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Towards sustainable pavements:
A reference document

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A thesis submitted in partial fulfillment of the requirements for the degree of

PHILOSOPHIAE DOCTOR (ENGINEERING)

In the

FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

UNIVERSITY OF PRETORIA

October 2021

THESIS SUMMARY

Towards sustainable pavements: A reference document

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Summary

A sustainable pavement has to be economically, socially and environmentally feasible at an acceptable level of risk over its design life. Practically, a sustainable pavement optimises a range of performance indicators including cost, functionality, safety, local economic and human development, emissions, climate change and resource use, amongst others, which is measured by using a suite of assessment methodologies.

This thesis focusses on providing practical guidelines to characterise and evaluate the sustainability of a pavement. The objectives focus on a practical systems framework, populated with various methodologies and data sets, for the analysis of holistic pavement sustainability in South Africa. The overall scope of this thesis is the field of pavement sustainability focussing on environmental and social tenets. Sustainability contributes to the state of knowledge by defining pavement sustainability, developing a life cycle inventory, creating a social life cycle inventory, determining climate change assessment, doing a cumulative risk assessment, determining a sustainability index and providing an improved understanding of issues relevant to pavement sustainability.

These methodologies include life cycle cost analyses, life cycle assessments, social life cycle assessments, performance evaluations and climate change assessments amongst others. Apart from a life cycle cost analysis few methodologies have sufficient-evidence-bases from which to draw confident results. The methodologies are rarely aligned to evaluate holistic sustainability. The fast pace of

methodology development has also arguably left behind gaps in research. Most notably is the consideration of risks that may affect sustainability.

Firstly, sustainability is an interrelated concept since the modification of one sustainable indicator affects the others. Secondly, changes to or addition of indicators, if not properly evaluated, may cause unanticipated and significant reduction in sustainability outcomes. It is essential to develop required evidence bases for these methodologies to enable holistic evaluations and provide for optimal pavement infrastructure provision in South Africa.

Although this thesis provides an improved comprehension of holistic pavement sustainability, much still needs to be done to improve this understanding and merge the various concepts into a clear and concise framework. The recommendations in this thesis should be elaborated to ultimately aid in the sustainable development and management of South African pavement infrastructure.

List of publications emanating from this study			
Year	**Title**	**Authors**	**Journal**
2020	Life cycle inventory of bitumen for South Africa	Blaauw, S.A., Maina, J.W., Grobler, L.J.	Transportation Engineering Journal
2021	Life cycle inventory for pavements - A case study of South Africa	Blaauw, S.A., Maina, J.W.	Transportation Engineering Journal
2021	Social life cycle inventory for pavements - A case study of South Africa	Blaauw, S.A., Maina, J.W., Grobler, L.J.	Transportation Engineering Journal
2022	Flexible pavement performance and life cycle assessment incorporating climate change impacts	Blaauw, S.A., Maina, J.W., Mturi, G.A.J., Visser, A.T.	Transportation Research Part D: Transport and Environment
2022	A cumulative risk and sustainability index for pavements	Blaauw, S.A., Maina, J.W., Visser, A.T.	Transportation Research Part D: Transport and Environment

Keywords

Pavement Sustainability, Life Cycle Assessment, Life Cycle Inventory, Carbon Dioxide Equivalent, Pavement Construction Materials, Pavement Construction Processes, Social Life Cycle Assessment, Social Sustainability, Indicators, Climate Change, Settlement Drought Risk, Road User Emissions, Pavement Deterioration, Cumulative Risk, Sustainability Index, Markov Chain Monte Carlo

Assigned to Giana, my Mother, family and friends

A Psalm of David

Fret not thyself because of evildoers, neither be thou envious against the workers of iniquity;
for they shall soon be cut down like the grass, and wither as the green herb.
Trust in the Lord, and do good; so shalt thou dwell in the land, and verily thou shalt be fed.
Delight thyself also in the Lord; and He shall give thee the desires of thine heart.
Commit thy way unto the Lord and trust also in Him; and He shall bring it to pass;
and He shall bring forth thy righteousness as the light, and thy judgment as the noonday.

'n Psalm van Dawid.

Wees nie toornig op die kwaaddoeners nie, beny hulle nie wat onreg doen nie;
want soos gras sal hulle gou verwelk, en soos groen grasspruitjies sal hulle verdroog.
Vertrou op die Here, en doen wat goed is; bewoon die aarde en beoefen getrouheid.
Verlustig jou in die Here; dan sal Hy jou gee die begeertes van jou hart.
Laat jou weg aan die Here oor en vertrou op Hom, en Hy sal dit uitvoer;
en Hy sal jou geregtigheid laat voortkom soos die lig, en jou reg soos die middag.

Psalm 37:1-6

ACKNOWLEDGEMENTS

I wish to express my appreciation to the following organisations and persons who made this thesis possible:

a) The University of Pretoria and the Council for Scientific and Industrial Research (CSIR). The analyses and conclusions that are based on data from these organisations are those of the author and do not necessarily represent the view or findings of the before mentioned.

b) Professor James Maina, my supervisor, for his clear guidance, invaluable advice and wealth of experience that made this thesis not only possible but highly enjoyable.

c) Dr Louis Grobler, my mentor, for sharing his broad experience throughout this study.

d) Professor Alex Visser and Mr Georges Mturi, for supporting the analyses required to complete this study and stimulating questions regarding climate change impacts on pavement deterioration.

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LIST OF ABBREVIATIONS

CO_2e	-	Carbon Dioxide equivalent
FU	-	Functional Unit
GHG	-	Green House Gas
GWP	-	Global Warming Potential
ISO	-	International Organisation for Standardisation
LCA	-	Life Cycle Assessment
LCCA	-	Life Cycle Cost Analysis
LCI	-	Life Cycle Inventory
NOx	-	Nitrogen Oxides
PAHs	-	Polycyclic Aromatic Hydrocarbons
PM	-	Particulate Matter
PVI	-	Pavement-Vehicle Interaction
S-LCA	-	Social Life Cycle Assessments
S-LCI	-	Social Life Cycle Inventory
SO_2	-	Sulphur Dioxide
SRT	-	Sustainability Rating Tools
TMI	-	Thornthwaite Moisture Index
UHI	-	Urban Heat Island
VOCs	-	Volatile Organic Compounds

1 INTRODUCTION

1.1 INTRODUCTION

Practically, a sustainable pavement optimises a range of performance indicators including cost, functionality, safety, local economic development, job creation, carbon emissions, amongst others and is measured using a suite of assessment methodologies (Van Dam et al., 2015).

Although different methods exist for incorporating sustainable practices into pavement management, these methods are not all-encompassing as they were not developed taking into consideration pavement realities in every part of the world, including South Africa. The fast pace of development of these methodologies has also arguably exposed gaps in research and largely omitted consideration of risks that may affect sustainability. (Berardi, 2013) A need exists to provide a practical approach to sustainable pavement evaluation in response to real-world challenges.

1.2 BACKGROUND

The purpose of pavement management generally focuses on ensuring road transportation is provided at the lowest total cost to society (Van Dam et al., 2015). This ideology has stemmed from the first generation of sustainable definitions which argued that sustainability is measured by affluence, strongly correlated with wellbeing (Meadows et al., 1974). What has become more prevalent in recent years is that economic activity shares a close relationship with environmental damage (IPCC, 2014) and has been identified as the main driver behind global climate change (Rockström et al., 2009) Transportation is the leading cause of this change which is dominated by pavement life cycle emissions (FHWA, 2014). Of great concern is that the sustainable evaluations of pavement infrastructure provision lack a strong evidence base on which to rely (Mani et al., 2015; Spence and Rinalfi, 2014; Varsei et al., 2014).

Sustainable assessments in the field of pavement engineering may be categorised as life cycle cost analyses, life cycle assessments, performance assessments, sustainability rating tools (Van Dam et al., 2015) and the newly introduced concepts of social life cycle assessments, climate change assessments, and the risk and sustainability indexing. Of these categories, most still lack sufficient data to conduct confident judgements throughout.

The majority of models evaluate pavements by considering only one tenet (e.g. cost or environment) and do not consider the effects across the domain of sustainability (FHWA, 2014). Life cycle cost analyses focus on determining the most cost-effective design, construction and maintenance options whereas life cycle assessments focus on the environmental impact in terms of carbon footprint (Benoît and Mazijn, 2009). Life cycle assessments typically provide little consideration of other forms of pollution (i.e. noise, soil and water toxicity etc.), social impacts (health and safety, user satisfaction, access and equity in terms of job creation etc.) or the impacts of various risks (managerial, social, environmental etc.) on holistic sustainability (ISO, 2006; ISO, 2018).

Performance assessments evaluate a pavement on its intended design function with terms such as ‘long-life pavements’ and ‘pavement-vehicle interaction’ commonly used as proxies (Jordaan, 2013). Sustainability rating tools, such as Greenroads, are generally used as a decision-making tool where various sustainable indicators are listed, and according to their implementation, projects are rated and scored on a qualitative basis only. It is important to note that many of these indicators are quantifiable, but a life cycle approach is often not adopted (Van Dam et al., 2015).

Furthermore, none of these models considers external risks which greatly affect sustainability such as maintenance, community participation, construction mafia, fundamental economic transformation in public projects and impact on service providers, suppliers and contractors, and so forth. Roads authority mandates, user-pay strategies (e.g. electronic-tolling or E-Toll) and other managerial risks are also commonly omitted from these assessments.

Firstly, sustainability is an interrelated concept where it is often difficult to adjust one indicator without affecting another (Berardi, 2013). Secondly, changes to or addition of sustainable indicators, if not properly evaluated, may cause significant and unanticipated reductions in overall sustainability, highlighting the need for a model where sustainable indicators and their relation to each other are properly defined. A simplified understanding of sustainability defines the actions of today as a cause of the effect and outcome of the future. This is discussed in more detail throughout this thesis. The model should also seek to identify vulnerable pavement systems (i.e. climate change, rural and urban settlement vulnerabilities, material weathering characteristics, congestion, road funding and safety, etc.) in terms of risks to complement the current pavement management systems.

1.3 PROBLEM DEFINITION

Numerous studies have been conducted on the impacts of pavement infrastructure on specific sustainable areas (UCPRC, 2010; FHWA, 2014; Taylor and Philp, 2015; Van Dam et al., 2015; Shoa et al., 2017), but holistic evaluation research is lacking. There is a need to identify and quantify a broad range of key sustainable indicators and risks and incorporate them into the modelling of pavement systems through consideration of current and future challenges. The undefined challenges are socio-economic impacts, environmental damage, maintenance, climate change, congestion, reduced capacity of the construction industry, market interference, lack of sufficiently skilled labour, required change in construction methods, material use and scarcity and aggregate weathering etc.

1.4 OBJECTIVES OF STUDY

The primary objectives of this study are twofold:

a. To develop a practical system framework to evaluate the various components of sustainable pavement infrastructure provision, and
b. To develop and verify a practical approach for the implementation of such a model at both project and network levels.

This thesis focuses on providing a practical guideline for evaluating sustainable development from a pavement design, construction and management perspective.

1.5 SCOPE

The overall scope of this thesis is the field of sustainable pavement infrastructure provision, focusing on the various life cycle stages of pavement. It falls within the scope and extent of this study to:

a. Indicate the current understanding of sustainability of pavement development through an extensive literature survey;
b. Identify and quantify the relevant indicators which have the greatest impact on pavement sustainability;
c. Locate climate change-related vulnerable pavement systems, and
d. Develop a practical approach for performing holistic sustainable evaluations of pavement infrastructure considering relevant risks.

It falls outside of the scope and extent of this study to:

a. Investigate and develop new techniques to quantify the economic, environmental or societal impacts of pavement infrastructure;
b. Generate new data for evaluation with the proposed models, and
c. Investigate the risk elements and sustainable indicators associated with the broader concept of transportation (e.g. bridges, signals, interchanges, etc.).

1.6 CONTRIBUTION TO THE STATE OF KNOWLEDGE

Much work has already been done in the field of life cycle cost analyses and life cycle assessments internationally. These methods often only consider easily quantifiable parameters and commonly lack sufficient consideration of social impacts. The assessments do not define the relationship among parameters, nor the effects of what the changes to indicators will have on others.

It is the purpose of the study to contribute to the state of knowledge in terms of:

a. Establishment of a holistic system approach to the sustainable evaluation of pavement infrastructure;
b. Provision of a method for estimating the sustainability of pavement infrastructure, and
c. Provision of a practical approach for evaluation and management of pavement systems.

This research does not aim to provide detailed assessments of every aspect related to sustainable pavement evaluation as that would be a considerable undertaking. This study rather aims to 'set-the-scene' relevant to the basis of this research. As such, it is the long-term view of the writer that further work will be required to enhance the quality of data and investigate various detailed system-level interactions that are identified as being in need of research through this study.

1.7 LAYOUT OF THESIS

This thesis consists of 12 chapters. The relationship between the various chapters are shown schematically in Figure 1-1.

The thesis starts with a short introduction to the background and context of this study (*Chapter 1*). This is followed by a series of chapters, which represent the literature study. *Chapter 2* investigates the evolution of sustainable development and its correlation to pavement infrastructure provision. Sustainability is the core of this research and provides the umbrella under which the subsequent literature chapters fall. *Chapter 3* discusses risk management and its application in the pavement engineering field. *Chapter 4* discusses climate change, its impacts on pavement performance, associated risks and sustainable impacts. *Chapter 5* investigates the various methods for sustainable pavement probabilistic modelling.

In *Chapter 6* the study approach developed for the research is presented. Here the issues on which attention is focused in the thesis are highlighted, and the approach to investigate these issues is discussed. In *Chapter 7* an adapted methodology is presented for the development of a life cycle inventory for commonly used pavement materials. In *Chapter 8* a methodology is proposed for the development of a social life cycle inventory focussed on all pavement life cycle stages. *Chapter 9* is devoted to locating vulnerable pavement systems in the face of predicted climate change impacts. *Chapter 10* provides a methodology, which translates the climate change impacts into accelerated pavement deterioration and increased use phase emissions, emphasising the importance of rigorous maintenance regimes. *Chapter 11* seeks to incorporate and consolidate the findings of the previous four chapters and provide a practical probabilistic model which may be used to predict the sustainable performance of alternatives over their design life underpinned by leading risks which may affect their performance.

Chapter 12 seeks to delineate the framework for easy implementation in the field of pavement engineering through the development of practical guidelines for sustainable pavement evaluation and management. *Chapter 13* provides concluding remarks and recommendations for future research.

1.8 SUMMARY

Chapter 1 provides an introduction to this thesis, followed by background for the study, the problem definition and objectives, scope and details of how this research contributes to the state of knowledge. This thesis is structured to provide relevant literature chapters, ranging from Chapter 2 through 5, focused on the fundaments of the research, followed by Chapter 6 through 11 detailing the relevant methodologies developed and results analysed. Chapter 12 and 13 detail guidelines for sustainable pavement evaluation and conclusion adn recommendations respectively. The thesis aims to provide a sensible approach to pavement sustainability assessment for the South African road network, and improve the understanding of the sustainable pavement concept.

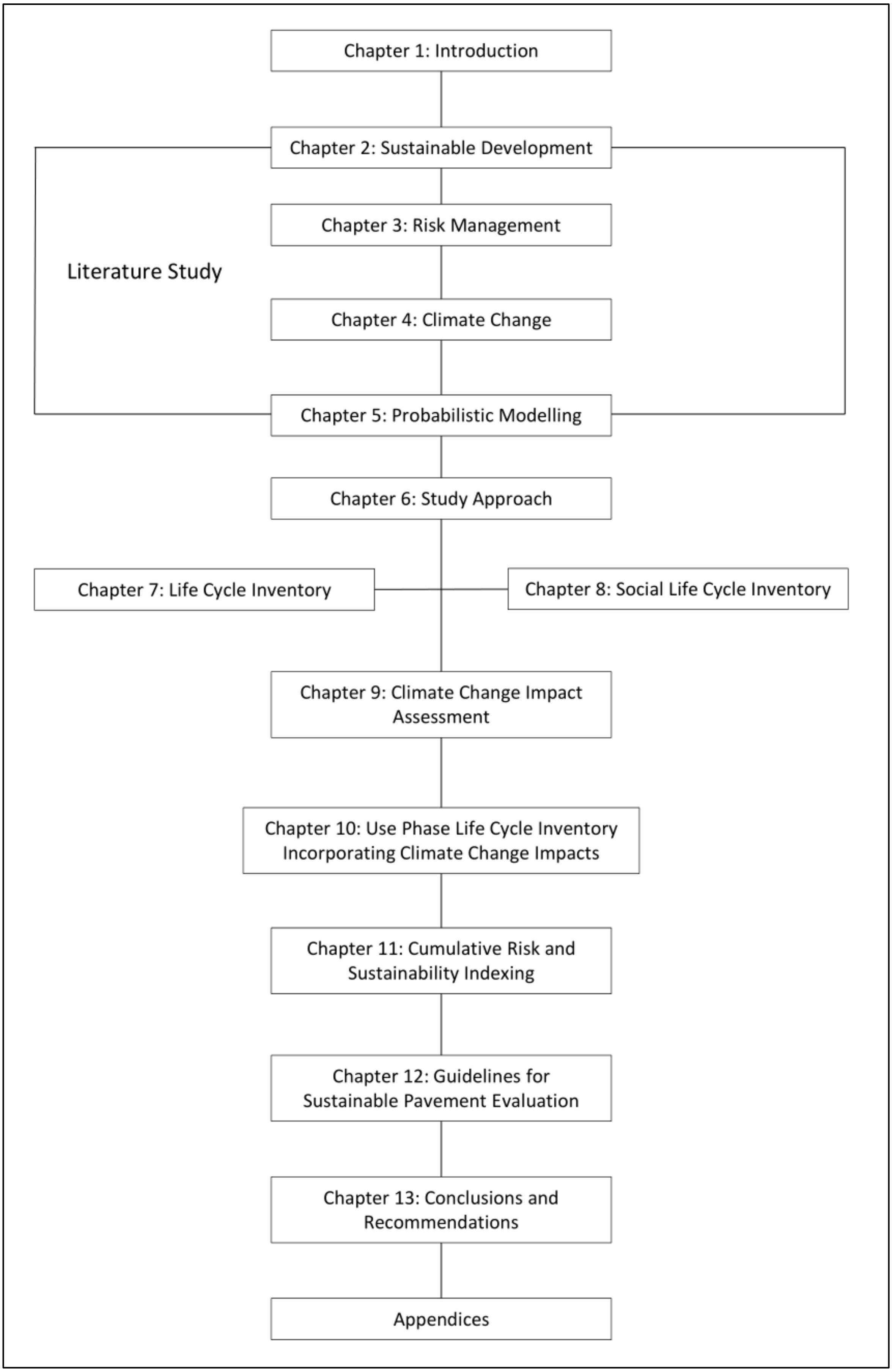


Figure 1-1: Schematic layout of thesis

2 SUSTAINABLE DEVELOPMENT

2.1 INTRODUCTION

Sustainability comprises three interconnected spheres that describe the relationship between economic, environmental and social aspects of the world we live in (UN, 2019). When combined, they form a solid basis from which important decisions and actions can be made. Examples of such decisions include land use planning, water management systems, and construction - further extended to policy and law-making (Blowfield and Murray, 2011). When the concepts of the three spheres are combined with real-world situations, collective success is achieved. Figure 2-1 illustrates this concept.

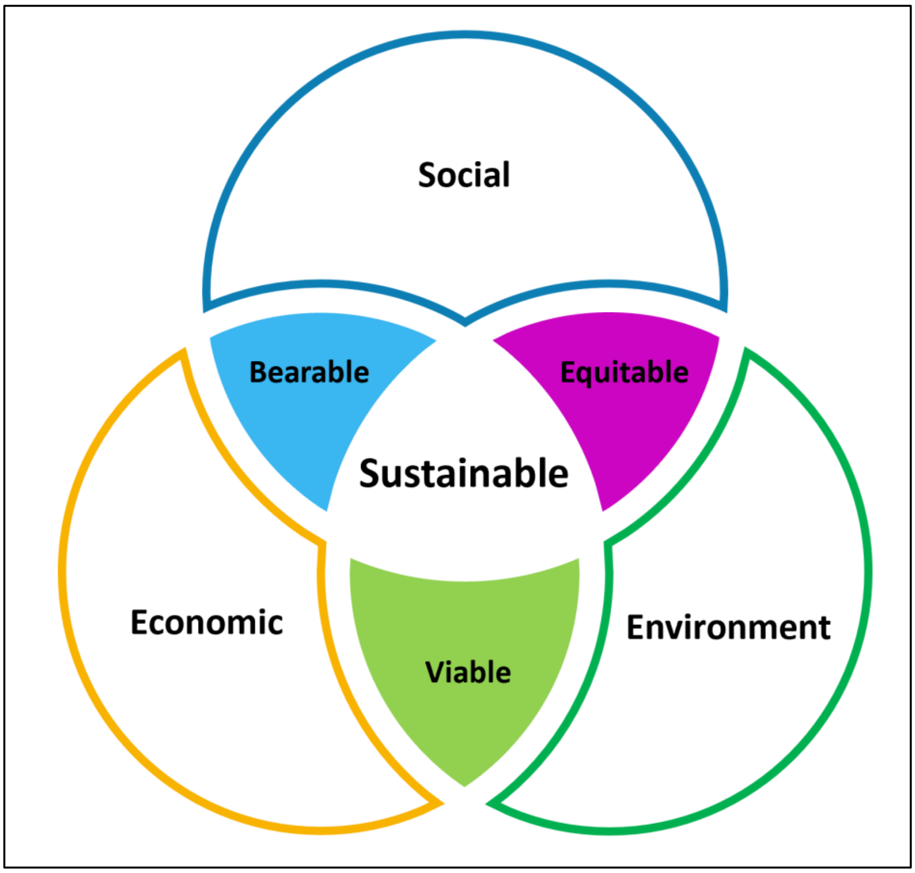


Figure 2-1: The three spheres of sustainability (adapted from Adams, 2006)

This chapter aims to assess various frameworks across the three spheres (or tenets) of sustainability related to pavement infrastructure provision, focussing on the environmental and social spheres, and their correlation to the economic sphere through the 'bearable' and 'viable' overlapping sections.

2.2 DEFINING SUSTAINABILITY

Berardi (2013) states that when defining sustainability, one must look at the common denominator between definitions in which peculiarities and uncertainties are often encountered (Grosskurth and

Rotmans, 2005) where sustainability is defined within multiple dimensions and levels of space (and scale) and is time and socially dependent (Acai and Amadi-Echendu, 2018).

When defining sustainability, Berardi (2013) suggests that spatial dependence should be considered and be regarded as locally specific and a matter of local interpretation rather than being universally applicable. Berardi goes on to state that the local perspective of sustainability will influence the boundaries of sustainable development as the interconnectedness of systems, people and markets tend to counteract a local approach. Sustainable development actions should thus commence from a local scale and develop into the larger global dimension, rather than taking a top-down approach which often disregards location specific challenges and circumstances. In pavement engineering, this may include consideration of societal and local climate challenges, materials and analytical design methodologies, among others.

The time dependency, as illustrated in the generational approach of the Brundtland definition (WCED, 1987) and the 15 years for both the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs), requires the long-term consideration of our actions today, leading to the question of how far into the future we should look and how much uncertainty we are willing to accept as a result (Kemp and Martens, 2007). In supporting the debate of time dependency, Hjorth and Bagheri (2006) argue that linear cause-effect mechanisms are not able to explain the complexities inherently present within the issues of sustainability. Hjorth and Bagheri suggest a ‘project’ should not be considered as having an end point but be regarded as an ongoing process part of everyday life, similar to the recently introduced concept of circular economy (WEF, 2014).

The third concept of sustainability, regarding the domain in which it is divided, is based on the categorisation in terms of the three tenets of sustainability, i.e. 1. environmental, 2. economic and 3. social. These dimensions have been widely accepted and implemented within the realm of sustainability. However, recent developments have increased the pressure of recognising cultural and political dimensions (Vallance et al., 2011). In South Africa this presents various complexities in the political arena which is segregated and risks the determination of sustainable interventions.

Further uncertainties arise within the multiple interpretations of sustainable development which advance the necessity to consider various points of view and requires acceptance of uncertainty and differences (Berardi, 2013). This is illustrated by Solow (1993) who defines sustainability as preserving production capacity for a long future. Walker and Salt (2012) define it in terms of resilience and safeguarding the balance between function and structure, observing that sustainability is the capacity of a system to absorb a shock or disturbance and still retain its basic function and structure. The resilience disposition of sustainability echoes the challenge of servicing current system demands without jeopardising the potential to meet those of the future (Acai and Amadi-Echendu, 2018). This demands that political leaders adopt a single vision and unified commitment to sustainability.

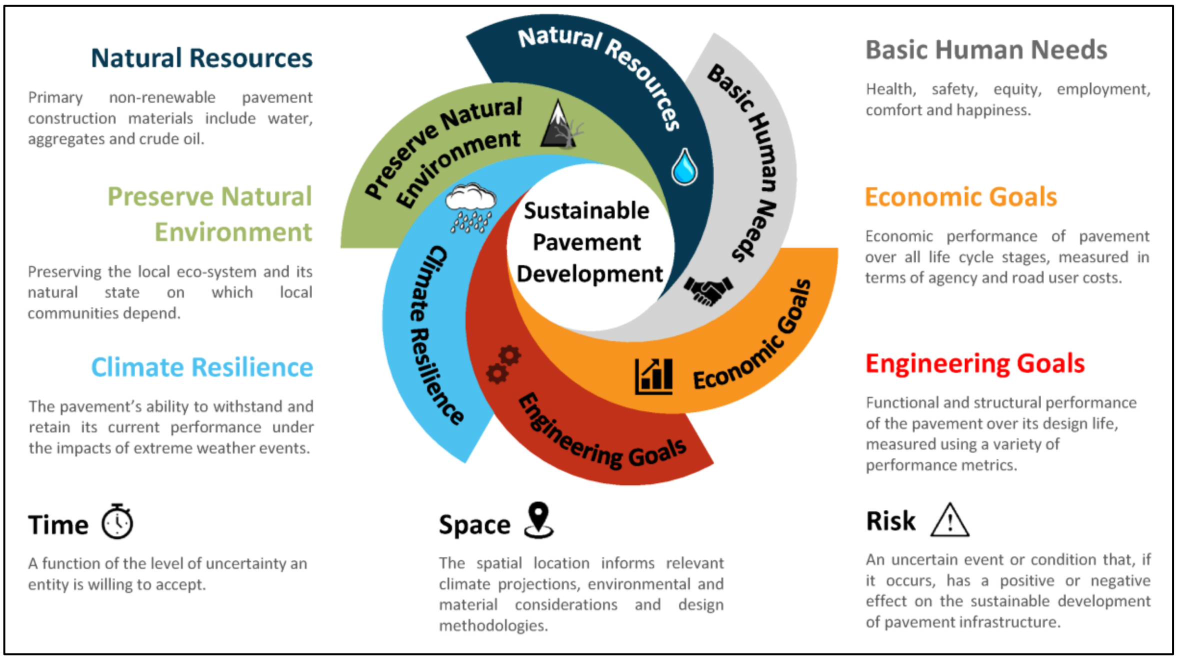
Further attempts at defining sustainability have been made by the likes of Korczak and Kijewska (2016) who defined sustainability from a transportation perspective, stating that to achieve sustainability, special attention should be given to the degree of satisfaction of individuals who make use of transport infrastructure, demanding governments clearly define sustainability taking into account basic human needs when strategic plans and budgets are developed. In developing nations this is paramount in planning sustainability and projecting into future undertakings.

The World Bank (1995) defined biophysical sustainability as the preservation of the integrity of life-supporting systems on earth, with others defining it according to the common definition of preserving the current state (Klauer, 1999). Brundtland's definition focuses on the ability of humans to meet their current needs whereas Schröter et al.’s (2017) definition centres around the conservation of the planetary eco-system. This creates a necessary conflict which leaves an academic reflecting on human fallability and the challenges of uniting governments and communities in obtaining an outcome which is beneficial and can be projected into the longterm.

These definitions indicate that sustainability has shown a need for a pluralistic approach, taking into account multiple factors to create a common definition by minimising trade-offs and the different perceptions of stakeholders. Hjorth and Bagheri (2006) offer concluding remarks, stating that even though it is difficult to put sustainable definitions into operational practice, the often single or multi-purpose approach to projects should be changed to a holistic and integrated approach that links the three tenets of sustainability (environmental, economic and social). and evaluates the effect of the project across these tenets.

Applying these considerations to pavements, Van Dam et al. (2015) states sustainability should be defined as the system characteristics that encompass a pavement’s ability to “achieve the engineering goals for which it was constructed, preserve and (ideally) restore surrounding ecosystems, use financial, human, and environmental resources economically, and meet basic human needs such as health, safety, equity, employment, comfort, and happiness”.

It is proposed that this definition includes an additional crucial component, ‘climate resilience’, and may be simplified as follows: the system characteristics that encompass a pavement’s ability to meet basic human needs while achieving the economic and engineering goals for which it was constructed, enhancing its climate resilience, preserving and (ideally) restoring the natural environment whilst consuming natural resources in a responsible manner. Figure 2-2 provides a visual illustration of this definition.



Natural Resources

Primary non-renewable pavement construction materials include water, aggregates and crude oil.

Preserve Natural Environment

Preserving the local eco-system and its natural state on which local communities depend.

Climate Resilience

The pavement's ability to withstand and retain its current performance under the impacts of extreme weather events.

Basic Human Needs

Health, safety, equity, employment, comfort and happiness.

Economic Goals

Economic performance of pavement over all life cycle stages, measured in terms of agency and road user costs.

Engineering Goals

Functional and structural performance of the pavement over its design life, measured using a variety of performance metrics.

Time

A function of the level of uncertainty an entity is willing to accept.

Space

The spatial location informs relevant climate projections, environmental and material considerations and design methodologies.

Risk

An uncertain event or condition that, if it occurs, has a positive or negative effect on the sustainable development of pavement infrastructure.

Figure 2-2: Defining sustainability related to pavement engineering

2.3 MEASURING PAVEMENT SUSTAINABILITY

An ever-growing number of governing bodies, organisations, agencies, institutions and corporations are embracing the principles of sustainability in the management of their business-related activities. This approach focuses on the overarching goal of converging the three sustainable tenets in their decision-making processes.

The implementation of sustainable practices is not a new trend and has been applied to the goods manufacturing industry as far back as the 1960s and in recent years has gained increased attention in the transportation industry, specifically focused on quantifying sustainable efforts and aligning decision-making with sustainable goals (FHWA, 2014).

A variety of tools and techniques have been used to assess sustainable aspects of pavements, used either individually or in concert, of which the most widely cited are Life Cycle Cost Analyses (LCCAs), Life Cycle Assessments (LCAs), Sustainability Rating Tools (SRTs), Performance Assessments, and recently introduced Social Life Cycle Assessments (S-LCAs) (Benoît and Mazijn, 2009; FHWA, 2014) qualitatively and quantitatively. Each of these tools is individually discussed in the following sections and relevant aspects linked to the objectives of this research are highlighted. Figure 2-3 shows a flow chart of this process.

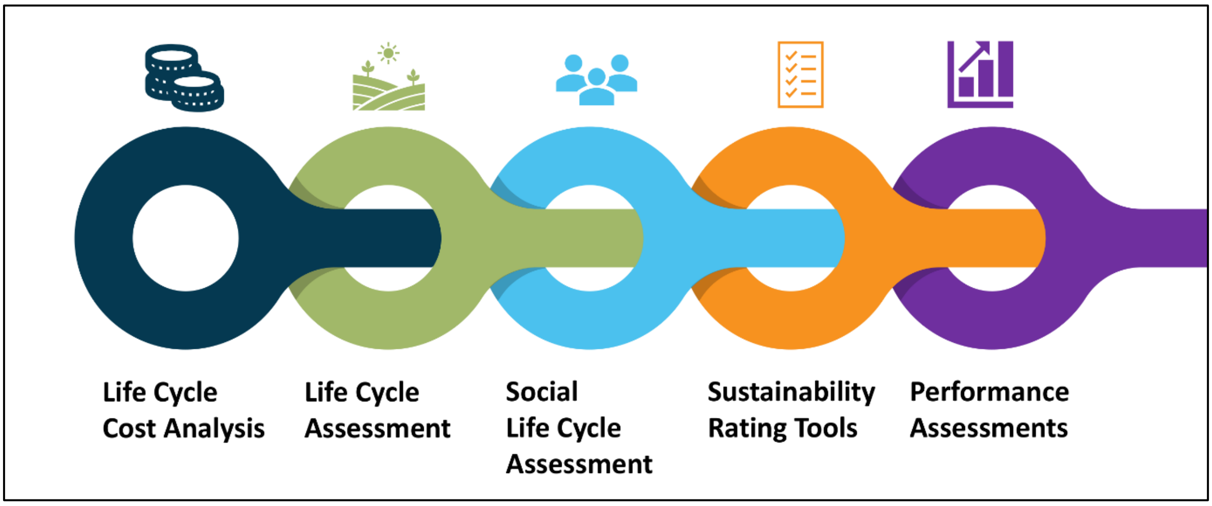


Figure 2-3: Measuring Pavement Sustainability

2.4 LIFE CYCLE COST ANALYSIS

LCCAs are a well-established leading consideration in decision-making processes related to infrastructure projects and require little detailed introductions. This review will rather focus on the relation between LCCAs and the environmental and social principles, with focus given to the latter. A key economic indicator, which impacts the social realm and is used by most governmental organisations and institutions, is 'value for money' (World Bank, 2016). Value for money, viewed from a public perspective, is the most advantageous use of public funds to meet the quality, functionality and sustainability of a product or infrastructure it provides. An LCCA aims to evaluate alternative design solutions and determine the solution which provides the best value for money spent over the analysis period of the product or asset (FHWA, 2014). Numerous costs need to be considered in an LCCA, including initial costs (e.g. purchase, acquisition and construction costs), fuel costs, operational, maintenance and rehabilitation costs, replacement costs, residual value estimates and finance charges. Furthermore, non-monetary benefits or costs, which do not necessarily have an objective way of assigning a monetaray value to them, are also included as key considerations during the LCCA (RICS, 2016). In the field of pavement engineering, these non-monetary costs may include 'carbon cost', 'educational opportunities', and 'empowerment', among others.

In addition to 'value for money' being a key socio-economic indicator, the additional non-monetary indicators are most closely aligned with the objectives of this study. These non-monetary costs (e.g. travel time, user comfort) are further strongly impacted by regional and industry-specific goals and reflect the need to develop sustainable assessment models on a spatially dependent platform. For instance, 'fundamental economic transformation', an indicator of significant importance in South Africa and discussed in later sections, is not necessarily relevant to other regions which do not have the same socio-economic objectives.

2.5 LIFE CYCLE ASSESSMENT

An LCA is a structured methodology, which enables the quantification of impacts of infrastructure-related processes such as operational, construction and maintenance to the environment over its full life cycle. An LCA aims to account for all processes, from the extraction of raw materials to the point at which those materials are returned to the environment at the end of life, often referred to as the "cradle to grave" concept (FHWA, 2014).

The LCA can be further used to inform and guide decision-makers in industry, governments and non-government organisations for purposes including strategic planning, goal and priority setting and product and process design selection (FHWA 2014). An LCA is particularly useful to determine the 'carbon footprint' of pavement processes or the amount of energy or water consumed during each process, but also allows for the measurement of other sustainable aspects such as overall waste generation (Muench, 2010). In a developing country like South Africa determining the carbon footprint may seem complex, however tools exist to conduct a risk assessment which although not exact would be valuable in sustainable execution. Legislation and standardisation would provide a framework for application.

The forerunners of LCAs were originally developed in the 1960s and largely focused on analysing air, land and water pollutions from solid waste emissions. These tools were later expanded to include energy, resource use and pollution with a focus on consumer products rather than complex infrastructure projects (Hunt and Franklin, 1996, Guinée, 2012). Between 1990 and 2000, efforts shifted to standardising a full-fledged impact assessment methodology by the International Organisation for Standardisation 14040 (ISO, 2006). International attempts have been made to standardise an LCA procedure for pavement infrastructure projects, e.g. UCPRC (2010), FHWA (2014) and Highways England (HE, 2019); however, there is currently no governing agency or government-issued guidelines for South Africa.

The LCA divides a pavement life cycle into six stages (Van Dam et al., 2015), briefly described below:

- Material Production - includes all processes used in the acquisition (e.g., mining and crude oil extraction) and processing (e.g., refining, manufacturing and mixing) of pavement materials;

- Design – processes that identify the structural and functional requirements of pavement infrastructure for specific conditions (i.e., subgrade, climate, traffic, existing pavement structure) together with the determination of the pavement structural composition and accompanying materials;

- Construction - includes all processes and associated equipment related to the construction of the initial pavement;

- Use Phase – the period during which the pavement is in service, carrying vehicles, interacting with the environment and providing lighting and other electrical services;
- Maintenance/rehabilitation – activities applied at various times during the service life of the pavement, and
- End of life – this stage refers to the final disposition and subsequent reuse, processing, or recycling of the pavement after it has reached the end of its useful life.

The LCA starts by defining the aim and scope of the study with the main work residing in the development of the Life Cycle Inventory (LCI), considering each life cycle stage individually. The LCI contains information regarding the predominant environmental burdens arising over the lifetime of the project. This is commonly followed by an Life Cycle Impact Assessment (LCIA) which presents and quantifies the results in a predefined manner, supporting further analysis comparisons (ISO, 2006).

2.5.1 Life Cycle Inventory

The LCI phase consists of the tracking of environmental flows (inputs of material, resources and energy and outputs of waste, pollution and co-products) for the system being studied (FHWA, 2014). The development of an LCI requires defining the Functional Unit (FU) of the model and its system boundaries. The material and energy flow related to the process being modelled are then identified and calculated, e.g. "Material Processing", so too the pollution and waste flows are identified and calculated.

For pavement aggregates, the background data processes may involve blasting and extraction processes whereas for energy, they may include delivering the aggregates to the place processing and crushing the aggregates. Due to the influence of the background data processes, it is important to develop inputs to an LCI regionally and consider the typical practices and available resources in that region. It is often challenging to collect reliable information for regions, which do not voluntarily publish data regarding the processes or resources used to produce pavement materials. In these situations, published data sets (either commercial sources or from literature) are often utilised. The issues related to the use of default data were observed in the early years of the development of pavement LCI (Santero et al., 2011) when studies were rapidly published and had numerous flaws. These flaws commonly manifested as poor-quality data, gaps in research being filled by default data and a general lack of consideration for location-specific evaluations.

Certain inventories are often viewed as 'golden black boxes' (Harvey et al., 2014) and applied without much appreciation for inherent limitations in the inventories. Considering the widely cited Eurobitume inventory, originally published in 2012 (Eurobitume, 2012) and revised in 2020 (Eurobitume, 2020).

The inventory has varying embodied Carbon Dioxide factors applied to certain elements of the inventory between the two data sets, with up to 50% differences in some instances. This highlights the impacts of the lack of quality data on predictions. An additional flaw present in LCI models is the inconsistency in selecting indicator categories where energy and Carbon Dioxide emissions are typically focused on with other important indicators such as socially relevant emissions and water use being omitted (Gulotta et al., 2019). Focus on a holistic inventory, which incorporates both environmental and social related indicators, as demonstrated by Bressi et al. (2018), is required.

Supporting the need to quantify these indicators, Giunta et al. (2020) demonstrate the contributions of various pavement life cycle phases (excluding the use phase emissions related to road users) to the total energy and carbon footprint estimates for a typical pavement project. Giunta et al. found that the production phase generally accounted for more than 50% of the total energy and emissions related to pavement development, with bitumen production being the leading contributor. These findings are in line with other studies (Stripple, 2001). Additionally, the use of recycled material has shown significant environmental benefits in both concrete pavement structures (Li et a., 2021) and bituminous pavement structures (Sanchez-Cotte et al., 2020).

However, a crucial shortcoming of these studies is that they generally omit consideration of the pavement use phase and the environmental burden attributed to it.

2.5.2 Functional unit

The FU is the heart of all LCA studies, defining how performance will be quantified and compared. A fixed unit should be defined to which output results are linked and environmental impacts are measured. As specified by Harvey et al. (2016), the FU for pavements should include: (i) specifications related to physical dimensions (e.g. length, width, and the number of lanes), (ii) indicators of the performance of the pavement (e.g. design life), and (iii) criteria for performance (e.g. safety, ride quality, traffic levels, load spectrum, speed characteristics, climatic conditions and engineering, etc.). Hammond and Jones (2019) further advise that a comparative study should consider the quantity of materials required to provide a set function, e.g. the amount of asphalt base required per square meter to provide the same structural support as an unbound granular base.

2.6 SOCIAL LIFE CYCLE ASSESSMENT

Rights-based approaches to sustainable development have been promoted since the 1990s, but little progress has been made in quantifying the effectiveness of these approaches. An S-LCA is one method used to measure social sustainability, by analysing, monitoring and managing the desirable and undesirable social consequences of planned interventions (policies, programs, projects etc.), and any social changes invoked by those interventions. The primary objective of an S-LCA is to bring about a more sustainable and equitable human environment (Vanclay, 2003).

An S-LCA is a relatively new concept that has yet to be standardised (Huarachi et al., 2020; Ramirez et al., 2014; Kühnen and Hahn, 2017). Similar to an (environmental) LCA, an S-LCA generally comprises four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Ramirez, 2014). The evolution of S-LCAs may also be categorised into four stages, namely: the first steps towards S-LCA development (1996-2009), the years of uncertainty (2009-2012), the years of development (2013-2016), and the standardisation years (2017-present). Current attempts at S-LCA framework development focus largely on methodological standardisation, where the leading efforts centre on 1) selection of key indicators and 2) assessment of subcategories (Huarachi et al., 2020).

In the selection of key indicators, Huarachi et al. found that the most common method applied in literature was the development of a large database of possible indicators and applying a social 'hotspot' technique. These 'hotspots', represented by key social indicators, describe unit processes of a product life cycle - in this study a pavement life cycle - which contribute substantially to the total social impact of the product.

One issue with database selection and development is that social impacts are often dependent on the location and, therefore, location-specific data needs to be collected for confident assessments. Furthermore, as noted by Kühnen and Hahn (2017), attempts at the development of an S-LCA tend to consider a broad range of industries and sectors, with few receiving sufficient empirical attention to draw reasonable conclusions. The S-LCA in the field of pavement engineering is still underdeveloped and lacks empirical experience.

The first response to these challenges is to identify and secure universal acceptance for indicators (Gulotta et al., 2019), which measure social impacts of pavements and the broader impacts of technical and managerial choices in pavement infrastructure provision. These indicators will be used to develop a Social Life Cycle Inventory (S-LCI). A significant constraint in the development of such an inventory is the complex nature of social impacts, the relationship between indicators across the three tenets of sustainability (i.e. economic, environmental, and social), and the changing political landscape that shapes the relative weights of the indicators.

In extending the social 'hotspot' methodology, Castillo and Pitfield (2010) present the Evaluation and Logical Approach to Sustainable Transport Indicator Compilation (ELASTIC) framework, developed for identifying and selecting a small subset of key sustainable transport indicators. The framework proposes the development of a long list of potential sustainable transport indicators and systematic evaluation of each indicator for preliminary selection of key indicators (similar to the social 'hotspot') methodology. The evaluation is based on a Social Significance Index (SS_i) score, which uses goals and sub-goals with pre-set empirically derived weights. The framework further recommends the implementation of sensitivity analyses to select key indicators for consideration.

In agreeance with this approach, Zheng et al. (2020) also put forward the use of sensitivity analyses to incorporate uncertainty modelling during the selection of key indicators. It is suggested that a baseline aggregated score, similar to the SS_i proposed in the ELASTIC framework, be calculated for each indicator, and then apply probabilistic modelling to determine a final aggregate score – representing the importance of each indicator relative to others. Additionally, Zheng et al. (2020) submit that these key indicators be categorised and used in the Social Life Cycle Impact Assessment phase (S-LCIA).

The Subcategory Assessment Method (SAM), a characterisation method that evaluates subcategories to be used in the S-LCIA, was found to be the most common framework applied to categorise identified indicators in the literature (Huarachi et al., 2020). The United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) (Benoît and Mazijn, 2009) define two types of approaches for the characterisation of life cycle social impact assessments. For the first type, Type-1, 31 subcategories related to five main stakeholder categories (consumer, worker, local community, society, and value chain actors) shall be considered during assessments. UNEP and SETAC (Benoît and Mazijn, 2009) state that failure to consider any of the categories or subcategories should be justified but also new subcategories may be included (Huarachi, et al., 2020). The assessment of these subcategories is generally conducted through qualitative performance reference points, providing thresholds to assess the inventory phase. An example of such a reference point in the pavement engineering field may be the environmental pollution generated as a result of pavement construction activities. A project that seeks to actively reduce pollution is accorded a higher score than a project which does not have strategies for pollution reduction. This example also illustrates the complex nature of social impacts and its correlation to environmental sustainability, where the increased pollution of the environment has a delayed but significant impact on the society, as seen through the exacerbation of climate change.

In applying the UNEP and SETAC SAM, it is noted that consideration of all subcategories is not always relevant to a specific industry. An example may be examining an S-LCA developed for the agri-food industry by Group Ageco and sustainable consultants QUANTIS, where certain subcategories were omitted and new subcategories included to better reflect the industry-specific social impacts and considerations (Couture et al., 2012).

For the second type of assessment, Type-2, impacts are evaluated according to their impact pathways, where a key indicator is translated into a midpoint- and subsequently an endpoint-indicator (Ramirez et al., 2014), similar to an LCA. UNEP and SETAC (Benoît and Mazijn, 2009) provide seven midpoint-indicators (health, autonomy, safety, security and tranquillity, equal opportunities, participation and empowerment, and resource (capital) productivity) and three endpoint-indicators (human capital, cultural heritage and human well-being).

Given the multiplex nature of social considerations, it is difficult to develop a generic framework robust enough to assess unknown future situations. To circumvent this problem, an S-LCA could be developed to become situational, location-specific and time-dependent. It is then important to clearly define the framework boundaries in which the assessment is to be applied. Nicaise (2008) states that an S-LCA should be considered as legally required and not optional, be ex-ante in nature, and require the participation of stakeholders for continual improvement and development.

From the writers' experience, the development and application of high-quality S-LCAs are demanding, time-consuming and expensive. A balance is therefore needed between the investment required and the importance of the measures that are assessed (Nicaise, 2008). The statistical data, analytical capacity and stakeholder participation required for a good S-LCA cannot be developed overnight and should be viewed as a living framework subject to continuous evaluation and improvement.

In South Africa, few attempts have been made to develop similar socially oriented frameworks. Most worthy of note and applied by the Provincial Administration of the Western Cape, Department of Transport and Public Works are the Broad-Based Black Economic Empowerment (B-BBEE, 2013) Act and the Empowerment Impact Assessment (EmpIA) protocol developed.

2.6.1 Broad-Based Black Economic Empowerment

The B-BBEE Act of 2013 aims to "promote the achievement of the constitutional right to equality, increase the broad-based and effective participation of black people in the economy… and establish a national policy on broad-based black economic empowerment to promote the economic unity of the nation" (B-BBEE Act, 2013).

Key objectives of the B-BBEE Act relevant to this study are (B-BBEE Act, 2013):

- "Promoting economic transformation to enable meaningful participation of black people in the economy;
- Achieving a substantial change in the racial composition of ownership and management structures and the skilled occupations of existing and new enterprises;

- Increasing the extent to which communities, workers, cooperatives and other collective enterprises own and manage existing and new enterprises and increasing their access to economic activities, infrastructure and skills training;
- Increasing the extent to which black women own and manage existing and new enterprises, and increasing their access to economic activities, infrastructure and skills training;
- Promoting investment programmes that lead to broad-based and meaningful participation in the economy by black people to achieve sustainable development and general prosperity, and
- Empowering rural and local communities by enabling access to economic activities, land, infrastructure, ownership and skills".

These objectives can generally be summarised by the overarching objective of initially 'economic transformation', later 'radical economic transformation', and more recently 'fundamental economic transformation'.

2.6.2 Western Cape Empowerment Impact Assessment

The EmpIA protocol developed by the Provincial Administration of the Western Cape, Department of Transport and Public Works, in 2000, was one of the first attempts in South Africa at measuring empowerment impacts of technical and managerial choices in transportation infrastructure projects and was applied on several projects in the Western Cape (WCDTPW, 2010). After initial implementation, the model was reviewed and outcomes evaluated, which signified a need for revision. This revision included consideration of employment impacts post-construction as opposed to only focusing on temporary employment during the design and construction phases. Additionally, the need to focus on the broader concept of social sustainability was observed compared to merely considering initial empowerment impacts.

The EmpIA protocol focuses on five key social impacts, namely (WCDTPW, 2010):

1. Labour enhanced task opportunities;
2. Local economic development opportunities;
3. Local plant/material resources opportunities;
4. Beneficiary identification and quantifying needs, and
5. Skills identification and training.

The target beneficiaries of this framework are previously disadvantaged individuals with a specific unemployed requirement for project involvement. Beneficiaries must generally be residents and attention is given to black women and youth as prescribed by the B-BBEE Act.

The protocol incorporates indicators such as jobs created per unit investment, beneficiaries reached, and additional support provided. The original protocol does not provide the facility to determine the increase in project cost as a result of implementing empowerment compared to alternatives nor does it quantify the socio-economic impact of implemented initiatives. The EmpIA analysis tool (WCDTPW, 2010) did indeed introduce the indicator of allowable cost premium above which no further uneconomical labour absorption or local resourcing is justified. What such frameworks lack is the ability to evaluate the long-term impacts of technical and managerial choices and determine if the premium investment in empowerment has indeed assisted in reaching long-lasting sustainable goals (such as e.g. reflected in the National Development Plan (NDP, 2012)).

2.6.3 Uncertainty in Social Life Cycle Assessments

Costa et al. (2019) state that in applying an S-LCA, the key challenges include the absence of standardised inventory data, inconsistent system boundaries and difficulty in developing methodological frameworks. Additionally, Costa et al. state that the leading challenge is a lack of fully performing uncertainty analyses, an activity strongly recommended by UNEP and SETAC guidelines and various researchers (Zamagni et al., 2013; Onat et al., 2016; Costa et al., 2019). Zheng et al. (2020) conducted a literature review on the implementation of uncertainty analyses in S-LCAs, particularly in the field of pavement engineering, and found that no studies have incorporated uncertainty into S-LCA frameworks. In addressing this shortcoming, Zheng et al. (2020) proposed a methodology for incorporating uncertainty into pavement S-LCAs using an analytical hierarchy process (AHP) supplemented by Monte Carlo simulations for sensitivity analyses. An AHP is a structures technique for organising and making decisions in complex environments where numerous variables or criteria need to be considered in the prioritisation of key considerations including indicators. Zheng et al. (2020) used the AHP to develop initial scores and weights to be used to calculate a final sustainable score for a project. Monte Carlo simulations were then implemented on the baseline scores to convert the sample into random scores with uniform distributions, and in so doing reduced uncertainty. Zheng et al. (2020) were able to successfully determine a final aggregated social sustainable score for a project with a 95% confidence level.

2.7 SUSTAINABLE RATING TOOLS

The Federal Highway Administration (FHWA) defines a sustainable approach to highways as helping decision-makers make balanced choices, which consider environmental, economic and social aspects that will benefit current and future road users (FHWA, 2014).

An SRT has been found to work well in this regard, allowing for the measurement of sustainable indicators of various pavement development processes and delineating the effects to a scale relevant to projects. An SRT generally contains a list of phases a project undergoes with sustainable features/goals for each phase where applicable. Sustainable indicators are assigned for each feature and the project receives a score indicating its level of sustainability (Zhang and Mohsen, 2018). An SRT tracks the three tenets of sustainability and provides targets against which project indicators are scored. SRTs are applied either in self-assessment or in the verification by an independent party (Griffiths et al., 2015).

A notable rating tool is a Leadership in Energy and Environment Design (LEED), which was developed by the US Green Building Council in 1993 and is reported to be the most commonly used green building rating system globally (LEED, 2010). LEED has provided the basis for, and inspired the development of, SRTs in the transportation field (Yudelson, 2008; Zhang and Mohsen, 2018). Such rating tools include Greenroads, Envision, Green Leadership in Transportation Environmental Sustainability (GreenLITES), Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), Livable And Sustainable Transportation (I-LAST), Sustainable Transportation Analysis and Rating System (STARS), and the Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE^{2}ST-In-Highways) (Sarsam, 2015). Additionally, SANRAL has recently developed their SRT, the Sustainable Roads Forum (SuRF) rating tool.

2.7.1 Characterisation of Sustainable Rating Tools

Generally, each SRT is environmentally dominated and considers the impacts of pavements on the natural environment in terms of material depletion, various forms of pollution and preservation of its natural state. Furthermore, water quality, affected by construction, and impacts of project alignment to natural water sources are unanimously accepted to be key indicators for sustainability. However, water use for construction purposes and its effects on the local community, for instance, is not considered among SRTs. It is difficult to justify the use of large volumes of treated water in relatively arid areas common in South Africa, where the local population struggle to meet their own daily water needs (Steyn and Paige-Green, 2009).

