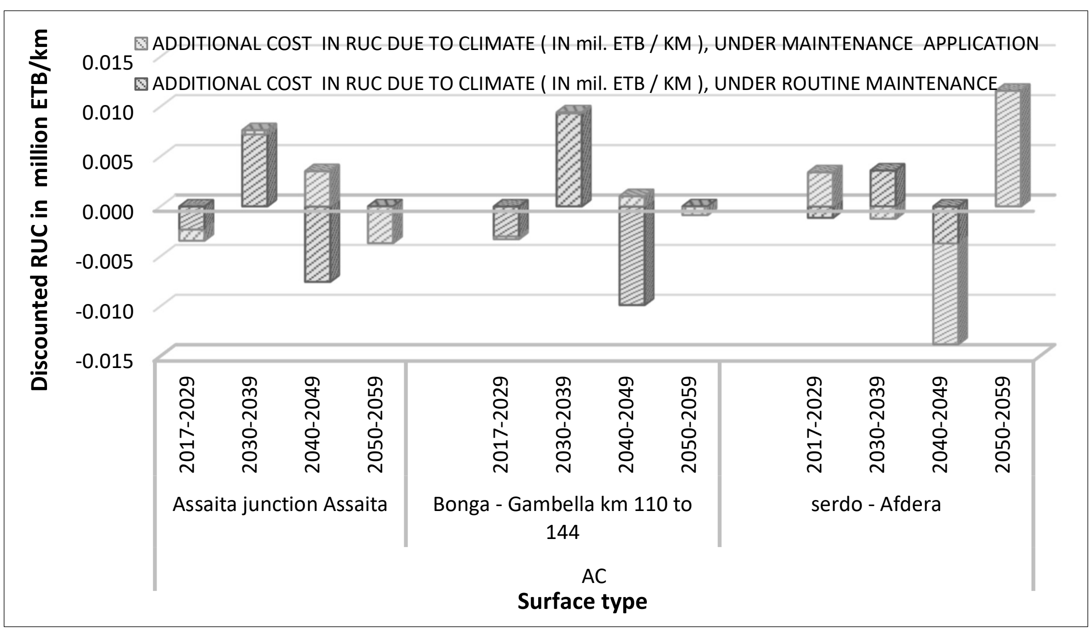


Figure 1.2 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

CLIMATE : ARID TRAFFIC LEVEL: MT

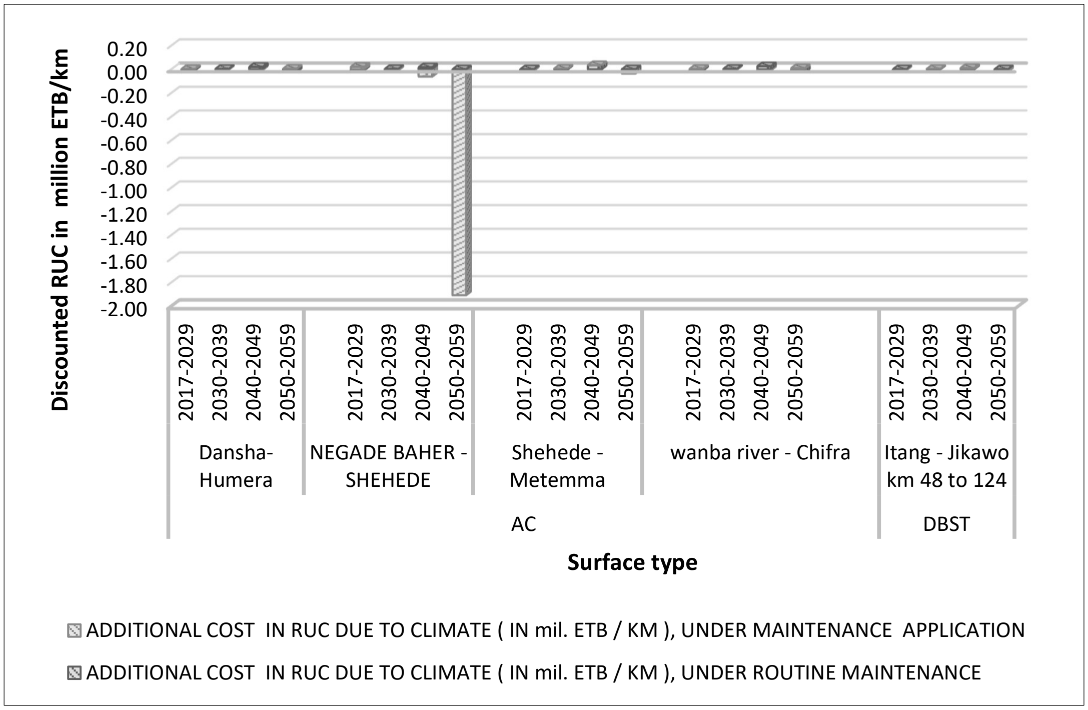


Figure 3.3 additional cost incured in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