In the case of social impacts, SRTs tend to focus on mobility in terms of requirements for park-and-ride lots and bus lanes, further focusing on user safety. The SRTs do not generally consider the effect of a project on the local community and the opportunity of employment through the implementation of labour-intensive construction methods as an example, with SuRF being the only SRT considering these indicators. Greenroads (2012) and STARS (STC, 2010) together with SuRF are the only three SRTs for which the implementation of social indicators is compulsory, with the remaining SRTs providing indicators, which address social considerations but are not required to receive accreditation.

When measuring social impacts, the target beneficiaries are typically those who will be directly empowered through sub-contracting, temporary jobs, and education. The provision of jobs for these beneficiaries also tend to be limited to the construction phase and long-term employment opportunities are not focused on in these assessments. An ideal socio-economic impact of pavements may be described as reaching unemployed beneficiaries, providing them with jobs and education/training opportunities to ensure the sustainability of their future employment.

The SRTs found in the literature are commonly developed for implementation during the conceptual and design phases. Thus, the SRTs typically do not specify performance metrics to evaluate pavements, with only BE^{2}ST (Edil, 2012) utilising the International Roughness Index metric. Considering performance, GreenLITES (2008) promotes the use of bio-engineering techniques (e.g. organosilanes) to enhance material properties and increase the durability of pavement structures but lacks the functionality to quantify the relationship between the indicator and sustainable pavement performance.

Only one rating system, Envision (ISI, 2018), considers the impacts of climate change from a risk perspective and provides indicators, which focus on enhancing the climate resilience of pavement infrastructure in the face of future impacts. Envision does not consider the impacts of climate change on local communities and how pavement development may exacerbate those impacts. Further risks related to the community, market interference, etc. are not included in any of these assessments.

SRTs are often developed using a bottom-up approach making them spatially dependent making it hard to implement them in different locations. They are developed based on practices perceived to be sustainable, evaluating infrastructure based on outcomes rather than quantitatively measuring the impacts of achieving those outcomes. They limit criteria to those that are standardised and well understood, often neglecting important criteria which are difficult to measure (Johansson, 2011).

A review of the various SRTs reveals that all tools support the implementation of sustainable best practices. Each system, however, differs in its method of evaluation, whether through comparisons to base designs, quantitative methods, the use of expert opinions in the form of third-party validation or self-assessments. Regardless of the methodologies, all systems pursue the same objective of sustainability.

2.8 PERFORMANCE ASSESSMENTS

Performance assessments evaluate a pavement in terms of its intended design, function and physical attributes required to meet that function (Van Dam et al., 2015). Various methods are available globally to measure pavement performance, which include rutting, roughness, texture, subgrade stiffness, deflection and visual indicators, composite condition rating systems, pavement bearing capacity, specified material attributes (e.g. thickness, asphalt content, level of compaction, gradation); as well as methods to compare these attributes to expected design parameters through the use of, for instance, mechanistic-empirical design methodologies (Jordaan, 2013). Performance assessments of pavements are a longstanding evaluation method and are built into most design and specification standards and as such, detailed descriptions are not provided in this study. Rather, following a similar approach previously implemented in evaluating assessment methodologies, the focus is on the performance indicators most closely related to environmental and social sustainability. These performance indicators, which seek to also extend the structural and functional performance of pavements in general, share a strong correlation to financial sustainability as well (Lee et al., 2020).

From a pavement performance perspective, the functional performance of a pavement is most closely aligned with social sustainability. Functional performance generally refers to the performance not related to the pavement structure, such as providing a smooth, ‘safe’, ‘noise’ reducing surface for use by both motorised and non-motorised road users year out. Functional performance, from a transportation perspective, extends to ‘travel time’, ‘user cost’ and ‘congestion’ as well as providing adequate ‘pedestrian facilities’ to ensure ‘accessibility’ of non-motorised road users and provide ‘traveller information systems’ during both construction and use phases. The South African Municipal Infrastructure Investment Framework (MIIF 7, 2011) guidelines in part simplify the functional performance requirements to ‘all-weather access to within 500 m of the dwelling’ which may be compared to the functional performance required by the Sustainable Development Goals of an ‘all-seasoned road within 2 km of the dwelling’.

In extending the functional performance, ‘road user cost’, affected by pavement roughness, is a leading contributor to increased vehicle emissions and subsequently environmental damage (Bester, 1984; Zaabar and Chatti, 2010). This relationship is further discussed in subsequent chapters.

2.9 SUMMARY

This chapter provides a general overview of sustainability concepts and methods used to measure sustainable parameters and how those parameters relate to pavements. This includes a definition of sustainability, a discussion on why it is important that sustainability should be considered a holistic approach and how its application should fall within the priorities and goals of organisations and projects. The role pavements play in sustainability is typically described using a common proxy (greenhouse gas emissions) and key components inherent in the life cycle (material and energy consumption) are also presented. A comparison of various sustainability measurement methods is provided and general risks surrounding sustainable practices are briefly discussed.

A critical review of notable LCA studies shows that LCAs have evolved rapidly in recent years, taking on a more holistic evaluation perspective related to sustainability, with increased efforts being placed on quantifying social impacts and placing the tenet high up in the hierarchy of sustainability. However, the evidence base for social impacts is still found to be wanting.

LCA studies typically do not consider the impacts of climate change nor do they consider other risks such as deviations from planned maintenance activities and what its effect is on the quantified assessment. As LCAs aim to quantify impacts, they cannot influence sustainability given that they do not define nor particularly encourage more sustainable practices or innovations, as SRTs commonly do.

Regarding SRTs, it is found that even though social indicators are considered, they are generally not mandatory. Furthermore, water use and the impact on rural communities are also not considered. Designing for climate change is deemed necessary by only one rating tool, however, the author contends climate change may significantly contribute to the sustainability of pavement infrastructure in the near future and should be a leading factor considered, from both a risk and opportunity perspective. SRTs are qualitative evaluation tools and do not include the consideration of risks. Where these methods consider maintenance activities, they fall short similar to LCAs in assuming maintenance activities will take place and do not allow for the inclusion of deviation probability.

What is further important to take from this chapter is the need identified by Bryce et al. (2016), where a framework is required in which sustainable indicators and risks related to pavement infrastructure and their relationships are adequately defined according to the requirements of prioritisation provided by Van Dam et al. (2015).

Of the various sustainability assessment tools that are available each focus on certain aspects of sustainability, be it performance-driven, managerial or purely impact or economic quantification. Each of these methods has flaws, but if they are to be combined into one model and holistic sustainability is evaluated, it is the opinion of the author that the most accurate estimations of sustainability will be achieved. To create such a model, it is necessary to identify all relevant sustainability indicators and risks, allow for quantification of these indicators and risks, define the relationship among the indicators and risks across tenet domains and include location-specific risks and opportunities during the evaluations.

3 RISK MANAGEMENT

3.1 INTRODUCTION

Risk management from a sustainability perspective is a fairly new concept combining traditional risk management practices with the ever-evolving concept of sustainability (WBCSD, 2016). It is a crucial part of any organisation engaging in the construction industry. The complex nature of the concept has yet to fully be defined. To address this problem, this chapter provides a detailed description of both risk and the various risk categories associated with pavement sustainability.

The following sections will discuss the risk categories covering aspects related to construction-, socio-economic-, environmental-, climate change-, social-, and maintenance-risks related to pavement infrastructure development. An additional section describing the cumulative risk assessment process is also provided which will be utilised in this thesis to develop a risk and sustainability index. A flow chart of the process followed is shown in Figure 3-1

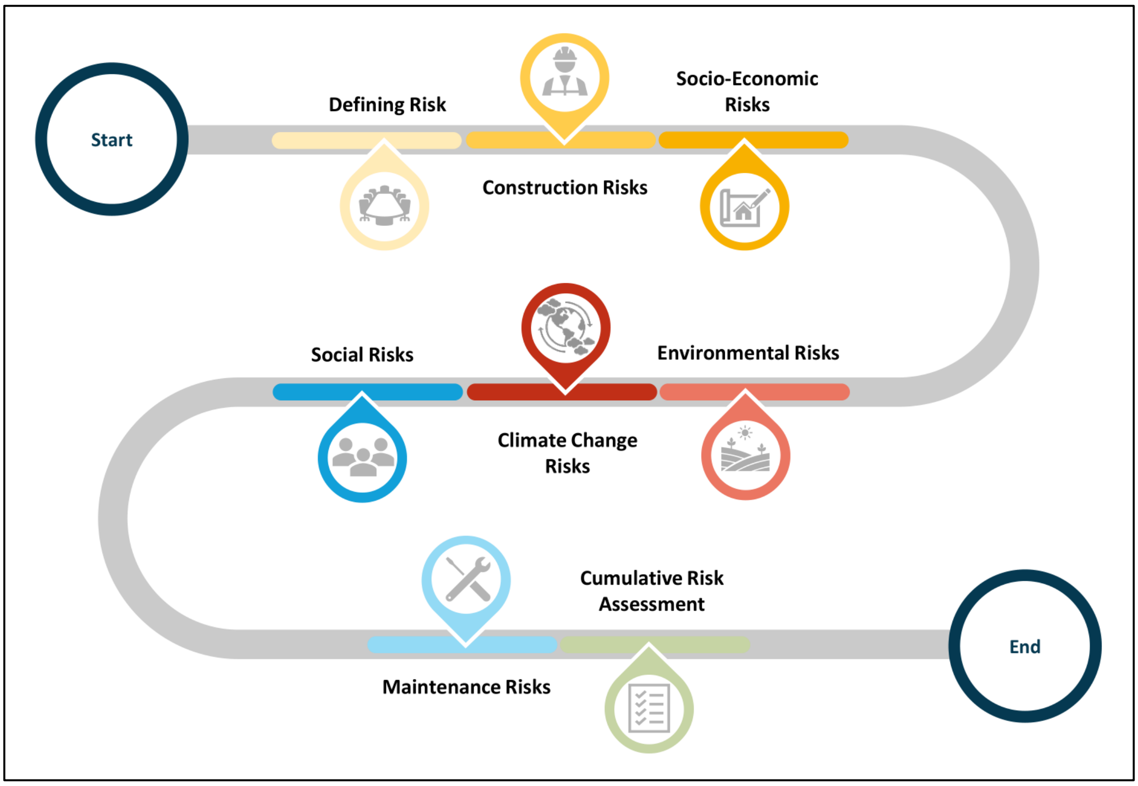


Figure 3-1: Structure of the chapter

3.2 DEFINING RISK

Various definitions are available for ‘risk’ and subsequently ‘risk management’. To most, risk is synonymous with uncertainty and is generally viewed as a negative deviation from what is anticipated

(ISO, 2018). This is illustrated by the Oxford English Dictionary's definition of risk as "chance or possibility of danger, loss or injury". However, risk may also be defined as having positive effects when related to opportunity (OECD 2008).

Knightian uncertainty, an ideology from decades past (Knight, 1921) may perhaps be the most famous of definitions, stating that risk and uncertainty should be viewed separately: "Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated". Many economists in the 1920s and 1930s shared this view, while others argued the distinction is overblown (Dizikes, 2010).

Risk is generally defined as either industry or situationally dependent instead of being universally applicable. Fischhoff et al. (1984) considered defining risk in a policy setting, stating that its definition is often controversial and that the choice of definition influences the outcome of the policy debates, the allocation of resources among safety measures and the distribution of political power in society. In asset management, risk management seeks to determine the consequence and probability of functional failure of an asset. In this study, the definition may be viewed as the consequence and probability that sustainable performance will be maintained into the future, shown in Equation 3-1:

$$\boldsymbol{Risk = Consequence\ of\ Failure\ (CoF)\ \times Probability\ of\ Failure\ (PoF)} \quad \text{(Eq. 3-1)}$$

Within the framework of a project, risk management typically follows a systematic process aiming to reduce or exploit the impacts and consequences of a risk occurring (PMI, 2004), affecting one or more of the triple constraints (time, cost, scope) of a project.

3.3 CONSTRUCTION RISKS

The construction industry, compared to many other industries, is commented on to be more vulnerable to risks due to the unique feature of construction activities such as long project timelines, complicated and integrated processes, financial intensity and dynamic organisational structures (Akintoye and MacLeod, 1997). It is thus clear that taking the necessary steps to ensure effective risk management in the industry is essential for the sustainable delivery of projects.

Substantial research has been conducted in the field of construction-related risk management where the most significant outcomes are typically related to risk identification and qualitative assessments of risk, as compared to the lesser studied quantitative analysis processes (Zou and Zhang, 2009).

Shen et al. (2001) conducted a questionnaire-based study where the majority of correspondents were considered mature professionals. Pre-identified risks were presented to each participant with the aim of analysing the significance of the risks relative to the sample population and identify new risks potentially omitted from the original list.

Shen et al. were able to successfully develop a significance index of 58 risks, which could be applied to most construction projects and grouped the risks as either financial-, legal-, management-, market-, policy and political- or technical risks.

Chen et al. (2004) conducted a similar study and found that project risks could be divided into three groups, namely: Resource factors – on "price escalation of material"; Management factors – on "inaccurate cost budget" and "supplier or subcontractors' default", and Parent factors – on "excessive interface on project management". Similar research was conducted by Tam et al. (2004) which also took the form of a survey questionnaire to determine health and safety-related risks on construction sites and concluded that the main risks are: poor safety awareness of top management and project managers, lack of training, reluctance to input resources to safety, and reckless operation.

While these research studies are aimed at largely identifying and categorising risks over a project life cycle, other studies focused more on the risks during certain project phases. Uher and Toakley (1999) investigated the factors affecting risk identification during the conceptual phase of a project, looking at structural and cultural driven factors and concluded that while most industry practitioners are familiar with risk management, few implemented it during the conceptual phase, its application was often qualitative rather than quantitative and its implementation largely impeded by low knowledge and skill base, resulting from a lack of commitment to professional development.

Chapman (2001) focused on the risks during the design phase, by translating published risks from other sectors, and stated factors increasing risk during design include: difficulty in capturing and specifying the user requirements, difficulty of measuring progress during the development of the design, and difficulty in estimating time and resources required to complete the design. Chapman however highlighted an opportunity in the design phase in that the design team's in-depth knowledge of the sources of risk can greatly influence its identification and can positively influence the three project constraints. Chapman went on to group the risks into four categories: environment, industry, client and project. Further similar studies were conducted by Vishwakarma et al. (2016) using a Risk Importance Index, similar to the Risk Significance Index developed by Shen et al. (2001), and successfully implemented on highway projects.

Of the more notable research conducted regarding risks related to the construction industry, is that of Zou and Zhang (2009) who identified and qualitatively assessed risks associated with the development of construction projects from both project stakeholder and life cycle perspectives. The methodology followed was that of a postal questionnaire to construction industry practitioners, in which 88 risks associated with typical construction projects (sourced from Ahmed et al. (1999), Chapman (2001) and Tang et al. (2007)) were listed. Respondents were then required to qualitatively assess the risks. Using this data, Zou and Zhang (2009) found that the predominant stakeholders who increase risk are Contractors, Clients, and Consultants (in this order). Causes include “unsuitable construction program planning”, “tight project schedules”, and “design variations” (in this order) and risks were grouped as either cost-, time-, quality-, environmental-, or safety-related risks. The study revealed that the construction phase is the highest risk phase in the project life cycle due to complexities mentioned.

3.4 SOCIO-ECONOMIC RISKS

Transportation infrastructure is considered a means to an end, which supports quality of life and economic growth through delivering accessible and reliable services to individuals and institutions (NIMS, 2007). Access and reliability in this context imply sustainability, which if not achieved, will result in the structural or functional failure of the infrastructure. Socio-economic related risks which influence pavement sustainability are found in lack of funding, market interference, poor government capacity and specifically in South Africa, population demographics and distribution (NIMS, 2007).

3.4.1 Lack of funding

Funding for transportation infrastructure in South Africa is obtained from various sources, distributed through the three spheres of government known as national, provincial and municipal and used largely for maintenance purposes as opposed to new construction (World Road Association, 2014).

A large part of this funding is obtained from the annual national revenue where approximately only 5% of the annual budget is allocated to economic regulation and infrastructure (Budget Review, 2019). These allocated funds are then distributed between the spheres of government through the Distribution of Revenue Bill (DoRA) according to each authorities needs, referred to as an equitable share. Further funds are obtained through conditional grants, loans, private participation and own revenue generation such as additional taxes or user-pay systems, among others. Notwithstanding the various methods of revenue generation, many roads authorities across government spheres still lack sufficient funds to adequately maintain and rehabilitate their respective road networks (NIMS, 2007).

3.4.2 Market interference

South Africa’s economic freedom score for 2020 was 58.8 (Statista, 2021), making its economy the 106th freest in the 2020 Index, down from 63.0 in 2018. Its overall score has decreased because of a steep plunge in the score for judicial effectiveness, declines in fiscal health, threatened property rights, reducing government integrity, increased government interference, and limited investment freedom. Ever-increasing market interference by Government is demonstrated by:

- Tender pre-qualification based on company turn-over e.g. only Exempt Micro Enterprises (EMEs) and Qualifying Small Enterprises (QSEs) may tender on works value below R100 million ($6.69 million);
- Targeting policies e.g. tenderer must be Black Economic Empowerment (BEE) Level 1 or 2;
- Sub-contracting targets e.g. 30% of the contract value must be sub-contracted to local targeted enterprises, and
- Tenderer must have its head office in the province to be allowed to tender.

Recent restrictions by SANRAL demonstrate how market interference affects pavement infrastructure, namely:

- Targeting requirements - only BEE 1, 2, 3 and 4 may tender on SANRAL projects;
- Sub-contracting conditions – 30% of the total contract value must be subcontracted to a targeted enterprise with a BEE level equivalent or higher than the main tenderer;
- Assistant contractor requirements – assistant contractor must be black;
- Key staff requirements – trial projects require at least two black key staff members, and
- Future planned restrictions – projected future planned restrictions to be implemented include only black assistant route managers may be employed, with at least one black woman, and further increases to the minimum number of required black staff.

A survey conducted by ECSA (2019) showed that registered professional black engineers constituted only 11% of the total engineering workforce in South Africa, with less than half being female. Whatever political justifications there are for demographic targeting, it poses a significant risk to project implementation and quality completion. In the event that you employ only black women or black assistant contractors, the quality of skills is inevitably lower simply because the current pool of engineers/skilled workers is lower among those individual demographic groups. Ever- increasing legislation required minimums representing a particular demographic group impacts the recruitment of competency levels in favour of skin colour. It is not currently possible to target only black workers without ultimately producing a decrement in the quality of skill pools which reverts to an impact in the delivery of desired project outcomes.

Further requirements which directly impact delivery are imposed by various governmental organs including the BBBEE Commission, the Department for Trade and Industry and the Construction Charter Council to name a few. Stringent labour laws which dictate minimum employment benefits, minimum wages and the introduction of additional revenue streams e.g. skill development levies have had various impacts on the industry and have often been commented on as contributory factors significantly increasing the cost of infrastructure delivery (SIPDM, 2016).

3.4.3 Poor government capacity

Poor government capacity is manifested in insufficient service delivery which South Africa is currently experiencing. Deficient service delivery is a reflection of all spheres of government and has been fuelled by loss of technical staff, ageing infrastructure, low maintenance, poor governance and corruption in public departments. Refusal by local municipalities to rely on available resources for instance, the South African Bitumen Association (SABITA) and the South African Institute of Civil Engineers (SAICE), has devolved into general decline in infrastructure and systems.

Programs run by SAICE which sought to aid municipalities with jurisdictional pavement management were seen as outside interference and abruptly ended in recent years which has arguably led to rapidly declining management practices since the last audits were conducted. The severity of poor governance is not well known as little public information is available to monitor the current state of affairs. SABITA also ran initiatives with municipal Councillors but were advised to cease assistance. Various reasons have been provided, which aimed to reduce the outside influence and public knowledge of operations. Corruption has been identified as a significant factor (Hanyane and Naidoo, 2015).

Following this argument, the Public Service Accountability Monitor of the UN confirms that a major obstacle to poor service delivery in South Africa, especially at local government, is poor governance practices, rampant corruption, and poor performance by leadership and officials in their management of public resources. “A lack of political will to act against underperforming officials is another critical factor resulting in poor service delivery” (Luyt, 2008; Naidoo, 2009).

3.4.4 Fundamental Economic Transformation

Achieving ‘Fundamental economic transformation’ is observed and experienced by many as one of the leading objectives in South Africa. This is exemplified by SANRAL in its Horizon 2030 Vision Statement as one of its 10 long-term objectives. This objective is most practically implemented using the Preferential Procurement Policy Framework Act (PPPFA, 2011) and the Preferential Procurement Regulations (PPR, 2017), which requires organs of state to award contracts based on preferential procurement through assigning preference points for predominantly BBBEE beneficiaries. For the majority of SANRAL projects, the relevant preference point system followed is detailed as follows (PPR, 2017): “for contracts with a Rand value above R50,000,000.00, a maximum of 10% points may be allocated for specific (preference) goals, provided that the lowest acceptable tenderer scores 90 points for price”. For projects below this threshold, an 80/20-point system is used, and applicable to many SANRAL pavement projects.

Effective implementation of these point systems allows for projects to be considered favourably given the specific socially orientated goals and, if the specific goals are adhered to by the tenderer, the tenderer may increase their price substantially compared to a tenderer who does not meet the social goals. Generous price increases often benefit stakeholders who form part of the tender approval authority. The Standard for Infrastructure Procurement and Delivery Management (SIPDM) states that “not less than 50% of the points shall be allocated to BBBEE goals”. These point systems can carry a price premium as high as 25% (SIPDM, 2016). Anthony (2018) reports that government procurement may account for as much as 21% of the total Gross Domestic Product of South Africa, which, if combined with a 25% price premium, may have detrimental impacts on the economy. The long-term effects of such procurement are not well documented and the impacts on ‘value for money’, a key indicator of both the World Bank and the South African Treasury, are yet to be understood (Jeffery, 2014).

A prominent risk of fundamental- or ‘radical’-economic transformation in South Africa is ‘radical economic robbery’. Radical economic robbery is a term used by the President of South Africa during the 2020 State of the Nation Address (SONA, 2020) to refer to the ‘so-called’ business forums that demand a share from any construction projects, often located within proximity to where the members live. What has largely fuelled the increasing negative impact of these business forums or ‘construction mafia’ are the misperceptions regarding beneficiaries in the South African public. There are those who believe that fundamental economic transformation gives one automatic access to contractual participation without being subjected to competitive bidding or having to contribute resources, work and guarantees. Large scale projects affected include the N2 Wild Coast Road Construction project and the R2.4-billion German oil storage investment project in Saldanha, among countless smaller projects (Carte Blanche, 2020).

3.5 ENVIRONMENTAL RISKS

Environmental risks are related to the impact of pavement infrastructure provision on the environment. This impact is predominantly characterised by emissions generated through infrastructure provision. These emissions affect the environment, but also have a direct effect on human health and well-being, highlighting the multi-dimensional nature of the risk.

3.5.1 Emissions

In this study, two separate types of emissions are focused on, namely environmental and social relevant emissions. Environmental emissions are “greenhouse” gasses (GHGs) affecting the climate, covered under the Kyoto protocol, such as CO_2 and Methane (IPCC, 2007). Emissions to water are also covered under environmental emissions. Social relevant emissions are those that predominantly affect human health such as Sulphur Dioxide (SO_2), Nitrogen Oxides (NOx), Particulate Matter (PM) and Volatile Organic Compounds (VOCs) (WHO, 2005).

3.5.2 Environmental emissions

To measure the environmental impact of the provision of pavement infrastructure, it is important to understand the various terms used to define it and its effect on the environment, such as "greenhouse gases", "CO_2", "CO_2e", and "carbon" as these terms may often be used interchangeably, and their meaning may become confusing (Brander, 2012).

A GHG is any gas in the atmosphere which adds to the greenhouse effect by absorbing and re-emitting heat, increasing the temperature of the planet above what it would normally be. CO_2 is the most common GHG emitted from human activities in terms of quantity and total global warming potential (GWP). The GWP indicates the amount of warming a gas causes over several years (typically 100 years). CO_2e is a term used to describe the collection of greenhouse gases in a common unit. For any quantity or type of GHG, CO_2e signifies its equivalent CO_2 and the GWP impact on the atmosphere. Embodied carbon refers to the CO_2e associated with the non-operational phase of the project. This includes the emissions caused by the extraction, manufacturing and production of material, transportation, construction, maintenance, rehabilitation, deconstruction and disposal and end of life aspects that make up the materials of a pavement. The whole life carbon of pavement infrastructure is both the embodied carbon and the CO_2e associated with the use (i.e. operational) phase of the pavement (IPCC, 2007; Brander, 2012).

An additional source of pollution, because of the provision of road pavement infrastructure, is emissions to water. Emissions to water include diesel, petrol and oil, harmful chemicals, paints, solvents and cleaners, construction debris and dirt, and polycyclic aromatic hydrocarbons (PAHs). These emissions are caused by, among others, typical vehicle use. Surface water run-off is a leading pathway for these pollutants with receptors typically including lakes, rivers, streams, groundwater and bays (UN, 2019). When the pollutants enter water sources, they poison the water life or lead to eutrophication, as well as any animal or human which drinks from them. This study focuses on PAHs and Nitrogen (represented by NOx in this study) as indicators of the emissions to water. PAHs are produced by the burning of crude oil-based products (diesel or heating oil in this study). When diesel or heating oil is burned, a certain number of PAHs are released into the atmosphere which eventually return to the Earth's surface and can contaminate water sources. The impacts of PAHs on water sources include lung, bladder as well as skin cancer. Nitrogen can also find its way back into water sources, but in this study, it is categorised as a social emission because of its direct impact on human health. Nitrogen in water sources often leads to a process of eutrophication with the result being hypoxia of the water source (Khan et al., 2014).

Specific site contamination as a result of sediment or debris runoff, for instance, is difficult to quantify and it depends, predominantly, on the quality of contamination management practices of the specific site. As such, this study does not focus on these types of contaminations, but their importance is acknowledged and highlighted.

3.5.3 Social emissions

Emissions from pavement infrastructure development that predominantly affect human health include SO_2, NOx, PM and VOCs. When these emissions are breathed in, they may cause nose, throat and airway problems, exacerbate asthma and in some cases cause cancer (WHO, 2005). Zietsman and Khreis (2019) argue that a child with asthma depends on a vehicle for transportation to a medical facility for treatment, where the vehicle spewing toxins, exacerbates the need for such treatment in the first place. This highlights the need to better understand the impacts of pavement infrastructure provision and their use in health.

3.5.4 Legislation governing emissions in South Africa

The main legislation which governs these emissions in South Africa is the National Environmental Management: Air Quality Act (AQA, 2004). The act forms the framework for the control of air pollution and defines the air emissions limits for specific activities and processes. According to section 29 of the AQA, any production process with over 0.1 Megatonnes of CO_2e emissions annually is required to provide a pollution prevention plan to the Minister for approval. The processing of crude oil at a refinery requires an Atmospheric Emission License. Defined emission limits (taken as daily averages) are provided for refineries in South Africa under the AQA. These emission limits are 20 tonne/day for SO_2, 4 tonne/day for NOx and 1 tonne/day for PM.

Although the Act does not place specific requirements on vehicle emissions, it does impose environmental levies on CO_2e emissions of new vehicles imported to or manufactured in South Africa. Furthermore, South African refineries are currently expected, by the Department of Energy, to produce Euro-5 specified fuels as part of the newly introduced Clean Fuels 2 program.

3.6 CLIMATE CHANGE RISKS

The climate we currently know is projected to change in the coming decades, being accompanied by wide-ranging known and unknown effects on physical, ecological and societal systems (Wardekker, 2011). Weather patterns are showing signs of increased severity globally and further discussions on the risks of climate change are presented in subsequent chapters.

3.7 SOCIAL RISKS

The vulnerabilities of South Africa's informal settlements have arguably increased over recent years, where a combination of lack of infrastructure, governance mismanagement, crime, increasing unemployment and expanding impacts of climate change have reduced the ability for many, especially in poorer rural areas, to meet their basic daily needs. It is often perceived that, for instance, providing better roads to these rural areas would increase the population mobility and employment opportunities. However, it is lesser known that the construction of roads in these areas may greatly exacerbate the already fragile social stability of the local populations. Steyn and Paige-Green (2009) demonstrate that a typical pavement structure per kilometre may use as much as 800,000 litres of water for construction purposes in South Africa equating to the water needs of roughly 5,000 people for one week (FBWP, 2007). This is one example of the multi-dimensional challenges settlements may experience.

As South Africa is expected to follow the global trend of rapid urbanisation (UN, 2018), the ever-growing number of cities and towns will become increasingly exposed to the devastating impacts of weather-induced natural hazards owing to enlarging socio-economic constraints already present within the settlement areas. Due to a growing population, and the projected increases in extreme weather events this poses increased, sometimes overlooked risk (Engelbrecht et al., 2019; Le Roux et al., 2019).

It would be short sighted to overlook the unique constraints and factors when considering pavement design, construction and management in these areas, to address the potential risks through effective planning and interventions to ultimately reduce vulnerabilities and strengthen settlement resilience. The Sustainable Development Goals (UN, 2019) stress the importance of profiling and identifying these vulnerabilities to develop an evidence base for necessary action.

Vulnerability profiling is however complicated due to a lack of quality data, socio-economic dynamics and complexity of social indicators, among others. The Council for Scientific and Industrial Research (CSIR) has created a framework, which may be used to profile the multi-dimensional and context-specific inherent vulnerabilities of settlements in South Africa (Le Roux et al., 2019). The framework describes, and in some instances quantifies, the vulnerabilities of people, infrastructure, economic activities,service provision and natural resources, among others and may be used as a good basis for settlement vulnerability identification.

The framework provides indicators for the social vulnerability (sensitivity and ability to respond to natural hazards), economic vulnerability (hazards that result in job losses, increased poverty, interruptions in business activities, etc.), physical vulnerability (built structures and expected degree of loss resulting from hazards) and environmental vulnerability (ecosystems, habitats, physical and biological processes, etc.).

From a pavement perspective, two key vulnerabilities are identified which may be greatly exacerbated by pavement development, namely settlement drought risk and settlement heat stress. Research by the CSIR (Beraki et al., 2019) modelled the future impact of drought on local settlements in South Africa, finding that 35% of settlements are at high or extreme drought risk for the period 2020-2050. In adaptation, it is necessary to determine the vulnerabilities of local settlements and adapt construction processes to mitigate the vulnerabilities through, among others, reducing or finding alternative sources for water use during construction.

3.8 MAINTENANCE RISKS

When considering risks to sustainable pavement infrastructure provision, maintenance is a key risk that deserves a focussed approach. Maintenance of the existing pavement involves performing roadworks required to arrest the deterioration of roads and to lower road user costs by providing a smooth-running surface and keeping the road open (SANRAL, 2009). There are various maintenance strategies that road authorities adopt which may be simplified into categories of either reactive-, partial reactive/proactive- or proactive- maintenance.

Reactive maintenance is a strategy that is effected only after a pavement failure or issue has occurred. These issues include development of potholes, damaged drainage structures or open surface cracks which require crews to be dispatched to remedy the situation. Reactive maintenance is considered an unsustainable strategy that decreases road user safety, costs more over the long-term and is often significantly more environmentally damaging.

Proactive maintenance, also referred to as preventative maintenance, entails adequate evaluation and planning of maintenance interventions in such a manner as to avoid acting out of a reactive stance. Well-developed pavement management systems require regular inspections, timely road-life-extension treatments and a timeline that ensures the long-lasting functional and structural performance of pavements. This maintenance strategy is significantly more economically, environmentally, and socially sustainable (Steyn and Visser, 2001).

3.9 CUMULATIVE RISK ASSESSMENT

Cumulative impacts can occur over different spatial and temporal scales by combining, interacting and compounding the overall effects, which often exceeds the traditional method of the simple sum of previous effects (Kotze, 2004). The challenge in applying a cumulative approach to risk management in the field of sustainable pavement engineering is understanding that pavements will be exposed to simultaneous effects of multiple risks. Commonly, these interactions have been modelled through multiple regression. However, an obstacle to this methodology is that as the number of potential risks grows, the number of possible outcomes become unwieldy (Rauer et al., 2008). In overcoming this obstacle, various researchers across numerous domains have employed the cumulative risk model (Rutter, 1979, Dawber, 1980, Kotze, 2004). Cumulative risk models proceed from the assumption of equifinality. In the case of sustainable pavement engineering, equifinality is the idea that different construction, maintenance and managerial choices, as well as impacts from a governmental and political sphere, can lead to similar sustainable outcomes over a pavement's design life. From this perspective, the number of risks, which characterise a pavement may account for sustainability more efficiently than the presence or absence of specific risk factors.

It is however commented that the approach of cumulative risk does inevitably result in lost information on variability within each risk factor (Rauer et al., 2008). Yet, this approach still offers advantages over multivariate approaches, in that a cumulative risk model can capture the natural covariation of risk within a given subject area. As the variable of interest is the total number of risks, the approach does not require that individual risks which may overlap, be treated as independent. Given that a cumulative risk assessment can be confidently used to determine how a pavement's experience of multiple risks moderates the association between a particular risk factor and sustainability (Gutman et al., 2003)

As no standardised methodology exists for cumulative risk impacts on pavement sustainability, the Cumulative Effects Assessment (CEA) developed by the South African Department of Environmental Affairs and Tourism for use in environmental management (Kotze, 2004) is focused on. This methodology includes three elements:

- Scoping;
- Describing the affected environment, and
- Determining the environmental consequences.

The cause or source is either naturally occurring events, such as climate change, or human-induced actions, such as maintenance strategy selection and implementation, which occur over time and space contributing to the cumulative impact on sustainability. The system structure and processes include economic, environmental and social systems which are affected by temporal and spatial processes. The similarities of this approach to pavements is highlighted.

In determining the environmental consequences, identifying and conceptualising the cause-effect relationships are often the most difficult to achieve. The US Environmental Protection Agency (US EPA, 2003) recommends that network or system diagrams are used for conceptualising. These models can be developed without knowing precisely the response to risk changes (i.e. the mechanism of the cause-effect relationship) and are used to visualise both relationships among risks and their relative impacts on the subject being studied (i.e. sustainability in this study). Rossouw et al. (1997) provide a conceptual depiction of the cause-effect relationships for roads, developed predominantly from an industrial development zone perspective, shown in Figure 3-2.

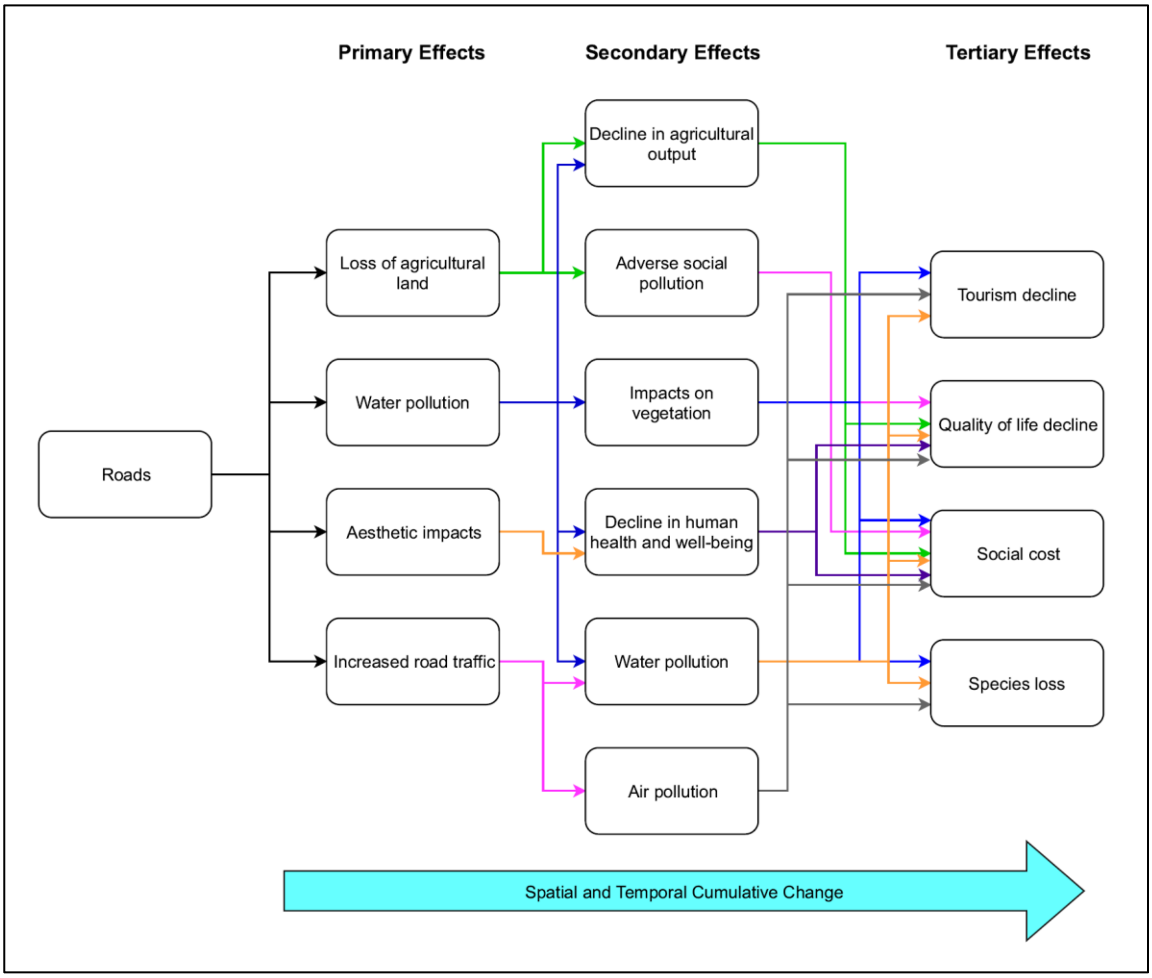


Figure 3-2: Simplified reproduction of negative cumulative effects and linkages (Rossouw et al., 1997)

The conceptual framework employed by Rossouw et al. (1997) is similar to the influence diagrams used in conceptualising complex neural networks for machine learning purposes. It is noted that the conceptualisation proposed by Rossouw et al. (1997) looks outwards, (i.e. starting at the road and viewing what it impacts), compared to the objective of this study which aims to look inward (i.e. looking at which risks affect the sustainability of the road). The use of this approach may be beneficial in developing a cumulative risk assessment for pavements if supplemented by probabilistic models which could model probability over both space and time. Markov-Chain Monte Carlo (MCMC) simulations are particularly useful in this regard.

3.10 SUMMARY

This chapter investigates the principles of risk management and how it is conducted within the context of pavement engineering. The risk analysis process can be an intricate process riddled with complexity in the modelling of often-subjective data, as the majority of studies utilise survey-based data. Furthermore, the complex nature of risk analysis has limited most studies to only qualitatively assessing risks and few cited studies have attempted to determine the relationship among risks and how the occurrence of one risk may increase another. Risks related to the pavement engineering field typically focus on construction and few studies have considered external risks (i.e. socio-economic risks, maintenance, etc.). No studies have aimed to quantify the effects of external risks on pavement infrastructure development.

When risks are studied, they are typically qualitatively assessed and a risk matrix or risk ranking is the most common method to provide significance to results. These studies provide a basis for understanding and the identified risks generally agree among literature. However, the prioritisation of risks may be situationally dependent and vary when considering the risks from either the contractor, client or consultants' perspective.

Quantitatively evaluating identified risks is a seemingly more complex procedure requiring knowledge of intricate mathematical models. However, the general complexity of the process is not overwhelming and the results are often highly valuable. As illustrated by McGoey Smith et al. (2010), construction elements may be isolated and individually evaluated, and if so chosen, the various elements may be grouped and analysed across a project's life cycle using time-dependent Monte Carlo simulations.

There are various methods of collecting data and assessing risks during pavement development. It is important that the rationale behind the choice of a method service the purpose of the research. Additionally, if a survey-based method is used, it is important to understand the principles behind the good practice in the conducting and reporting of survey research.

The key risk information gathered from the literature provided in this chapter is:

- Construction risks: lack of skills, quality assurance, impact on pavement performance and water use;
- Socio-economic risks: lack of funding, market interference, poor government capacity, demographics and distribution, local economic development, fundamental economic transformation;
- Environmental risks: emissions; water pollution, air quality, and material use;
- Climate change risks: changing weather patterns affecting pavement performance;
- Social risks: settlement drought risk and heat stress.
- Maintenance risks: long-term pavement performance.

These key risks will inform the development of various sustainable assessment methodologies throughout this thesis, building on the notion that sustainability and risk are two sides of the same coin.

4 CLIMATE CHANGE

4.1 INTRODUCTION

The Earth's climate has been unusually stable for the past 10,000 years, a period known to geologists as the Holocene, in which human civilisations arose, developed and thrived. Since the industrial revolution, a new era has arisen, referred to as the Anthropocene, in which human activities are believed to contribute to climate change (Crutzen, 2002; Steffen et al., 2007) and are pushing the Earth's system outside of the stable Holocene.

The Earth's complex systems often respond well to changing pressures, however, in the future, this may rather be the exception than the rule. As the environment becomes increasingly unstable, small shocks may push certain parts through the ceiling/threshold with potentially detrimental or even catastrophic consequences (IPCC, 2014; UN, 2019). Most of the thresholds are defined by either a critical value for a given control variable, such as CO_2e concentration, but not all subsystems have well-defined thresholds. For any quantity or type of greenhouse gas, CO_2e signifies its equivalent CO_2 and correlating global warming impact on the atmosphere.

Rockström et al. (2009) have identified nine such thresholds which are used to define the planetary boundaries, namely: climate change, rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorous cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading. This study focuses on predominantly climate change and global freshwater use boundaries.

The climate change boundary is based on two thresholds that individually and quantitatively define different climate-system states. The first is the atmospheric concentration of CO_2e and the second is radiative forcing (measured in watts per square meter) (Rockström et al., 2009). Considering these thresholds, Rockström et al. suggested that atmospheric CO_2e concentrations should not exceed 350 p.p.m.v. and that radiative forcing should not exceed 1.0 $W.m^{-2}$ above pre-industrial levels. It is believed that if these thresholds are crossed, irreversible climate change would occur. At the time of writing this chapter, the global CO_2e concentrations are 415 p.p.m.v and radiative forcing is estimated to be above 1.6 $W.m^{-2}$ (NASA, 2021).

The effects of climate change in South Africa, up until recently, have been understood to generally mean a gradual increase in temperature and accompanied drying of the atmosphere, which for most pavement structures, are expected to have minimal influence (Paige-Green et al., 2019) and may even present positive impacts. Taylor and Philp (2015) modelled the effects of gradual drying on pavement infrastructure using the Thornthwaite Moisture Index (TMI) as a key climate variable and concluded that climate change may present performance opportunities, especially in granular base pavements.

Given this multiplex relationship, the impacts of climate change on pavement infrastructure have not yet holistically been defined in road construction and have been at best disjointed to date. To address this issue, the Africa Community Access Partnership (AfCAP) research programme was commissioned to help mitigate the significant threat of climate change to Africa's development and produce regional guidance on the adaptation of roads to climate change (Head et al., 2019).

The programme suggestion is that 'new or upgraded/rehabilitated roads must be designed to minimise vulnerabilities' and that 'climate change risk assessments must be embedded in road asset management systems' (Paige-Green et al., 2019). The development of climate change risk assessments is however fractured and standardisation is still required. In this chapter, a literature review is conducted to identify the key climate change risks, extended to include certain settlement vulnerabilities. The review further seeks to detail potential sources for obtaining climate change projections for the key risks identified. A flow chart of the process followed is shown in Figure 4-1.

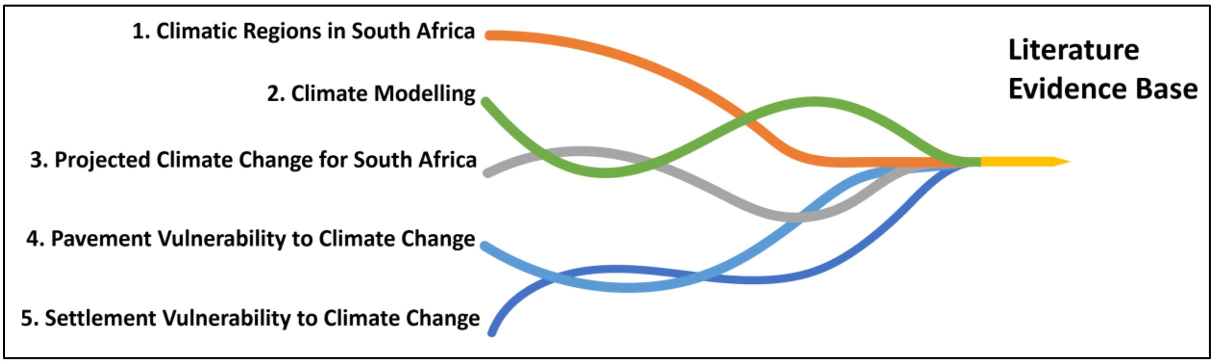


Figure 4-1: Structure of the chapter

4.2 CLIMATIC REGIONS IN SOUTH AFRICA

4.2.1 Thornthwaite's Moisture Index

The Thornthaite Moisture Index (TMI), introduced in 1948, is a global climate classification system describing the humidity or aridity of the climate and soil of a region and, since its advent, its applications have extended far beyond climate classification to pavement systems. The TMI calculation, Im, is shown in Equation 4-1 (Mather, 1974):

$$Im = 100[(P/PE) - 1] \qquad \text{(Eq. 4-1)}$$

where:

Im is the Thornthwaite Moisture Index (unitless);

P is the annual precipitation (cm), and

PE is the annual potential evapotranspiration (cm).

The following threshold values in terms of TMI are used to classify a region (Thornthwaite, 1948):

- TMI < -40 – arid;
- -40 < TMI < -20 – semi-arid;
- -20 < TMI < 0 – dry sub-humid;
- 0 < TMI < 20 – moist sub-humid, and
- TMI > 20 – humid.

As climate change is expected to manifest in a gradual increase in temperature and accompanied drying of the air, the TMI for the majority of South Africa is expected to reduce and climatic zones to shift from more humid zones to increasingly arid zones. These shifts are understood to be positive from a pavement performance perspective (Taylor and Philp, 2015; Shoa et al., 2017), as moisture damage is a leading contributor to accelerated pavement failure (SAPEM, 2017). The climate change projections produced by the CSIR are evaluated later in this thesis, and the effects of changes in TMI are inventoried. Note that TMI does not reflect flooding or sheet flow, water erosion and other types of damage caused by excessive rainfall nor its impact on the water table, even for a relatively short duration. TMI is similar to the Weinert N-value which relates the ratio of evaporation during the warmest month and monthly rainfall to the durability of road-building materials (Weinert, 1980).

4.3 CLIMATE MODELLING

4.3.1 Modelling scenarios

Due to the increased attention and modelling efforts of climate change, the Intergovernmental Panel on Climate Change (IPCC) developed one metric and baseline to be used as a starting point for climate change-related research. This is to allow for easy comparison and correlation among studies.

The first set of climate change scenarios was published in 1992, called the IS92, shortly followed by the second generation (Special Report on Emissions Scenario), the third generation (Third Assessment Report), and the fourth generation (Assessment Report Four) of scenarios (Wayne, 2013). The fifth and currently used generation (Assessment Report 5) scenario is called the Representative Concentration Pathways (RCPs) (IPCC, 2014).

The RCPs constitute the cumulative emissions of CO_2e and are used to model the global mean surface warming by the late 21st century and beyond. The RCPs are a set of four scenarios which are used to simulate the future contribution of global warming to climate change. These four scenarios are RCP8.5 (with radiative forcing >8.5 $W.m^{-2}$), RCP6 (with a radiative force of approximately 6 $W.m^{-2}$), RCP4.5

(with a radiative force of approximately 4.5 W.m^{-2}) and RCP2.5 (with a radiative force of approximately 2.5 W.m^{-2}).

RCP2.5 represents a scenario, which aims to keep global warming below 2°C above pre-industrial temperatures. Even though RCP2.5 is potentially still within reach, most literature suggests that RCP8.5 (representing the extreme scenario) is the most likely pathway which will be followed up until 2100 and is subsequently used in most climate change models and studies (Lahera, 2017).

4.3.2 Climate models

Climate models are computer programs utilising mathematical algorithms governed by the laws of physics and chemistry, used to simulate the Earth's climate and the projected changes to the climatic system (USDA, 2013).

These models typically use a three-dimensional grid, which divides the atmosphere and oceans into cells and are used as computational units (USDA, 2013). These cells are commonly quite large (i.e. 50 × 50 km) and have a low resolution due to the high system processing requirements of climate change modelling. Regional climate models, focusing on either a small country or region of a country may be limited by the exclusion of accurate global influence on the region (Lahera, 2017). Climate models further vary over a wide range of areas depending on both projected socio-economic developments and the climate policy of the region (IPCC, 2014).

Currently, the most accurate and highest resolution (8 × 8 km) regional climate models for South Africa are produced by the CSIR delineated in the Green Book (Engelbrecht et al., 2019a). These models are the most detailed projections ever generated for the region (Engelbrecht et al., 2019a). The Green Book (Engelbrecht et al., 2019a) models utilise two of the RCPs (RCP 4.5 and RC P8.5) and assume low implementation of mitigation measures in the future by southern African authorities.

4.4 PROJECTED CLIMATE CHANGE FOR SOUTH AFRICA

The climate we currently know is projected to change in the coming decades, being accompanied by wide-ranging known and unknown effects on physical, ecological and societal systems (Wardekker, 2011).

IPCC AR5 projections point to an annual temperature increase of between 0.3 to 2.5°C by 2050, relative to the 1985-2005 climate average (Stocker et al., 2013). Over southern Africa, temperatures are expected to rise faster than the global average and are accompanied by reduced rainfall. Although invariably, debate about the impact of climate change has negative connotations, road managers in

South Africa are fortunate that less rainfall is expected to be beneficial. However, climate change will present additional risks specifically to settlements, focusing predominantly on water usage for pavement construction.

4.5 PAVEMENT VULNERABILITIES TO CLIMATE CHANGE

4.5.1 Vulnerability to temperature

The predominant flexible pavement hazards related to increased temperatures are, among others (Paige-Green et al., 2019):

- Accelerated age hardening of bitumen (i.e. loss of volatiles) and softening of bitumen binders under high temperatures;
- Reductions in moisture content (shrinkage of soils);
- Faster reaction rates during alteration of road materials (i.e. weathering) and chemical stabilisation, and
- An additional hazard related to settlement vulnerabilities is the greater water requirements for constructing stabilised layers.

High temperature is known to accelerate asphalt ageing, which occurs in two stages, namely, short term- and long term-ageing. Short-term ageing refers to the ageing that asphalt undergoes during manufacturing, storage, transport, and paving, whereas long-term ageing occurs over the lifetime of the asphalt and is primarily affected by traffic and environmental impacts. The mechanisms of ageing are complex with the main mechanisms summarised as oxidation, loss of volatiles, steric hardening, exudation, and internal/external oxidative coupling (O'Connell and Steyn, 2017).

The maximum air temperatures throughout South Africa exceed 35°C with sunshine varying between 80% in the north-west, 70% over the remaining interior and 60% over coastal areas. These high summer temperatures coupled with high levels of ultraviolet exposure accelerate in-service ageing of thin bituminous surfaces throughout South Africa and are expected to increase due to climate change (Paige-Green, 2009).

Thermal ratcheting, referring to the successive cycles of heating and cooling, may also influence the asphalt mix, where rapid temperature fluctuations require a more balanced mix (Croll, 2009). Thermal ratcheting is prevalent in places such as the Highveld, South Africa, where warm summer afternoons are prone to sudden thunderstorms which greatly fluctuate the pavement temperature, more specifically the surface temperature. This is especially important in these areas as these temperature fluctuations often occur in concert with peak hour traffic and require asphalt mixes, which can resist both rutting and fatigue cracking simultaneously under the effects of traffic loading (TRL, 2008).

Pavement temperature gradient variations, referring to the fluctuation of temperature with pavement depth (from the surface layer to lower pavement layers) particularly if they are great, influence the disintegration of aggregate. In granular base pavements, the upper layer of the base is heated during the day while the lower interior aggregate remains fairly cold (Weinert, 1980; Teltayev and Suppes, 2019). The boundary between hot and cold aggregate creates stress concentrations that, together with unloading effects, lead to horizontal crack development and failure. During the night, the process reverses with the outer layer cooling down quicker than the interior, shrinking more and developing vertical cracks. This is an example of aggregate disintegration previously discussed.

Decomposition of rock, which even though requires moisture, is also affected by temperature, where increased temperatures may dramatically accelerate the rate of oxidation and reduction, carbonation and hydration (Weinert, 1980).

4.5.2 Temperature influence on pavement life

Miner's law, popularised by M.A. Miner in 1945, is one of the most widely used, and potentially simplest, cumulative damage models for fatigue-related failure (Jordaan, 1994). Miner's law, shown in Equation 4-2, states that if there are n different stress levels and the average standard repetitions to failure at the ith stress is Ni, then the damage fraction, D, is:

$$D = \sum_{i=1}^{n} \frac{ni}{Ni} \qquad \text{(Eq. 4-2)}$$

Where:

D = the total fraction of the pavement life used at each different stress/strain level;

ni = the number of standard repetitions at the i stress/strain level, and

Ni = pavement life at the i stress/strain level.