For Semi-Arid Climate Region

CLIMATE : SEMI-ARID TRAFFIC LEVEL: HT

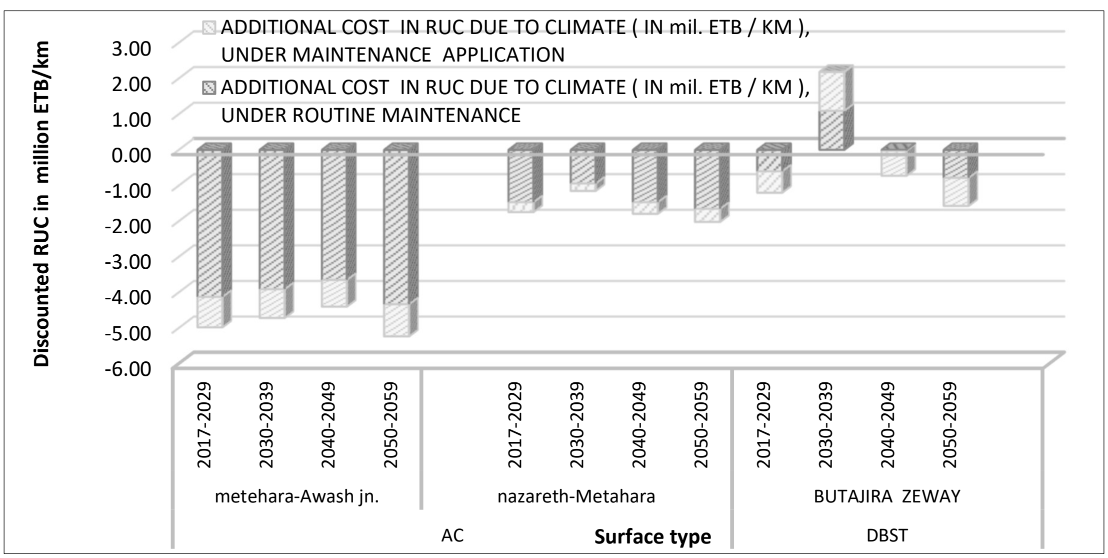


Figure 3.4 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

CLIMATE : SEMI-ARID TRAFFIC LEVEL: LT

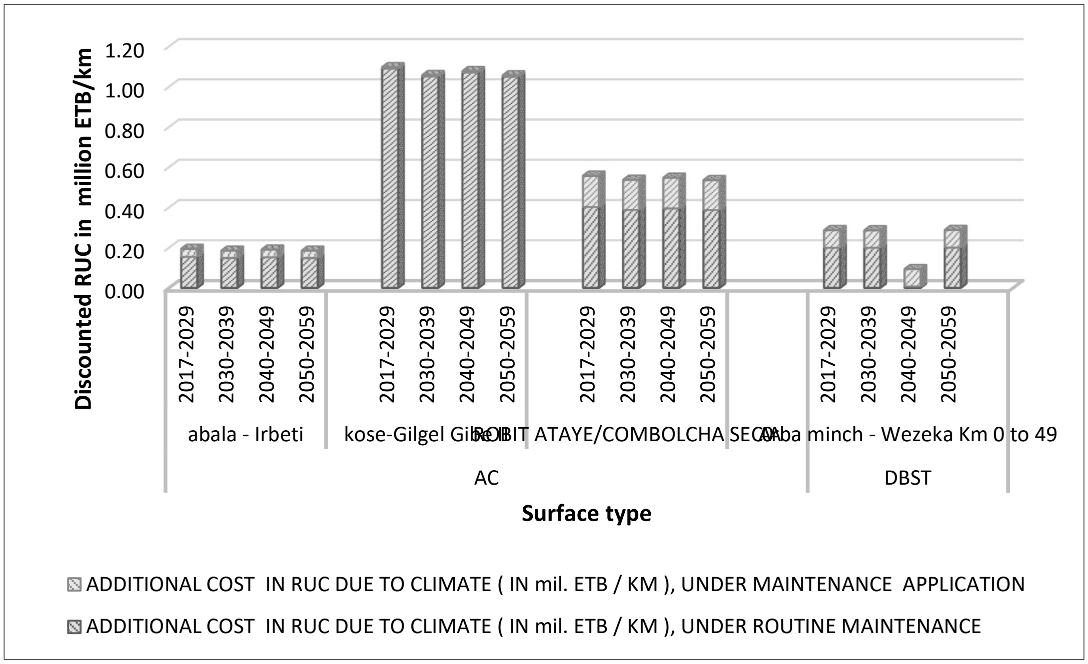


Figure 3.5 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

CLIMATE : SEMI-ARID TRAFFIC LEVEL: MT

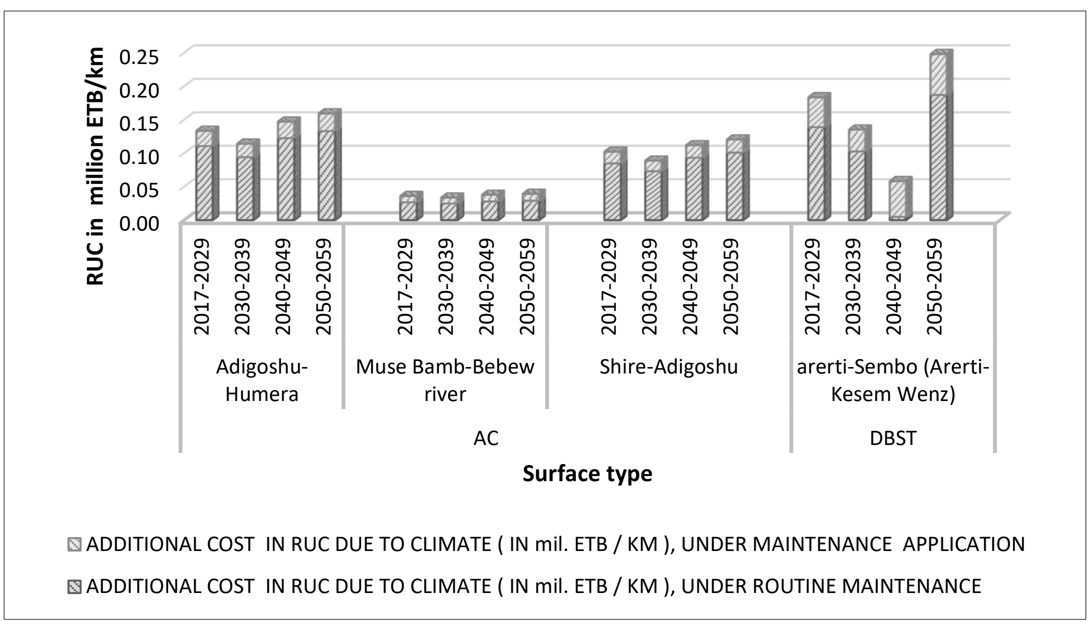


Figure3.6 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

For Sub-Moist Climate Region

CLIMATE : SUB-MOIST TRAFFIC LEVEL: HT

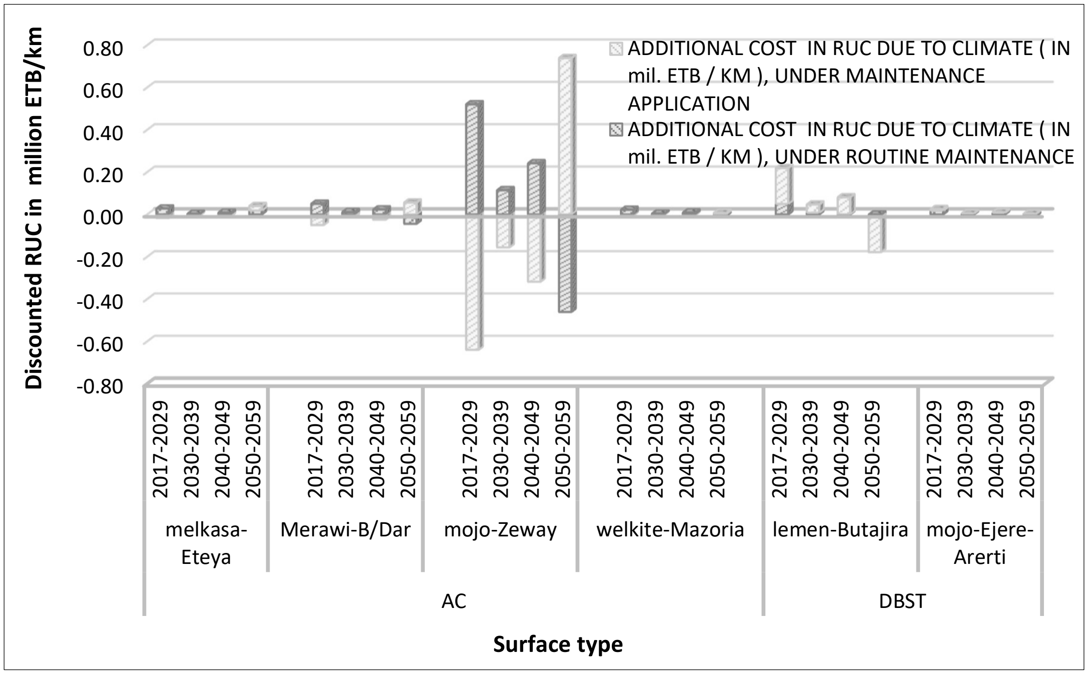