Combining Miner's Law with the Mean Monthly Pavement Temperature ($MMPT$), shown in Equation 4-3, the influence of temperature on pavement damage may be calculated.

$$MMPT = \frac{5}{9}\left(\left[0.76\frac{Z}{25} - 1.7\right] + \left[1.8 - 0.017\frac{Z}{25}\right]\left[\frac{9MMAT}{5} + 32\right]\right) - 32 \qquad \text{(Eq. 4-3)}$$

Where:

$MMPT$ and Mean Monthly ambient Temperature ($MMAT$) are measured in °C, and

Z = Depth (mm).

Jordaan (1994) demonstrates these impacts by showing that typical seasonal temperature variations may increase pavement damage between 5-15% compared to common fair-weather conditions in South Africa.

A similar study (Gudipudi et al., 2017) modelled the impacts of climate change on pavements across the United States and found that temperature increases predicted from climate change models using RCP8.5 may result in increased fatigue cracking of between 2-9% and increased rutting of between 9-40%, supported by Chen et al. (2021) The study did not model the impacts of increased precipitation alone, but rather incorporated precipitation data along with temperature projections in a separate analysis and concluded no substantial differences were observed in pavement performance.

Further modelling climate change-induced temperature impacts on pavements, Chen et al. (2021) found that an average air temperature increase of 4°C could reduce service lives of asphalt overlays by 3 years before the first overlay and 7 years before the second overlay based on a failure threshold of 20% fatigue cracking.

It is evident that temperature plays a crucial role in pavement performance and that both the climate change-induced gradual temperature increase (affecting PG specification) and the increased frequency and intensity of very hot days (accelerating pavement degradation) should be considered during pavement design.

4.5.3 Vulnerability to moisture

It is generally projected that precipitation will decrease over South Africa. However, the intensity and frequency of extreme rainfall events are likely to increase significantly with longer periods of reduced rainfall between these extreme events. These climate change impacts will have the following effects on flexible pavements (Paige-Green et al., 2019):

- Damage to thin surfacings and asphalt;
- More rapid binder deterioration;
- Reduced equilibrium moisture contents;
- Reduced soil and construction material strengths;
- More erosion and siltation, and
- Increased demand for fit-for-purpose drainage systems.

In a general sense, moisture damage in asphalt may be defined as the loss of adhesion between binder and aggregate which results in decreased strength and durability and commonly manifests itself in the form of stripping. Stripping refers to the loss of bond between the aggregate and asphalt binder that typically begins at the bottom of the asphalt layer and progresses upwards. However, it may also begin at the surface and progress downwards, commonly referred to as ravelling. Increased moisture may accelerate moisture damage and associated stripping of asphalt, being the most common cause of pavement failure in South Africa (SAPEM, 2017).

Similar to temperature variations, moisture too influences pavement response under loading. The characteristics of granular material changes depending on the moisture regime, where increased moisture content typically decreases the bearing capacity of the granular layers and subgrade.

It is known that performance indicators such as deflection measurements are influenced by moisture, where the maximum deflection is often recorded after a rainy season. The effect of moisture on pavement life has yet to be quantified in South Africa and as such, no procedure considering moisture content is available (Jordaan, 1994). Jordaan does however recommend that the effect of moisture may again be quantified using Miner's law, where similar to temperature increases, an increase in moisture content is expected to reduce effective pavement life.

4.5.4 Moisture influence on effective pavement life

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4.5.5 Vulnerability to extreme weather events

In this thesis, the focus is on the impacts of climate change as the gradual warming and drying of the atmosphere, on the performance and life cycle assessment of a typical flexible pavement. However, impacts of extreme weather events are not considered in this thesis, which will typically manifest as changes in the intensity and frequency of storm events, flooding and very hot days. Further discussions of their omission are provided in Chapter 9 and reside predominantly in the increased error associated with modelling and are accompanied by higher uncertainty of predictions. These extreme events are expected to have an impact on pavement sustainability and will notably result in distresses associated with accelerated asphalt binder ageing, stripping, rutting and shoving, among others. Changes in pavement design (Qiao et al., 2020) and asphalt material selection to meet the quality needed for future thermal and moisture conditions will be required (Practicò et al., 2011). For instance, better-performing asphalt surfacing layers could be achieved with bitumen modification (Sarroukh et al., 2021) and through specifying performance graded asphalt binders (Bredenhann et al., 2019; Mokoena et al., 2019), as currently being trialed in South Africa and internationally.

4.6 PAVEMENT DETERIORATION MODEL INCORPORATING CLIMATE CHANGE IMPACTS

In determining the impacts of climate change on pavement performance and deterioration, the selection of environmental dependent deterioration models is important. Pavement roughness, a key variable used in modelling pavement deterioration, is utilised by SANRAL (SAPEM, 2014) as well as many international road authorities (FHWA, 2017). Various methods exist to measure pavement roughness. These methods do not all measure roughness the same way and their varying sensitivities do not make all methods applicable for the same conditions. As such, the World Bank sponsored a major study to investigate and standardise pavement roughness measurements leading to the development of the International Roughness Index (IRI) (Sayers et al., 1986 a,b). The IRI best satisfies the requirements of being time-stable, transportable, relevant and readily measurable (Sayers et al., 1986a).

Currently, the South African Pavement Engineering Manual (SAPEM, 2014) presents the following formula, shown in Equation 4-4, for use in estimating IRI deterioration for roads in South Africa:

$$IRI = \frac{N}{10^6} \times \left(\frac{\in}{1350\mu strain}\right)^4 \qquad \text{(Eq. 4-4)}$$

Where

IRI = International Roughness Index (m/km);

N = load repetitions to cause present condition, and

$\in$ = normal strain.

It is observed that Equation 4-4 does not readily take into account the direct impacts of environmental influence. However, an earlier version of the simplified equation, developed as part of the Highway Design and Maintenance Standards Model 3 (HDM-III) (World Bank, 1987), also used in the revised HDM-4, does take environmental impacts into account. This empirical equation is shown in Equation 4-5 and Equation 4-6:

$$IRI_1 = IRI_0 + \Delta IRI \qquad \text{(Eq. 4-5)}$$

where

IRI_1 = IRI at year 1;

IRI_0 = IRI at year 0;

ΔIRI = predicted change in IRI during the analysis year, given by Equation 4-6:

$$\Delta \text{IRI} = K_{gp}[134e^{mt}(SNCK+1)^{-5}YE4 + 0.114\Delta RDS + 0.0066\Delta CRX + 0.42\Delta APOT] + K_{ge}(0.023IRI_0) \qquad \text{(Eq. 4-6)}$$

and

K_{gp} = user-specified deterioration factor for roughness progression (default value = 1);

K_{ge} = user-specified deterioration factor for the environment-related annual fractional increase in roughness (default value = 1);

$SNCK$ = modified structural number adjusted for the effect of cracking;

$YE4$ = annual loading ;

ΔRDS = annual increment in standard deviation of rut depth;

ΔCRX = annual increment in indexed cracking;

$\Delta APOT$ = annual increment in potholing;

m = environmental coefficient (determined from TMI), and

t = years since last major treatment.

A study by Taylor and Philp (2015) extended the use of this equation to model pavement deterioration incorporating climate change impacts, with IRI as the key output variable. This model is shown in Equation 4-7:

$$IRI(t) = IRI_0 + 196.74Z(t) + 0.016c\,(t) + 0.25r(t) + 0.972E(t) \qquad \text{(Eq. 4-7)}$$

Where:

t = analysis period;

$IRI(t)$= Roughness at end of analysis period;

IRI_0 = Roughness at end of analysis period;

Z = Cumulative traffic loading;

c = Percentage cumulative cracking;

r = Cumulative rutting deterioration, and

E = Environmental factor (determined from TMI).

Equation 4-7 was successfully implemented by Taylor and Philp (2015), and subsequently by Shoa et al. (2017), to model the effects of changes in TMI, as a result of gradual climate change, on pavement performance. Both Taylor and Philp and Shoa et al. found that a decrease in TMI as a result of gradual drying of the environment over most of the study area, slightly improved the performance of pavements when measured using IRI. Incorporating this approach into Equation 4-5, the effects of climate change on pavements in South Africa may be modelled.

4.6.1 Effect of pavement deterioration on fuel consumption

Zaabar and Chatti (2010) researched the relationship between pavement deterioration and vehicle fuel consumption, using HDM-4 calibrated with field data. The calibrated model accurately predicted the fuel consumption of five different vehicle classes compared to a change in IRI. Relevant simplified results are reproduced in Figure 4-2.

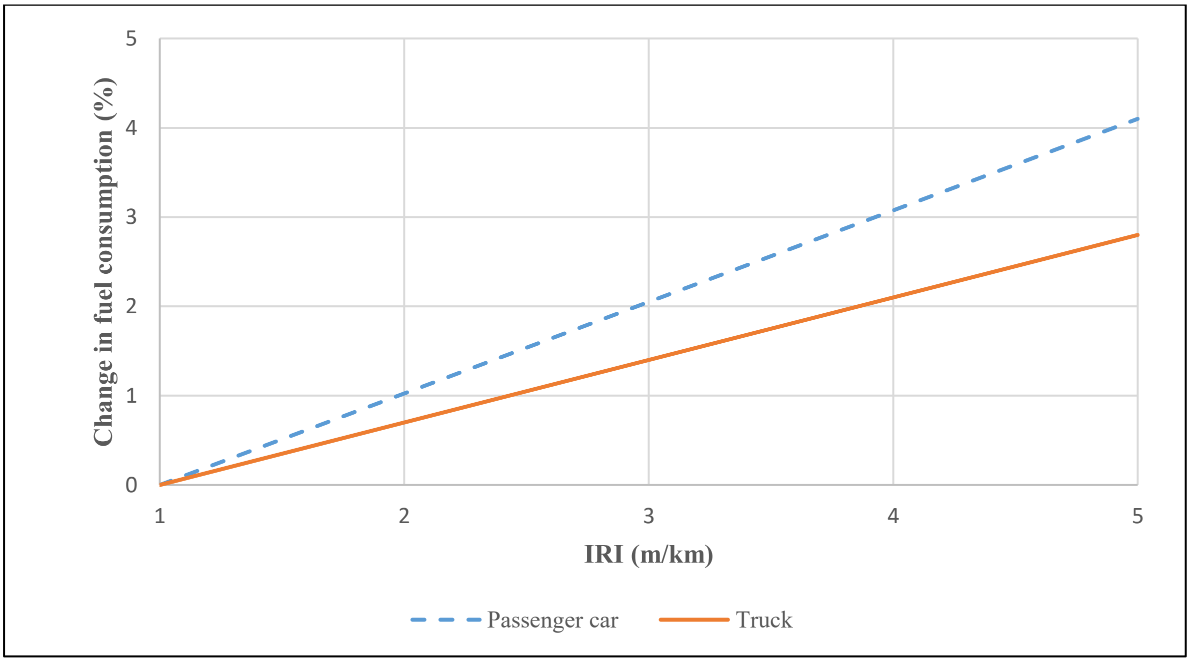


Figure 4-2: Simplified reproduction of the effects of pavement roughness on fuel consumption (adapted from Zaabar and Chatti (2010))

Similarly, Bester (1984) researched the impacts of pavement type and roughness on vehicle fuel consumption in South Africa to develop a justification model for major road maintenance projects. Bester concluded that pavement type and other influencing factors bear little influence on fuel consumption, but that pavement roughness is the leading variable. Bester presented the following empirical formulas for both passenger cars on surfaced (Equation 4-8) as well as trucks on all roads (shown in Equation 4-9):

Passenger car

On surfaced roads:

$$F = 18.4 + 0.91R + \frac{450}{V} + (0.0518 + 0.0013R)V^2 + 1224G \qquad \text{(Eq. 4-8)}$$

Truck

On all roads:

$$F = 47.4 + 10.67R + \frac{600}{V} + 0.178V^2 + 5750G \qquad \text{(Eq. 4-9)}$$

Where

F = fuel consumption (ml/vkm);

R = road roughness (m/km);

V = speed (m/s), and

G = gradient (m/m).

Extending this research, Du Plessis et al. (1990) aimed to quantify the impacts of pavement roughness on vehicle resistance and subsequently fuel consumption in South Africa. Du Plessis et al. made use of a quarter-car index (QI) range between 15 and 80 QI to measure roughness. This range corresponds to an IRI range of roughly 1.2 and 6.2 m/km.

Du Plessis et al. (1990) found that fuel consumption for a passenger car increases between 2.5% and 5.1% after a jump in roughness from 1.2 m/km to 6.2 m/km. For trucks, an increase of between 6.1% and 6.8% for a similar change in roughness. Du Plessis et al. (1990) concluded that the relationship is very similar to that of Bester (1984), and considering more recent research, both relationships are in line with the findings of Zaabar and Chatti (2010).

4.6.2 Translating pavement deterioration to use phase emissions

In translating pavement deterioration effects (measured using IRI) into use phase emissions, Xu et al. (2019) proposed Equation 4-10:

$$GWP_{IRI} = \sum_{t=1}^{T} \Delta IRI_t \times \left(\Delta AADTT_t \times K_{fc_{truck}} \times EF_{diesel} + \Delta AADT_t \times K_{fc_{car}} \times EF_{petrol/diesel}\right) \times t \qquad \text{(Eq. 4-10)}$$

Where

GWP_{IRI} = Global Warming Potential (GWP) from roughness induced pavement-vehicle interaction (PVI);

ΔIRI_t = change in IRI within time interval t;

$\Delta AADTT_t$, $\Delta AADT_t$ = truck and car traffic during time t;

$K_{fc_{truck}}$, $K_{fc_{car}}$ = empirical coefficients translated to IRI fuel consumption derived from Zabaar and Chatti (2010), and

EF_{diesel}, $EF_{petrol/diesel}$ = GWP emission factors for diesel and petrol.

Equation 4-10 is simply an adaptation of Equation 4-5 previously discussed and translates the effects of IRI changes to vehicle emissions using GWP emission factors for petrol and diesel. An evident limitation of Equation 4-10 is that it focuses only on GWP measured using CO_2e and omits consideration of other important emissions which do not necessarily impact climate change, but on human health for instance.

4.7 SETTLEMENT VULNERABILITIES TO CLIMATE CHANGE

The vulnerabilities of South Africa's settlements have arguably increased over recent years, where a combination of existing challenges and the expanding impacts of climate change have reduced the ability for many, especially in poorer rural areas, to meet their daily basic needs. It is often perceived that, for instance, providing better roads to rural areas increases their mobility and employment opportunities. However, it is lesser known that the construction of roads in these areas may greatly exacerbate the social stability of local populations. Steyn and Paige-Green (2009) demonstrate that the construction of a typical pavement in South Africa may use as much as 800,000 litres of water per kilometre equating to the water needs of roughly 5,000 people for one week (FBWP, 2007). This is one example of the multi-dimensional challenges settlements may experience, and these challenges are often location-specific and not constant globally.

4.7.1 Water use during pavement construction

Water use may be classified as a non-renewable material (Steyn and Paige-Green, 2009; Netterberg, 2004) and is primarily needed during material extraction and compaction of pavement layers, especially granular layers. The quality of the water used for both processes generally needs to be of a near potable or 'drinkable' quality (COLTO, 1988; SABITA, 2019) as contaminated water may lead to accelerated weathering of aggregate, among other concerns.

'Drinkable' quality water in South Africa is arguably rare, and its availability for use in road pavement construction, especially in rural areas, is a serious challenge. The recent Blue Drop report released by the Department of Water and Sanitation of South Africa (Blue Drop, 2017) reported that only 44 out of 1036 municipal drinking water systems complied with Blue Drop standards. This is a notable decline from the previous Blue Drop report. Verlicchi and Grillini (2020) state that South African rural populations typically do not have access to safely managed water, with the situation predicted to greatly worsen in coming years due to various factors, including climate change. It has become common practice for these populations to rely on untreated surface and groundwater sources.

Given the state of water availability and quality in South Africa, the use of treated water in road pavement construction is an unjustifiable requirement. Having recognised this, the updated Committee of Transport Officials (COTO, 2020) standard water quality requirements for pavement construction have been considerably relaxed, with key specifications reproduced in Table 4-1.

Table 4-1: Construction water for earthworks and pavement layers in South Africa (COTO, 2020)

Purpose	**Electric Conductivity at 25°C (maximum)**	**Total Dissolved Solids (TDS) (maximum)**	**pH range at 25°C**
Crushed stone base layer compaction and slush - compaction	170 mS/m	1200 mg/l	5.0-9.7
Chemical stabilization compaction and curing	170 mS/m	1200 mg/l	5.0-9.7
Bituminous stabilization	170 mS/m	1200 mg/l	5.0-9.7
Other layers and materials	370 mS/m	2400 mg/l	4.0-10.0
Potable water*	0-70 mS/m	0-450	6.0 – 9.0

* South African Water Quality Guidelines (WQG, 1996)

A review of recent dam, lakes and river water quality data, consisting of over 70,000 samples taken for the period 1999-2012 by the Department of Water Affairs in South Africa (Huizenga et al., 2013), shows that the quality of raw water found across South Africa conforms to the water quality requirements (COTO, 2020) for earthworks and pavement layer construction. The results are summarized in Table 4-2.

Table 4-2: Average raw water quality for dams, lakes and rivers in South Africa (1999-2012) (Huizenga et al., 2013)

	Electric Conductivity at 25°C	**Total Dissolved Solids (TDS)**	**pH range at 25°C**
Dams and lakes	38.5 mS/m	251.5 mg/l	8.0
Rivers	74.6 mS/m	487 mg/l	7.9

Given that most raw (i.e. untreated) surface water in South Africa conforms to the requirements for use in pavement construction, treated water is essentially only required to produce bitumen emulsion and concrete.

As stated by Steyn and Paige-Green (2009), a layer kilometre generally requires between 150 and 200 thousand litres of water for compaction, equating to between 20.83 and 27.79 l/m^2 per compacted layer in South Africa, or 800,000 litres per kilometre pavement. Although much of this water will evaporate and return to the earth's surface in the form of precipitation or form part of the surface or groundwater flows, it is a long process and local depletion of water can occur rapidly especially in water-scarce areas and areas under threat of becoming drier due to climate change. Injudicious water use for construction may effectively reduce the natural capital of an area and as such, it is difficult to justify the use of both treated and untreated water in relatively arid areas, where the local populations struggle to meet their own daily water needs (Steyn and Paige-Green, 2009; Netterberg, 2004).

The ongoing problems associated with water use for pavement construction has led to numerous discussions in recent years, where the potential use of seawater is often raised (Netterberg, 2004; de Carteret et al., 2010). Seawater currently does not conform to the COTO (2020) requirements listed in Table 4-2. Early studies in southern Africa (Woodbridge et al., 1994) have however trialled various construction approaches using seawater and found that even though salt does pose a significant threat to pavement performance, predominantly through affecting the bond between the base and surface course (i.e. mechanical delamination caused by crystallisation), the use of impermeable membranes in lower layers could prevent this mechanism of distress through prohibiting the salt to reach the upper levels of the base layer. Experimental sections of a road constructed in Lüderitz in 1976 have further shown that seawater can be used to effectively construct pavement layers and provide long-term performance, provided certain precautions are taken in design and construction (Netterberg, 2013). The use of seawater may be a significant opportunity, especially for coastal towns such as Cape Town. Further research is however required to allow the development of suitable guidelines in South Africa and incorporation into pavement design and construction.

4.8 SUMMARY

Climate change vulnerability and impact assessments have become a global concern and their implications on transport policies profound. Yet, as illustrated in this chapter, current design, construction and maintenance strategies need to be adapted to the key risks, not only regarding pavement infrastructure provision, but its impacts on human settlements as well if long-term sustainable aspirations are to be achieved. Sufficient methodologies are currently available to quantify the impact of climate change on pavement performance in terms of structural and functional performance as well as environmental damage caused by increased road user emissions.

South Africa is predicted to be more affected by climate change than most other regions, despite having only marginally contributed to it. The future South African climate will predominantly take the form of warmer drier weather patterns due to gradual climate change, emphasising water constraints and the social impact of water use. However, the occurrence of climate change is expected to be beneficial for the majority of pavements across South Africa. This is predominantly due to the gradual ryign and warming of the atmosphere across the majority of South Africa, which will increase the aridity of most climatic zones which is closely correlated to improved pavement performance. Further details to these observations are provided in Chapter 9 where climate change impacts on pavements across South Africa are quantified and detailed.

It is submitted that pavement engineers, contractors and road authorities need to consider a future climate during pavement development and maintenance and incorporate additional adaptation measures to increase the resilience of pavements and reduce impacts on local settlements. This may practically be achieved through basing designs on future climate projections compared to observed historical climate data, and that design charts which consider climatic regions (i.e. TMI) be updated for a future climate analysis. There is a general requirement for more design charts that highlight high risk regions related to settlement vulnerabilities.

5 PROBABILISTIC MODELLING

A variety of probabilistic models are available which have been successfully implemented in the field of sustainable pavement engineering aiming to capture uncertainty within datasets. Prominently used models include Bayesian analyses, Monte Carlo simulations and Markov Chains (Wang, 2016). This chapter provides an introduction to the basic methodologies of application related to the before-mentioned models and comparing the models to determine the suitability for risk-based sustainable pavement engineering applications.

5.1 BAYESIAN ANALYSIS

Bayesian analysis is a statistical technique, which endeavours to estimate underlying distribution parameters based on an observed distribution (Gelman et al., 1995). The method begins with a 'priori distribution' that has no limitations and may even be non-Bayesian observations. The priori is the value that a statistician would expect from the outcome without having any evidence or data to support it. Data are then collected from various sources (e.g. trials, experiments, field data, expert opinions, literature, etc.) to form the observed distribution. Probability is then calculated as the likelihood of the observed distribution, which is a function of the underlying distribution parameters. Multiplying this likelihood with the priori distribution and normalising the data results in a unit probability over all possible values known as the posteriori distribution (Hoel et al., 1971). Posteriori distributions are more homogenous than priori or likelihood distributions. The probability theorem may be simply illustrated using Baye's rule for two events A and B which have probabilities P(A) and $P(B) \neq 0$ respectively. The definition of the conditional probability of A given B is:

$$P(A \mid B) = P(A \,\&\, B) / P(B)$$

where (A & B) denotes the event where both A and B occur and P(A & B) denotes its probability of occurrence. Parameter P(A | B) describes the probability of event A occurring given that event B has already occurred. Considering the Venn diagram shown in Figure 5-1, as long as both event A and B are possible, then symmetry implies that the probabilities of conjunction A & B are equal to:

$$P(A \mid B)\, P(B) = P(A \,\&\, B) = P(B \mid A)\, P(A),$$

simple arithmetic rearrangement shows that

$$P(A \mid B) = P(A)\, P(B \mid A) / P(B)$$

which is Bayes' rule. The rule shows that the probability of A given B may be converted into the probability of B given A. In simpler terms the theorem may be used to calculate the probability of A through calculating the probability of B if, for instance, there is a lack of information of A and sufficient information for B. This may be illustrated in the probability of a pavement being sustainable given a certain level of risk which may be computed from the probability that risk will determine the level of sustainability of a pavement.

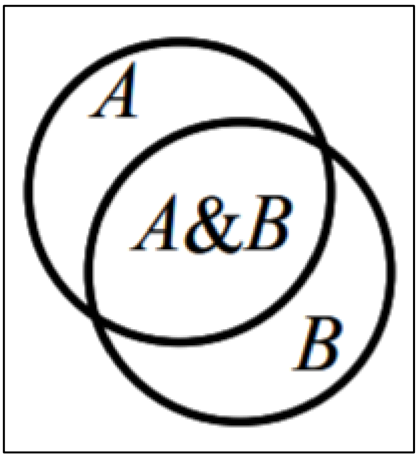


Figure 5-1: Venn diagram illustrating Baye's theorem

Bayesian analysis has been commented on to be controversial given the validity of results depends on how valid the priori distribution is - which cannot be statistically assessed (Press et al., 1992). However, the method has successfully been implemented in numerous pavement engineering related studies, especially where poor-quality data is available (Wang, 2016).

Baye's theorem works well when combined with sampling techniques and approaching a mathematical problem by observing results from a large set of trials or experiments instead of focusing on a close form solution. By using a large dataset, the law of large numbers applies, ensuring that the approximation will be a true value of the unknown parameter modelled. Bayesian statistics thus allows for a model which can learn from experience, consider human opinions and recognise the existence of uncertainty among predictors. Together, the model takes advantage of conditional probabilities, to produce a probabilistic representation of model parameters that best fit the observed data.

5.1.1 Examples of Bayesian application in construction risk management

Otobo (2016) conducted a survey questionnaire focused on risks affecting construction projects within an African developing countries context. The study provided respondents with 79 pre-identified risks and allowed respondents to assess their perception of the 79 risks based on the likelihood and impact of occurrence on construction projects. 27 critical risks were subsequently identified from the survey and Bayesian analysis techniques were applied to the critical risks to examine the cause and effect relationship among the risks. The relationships and relationship weights between risks were determined from literature and subjective judgement. The results provided a clear indication of which risks affected, and how they affected, the three projects constraints of time, cost and quality. The study concluded by providing a model which may be applied to various construction projects to improve the performance of the project.

A similar survey-based study by Park and Kim (2011) considered a Bayesian-based model which aimed to predict project profits at the tender stage. The study identified appropriate risk factors affecting profit from a questionnaire survey. Using the identified risk factors, a regression model was developed and acted as a baseline to which the subsequently developed Bayesian regression model was compared. The Bayesian-based model was found to more accurately predict profit margins compared to traditional regression models.

5.1.2 Quantitative assessment of risks

Lin et al. (2011) attempted to quantify accidents using a similar approach to that of Shen et al. (2001) through developing an accident factor, which used identified accident-related indicators as input. The methodology followed the systematic process of risk identification and influence relationship determination using the fuzzy influence (network) diagram. Network diagrams are particularly useful in situations where uncertainty surrounds how one risk might affect (enhance or mitigate) another risk and has been successfully implemented in construction-related risk management processes in the past (Janjic et al., 2015). Lin et al. highlight that the construction industry has a higher rate of accidents than any other industry and these accidents don’t only pose risk to health and safety, but greatly affect the three project constraints.

Dikmen et al. (2007) proposed a fuzzy risk rating method for international construction cost overrun. A simplistic approach was followed where risks were first identified and then modelled using influence diagrams. A membership function for each risk was selected and expert opinions were captured using aggregate rules which together were fed into a fuzzy rules system and cost overruns were successfully determined.

Sato et al. (2005) conducted research that aimed to quantitatively analyse risks in road projects in Japan using empirical techniques. From real road data, the study methodology identified risks, determined the risk frequency and the impact of occurrence and presented their findings in a risk ranking matrix. Arrow diagrams were used to represent the sequence of project steps and were used as input for a Monte Carlo simulation system. The simulation ultimately demonstrated the process of quantifying risks and concluded that the impact of a risk on project time and cost can be established before the start of the project, allowing for mitigation measures to be implemented from the project start date.

5.1.3 Examples of Bayesian application in climate change assessments

Bernier (1994) studied droughts associated with climate change in the Senegal river basin in West Africa, considering uncertainties within the probability distribution of annual flows Q using a Bayesian-based approach. Bernier looked to answer the following questions:

1. When did the mean annual discharge E(Q) change?
2. What is the probability of system failure, defined as P(Q<150m3/s), i.e. a shortage of water supply?

In the study, the year of failure was unknown, together with the Bayesian parameters. The study considered data ranging from 1903 to 1986. Observations of data had shown that the annual flow for the period between 1903 and 1965 was significantly higher than from 1965 to 1986. To answer the first question, the year in which the mean flow changes is defined as θ, with P(θ) being considered equal for all years. Z consisted of the observed flows for 1902 to 1986 and P(Z | θ) was passed on a log-normal distribution, where its mean and standard deviation is dependent on the relation of the year in which the mean changed.

The second question posed by Bernie was answered through the assumption that the mean flow would remain at its post-1967 value, whereby θ is based on a log-normal distribution and used to calculate P(Q<150m^3/s) with Z defined as 1976 to 1986 annual flows. Baye's theorem was applied and subsequently produced a posterior distribution for θ for all possible values of P(Q<150m^3/s). The mode of P(Q<150m^3/s) was calculated as 0.0035. The expected value was much higher at approximately 0.025. The limited historical data produced a wide credible range in which there is a 90% chance that the true value is between 0.001 and 0.059. Bernier (1994) had thus successfully illustrated the application of Bayesian theory to quantify uncertainty surrounding the probability of droughts.

Mann et al. (2016) applied both traditional frequential techniques and Bayesian methods to determine the impacts of climate change on the occurrence of extreme weather events. The study started by considering the occurrence of extreme weather events dependent on historical climate data, where an equal probability of an extreme event occurring is assumed for a given year or season. This situation is similar to a discrete binary statistical process of a coin toss, and as such the probability distribution was defined using a binomial distribution for N (years) events:

$$P(\theta, N, k) = \binom{N}{k} \theta^k (1-\theta)^{N-k}$$

where k = 0, 1, 2, …, N and θ represents the fractional probability of a positive year (probability of an event occurring greater than the average) or a negative year (probability of an event occurring fewer than the average), and where

$$\binom{N}{k} = \frac{N!}{k!\,(N-k)!}$$

is the binomial coefficient N events taken at k intervals.

In the absence of the effects of climate change, there is an equal probability of occurrence of a negative or positive year, with an active year fraction $\theta = \theta_o = 0.5$. Climate change was then introduced into the study to see how it would impact (i.e. increase) the occurrence of events. The probability was defined as $\theta = \theta_o > 0.5$ for positive years only. Using Baye's theorem, a posterior distribution was determined to describe the event. Monte Carlo simulations of the binary-valued process were conducted with $N_{max} = 64$ for three scenarios:

1. $\theta_o = 0.5$ (unbiased case);
2. $\theta_o = 0.6$ (modestly biased), and
3. $\theta_o = 0.75$ (strongly biased).

Scenario 2 and 3 corresponded to a 20% and 50% increase in the likelihood of occurrence, respectively, for positive and negative years.

What is important to note from the study is that as the bias was increased, the null hypothesis, stating that climate change does not impact the occurrence of extreme weather events, was rejected.

When the Bayesian method was applied to the data, it was noticed that as the bias increased, so did the error for the null hypothesis. What this study shows is that Bayesian inference has confident applications in climate modelling and that an approach wherein probability of impact is continually updated as data becomes available is a preferred method and often produces more favourable results.

5.1.4 Examples of Bayesian application in sustainability assessments

Tymošenk and Golovach (2018) applied Bayesian networks to study the sustainable elements associated with agriculture and rural development of territorial communities, focusing on social and economic impacts. The study obtained data through questionnaires seeking to obtain data relevant to the study objective, of which certain factors are believed to increase the capacity for sustainable development of the rural territory in the future. Bayesian belief networks were utilised to assess the data and concluded that the predominant factors affecting the sustainable development of the communities were: revival of high-quality agricultural production, employment creation, conservation of soil fertility, lack of employment opportunities, and the particulars relevant to the specific community respondents lived in. The study had shown the simplistic application of Bayesian techniques to qualitatively assess sustainable development in a developing country with attention given to social and economic impacts.

Another study by Tang et al. (2019) researched the general resilience of road infrastructure in Beijing using a time-dependent approach from 1997 to 2016, focusing on system qualities related to sustainability. Multiple sourced data sets were used, and a Bayesian network model was developed. A tree-style model was utilised, where multiple indicators were attributed to the same functional element. The probability of each indicator was determined for a given year and the aggregated mean was calculated. For indicators, which had a negative effect, such as a free-flow index of 82.4% (2.06/2.5), the values were normalised by 1-82.4% = 17.6% and used for further analyses. Conducting further sensitivity analyses, Tang et al. were able to determine the indicators with the largest impact on resilience and what the relationship and weights are between indicators. The sensitivity analysis showed that the top indicators affecting resilience are a function of rebuilding, changeability, adaptability, repairability and robustness, illustrated in Figure 5-2.

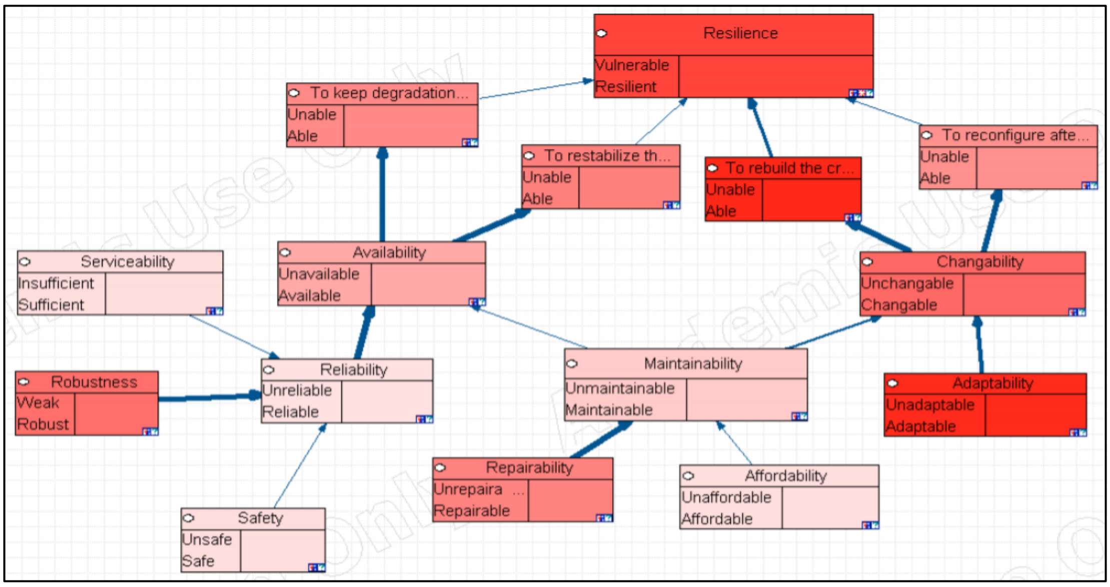


Figure 5-2: Sensitivity test and strength of influence analysis (Tang et al., 2019)

The study showed the successful implementation of the Bayesian theorem to determine the impact of largely literature-derived data subjectively influenced by the writer's perception of relevant data, and how such data may be used to determine resilience impacts - as a proxy for sustainability - on transport-related infrastructure.

5.2 MONTE CARLO

Monte Carlo simulations are computational algorithms that use repeated random sampling to determine numerical results and solve problems that are often deterministic, relying on data input and distribution definition. A great strength of Monte Carlo simulations is that they can be used to draw data from a distribution where, for example, the only thing known of the distribution is its density or frequency (van

Ravenzwaaij et al., 2018). This is particularly useful in concepts, which are difficult to quantify, such as sustainable impacts relevant to pavement infrastructure. Similar to the use of Bayesian analyses, Monte Carlo Simulations are more commonly applied in risk- (McGoey-Smith et al., 2010; Ling et al., 2013) or environmental impact-assessments (Knott et al., 2019), and more recently proposed for use in S-LCA frameworks (Castillo and Pitfield, 2010; Zheng et al., 2020).

Monte Carlo simulations are further widely used in industries such as marketing, customer services and health care to process chance and uncertainty, more specifically either filling gaps in data of social surveys of population groups difficult to reach (e.g. the elderly) or developing ‘average’ behavioural trends of those population groups (Furness, 2011). This is especially beneficial in evaluating the uncertainty in sustainable assessments where the impacts perceived most influential are uncertain. In applying Monte Carlo simulations, the selected distribution may significantly affect results. Commonly used distributions include lognormal distributions for quantifying uncertainty in unit cost (Swei et al., 2013), normal distribution for uncertainty in construction costs (Sundeep, 2016) and triangular distributions in uncertainty where little information is available (Wu et al., 2017). Zheng et al. (2020) proposed the use of uniform distributions when uncertainty is analysed among social impacts and is the distribution selected for use in this study. The study further aims to include Bayesian principles in defining an expected priori obtained through the social ‘hotspot’ methodology and adapted baseline SS_i score.

5.3 MARKOV CHAIN MONTE CARLO

Classical statistical methods often have great difficulty in determining uncertainty for two or more parameters from the same data set, especially when the distributions are correlated. These methods commonly assume that uncertainty distributions are normally distributed and rely on covariance matrices or resampling techniques such as the Bootstrap method.

To overcome these limitations, the ever-growing popular Markov-Chain Monte Carlo (MCMC) simulations were introduced which allowed analysts to avoid making unrealistic assumptions about the stochastic processes that generate the data being analysed (Gilks et al., 1996).

MCMCs are a statistical method used in probability analyses to obtain information about distributions, used especially for posteriori distributions in Bayesian inference (van Ravenzwaaaij et al., 2018). A great strength of MCMCs is that they can draw data from a distribution where, for example, the only thing known of the distribution is its density. This is particularly useful in concepts which are difficult to quantify, such as sustainability.

By using random samples from a distribution, the mean can be calculated for the sample population. The benefit of this approach is that calculating the mean from a sample population can be easier than calculating it from a distribution's equations, especially when the distribution equations are hard to work with in other ways. The Markov Chain property of MCMC generates samples based on a special sequential process, where each random sample is used as a steppingstone to generate the next random sample – hence the chain, allowing for the incorporation of temporal scales.

These methods have been successfully implemented in the field of pavement risk management. McGoey-Smith et al. (2010) used Monte Carlo simulations to estimate the cost of various risk occurrences on highway projects. Ling et al. (2013) developed a two-parameter exponential model using MCMCs to predict airport pavement performance which was described using Visual Condition Index (VCI) deterioration. Furthermore, Knott et al. (2019) investigated the effects of incremental temperature and groundwater increases due to climate change on pavement performance.

The study by Knott et al. utilised a hybrid bottom-up/top-down approach to investigate the time dependence of the climate risks which may be used to identify critical effects for intervention planning. The study started by identifying climate stressors through literature and engaging with experts and stakeholders. Secondly, the study identified vulnerable pavement systems, such as coastal roads at risk of sea-level rise and pavements located in regions where there is a high risk of extreme temperature and moisture intense events. Thirdly pavement performance was measured using MnPAVE software where a variety of performance metrics were analysed. The performance modelling acted as a baseline to investigate climate change effects.

Next, a pavement climate sensitivity catalogue (PCSC) was created for vulnerable identified roads and used to calculate the sensitivity to incremental changes in climate parameters. Knott et al. state that a PCSC can provide information to pavement response given climate and traffic variations and is a powerful tool, which is to be used by practitioners in implementing adaptation options.

The study concluded by constructing adaptation pathways using the PCSC, down-scaled climate projections, performance metrics and sustainability indicators. The performance metric was modelled using Monte Carlo simulations and two typical pavement scenarios were modelled:

- HMA thickness required to achieve minimum 85% reliability for <1 MESA, and
- HMA thickness required to achieve a minimum of 90% reliability for >1 MESA.

A cost metric was included as the life cycle adaptation cost, defined as the costs both the agency and road user would incur.

The study timeline was 60-years and modelled climate impacts used three climate scenarios, namely: RCP4.5, RCP6.5 and RCP8.5 (see IPCC (2014) for details). Traffic was simulated with a 1% annual growth rate. The study effectively modelled how HMA overlay thickness and timing would affect the performance of a pavement given climate change impacts such that it can inform budget planning and allow for the best life cycle costing.

The approach by Knott et al. is particularly relevant to the objectives of this study as the developed model in this study aims to include environmental and social life cycle assessment methodologies, as well as climate change impacts. These results may then further be utilised to conduct a cumulative risk assessment incorporating a holistic sustainability approach to pavement evaluation.

5.3.1 Limitations of Markov Chain Monte Carlo Simulations

The MCMC algorithm is a powerful tool to draw samples from a distribution when all that is known of the distribution is its likelihood. As an example, one can calculate the likelihood of a test score of 50 easier if the mean population score is fifty compared to if the mean were 100. This theory 'works' as long as certain conditions, representing the limitations, are met.

Firstly, the likelihood calculated during the analysis and used to reject or accept the null hypothesis must accurately reflect the distribution function of the proposal in the target distribution. When MCMC is applied to Bayesian inference, the values calculated are required to be from posteriori likelihoods, or at least proportional to the posteriori distribution. Secondly, the proposed distribution should be symmetrical. If the distribution is asymmetric, a modification step is required using, for instance, the 'Metropolis-Hastings' algorithm. Thirdly, as the initial estimate of the Markov chain might be very wrong, it should be ignored. If considering a typical Markov chain simulation graphically shown in Figure 5-3, it is seen that the initial guesses deviate substantially from the final estimate and have likely not been obtained from the target distribution. Only after the first few iterations have been run does convergence occur, and the results may confidently be used. One way to alleviate this problem is to use better starting points. Starting values that are closer to the mode of the posteriori distribution will ensure faster convergence and fewer problems associated therewith (van Ravenzwaaij et al., 2018). It is also noted that convergence is a key indicator to assess the ability of MCMCs to conform to data sets and are often used to validate results.

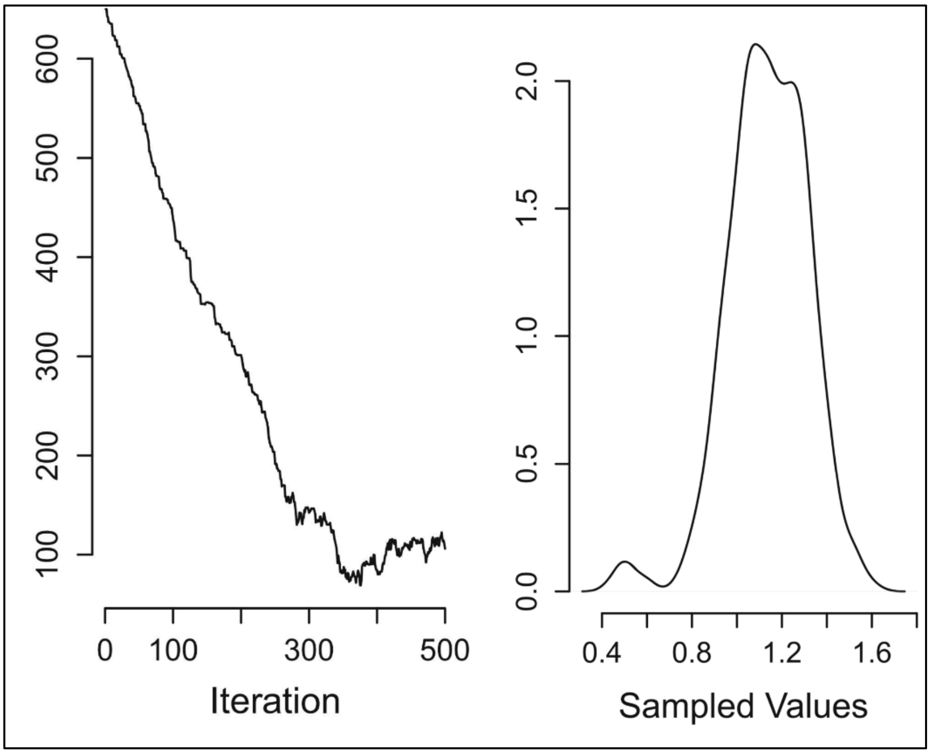


Figure 5-3: A simple example of MCMC simulation results (van Ravenzwaaij et al., 2018)

5.4 SUMMARY

In this chapter Bayesian inference is introduced as the basis of probabilistic modelling which will be implemented in this thesis. There are numerous methods and popular algorithms available for modelling, with the majority of algorithms currently relying on MCMC methods to sample from the posteriori probability, in such a manner that the Markov chain's stationary distribution is the desired posteriori distribution, computed using the likelihood and priori distributions. Therefore, reliable sustainable pavement estimates depend on the ability of the Markov chain to reach its stationary distribution before the estimate is inferred. Numerous methods are heuristically implemented to ensure the Markov chains converge quickly to their stationary distribution. Such methods include multiple starting points and increasingly sophisticated algorithms, among others. It is noted that the ability of the model to converge quickly is a key indicator to validate results.

When Bayesian methods are applied to the categories of risks and sustainability, the data tends to be subjective and often obtained through survey-based methods whereas data related to pavement engineering and climate change are often based on measured data and conclusions are performance-based. Bayesian inference has shown improved capabilities in measuring probabilities and is the preferred method that will be applied to the remainder of this study.

To develop an MCMC model for this research, it is proposed to first develop a Probability Transition Matrix for each combination of factors. The Probability Transition Matrix should be populated from prioritised inficators from literature and developed methodologies.

Following on to this research, Tang et al. (2019) demonstrated the use of Bayesian inference and sensitivity analyses to identify which weighted indicators most influenced the sustainability of a pavement on a time-dependent variation and will be utilised as the subsequent step during model development. Knott et al. (2019) showed the use of MCMC simulations to model pavement behaviour. The model considered environmental and climate change influences and utilised a performance metric to investigate vulnerable pavement systems on a time-step basis and how maintenance could best enhance the climate resilience of the systems. This model will be used as the baseline model for this research. Ling et al. (2013) illustrated the use of MCMC simulations and previously developed models to predict with confidence the VCI of a pavement given insufficient data. This method will complement the model developed by Knott et al. and allow for analysis of vulnerable pavement systems, especially useful in developing countries, which often lack sufficient historic data capturing capacity.

6 STUDY APPROACH/METHODOLOGY

6.1 INTRODUCTION

The various components of pavement sustainability were investigated in the previous five chapters, with the focus on five distinct themes to establish current practice and knowledge. In terms of the problem statement, study objectives and scope of this thesis, further developmental work is performed for all five of these themes concentrating on developing life cycle inventories, quantifying climate change impacts and providing a risk and sustainability index for pavement infrastructure. In this chapter the study approach followed for the necessary development and improvements identified is presented.

6.2 PROBLEM STATEMENT AND STUDY OBJECTIVES

The problem statement for this thesis states that the current sustainable approach to pavement infrastructure provision lacks experimental evidence required for holistic evaluation. The deficit lies predominantly in immature methodologies that need to be developed to keep up with the fast pace of changing global challenges, such as climate change.

The two primary objectives of this thesis are to develop a practical system framework to evaluate the various components of pavement sustainability and develop and verify a practical approach for its implementation, where appropriate.

6.3 LIFE CYCLE ASSESSMENT

For many years, road authorities have taken measures to reduce costs of road construction, vehicle operating costs as well as road fatalities while enhancing road performance to improve the sustainability of pavement infrastructure. These efforts have commonly been realised through reducing economic costs evaluated using LCCAs. However, efforts to address sustainability are incomplete if environmental and social impacts are not considered. An LCA is an approach which can quantify the environmental and social impacts of pavement infrastructure provision. At present, no such protocol is in place in most countries including South Africa. Chapter 7 addresses this shortcoming by proposing a framework for the development of an LCA model, by documenting the LCI for common pavement materials and construction activities.

The LCI acts as a building block to the LCA by evaluating primary flows related to the supply chain of pavement materials and construction activities. The primary flows are represented by indicators which quantify impacts, including key indicators for emissions to air and water, energy- and water-use. The LCI further provides indicators for novel and recycled materials which may greatly assist in evaluating the sustainability of pavement options. A worked example is provided to demonstrate implementation of the LCI.

6.4 SOCIAL LIFE CYCLE ASSESSMENT

Social consideration, assessed using an S-LCA, is a relatively new concept that has yet to be standardised. Attempts at measuring social sustainability in pavement management have been made in South Africa, using social impact assessments and EmpIAs. However, these models only focus on certain social considerations and do not incorporate holistic social sustainability in evaluations. The first response to these challenges is to identify and secure universal acceptance for indicators which measure social impacts of pavements and the broader impacts of technical and managerial choices in pavement infrastructure provision. These indicators may then be used to develop a situational- and location- specific S-LCI.

Chapter 8 starts by identifying key social indicators in pavement infrastructure provision and proposes a framework for an S-LCA. Potential indicators are sourced from a large database, focusing on indicators most aligned with social sustainability. Indicators are assessed and scored using an adapted methodology and refinement, conducted through sensitivity analyses employing Bayesian-based Monte Carlo simulations. By allowing weightings and scores of sub-goals and criteria to be changed, the results reflect the importance of inputs from local stakeholders on the impacts of sustainability. A worked example is provided to demonstrate its implementation.

6.5 CLIMATE CHANGE IN SOUTH AFRICA

The effects of climate change up until recently, have been understood to generally mean a gradual increase in temperature and accompanied drying of the atmosphere, which for most pavement structures, are expected to have minimal influence.

Chapter 9 provides a climate change assessment for typical flexible pavement structures and maintenance regimes in South Africa, aiming to extend current research and incorporate both climate projections, pavement deterioration models and settlement risk tools into pavement design, construction and management. High-resolution climate projections were used for the period 2020-2050 and the significance of maintenance as a key instrument to combat the impacts of climate change on pavements is demonstrated.

6.6 ROAD USER LIFE CYCLE ASSESSMENT INCORPORATING CLIMATE CHANGE IMPACTS

Often the impact of pavements during construction, maintenance and demolition are considered to be the only environmental burden. However, road user fuel consumption and corresponding emissions, influenced by factors such as road roughness and accelerated pavement deterioration due to climate change, are important measurements of pavement sustainability. Chapter 10 analyses the road user emissions of flexible pavements. Existing deterioration models and climate change projections are used to analyse emissions during use, with the ensuing intention to promote rigorous maintenance strategies by road authorities if sustainable aspirations are to be achieved.

6.7 CUMULATIVE RISK AND SUSTAINABILITY INDEXING

A sustainable pavement has to be economically, socially and environmentally feasible at an acceptable level of risk over its design life. Practically, a sustainable pavement optimises a range of performance indicators including cost, functionality, safety, local economic and human development, emissions, climate change, and resource use, measured using a suite of assessment methodologies.

The fast pace of development of these methodologies has arguably left gaps in research. Most notably, consideration of risks that may affect sustainability have largely been overlooked. Sustainability is an interrelated concept since the modification of one risk affects others. Furthermore, changes to or addition of risks, if not properly evaluated, may cause unanticipated and significant reductions in sustainability outcomes. A model that defines the interdependence of risks and their sustainability outcomes is needed.

The objective of Chapter 11 is to develop and present a method of holistic pavement sustainability quantification and a practical sustainability index.

6.8 ROAD SCENARIO

To assess and illustrate the use of the various methodologies described above and detailed in subsequent chapters, a typical road scenario has been developed which considers two traffic classifications, four pavement build-ups and two maintenance regimes. An additional novel pavement structure developed by Jordaan et al. (2017) is also introduced to illustrate how new technology may be utilised to reduce emissions.

6.8.1 Functional Unit and System Boundaries

The functional unit, representing the reference unit used to quantify impacts, is one kilometre, 7.4 m wide single carriageway with a 30-year design life. The analysis period selected for this study is 2021 to 2050.

6.8.2 Pavement Structures

For modelling, two design traffic classifications are utilised representing an ES1 and ES10 (1 and 10 million standard axles), for which two pavement structures are specified for each design traffic, one for a wet region (relatively stronger structure) and one for a dry region (relatively weaker structure). All pavement structures correspond to a Category B flexible pavement as specified in SAPEM (2017), with a 2% annual growth rate. The traffic loading is as given by SANRAL and is used over a 30-year analysis period. These design traffic classifications and pavement structures are shown in Table 6-1. The specific parameters utilised for modelling reflect empirical understanding of the most common pavement structures, categories, traffic loadings and analysis periods found across all road authorities in South Africa. Modelling of these pavements is therefore expected to reflect a large percentage of the South African road network.

Table 6-1: Road structure inputs

Design Traffic	**AADT/ lane***	**AADTT/ lane****	**Pavement Structure – Wet region**	**Pavement Structure – Dry region**
ES1	1030	30	Double surface treatment on 150 mm G2 and 150 mm C4 on 7% CBR (SNP 2.72)	Double surface treatment on 125 mm G4 and 150 mm C4 on 7% CBR (SNP 2.48)
ES10	10 300	300	40 mm continuously graded asphalt on 150 mm G1 and 300 mm C4 on 7% CBR (SNP 4.07)	40 mm continuously graded asphalt on 150 mm G2 and 200 mm C4 on 7% CBR (SNP)3.44
Design Traffic	**AADT/ lane***	**AADTT/ lane****	**Additional Pavement Structure (Jordaan et al., 2017)**	
ES10	10 300	300	30 mm A-E2 SBS modified asphalt (3%) on 150 mm G5 + 1.2% Organosilane on 150 mm G5 + 0.7% Organosilane.	

* AADT = Annual Average Daily Traffic

** AADTT = Annual Average Daily Truck Traffic

SNP = Adjusted Structural Number

The two pavement structure designations shown in Table 6-1 refer specifically to the climatic zones in which the structures are to be utilised, with stronger pavement structures generally preferred in humid climates and weaker pavement structures employed in more arid climates.

6.8.3 Maintenance Regimes

The SANRAL maintenance regimes available for modelling are either a base alternative (representing a routine maintenance regime of pothole repair, crack sealing, edge repair and ancillary works) or heavy maintenance (representing major interventions such as resurfacing or rehabilitation besides routine maintenance). For the heavy maintenance option, the appropriate maintenance strategy to follow for the analysis period is selected by existing models which have been calibrated with SANRAL specific maintenance options. These two maintenance regimes are used for modelling the deterioration of the pavements to incorporate the impacts of climate change.