Figure3.7 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

CLIMATE : SUB-MOIST TRAFFIC LEVEL: LT

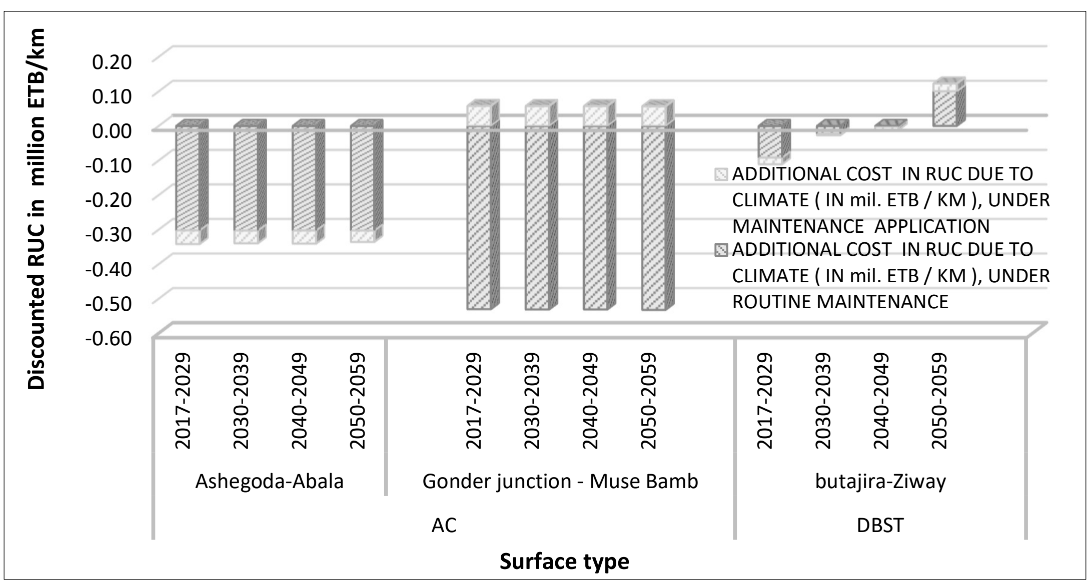


Figure 3.8 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

CLIMATE : SUB-MOIST TRAFFIC LEVEL: MT

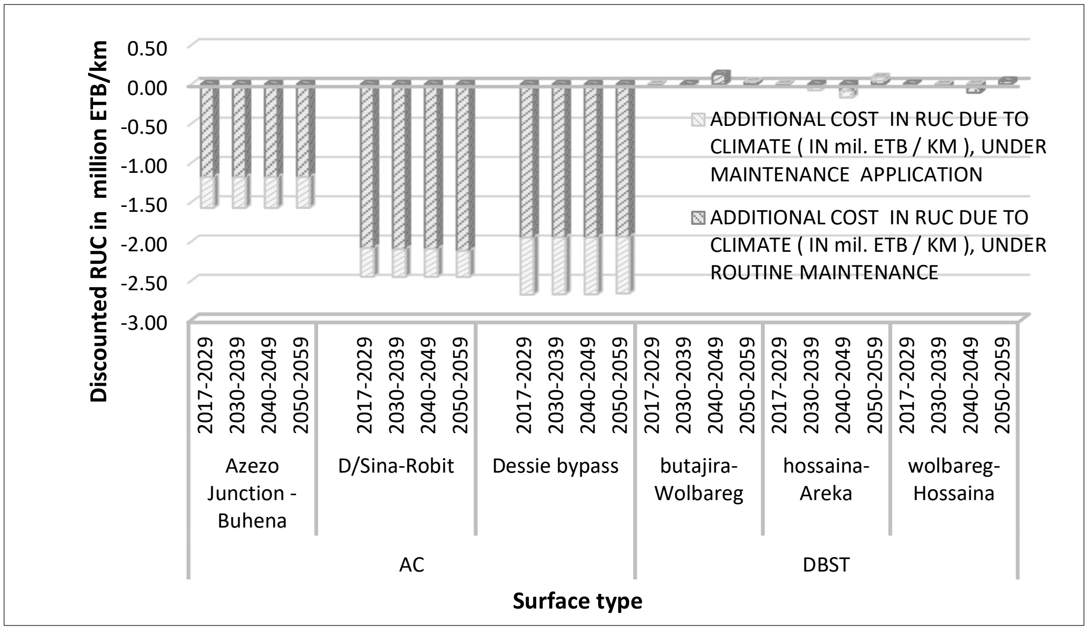


Figure 3.9 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

For Moist Climate Region

CLIMATE : MOIST TRAFFIC LEVEL: HT

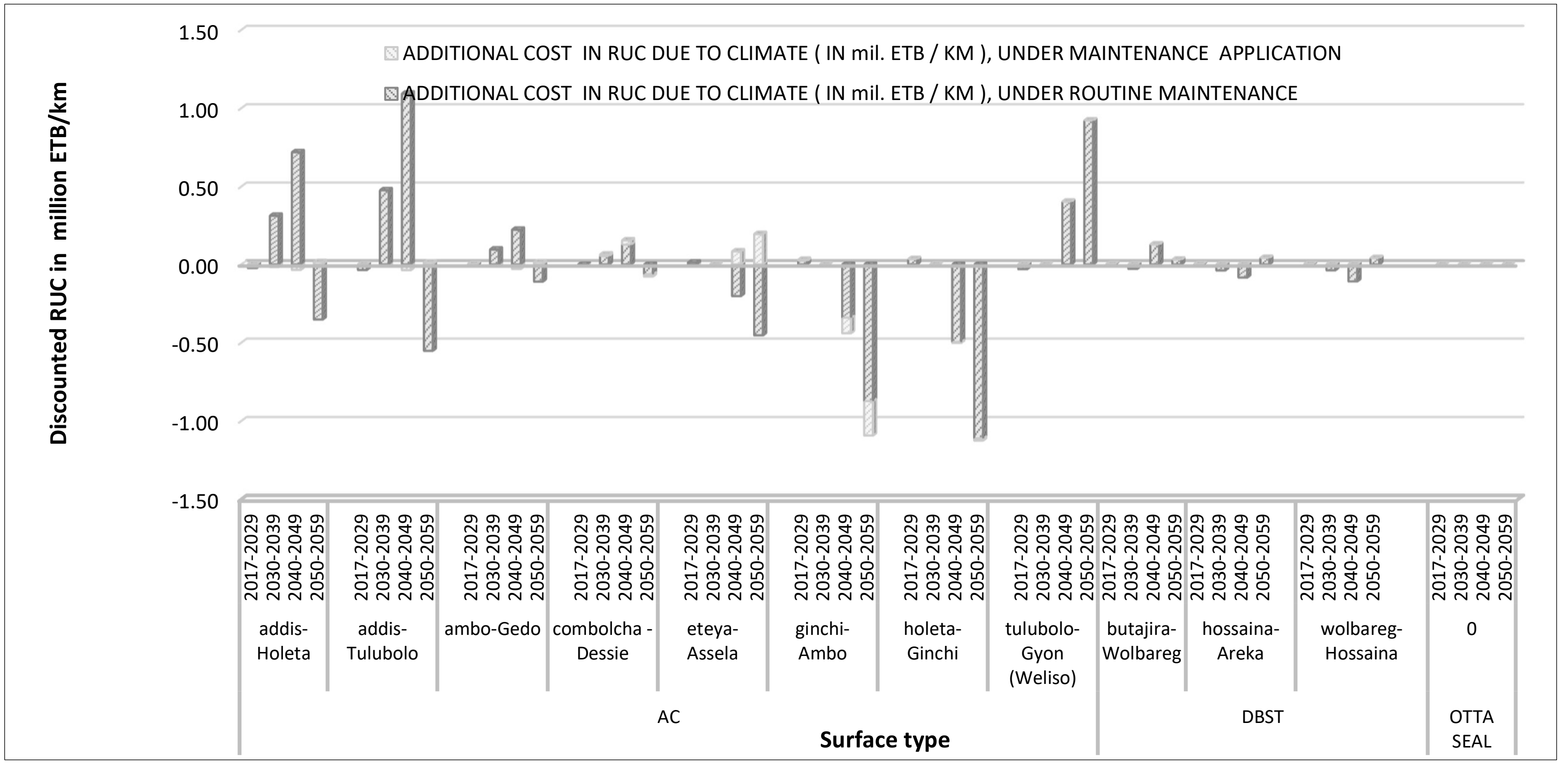


Figure 3.10 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

CLIMATE : MOIST TRAFFIC LEVEL: LT

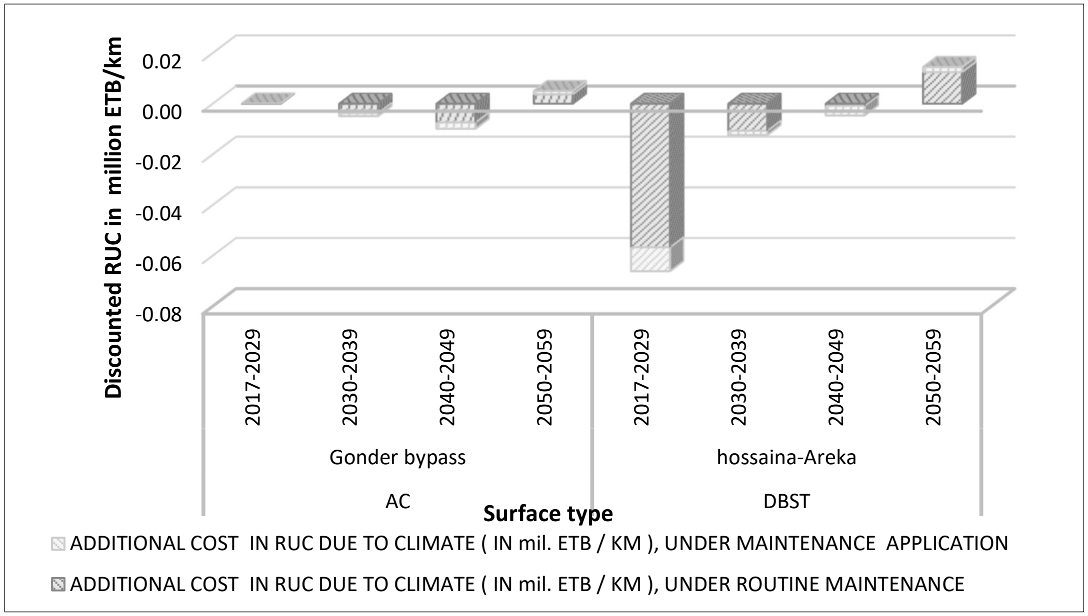


Figure 11 additional cost incurred in discounted RUC under max A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC

CLIMATE : MOIST TRAFFIC LEVEL: MT

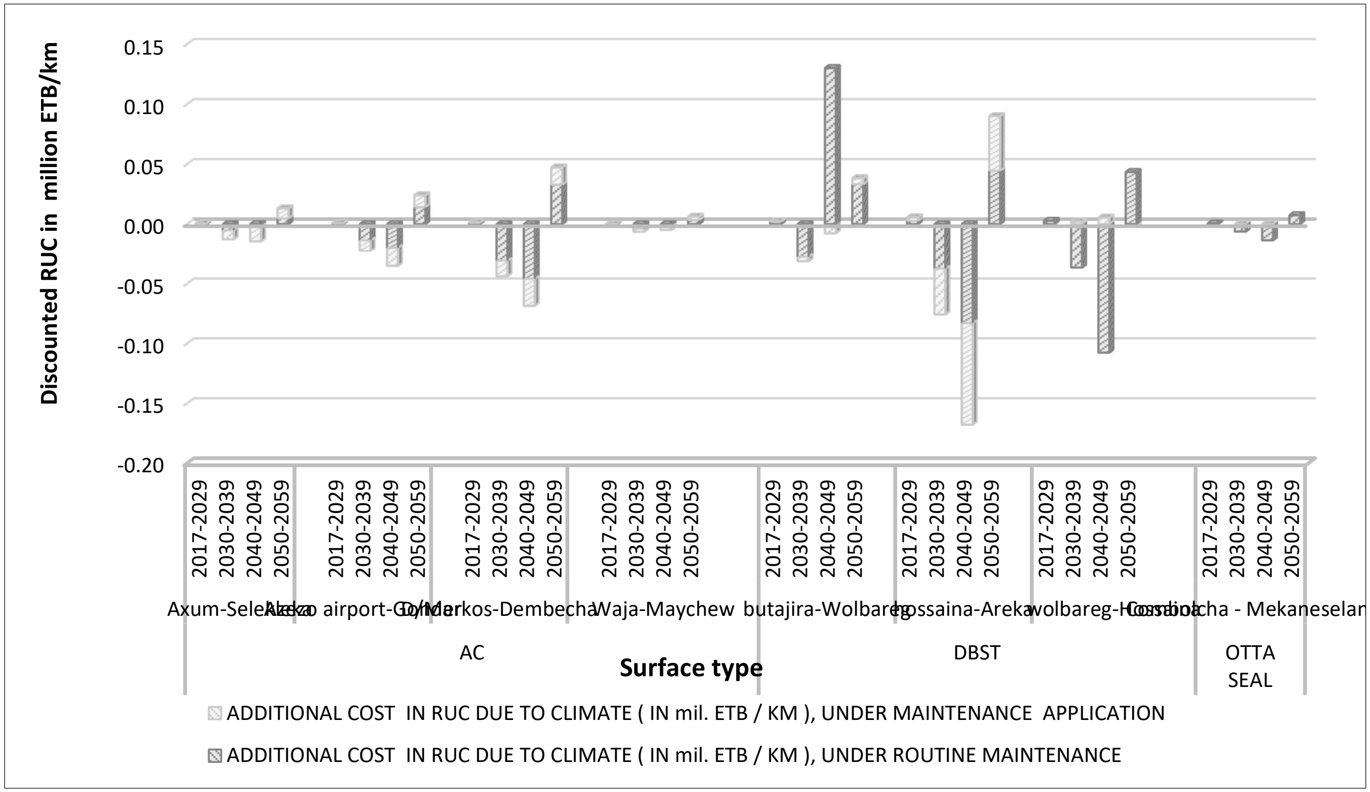


Figure 3.12 additional cost incurred in discounted RUC under max A2-emission senario

<u>ADDITIONAL DISCOUNTED COST IN RUC</u>

<u>For Sub-Humid Climate Region</u>

CLIMATE : SUB-HUMID TRAFFIC LEVEL: HT

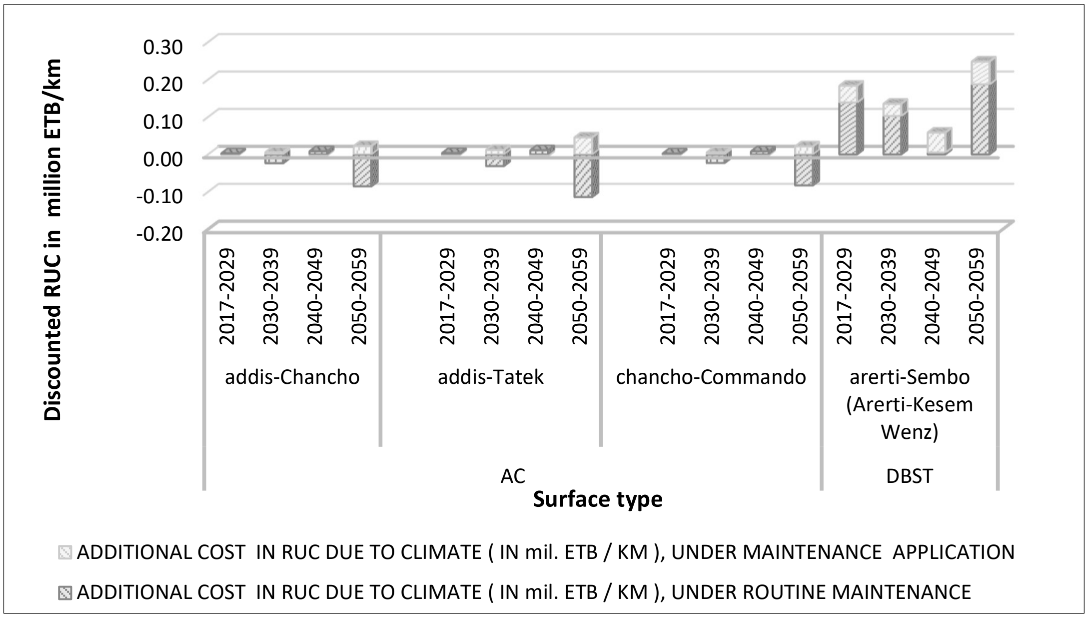


Figure 3.13 additional cost incurred in discounted RUC under max A2-emission senario