6.8.4 Probability Modelling

For probability modelling, each road scenario is detailed in Table 6-2.

Table 6-2: Three road scenarios used for probability modelling

Traffic Class	Road Scenario	Pavement Structure	Maintenance Regime	Climate Zone
ES10	1	Weak	Baseline	Subhumid-Dry
	2	Weak	Heavy Maintenance	
	3	Strong	Baseline	
	4	Strong	Heavy Maintenance	

It is noted that for probability modelling, only ES10 pavement structures are considered in contradiction with what has been shown in Table 6-1, omitting the ES1 structures. The purpose of the probabilistic model developed in this thesis, discussed in Chapter 11, is simply to demonstrate how the complex concept of sustainability may be simplified and quantified. It therefore adds no value to model the ES1 structures as well and an overburden of results may cause confusion with readers. The ES10 structures, representing typical national roads in South Africa, were retained for this modelling. It is noted that the results may be easily reproduced for the ES1 pavements and their omittance is purely for simplification of the probabilistic process.

6.9 SUMMARY

A study approach for dealing with the problem statement identified for this thesis is discussed. The study approach consists of the development of a framework for sustainable evaluation of pavement infrastructure, development of tools for performing these evaluations and verification of the benefits of incorporating these assessments in pavement design.

7 LIFE CYCLE INVENTORY

7.1 INTRODUCTION

This chapter aims to present the results of a detailed inventory listing the environmental flow of typical pavement materials, construction activities and equipment required to build and maintain a road. A worked example is provided to demonstrate implementation of the inventory.

7.2 METHODOLOGICAL FRAMEWORK

The methodological framework implemented in this chapter is specified by ISO standard 14040 (ISO 14040, 2006) for the development of an LCA. As this chapter only aims to develop an LCI, certain steps of ISO 14040 (2006) are omitted. Figure 7-1 shows the ISO 14040 (2006) framework, with the steps which are implemented in this chapter highlighted in blue (steps 1 to 5), and the steps omitted highlighted in grey (steps 6 to 8). Further details regarding each step are provided in subsequent sections. Omitted steps are covered in later chapters.

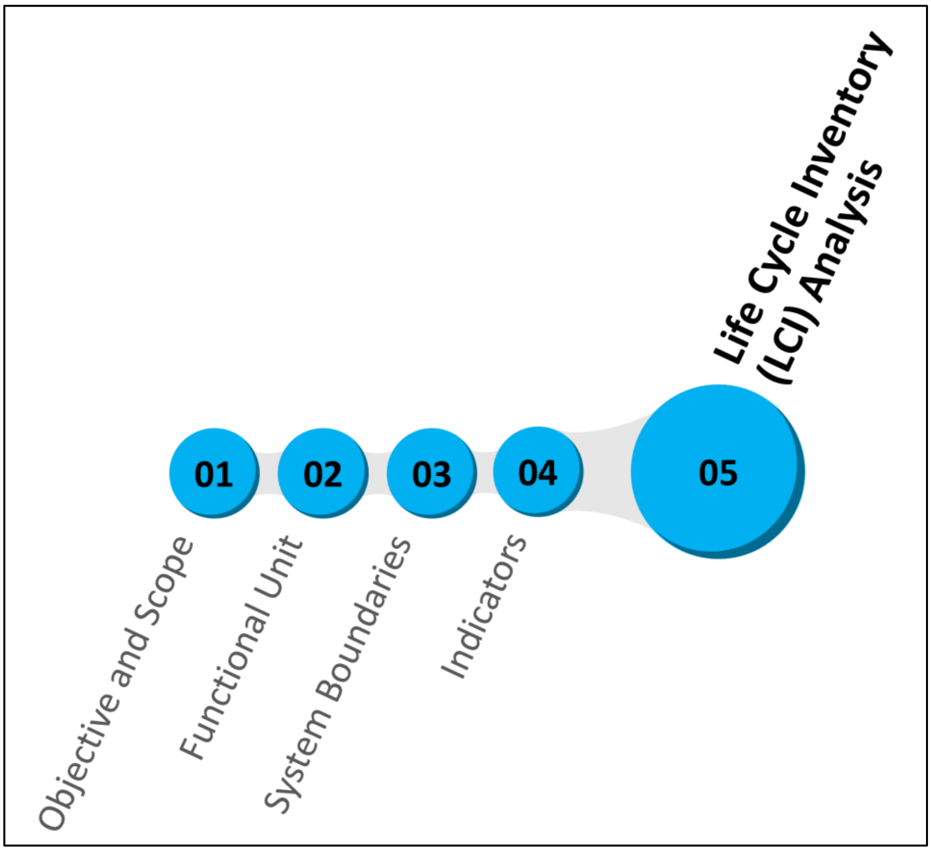


Figure 7-1: Methodological framework for LCI development in South Africa

7.3 OBJECTIVE AND SCOPE

The objective of this chapter is to provide an LCI for leading materials used in the provision of road pavement infrastructure. ISO 14040 (2006) is used as a guide in the development of the LCI.

The scope of the chapter considers a ‘cradle-to-grave’ scenario but excludes the use phase emissions related to road users, for the development of a typical road pavement. The LCI provides indicators for emissions, energy- and water-use. Certain uncommon alternative materials, such as the use of nano-modifiers (organosilanes) are introduced in this chapter to demonstrate how the implementation of these alternative materials may improve the sustainability of road pavements.

7.4 FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The FU, representing the reference unit used to quantify performance of the indicators, is one-tonne of product depending on the relevant pavement layer considered. For construction, maintenance and demolition activities, the FU is either one square- or cubic-meter, or one tonne-km transported. This chapter comprises all the processes and activities related to raw material sourcing, material production, construction activities, maintenance and end-of-life of a pavement for a cradle-to-grave approach. The system boundaries include the following steps, shown in Figure 7-2:

1. Raw material extraction;
2. Material processing and production;
3. Construction;
4. Maintenance;
5. Recycling, and
6. Transportation between phases.

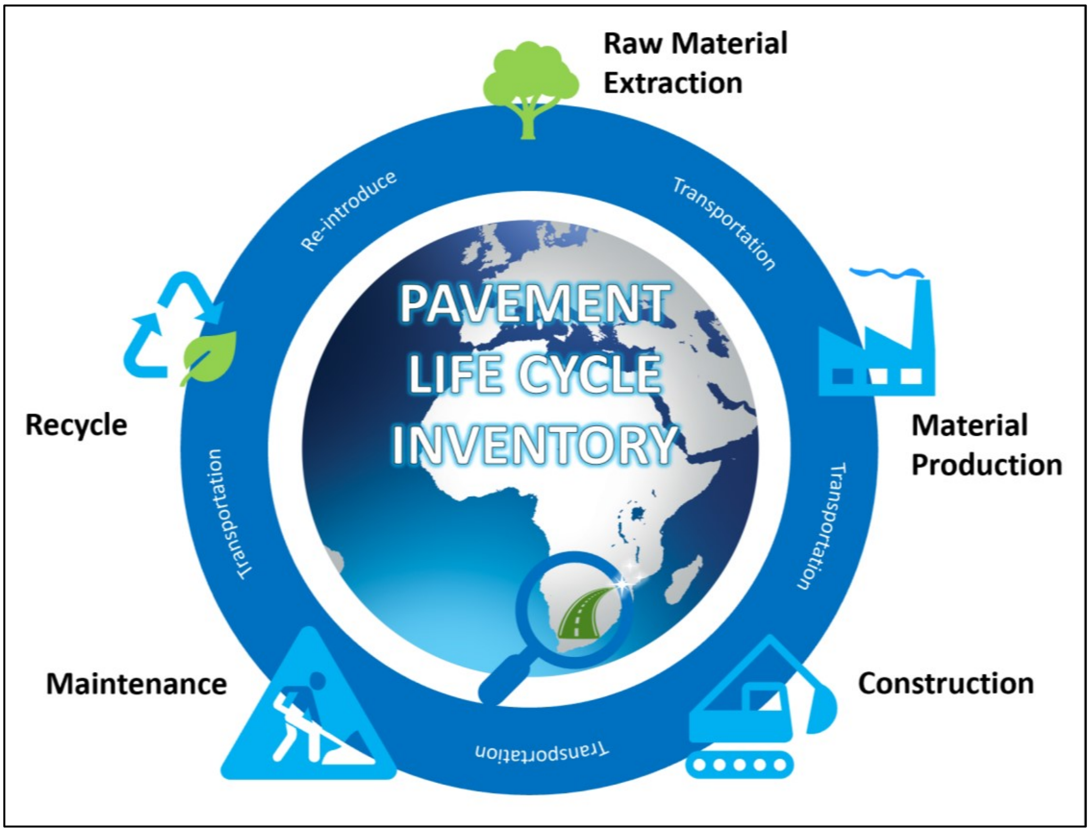


Figure 7-2: System boundaries of the assessed system

7.5 MATERIALS

The common pavement materials and construction activities focused on in this chapter are listed in Table 7-1.

Table 7-1: Common materials, construction activities and equipment considered in this chapter

Materials				
Bitumen	Polymer Modified Bitumen	Bitumen emulsion	Treated water	Hot-, warm- and cold-mix asphalt
Recycled asphalt pavement	Organosilane	Crushed stone	Natural aggregate	Recycled aggregate
Cement	Lime	Pavement concrete	Pavement steel	
Construction activities				
Milling asphalt	Compaction - soil	Compaction - asphalt	Concrete sawing and sealing	Concrete milling
General activity				
Equipment				
Wheel loader	Excavator	Dumper	Paver	Grader
14-ton short distance transport	32-ton long distance transport			

7.6 INDICATORS

For this chapter, the following indicators are used:

- Energy use (MJ/t) – Key input variable;
- Carbon Dioxide emissions (kg CO_2e/t);
- Water use (l/t);
- Emissions to water (kg PAHs/t);
- Sulphur Dioxide emissions (kg SO_2/t);
- Nitrogen oxides emissions (kg NOx/t);
- Particulate Matter emissions (kg PM_{10}/t), and
- Volatile Organic Compounds emissions (kg VOC/t).

This inventory focuses on the main construction materials used in pavement infrastructure provision in South Africa. In sourcing data, this chapter has focused on energy requirements for processes and activities related to pavement materials. The reason being energy generation in South Africa is typically accepted to be more environmentally damaging than many other countries (CER, 2019), with an average threefold higher emissions per energy unit than most European nations. The Cape Town-based Centre for Environmental Rights (CER) states that the emissions generated by Eskom, which is the state-owned utility company in South Africa, during electricity production are often multiple of those recommended by the World Health Organisation (WHO, 2005), with CO_2 emissions somewhat double the recommended limit. As such, energy requirements are used to derive factors for other environmental and social impact categories in this study to allow indicators to be more representative of South Africa.

Data Quality Indicators (DQIs) are used in this chapter to assess the quality of data collected according to the applicable ISO 14040 (2006) guidance. To do this, a relevant data quality matrix is used and applied to all data. The data quality matrix utilised with the scores of each inventory item (i.e. material or construction activity) listed in this chapter are presented in Appendix A-3. DQI scores, for items where multiple DQIs are used, are calculated as the average of the DQIs used. For instance, the DQI score for organosilanes (DQI = 76%) is calculated as the average of the DQI scores for Eskom (2014) (DQI = 80%) and Silicones Europe (SE, 2019) (DQI = 72%). Reference to the DQIs used for each item is provided at the end of each table throughout this chapter, using the corresponding Roman numeral numbers as listed in Appendix A-4.

7.7 ENERGY

This study considers two sources of energy in the production of materials as well as construction, maintenance and demolition of the road pavement infrastructure. These sources are electricity and diesel.

South Africa obtains its electricity from Eskom, which uses a variety of methods to produce electricity, of which coal is the predominant source. Renewable energy is used to supplement electricity supply and occasionally diesel generators are required when the utility company cannot provide enough electricity or when maintenance is required on old infrastructure with large backlogs (CER, 2019). As a result of these factors, among others, Eskom is not considered to be an environmentally friendly provider of electricity to the nation and as such, the indicator factors for electricity production in South Africa are often higher than most other countries.

The diesel fuel and engines used in South Africa are assumed to generally conform to the requirements of Euro V diesel (EEA, 2019) and indicator factors utilised in this study are those of Euro V using typical corresponding calorific values. The indicator factors for electricity production (Eskom, 2014) and diesel combustion (EEA, 2019; UN-ESY, 2017) are shown in Table 7-2.

Table 7-2: Indicator factors for generation of one megajoule of energy in South Africa

Indicator	**Unit**	**Electricity**	**Diesel**
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/MJ	0.297	0.075
Water Use	l/MJ	0.41	0.001
Emissions to Water	kg PAHs/MJ	0.001	1.86E-09
Social Related Indicators			
SO_2 Emissions	kg SO_2/MJ	2.52E-03	3.59E-05
NOx Emissions	kg NOx/MJ	1.21E-03	6.78E-04
Particulate Matter Emissions	kg PM_{10}/MJ	1.00E-04	7.93E-04
Volatile Organic Compounds Emissions	kg VOC/MJ	0.00	4.56E-05
DQI		80%	92%
DQI Reference		IV	III, V

7.8 BITUMEN

South Africa does not have any crude oil reserves and imports the raw material to produce bitumen. The major contributors to crude oil imports data as provided by the South African Department of Energy (DoE, 2019) are divided into two regions; Africa (52%) and Middle East (48%). Bitumen is shipped to predominantly two ports in South Africa, namely: Durban (77%) and Cape Town (23%). South Africa has four refineries:

- Natref (Sasol and Total) – Sasolburg;

- Enref (Engen) – Durban;
- Sapref (Shell and BP) – Durban), and
- Astron (old Chevron or Caltex) – Cape Town.

These refineries are responsible for the supply of bitumen to the South African market.

7.8.1 Extraction

Oil extraction is the first process in bitumen production. The oil extraction process occurs in other countries from which South Africa imports (mainly African and the Middle Eastern countries) and the emissions so produced are specific to the extraction country and company. The International Association of Oil and Gas Producers published guidance on voluntary sustainability reporting for oil and gas producers worldwide. This is a parallel program to the Voluntary National Review developed by the UN and allows interested companies to publish data for certain indicators related to, among others, the environmental and social impacts of their operations. Using these data, with the Eurobitume (2020) estimates, typical values for the environmental and social emissions emitted and energy- and water-use related to crude oil extraction may be calculated, as shown in Table 7-3. These indicator factors account for all background processes typically required for crude oil extraction including preparation for transportation. These estimates have been obtained from various sources and do not necessarily represent the view or findings of the respective companies referenced.

Table 7-3: Weighted average indicator factors for crude oil extraction per tonne

Indicator	**Unit**	**Extraction**
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	157.38
Energy Use	MJ/t	1450.28
Water Use	l/t	290.92
Social related indicators		
SO_2 Emissions	kg SO_2/t	0.4
NOx Emissions	kg NOx/t	0.25
Particulate Matter Emissions	kg PM_{10}/t	0.02
Volatile Organic Compounds Emissions	kg VOC/t	0.33
DQI		74%
DQI Reference		XXIII - XXXII

7.8.2 Shipping

Crude oil tankers are available in a variety of sizes, namely PANAMAX, AFRAMAX, SUEZMAX, VLCC and ULCC. For this assessment, crude oil is assumed to be transported using an AFRAMAX vessel size of between 80 - 120 Dead Weight Tonne. This vessel size is popular among oil companies (US EIA, 2014) and assumed to be a conservative representation of typical vessel size from all regions to South Africa.

Typical AFRAMAX vessel specifications are used for this assessment (Wärtsilä, 2020). The fuel consumption is calculated on the assumption that the ship is fully loaded for the trip to South Africa, and the return trip is not considered as part of the overall journey. An adjustment is made in that 28% of South Africa's bitumen production is exported (SABITA, 2013). It is assumed then that the ship would be loaded for its return trip from South Africa and emissions related to the return trip are embodied in export products. The data for the marine engine emissions produced by the shipping vessel is obtained from the European Environment Agency (EEA, 2019). Consumption of fuel to load and discharge crude oil or petroleum products from the vessel are vessel- and port-specific. Accurate data are not available for South African ports and typical conservative values (Eurobitume, 2020) are used for the analysis. To determine transportation distance, a port to port distance calculation tool (SeaRates, 2020) is used. Missing information is supplemented with distance measurements. EEA (2019) provides estimates for social-related emissions for typical marine fuel used. It is noted that the type of marine fuel used affects these estimates. Using this information, typical indicator factors may be calculated for shipping one tonne of crude oil from all regions, shown in Table 7-4.

Table 7-4: Weighted average indicator factors for shipping one-tonne crude oil

Indicators	**Unit**	**Shipping**
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	11.12
Energy Use	MJ/t	140.15
Water Use	l/t	48
Social Related Indicators		
SO_2 Emissions	kg SO_2/t	0.13
NOx Emissions	kg NOx/t	0.51
Particulate Matter Emissions	kg PM_{10}/t	0.01
Volatile Organic Compounds Emissions	kg VOC/t	0.02
DQI		86%
DQI Reference		III, XXIII, XXXIII, XXXIV

These estimates are based on a range of assumptions and simplifications. This applies for the Eurobitume (2020) database which only considers one shipping vessel specification. More accurate results may be obtained if better quality data is acquired reflecting the actual shipping specifications of South Africa's oil imports. It is further worth noting that the relatively long shipping distances to South Africa significantly increase the environmental and social burden of imported oil compared to most countries.

7.8.3 Pipeline

South Africa makes use of various pipelines to transport crude oil from the ships to the four refineries. For instance, ships offloading at Durban Port are required to offload at an oil terminal roughly 2.5km offshore of the Bluff. Oil is pumped from the terminal through to the Enref and Sapref refineries, and further to Natref in Sasolburg with similar operations used for Astron in the Cape. Pipelines transport 100% of crude requirements to refineries in South Africa (Transnet, 2019). Pipeline lengths are obtained from Transnet (2019).

The energy required to pump crude oil to the different refineries is calculated using conservative data provided by Eurobitume (2020). It is noted that the energy use from the Eurobitume (2020) database is 260% higher than that from the Eurobitume (2012) database. This reflects the assumptions made and the effect different pipeline specifications and topography have on the energy consumption. Eskom (2014) provides estimates for social-related emissions for electricity obtained from the electrical grid. Emissions are provided for two scenarios, namely coastal (average for Astron, Sapref and Enref) and inland (Natref). Typical factors are shown in Table 7-5 for the transportation of one-tonne bitumen via pipelines.

Table 7-5: Average pipeline transport indicator factors for one-tonne crude oil for coastal and inland scenarios

Indicators	**Unit**	**Coastal average**	**Inland average**
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	0.3	11.77
Energy Use	MJ/t	1.01	39.6
Water Use	l/t	0.19	7.26
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	0	0.1
NOx Emissions	kg NOx/t	0	0.05
Particulate Matter Emissions	kg PM_{10}/t	0	0
Volatile Organic Compounds Emissions	kg VOC/t	Not reported	Not reported
DQI		75%	
DQI Reference		IV, XXXV	

More accurate data is required for the pipelines in South Africa, considering the energy efficiency of pump stations, the effect of topography (with Sasolburg being 1500 m above sea level, for instance), and the typical specifications of the various pipelines used to transport crude oil.

7.8.4 Bitumen refinery and storage

To produce bitumen, a complex refinery is required to conduct a straight-run distillation process on crude oil which produces a range of petroleum products. Bitumen is a major product of this process, estimated at 28.5% bitumen yield by mass (Eurobitume, 2020).

The energy used for the distillation process is not well reported, however, Eurobitume (2020) estimates that 510MJ/t is required and includes consideration of various back-ground processes such as crude oil handling, desalting, flaring, loading area, general heating and lighting. A further 100MJ/t is estimated for the storage of bitumen. CONCAWE (2018) data highlights that of the total energy used in a refinery, 96% is obtained from burning bi-products (84% refinery gas) and heavy fuel oil (12%). The remaining 4% is from the electrical grid. Eurobitume (2020) disregards the energy obtained from the electricity grid. Alternative opinions (Harvey et al., 2014) state that South African refineries may use heavy fuel oil as the primary fuel type. Based on this information, it was decided to use heavy fuel oil (90%) as the main fuel type, supplemented with estimated distributions for refinery gas (6%) and electricity (4%) from the electrical grid.

Each of these energy sources was further investigated. Using calorific values of 40.4 MJ/kg for heavy fuel and 49.5 MJ/kg for refinery gas (UN-ESY, 2017), the consumption of energy for the production of bitumen by straight-run distillation may be calculated. Social related emissions for typical refinery processes in South Africa are obtained from Sapref (2017). Table 7-6 shows the indicator factors for one-tonne bitumen production.

Table 7-6: Average refinery and storage environmental indicator factors for one-tonne bitumen production

Indicators	**Unit**	**Average**
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	53.09
Energy Use	MJ/t	610
Water Use	l/t	342.5
Social related indicators		
SO_2 Emissions	kg SO_2/t	0.6
NOx Emissions	kg NOx/t	1.75
Particulate Matter Emissions	kg PM_{10}/t	Not reported
Volatile Organic Compounds Emissions	kg VOC/t	0.28
DQI		76%
DQI Reference		XXXVI, XXXVII

The total emissions of 53.09 kg CO_2e/t for the refinery and storage of bitumen may be compared to the estimate by Eurobitume (2020) of 25.55 kg CO_2e/t. The increase in emissions is related to the differences in energy source distributions and higher emissions factors for South African electricity production, among others. It is further worth noting that the emissions related to bitumen refinery between the Eurobitume (2012) (46.03 kg CO_2e/t) and Eurobitume (2020) (25.55 kg CO_2e/t) represent a reduction of roughly 46% and highlights the requirement for further research and the need for quality data.

7.8.5 Bitumen life cycle

Summarising the results for the previous life cycle stages, indicator factors to produce one-tonne bitumen in South Africa may be calculated, shown in Table 7-7.

Table 7-7: Indicator factors to produce one-tonne bitumen in South Africa

Indicator	**Unit**	**Bitumen**Ɨ
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	221.89 (233.36)
Energy Use	MJ/t	2201.4 (2240.00)
Water Use	l/t	681.61 (688.68)
Emissions to Water	kg PAHs/t	2.61E-07 (2.61E-07)
Social Related Indicators		
SO_2 Emissions	kg SO_2/t	1.13 (1.23)
NOx Emissions	kg NOx/t	2.51 (2.56)
Particulate Matter Emissions	kg PM_{10}/t	0.03 (0.03)
Volatile Organic Compounds Emissions	kg VOC/t	0.68 (0.68)
DQI		80%
DQI Reference		II

Ɨ Values in brackets represent inland scenario, with remaining values representing coastal scenario.

7.9 BITUMEN PRODUCTS

For bitumen, four products are considered in this study, namely:

- Paving-grade bitumen;
- Polymer modified bitumen (PMB);
- Cut back bitumen, and
- Bitumen emulsion.

7.9.1 Polymer Modified Bitumen

Using the data previously produced as baseline data, together with Eurobitume (2012) estimates, typical indicator factors for PMB may be calculated. PMB is commonly used in South African pavement construction to provide effective solutions in certain situations. Various modifying agents are available, of which the most commonly used are homogenous Styrene-butadiene-styrene (SBS) modifiers (SABITA, 2011) in pellet form. PMB is produced by mixing bitumen with the SBS modifier and pumping the mixture through a high shear mill to blend the SBS pellets. Estimates for the production of SBS are obtained directly from Boustead and Cooper (1998). To determine the impact of material transportation, values provided by Stipple (2001) for fuel consumption and energy use are utilised. One truck size (14 ton) is considered for SBS transportation. It is assumed that the production of PMB occurs at the same refinery where bitumen is produced and that SBS polymer is transported 50 km from an external supplier to the refinery. Estimates for the energy use of PMB milling are provided by Eurobitume (2012). Using these data, typical indicator factors are calculated, shown in Table 7-8.

Table 7-8: Indicator factors to produce one-tonne Polymer Modified Bitumen in South Africa

Indicator	**Unit**	**3% SBS Bitumen[Ɨ]**	**4.5% SBS Bitumen[Ɨ]**	**6% SBS Bitumen[Ɨ]**
Environmental Related Indicators				
CO_2e Emissions	kg CO_2e/t	601.17 (612.59)	790.81 (801.77)	980.46 (991.24)
Energy Use	MJ/t	3433.85 (3472.26)	4051.49 (4088.35)	4668.19 (4704.47)
Water Use	l/t	880.56 (887.61)	980.32 (987.07)	1079.88 (1086.53)
Emissions to Water	kg PAHs/t	2.55E-07 (2.55E-07)	2.49E-07 (2.49E-07)	2.45E-07 (2.45E-07)
Social Related Indicators				
SO_2 Emissions	kg SO_2/t	4.37 (4.46)	5.99 (6.08)	7.6 (7.7)
NOx Emissions	kg NOx/t	4.01 (4.05)	4.75 (4.80)	5.5 (5.55)
Particulate Matter Emissions	kg PM_{10}/t	0.16 (0.16)	0.22 (0.22)	0.29 (0.29)
Volatile Organic Compounds Emissions	kg VOC/t	0.66 (0.66)	0.65 (0.65)	0.64 (0.64)
DQI		75%		
DQI Reference		I, II, VIII, IX		

Ɨ Values in brackets represent inland scenario, with remaining values representing coastal scenario.

7.9.2 Cut Back Bitumen

Cut back bitumen is produced by adding controlled amounts of petroleum products, commonly Kerosene, to bitumen to reduce the viscosity of the product. This is done to allow for easier application of the bitumen at lower temperatures relative to conventional bitumen application. Cut back bitumen is often used as a prime coat on newly-constructed crushed stone or natural gravel base courses before construction of a surfacing layer or as a tack coat in grit seals, sand seals, otta seals and single seals for lightly trafficked roads. In South Africa, three grades of (medium curing) cutback bitumen are available, namely (SABITA, 2011):

- MC10;
- MC30, and
- MC3000.

Kerosene is produced using the same distillation process required for the refinery of bitumen from crude oil. No quality data exists to the difference in energy use required for Kerosene production and this study assumes that Kerosene has the same indicator factors as bitumen for production. As such, the indicator factors for cut back bitumen are the same as paving-grade bitumen, summarised in Table 7-7.

7.9.3 Bitumen Emulsion

Bitumen emulsions are a two-phase system consisting of water containing an emulsifier with a dispersion of bitumen droplets. Emulsification of bitumen is a process which aims to reduce the viscosity of a binder to resemble properties of fluid during handling and application. Emulsifiers generally consist of between 60% to 70% bitumen and 30% to 40% emulsified water by mass. Bitumen emulsions are commonly available in two classes (SABITA, 2011):

- Cationic, and
- Anionic.

The production of bitumen emulsion is assumed to occur within the refinery premises including the production of the emulsifier required. This study presents factors for a cationic (positively charged) emulsion. Most aggregates used in pavement construction in South Africa, such as granite and quartzite, are negatively charged acidic aggregates (SABITA, 2011) and as such require a positively charged bitumen emulsion for compatibility purposes. Emulsions are stored at relatively low temperatures and require no additional external heating where the only emission from storage is assumed to be water (Eurobitume, 2012). The raw material composition by mass for typical cationic emulsified bitumen is paving-grade bitumen (65%), water (34%), hydrochloric acid (0.5%) and emulsifier (0.5%).

Hydrochloric acid is obtained when hydrogen chloride is mixed with water. Hydrogen chloride may be produced through the distillation of crude oil (Wu et al., 2016), among other means. This study assumes that all hydrogen chloride is produced by the refinery on-site and that the factors related to bitumen refinery reflect similar factors for hydrogen chloride, as shown in Table 7-7. The emulsifier and corresponding eco-profile used for this analysis is Redicote E-9 cationic emulsion. A distance of 50 km is assumed for the transportation of emulsion to the refinery. The indicator factors related to the production of the emulsion are obtained from Eurobitume (2012) using typical net calorific values for energy conversion and related emissions obtained from Eskom (2014). Further key steps required to produce bitumen emulsion are water heating and high shear milling of emulsions. This study assumes that water is heated from 10°C to 40°C and the energy required for this process is 125.57 MJ/t according to the specific heat capacity of water. The energy required to operate the high shear mill is the same as for PMB production. The indicator factors to produce bitumen emulsion are shown in Table 7-9.

Table 7-9: Indicator factors to produce one-tonne bitumen emulsion in South Africa

Indicator	**Unit**	**Bitumen Emulsion**Ɨ
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	1412.86 (1421.10)
Energy Use	MJ/t	5782.03 (5809.75)
Water Use	l/t	2551.22 (2556.30)
Emissions to Water	kg PAHs/t	2.05E-07 (2.05E-07)
Social Related Indicators		
SO_2 Emissions	kg SO_2/t	11.44 (11.51)
NOx Emissions	kg NOx/t	6.88 (6.92)
Particulate Matter Emissions	kg PM_{10}/t	0.44 (0.44)
Volatile Organic Compounds Emissions	kg VOC/t	0.44 (0.44)
DQI		82%
DQI Reference		I, IV

Ɨ Values in brackets represent inland scenario, with remaining values representing coastal scenario.

A notable observation made from Table 7-9 is that bitumen emulsion uses three times as much water as normal bitumen production.

7.10 WATER

Water use may be classified as a non-renewable material (Steyn and Paige-Green, 2009) and is primarily needed during material extraction and compaction of pavement layers, especially granular layers. The quality of the water used for both processes generally needs to be of a near potable or 'drinkable' quality (COLTO, 1998; SABITA, 2019), as contaminated water may lead to accelerated weathering of aggregate, among other concerns.

Given the state of water availability and quality in South Africa as discussed in Chapter 4.7.1, the use of treated water in road pavement construction is an unjustifiable requirement. Having recognised this, the updated Committee of Transport Officials (COTO, 2020) standard water quality requirements for pavement construction have been considerably relaxed, with key specifications reproduced in Table 7-10.

Table 7-10: Construction water for earthworks and pavement layers in South Africa (Table A4.1.5-19) (COTO, 2020)

Purpose	**Electric Conductivity at 25°C (maximum)**	**Total Dissolved Solids (TDS) (maximum)**	**pH range at 25°C**
Crushed stone base layer compaction and slush - compaction	170 mS/m	1200 mg/l	5.0-9.7
Chemical stabilization compaction and curing	170 mS/m	1200 mg/l	5.0-9.7
Bituminous stabilization	170 mS/m	1200 mg/l	5.0-9.7
Other layers and materials	370 mS/m	2400 mg/l	4.0-10.0

A review of recent dam, lakes and river water quality data, consisting of over 70,000 samples taken for the period 1999-2012 by the Department of Water Affairs in South Africa (Huizenga and Silberbauer, 2013), shows that the quality of raw water found across South Africa conforms to the water quality requirements (COTO, 2020) for earthworks and pavement layer construction. The results are summarized in Table 7-11.

Table 7-11: Average raw water quality for dams, lakes and rivers in South Africa (1999-2012) (Huizenga et al., 2013)

	Electric Conductivity at 25°C	**Total Dissolved Solids (TDS)**	**pH range at 25°C**
Dams and lakes	38.5 mS/m	251.5 mg/l	8.0
Rivers	74.6 mS/m	487 mg/l	7.9

Given that most raw (i.e. untreated) surface water in South Africa conforms to the requirements for use in pavement construction, treated water is essentially only required to produce bitumen emulsion and concrete.

Energy requirements for water treatment in South Africa were reported by (Swartz et al., 2013), with an average of 0.4 MJ/t water required. Other indicator factors, including the water required for electricity generation, are obtained from Eskom (2014). Indicator factors for water treatment to a near potable quality in South Africa are shown in Table 7-12.

Table 7-12: Indicator factors for treatment of one-tonne water in South Africa

Indicator	**Unit**	**Treated water**
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	0.12
Energy Use	MJ/t	0.4
Water Use	l/t	1000.16*
Emissions to Water	kg PAHs/t	0.00
Social Related Indicators		
SO_2 Emissions	kg SO_2/t	1.01E-03
NOx Emissions	kg NOx/t	4.84E-04
Particulate Matter Emissions	kg PM_{10}/t	4.00E-05
Volatile Organic Compounds Emissions	kg VOC/t	0.00
DQI		80%
DQI Reference		IV, VI

* Includes energy requirement for typical water treatment and energy generation.

These factors per tonne raw water are relatively low compared to treated water and other activities required to construct or maintain a pavement. As such, this study does not provide indicator factors for raw water, but rather focuses on the volume of water used during construction and provides practical methods to reduce consumption. As stated by Steyn and Paige-Green (2009), a layer kilometre generally requires between 150 and 200 thousand litres of water for compaction, equating to between 20.83 and 27.79 l/m^2 per compacted layer in South Africa. Although much of this water will evaporate and return to the earth's surface in the form of precipitation or form part of the surface or groundwater flows, it is a long process and local depletion of water can occur rapidly especially in water scarce areas and areas under threat of becoming drier due to climate change. Injudicious water use for construction may effectively reduce the natural capital of an area and as such, it is difficult to justify the use of both treated and untreated water in relatively arid areas, where the local population struggle to meet their own daily water needs (Steyn and Paige Green, 2009)

This study makes a conservative assumption that the higher threshold value is equivalent to the water requirements for the slush-compaction process of a crushed stone G1 base layer, and that the lower threshold value is equivalent to the water requirements for all other granular pavement layers, as summarised in Table 7-13.

Table 7-13: Water requirements for granular layer compaction in South Africa.

Layer	Unit	Water requirement
Crushed stone G1 base	l/m^2	27.79
All other layers	l/m^2	20.83

It is important to note that both the use of water for, and the contamination of water as a result of, provision of road pavement infrastructure, should be a leading concern to road authorities both in South Africa and globally. Practical methods to reduce consumption and contamination should be sought.

7.11 ORGANOSILANE

One of these practical methods is presented by Steyn and Paige-Green (2009), where water use can be considerably reduced using nano-silanes, referred to as organosilanes in this study. The main aim of the organosilane is to redirect the energy produced during the salt crystallization process to nurture new bonds (similar to cement bonds) rather than having their natural destructive forces accelerate the deterioration of aggregates.

A new generation of organosilanes has been developed and successfully trialled in South Africa (CSIR-CRRI, 2010) that interact with the free energy surrounding the natural material molecules. This interaction rearranges the surface atom arrangements of the aggregate and helps to drastically reduce the susceptibility of the aggregates to water and make the aggregates water-repellent.

Working with the CSIR, Jordaan et al. (2017) further studied the use of organosilanes in South Africa. The study looked at the impacts of organosilane modified emulsions in improving the material properties of lower quality locally available aggregates (as compared to sourcing high quality commercially sourced crushed stone). The study found that the organosilanes successfully improved the strength characteristics of the lower quality aggregates and reduced the susceptibility of the aggregates to moisture-induced deterioration allowing for the use of locally available material to meet the same strength requirements as sourced crushed stone.

A further study (Kidgell et al., 2019) considered the use of organosilanes as a stabilising agent on dolomite, a material known as a ‘problem’ soil in South Africa due to its susceptibility to weathering in the presence of water. The organosilanes made the aggregate water-repellent and reduced its moisture susceptibility. The study showed that the organosilane stabiliser improved the properties of the dolomite, reduced the PI, and in so doing the moisture in the material acted as a lubricant, reducing the required compaction effort and overall reduced the moisture sensitivity of the dolomitic material. The before mentioned research has already helped alleviate the effect of water use on the environment and society and increase the sustainability of pavements in South Africa.

To determine the indicator factors for a typical organosilane used in gravel stabilisation, a conservative approach was followed. Production energy requirement data produced by Silicones Europe (SE, 2019) for a similar organosilane-based stabiliser was utilised, with an average energy requirement of 6398 MJ/t. Other indicator factors, including the water required for electricity generation, are obtained from Eskom (2014). The indicator factors to produce a one-tonne organosilane are shown in Table 7-14.

Table 7-14: Indicator factors to produce one-tonne organosilane in South Africa

Indicator	**Unit**	**Organosilane**
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	1261.00
Energy Use	MJ/t	6,398.34
Water Use	l/t	1442.83
Emissions to Water	kg PAHs/t	5.36E-06
Social Related Indicators		
SO_2 Emissions	kg SO_2/t	8.97
NOx Emissions	kg NOx/t	6.21
Particulate Matter Emissions	kg PM_{10}/t	0.35
Volatile Organic Compounds Emissions	kg VOC/t	0.00
DQI		76%
DQI Reference		IV, VII

7.12 AGGREGATES

The three categories of aggregates typically used in South African pavement construction are crushed stone, as well as construction sands and gravels (referred to collectively as natural aggregates in this study (Weinert, 1980). Crushed stone is defined as aggregates taken from hard rock, through methods such as blasting, and then crushed to the desired size. Natural aggregates (sands and gravels) are commonly mined from alluvial deposits (i.e. pit run). A fourth uncommonly used category exists in which aggregates are manufactured to possess specific properties and characteristics, such as the combination of shale and clay to create light-weight aggregates. These types of aggregates are not considered in this study.

To obtain the various indicator factors for aggregate production in South Africa, an average energy requirement from various international sources was used (Refer to DQI references, shown in Appendix A-4). These data are assumed to represent similar processes and environments relevant to South Africa. A split of 1:1.25 is used for the energy differences between diesel and electricity, respectively (Stripple, 2001), with calorific values and electricity generation factors obtained following the steps of previous analyses. The stages of production considered for crushed stone are material extraction, transport and three stages of crushing. The stages of production considered for natural aggregates are material extraction and transportation. Average indicator factors to produce one-tonne of crushed stone and natural aggregate are shown in Table 7-15.

Table 7-15: Indicator factors to produce one-tonne aggregate in South Africa

Indicator	**Unit**	**Crushed Stone**	**Natural Aggregate**
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	14.38	6.35
Energy Use	MJ/t	72.99	32.22
Water Use	l/t	16.46	7.27
Emissions to Water	kg PAHs/t	6.11E-08	2.70E-08
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	0.10	0.05
NOx Emissions	kg NOx/t	0.07	0.03
Particulate Matter Emissions	kg PM_{10}/t	4.01E-03	1.77E-03
Volatile Organic Compounds Emissions	kg VOC/t	0.00	0.00
DQI		73%	71%
DQI Reference		IX - XVIII	IX - XIII

When considering recycled demolition aggregates typically obtained from existing unbound granular layers, energy-, emission- and water-savings are realised through the reduced need to excavate and transport the material to the site. To calculate these savings, a construction scenario has been utilised where the savings are calculated including only a 5 km site transport distance. The density of loose demolition aggregate is taken as 1750 kg/m^3. The resulting savings are calculated as 15%, with a 5% material spoil by volume included in the calculations. It is assumed that the recycled demolition aggregates won from the existing pavement structure generally conform to the natural aggregate material requirements of COTO (2020). Use of demolition aggregates for crushed stone layers is not advisable (COTO, 2020). Table 7-16 shows the indicator factors for typical demolition aggregates in South Africa.

Table 7-16: Indicator factors to produce one-tonne recycled demolition aggregate in South Africa

Indicator	**Unit**	**Recycled Demolition Aggregates**
Environmental Related Indicators		
CO_2e Emissions	kg CO_2e/t	4.4
Energy Use	MJ/t	22.33
Water Use	l/t	5.04
Emissions to Water	kg PAHs/t	1.87E-08
Social Related Indicators		
SO_2 Emissions	kg SO_2/t	0.03
NOx Emissions	kg NOx/t	0.02
Particulate Matter Emissions	kg PM_{10}/t	0.00
Volatile Organic Compounds Emissions	kg VOC/t	0.00
DQI		71%
DQI Reference		IX-XIII

7.13 CEMENT AND LIME

Cement and lime are typically used in South African pavement construction to stabilise granular pavement layers. Stabilisation may be required for a variety of reasons, including to modify the properties of poor-quality (marginal) or deleterious material and to increase the bearing strength of compacted layers. The production of cement and lime is generally localised to Gauteng, with scattered plants in Durban, Kimberley, Port Elizabeth and Cape Town (GCR, 2019). Energy requirements to produce cement and lime have been obtained from various international sources. It is noted no South African specific data currently exists for these processes. These data are assumed to represent similar processes and environments relevant to South Africa. Following the steps previously described, indicator factors are calculated for typical cement and lime production in South Africa, shown in Table 7-17. The water used during the extraction and transportation of raw material to the processing plant to produce cement has not been investigated in detail and typical water usage values provided refer to the water used in electricity generation alone and may be an underestimate.

Table 7-17: Indicator factors to produce one-tonne cement/lime in South Africa

Indicator	**Unit**	**Cement**	**Lime**
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	927.54	47.88
Energy Use	MJ/t	4707.00	243.00
Water Use	l/t	1061.43	54.80
Emissions to Water	kg PAHs/t	3.94E-06	2.03E-07
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	6.60	0.34
NOx Emissions	kg NOx/t	4.57	0.24
Particulate Matter Emissions	kg PM_{10}/t	0.26	0.01
Volatile Organic Compounds Emissions	kg VOC/t	0.00	0.00
DQI		76%	79%
DQI Reference		III – V, IX-XII, XVIII	III-V, X

7.14 HOT-, WARM- AND COLD-MIX ASPHALT

Hot-, warm-, and cold-mix asphalt (HMA, WMA and CMA) is designed pre-mixes of graded aggregates and bituminous-based binders, applied on road pavements to provide a smooth and safe riding surface and protect the underlying layers. Indicator factors are provided for all three of these asphalt types in this study.

To produce HMA, hot bitumen is mixed with heated aggregate, where the aggregate is typically heated using an oil burner. This study assumes the use of a medium-heavy oil (UN-ESY, 2017; NAEI, 2018) for the heating process with a mix design of 6% bitumen content. The energy requirements are predominantly met by medium-heavy heating oil (90%) and electricity (10%). A total of 480 MJ is assumed to be required for the HMA production process, including heating, mixing and other peripheral activities (Stripple, 2001; Lundberg et al., 2016; TRL, 2014). Calorific values (UN-ESY, 2017) and relevant factors (NAEI, 2018) are obtained following the steps previously described. Table 7-18 provides the indicator factors to produce one-tonne HMA both inclusive and exclusive of bitumen and aggregate indicator factors. A transport distance of 50 km is assumed for both bitumen and aggregate.

Table 7-18: Indicator factors to produce one-tonne HMA in South Africa

Indicator	**Unit**	**HMA Production Process**	**HMA**ł
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	39.34	69.36 (70.06)
Energy Use	MJ/t	480	723.14 (725.52)
Water Use	l/t	19.68	76.05 (76.47)
Emissions to Water	kg PAHs/t	8.04E-07	9.56E-07 (9.56E-07)
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	0.27	0.43 (0.44)
NOx Emissions	kg NOx/t	0.28	0.50 (0.50)
Particulate Matter Emissions	kg PM_{10}/t	5.14E-03	0.01 (0.01)
Volatile Organic Compounds Emissions	kg VOC/t	3.16E-04	0.04 (0.04)
DQI		79%	79%
DQI Reference		IV, V, IX, XIX, XX, XXI	II, IV, V, IX, XIX, XX, XXI

ł Values in brackets represent inland scenario, with remaining values representing coastal scenario.

To produce WMA, the energy requirement was simply reduced by 30% compared to HMA (Zaumanis et al., 2012). Table 7-19 provides the indicator factors to produce one-tonne WMA both inclusive and exclusive of bitumen and aggregate indicator factors. A transport distance of 50 km is assumed for both bitumen and aggregate.

Table 7-19: Indicator factors to produce one-tonne WMA in South Africa

Indicator	**Unit**	**WMA Production Process**	**WMA**ᵻ
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	27.54	48.6 (49.08)
Energy Use	MJ/t	336	506.24 (507.86)
Water Use	l/t	13.78	53.23 (53.53)
Emissions to Water	kg PAHs/t	5.62E-07	6.69E-07 (6.69E-07)
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	0.19	0.30 (0.31)
NOx Emissions	kg NOx/t	0.2	0.35 (0.35)
Particulate Matter Emissions	kg PM_{10}/t	3.60E-03	0.01 (0.01)
Volatile Organic Compounds Emissions	kg VOC/t	2.53E-04	0.03 (0.03)
DQI		79%	79%
DQI Reference		IV, V, IX, XIX, XX, XXI	II, IV, V, IX, XIX, XX, XXI

ᵻ Values in brackets represent inland scenario, with remaining values representing coastal scenario.

To produce CMA, an energy requirement was obtained from Lundberg et al. (2016). The remaining data were obtained following the steps previously described. Table 7-20 provides the indicator factors to produce one-tonne CMA both inclusive and exclusive of bitumen and aggregate indicator factors. A transport distance of 50 km is assumed for both bitumen and aggregate.

Table 7-20: Indicator factors to produce one-tonne CMA in South Africa

Indicator	**Unit**	**CMA Production Process**	**CMA**ᵻ
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	11.06	41.15 (41.84)
Energy Use	MJ/t	135	335.7 (338.01)
Water Use	l/t	5.54	61.9 (62.33)
Emissions to Water	kg PAHs/t	2.26E-07	2.99E-07 (2.99E-07)
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	0.076	0.24 (0.25)
NOx Emissions	kg NOx/t	0.079	0.30 (0.30)
Particulate Matter Emissions	kg PM_{10}/t	0.001	0.01 (0.01)
Volatile Organic Compounds Emissions	kg VOC/t	1.00E-04	0.04 (0.04)
DQI		79%	79%
DQI Reference		IV, V, IX, XIX, XX, XXI	II, IV, V, IX, XIX, XX, XXI

ᵻ Values in brackets represent inland scenario, with remaining values representing coastal scenario.

7.15 CONSTRUCTION AND DEMOLITION OPERATIONS

The energy usage and related emissions for general construction and demolition operations are considered in this LCI. The LCI accounts for most of the typical activities required to construct and demolish a road. The typical activities include loading, excavating, dumping, compacting, paving and general activities such as applying tack coat, spraying water and sweeping. Typical energy requirements were obtained from Stripple (2001) and Wang et al. (2012). Typical emission values were obtained from EEA (2019) and UN – ESY (2017) following the steps previously described. Average indicator factors for these construction activities in South Africa are shown in Table 7-21 and Table 7-22. Various assumptions are incorporated into these estimates to reflect the most experienced construction conditions. These assumptions are shown in Appendix A-5. The estimates were obtained from various sources and do not necessarily represent the view or findings of the respective companies referenced. Further research is required to provide a broader range of activities accounting for a wider range of plant machinery.

For transportation of one kilometer, fuel consumption requirements for a general 14-ton short distance hauler and a 32-ton long-distance hauler (Stripple, 2001) were used. Factors were obtained following the steps previously described and are shown in Table 7-23. It is understood these factors may be conservative and do not reflect the increased efficiency of newer construction vehicles.

Table 7-21: Indicator factors for construction and demolition activities per loose cubic meter in South Africa

Indicator	**Unit**	**Wheel loader**	**Excavator**	**Dumper**	**Milling - asphalt**
Environmental Related Indicators					
CO_2e Emissions	kg CO_2e/loose m^3	0.18	0.24	0.52	0.2
Energy Use	MJ/loose m^3	2.43	3.22	6.9	2.69
Water Use	l/loose m^3	0.00	0.00	0.00	0.00
Emissions to Water	kg PAHs/loose m^3	4.52E-09	5.99E-09	1.28E-08	5.00E-09
Social Related Indicators					
SO_2 Emissions	kg SO_2/loose m^3	8.74E-05	1.16E-04	2.48E-04	9.66E-05
NOx Emissions	kg NOx/loose m^3	1.65E-03	2.18E-03	4.68E-03	1.82E-03
Particulate Matter Emissions	kg PM_{10}/loose m^3	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/loose m^3	0.00	0.00	0.00	0.00
DQI		82%			
DQI Reference		III, V, IX, XXI			

Table 7-22: Indicator factors for construction and demolition activities per square meter in South Africa

Indicator	**Unit**	**Compactor - soil**	**Compactor - asphalt**	**Compactor – asphalt (pneumatic)**	**Paver**
Environmental Related Indicators					
CO_2e Emissions	kg CO_2e/m^2	0.04	0.06	0.04	0.05
Energy Use	MJ/m^2	0.6	0.79	0.48	0.66
Water Use	l/m^2	0.00	0.00	0.00	0.00
Emissions to Water	kg $PAHs/m^2$	1.11E-09	1.46E-09	8.84E-10	1.23E-09
Social Related Indicators					
SO_2 Emissions	kg SO_2/m^2	2.14E-05	2.82E-05	1.71E-05	2.37E-05
NOx Emissions	kg NOx/m^2	4.04E-04	5.33E-04	3.22E-04	4.47E-04
Particulate Matter Emissions	kg PM_{10}/m^2	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/m^2	0.00	0.00	0.00	0.00
DQI		82%			
DQI Reference		III, V, IX, XXI			
Indicator	**Unit**	**Grader**	**Concrete sawing and sealing**	**Concrete milling**	**General activity**
Environmental Related Indicators					
CO_2e Emissions	kg CO_2e/m^2	0.01	0.04	5.52	0
Energy Use	MJ/m^2	0.12	0.5044	73.7	7.54E-03
Water Use	l/m^2	0.00	0.00	0.00	0.00
Emissions to Water	kg $PAHs/m^2$	2.23E-10	9.38E-10	1.37E-07	1.40E-11
Social Related Indicators					
SO_2 Emissions	kg SO_2/m^2	4.31E-06	1.81E-05	2.65E-03	2.71E-07
NOx Emissions	kg NOx/m^2	8.13E-05	3.42E-04	5.00E-02	5.11E-06
Particulate Matter Emissions	kg PM_{10}/m^2	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/m^2	0.00	0.00	0.00	0.00
DQI		82%			
DQI Reference		III, V, IX, XXI			

Table 7-23: Indicator factors for transportation of one-tonne-kilometer in South Africa

Indicator	**Unit**	**14-ton short distance**	**32-ton long distance**
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/tonne-km	0.064	0.031
Energy Use	MJ/tonne-km	0.850	0.416
Water Use	l/tonne-km	0.00E+00	0.00E+00
Emissions to Water	kg PAHs/tonne-km	1.58E-09	7.73E-10
Social Related Indicators			
SO_2 Emissions	kg SO_2/tonne-km	3.05E-05	1.49E-05
NOx Emissions	kg NOx/tonne-km	5.76E-04	2.82E-04
Particulate Matter Emissions	kg PM_{10}/tonne-km	6.74E-04	3.30E-04
Volatile Organic Compounds Emissions	kg VOC/tonne-km	3.88E-05	1.90E-05
DQI		82%	
DQI Reference		III, V, IX, XXI	

7.16 ASPHALT WITH RECLAIMED ASPHALT PAVEMENT

Reclaimed asphalt pavement (RAP) is most often produced by milling an existing asphalt pavement and screening the material for use in a new asphalt mix or use as aggregate base. Asphalt recycling in South Africa is done by four methods: cold in-place recycling, cold in-plant recycling, hot in-place recycling, and hot in-plant recycling (SABITA, 2017).

This study considers two scenarios: cold- and hot-in plant recycling, corresponding to conservative scenarios to calculate the energy requirements and associated indicator factors to produce one-tonne of asphalt with RAP. Warm in-plant recycling is not covered by Manual 36/TRH21 (SABITA, 2017) and as such not considered in this study. The mixture contains 22% RAP by weight for a mix design of 6% bitumen content, representing a common mix design implemented in South Africa (SABITA, 2017). This mix design aims to act as a benchmark scenario, but designers may design their own mixtures and calculate corresponding indicator factors using the inventory provided in this study.

Indicator factors to produce one-tonne of asphalt with RAP in South Africa are shown in Table 7-24 for an average for both inland and coastal scenarios, as the difference between scenarios is minute. These indicator factors include consideration of asphalt milling and crushing operations.

Table 7-24: Indicator factors to produce one-tonne asphalt with RAP in South Africa

Indicator	**Unit**	**HMA+RAP**	**CMA+RAP**
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	50.82	22.55
Energy Use	MJ/t	620.15	275.15
Water Use	l/t	25.43	11.28
Emissions to Water	kg PAHs/t	1.04E-06	4.61E-07
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	0.35	0.16
NOx Emissions	kg NOx/t	0.36	0.16
Particulate Matter Emissions	kg PM_{10}/t	0.01	2.94E-03
Volatile Organic Compounds Emissions	kg VOC/t	4.67E-04	2.07E-04
DQI		79%	
DQI Reference		IV, V, IX, XIX, XX, XXI	

A notable observation from Table 7-24 is that the energy use and associated indicator factors for asphalt with RAP are between roughly 27 to 46% lower than their conventional asphalt counterparts.

7.17 CONCRETE AND STEEL

Concrete pavements have long been used in South Africa, especially on high trafficked truck arterials linking South Africa's economic zone (Gauteng) to its harbours (Durban, Port Elizabeth and Cape Town). Using a typical energy requirement of 65.4 MJ for the mixing process of concrete and an energy split of diesel (75%) and electricity (25%), the indicator factors for pavement concrete were calculated. The mixture constituents are shown in Table 7-25 with indicator factors shown in Table 7-26. For pavement steel, indicator factors are obtained directly from the World Steel Association (2019), also shown in Table 7-26.