<u>ADDITIONAL DISCOUNTED COST IN RUC</u>

CLIMATE : SUB-HUMID TRAFFIC LEVEL: LT

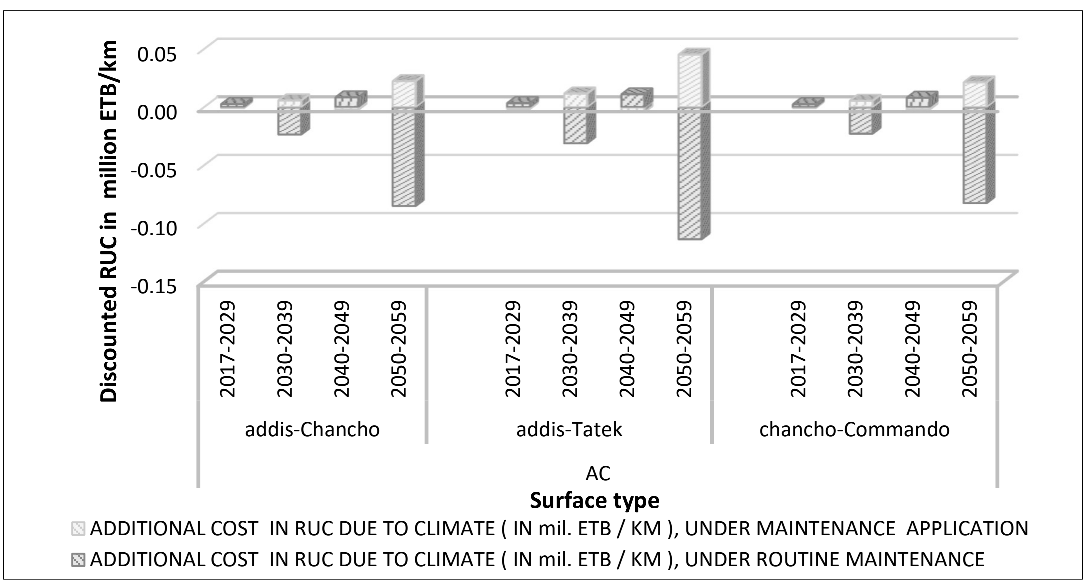


Figure 3.14 additional cost incurred in discounted RUC under max A2-emission senario

<u>ADDITIONAL DISCOUNTED COST IN RUC</u>

CLIMATE : SUB-HUMID TRAFFIC LEVEL: MT

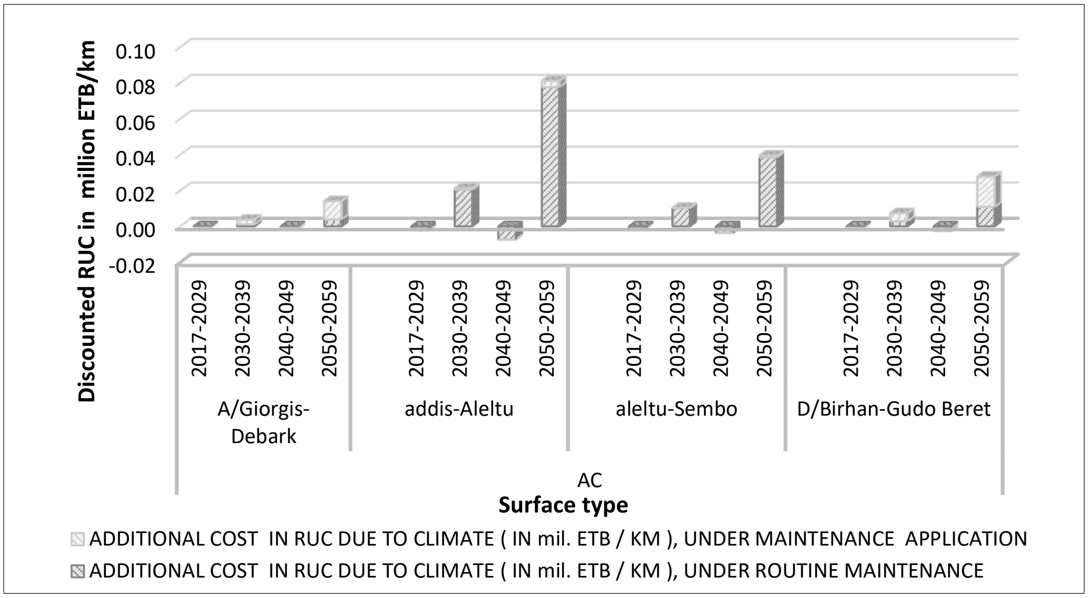


Figure 3.15 additional cost incurred in discounted RUC under max A2-emission senario

<u>ADDITIONAL DISCOUNTED COST IN RUC (MIN)</u>

<u>For Arid Climate Region</u>

CLIMATE : ARID TRAFFIC LEVEL: HT

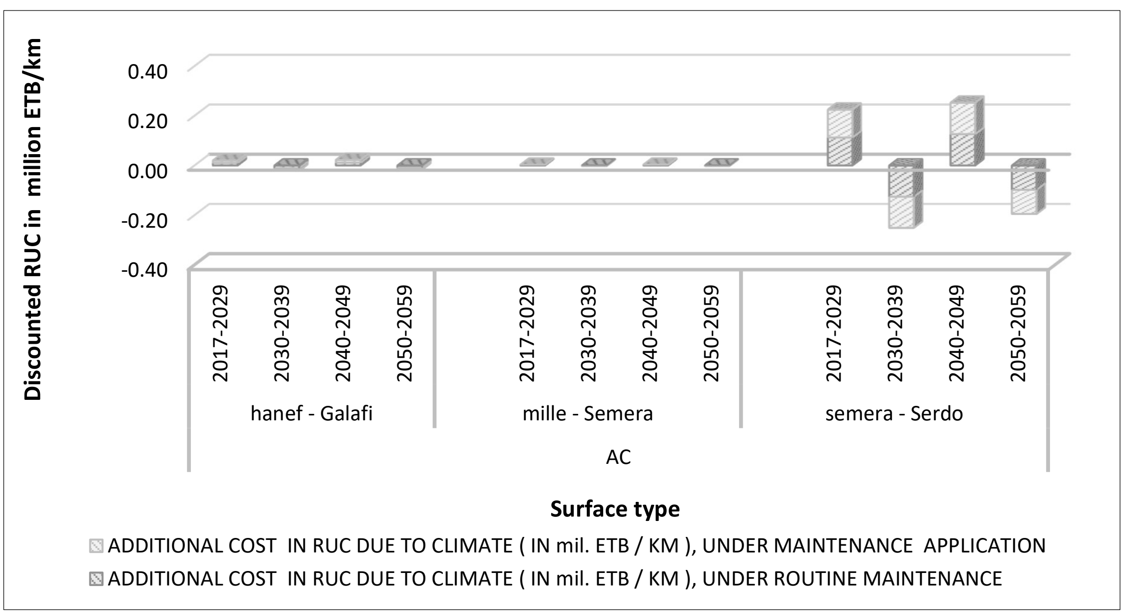


Figure 3.16 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

CLIMATE : ARID TRAFFIC LEVEL: LT

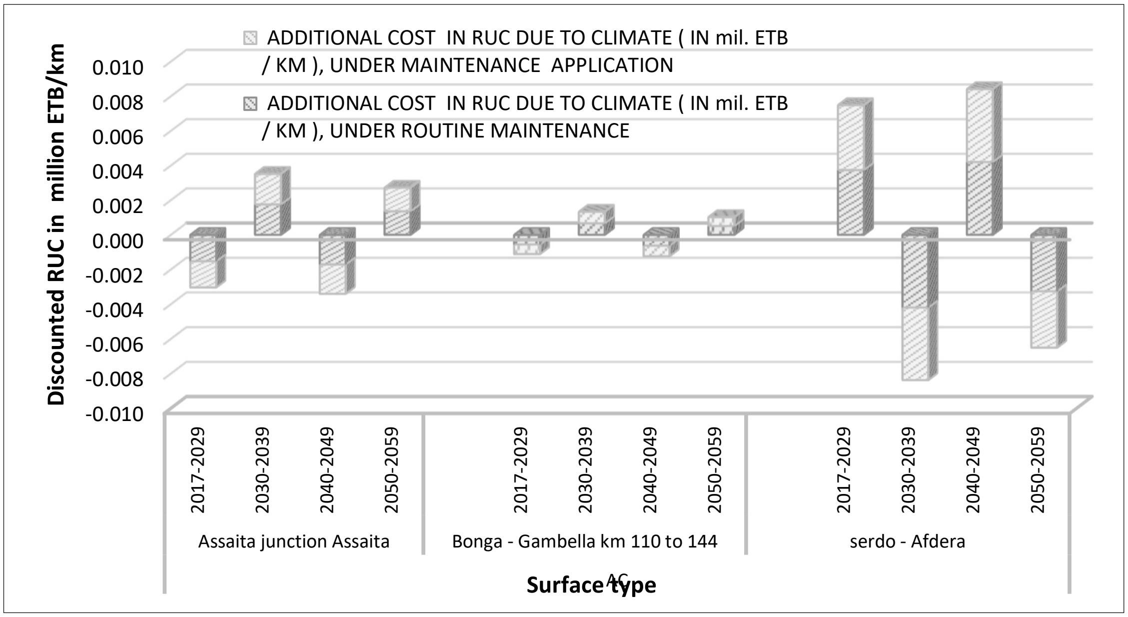


Figure 3.17 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

CLIMATE : ARID TRAFFIC LEVEL: MT

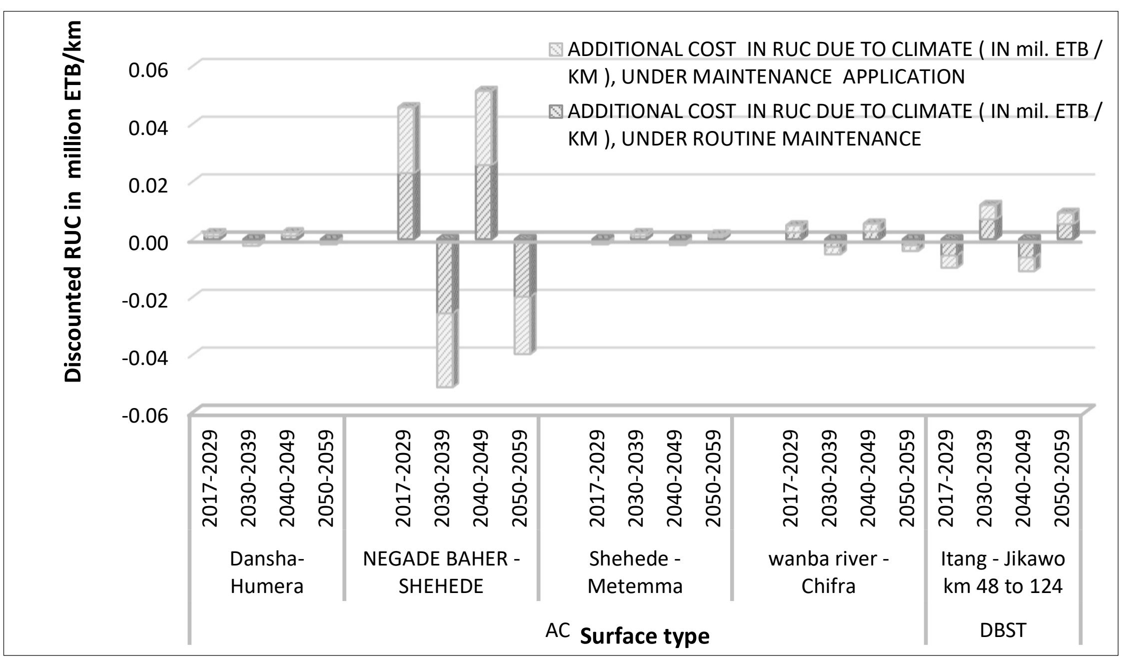


Figure 3.18 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