Table 7-25: Basic material to produce pavement concrete

Mixture	**Weight per m^3 produced concrete (kg)**
Cement	400
Crushed aggregate	1200
Put run natural aggregate	700
Water	170

Table 7-26: Indicator factors to produce one-tonne pavement concrete and steel in South Africa

Indicator	**Unit**	**Pavement concrete**	**Pavement steel**
Environmental Related Indicators			
CO_2e Emissions	kg CO_2e/t	159	1263.6
Energy Use	MJ/t	806.89	2.00E+04
Water Use	l/t	319.61	527.9
Emissions to Water	kg PAHs/t	6.75E-07	0.00
Social Related Indicators			
SO_2 Emissions	kg SO_2/t	1.13	2.584
NOx Emissions	kg NOx/t	0.78	2.162
Particulate Matter Emissions	kg PM_{10}/t	0.04	0.8107
Volatile Organic Compounds Emissions	kg VOC/t	0.00	0.08402
DQI		76%	87%
DQI Reference		III – VI, IX-XII, XVIII	III-V, XXI

7.18 DATA VALIDATION

To validate results, a comparison may be made between the carbon equivalent emissions (used as key output variable for this analysis) of similar notable life cycle inventories for common pavement materials and construction processes. The carbon equivalent emissions indicator is selected as key output variable as most LCIs consistently report on it and it is used by most countries as a default to quantify environmental sustainability. This comparison is shown in Table 7-27.

Table 7-27: Comparison of carbon equivalent emissions for common pavement materials

LCI	**Unit**	**Bitumen**	**Asphalt**	**Aggregate**	**Concrete**	**Steel**
Eurobitume (2012)	kg CO_2e/t	174.25	-	-	-	-
Eurobitume (2020)	kg CO_2e/t	136.80	-	-	-	-
Stripple (2001)	kg CO_2e/t	173.00	34.4	1.42	328.00	2220.00
Hammond and Jones (2019)	kg CO_2e/t	191.00	53.60	17.00	152.33	1270.00
South Africa (this study)	kg CO_2e/t	**233.36***	**70.06***	**36.53**	**159.00**	**1263.60**

* Inland bitumen factors used for comparison

What is demonstrated from the above comparisons is that the indicator factors for South African materials are often higher than most other inventories. This is largely attributed to the increased emissions associated with energy generation in South Africa (CER, 2019). What is not shown in Table 7-27, is the general lack of consideration by many inventories to include other key indicators such as water use and the various social emissions. The inventories used for comparison each incorporate various specific assumptions, such as using energy requirements as a key input variable and utilising location specific electricity generation and fuel consumption factors used by Stripple (2001). A similar methodology has been applied to develop the inventory presented in this chapter.

As previously discussed, viewing certain inventories as 'golden black boxes' often results in the use of poor-quality data, gaps in research being filled by default data and a general lack of consideration for location-specific evaluations. An additional flaw present in LCI models is the inconsistency in selecting indicator categories where energy and carbon emissions are typically focused on with other important indicators omitted. Focus on a holistic inventory which incorporates both environmental and social indicators is important to report on and this approach has been followed during this study.

7.19 WORKED EXAMPLE

To demonstrate the use of the LCI developed in this study, a worked example is provided for the pavement structures provided in Chapter 6. For the analysis, it is assumed that crushed stone is obtained from a commercial source 50 km away from the project location, with bitumen-based products obtained from the Natref refinery in Sasolburg (100 km away). For the C4 and G5 layers, locally available materials are utilised with organosilane and cementitious products sourced from 50 km away. It is noted these transportation distances are arbitrary and merely utilised to demonstrate consideration the impact transportation distance may have on the environmental impact of the construction phase. Typical construction processes and activities (e.g. material extraction, production, transportation and construction) are considered for both pavement options. Compaction densities are obtained from COTO (2020). The results of the analysis are summarised in Table 7-28 for the high-volume roads (ES10), and Table 7-29 for the low-volume roads (ES1).

Table 7-28: Life cycle analysis results for ES10 pavement construction options

Indicator	**Unit**	**ES10 – Wet**	**ES10 – Dry**	**ES10 – Alternative**
Environmental Related Emissions				
CO_2e Emissions	kg CO_2e/FU	264 298	207 711	137 144
Energy Use	MJ/FU	1 596 095	1 307 566	867 678
Water Use	l/FU	662 969	546 936	454 103
Emissions to Water	kgPAHs/FU	0.001	0.001	0.001
Social Related Emissions				
SO_2 Emissions	kg SO_2/FU	1 838	1 436	964
NOx Emissions	kg NOx/FU	1 432	1 153	747
Particulate Matter Emissions	kg PM_{10}/FU	503	383	34
Volatile Organic Compounds Emissions	kg VOC/FU	53	47	26

Table 7-29: Life cycle analysis results for ES1 pavement construction options

Indicator	**Unit**	**ES1 – Wet**	**ES1 – Dry**
Environmental Related Emissions			
CO_2e Emissions	kg CO_2e/FU	159 422	135 535
Energy Use	MJ/FU	1 009 212	887 990
Water Use	l/FU	486 787	459 451
Emissions to Water	kgPAHs/FU	0.001	0.001
Social Related Emissions			
SO_2 Emissions	kg SO_2/FU	1 094	924
NOx Emissions	kg NOx/FU	885	767
Particulate Matter Emissions	kg PM_{10}/FU	310	260
Volatile Organic Compounds Emissions	kg VOC/FU	35	32

The results from Table 7-29 show that in line with expectation, as a pavement structure's thickness and strength is reduced, so is its environmental burden. The majority of the energy used and emissions generated for pavement construction is concentrated in the material extraction and production phases whereas the majority of the water used is in the construction phase. Analysis of the alternative design shows the promise of reduced environmental impact for the novel materials currently being road tested. This is particularly noticeable when focusing on water use, where the alternative design can save as much as 208 866 litres of water per pavement kilometer. Using the South African Free Basic Water Policy (FBWP, 2007) minimum daily water requirement recommendations of 25 litres per capita per day for drinking, basic- and food-hygiene, the water savings realised from the alternative design are equivalent to the water needs of a typical local settlement of 1,200 people for one week per kilometer pavement built.

7.20 GUIDANCE FOR FUTURE RESEARCH

This section aims to provide guidance for future research focused on the environmental sustainability of pavement systems. For future research it is important to note that quality data, such as Environmental Product Declarations, which detail the environmental flows of construction materials in South Africa and internationally are scarce and the use of default data is a common approach utilised by academics to fill data gaps. This study has identified that by utilising energy requirement for each material or construction activity and back-calculating the carbon foorprint using South African specific energy indicator factors provided higher quality estimates than solely relying on the carbon footprint data from sources, especially when the sources are from international databases. Further guidance is provided in Chapter 12.

7.21 SUMMARY

The chapter provides an LCI for most materials, processes, and construction activities required for pavement construction and maintenance in South Africa. The inventory is summarised in Appendix A-1 and Appendix A-2. The LCI is based on reasonable quality data and provides rational estimates for environmental and social impacts of pavement development. There is a drive within South African roads authorities to promote sustainable technologies and practices. However, targeted efforts are required from roads authorities to focus on the supply chain of pavement materials, which account for most of the environmental and social impacts of pavement construction. It is recommended that authorities promote the participation of industry in furthering the development of the inventory proposed in this chapter. Better information is required specifically for the production of pavement construction materials. Certain social indicators are not yet well understood. Further research is required to develop valid quantification and impact models. A worked example is provided to demonstrate the implementation of the inventory.

8 SOCIAL LIFE CYCLE INVENTORY

8.1 CONTEXT AND SYSTEM DESCRIPTION

In the field of S-LCA, a screening tool is believed to provide a meaningful way to prioritise efforts in evaluating the social impacts of business models or product life cycles (Benoît and Mazijn, 2009). In (environmental) LCAs, ‘default’ or industry average data are often used for common product background processes that make small individual (but possibly large cumulative) contributions to the impacts of a product over its life cycle (Benoît-Norris et al., 2012). A comparable method is employed in LCCAs to evaluate economic performance of alternatives. Through these evaluations, the processes or activities that contribute predominantly to the total impacts are identified, and these ‘hotspots’ become priorities for data refinement and further improvement (Benoît-Norris et al., 2012). A similar approach of ‘hotspot’ identification may be useful in the early stage development and standardisation of S-LCA frameworks. In S-LCAs, these ‘hotspots’ - represented by key social indicators - describe the unit processes of a product life cycle, forming either a risk or an opportunity to contribute substantially to the total social impact of the product.

To achieve this, a top-down approach, proposed by the UNEP and SETAC Guidelines (Benoît and Mazijn, 2009), is implemented in this chapter using various existing methods (i.e. LCCAs, LCAs, performance assessments, etc.) which assess pavement sustainability across the three tenets (i.e. economic, environmental and social). Considering the strong correlation among the tenets, the similarities may be used as guidance in the determination of social ‘hotspot’s and refined to key social indicators related to pavement infrastructure provision. To do so, each tool is individually assessed to develop a basis for applying the social ‘hotspot’ methodology. Additional tools and techniques which are not specifically developed for pavement evaluation, but are commonly implemented in South Africa to measure social impacts across various industries, such as EmpIAs, are also included in this assessment. A flow chart of the process followed in developing a database of potential indicators using a top-down approach, to be used for further social ‘hotspot’ and subcategory assessments, is shown in Figure 8-1.

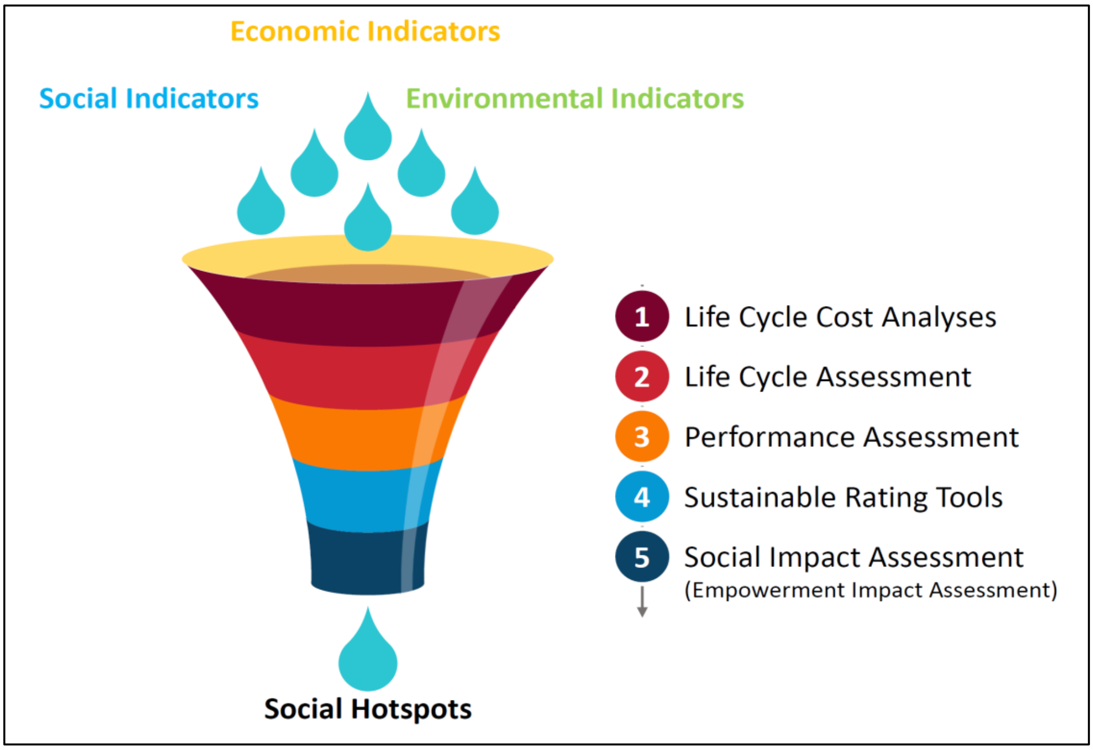


Figure 8-1: Top-down approach to database development

The following sections detail the main assessment specific indicators which have a direct relation to social sustainability.

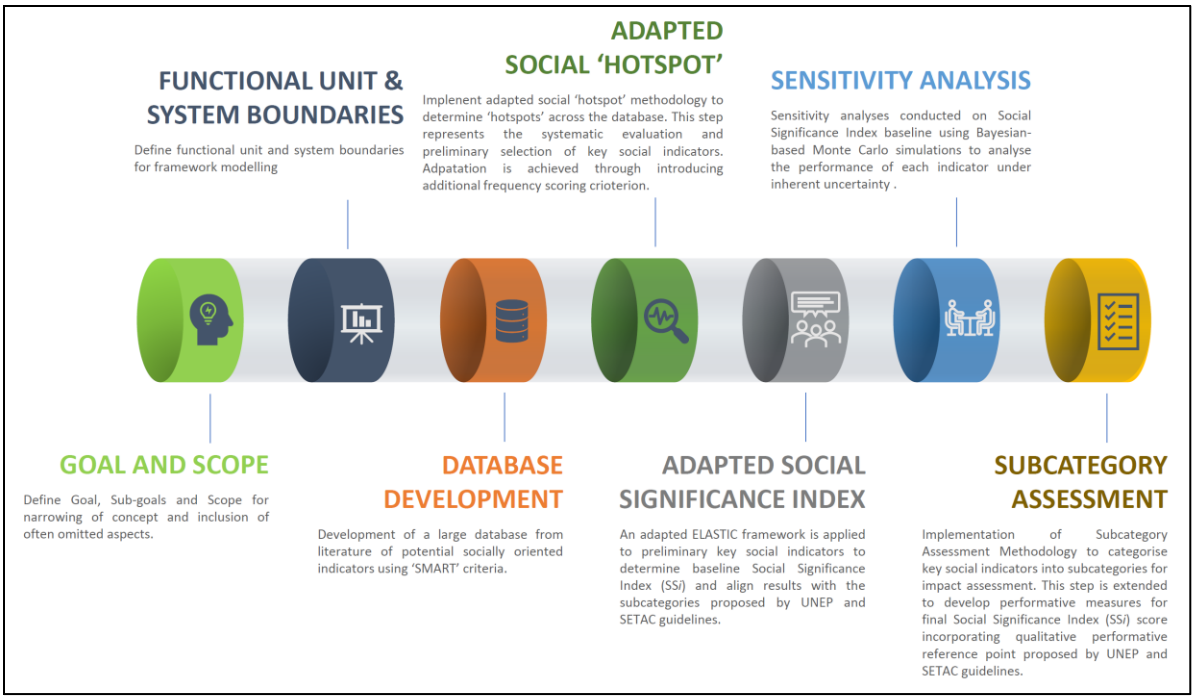
8.2 PROPOSED METHODOLOGICAL FRAMEWORK

As methodological standardisation has not yet been achieved to implement this general framework, a framework consisting of seven steps for S-LCI development is proposed in this chapter, combining the steps most commonly included and successfully applied in the literature. This proposed framework is detailed below and illustrated in Figure 8-2.

1. **Define Goal, Sub-goals and Scope:** In extending the general LCA framework requirements of goal and scope definition, additional sub-goals included in the ELASTIC framework (Castillo and Pitfield, 2010) are included to create a link with the subcategories proposed by UNEP and SETAC guidelines (Benoît and Mazijn, 2009). The sub-goals provide further decomposition through the specification of selection criteria adapted from the 'SMART' criteria (Broughton and Hampshire, 1997), summarised in Table 1.
2. **Functional unit and system boundaries:** The functional unit (FU), constituting the reference unit used to measure the performance of indicators, is often easily defined in typical LCA studies. However, when applied to S-LCAs, it may not be as simple and linking results to the FU is often difficult to achieve (Benoît and Mazijn, 2009). However, the UNEP and SETAC guidelines stress

the importance of creating a set of FUs and accompanied system boundaries, and state that in situations where alternatives are to be compared, the FU must be based on a function rather than an item or product. System boundaries determine which unit processes along the product life cycle are included in the system being assessed (Benoît and Mazijn, 2009).

3. **Database development:** Assembling a large database of potential sustainable pavement indicators from renowned sources was conducted following the UNEP and SETAC guidelines together with proposed methodologies detailed in the literature. ISO 14040 (2006) indicator data quality requirements are satisfied using peer-reviewed, local and international sources which have successfully been implemented in public and private practices. 'SMART' criteria are further introduced to reduce the database to relevant indicators linked with the ELASTIC sub-goals, providing a pathway to the subcategories proposed by UNEP and SETAC.
4. **Adapted social 'hotspot' methodology:** This step seeks to implement an adapted social 'hotspot' assessment to determine the 'hotspots' across the socially-oriented database and represents the systematic evaluation and preliminary selection of key social indicators. The adaptation is achieved by applying an additional frequency scoring criterion proposed by Kühnen and Hahn (2017) and Huarachi et al (2020) incorporating 'selection' bias. The frequency scoring refers to the number of times an indicator appears among datasets and is used to enhance the ELASTIC Social Significance Index (SS_i) score (Castillo and Pitfield, 2010) and uncertainty analyses in following steps.
5. **Adapted Social Significance Index:** The Elastic framework is adapted and implemented in this study predominantly to determine the baseline SS_i score (Castillo and Pitfield, 2010) for each indicator to be used as input for sensitivity analyses. The adaptation is realised through the inclusionof the frequency score determined from the social 'hotspot' assessment.
6. **Sensitivity analysis and key social indicator selection incorporating uncertainty:** This step seeks to conduct sensitivity analyses on the baseline SS_i scores obtained from the previous step and is achieved through incorporation of Bayesian-based Monte Carlo simulations, to analyse the performance of each indicator under inherent uncertainty (Zheng et al., 2020). A final SS_i score is determined and used as a performative reference baseline in the SAM analysis.
7. **Subcategory assessment method:** In the final step, a Type-1 SAM is applied to the key social indicators identified from Step 6. Develop performative measures and allow for final SS_i scoring as proposed by Zheng et al. (2020). The final SS_i score is further aligned to the qualitative performance reference point principle proposed by UNEP and SETAC guidelines (Benoît and Mazijn, 2009). The performative measures may be used to develop social life cycle impact assessments and interpretation, completing the framework for an S-LCA.



GOAL AND SCOPE

Define Goal, Sub-goals and Scope for narrowing of concept and inclusion of often omitted aspects.

FUNCTIONAL UNIT & SYSTEM BOUNDARIES

Define functional unit and system boundaries for framework modelling

DATABASE DEVELOPMENT

Development of a large database from literature of potential socially oriented indicators using 'SMART' criteria.

ADAPTED SOCIAL 'HOTSPOT'

Implenent adapted social 'hotspot' methodology to determine 'hotspots' across the database. This step represents the systematic evaluation and preliminary selection of key social indicators. Adpatation is achieved through introducing additional frequency scoring crioterion.

ADAPTED SOCIAL SIGNIFICANCE INDEX

An adapted ELASTIC framework is applied to preliminary key social indicators to determine baseline Social Significance Index (SS*i*) and align results with the subcategories proposed by UNEP and SETAC guidelines.

SENSITIVITY ANALYSIS

Sensitivity analyses conducted on Social Significance Index baseline using Bayesian-based Monte Carlo simulations to analyse the performance of each indicator under inherent uncertainty .

SUBCATEGORY ASSESSMENT

Implementation of Subcategory Assessment Methodology to categorise key social indicators into subcategories for impact assessment. This step is extended to develop performative measures for final Social Significance Index (SS*i*) score incorporating qualitative performative reference point proposed by UNEP and SETAC guidelines.

Figure 8-2: A proposed methodological framework for S-LCI development

8.3 GOAL, SUB-GOALS AND SCOPE

8.3.1 Goal

The proposed framework utilises and evaluates a lengthy list of indicators to identify a subset that maximises desirable qualities. As such, the overarching vision is pre-defined (Castillo and Pitfield, 2010). The goal of this study is to provide an inventory for key sustainability indicators related to the development and management of pavement infrastructure in South Africa with an emphasis on the social tenet. The inventory is intended to act as a building block on which to improve and develop further life cycle inventories where specific social consideration is given to provide a holistic sustainable life cycle assessment model for pavement infrastructure in South Africa.

8.3.2 Sub-goals

Following the guidance of the ELASTIC methodology (Castillo and Pitfield, 2010), three adapted specific and non-changing sub-goals are prescribed, namely:

i. Maximise the methodological quality of indicators;
ii. Maximise the relevance of indicators to the concept of sustainable pavements, and
iii. Maximise the importance of indicators to the concept of sustainable pavements, achieved through an adapted frequency analysis proposed by Kühnen and Hahn (2017) and Huarachi et al. (2020) (this is an additional sub-goal used to supplement the existing ELASTIC framework).

These goals allow for a narrowing of the vision but are still broad enough to allow for evaluation of indicators using quantifiable criteria, shown in Table 8-1.

Table 8-1: Adapted SMART indicators (Broughton and Hampshire, 1997)

Importance	Measurable	Attainable	Timely	Interpretable	Isolatable
Indicators should be considered important to the relevant stakeholders.	Each indicator should be measurable and hence requires a precise definition.	The indicator must be attainable at a reasonable cost using an appropriate collection method.	An indicator needs to be collected and reported at the right time to influence many management decisions.	Indicators should be easily interpretable to the people who will use the data.	Key indicators need to be easily isolatable and not create confusion through comparison to other indicators.

8.3.3 Scope

The study considers a cradle-to-grave scenario for the construction, maintenance, rehabilitation and salvaging of pavement infrastructure, and is representative of any pavement system in South Africa. The model provides key social indicators focused on health, safety, environmental, socio-economic and empowerment impacts of pavement infrastructure.

8.4 FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The FU used for this analysis is a 7.2 m wide, 1 km long pavement structure. For analysis purposes, the focus will be given to the functional performance and direct social impact of background processes, detailed throughout literature, required to provide the pavement infrastructure. The system boundaries include the following steps:

1. Raw material extraction;
2. Material processing and production;
3. Construction;
4. Use phase;
5. Maintenance, and
6. Demolition

8.5 DATABASE DEVELOPMENT

For the application of the proposed framework in South Africa, an initial long list of 1 352 sustainable transport indicators were identified from 25 renowned local and international sources. These sources include relevant sustainable pavement assessment frameworks described in this study and additional assessment frameworks commonly applied in the industry, such as the Sustainable Development Goals. In applying the adapted 'SMART' criteria listed in Table 8-1, the database is reduced to indicators which are socially focused. As previously discussed, environmental and economic indicators which have either direct or indirect social consequences are retained, reducing the initial long list of 1 352 indicators to 366 socially relevant indicators. These indicators are used for further analyses during this study. A summary of the database is shown in Appendix B-1, with detailed information withheld due to proprietary relationships.

8.6 ADAPTED SOCIAL HOTSPOT METHODOLOGY

As various datasets developed by numerous researchers were used for this study, a range of words and phrases have been utilised throughout, which ultimately have the same implication, such as 'water quality' and 'water pollution'. To obtain the social 'hotspots' from the reduced database, a word heat map was drawn on to analyse and identify the words or phrases most listed. The additional frequency step proposed by Kühnen and Hahn (2017) and Huarachi et al. (2020) is also applied to these 'hotspots', representing the preliminary key social indicators. It is noted that the frequency of certain 'hotspots' has been altered to better reflect their importance to the South African pavement engineering field and current global political landscape, through applying the principle of 'survival' or 'selection' bias.

8.6.1 Selection bias

Selection bias refers to the logical error of concentrating only on indicators that made it past the selection process and overlooking those that did not. An example of this would be considering the 'climate change' indicator, which among others, did not receive a high enough frequency score (i.e. 3) to be considered a 'hotspot' as it is omitted in most data sets used to develop this database. The results of the social 'hotspot' methodology incorporating selection bias are shown in Figure 8-3, providing 23 'hotspots', with the frequency results detailed in Table 8-2. The heatmap was developed with the 366 socially relevant indicators obtained from the database development phase.

Figure 8-3: Heat map of common 'hotspots' derived from a reduced database

Table 8-2: Frequency of indicators derived from a reduced database

Social 'Hotspots'	**Frequency**
Emissions	19
Value for Money	19*
Climate Change	19*
Fundamental Economic Transformation	19*
Safety (Road User & Worker)	18
Water use and pollution	17
Noise	16
Health (Road User & Worker)	16
Community Participation	15*
Air Quality	13
Provision of Pedestrian Facilities	12
Jobs	12
Travel Time	11
Accessibility	11
Local Economic Development	11
User Cost	10
Education	9
Energy use	8
Pollution	8
Provision of Traveller Information Systems	7
Congestion	6
Resilience	6
Empowerment	5

* 'Hotspot' frequency altered by the author to reflect importance in South Africa (required as most databases utilised in this study were internationally developed)

8.7 ADAPTED ELASTIC SOCIAL SIGNIFICANCE INDEX

In preparation for sensitivity analyses and uncertainty modelling, an adapted ELASTIC SS_i is applied to determine the baseline SS_i scores of each indicator. This adaptation is realised by including the frequency step previously discussed to represent the 'Importance' of the indicators, combined with the 'Relevance to sustainable pavements' and 'Methodological quality' sub-goals of the ELASTIC framework.

For the 'Importance' criterion, the score is calculated as the indicator frequency divided by the highest indicator frequency (i.e. 19) normalised to a score out of 5. Secondly, the 'Methodological quality' sub-goal is scored on a Likert scale using the scoring matrix shown in Appendix B-2 together with the sub-goal weights. The 'Relevance to sustainable pavements' sub-goal is not scored for individual indicators in this study and the weights determined by Castillo and Pitfield (2010), also shown in Appendix B in Figure B-1, are rather applied. Indicators are then numerically aggregated employing a Simple Additive Weighting (SAW) approach and an adapted SS_i score is calculated for each indicator, where the best performing indicator is the one with the highest total weighted sum score. The SS_i is calculated as follows (Castillo and Pitfield, 2010):

$$\boldsymbol{SS_i = \sum_{j=1}^{n} s_j^a (g_k w_j) + II} \qquad \text{for all } \boldsymbol{j} = 1, 2, 3, \ldots, \boldsymbol{n} \text{ and } \boldsymbol{k} = 1, 2$$

Where:

SS_i is the overall weighted performance score of indicator a;

g_k is the importance weight of sub-goal k;

w_j is the importance weight of criterion j;

s_j^a is the normalised outcome score for indicator a on criteria j, *and*

II is the performance of indicator a determined by the frequency (representing the adaptation).

The baseline SS_i score results are shown in Table 8-3. Additionally, the 'Relevance to sustainable development' sub-goals are also shown in Table 8-3.

Table 8-3: Baseline SS_i Scores

Relevance to sustainable pavements	Key Social indicators	Baseline SS_i
Liveable Streets and Neighbourhoods	Noise	0.92
	Air Quality	0.80
	Travel Time	0.74
	Congestion	0.65
	Resilience	0.60
Protection of the Environment	Emissions	0.94
	Water use and pollution	0.96
	Energy use	0.83
	Pollution	0.78
	Climate Change	0.91
Equity and Social Inclusion	Accessibility	0.68
	Local Economic Development	0.94
	Fundamental Economic Transformation	0.87
	Community Participation	0.87
Safety	Safety (Road User & Worker)	1.14
	Health (Road User & Worker)	1.14
	Provision of Pedestrian Facilities	1.06
	Provision of Traveller Information Systems	0.93
Vibrant and Efficient Economy	Jobs	0.86
	User Cost	0.94
	Value for Money	0.75
	Education	0.79
	Empowerment	0.71

8.8 SENSITIVITY ANALYSES INCORPORATING UNCERTAINTY

The baseline SS_i scores from the previous step are used as key input for sensitivity analyses. The ELASTIC methodology provides weightings for each indicator sub-goal and criterion which were used to determine the baseline scores. These weights, influenced by the goal and scope of this framework, are further used for sensitivity analyses to determine their impact on the key social indicator selection. This approach follows the proposal of UNEP and SETAC guidelines (Benoît and Mazijn, 2009) stating 'it is recommended that S-LCA studies attempt to characterize the sensitivity of their data due to system boundary decisions'.

Implementing these weightings and the baseline scores, a sensitivity analysis was conducted using Bayesian-based Monte Carlo simulations in which 50,000 outcomes were modelled using a uniform distribution (Zheng et al., 2020). The model accounted for every possible scoring scenario and provided results for the indicators which consistently performed well-given input changes and uncertainty. The results of the simulations are summarised in Table 8-4. Typical results of the simulations are shown in Appendix D. The hierarchy of results presented are based on the Monte Carlo simulation outcomes and the position change describes how the importance of each indicator changed from the baseline to the simulation results.

Table 8-4: SS_i-Baseline and -Monte Carlo Simulation Comparison Results

Social sustainable indicator	**SS_i - Baseline**	**SS_i – Monte Carlo simulations**	**Position change compared to baseline**
Safety (Road User & Worker)	1.14	1.03	-
Health (Road User & Worker)	1.14	1.00	-
Provision of Pedestrian Facilities	1.06	0.93	-
Emissions	0.94	0.86	↑
Climate Change	0.91	0.86	↑
Provision of Traveller Information Systems	0.93	0.84	↑
Water use and pollution	0.96	0.83	↓
Fundamental Economic	0.94	0.81	↓
Value for money	0.94	0.81	↓
Community Participation	0.87	0.75	↑
Local Economic Development	0.87	0.75	↑
Noise	0.92	0.74	↓
Air Quality	0.80	0.69	↑
Jobs	0.86	0.69	↓
Accessibility	0.68	0.67	↑
Energy use	0.83	0.67	↓
Pollution	0.78	0.67	-
Travel Time	0.74	0.66	↑
Congestion	0.65	0.66	↑
Resilience	0.60	0.66	↑
User Cost	0.75	0.66	↓
Education	0.79	0.64	↓
Empowerment	0.71	0.57	↓

8.9 SUBCATEGORY ASSESSMENT METHOD

In this study, a Type-1 SAM analysis is applied to characterise indicators into relevant impact categories. In applying the Type-1 SAM analysis, UNEP and SETAC guidelines require that the impact categories, which should correspond to the goal and scope of the study, represent the key social issues of interest regarding the stakeholders affected. It is noted that this approach in impact category definition may vary from the commonly understood and accepted impact categories used in LCAs, such as ‘global warming’. This is largely due to a lack of sufficient experience to determine universally accepted impact categories for S-LCAs as the cause-effect relationships are not simple enough or not known with enough precision for confident modelling (Benoît and Mazijn, 2009).

In applying the Type-1 SAM analysis, relevant indicators and their SS_i scores are aggregated into subcategories according to the overall indicator objective related to the resulting end-category. This allows for each impact category to carry a certain weight determined from previous steps, which ultimately contributes to social sustainability as proposed by Zheng et al. (2020).

To determine the final aggregated score, or Social Sustainable Score (SSs), each impact category is scored on a Likert scale (between 1 to 5) and the score is multiplied by a normalised grouping weight (obtained as the sum of the indicator weights grouped into subcategories). The subcategories, corresponding weights and endpoint impact categories are shown in Table 8-5.

Table 8-5: Proposed Impact Categories

Impact category	**Subcategory**	**Score***	**Subcategory weight**	**Final score**
*To what extent do you agree with the following statements (1 = strongly disagree; 5 = strongly agree) If the project has not made consideration for a performative measure, a score of '0' is awarded.				
1. Pollution	A life cycle assessment has been conducted and reduction of Emissions, Waste, Energy use, and Water contamination has been achieved.		4.29	
2. Socio-economic Impact	The project achieves Fundamental Economic Transformation through, inter alia, providing Educational opportunities for, and seeking the Empowerment of, targeted beneficiaries ensuring long-lasting Jobs.		3.15	
3. Safety	There are good systems in place to ensure Health and Safety of workers, motorised and non-motorised road users.		2.26	
4. Functional Performance	The project ensures a reduction in Travel Time, User Cost and Congestion through both construction and use phases.		2.3	
5. Functional Performance	Adequate Pedestrian Facilities have been provided to ensure the Accessibility of non-motorised road users.		1.83	
6. Climate change	The predicted impacts of local Climate Change have been considered and vulnerable pavement systems (including local communities) have been identified. Pavement Resilience has been increased and pavement construction and maintenance impacts on local communities decreased.		1.74	
7. Local economic development	The project achieves Local Economic Development through promoting and favouring Community Participation and Labour Enhanced Construction Methods.		1.71	
8. Functional Performance	Traveller Information Systems are provided during construction and use phases.		0.95	
9. Financial Performance	The project ensures good Value for Money.		0.92	
10. Pollution	Efforts have been made to reduce Noise during construction and use phases.		0.85	
SS$_s$ Total (100)				

Using the final SSs determined in Table 8-5 where a maximum of 100 points is achievable, a project's sustainability may be evaluated by comparing the score against a set of proposed benchmarks, shown in Table 8-6. The proposed benchmarks have been determined as 'unsustainable', where sustainable interventions are not implemented, 'business as usual', where only commonly accepted sustainable interventions are implemented, and 'silver, 'gold' and 'evergreen' where an increasing amount of sustainable interventions are implemented above the norm.

Table 8-6: Proposed sustainable levels for pavements in South Africa

Weighted score	Sustainable level
<50	Unsustainable
50-60	Business as usual
60-75	Silver
75-90	Gold
>90	Evergreen

Projects may be scored either through self-assessment or third-party validation.

8.10 WORKED EXAMPLE

To demonstrate the use of the impact categories developed in this study, a worked example is provided based on a case study previously assessed using an EmpIA (WCDTPW, 2010). This worked example considers the sidewalk next to the road scenario described in Chapter 6. This worked example is firstly evaluated based on only the social indicators utilised in the EmpIA and reevaluated incorporating broader social considerations as proposed in the S-LCI of this study.

The worked example considered the construction and upgrading of 2 km of the sidewalk and the demarcation of taxi embayment on the main access road to the informal part of Nkqubela, a settlement in the Western Cape. The project aimed to increase the safety of non-motorised users and access to public transport. Since the ownership of vehicles in the area is very low, the use of public transport is dominant. The project value was R3 million ($200,000) and emphasis had been given to empowerment through labour enhancing construction methods.

Applying the EmpIA, local beneficiaries were identified favouring black women, youth and disabled individuals. The beneficiaries were identified through community engagement and discussions with community leaders on the local needs. The literacy and training of each beneficiary was assessed ranging from unskilled to skilled and the beneficiaries were assigned to certain construction tasks according to their abilities. The methods of construction for each task were adapted to increase labour inputs and meet the skill levels of the beneficiaries. Additional training opportunities were evaluated, and it was determined that increased awareness of life skills, diseases, construction health and safety, and construction administration were focus areas.

The results of implementing the EmpIA were that the project employed roughly 55 previously unemployed local beneficiaries consisting of unskilled, semi-skilled and skilled individuals with a composition favouring black women, youth and disabled individuals sourced from the local community. 30% of the project value was spent on labourer fees by promoting labour enhancing construction methods and approximately 5% of the project value was spent on training, which included life skill-, HIV/Aids-, construction health and safety-, and administration-training. Due to the project experience and additional training, the beneficiaries were provided with long-term empowerment, employment and wellness.

In formulating and designing the construction around empowerment, favourable results were obtained. However, certain key social issues were not considered which include evaluating alternative designs through a life cycle assessment to compare construction impacts. Furthermore, the impacts of local climate change was not considered, nor is there evidence of attention to additional traveller information systems (including safety notices) or reducing construction and use phase noise. These are some of the key shortcomings identified in the EmpIA which are considered in the S-LCI proposed in this study.

In evaluating the case study, the project is scored against the proposed impact categories shown in Table 9-5, initially only considering the indicators used in the EmpIA. This score is referred to as the baseline SS_S. The project is then re-assessed implementing additional sustainable evaluations not considered in the EmpIA but listed in the S-LCI of this study. Table 8-7 summarises the baseline SS_S for the case study.

Table 8-7: Nkqubela construction and upgrading of baseline Social Sustainable score (Categories rearranged)

Category	**Performative social sustainability measures**	**Score***	**Grouping weight**	**Final score**
*To what extent do you agree with the following statements (1 = strongly disagree; 5 = strongly agree) If the project had not considered the performative measure, a score of '0' is awarded.				
Pollution	A life cycle assessment had been conducted and reduction of Emissions, Energy use and Water contamination had been achieved.	0	4.29	0
Pollution	Efforts have been made to reduce Noise during construction and use phases.	3	0.85	2.55
Climate change	The predicted impacts of local Climate Change had been considered and vulnerable pavement systems (including local communities) had been identified. Pavement Resilience had been increased and pavement construction and maintenance impacts on local communities decreased.	0	1.74	0
Socio-economic Impact	The project achieved Fundamental Economic Transformation through, inter alia, providing Educational opportunities for, and seeking the Empowerment of, Targeted Beneficiaries ensuring long-lasting Jobs.	5	3.15	15.75
Local economic development	The project had achieved Local Economic Development through Community Participation, preferential procurement, training, contractor mentorship, etc.	5	1.71	8.55
Safety	Full compliance with Construction Health and Safety Regulations, Road Safety Audit or similar road user's safety assessment.	5	2.26	11.3
Functional Performance	The project ensures an improvement in Stable Flow with a reduction in Travel Time evidenced by a traffic study.	4	2.3	9.2
Functional Performance	Due consideration had been given to Pedestrian Facilities for Safety and Accessibility.	5	1.83	9.15
Functional Performance	Traveller Information Systems are provided during construction and use phases.	3	0.95	2.85
Financial Performance	The project ensured good Value for Money, evidenced by a cost analysis showing an acceptable cost premium against process deliverables.	5	0.92	4.6
SS_s Total (100)				**64**

For the LCA and climate change impact categories, a score of zero was awarded as these measures were not considered and the project receives a total SS_s of 63.95 points and a 'Silver' level of sustainability. By considering the predicted local climate change impacts and settlement vulnerabilities, as well as conducting a life cycle assessment, sustainability may be greatly enhanced. It has been shown that an alternative pavement design can save between 25-56% on emissions, 56% on energy use and 58% on water use in South Africa. The water savings may be equivalent to the water requirements for 2,000 people for one week per kilometer pavement constructed, as discussed in Chapter 7 of this thesis. Combined with the predicted climate change impacts of a medium to high risk of heat stress, droughts, very hot days and flooding (Engelbrecht et al., 2019), the life cycle savings may greatly assist in reducing these impacts and vulnerabilities. Furthermore, an alternative design may not only present environmental and social savings but commonly also economic savings. An opportunity then exists to utilise the economic savings to provide further training (e.g. sponsoring a local beneficiary for tertiary education).

In re-evaluating the worked example applying these additional sustainable evaluations, the alternative approach may be scored using the impact categories proposed in Table 8-5. A final SS_s of 94 points is achieved with a sustainability level 'Evergreen', shown in Table 8-8.

Table 8-8: Nkqubela construction and upgrading of baseline Social Sustainable score (Alternative approach evaluated)

Category	**Performative social sustainability measures**	**Score***	**Grouping weight**	**Final score**
Pollution	A life cycle assessment had been conducted and reduction of Emissions, Energy use and Water contamination had been achieved.	4	4.29	17.16
Pollution	Efforts have been made to reduce Noise during construction and use phases.	3	0.85	2.55
Climate change	The predicted impacts of local Climate Change had been considered and vulnerable pavement systems (including local communities) had been identified. Pavement Resilience had been increased and pavement construction and maintenance impacts on local communities decreased.	5	1.74	8.7
Socio-economic Impact	The project achieved Fundamental Economic Transformation through, inter alia, providing Educational opportunities for, and seeking the Empowerment of, Targeted Beneficiaries ensuring long-lasting Jobs.	5	3.15	15.75
Local economic development	The project had achieved Local Economic Development through Community Participation, preferential procurement, training, contractor mentorship, etc.	5	1.71	8.55
Safety	Full compliance with Construction Health and Safety Regulations, Road Safety Audit or similar road user's safety assessment.	5	2.26	11.3
Functional Performance	The project ensures an improvement in Stable Flow with a reduction in Travel Time evidenced by a traffic study.	5	2.3	11.5
Functional Performance	Due consideration had been given to Pedestrian Facilities for Safety and Accessibility.	5	1.83	9.15
Functional Performance	Traveller Information Systems are provided during construction and use phases.	5	0.95	4.75
Financial Performance	The project ensured good Value for Money, evidenced by a cost analysis showing an acceptable cost premium against process deliverables.	5	0.92	4.6
SS_s Total (100)				**94**

This final SSs illustrates the importance of considering a broad range of social sustainable interventions to ensure long-term performance of the pavement and its impacts on society.

8.11 DISCUSSION OF RESULTS

It is important to note that the EmpIA (WCDTPW, 2010) only focuses on social sustainability from an empowerment perspective. The EmpIA works well to quantify the increased premium on social investment, but does not consider the justification of this increased premium on life cycle benefits, assuming that long-term positive economic impacts will be achieved.

The model proposed in this study is qualitatively based but may be applied quantitatively by assessing the premium on the initial investment of the increased process deliverables (e.g. conducting an LCA) and comparing the cost premium of design and process choices (e.g. labour intensive method specifications, training, contract participation goals for local participation, etc.) to alternative options where the increased deliverables are not considered. It is well understood that the increased process deliverables are accompanied by an increased initial investment (SIPDM, 2016). However, there is usually a long-term return on investment which may be quantified using standardised methods. It is proposed that an LCCA be used where the premium on initial investment is discounted and compared to economic growth and other economic metrics to assess the sustainability of options.

Even though both models aim to maximise social impacts of pavements, the model proposed in this study considers a broader scope of social sustainability compared to the EmpIA and better considers current challenges (e.g. climate change) and common practices (e.g. LCAs).

8.12 FINDINGS AND CRITICAL SHORTCOMINGS

Throughout literature, various frameworks are available to measure the sustainability of pavement infrastructure provision, focusing on certain aspects of sustainability such as economic (i.e. LCCAs), environmental (i.e. LCAs) or certain social themes (i.e. EmpIAs), with SRTs being the only standardised framework considering a broader range of sustainability, even though SRTs are typically environmentally dominated. As S-LCAs have been recently been introduced to fill the gaps required for confident assessments, standardisation of S-LCA frameworks is not yet available.

In attempts at standardisation, many researchers propose diverse and fragmented S-LCA approaches (Kühnen and Hahn, 2017), whilst overlooking core issues preventing the consolidation of information. Furthermore, many researchers simply derive indicators from literature without a deeper elaboration of the rationale behind the selection of certain indicators (Aparcana and Salhofer, 2013; Lehmann et al., 2011; Corbière-Nicollier et al., 2011, Varsei et al., 2014). Attention is typically given to indicators which are most commonly used among data sets, neglecting those that might not have made it past the selection process but may be relevant. These indicators are often proposed for general use in a broad range of industries and sectors, with few receiving sufficient empirical attention to draw reasonable conclusions (Kühnen and Hahn, 2017; Matos and Hall, 2007; Seuring et al., 2003). Inability to draw reasonable conclusions is extended by the lack of consideration of location-specific evaluations (Berardi, 2013), with disregard for regional challenges and goals (Blaauw et al., 2020). Moreover, implementing identified indicators may be tedious when practitioners are presented with a long list of indicators as compared to the alternative approach of focusing on the key indicators which contribute significantly to social sustainability.

A crucial shortcoming is found where S-LCAs are developed for a certain life cycle phase or more commonly, a ‘cradle-to-gate’ approach, neglecting use- and end of life-phases. This shortcoming also leads to a general lack of risk consideration, which as detailed in this study, may significantly impact on social sustainability. Risk evaluation is of particular importance when socio-economic impacts are assessed and the long-term return on investment of non-monetary costs are evaluated. Furthermore, gaps in S-LCA subcategories are equally identified where researchers increasingly integrate subjective experiences and perceptions (such as stakeholder satisfaction) into social performance measurements (Kühnen and Hahn, 2017), which is virtually absent in the UNEP and SETAC guidelines (Benoît and Mazijn, 2009). In the implementation of S-LCAs, a shortcoming is observed in the approaches of both researchers and industry, where proposed S-LCA frameworks are applied without refining the frameworks to the organisation’s specific responsibilities and sustainable objectives, making execution fractured and incoherent (Mani et al., 2015; Spence and Rinalfi, 2014; Varsei et al., 2014).

8.13 GUIDANCE FOR FUTURE RESEARCH

This section aims to provide guidance for future research focused on the social sustainability of pavement systems. For future research it is important to note that the results presented in this Chapter are not all inclusive and should only be used as a guideline for the development of new socially oriented inventories. These inventories should be developed utilising a bottom-up approach, employing the key social indicators presented as a basis for development and obtaining stakeholder inputs to form the social inventory temporally and spatially relevant. The stakeholder inputs are also required to update the weighting for the key social indicators. It is noted that variation to the results presented in this Chapter is not only to be expected, but should be promoted as well. Adhering to these simple guidance notes, researchers may develop situationally specific social inventories and significantly improve project outcomes. Further guidance is provided in Chapter 12.

8.14 SUMMARY

Following a general tendency of literature, most of the studies on sustainability entailing a life cycle perspective, focus on fundamental themes recognised as crucial to be protected, i.e. health and safety, natural environment and resources, economic- and functional-performance of pavements related to both motorised and non-motorised road users. These themes have been applied individually and in concert among the various frameworks detailed. However, as concluded by Reitinger et al. (2011), ‘we are faced with the paradoxical situation of avoiding harm to the environment and human health while ignoring other aspects of human life and thus the aims of sustainability’. This highlights the complex relationships that exist among the three tenets of sustainability. It is, therefore, suggested that S-LCAs should complement existing frameworks by focusing on a broader range of social consequences, including social well-being and various socio-economic impacts. A method to achieve this objective is to consider direct effects to stakeholders across the three tenets detailed by a wide range of indicators measuring the quality of life of people on both an individual and collective level (Falcone and Imbert, 2018). Standardisation of S-LCA frameworks and universal acceptance of social indicators could present road authorities and engineers with relevant information to better understand the important social factors during technical and managerial choices in pavement infrastructure provision.

This research has attempted to achieve this objective by identifying key socially relevant sustainability indicators related to the development and management of pavement infrastructure, using South Africa as a case study. Potential indicators were sourced from a large database consisting of several renowned international inventories and focus was given to the indicators most aligned with social sustainability. Indicators were assessed and scored using an adapted methodology and refinement was conducted through sensitivity analyses using Bayesian-based Monte Carlo simulations to reduce uncertainty. By allowing weightings and scores of sub-goals and criteria to be changed, the results reflect the importance that inputs from local stakeholders have on the impacts of sustainability. This further demonstrates that the methodology adopted in this thesis meets the sustainable principle of context and location specificity.

Through literature, certain risks (e.g. fundamental economic transformation) have also been identified which may have validity for consideration when identified key social indicators are applied to real projects. Typical limitations of similar social impact models, such as spatial dependence, and the omittance of key indicators which are not well understood, have been addressed in this study. The model proposed is spatially relevant to South Africa but can easily be adapted for application in other countries or locales. Furthermore, all key social indicators, regardless of the difficulty in quantification, have been considered and included in the results with a focus on their impact as opposed to being outcome-based. A worked example is provided which delineates the design and managerial steps ensuring a high performance of social sustainability.

As S-LCA standardisation is the main aim of researchers among the literature reviewed, recommendations provided in this study seek to address the shortcoming that needs to be considered during standardisation. For future research, there is a need to develop S-LCA frameworks to specific industries and locations rather than detailing a blanket approach for social sustainable assessments. The frameworks should aim to provide industries and specific organisations with key information that needs to be absorbed, refined, and aligned with their specific sustainable objectives, to allow confident and long-lasting application. Through this long-lasting application attention should also shift to a ‘cradle-to-grave’ approach and aim to measure the social impacts of a product or service over an extended period, to identify the long-term consequences of current sustainable interventions. This should be supplemented by introducing risk-based approaches where the cause-effect relationships of social sustainability are increasingly enhanced.

9 CLIMATE CHANGE ASSESSMENT

9.1 INTRODUCTION

In South Africa, and similarly in many developing countries, Government, Ministry, Department and/or Agency/Authority policies on climate adaptation for road and transport are virtually absent. Where present, roads are typically represented as a subset of all infrastructure sectors with multi-sectoral policies more common and focus on roads lacking (Head et al., 2019). Development parties such as the World Bank have recently realised the importance of establishing specific policies and strategies for the road sector. These policies and strategies however rely on an evidence base, which in its current form in South Africa is insufficient. The objective of this chapter is thus to support the development of required evidence through an analysis of the likely impacts of climate change on pavement deterioration. The chapter utilises high-resolution climate change projections and existing HDM-4 deterioration models. HDM-4 ver 2.08 is the current version of the package and is used to evaluate deterioration.

9.2 CLIMATE CHANGE INPUTS FOR MODELLING

For modelling the road scenario, a series of climatic data are required as input to HDM-4. The climatic inputs, obtained from the South African calibrated factors listed in HDM-4, are detailed in Table 9-1. The road scenario described in Chapter 6 will be assessed using these climatic data. Performance calibration factors developed in South Africa and prescribed by SANRAL are also used to relate the analysis to local conditions.

Table 9-1: Climate inputs

Climate Zone	**SA - Arid (lm <-40)**	**SA - Semi Arid (-40<lm<-20)**	**SA - Sub Humid Dry (-20<lm<0)**	**SA - Sub Humid Moist(0<lm<20)**	**SA - Humid (lm > 20)**
Moisture Class	0	1	2	2	3
Temperature Type	1	1	2	1	3
Days Greater than 32°C	60	60	40	30	15
Annual Temperature Range (°C)	17	17	13	12	10
Freeze Index	60	50	30	10	5
Moisture Index	-50	-30	-10	10	50
Mean Monthly Precipitation (mm)	12	38	48	66	92
Mean Temperature (°C)	21	18	16	18	18
Dry Season Length (Months)	10.8	8	6	6	6
Percentage Time Driven on Snow Covered Roads	0	0	0	0	0
Percentage Time Driven on Wet Covered Roads	2	5	8	10	15

9.3 CLIMATE CHANGE FOR SOUTH AFRICA

The projections produced by the CSIR together with Equation 4-1 were used to predict the locations of climatic zones for South Africa. Figure 9-1 shows the proposed revised TMI boundaries for the period 2021-2050 compared to the previous boundaries currently utilised by SAPEM (2017).

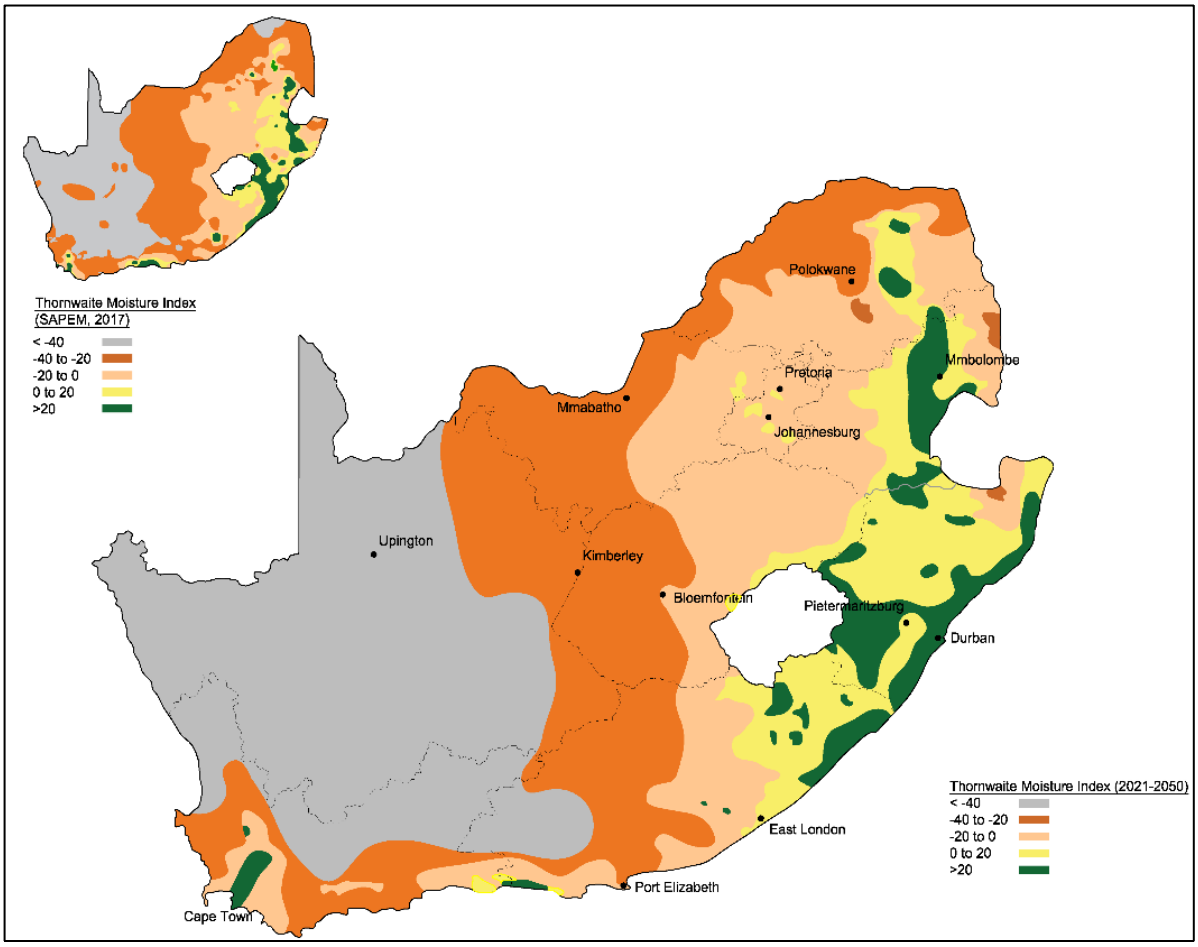


Figure 9-1: TMI changes for South Africa (2021-2050) (Engelbrecht et al., 2019)

The results from Figure 9-1 show that in line with climate projections, a gradual drying of the atmosphere is observed with climatic zones becoming increasingly arid across the majority of South Africa.