For Semi-Arid Climate Region

CLIMATE : Semi- ARID TRAFFIC LEVEL: HT

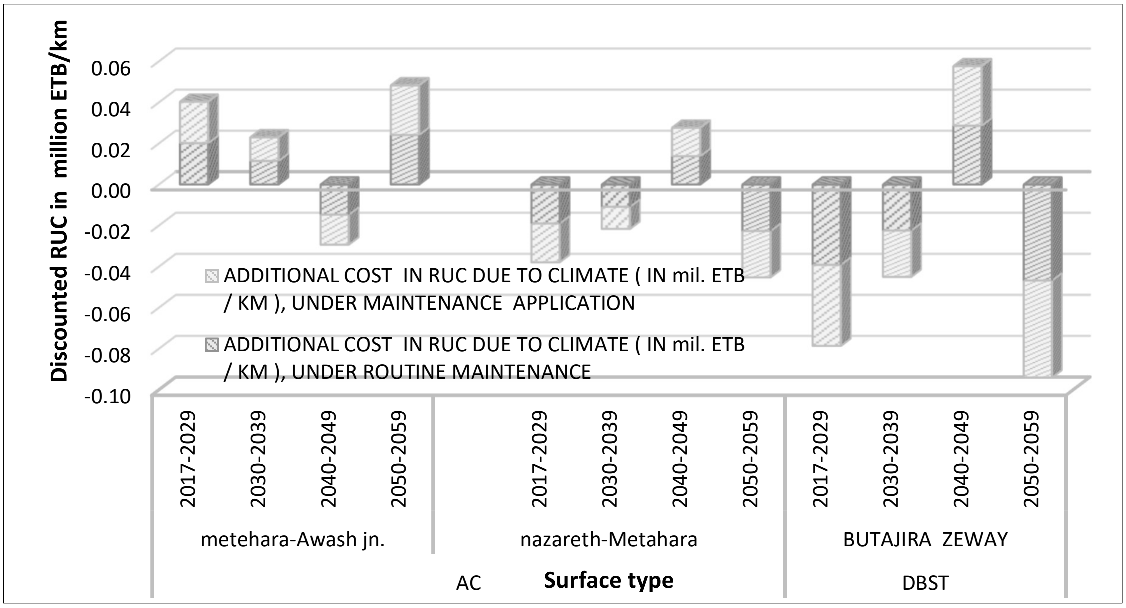


Figure 3.19 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

CLIMATE : Semi- ARID TRAFFIC LEVEL: LT

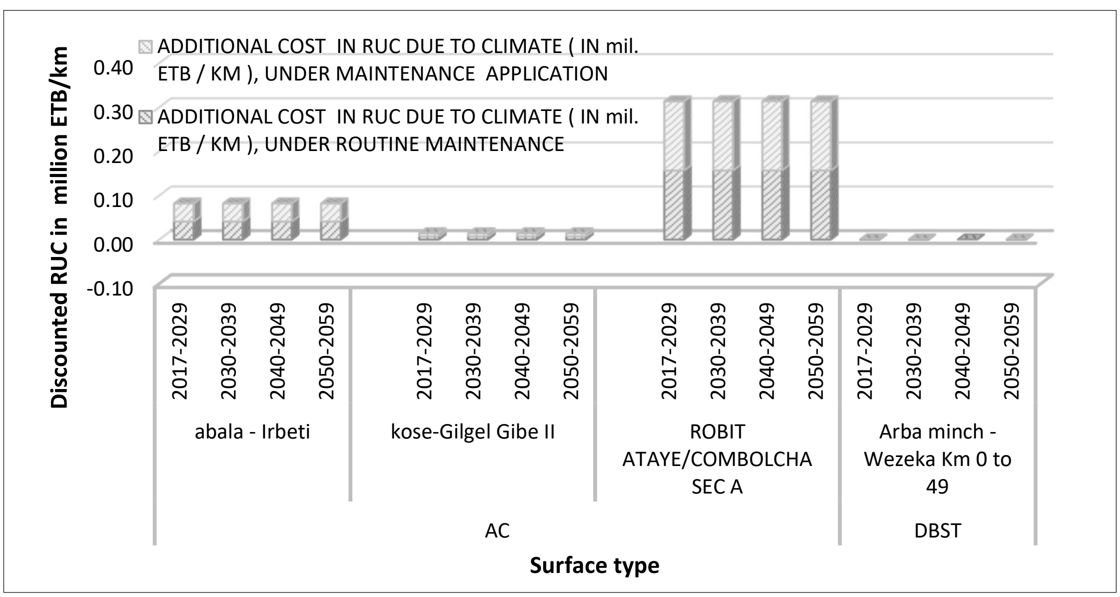


Figure 3.19 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

CLIMATE : SUB ARID TRAFFIC LEVEL: MT

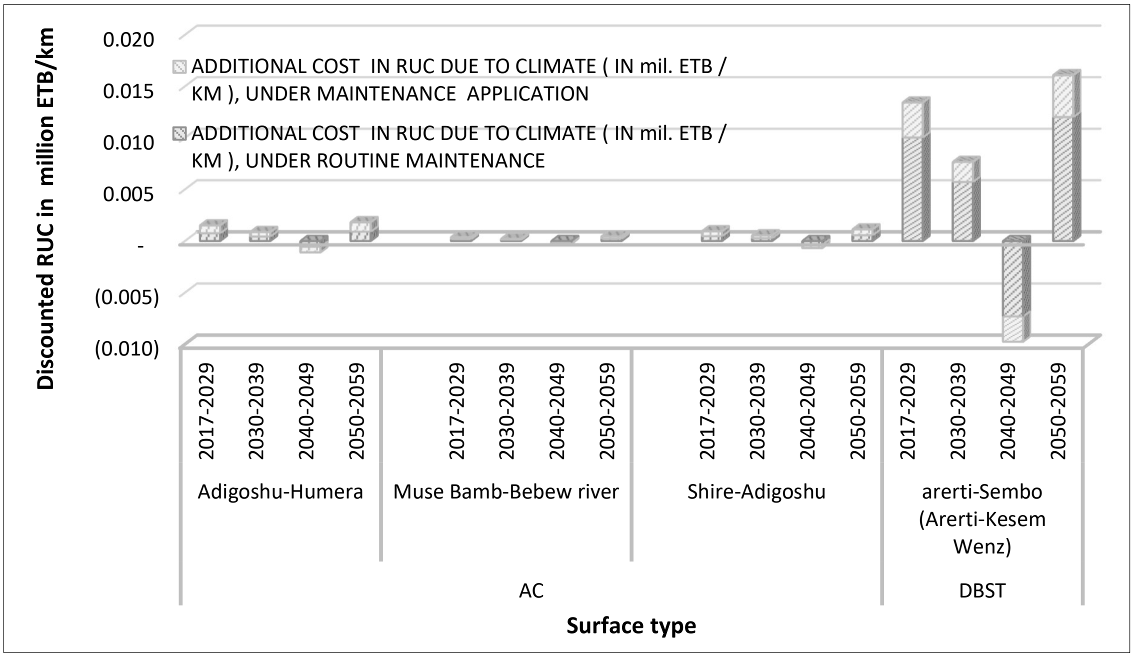


Figure 3.20 additional cost incured in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTD COST IN RUC (MIN)

CLIMATE : SUB MOIST TRAFFIC LEVEL: LT

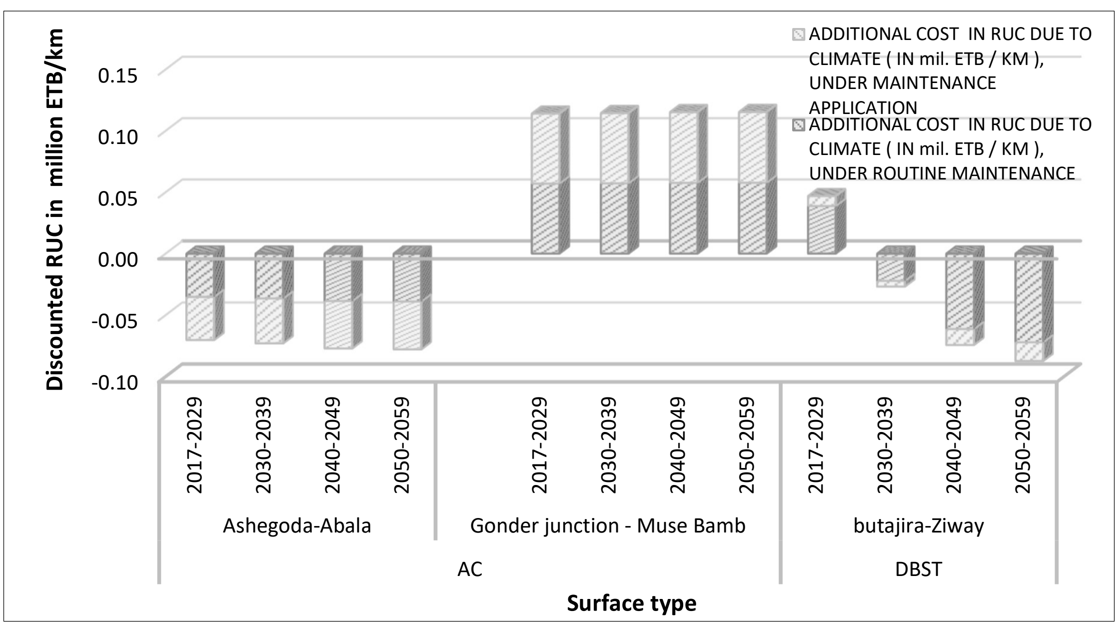


Figure 3.21 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

CLIMATE : SUB MOIST TRAFFIC LEVEL: MT

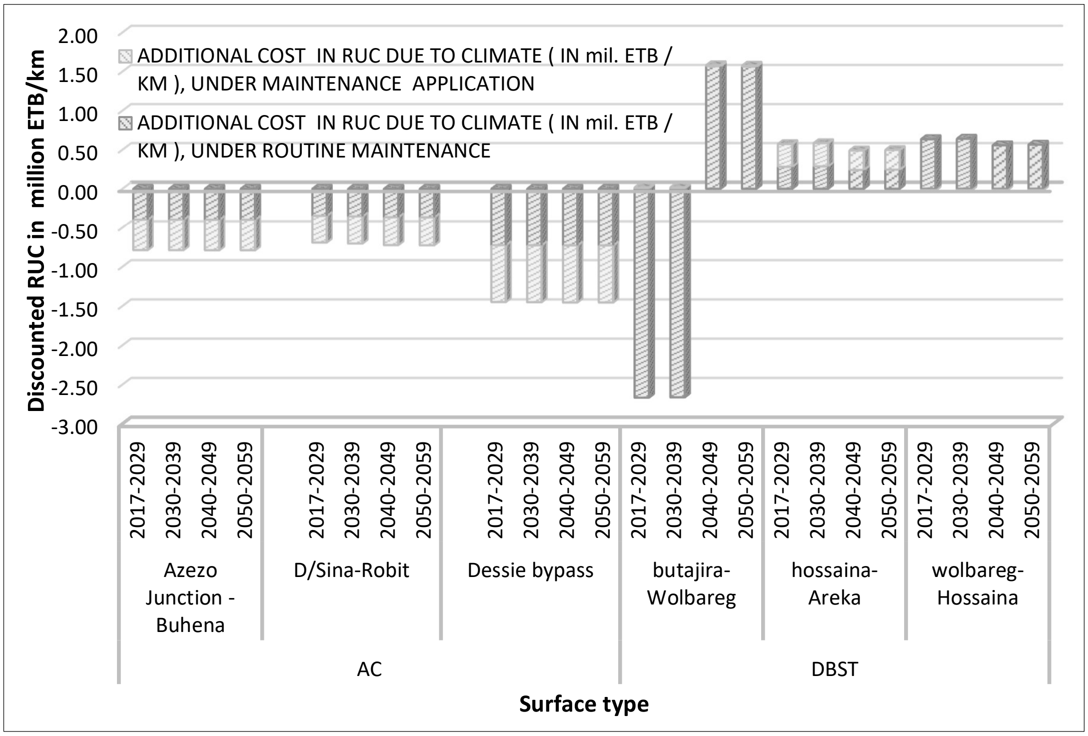


Figure 3.22 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

For Moist Climate Region

CLIMATE : MOIST TRAFFIC LEVEL: HT

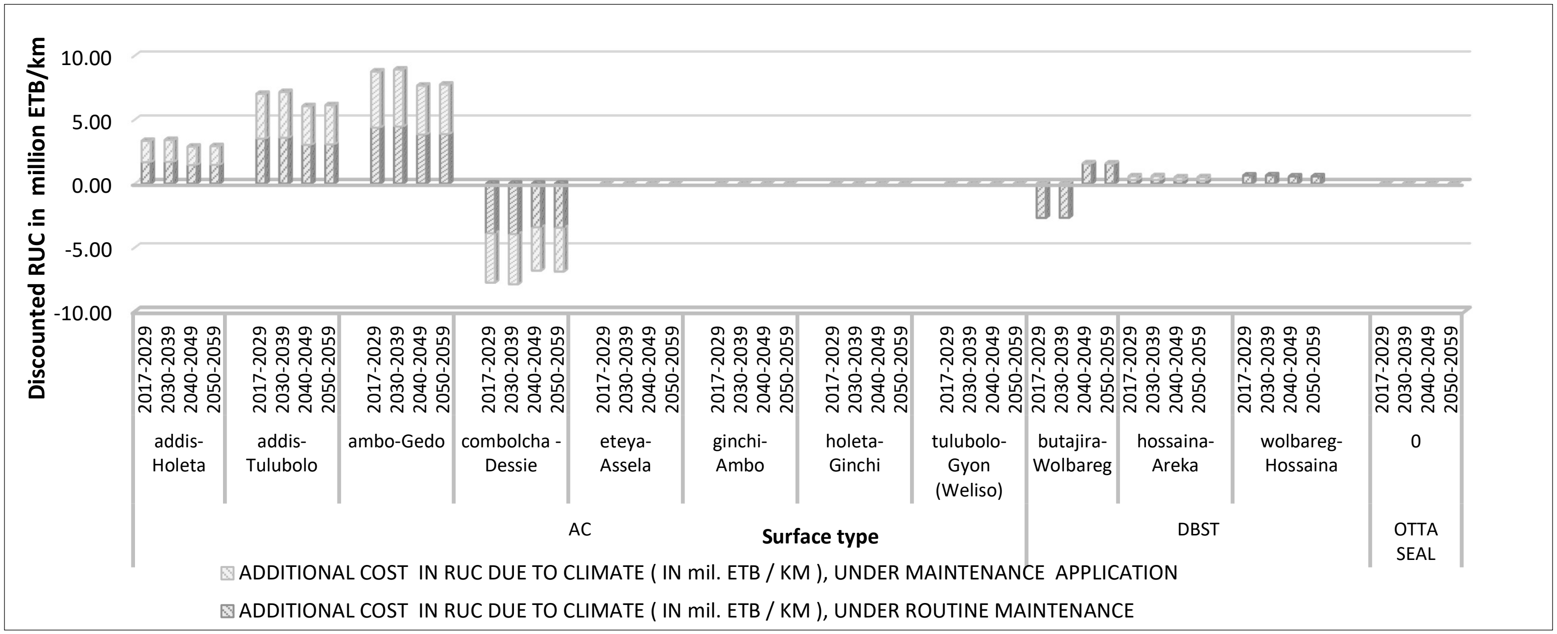


Figure 3.23 additional cost incurred in discounted RUC under min A2-emission senario

ADDITIONAL DISCOUNTED COST IN RUC (MIN)

CLIMATE : MOIST TRAFFIC LEVEL: LT

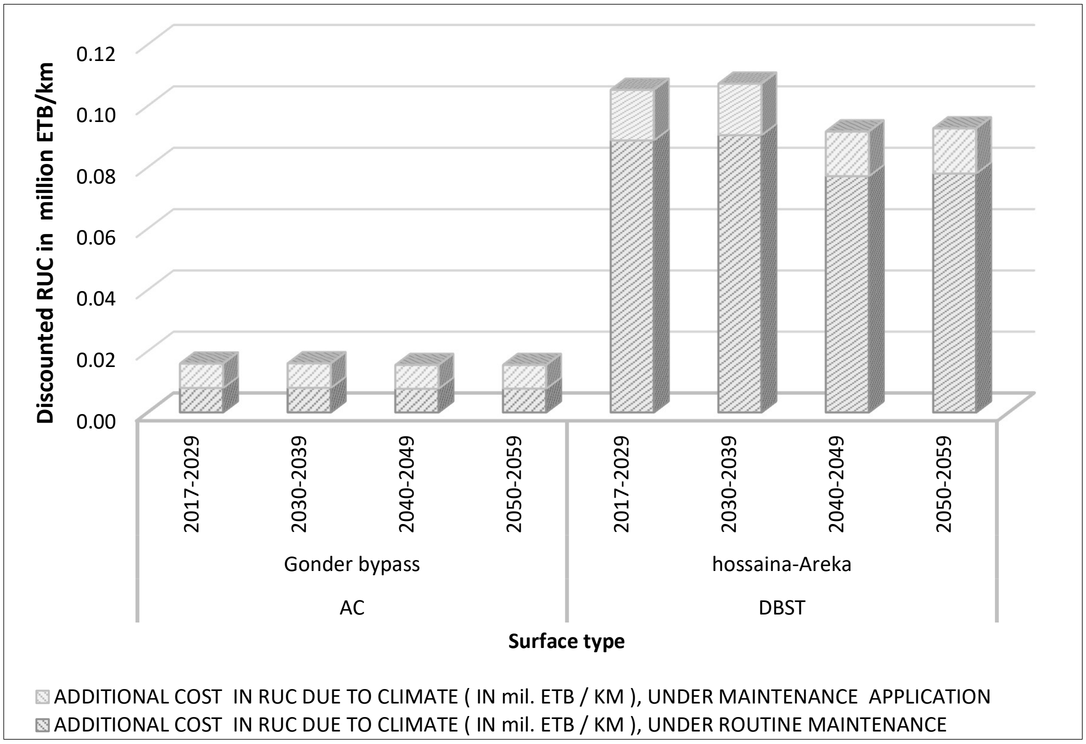


Figure 3.24 additional cost incurred in discounted RUC under min A2-emission senario