9.4 PAVEMENT ROUGHNESS

Incorporating the traffic volumes, road structures, maintenance regimes and climate change inputs into HDM-4, pavement deterioration was assessed for a 30-year analysis period. The results are shown in Figures 9-2 to 9-5 and are summarised in Table 9-2. Noted the alternative pavement structure described in Chapter 6 and Chapter 8 is not analysed as the new technology used for construction is not available in the current HDM-4 models.

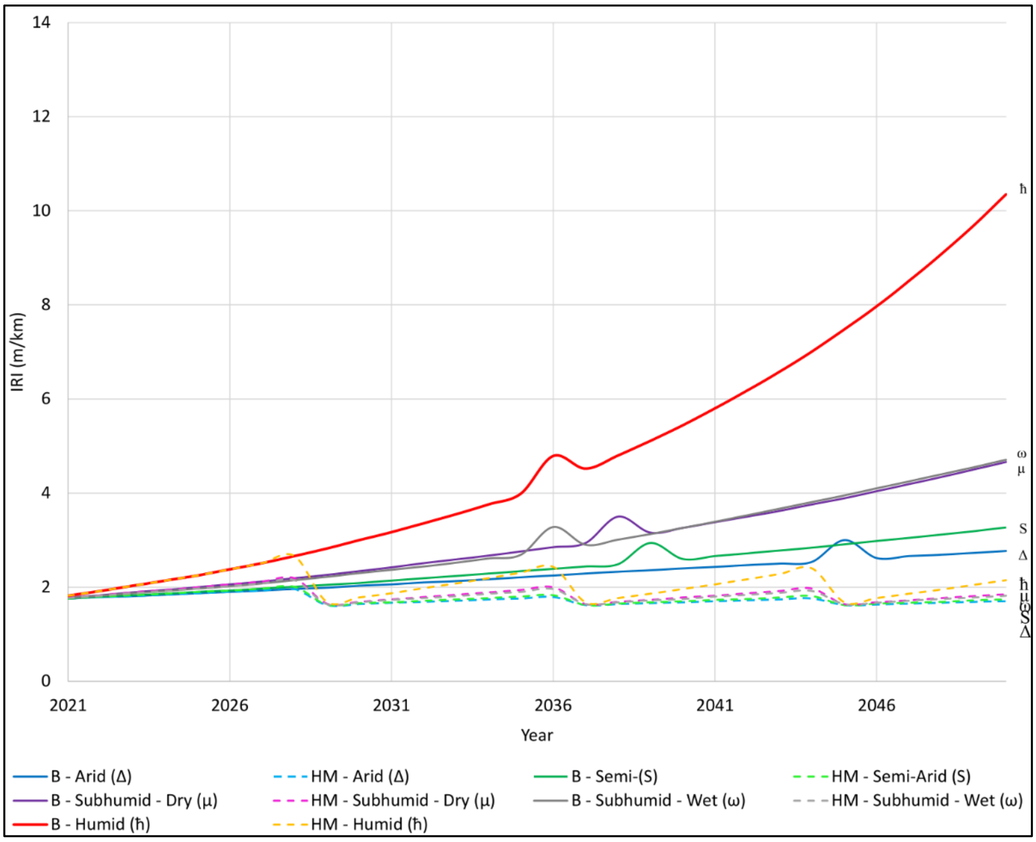


Figure 9-2: ES10 Strong Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

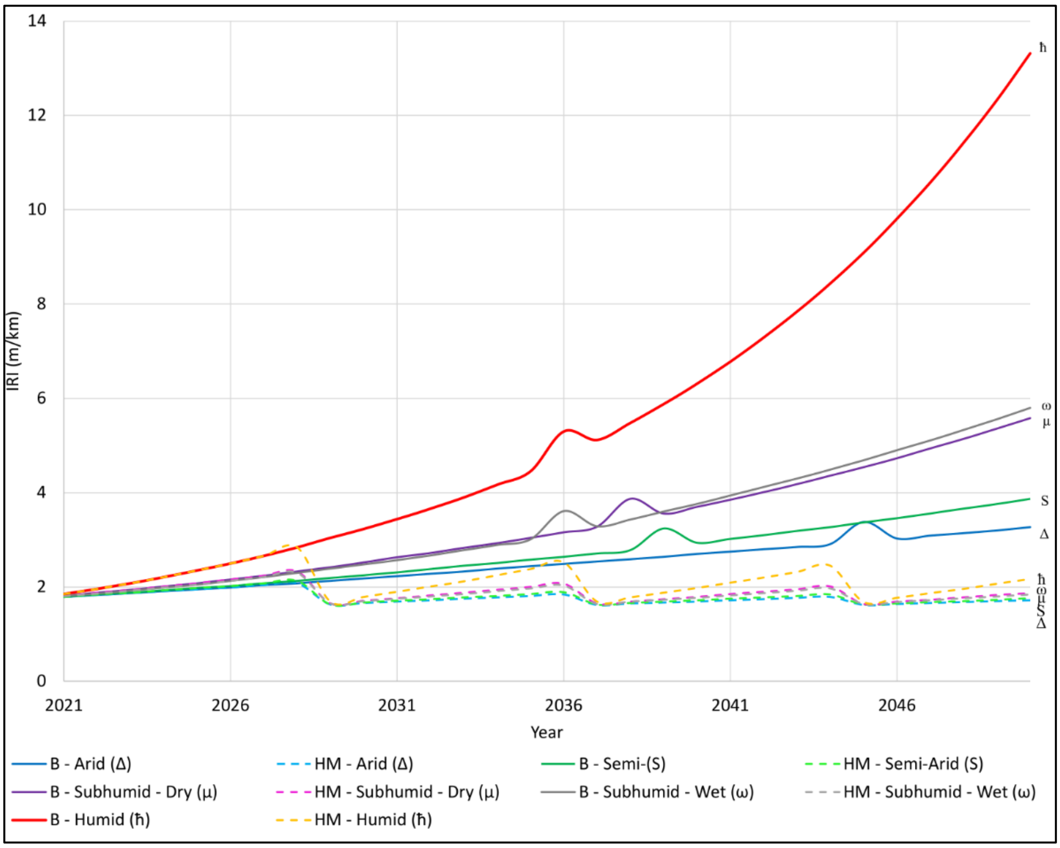


Figure 9-3: ES10 Weak Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

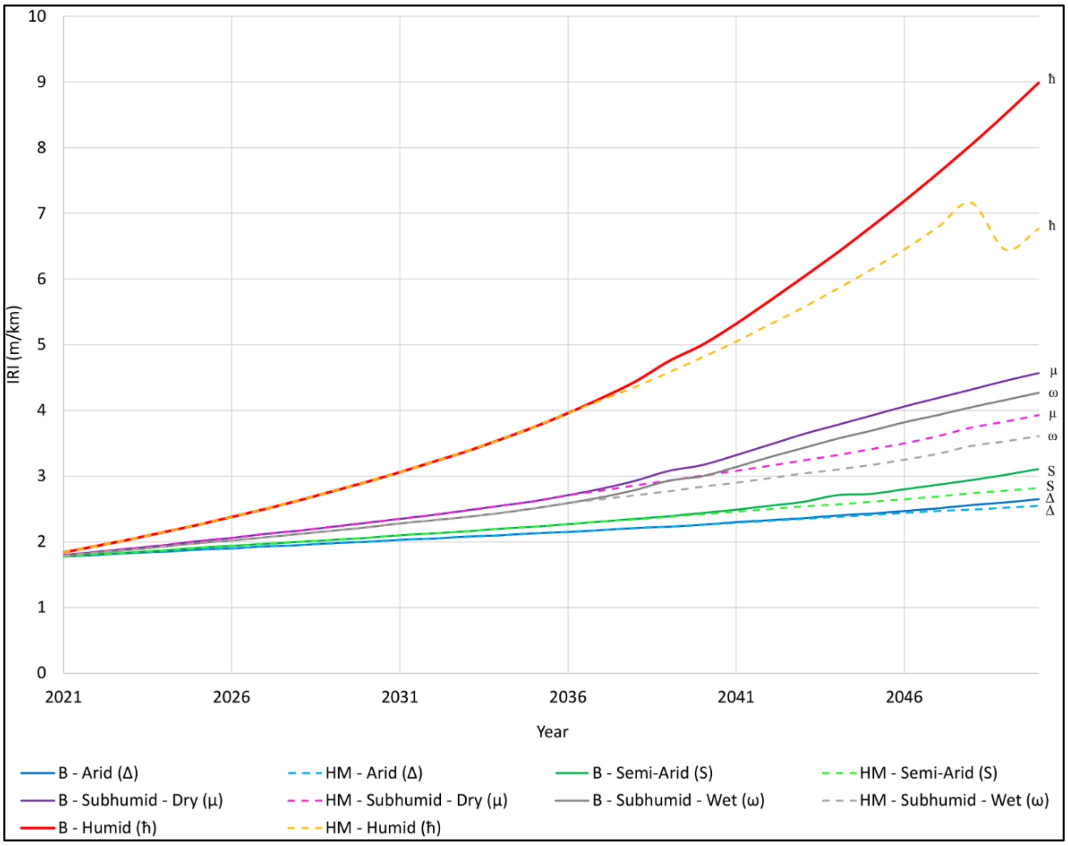


Figure 9-4: ES1 Strong Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

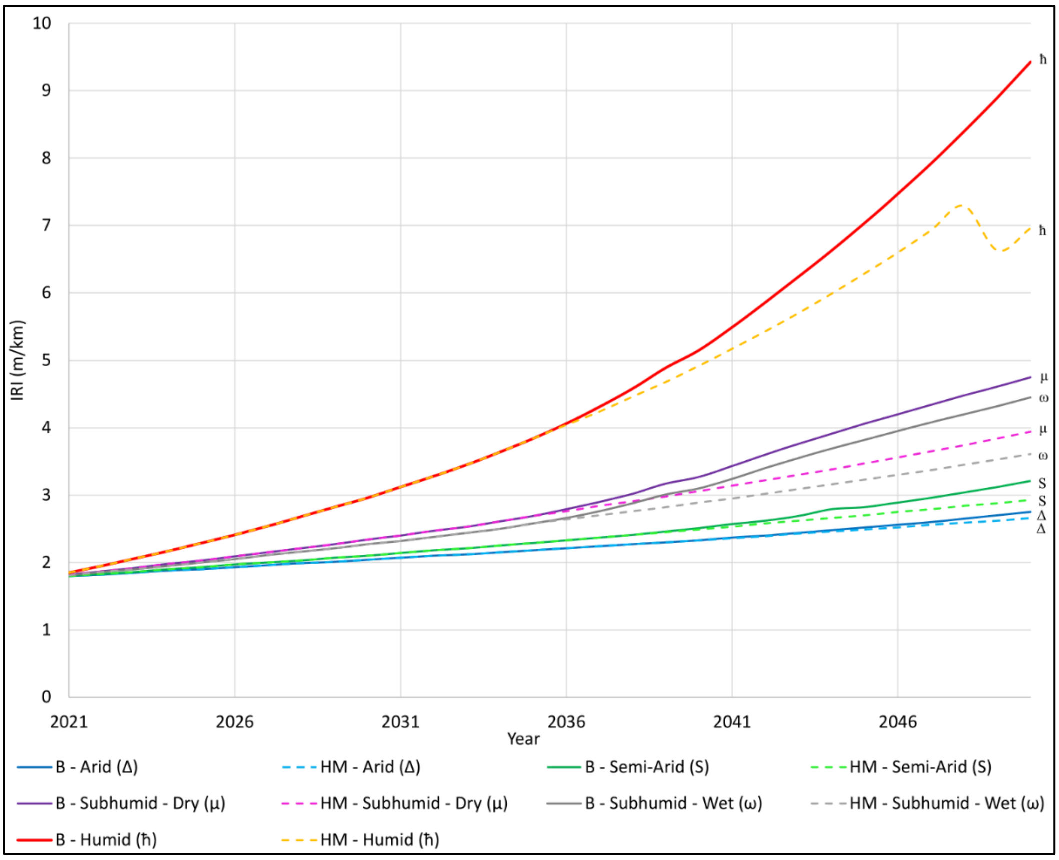


Figure 9-5: ES1 Weak Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

Table 9-2: Summary of pavement deterioration using International Roughness Index (B = Baseline, HM = Heavy Maintenance)

	ES10 Strong		ES10 Weak		ES1 Strong		ES1 Weak	
	Average (m/km)	**Max (m/km)**	**Average (m/km)**	**Max (m/km)**	**Average (m/km)**	**Max (m/km)**	**Average (m/km)**	**Max (m/km)**
B - Arid	2.25	3	2.49	3.38	2.16	2.65	2.22	2.75
HM - Arid	1.73	1.96	1.77	2.08	2.15	2.55	2.21	2.66
B - Semi-Arid	2.43	3.27	2.7	3.87	2.32	3.11	2.38	3.21
HM - Semi-Arid	1.76	2.01	1.79	2.13	2.27	2.82	2.33	2.93
B - Subhumid - Dry	2.97	4.66	3.33	5.58	2.91	4.57	2.99	4.75
HM - Subhumid - Dry	1.84	2.19	1.88	2.33	2.73	3.93	2.77	3.94
B - Subhumid - Wet	2.96	4.71	3.37	5.8	2.78	4.27	2.86	4.45
HM - Subhumid - Wet	1.82	2.15	1.86	2.3	2.6	3.61	2.64	3.61
B - Humid	4.82	*10.35*	5.64	*13.32*	4.44	*8.99*	4.58	*9.43*
HM - Humid	2.06	2.66	2.1	2.84	4.13	*7.16*	4.21	*7.29*

(values in red (italic) indicate exceedance of critical 6 m/km threshold)

From the pavement deterioration results summarised in Table 9-2, it is observed that pavement structures located in arid climate zones perform significantly better than structures located in humid climate zones under the same traffic conditions and maintenance scenarios. The humid climate zones are seen to be the only scenarios where the IRI exceeds the critical threshold of 6 m/km. Comparison between the strong and weak pavement structures indicate better performance for the strong structures in line with expectations. Comparison between the ES1 and ES10 pavement structures shows that ES1 roads typically last longer under reduced maintenance conditions, attributed predominantly to the low traffic volumes. A notable observation is the importance of rigorous maintenance regimes, especially in humid climates (i.e. TMI > -20), to mitigate the impacts of climate change on pavement deterioration. Detailed pavement deterioration results are presented in Appendix C.

To better visualise the impacts of changes to TMI on pavement performance, an additional graph is presented showing only two boundaries, 1) positive TMI changes (where the TMI is reduced and climate zones become more arid), and 2) negative TMI changes (where the TMI is increased, and climate zones become more humid). These boundaries are shown in Figure 9-6.

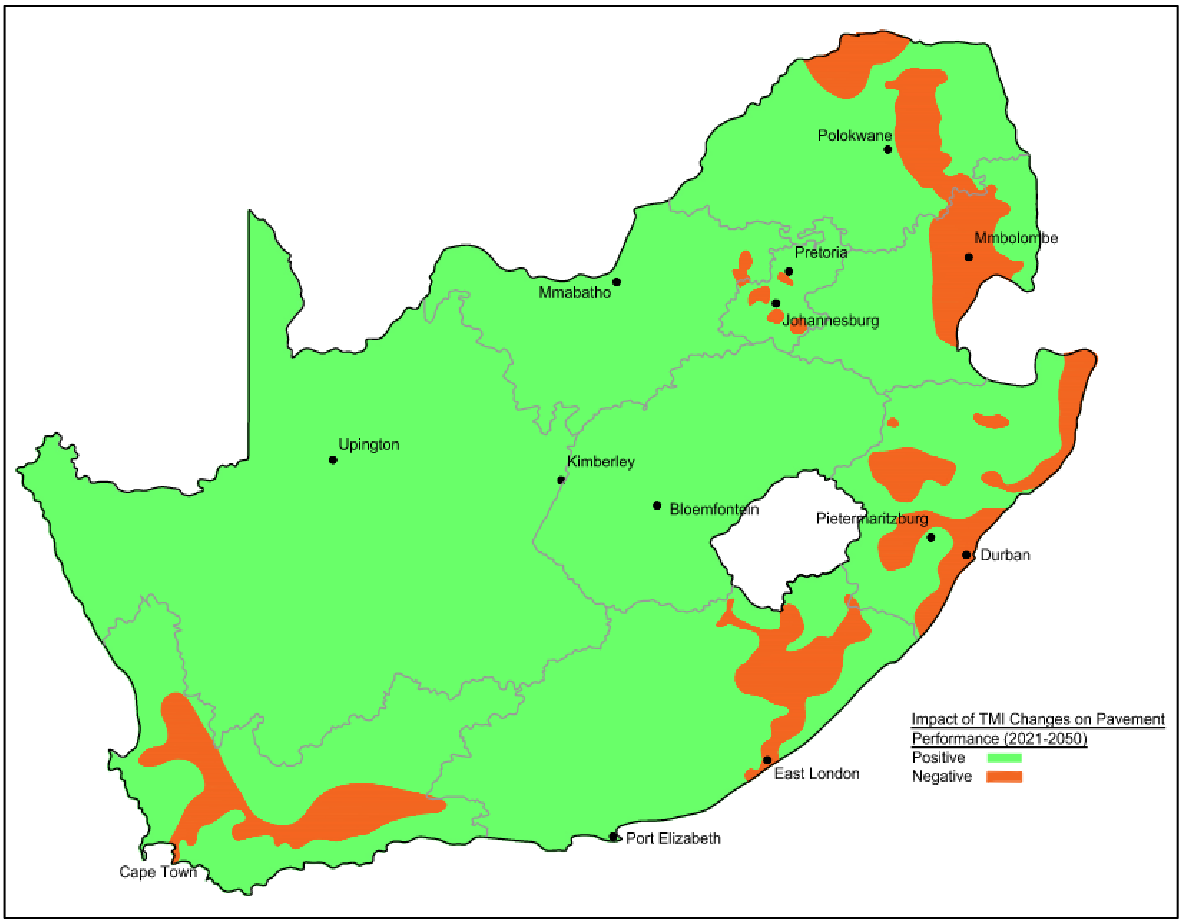


Figure 9-6: Impact of TMI changes on pavement performance

From Figure 9-6 it is seen that most of the South African pavement network is expected to be positively impacted by climate change through the gradual warming and drying of the air, thus reducing the aggravating moisture related circumstances which accelerate pavement deterioration. The areas which are indicated as being negatively impacted by climate change, are projected to become more humid in the future, in contrast with the gradual drying of the atmosphere of the majority of South Africa. It is noted that increases in humidity accelerate pavement deterioration.

9.5 EVALUATING IMPACT OF TEMPERATURE AND MOISTURE CHANGES

The approach followed in this study to quantify the impacts of climate change on pavement performance focuses on TMI as the key climate variable specified by HDM-4 and is the methodology implemented by leading studies for similar climatic regions (Choa et al., 2014; Taylor and Philp, 2015; Shoa et al., 2017). It is understood that climate change will also be accompanied by a gradual increase in temperatures and moisture, with South Africa being no exception. Additionally, the frequency and intensity of extreme weather events are also predicted to increase in the coming years, albeit projected with less confidence.

To evaluate the effects of gradual changes to temperature and moisture on South African pavements, the above analyses were recomputed with negligible differences observed. Evaluation of extreme events is currently not possible with the existing HDM-4 model. Extreme events are however expected to have an impact on pavement sustainability and will notably result in distresses associated with accelerated asphalt binder ageing, stripping, rutting and shoving, among others. Changes in pavement design (Qiao et al., 2020) and asphalt material selection to meet the quality needed for future thermal and moisture conditions will be required (Practicò et al., 2011). For instance, better-performing asphalt surfacing layers could be achieved with bitumen modification (Sarroukh et al., 2021) and through specifying performance graded asphalt binders (Bredenhann et al., 2019; Mokoena et al., 2019), as currently being trialed in South Africa and internationally.

9.6 WATER USE DURING CONSTRUCTION

In considering settlements, the main variable related to pavement infrastructure provision in South Africa is increased settlement drought stress. The boundaries for settlement drought stress have already been defined following the qualitative thresholds set by Engelbrecht et al. (2019) and Beraki et al. (2019), namely:

- Low;
- Medium;
- High, and
- Extreme.

These boundaries are shown in Figure 9-7. It is observed the majority of the Western Cape and large parts of the Northern Cape are at high or extreme risk of drought and these risks should be considered during construction and maintenance activities.

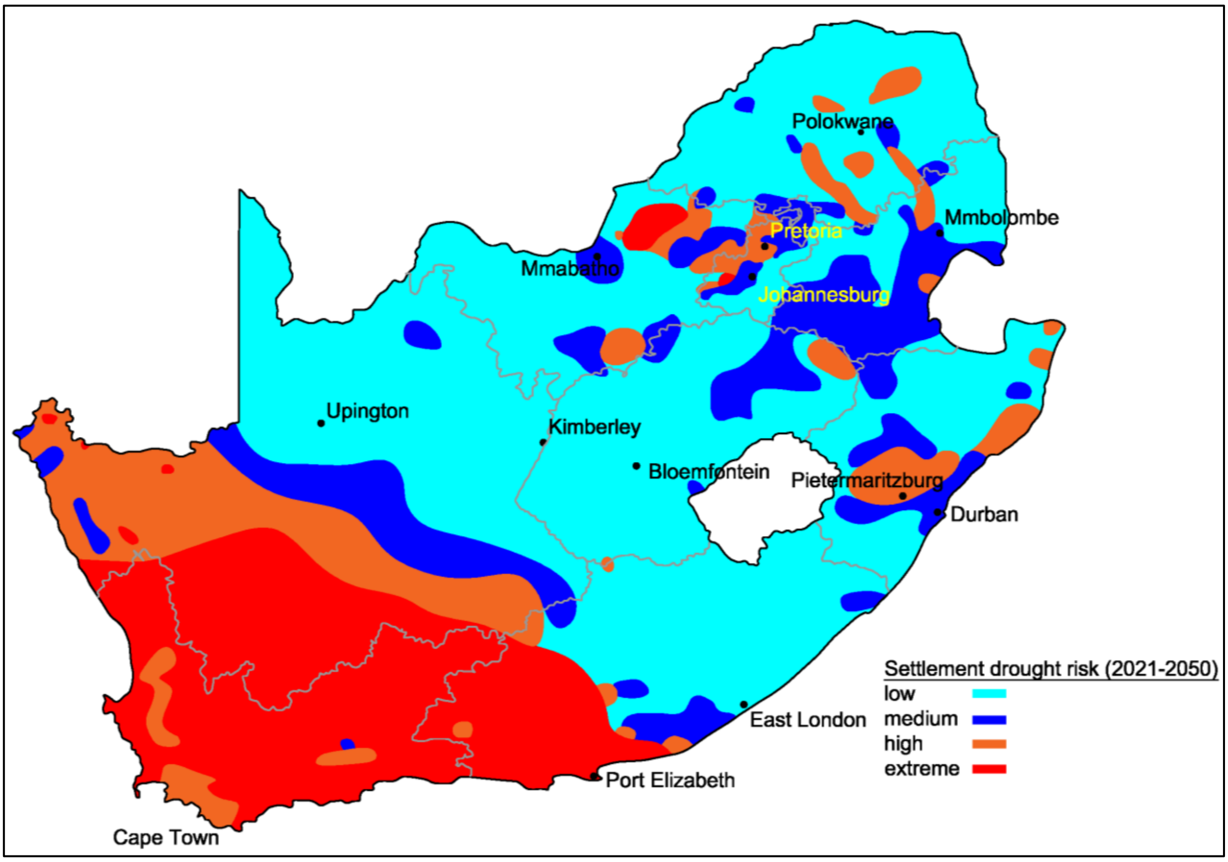


Figure 9-7: Drought Increase Risk (2021-2050)

9.7 GUIDANCE FOR FUTURE RESEARCH

This section aims to provide guidance for future research focused on the pavement deterioration estimation of road networks across South Africa incorporating climate change impacts. As climate change is ever evolving, researchers should seek to utilise the most up to date projections available for modelling. Considering the analysis period, it should also be noted that the further one looks into the future (i.e. larger analysis periods), the more risk is assumed as the error in projections become increasingly large when the typical 30-year analysis period is exceeded (Engelbrecht et al., 2019). Clear definition of the maintenance regimes are required, as well as locally calibrated factors if the HDM4 software package is utilised. Further guidance is provided in Chapter 12.

9.8 SUMMARY

In this chapter, the effects of climate change on pavement deterioration are demonstrated. Although the occurrence of climate change has been expected to negatively impact the road infrastructure, the results presented in this study indicate that the gradual drying of the atmosphere across the majority of South Africa will have positive contributions to slow the rate of pavement deterioration.

Many local settlements are expected to be negatively impacted through increased drought risk, which may be exacerbated by pavement infrastructure provision. There is a need to include these impacts in the design, construction and management of pavement infrastructure in South Africa. Additional work is however required to quantify the effects of climate change on settlement vulnerabilities.

The results presented in this study may enable road authorities to make more reliable decisions regarding maintenance actions designed for pavement roughness maintenance.

10 LIFE CYCLE ASSESSMENT INCORPORATING RESULTS FROM PREVIOUS CHAPTERS

10.1 INTRODUCTION

In previous chapters, the background and major findings of the contribution of construction, maintenance and demolition of a pavement to emissions were presented, as well as the influence of climate change on pavement deterioration. In this chapter, the focus is on quantification of the road user emissions to complete a holistic life cycle assessment of a typical South African pavement. Existing deterioration models were used to analyse emissions during use. Economic results are presented to support environmental considerations.

To determine the road user emissions, the pavement deterioration trends were assessed in Chapter 9 with HDM-4 using default values for typical fuel usage emission factors. The results of this assessment are shown in Figure 10-1 to Figure 10-4.

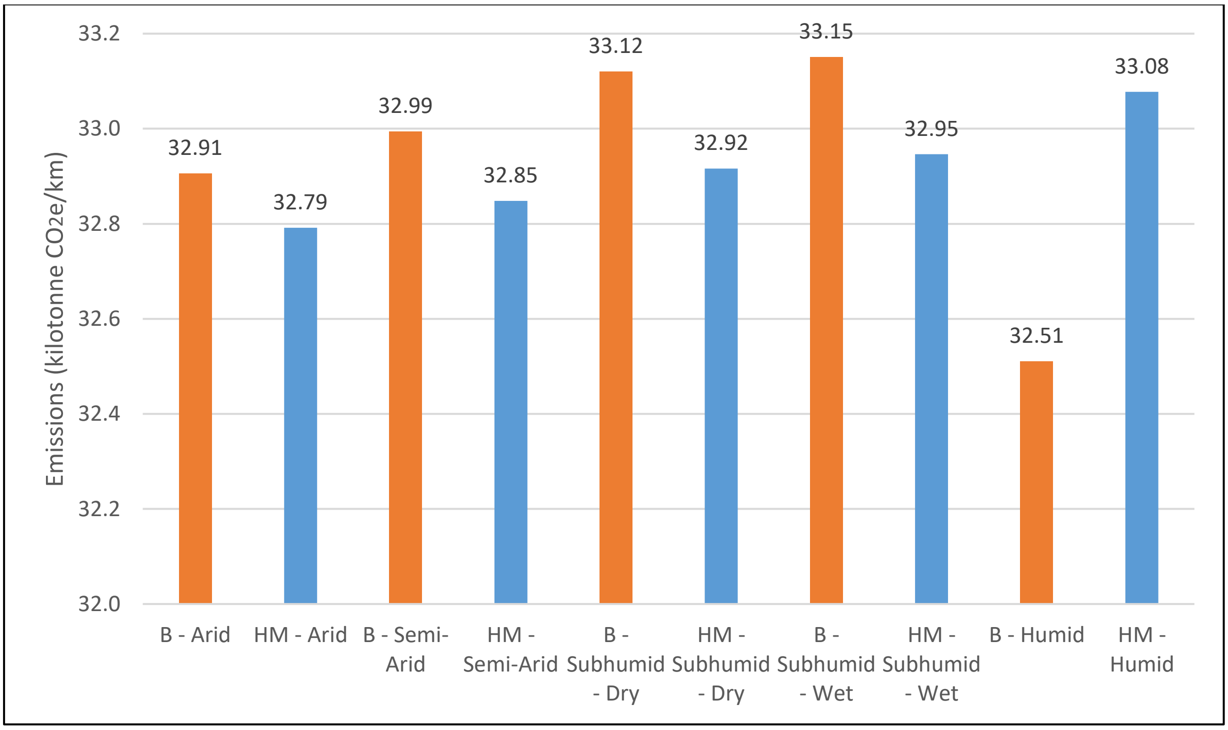


Figure 10-1: ES10 Strong Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

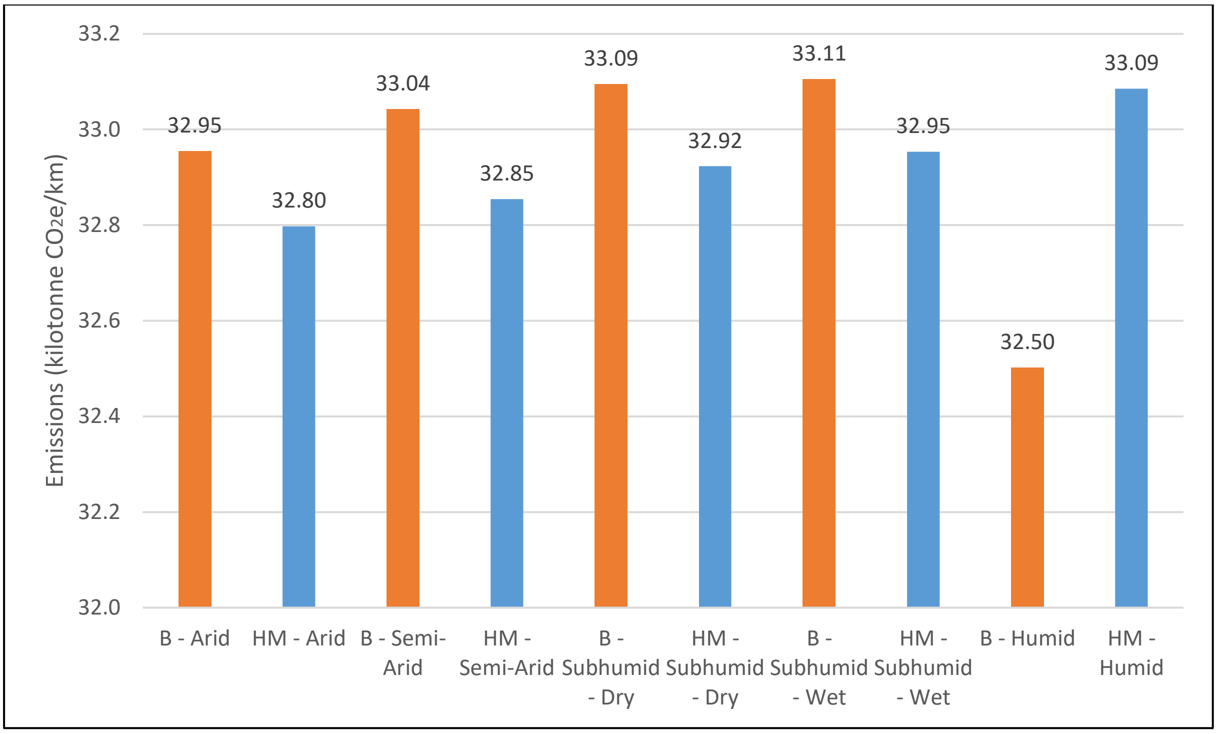


Figure 10-2: ES10 Weak Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

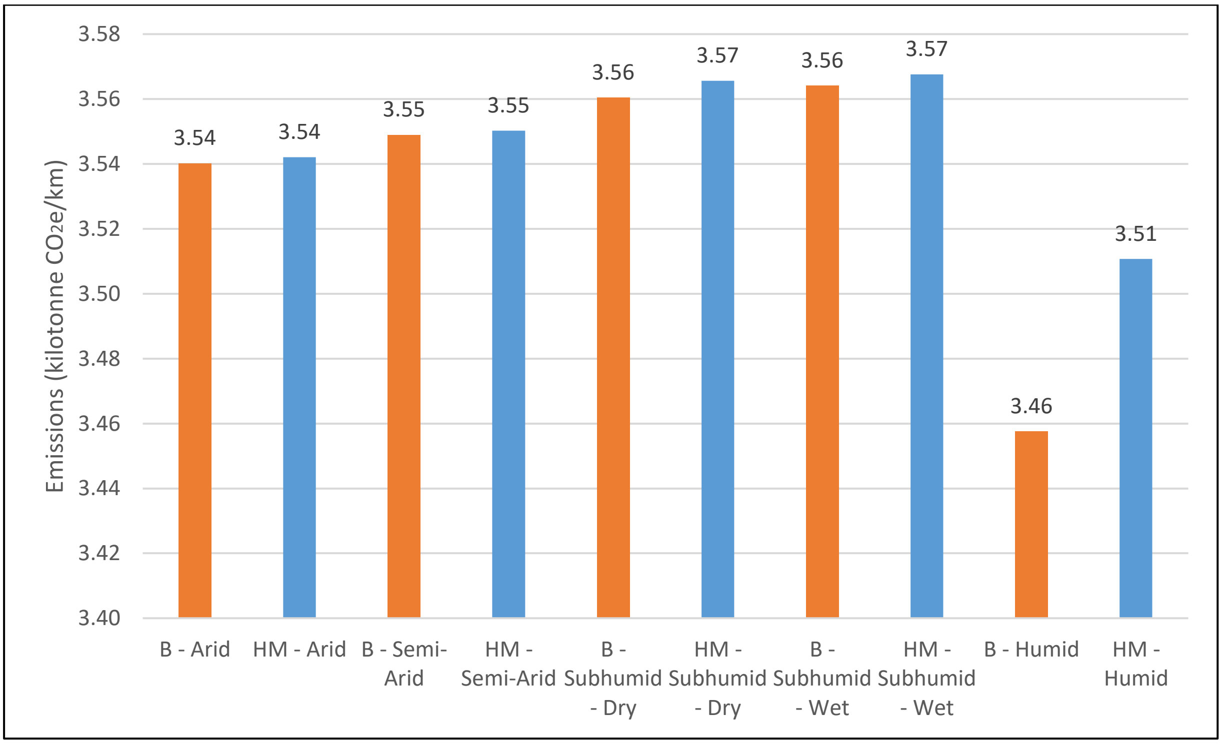


Figure 10-3: ES1 Strong Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

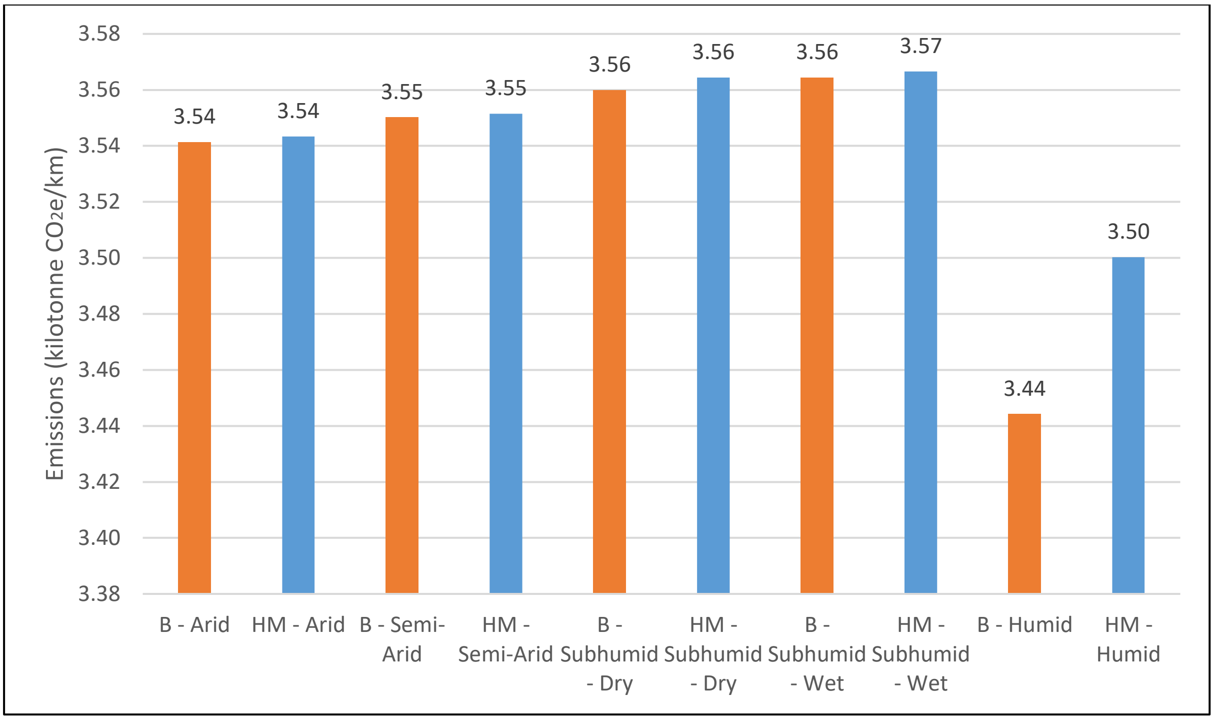


Figure 10-4: ES1 Weak Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

Similar to the pavement deterioration trends previously observed, pavements in the arid climate zones tend to perform better compared to those in the humid climate zones, with emissions dictated largely by traffic volumes, operating speeds and increases in road roughness. In contrast to what would normally be expected, the weak pavement structure for the low-volume roads (ES1) performs better throughout, compared to the strong structure, especially in humid climate zones. This deviation may be best explained by the reduced road user safety and associated operating speeds for the weaker structures, discussed in subsequent sections.

A notable outlier is observed in the data, where the Baseline – Humid scenario, which has the highest pavement deterioration rates among the alternatives, has the lowest road user emissions over the analysis period. This deviation from expected results is explained by correlating pavement deterioration, operating speeds with accompanied fuel consumption. Due to the high IRI values of the Baseline – Humid scenarios (exceeding 6 m/km throughout), operating speeds are significantly reduced as the road surface becomes increasingly unsafe to drive on. The HDM-4 model, therefore, predicts a corresponding reduction in fuel consumption as the reduced operating speeds generally fall within the 'optimum range' of fuel consumption between roughly 50-80 km/hr (Chen et al., 2017).

Due to the high IRI values of the Baseline – Humid scenarios (exceeding 6 m/km throughout), operating speeds are significantly reduced as the road surface becomes increasingly unsafe to drive on, and fuel consumption correspondingly reduces. Figure 10-5 shows the decrease in the operating speeds for the

Baseline – Humid scenario to illustrate this phenomenon. The phenomenon is also observed for the ES1 pavement structures where the heavy maintenance options generally have higher emissions compared to the baseline results, attributed to reduced operating speeds for the baseline options. Detailed emission results are presented in Appendix D.

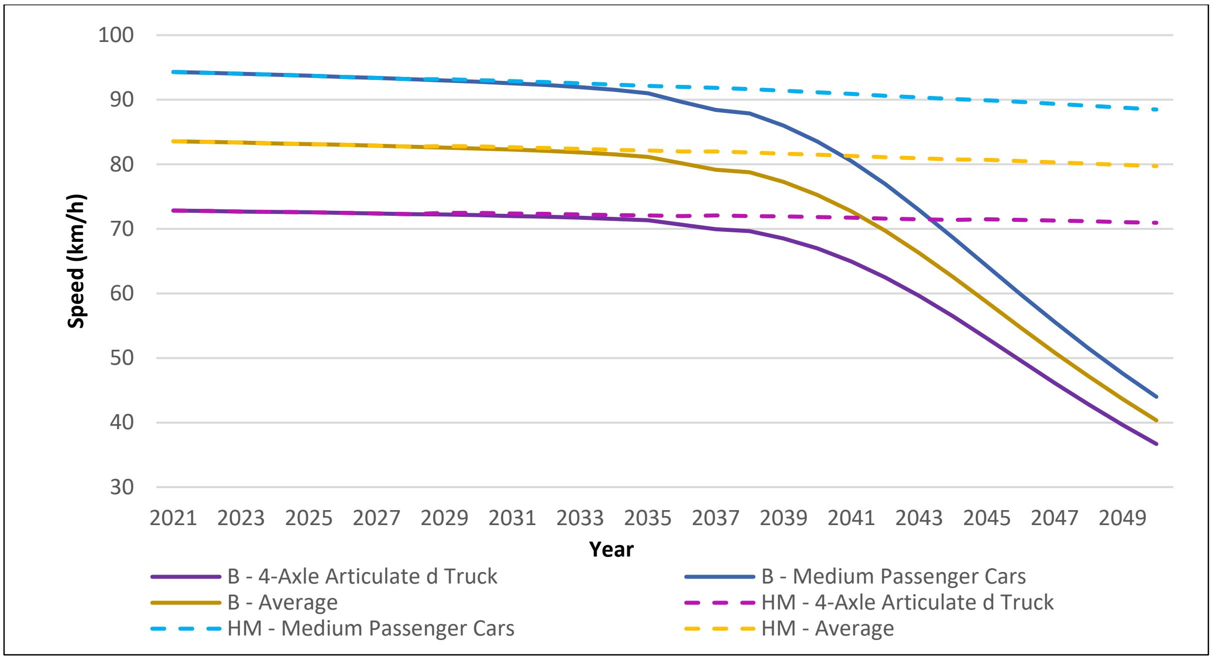


Figure 10-5: ES10 Weak Pavement Structure - Baseline - Humid Operating Speeds

10.2 CUMULATIVE DISCOUNTED AUTHORITY COSTS AND USER BENEFITS

For the comparative assessment, cumulative discounted authority costs related to the maintenance regimes were calculated, as well as the resultant Net Present Value (NPV) which is summarised in Table 10-1.

The assessment was conducted with HDM-4 and utilised local calibration factors. The results represent the costs associated with new construction and maintenance works (i.e. road improvement works) for the analysis period. Road improvement works are either categorised as baseline or heavy maintenance as previously discussed, and the model selects the appropriate interventions provided that certain triggering conditions used in practice are met. For the baseline maintenance regime, the triggering condition is predominantly dictated by asphalt age and associated deterioration (i.e. percentage cracking, potholing, rutting etc.) and for heavy maintenance, an IRI threshold of 6 m/km commonly triggers major maintenance interventions. It is important to note that interventions differ by climate zone where enhanced crack sealing is common in more arid zones, and similarly pothole repair in more humid zones, for instance. Cost calculation for each road scenario is defined in terms of the road surface class to which it applies, the triggering condition, an improvement type, the costs and duration of the works, and the resultant effect on the pavement in terms of condition, strength, etc. (constituting the asset valuation). This analysis follows the same standardised methodology applied in typical life cycle cost analyses. Further information may be found in standardisation documents such as the International Organisation for Standardisation 15686-5:2017 (ISO, 2017), with the key variable, NPV, indicated in Equation 10-1:

$$NPV = \sum(Cn \times q) = \sum_{n=1}^{p} \frac{Cn}{(1+d)^n} \qquad \text{(Eq. 10-1)}$$

where

C is the cost in year, n;

q is the discount factor;

d is the expected real discount rate per annum;

n is the number of years between base date and the occurrence of the cost, and

p is the period of analysis (analysis period is not the design period).

Note that accident costs were not included as geometry changes, and thus safety, was not considered in the assessment.

Table 10-1: Cumulative Discounted Authority Costs for the Baseline, the increase in HM cost and the net present value per km (costs in million)

Traffic Class	Pavement Structure	Maintenance Regime	Arid (R)	Semi - Arid (R)	Subhumid - Dry (R)	Subhumid - Wet (R)	Humid (R)
ES10	**Strong**	**Baseline**	0.596	0.598	0.581	0.597	0.598
		HM Increase	0.941	0.937	0.954	0.938	0.937
		NPV	-0.775	-0.71	-0.328	-0.309	3.49
	Weak	**Baseline**	0.598	0.598	0.583	0.598	0.6
		HM Increase	0.939	0.937	0.952	0.937	0.935
		NPV	-0.681	-0.548	0.056	0.144	6.72
ES1	**Strong**	**Baseline**	0.549	0.553	0.566	0.566	0.566
		HM Increase	0.182	0.178	0.31	0.31	0.31
		NPV	-0.185	-0.179	-0.298	-0.299	-0.236
	Weak	**Baseline**	0.549	0.553	0.566	0.567	0.567
		HM Increase	0.182	0.178	0.189	0.188	0.188
		NPV	-0.185	-0.179	-0.171	-0.172	-0.094

The results fromTable 11-1 show that for the high-volume roads (ES10), the maintenance costs are relatively constant regardless of the climate. For low-volume roads (ES1), maintenance costs significantly increase as the climate becomes wetter, with the weak pavement structure performing better in the wetter climates, in contrast to what would be expected but consistent with the emission results previously reported. This trend is also true for the NPV results, with the weak pavement performing significantly better in humid climates compared to the strong structure for both traffic classifications. This deviation, as previously discussed, is primarily due to the reduced level of service reflected by the operating speeds shown in Figure 12 associated with the weak pavement structures compared to the strong structure. This is further emphasised in humid conditions, where accelerated deterioration significantly affects the weak structure and the data does not reflect the true benefits of the strong structures over weak structures in these conditions, especially in terms of level of service. It is important to note that the desired level of service is not a key input variable for HDM-4, and the model rather attempts to maintain the current level of service at the time of maintenance intervention, rather than strengthen interventions to achieve the level of service that was present after the initial construction. This becomes increasingly evident the faster a pavement deteriorates over its life cycle. These results highlight the need for academics and decision-makers to view the data holistically and implement design and construction decisions according to the most sustainable solution, which should not only be the most economically- or environmentally-friendly but also provide due consideration of key social impacts such as level of service.

10.3 LIFE CYCLE ASSESSMENT

The results of the previous analyses are difficult to understand without a baseline for comparison. To assist in understanding the results, life cycle results from Chapter 7 for other life cycle phases for the same pavement structures and maintenance regimes used in this study are included. These life cycle phases are:

- C – representing material extraction and production, transportation, and construction activities required to construct the initial pavement structure;
- M&D – representing the material extraction and production, transportation, maintenance and demolition activities for each pavement structure, and
- RU – representing the road user emissions.

The results of this comparison are presented in Figure 10-6, focusing on the arid climate zones for simplicity. The relative comparison in results is similar for all climatic zones.

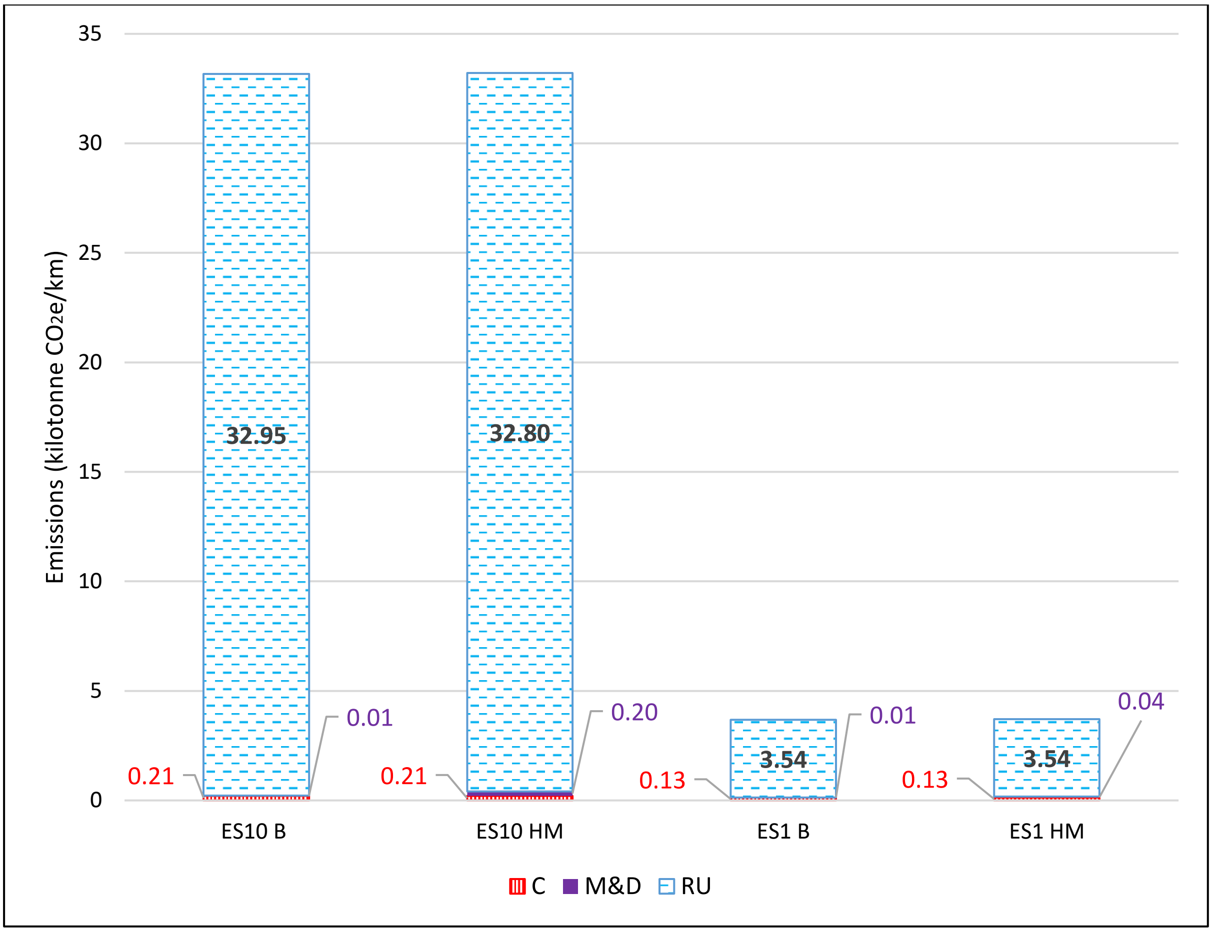


Figure 10-6: Life Cycle Assessment Results for Pavement Alternatives in Arid Region

Figure 10-6 shows that the road user emissions significantly outweigh the other life cycle phases in terms of environmental impacts. For the ES10 pavements, the road user emissions represent 99% of the total life cycle emissions for both maintenance regimes, and for the ES1 pavement, the road user emissions represent 96% of total emissions. Minimal difference is observed when the emissions of the baseline are compared to the heavy maintenance options for the same traffic loading.

10.4 DISCUSSION OF RESULTS

The results from the analysis show that as the climate becomes increasingly arid, pavement deterioration and user emissions are reduced for all pavement structures and traffic classifications. The outcome of the analysis is good news for the road authorities since the reduced rainfall resulting in more arid conditions will be beneficial to the performance of roads. The exception is that in an increasingly humid region the pavement should be strong to avoid unnecessary maintenance and rapid deterioration. From a road authority perspective, the technical issues of management are more important than having a poor road where speeds are well below the desired speed and thus lower fuel consumption and consequently emissions. Note that the value of time (which requires road specific data such as peak hour congestion, geometry, etc.) was not considered in the analysis, which could become important on poor roads resulting in reduced speed.

10.5 RESILIENCE AND POLICY IMPLICATIONS

Climate resilience from a pavement perspective may generally be defined as the pavement's ability to withstand and retain its current performance under the impacts of a changing climate. Selecting appropriate design options and implementing rigorous maintenance regimes are key to addressing the resilience issues of pavement networks. Traditionally, design has utilised historic data on environmental stressors, such as 100-year floods. However, as shown in this study there is a need to increasingly consider climate projections which will eventually render historic climate data obsolete.

The results of this study show that road authorities in South Africa will generally benefit from the gradual drying of the atmosphere due to climate change with select regions that will become more humid requiring stronger structures and increased maintenance interventions. Design and maintenance strategies should vary according to the climate to which infrastructure is exposed. The key climate/environment parameter considered by HDM-4 and applied in this study is TMI, a well-known variable developed for use in agriculture and infrastructure engineering. This should provide a useful first contribution to climate adaptation and policy.

A leading limitation of this study is omitting consideration of extreme weather events on pavement performance, a topic lacking experimental maturity, but is crucial for a complete analysis (Haslett et al., 2021). The impacts of extreme weather events have already been felt locally but tracking and projecting their occurrence is still accompanied by significant error, making scenario planning challenging. Increasing the resilience of pavements to these extreme events then requires increased monitoring of the pavement network across South Africa and swift intervention until further work has been completed to better understand their impacts. Even though methods for quantification of extreme events on pavement performance are still being developed, they can more readily be incorporated into the drainage and geotechnical design and road authorities will benefit from utilising future projections rather than historic data.

10.6 COMPARISON TO OTHER REGIONS

Limited research has been conducted on the effects of climate change on pavement deterioration globally. Comparison between studies is also troublesome as regions with different climatic zones and climate change projections have widely varying results, highlighting the need to conduct analyses regionally specific to truly understand their impacts. Chao et al. (2014), Taylor and Philp (2015) and Shoa et al. (2017) each conducted in-depth analyses of climate change for Australian regions with similar climatic zones to South Africa and all used the same HDM-4 methodology calibrated to local Australian conditions. Each study focused on the changes in TMI using down-scaled climate projections and translated these variations to pavement deterioration measured in IRI. However, these studies did not evaluate the effects of design and maintenance to increase the climate resilience of pavements as has been demonstrated in this study. None of the studies sought to quantify road user emissions and complete an LCA of a typical pavement.

What these studies did show, however, is that as the climate gradually dries up and moves to more arid climatic zones, pavement performance generally increases similar to the results presented in this study, as demonstrated in Figure 10-7.

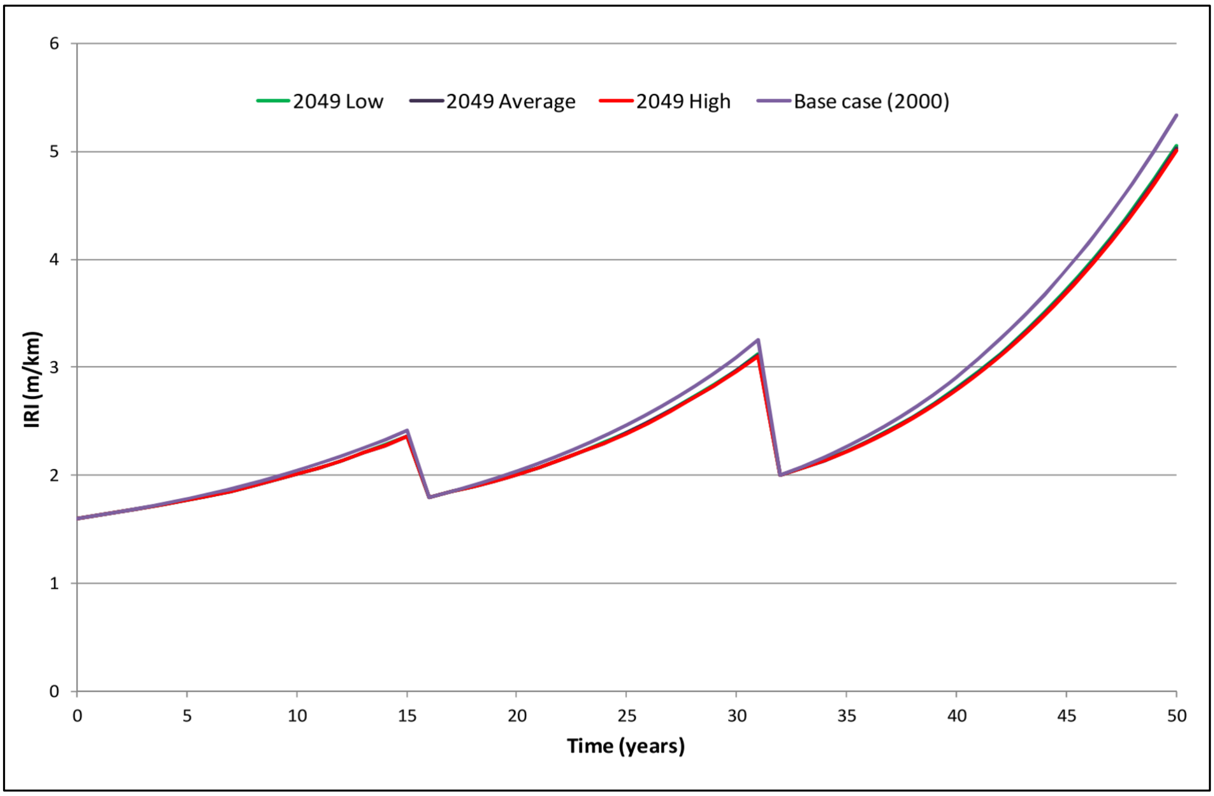


Figure 10-7: Typical pavement deterioration results measured using the International Roughness Index incorporating climate change impacts (Taylor and Philp, 2015)

10.7 GUIDANCE FOR FUTURE RESEARCH

This section aims to provide guidance for future research focused on completing a holistic life cycle assessment of a pavement system. From the results presented in this Chapter and previous chapters, it is important to note that a high quality of data inputs is required for accurate assessment of the environmental impact of a pavement over its life cycle. The success of the life cycle assessment therefore depends on the quality of the data produced from the methodologies detailed in previous chapters. Researchers should note that accurate traffic predictions are essential, and that the environmental burden of road users significantly dominates all other life cycle phases. Further guidance is provided in Chapter 12.

10.8 SUMMARY

In this chapter, the effects of deterioration of the road surface condition incorporating climate change impacts on user emissions and economic analyses are demonstrated. Pavement roughness is the primary cause of increased user emissions from increased energy use, but it also has the effect of reduced speed as was shown in Figure 10-5. Control and management of pavement roughness can aid in limiting the environmental burden of during-use emissions by balancing roughness within technical limits and the consequent increase in emissions.

This chapter has completed a pavement LCA that accounts for all life cycle phases. The analyses have been applied to a range of scenarios with different climate conditions and traffic levels. Although the results from the analysis do not encompass all pavement contexts, the wide range of climate zones, traffic levels and pavement structures analysed means that the conclusions presented in this study make a meaningful contribution to the understanding of the impact of road-user emissions on the overall life cycle emissions of pavement and how that varies by contexts.

Although the occurrence of climate change has been expected to negatively impact the road infrastructure, the results presented in this study indicate that the projected gradual drying of the atmosphere across the majority of South Africa will have positive contributions to slow the rate of pavement deterioration, user emissions and enhance user benefits alike.

Based on the information provided in this chapter it is recommended that the principles discussed regarding minimising road roughness be adhered to during pavement design, road construction, rehabilitation and maintenance.

It is further recommended that refinements in the range of vehicle types currently being developed are incorporated into HDM-4, focusing specifically on hybrid- and electric-vehicle types. As electric vehicles are expected to increasingly replace internal combustion engines in future, methods to quantify the effects of pavement roughness on electric vehicle energy use are required.

11 CUMULATIVE RISK AND SUSTAINABILITY INDEXING

11.1 INTRODUCTION

An ever-growing number of governmental institutions and non-governmental organisations are embracing sustainability in their business models and/or product life cycles. This approach pursues the overarching goal of enhancing and balancing the economic, environmental, and social impacts of living and resource use. Various risks are associated with achieving sustainable objectives which have not yet been defined holistically in road projects and have been handled in a disjointed manner to date, precipitating the need for a risk approach to the sustainable provision of pavement infrastructure.

These risks are underpinned by a general inability to confidently measure the three pillars of sustainability, with only the economic tenet having mature methodologies available. In previous chapters, methodologies were presented to quantify the environmental and social impacts of pavement infrastructure provision. This chapter aims to determine the impact cumulative risks have on sustainability, by providing a sensible sustainability index and risk evaluation for pavements.

11.2 STRUCTURE OF THE CHAPTER

This chapter proposes a framework for the development of a risk and sustainability index based on a weighted cumulative approach, aiming to extend current research and capable of incorporating novel risks that may arise from impacts such as climate change. The chapter structure is detailed as follows:

1. First, sustainability is conceptualised using an influence diagram where the relationship between the sustainable indicators are defined as the basis of the probabilistic model. The key objective of conceptualisation is to unify the three tenets of sustainability.
2. Second, MCMC techniques are applied to the conceptualisation used to determine the sustainability index and risk of pavement alternatives.
3. Third, discussions and critical shortcomings are provided, together with guidance for future research.

11.3 CONCEPTUALISING SUSTAINABILITY

For the purpose of conceptualising, the identified risks from literature and previous research are categorised and simplified. To achieve this an influence network diagram is employed. Each risk is assessed against four main sustainable categories or ‘nodes’, namely: environmental impact, social impact, functional performance and governance. The relationship among risks is empirically derived and conceptualisation is based on abstract principles. This is discussed further in this chapter. It is noted that the main objective of this chapter is not to provide an all encompassing model applicable to all road authorities and locales, but rather to demonstrate the development of such a model. As with the definition of sustainability, the model proposed in this chapter should be redeveloped within each road authority where new risks may be included over and above the key risks shown in this chapter. Specific weightings for each risk, and their relationship to the four sustainability nodes should also be determined on a local scale.

The results of this assessment are shown in Figure 11-1 and used to develop the MCMC model in subsequent sections.

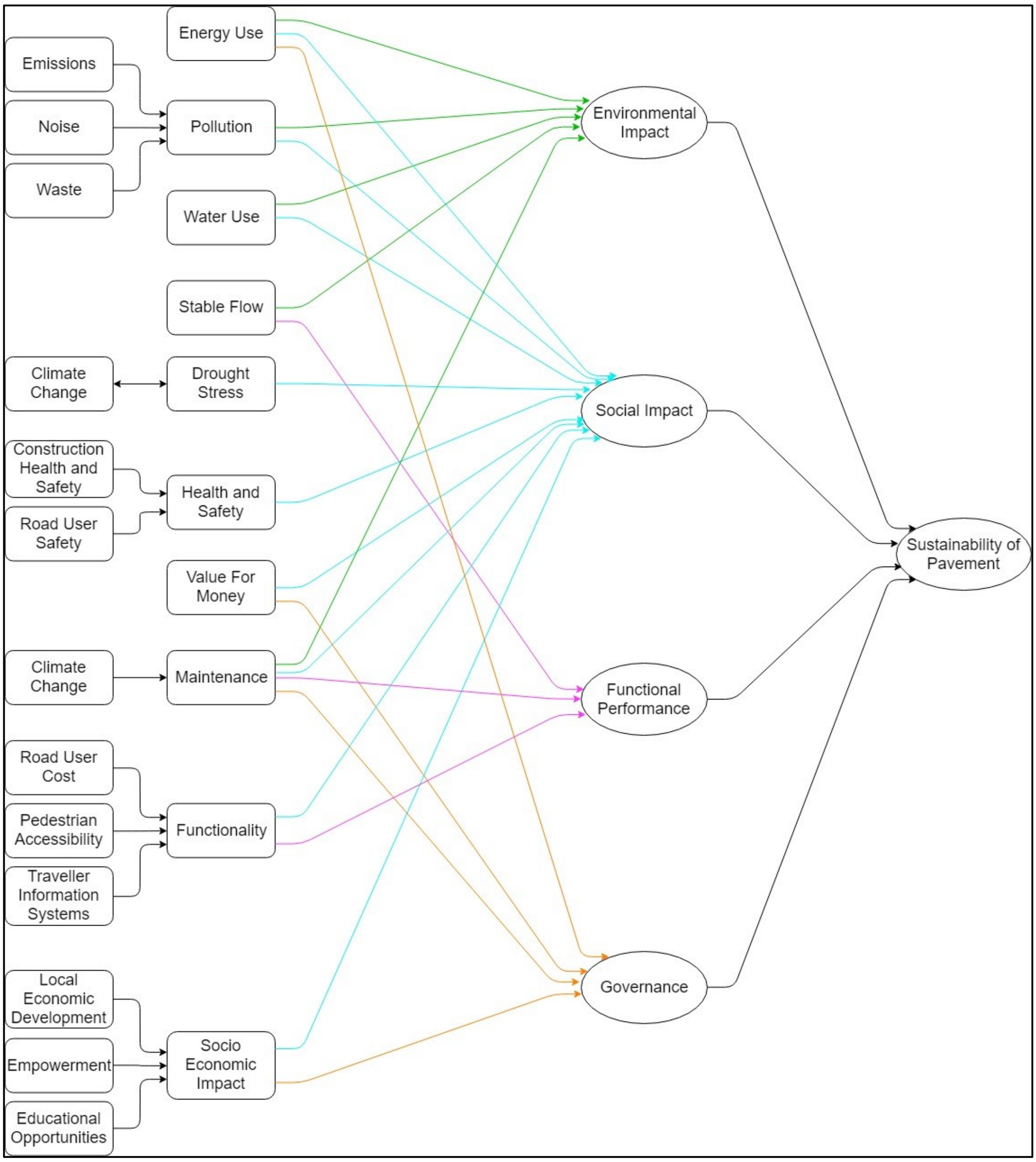


Figure 11-1: Influence network diagram of sustainable pavement risk factors

11.4 MODEL DESCRIPTION

In developing the MCMC model to be applied to the key risks conceptualised in Figure 11-1, an approach to align the model with the definition and system boundaries of sustainability provided previously in Figure 2-2 is followed. This approach utilises a hybrid bottom-up/top-down strategy to incorporate the temporal and spatial dependence of risks relevant to sustainable pavement infrastructure allowing for the model to circumvent the common shortcomings of many pavement response models that rely on the linear-elastic theory. These shortcomings manifest as simplified assumptions, that stresses or strains, for instance, are not influenced by histories resulting in often non-hereditary evaluations. Rather, this model considers both past and future risks which collectively influence the sustainability of a pavement over its life cycle.

In simple terms, the model is developed to be dynamic, allowing constant inputs of new data during the pavement management process to not only assess performance against the baseline projections determined during the design phase but to also determine the nature and extent of interventions required in the future to retain a predetermined level of sustainability. Key factors that will influence this performance are climate change and resulting pavement deterioration, true traffic volumes and implemented maintenance actions. Furthermore, settlements that are impacted by the pavement may be monitored for vulnerabilities and the management of the infrastructure may be altered to ensure these vulnerabilities are not further exacerbated, and in an ideal sense, are mitigated. The main settlement vulnerability focused on in this study is drought risk, exacerbated by the use of large volumes of water for construction.

For model development, risks are initially provided equal weights throughout. This contrasts with the common method of assigning different weights to each risk according to its relative impact. The approach was deliberately selected as there is no objective process to determine weights that would apply to all road authorities in South Africa, nor internationally. Rather, the compounding effect of each risk on the four risk categories, shown in Figure 11-1 is used to reflect the impact of each risk where, for instance, even though ‘maintenance’ initially has the same weight as ‘drought risk’, the compounding effect of ‘maintenance’ results in four times greater impact on sustainability. This also allows for relative ease in identifying the sensitivity of the model to each risk. It is proposed that road authorities incorporate this model into their pavement management systems and determine the relative weights of each risk individually according to the mandates and sustainable objectives of each authority. Stakeholder engagement and expert interviews may be best suited to determine these weights. Figure 11-2 provides a visual illustration of the model description.

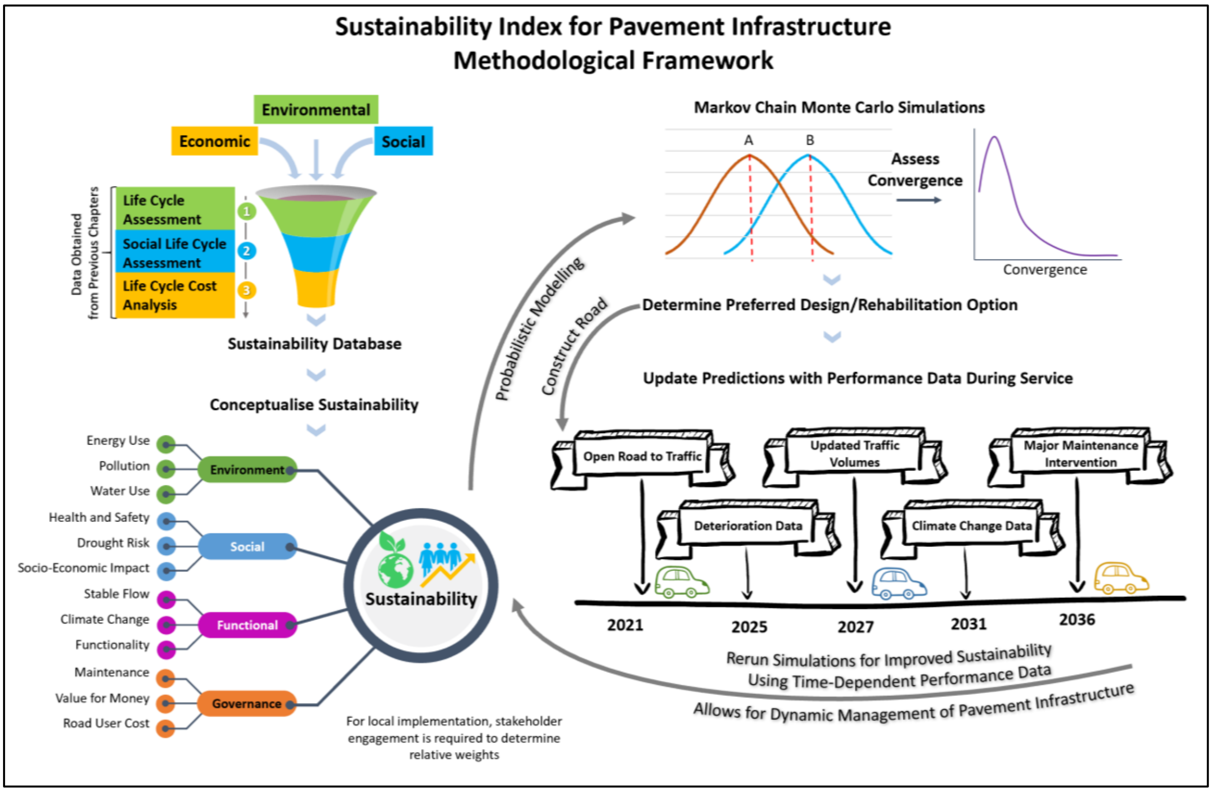


Figure 11-2 Model Description for Implementation

Additionally, the model is developed to be a comparative model during the design phase as the probability of sustainability is modelled amongst alternatives, requiring multiple data sets meaning a minimum of at least two alternatives is required. After selection of the preferred design, that design is carried forward and may further be modelled on a singular comparative basis incorporating new measured data. The comparison occurs between the new data (i.e. pavement survey data, observed climate change impacts, etc.) and the original design (which acts as the new baseline). This allows for ease in highlighting weakness or strengths in the in-service pavement performance and interventions may be more easily identified and implemented.

In using alternative designs, the score of each risk is normalised to a value between 1 and 5 based on the least sustainable alternative, where 1 is the ‘worst’ achievable score. It is further noted that the development of the model, following the above-described approach, is inevitably biased towards a high probability of sustainability meaning that alternatives that are likely to result in a low probability of sustainability will generally not conform well to the model and outputs are expected to reflect this, most notably in the ability of simulations to converge.

Convergence occurs when the generated Markov Chain distribution converges to the posteriori distribution being modelled and is assessed based on the ability of the distribution to reach stationarity.

Convergence is also used to determine the accuracy of the probability predictions and the ability of the model to conform to the data set. A shrink factor is used to monitor whether the simulations have converged to equilibrium. If equilibrium is achieved, the shrink factor will be one. The data sets used in this study consider four possible alternative road scenarios, detailed in subsequent sections. It is noted that cleaning and pre-processing of raw data occur during the various life cycle assessments conducted to develop the 'sustainable database' as illustrated in Figure 11-2.

11.5 ROAD SCENARIOS

To apply the MCMC model and determine the impacts of an accumulation of risks on the probability of sustainability, the four road scenarios listed in Table 6-2 are utilised, reproduced in Table 11-1 for convenience.

Table 11-1: Three road scenarios used for probability modelling

Traffic Class	Road Scenario	Pavement Structure	Maintenance Regime	Climate Zone
ES10	1	Weak	Baseline	Subhumid-Dry
	2	Weak	Heavy Maintenance	
	3	Strong	Baseline	
	4	Strong	Heavy Maintenance	

These four road scenarios empirically represent two of the most common traffic loadings found in South Africa, as well as the most common pavement structures (dependent on climate zone) for each traffic loading.

11.6 DATA INPUTS

For each road scenario, quantifiable data inputs are obtained from previous assessments. Environmental data has been obtained from Chapter 7 and 10 where as social data has been obtained from Chapter 8. Economic data was obtained from Chapter 10. These data have been calculated for each year over the 30-year analysis period and the performance of the data are indicated predominantly by maintenance interventions over the life cycle which predominantly affect the NPV, user benefits, and road user emissions. For each road scenario, the average value for each indicator and calculated node value shown in Figure 11-1, are summarised in Table 11-2.

Table 11-2: Average 30-year data inputs for model

Indicators	**Scenario**	**Scenario**	**Scenario**	**Scenario**
Energy Use	2.67	4.12	3.04	4.16
Pollution	3.77	2.77	3.77	4.11
Water Use	3.00	3.50	4.00	3.50
Stable Flow	1.93	3.68	2.56	4.61
Drought Stress	3.00	3.50	4.00	3.50
Health and Safety	3.00	5.00	3.00	5.00
Value for Money	3.75	4.32	4.01	4.86
Maintenance	1.00	5.00	1.00	5.00
Functionality	3.77	4.10	3.77	4.30
Socio-Economic Impact	4.12	4.83	4.49	5.00
Nodes				
Environmental Impact	3.01	3.43	3.35	4.01
Social Impact	3.27	3.76	3.70	4.05
Functional Performance	3.07	4.08	3.08	4.08
Governance	3.50	5.00	4.00	5.00

11.7 SUSTAINABILITY INDEXING

Utilising the results from previous chapters and road scenarios described in Chapter 6, the proposed MCMC model was applied to the four road scenarios using the influence diagram shown in Figure 11-1, to model the cumulative effects of identified risks on the probability of sustainability. The MCMC simualtions were conducted using R Studio software running the RJAGS package (Plummer et al., 2021). These results are shown in Figure 11-3 to Figure 11-6 for scenarios 1 to 4 respectively. On each figure, the convergence is shown on the left and probability distribution on the right. It is noted that even though the probability shapes are similar, results differ substantially and readers should consider the axes when reviewing the data.

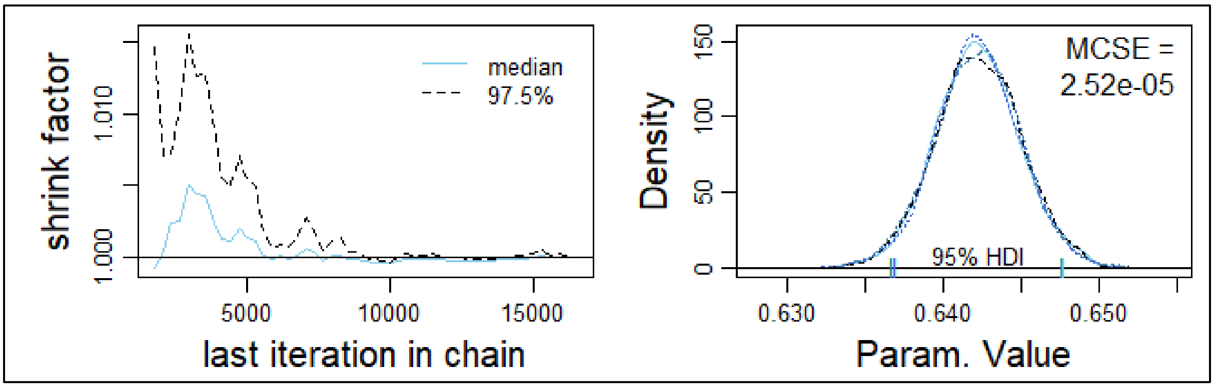


Figure 11-3: Scenario 1: convergence (left) and probability of sustainability (right)

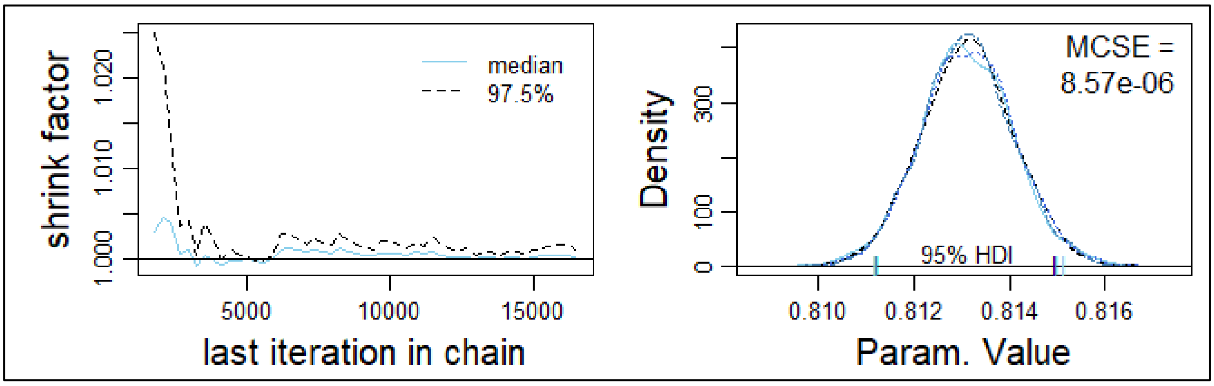


Figure 11-4: Scenario 2: convergence (left) and probability of sustainability (right)

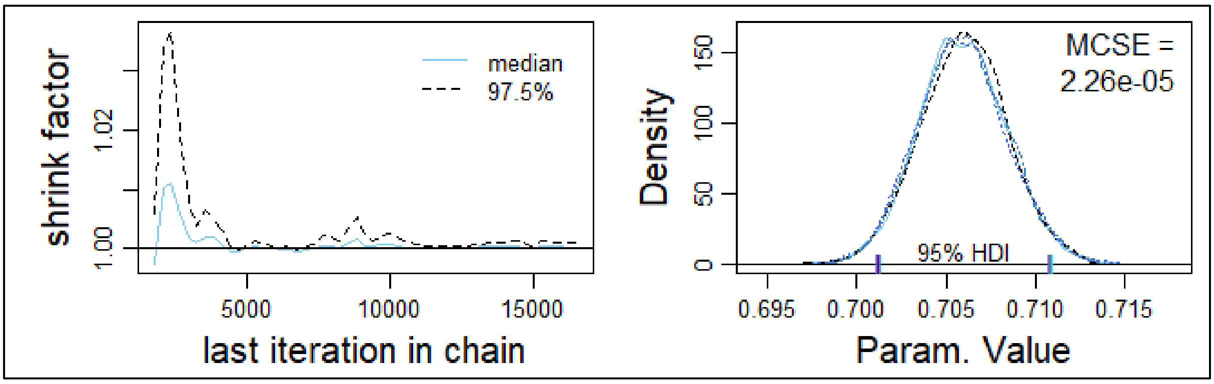


Figure 11-5: Scenario 3: convergence (left) and probability of sustainability (right)

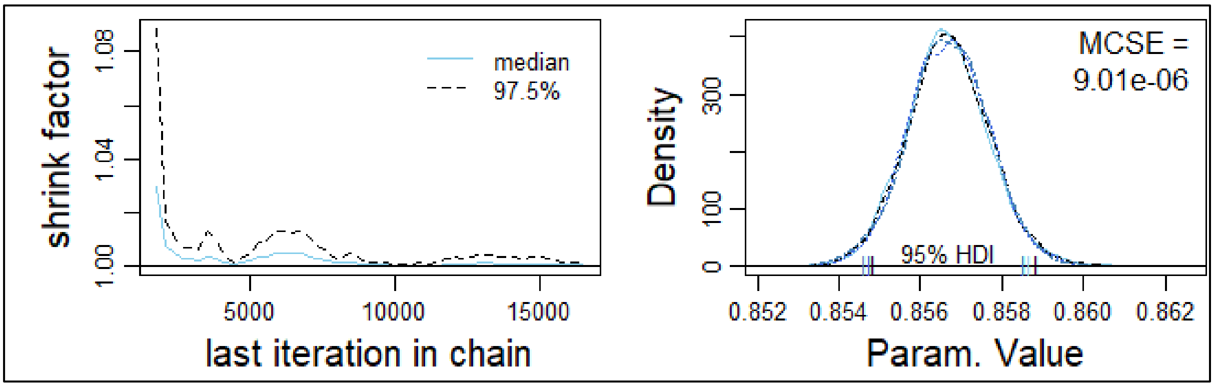


Figure 11-6: Scenario 4: convergence (left) and probability of sustainability (right)

Road scenario 4 has the highest probability of sustainability at 85.67% (shown in Figure 11-6 – probability of sustainability (right)), followed by Scenario 2 (81.31%) and Scenario 3 (70.60%). Scenario 1 has the lowest probability of sustainability at 64.23%, summarised in Table 11-3. It is seen for all simulations that the shrink factor is one, meaning equilibrium has been achieved and a normal distribution is observed throughout.

Table 11-3: Sustainability Index of alternatives

	Sustainability Index (*SI*)
Scenario 1	64.23%
Scenario 2	81.31%
Scenario 3	70.60%
Scenario 4	85.67%

These results may also be viewed as Scenario 4 having 14.33% (i.e. 1-85.67%) probability of sustainable failure, compared to Scenario 1 with a 35.77% probability of failure. The results are consistent with the life cycle assessment, social life cycle assessment, and climate change assessment results for the same road scenarios. Furthermore, the model converges rapidly for Scenario 4 and declines throughout the scenarios as the probability of sustainability is reduced. This too is expected as the model is inherently biased towards a high probability of sustainability and its inability to conform to the latter scenarios validates the level of the unsustainability. Figure 11-7 provides a visual illustration of the simulations, translated into the sustainability index for each road scenario.

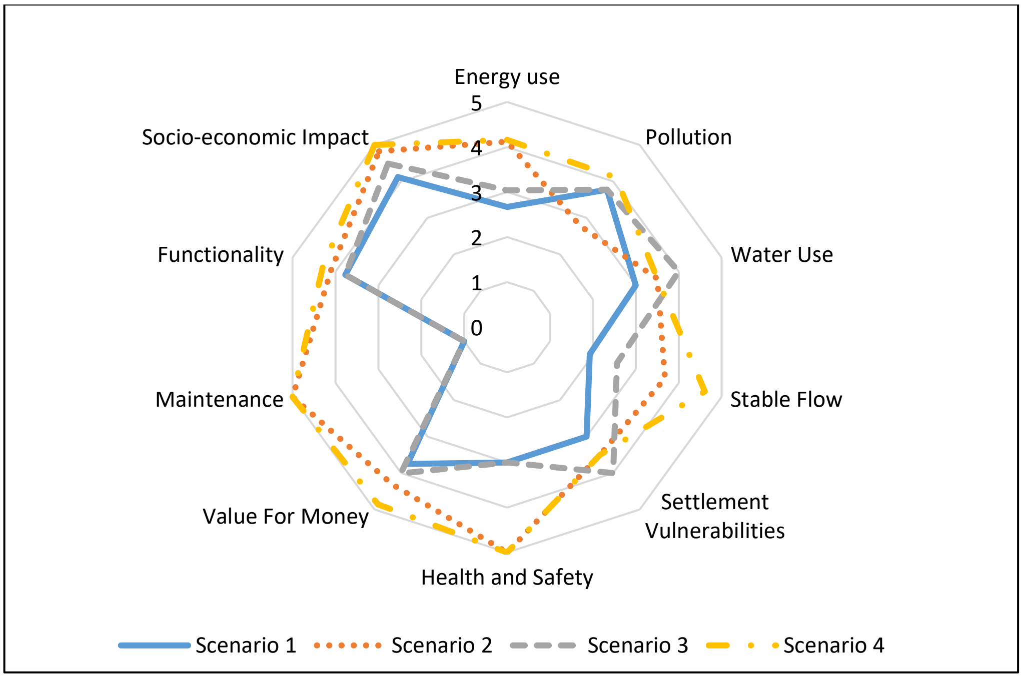


Figure 11-7: Sustainability Index for four road scenarios

11.8 SUSTAINABLE RISK

In the previous section, the sustainability index was calculated for various pavement alternatives and reflects the probability of failure, determined by Equation 11-1:

$$PoF = 1 - SI \qquad \text{(Eq. 11-1)}$$

where PoF is the probability of failure and SI is the sustainability index shown in Table 11-3.

Consequences of failure in asset management are often a combination of qualitative and quantitative factors and are linked to asset types including maintenance costs, level of service, health and safety, environmental damage, and so forth. In this chapter four main criticality indices, previously referred to as sustainable nodes, are used: environmental impact, social impact, functional performance and governance. The values for these nodes have been predetermined from the results presented in Chapter 8 and are summarised in Table 11-2. Using these values, the consequence of failure may be determined utilising a simple unweighted index shown in Equation 11-2:

$$CoF = 5 - \sum_i^n (node_i \times weight_i) \qquad \text{(Eq. 11-2)}$$

where $node_i$ refers to the four nodes listed in Table 11-2 and $weight_i$ equals the importance weighting of each node to sustainability (0.25 used in this chapter). The importance of each node should be determined by specific road authorities, based on risk profiling relative to the locale.

Using Equations 11-1 and 11-2, the probability and consequence of failure for each road scenario is calculated, summarised in Table 11-4 and visually illustrated in Figure 11-8.

Table 11-4: Consequence of Failure for road scenarios

	Probability of Failure (PoF)	**Consequence of Failure (CoF)**
Scenario 1	0.36	2.32
Scenario 2	0.19	0.81
Scenario 3	0.30	1.92
Scenario 4	0.14	0.49

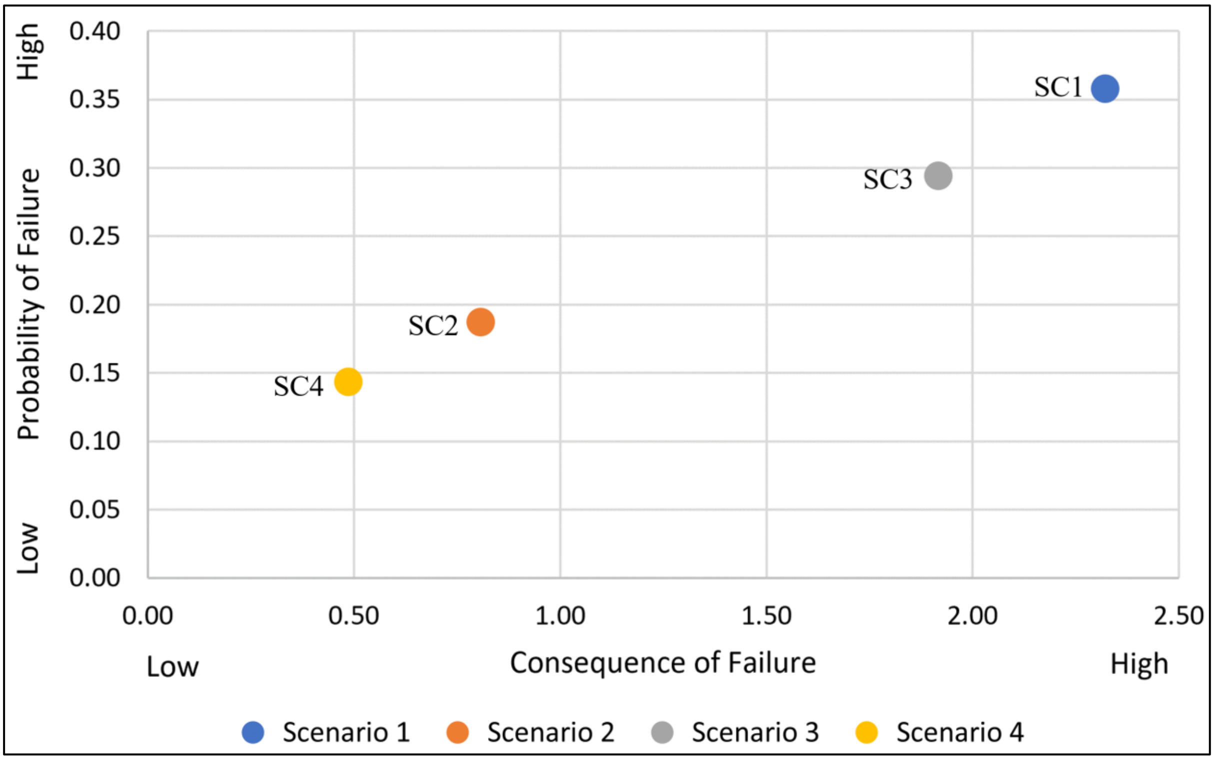


Figure 11-8: Sustainability Risk Profile

From Figure 11-8 it is seen that risk profile for each scenario follows a similar trend to the sustainability index results previously presented, with Scenario 4 performing best and Scenario 1 performing worst. Finally, the sustainable risk may be calculated using Equation 3-1, summarised in Table 11-5.

Table 11-5: Sustainable Risk for road scenarios

	Sustainable Risk
Scenario 1	0.83
Scenario 2	0.15
Scenario 3	0.56
Scenario 4	0.07

From Table 11-5, it is seen that Scenario 4 has the lowest sustainable risk. Simply put, risk, even though unweighted in this study, reflects the physical risks of environmental damage, climate change, socio-economic impacts, road user benefits, and so forth of a specific road scenario. Therefore, the selection of Scenario 4 as the preferred design option is expected to provide the most sustainable pavement with the lowest cumulative risk of the infrastructure being unsustainable in the long term.

11.9 DISCUSSION AND CRITICAL SHORTCOMINGS

The framework presented in this thesis calculates the probability of pavement sustainability over its life cycle given the occurrence of certain risks directly related to sustainability. These risks are categorised as either environmental, social, functional or governance risks which individually and collectively have a cumulative impact on pavement sustainability. The risks were sourced from literature and previous studies on the subject and are either qualitative or quantitative but have a measurable impact on sustainability regardless. ISO 31000 (2018) suggests risk management is an ever-evolving process where risks are continuously identified, assessed, managed, and fed back into the system for improvement. This framework is in line with this suggestion as it is developed for constant monitoring, enhanced intervention planning and improvement for future projects.

The framework in this chapter was developed in such a way that it is inherently biased towards a high probability of sustainability and its results are most influenced by ‘maintenance’. Maintenance has commonly been cited as the leading risk in the performance and sustainability of pavements (Steyn and Visser, 2001) in South Africa and internationally (Knott et al., 2019). The findings of this chapter support this notion and it is submitted that if sustainable aspirations are to be realised, rigorous proactive maintenance regimes need to be implemented by road authorities, especially in current or future humid climates.

It is noted that the impact of the ‘energy use’ risk has been determined based on current observations in South Africa. However, it is expected that the impact of this risk will significantly increase in the future as the energy market in South Africa continues to degrade and the social impacts of ‘energy use’ become increasingly evident, even more so when the electric vehicle market expands.

Currently little research exists on cumulative risk assessment in the field of infrastructure development, where existing risk management commonly follows the traditional singular approach. This chapter has aimed to provide a basis for incorporating a cumulative approach to risk management for pavements, where the probability of sustainability is affected by the collective impacts of a variety of risks. The model was developed to be used by road authorities to not only determine the most sustainable alternative during the design phase, but to monitor the preferred design during its in-service life, evaluating both observed performance and additional required interventions if poor performance is detected. This adds an extra metric to be used by road authorities to improve their pavement management systems.

In practice, carbon assessments increasingly accompany economic evaluations of alternative options with little guidance available to determine the preferred solution when the results of the methodologies are in contradiction. It is however understood that the economic tenet typically drives decision making (Practicò et al., 2011). In other sectors, methodologies have been developed to unify the various sustainable tenets (Atai et al., 2020), but current efforts in the field of pavement engineering are lacking. Furthermore, when social consideration is provided, it is limited and often only supplements the other methodologies without fully being utilised in decision making. Thus, in comparison with similar assessment methods such as life cycle assessments or life cycle cost analyses, the value of the model developed in this chapter is that not only does it include full consideration of these methodologies, it extends their use far beyond what has typically been achievable. The model unifies the three tenets of sustainability for confident decision making about the impacts a design option will have on the local environment, society and economy. The results of this study further show that when the essence of sustainability is holistically evaluated, optimal outcomes are easily achievable across the three tenets.

A critical shortcoming of current risk assessment frameworks is that they are often unable to measure the direct impact of climate change on pavement performance, and typically adopt a qualitative approach for simplification. This presented model rather allows for quantifiable assessment of the impacts of climate change on pavement sustainability, by translating high-resolution climate change projections into direct pavement impacts, such as accelerated pavement deterioration and its effects on road user emissions which have been found to account for 99% of the total emissions over a typical pavement life cycle.

11.10 GUIDANCE FOR FUTURE RESEARCH

For reproduction of the methodology proposed in this study, key guidance notes are provided:

1. Risk and sustainability need to be defined within the context of the project or authority in which the definitions are to be applied;
2. Stakeholder engagement and expert interviews are required to select the key relevant sustainable indicators as well as their relative importance through indicator weighting, and
3. System boundaries need to be clearly defined and should include the functional unit as well as spatial and temporal scales.

Adhering to these simple guidance notes, researchers may develop situationally specific sustainability indices and significantly improve project outcomes. Further guidance is provided in Chapter 12.

11.11 SUMMARY

The complex nature of sustainability has often resulted in simplification of quantification, focused only on certain sustainability aspects considered to be crucial. These attempts at simplification have further omitted consideration of key sustainability indicators and risks which are difficult to quantify but collectively impact on sustainability, echoing the sentiment of Reitinger et al. (2011), ‘we are faced with the paradoxical situation of avoiding harm to the environment and human health while ignoring other aspects of human life and thus the aims of sustainability'.

In this chapter, a method of holistic sustainable pavement quantification and sensible sustainability indexing is presented. A sustainability database is developed from previous studies, with all key indicators and risks considered regardless of the difficulty in quantification. MCMC techniques were applied to the database allowing for time-step modelling of risk over a pavement life cycle, where the start point of modelling can be any time along the life cycle, and both past and future impacts may be modelled collectively. Pavements are living infrastructures that continuously evolve and change and therefore the management tools applied to them should be of a similar dynamic nature, allowing constant inputs of data to monitor and react to any impacts, whether positive or negative.

The model is spatially relevant to South Africa but easily adapted for application in any locale. A key objective of this chapter is to demonstrate that when the concept of sustainability is unified, optimal outcomes across the tenets are often easily achievable and the preferred design option will not only be the most economically-, but also the most environmentally- and socially-friendly.

Following a cumulative approach, a method for quantification of the sustainable risk of alternatives is also presented. The physical meaning of sustainable risk reflects the anticipated impact of the alternative on the environmental-, social- and economic-tenets of sustainability. Control and management of pavement sustainability can aid in limiting these impacts.

The results presented in this chapter show that even though sustainability is complex, simplification is achievable. These results add an additional metric that road authorities may apply to govern their respective pavement networks and make more reliable decisions regarding pavement alternatives designed for sustainable outcomes.

The model proposed in this chapter is based on abstract principles and is unweighted, meaning the relative impact of key risks to each other and collectively to sustainability are equal. For the implementation of the model within specific road authority management systems, local stakeholder engagement and expert inputs are required to determine the weights relative to the community that both utilises and is affected by the road network. This should be accompanied by due recognition of the definitions of both risk and sustainability within the context of application. It is recommended that road authorities integrate the framework into their day-to-day management of pavements in South Africa and continuously improve the model for future use.

12 GUIDELINES FOR SUSTAINABLE PAVEMENT EVALUATION

12.1 INTRODUCTION

The objective of this chapter is to consolidate the information provided in this thesis into a framewok to be used for sustainable pavement infrastructure provision. This is further supported by a set of guidelines for pavement evaluation. Firstly the identification of critical and sustainable parameters for consideration is provided and secondly guidelines for the incorporation of these parameters into day-to-day pavement engineering In Chapter 6 and throughout this thesis, the five themes used in a holistic approach framework are 1. Life cycle assessment, 2. Social life cycle assessment, 3. Climate change assessment, 4. Road user life cycle assessment incorporating climate change impacts and 5. Risk and sustainability. Each of these themes are individually addressed in this chapter.

12.2 LIFE CYCLE ASSESSMENT

12.2.1 Critical parameters

The critical parameters for consideration in a typical pavement life cycle assessment are:

- Environmental emissions;
- Social emissions;
- Analysis period;
- Functional unit;
- Traffic data;
- Alternative pavement materials and designs;
- Maintenance strategies, and
- Water use.

These parameters are found to predominantly influence the outcomes of pavement life cycle assessments and allow for simplification of the complicated concept.

12.2.2 Guidelines

The guidelines for implementing a life cycle assessment for pavements is demonstrated using the current general structure for pavement design in South Africa. This general structure is shown in Figure 12-1. The sections that are highlighted in green are those that are affected by the results presented in Chapter 7 on the life cycle inventory and Chapter 10 on the life cycle assessment. The affected sections are Materials (Section 5) and Practical Considerations (Section 7).

Materials (Section 5)

Material considerations are currently concerned with:

1. Quality of materials;
2. Availability of materials, and
3. Unit cost of materials.

It is proposed that an additional consideration is included, namely:

4. Life cycle impact of materials

Practical Considerations (Section 7)

Practical considerations are currently concerned with:

1. Drainage;
2. Compaction;
3. Problem subgrades;
4. Cross-section;
5. Labour intensive construction, and
6. Environmental impact.

It is proposed that a new consideration is included, to replace the 'Environmental impact' consideration:

6. Life cycle assessment

The life cycle impact of materials has been a consideration during design of pavement infrastructure for an extended period, but an inventory listing good quality data on which to rely, has been lacking in South Africa where assumptions of the life cycle impacts of certain materials have been defined within a wide range and display errors. Furthermore, when considering life cycle stages, the use phase, which is the period during which the pavement is in service, has often been omitted. This thesis provides a robust inventory to determine all life cycle impacts of pavements in South Africa.

12.3 SOCIAL LIFE CYCLE ASSESSMENT

12.3.1 Critical parameters

The critical parameters for consideration are in a typical pavement social life cycle assessment are:

- Analysis period;
- Functional unit;
- Relevant social indicators;
- Settlement vulnerabilities and needs;
- Alternative pavement materials and designs;

- Maintenance strategies, and
- Water use.

These parameters are found to predominantly influence the outcomes of pavement social life cycle assessments and allow for simplification of the complicated concept.

12.3.2 Guidelines

The guidelines for implementing a social life cycle assessment for pavements is demonstrated using the current general structure for pavement design in South Africa. This general structure is shown in Figure 12-1. It is determined that the increased premium placed on life cycle benefits is not justified in assuming the achievement of long-term positive benefits. The affected section is Practical Considerations (Section 7).

Practical Considerations (Section 7)

Practical considerations are currently concerned with:

1. Drainage;
2. Compaction;
3. Problem subgrades;
4. Cross-section;
5. Labour intensive construction, and
6. Environmental impact.

It is proposed that a new consideration is included, to replace the ‘Labour intensive construction’ consideration:

5. Social life cycle assessment

Social considerations have been a part of the general design and managerial considerations for a long time in South Africa, but have only focused on limited areas. Holistic social sustainability has not been effectively captured by indicators such as ‘Labour intensive construction’. It is proposed that the social life cycle assessment proposed in this thesis replace the before mentioned indicator to allow for a wider evaluation of the social impacts of pavements in South Africa.

12.4 RISK AND SUSTAINABILITY INDEX

The guidelines for implementing a risk and sustainability index assessment for pavements is demonstrated using the current general structure for pavement design in South Africa, shown in Figure

12-1. The section highlighted in amber (Section 10) is that which is affected by the results presented in Chapter 11 on cumulative risk and sustainability and are proposed as an additional step in the current design process.

The current pavement design process typically considers risk from a performance perspective and risk allocation is incorporated into most of the design methods available in South Africa using the linear-elastic theory. However, risk from a broad sustainable perspective is not considered throughout. It is proposed that an additional design step, ‘Risk and Sustainability Index’ which gives consideration to both past and future risks, be incorporated into the existing framework. It is further proposedthat practitioners conduct the assessment using alternative designs developed throughout the design process. This outcome extends the cost analysis step to include consideration of other sustainable factors.

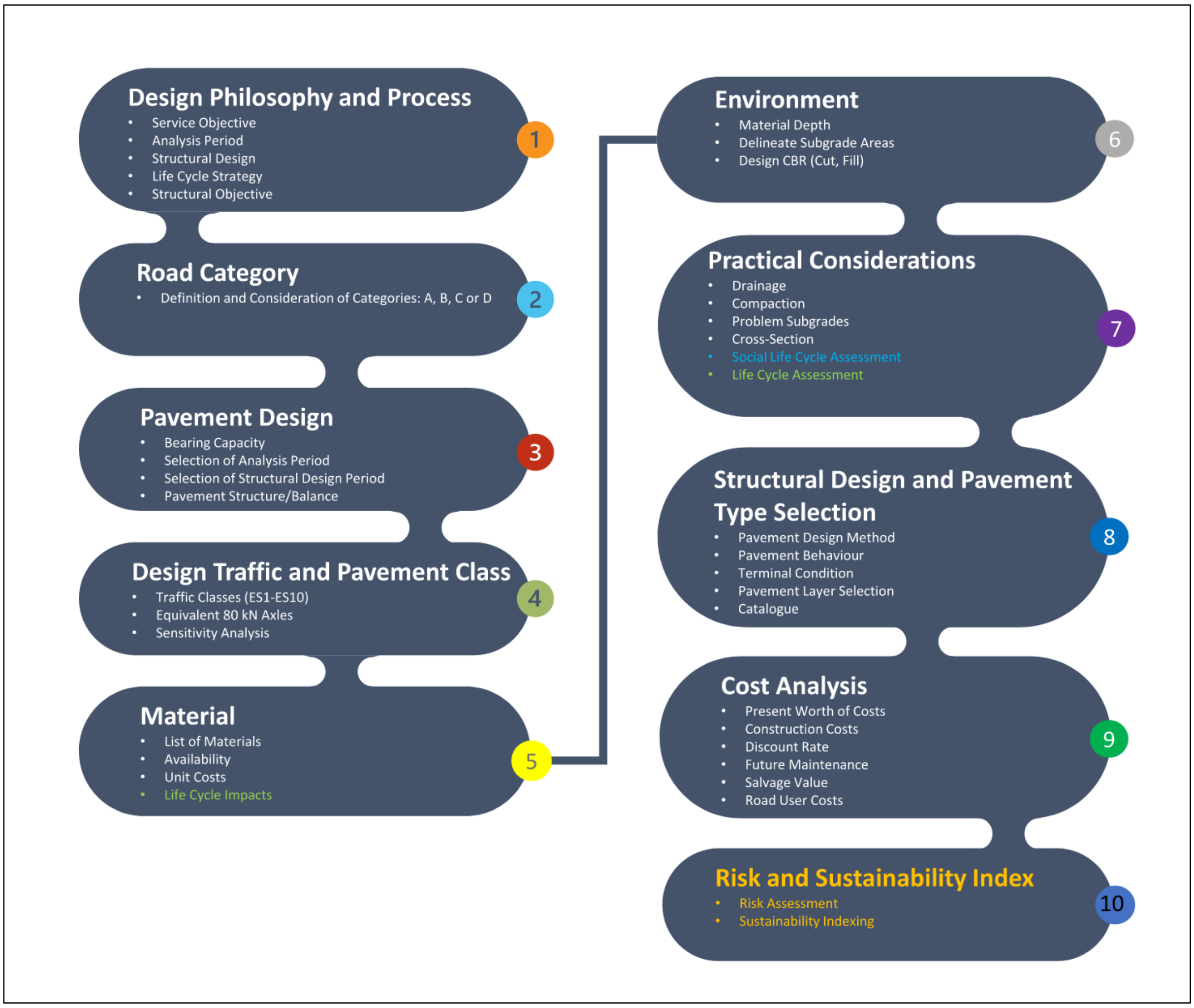


Figure 12-1: Proposed pavement design process (adapted from SAPEM, 2017)

12.5 UNRESOLVED ISSUES

12.5.1 Introduction

To keep the scope of this thesis manageable, several issues were identified which fall outside of the scope of the thesis. These were listed in Chapter 1 as:

a. Investigate and develop new techniques to quantify the economic, environmental or societal impacts of pavement infrastructure;
b. Generate new data for evaluation with the proposed models, and
c. Investigate the risk elements and sustainable indicators associated with the broader concept of transportation (e.g. bridges, signals, interchanges, etc.).

The main unresolved issues given these system boundaries are:

a. Development of an internationally accepted definition for pavement sustainability;
b. Validity and use of default data for the life cycle inventory and social life cycle inventory;
c. Relevance of social emissions listed in the life cycle inventory;
d. Socio-economic impact assessment for fundamental economic transformation widely implemented in South Africa;
e. Qualitative nature of certain climate change data;
f. Requirement for updated electric-vehicle energy use models;
g. Clearer understanding of the risks affecting pavement sustainability;
h. Requirement of a larger database for sustainability indexing of pavements, and
i. Extending the research to cover the broader concept of transportation of which pavements play a pivotal role and interact with.

Although these factors are outside the scope of the current thesis, it in no way implies that they are not important or should be overlooked. Some of the assumptions (i.e. indicator factors listed in the life cycle inventory) can have a major influence on the perceived sustainability of the South African pavement network. These unresolved issues are discussed in the thesis and suggestions are provided for their incorporation into the overall model. An indication of the expected effect of these concerns on the outcome of this thesis, is also provided. The discussion in the next section around their expected effect is not based on further analyses, but rather on an interpretation of the possible outcome, using the existing knowledge and understanding of pavement sustainability of the writer and taking into consideration available literature. Recommendations are also made for specific further research needed to solve some of these issues.

12.5.2 Discussion of unresolved issues

Firstly, is the unresolved issue relating to the development of an internationally accepted definition for pavement sustainability. As noted throughout this thesis, and particularly in Chapter 2, defining sustainability needs to be temporally and spatially relevant, as well as industry or organisationally specific. As such, it is accepted that a benchmark definition to be used by international road authorities might be arduous, but its value will extend far beyond the pavement engineering field. Aligning road authorities with the crucial concepts of pavement sustainability, and allowing them to integrate those concepts into a definition that suits their mandates and objectives, may alleviate the difficulty of the task. This thesis proposes the following definition for pavement sustainability as baseline for future incorporation: the system characteristics that encompass a pavement's ability to meet basic human needs while achieving the economic and engineering goals for which it was constructed, enhancing its climate resilience, preserving and (ideally) restoring the natural environment whilst consuming natural resources in a responsible manner

Secondly, a key unresolved issue in this study is the use of default data to develop the life cycle inventory presented in Appendix A-1 and Appendix A-2. The global construction industry has in recent years taken positive steps to incorporate sustainable construction alternatives and has begun to declare the carbon footprint of certain construction materials and activities. However, the small-scale database that exists is highly biased towards developed countries, specifically Europe and North America. As such, the direct use of this database for the South African construction industry will inevitably produce skewed results and in some instances great over/under estimations. A clear example of this is seen in the Eurobitume database for bitumen between 2012 and 2020, where up to 50% differences in emissions are reported for the same processes, influenced by the use of default data. There is a pressing need for South African construction material suppliers as well as contractors to actively engage in declaring the carbon footprint of the materials and activities required to construct a road.

Further to the life cycle inventory, social emissions have been included to broaden the scope of indicators focused on. Social emissions are those considered to directly influence human health. There is not yet sufficient evidence to provide meaning to, or definition of , the social emissions from a construction and pavement use phase perspective. It is however understood that these social emissions may linger in the air surrounding pavement networks. The effect of an increased concentration of these emissions needs to be further investigated.

The social life cycle inventory presented in this study is based on a large database influenced by both International and South African frameworks. The indicators have been assessed using a detailed methodology, but certain indicators were subjectively influenced by the writer to reflect their importance in South Africa. One of these indicators, fundamental economic transformation, draws attention to the great economic cost attributed to the construction industry in order to implement the indicator. There is a need to conduct a detailed socio-economic impact assessment on the indicator within the construction industry to determine what value it adds and verify the elevated importance placed on it by the South African government.

Considering the available climate change data, this study has made use of both quantitative and qualitative data to develop the climate change assessment detailed in Chapter 9. Qualitative data was used to define settlement vulnerabilities, with quantitative data available for changes to climatic zones. It is understood that settlement vulnerabilities are not easily quantified and a qualified assessment may be more applicable. However, to enhance the climate change impact assessment presented in this study, quantitative data throughout are required.

The comprehensive list of issues previously discussed highlight various risks associated with sustainability, ranging from material availability, construction methods, pavement vulnerabily, socio-economic indicators, environmental factors, climate change and maintenance strategies, to mention a few. The issues were further investigated as an integrated system with consideration given to how these risks may exacerbate or mitigate others. Insufficient research has been conducted to determine the relationship of these risks across the tenets of sustainability and the required experience to conduct holistic sustainable evaluations, is currently lacking. There is a need to not only further investigate these risks within the pavement engineering field, but to also extend them to the broader transportation field.

12.6 OBSERVATIONS

The following observation is made based on the information in this chapter:

- Pavement sustainability is a highly complex and interrelated concept with a multitude of variables that play important roles in the design, construction and management of pavements. It is however observed that the concept can be simplified and streamlined for easy interpretation and evaluation.

12.7 SUMMARY

This chapter has provided practical guidelines for the incorporation of a suite of sustainable evaluation tools, developed throughout this thesis for proposed incorporation into the existing pavement design process accepted in South Africa. The tools include a life cycle assessment (focused on environmental sustainability), a social life cycle assessment (focused on social sustainability), a pavement deterioration analysis incorporating climate change impacts (focused on performance assessments), and a cumulative risk and sustainability index (focused on holistic sustainability. These tools are based on fundamentally high quality data and provide evidence for making design and managerial choices. Adherence to the guidelines provided in this chapter, and the general guidance detailed throughout the various methodological chapters of this thesis (Chapter 7 through 11), road authorities may substantially improve their ability to achieve sustainable outcomes. It is proposed that while further research is conducted, the additions to the pavement design process advocated in this thesis be incorporated.

The following studies are recommended based on the information in this chapter:

- A study to develop a framework providing road authorities the platform on which to create their own definitions for sustainable pavements aligned with the core concepts agreed on an international basis;
- A study to enhance the life cycle inventory presented in this study focused on the material and construction phases;
- A study to determine the nature and impact of social emissions concentrated around pavement networks;
- A study to detail the socio-economic impact of fundamental economic transformation and BEE policy implementation in the construction industry;
- A study to quantify the impacts of climate change on settlements (drought risk and heat stress);
- A study to update existing deterioration models and extend their use to electric vehicles;
- A study to further investigate the risks affecting pavement sustainability and enhance the sustainability index model developed in this study, and
- A multitude of studies that utilise the methodologies presented in this study and extend their use to the broader transportation field to allow holistic sustainable evaluations of transportation networks.

13 CONCLUSIONS AND RECOMMENDATIONS

13.1 INTRODUCTION

This thesis focuses on providing practical guidelines through development of methodologies and data analysis to characterise and evaluate the sustainability of a pavement. The objectives of this study focus on a practical systems framework populated with various methodologies and data sets for the analysis of holistic pavement sustainability in South Africa. It is however noted that with relevant location-specific adjustments, the approach may be adapted and customised for any locale. The stated objectives of this study are met by developing such a framework and a practical approach for sustainable evaluations of pavements, and by verifying this approach using a variety of worked examples and data validation exercises. The overall scope of this thesis is the field of pavement sustainability, focusing on the environmental and social tenets.

13.2 CONCLUSIONS

The following primary conclusions are drawn based on the information in this thesis. More conclusions of a general nature can be found at the end of each chapter. Some of the conclusions may confirm existing knowledge, but are highlighted as they are seen to be vital for discernable assimilation of the effects of pavement design, construction and management on sustainability.

13.2.1 Practical system framework to evaluate sustainable pavement infrastructure provision

A practical system framework was developed for sustainable evaluation of pavement infrastructure by investigating critical components of sustainability and creating a suite of methodologies to measure these components. This has been achieved through:

1. Defining pavement sustainability;
2. Developing a life cycle inventory for pavements;
3. Developing a social life cycle inventory for pavements;
4. Developing a climate change assessment which may be used to assess future climatic risks and inform resilience interventions;
5. Developing a sensible risk and sustainability index for a pavement over its life cycle, and
6. Bringing forth a better understanding of the issues relevant to pavement sustainability from a design, construction and management perspective in South Africa.

Defining pavement sustainability has taken into account a variety of international definitions for sustainability in general, considered the common denominators among definitions, the difficulties with implementing these definitionsand the common trend to exclude certain important concepts which may be copious to understand or clearly define. The definition for pavement sustainability proposed in this thesis acts as the basis for the subsequent research conducted throughout this thesis, ensuring objectives and outcomes are aligned with a holistic perspective on sustainability and that concepts typically not widely included in the field of pavement engineering, such as social sustainability, are emphasised.

The *life cycle inventory* provided in this study lists environmental emissions for common pavement construction activities and road user emissions for a cradle-to-grave scenario. The *social life cycle inventory* provided in this study was developed using a large database of potential socially oriented indicators, and an adapted 'hotspot' methodology applied to identify key social indicators within the field of pavement engineering. The *climate change impact assessment* indicates the potential impact climate change will have on the performance of the South African pavement engineering network. Compiling the results of the previous methodologies, a *risk and sustainability index* statistical model is developed to evaluate the probability of pavement sustainability given the various sustainable interventions. The model allows for continuous monitoring over the pavement's life cycle and may be used to better plan future interventions depending on its performance. The model represents the culmination of the efforts of this thesis, to simplify outcomes and delineate the various methodologies into one single probability value of sustainability.

13.2.2 Practical approach for implementation at both project and network level

In Chapter 12 practical guidelines are presented for implementing holistic sustainable evaluations of pavement infrastructure by both designers and contractors at project level and road authorities at network level. Worked examples are provided through this thesis to demonstrate the implementation of developed methodologies and highlight critical parameters that need to be considered during everyday pavement design, construction and management activities.

13.3 RECOMMENDATIONS

The following primary recommendations are made based on the information in this thesis:

a. Road authorities should develop their own definition for sustainability, aligned with their specific mandates and integrate the definition to influence project and network level management of pavements (Chapter 2);
b. Road authorities should increasingly include consideration of risks and their impact on the level of sustainability of a pavement (Chapter 3);
c. Further work is required to enhance the quality of indicators provided in the life cycle inventory presented in this thesis (Chapter 7);
d. Road authorities should promote industry participation to enhance the data used to develop an expanded life cycle inventory (Chapter 7);

e. Alternative methods to reduce water use during construction should be investigated (Chapter 8 and Chapter 8);

f. Further work is required to investigate and quantify social indicators relevant to pavement infrastructure provision (Chapter 8);

g. Further work is required to enhance the quantitative nature of climate change projections (Chapter 9);

h. Updated models are required to measure the effect of pavement deterioration on electric-based vehicles (Chapter 10), and

i. Further work is required to enhance the quality of the risk and sustainability index model presented in this study. This may practically be achieved through direct stakeholder engagement. The work should seek to inform policy and other managerial activities in the governance of the South African pavement network (Chapter 11).

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APPENDIX A

LIFE CYCLE INVENTORY

DATA QUALITY MATRIX AND INDICATOR REFERENCES

ASSUMPTIONS

Table A-1: Inventory for pavement materials in South Africa

Indicator	Unit	Treated water	Bitumen[‡]	3% SBS PMB	4.5% SBS PMB	6% SBS PMB	Bitumen emulsion[‡]
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO_2e/t	0.12	221.89 (233.36)	601.17 (612.30)	790.81 (801.77)	980.46 (991.24)	1411.97 (1420.00)
Energy Use	MJ/t	0.4	2201.40 (2240.00)	3434.79 (3472.24)	4051.49 (4088.35)	4668.19 (4704.47)	5770.81 (5797.83)
Water Use	l/t	1000.16	681.61 (688.68)	880.75 (887.61)	980.32 (987.07)	1079.88 (1086.53)	2551.36 (2556.30)
Emissions to Water	kg PAHs/t	0	2.61E-07 (2.61E-07)	2.53E-07 (2.53E-07)	2.49E-07 (2.49E-07)	2.45E-07 (2.45E-07)	2.05E-07 (2.05E-07)
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO_2/t	1.01E-03	1.13 (1.23)	4.37 (4.46)	5.99 (4.80)	7.60 (7.70)	11.44 (11.51)
Nitrogen Oxides Emissions	kg NOx/t	4.84E-04	2.51 (2.56)	4.01 (4.05)	4.75 (4.80)	5.50 (5.55)	6.88 (6.91)
Particulate Matter Emissions	kg PM_{10}/t	4.00E-05	0.03 (003)	0.16 (0.16)	0.22 (0.22)	0.29 (0.29)	0.43 (0.43)
Volatile Organic Compounds Emissions	kg VOC/t	n/a	0.68 (0.68)	0.66 (0.66)	0.65 (0.65)	0.64 (0.64)	0.48 (0.48)

Indicator	Unit	HMA[‡]	WMA[‡]	CMA[‡]	HMA + RAP	WMA + RAP	CMA + RAP
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO2e/t	69.36 (70.06)	48.55 (49.04)	41.79 (41.08)	50.82	35.58	22.55
Energy Use	MJ/t	723.20 (725.51)	506.24 (507.86)	335.70 (338.01)	620.15	434.1	275.15
Water Use	l/t	76.05 (76.47)	53.23 (53.53)	61.90 (62.33)	25.43	17.8	11.28
Emissions to Water	kg PAHs/t	9.56E-07 (9.56E-07)	6.69E-07 (6.69E-07)	2.99E-07 (2.99E-07)	1.04E-06	7.97E-07	4.61E-07
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO2/t	0.43 (0.44)	0.30 (0.31)	0.24 (0.25)	0.35	0.24	0.16
Nitrogen Oxides Emissions	kg NOx/t	0.50 (0.50)	0.35 (0.35)	0.30 (0.30)	0.36	0.25	0.16
Particulate Matter Emissions	kg PM10/t	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01	4.65E-03	2.94E-03
Volatile Organic Compounds Emissions	kg VOC/t	0.04 (0.04)	0.03 (0.03)	0.04 (0.04)	4.67E-04	3.27E-04	2.07E-04

Indicator	**Unit**	**Organosilane**	**Crushed stone**	**Natural aggregate**	**Recycled aggregate**	**Cement**	**Lime**
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO2e/t	1260.82	3161.33	1395.42	4.4	927.54	47.88
Energy Use	MJ/t	6,398.34	72.99	32.22	22.33	4707	243
Water Use	l/t	1442.83	16.46	7.27	5.04	1061.43	54.8
Emissions to Water	kg PAHs/t	5,36E-06	6.11E-08	2.70E-08	1.87E-08	3.94E-06	2.03E-07
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO2/t	8.97	0.1	0.04	0.03	6.6	0.34
Nitrogen Oxides Emissions	kg NOx/t	6.21	41.41	18.28	0.02	4.57	0.24
Particulate Matter Emissions	kg PM10/t	0.35	0.01	0	0	0.26	0.01
Volatile Organic Compounds Emissions	kg VOC/t	0	0	0	0	0	0
Indicator	**Unit**	**Pavement concrete**	**Pavement steel**				
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO2e/t	159	1,367.23				
Energy Use	MJ/t	806.89	2.00E+04				
Water Use	l/t	250.78	7480.7				
Emissions to Water	kg PAHs/t	6.75E-07	0				
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO2/t	1.13	4.01				
Nitrogen Oxides Emissions	kg NOx/t	0.78	1.72				
Particulate Matter Emissions	kg PM10/t	0.04	4.17E-03				
Volatile Organic Compounds Emissions	kg VOC/t	0	0.62				

Ɨ Values in brackets represent inland scenario, with remaining values representing coastal scenario.

Table A-2: Inventory for pavement construction activities and equipment in South Africa

Indicator	Unit	Wheel loader	Excavator	Dumper	Milling - asphalt
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/loose m^3	0.18	0.24	0.52	0.2
Energy Use	MJ/loose m^3	2.43	3.22	6.9	2.69
Water Use	l/loose m^3	0	0	0	0
Emissions to Water	kg PAHs/loose m^3	4.52E-09	5.99E-09	1.28E-08	5.00E-09
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/loose m^3	8.74E-05	1.16E-04	2.48E-04	9.66E-05
Nitrogen Oxides Emissions	kg NOx/loose m^3	1.65E-03	2.18E-03	4.68E-03	1.82E-03
Particulate Matter Emissions	kg PM_{10}/loose m^3	0	0	0	0
Volatile Organic Compounds Emissions	kg VOC/loose m^3	0	0	0	0
Indicator	**Unit**	**Compactor - soil**	**Compactor - asphalt**	**Compactor – asphalt (pneumatic)**	**Paver**
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/m^2	0.04	0.06	0.04	0.05
Energy Use	MJ/m^2	0.6	0.79	0.48	0.66
Water Use	l/m^2	0	0	0	0
Emissions to Water	kg $PAHs/m^2$	1.11E-09	1.46E-09	8.84E-10	1.23E-09
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/m^2	2.14E-05	2.82E-05	1.71E-05	2.37E-05
Nitrogen Oxides Emissions	kg NOx/m^2	4.04E-04	5.33E-04	3.22E-04	4.47E-04
Particulate Matter Emissions	kg PM_{10}/m^2	0	0	0	0
Volatile Organic Compounds Emissions	kg VOC/m^2	0	0	0	0

Indicator	**Unit**	**Grader**	**Concrete sawing and sealing**	**Concrete milling**	**General activity**
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/m^2	0.01	0.04	5.52	0
Energy Use	MJ/m^2	0.12	0.5044	73.7	7.54E-03
Water Use	l/m^2	0	0	0	0
Emissions to Water	kg PAHs/m^2	2.23E-10	9.38E-10	1.37E-07	1.40E-11
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/m^2	4.31E-06	1.81E-05	2.65E-03	2.71E-07
Nitrogen Oxides Emissions	kg NOx/m^2	8.13E-05	3.42E-04	5.00E-02	5.11E-06
Particulate Matter Emissions	kg PM_{10}/m^2	0	0	0	0
Volatile Organic Compounds Emissions	kg VOC/m^2	0	0	0	0
Indicator	**Unit**	**14-ton short distance**	**32-ton long distance**		
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/tonne-km	0.85	0.42		
Energy Use	MJ/tonne-km	6.50E-02	3.20E-02		
Water Use	l/tonne-km	0	0		
Emissions to Water	kg PAHs/tonne-km	1.58E-09	7.73E-10		
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/tonne-km	0	0		
Nitrogen Oxides Emissions	kg NOx/tonne-km	0	0		
Particulate Matter Emissions	kg PM_{10}/tonne-km	0	0		
Volatile Organic Compounds Emissions	kg VOC/tonne-km	0	0		

Table A-3: Data Quality Matrix

Score	5 (Best)	4	3	2	1 (Worst)
Method compatibility	ISO or PAS 2050 or GHG Protocol for Products or Global Reporting Initiative	Other standardised method recognised nationally or internationally	-	Recognised method, but not standardised, e.g. ISO 14040/44 only, which is not a prescriptive method.	No recognised or standardised method
Assurance	External panel review (e.g. ISO 14040 panel review with 3 or more people)	2 External reviewers (e.g. academic papers often have two reviewer)	1 external reviewer (e.g. EPDs)	Internal review	No review process stated
Temporal correlation - Age of study	<= 5 years	<= 6 years	<= 7 years	< 10 years	>= 10 years
Geographical compatibility	Data from SA or relevant to SA supply chain	UK, European, North American or World Average	-	-	All other countries and regions
Transparency	Full calculation model and detailed report available *(very rare)*	Detailed report (e.g. full LCA report, documenting assumptions in detail), but no calculation model. Or transparent calculation model, but no detailed report.	-	Summary report covering an overview of method including key data (most EPDs will have this rating)	Limited details on the method, or key information missing

Table A-4: Data Quality Indicator scores

DQI Number	DQI Reference	Method compatibility	Assurance	Temporal correlation	Geographical compatibility	Transparency	DQI Score (20)	DQI (%)
I	Eurobitume (2012)	4	4	1	4	4	17	68%
II	Blaauw et al. (2020)	4	4	5	5	2	20	80%
III	EEA (2019)	5	5	5	4	4	23	92%
IV	Eskom (2014)	4	5	4	5	2	20	80%
V	UN-ESY (2017)	5	5	5	4	4	23	92%
VI	Swartz et al. (2013)	4	4	3	5	4	20	80%
VII	Silicones Europe (2019)	4	2	5	4	3	18	72%
VIII	Boustead and Cooper (1998)	5	4	1	4	2	16	64%
IX	Stripple (2001)	5	4	1	4	4	18	72%
X	Hänniken (1996)	4	2	1	4	2	13	52%
XI	Athena (2006)	4	4	1	4	4	17	68%
XII	EcoInvent (2011)	5	5	2	4	4	20	80%
XIII	US LCI (2012)	5	5	2	4	5	21	84%
XIV	Franzefoss EPD (2018)	5	3	5	4	2	19	76%
XV	Torr Quarry EPD (2018)	5	3	5	4	2	19	76%
XVI	Glensanda Quarry EPD (2018)	5	3	5	4	2	19	76%
XVII	Bardon Hill Quarry EPD (2018)	5	3	5	4	2	19	76%
XVIII	UK PC EPD (2014)	5	3	4	4	2	18	72%
XIX	NAEI (2018)	5	4	5	4	2	20	80%
XX	Lundberg et al. (2016)	4	4	5	4	2	19	76%
XXI	Wang et al. (2012)	4	4	2	4	4	18	72%
XXII	World Steel (2019)	4	4	5	4	4	21	84%
XXIII	Eurobitume (2020)	5	5	2	4	5	21	84%
XXIV	CNOOC (2018)	5	3	5	4	2	19	76%
XXV	Eni (2019)	5	3	4	4	2	18	72%

XXVI	Equinor (2019)	5	3	4	4	2	18	72%
XXVII	Occidental (2018)	5	3	4	4	2	18	72%
XXVIII	Chevron (2019)	5	3	4	4	2	18	72%
XXIX	BP (2019)	5	3	4	4	2	18	72%
XXX	Noble Energy (2018)	5	3	4	4	2	18	72%
XXXI	Tullow Oil (2018)	5	3	4	4	2	18	72%
XXXII	PDO (2018)	5	3	5	4	2	19	76%
XXXIII	Wärtsilä (2020)	4	4	1	4	4	17	68%
XXXIV	SeaRates (2020)	4	4	1	4	4	17	68%
XXXV	Inglesi-Lotz (2012)	4	4	2	4	4	18	72%
XXXVI	IMO (2015)	4	4	3	4	4	19	76%
XXXVII	Volker-Quaschning (2015)	4	4	3	4	4	19	76%

Table A-5: Assumptions for the calculation of indicator factors for construction and demolition activities in South Africa

Activity	Machine	Assumptions
Wheel loader	Volvo BML180	Normal working conditions, transport distance less than 10 m, effective working time is 50 min/hour, excavation class is average for 1-4 (easy - hard). Volume of material as loose volume.
Excavator	Volvo Akerman EC620	Excavator and dumper on same level, turn angle = 90-180 degrees, excavation class is average for 1-4 (easy – hard). Volume of material as loose volume.
Dumper	Volvo BMs Model A35	Swelling factor is 1.2, average driving conditions (level, hilly, good and bad ground conditions, etc.). Volume of material as loose volume.
Milling	Caterpillar PM622	Milling width is 2,235 mm, milling depth is 100 mm, milling speed is 60 m/min, working time is 50 min/h, asphalt swell factor is 1.25.
Compactor – soil (vibratory/static wheel)	Dynapac range	9.33 ton working weight, 6 passes at 85% cover width, 4 km/h, 2m roller width.
Compactor – asphalt (vibratory/static wheel)	Dynapac range	5.85 ton working weight, 7 passes at 85% cover width, 4 km/h, 1.4 m roller width.

Compactor – asphalt (pneumatic)	Dynapac range	6 ton working weight, 7 passes at 85% cover width, 4 km/h, 1.76 m roller width.
Paver	Dynapac range	Laying speed is 4 m/min (240 m/h), working time is 50 min/h, paving width is 5.75 m, fuel consumption is 21 l/h.
Grader	Caterpillar 140K	3 passes, effective blade width is 3.5 m, operating speed is 15 km/h.
Concrete sawing and sealing	-	Diesel based construction of 9 m width pavement concreted at the same time, joints and sealing from longitudinal centre joint and transverse joints at 5 m spacing.
Milling – concrete	-	Milling of concrete at tracks of 12 mm depth.
General activity	General (tack-coat, water truck, sweep, multi, etc.)	General activity.

APPENDIX B

SUSTAINABLE TRANSPORT INDICATOR DATABASE

ADAPTED TREE DIAGRAM

CRITERIA SCORING MATRIX

DETAILED MONTE CARLO SIMULATION RESULTS

Table B-1: Sustainable Transport Indicator Database for South Africa

Source	Number of Indicators
The Sustainable Development Goals (UN, 2019)	244
Greenroads (Greenroads, 2012)	61
GreenLITES (NYSDOT, 2012)	175
INVEST (INVEST, 2012)	33
I-LAST (IDOT, 2010)	153
ENVISION (ISI, 2018)	64
BE^{2}ST-IN-HIGHWAYS (RMRC, 2012)	9
OECD Environmental Indicators (OECD, 2001)	64
Developing indicators for sustainable and livable transport planning (Litman, 2019)	41
Framework for measuring sustainable regional development (Kirk et al., 2010)	38
Alberta GPI Blueprint (Pembina Institute, 2001)	32
Sustainable Transportation Performance Indicators (Gilbert, et al. 2003)	14
European Environment Agency core set of indicators (EEA, 2005)	206
Indicators of Airport Sustainability (Upham and Mills, 2003)	10
STARS Community Index (STC, 2010)	83
Sustainability Assessment Indicators (Jeon et al., 2008)	30
Broad Based Black Economic Empowerment (BEE Act, 2013)	7
WCDTPW EmpIA (WCDTPW, 2010)	5
CSIR – SIA (CSIR, 2016)	22
Vanclay (2003)	18
Burdge (1994) Indicators	26
Cement Sustainability Initiative (CSI, 2016)	7
Total number of Indicators	**1,342**

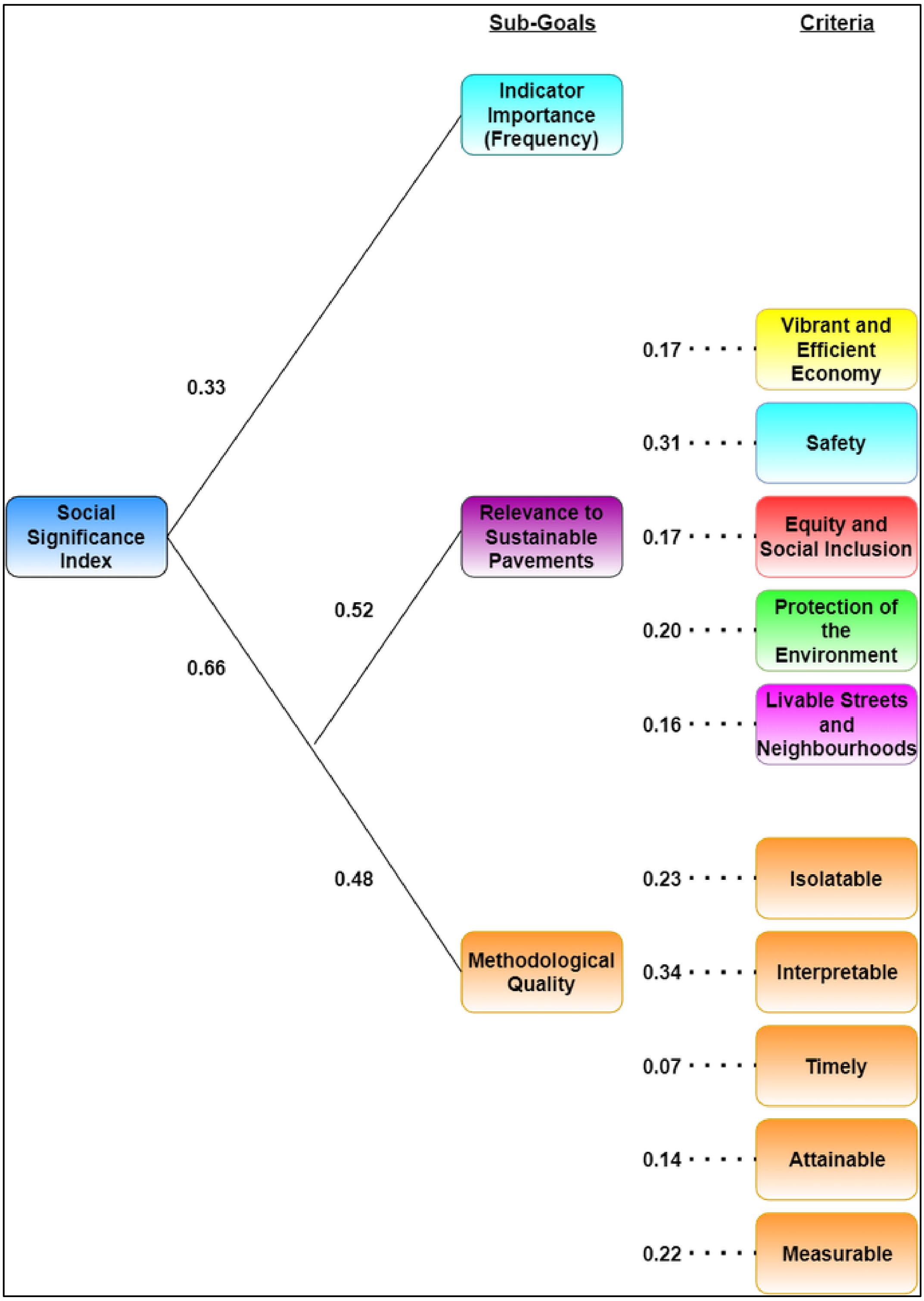
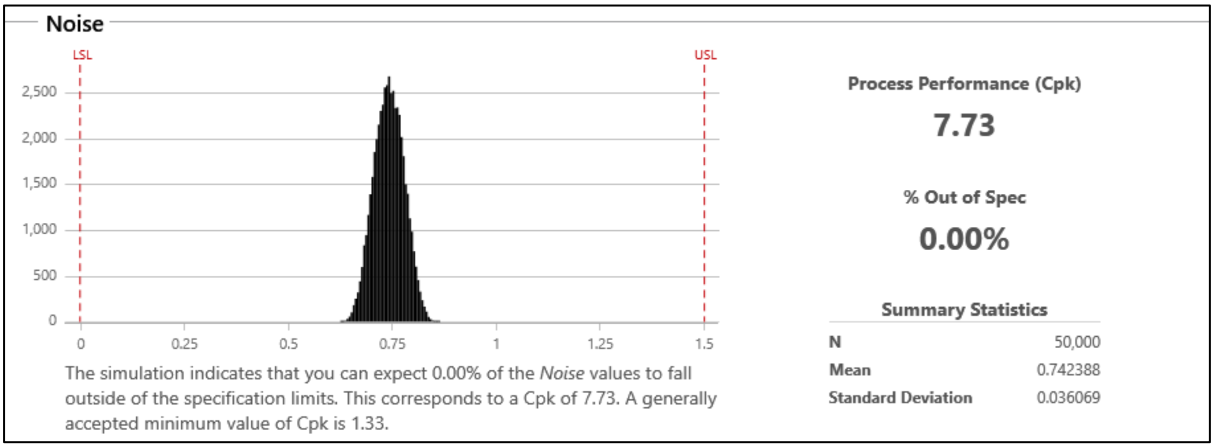


Figure B-1: Adapted tree diagram for sub-goal and criterion (Castillo and Pitfield, 2010)

Table B-2: Criteria Scoring Matrix

Criteria \ Score	1	2	3	4	5
Measurability	No measuring technique available	Measuring techniques available but not recognised	Measuring technique available but results need additional processing to confidently use	Well known measuring technique producing variable results	Well known measuring technique producing accurate results
Attainable	Results are unobtainable	Results require development of a model to obtain	Results require application of existing models and input of variables to obtain	Results are obtainable but require some additional processing	Results immediately obtainable
Timely	Results are unobtainable	Results take over a month to obtain	Results may take up to a month to obtain	Results may take up to a week to obtain	Results immediately obtainable
Interpretability	Results are uninterpretable	No consensus exists to interpret results	Confusion exists in interpretation of results	Results are interpretable within reasonable variation of definitions	Results easily interpreted
Isolatibility	Results cannot be isolated	No consensus exists to isolate results	Confusion exists in isolating results	Results isolatable within reasonable variation of definitions	Results easily isolatable

Monte Carlo Simulation Results



Noise

The simulation indicates that you can expect 0.00% of the *Noise* values to fall outside of the specification limits. This corresponds to a Cpk of 7.73. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

7.73

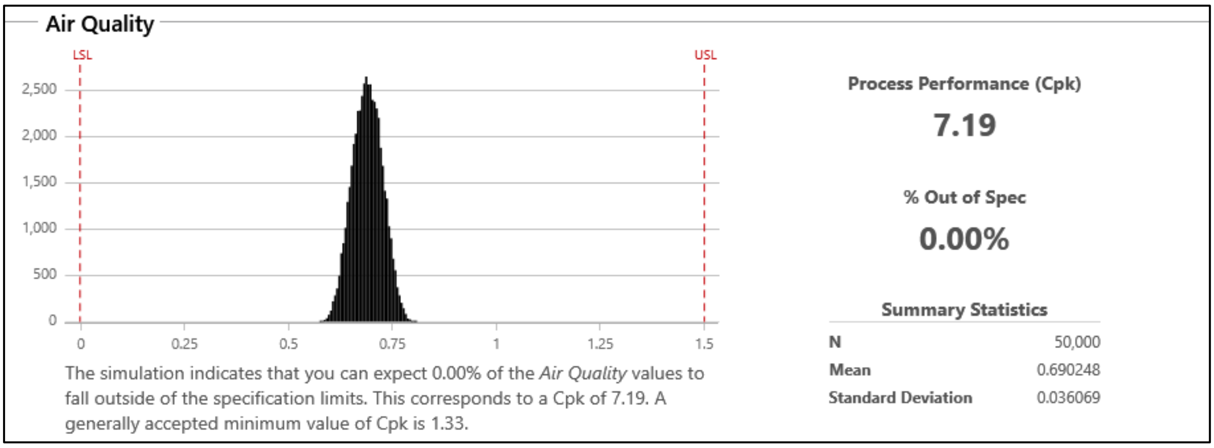
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.742388
Standard Deviation	0.036069

Figure B-2: Noise



Air Quality

The simulation indicates that you can expect 0.00% of the *Air Quality* values to fall outside of the specification limits. This corresponds to a Cpk of 7.19. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

7.19

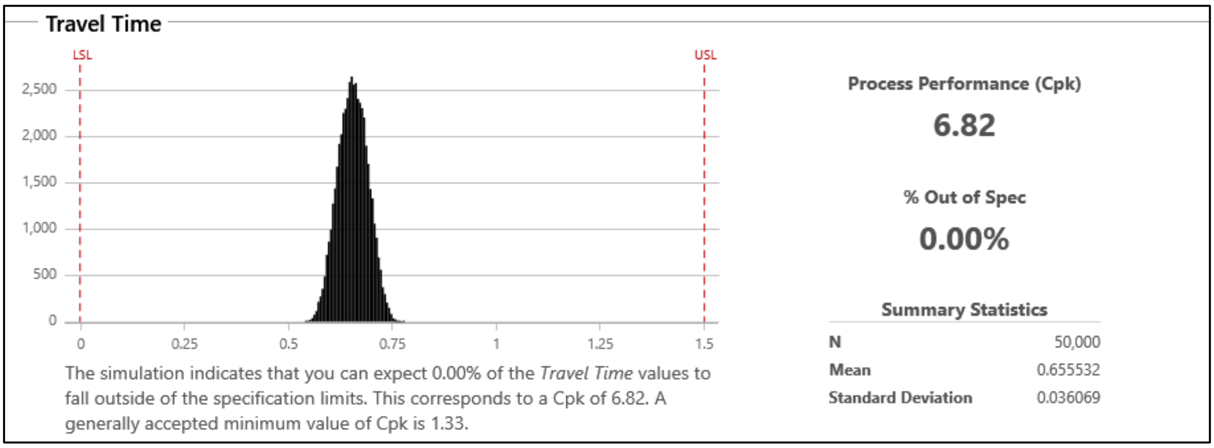
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.690248
Standard Deviation	0.036069

Figure B-3: Air Quality



Travel Time

The simulation indicates that you can expect 0.00% of the *Travel Time* values to fall outside of the specification limits. This corresponds to a Cpk of 6.82. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

6.82

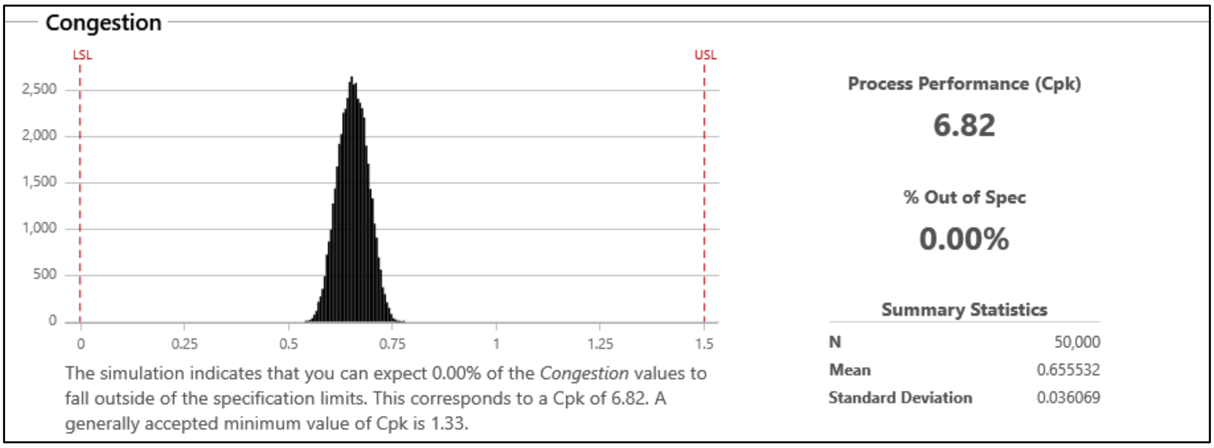
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.655532
Standard Deviation	0.036069

Figure B-4: Travel Time



Congestion

Process Performance (Cpk)

6.82

% Out of Spec

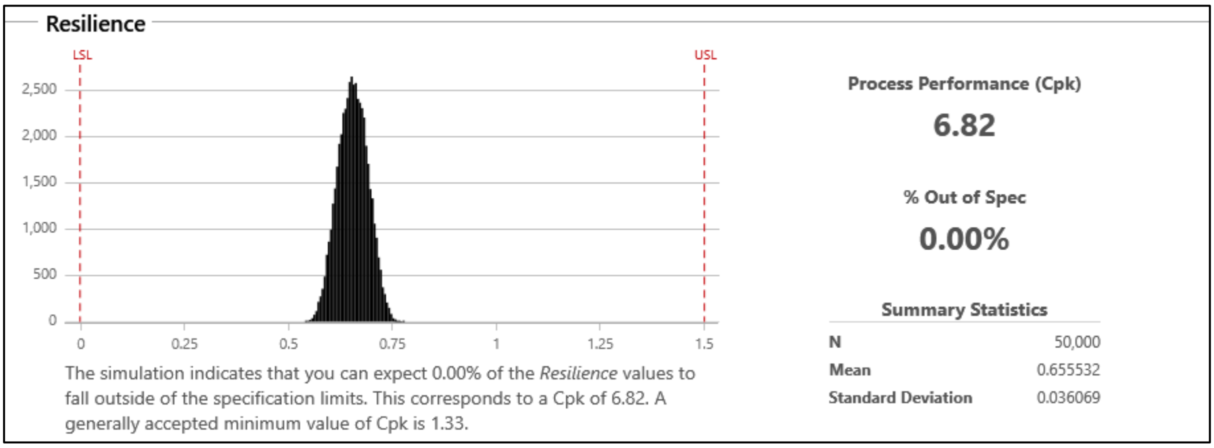
0.00%

Summary Statistics

N	50,000
Mean	0.655532
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Congestion* values to fall outside of the specification limits. This corresponds to a Cpk of 6.82. A generally accepted minimum value of Cpk is 1.33.

Figure B-5: Congestion



Resilience

Process Performance (Cpk)

6.82

% Out of Spec

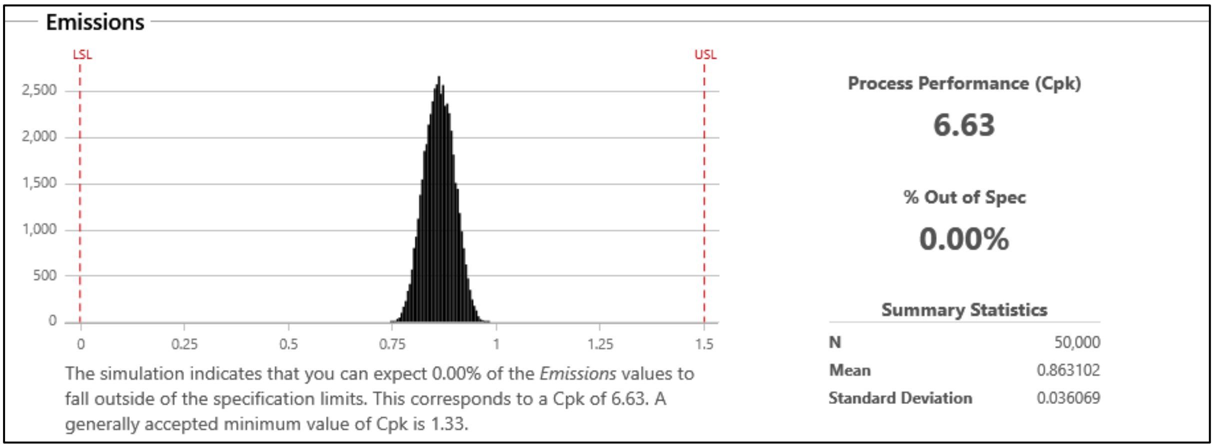
0.00%

Summary Statistics

N	50,000
Mean	0.655532
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Resilience* values to fall outside of the specification limits. This corresponds to a Cpk of 6.82. A generally accepted minimum value of Cpk is 1.33.

Figure B-6: Resilience



Emissions

Process Performance (Cpk)

6.63

% Out of Spec

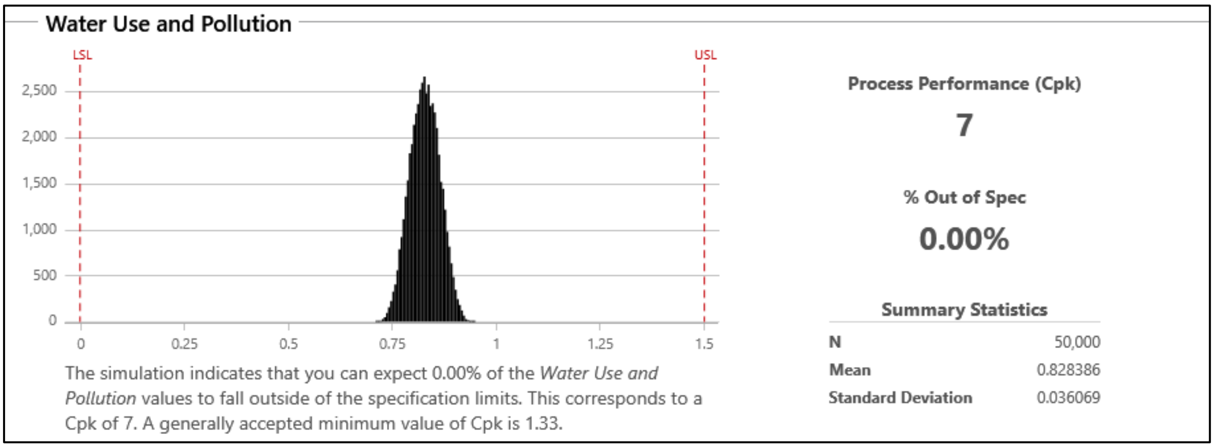
0.00%

Summary Statistics

N	50,000
Mean	0.863102
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Emissions* values to fall outside of the specification limits. This corresponds to a Cpk of 6.63. A generally accepted minimum value of Cpk is 1.33.

Figure B-7: Emissions



Process Performance (Cpk)

7

% Out of Spec

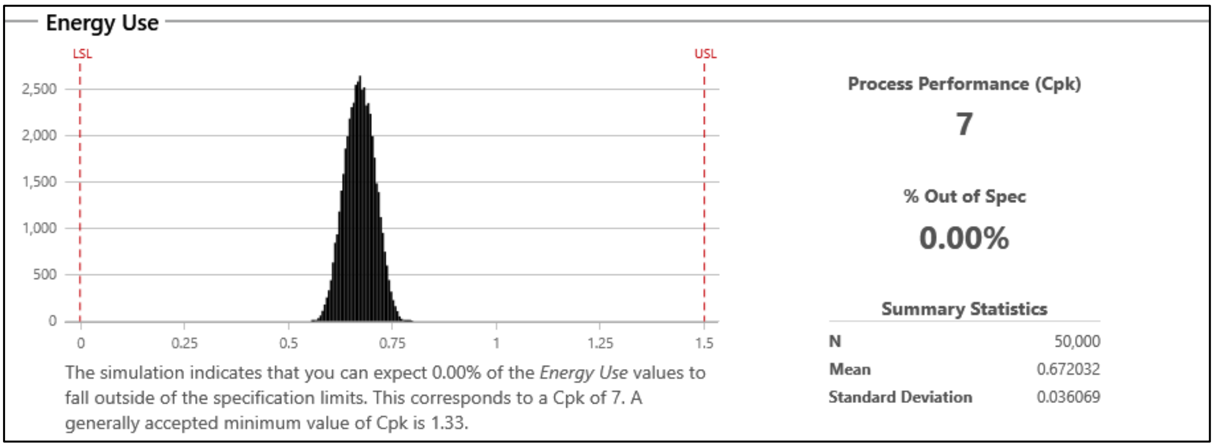
0.00%

Summary Statistics

N	50,000
Mean	0.828386
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Water Use and Pollution* values to fall outside of the specification limits. This corresponds to a Cpk of 7. A generally accepted minimum value of Cpk is 1.33.

Figure B-8: Water Use and Pollution



Process Performance (Cpk)

7

% Out of Spec

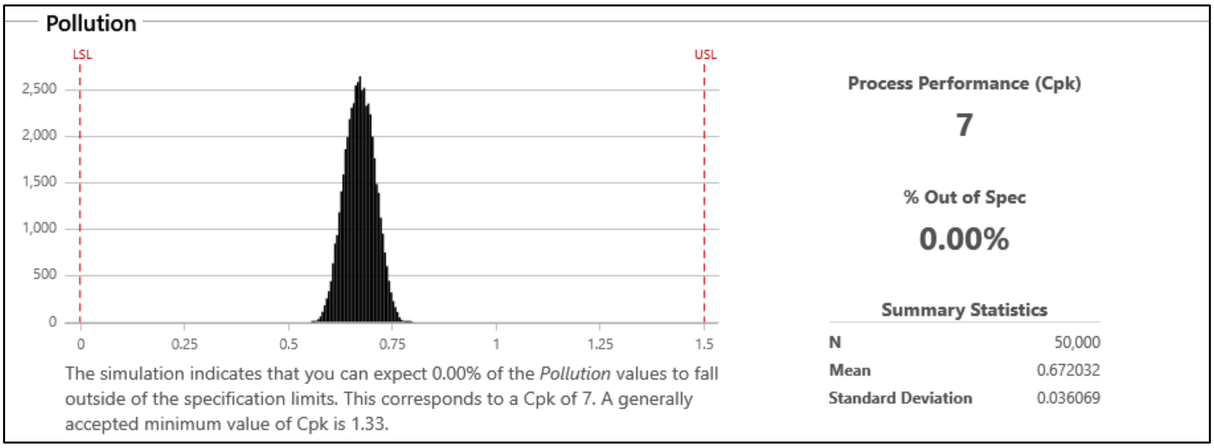
0.00%

Summary Statistics

N	50,000
Mean	0.672032
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Energy Use* values to fall outside of the specification limits. This corresponds to a Cpk of 7. A generally accepted minimum value of Cpk is 1.33.

Figure B-9: Energy Use



Process Performance (Cpk)

7

% Out of Spec

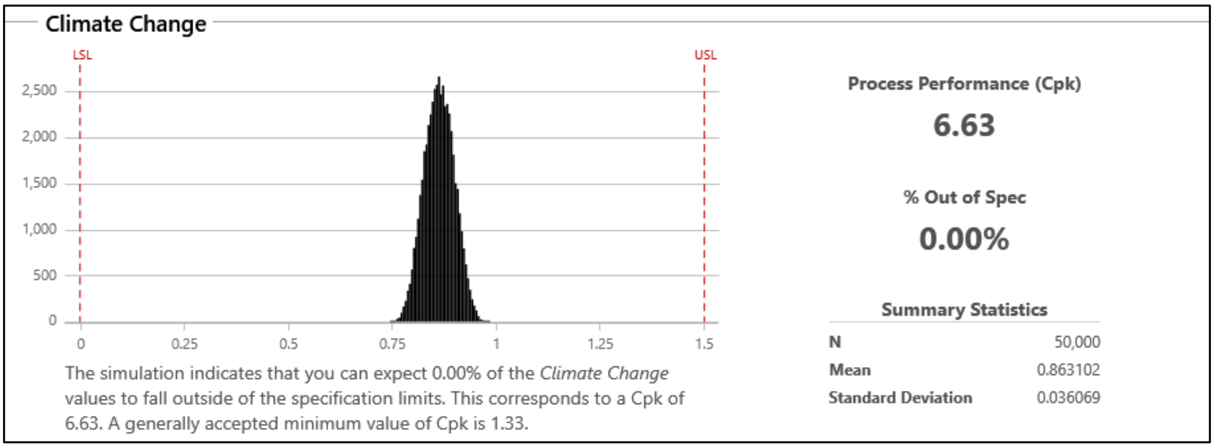
0.00%

Summary Statistics

N	50,000
Mean	0.672032
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Pollution* values to fall outside of the specification limits. This corresponds to a Cpk of 7. A generally accepted minimum value of Cpk is 1.33.

Figure B-10: Pollution



The simulation indicates that you can expect 0.00% of the *Climate Change* values to fall outside of the specification limits. This corresponds to a Cpk of 6.63. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

6.63

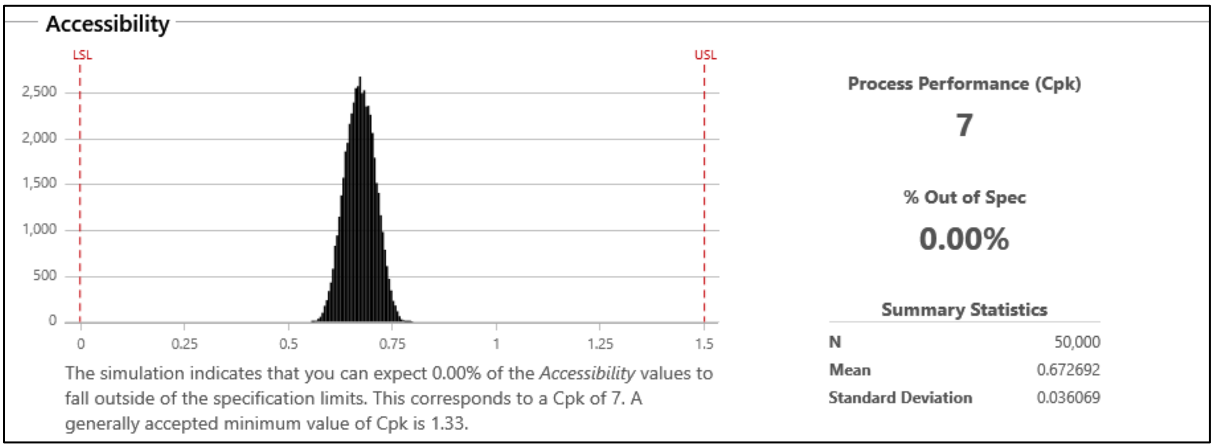
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.863102
Standard Deviation	0.036069

Figure B-11: Climate Change



The simulation indicates that you can expect 0.00% of the *Accessibility* values to fall outside of the specification limits. This corresponds to a Cpk of 7. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

7

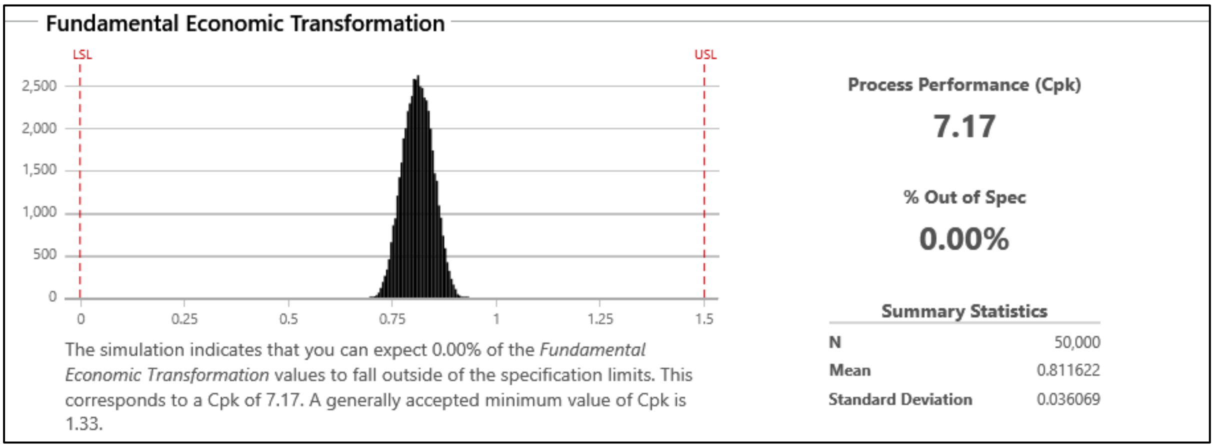
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.672692
Standard Deviation	0.036069

Figure B-12: Accessibility



The simulation indicates that you can expect 0.00% of the *Fundamental Economic Transformation* values to fall outside of the specification limits. This corresponds to a Cpk of 7.17. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

7.17

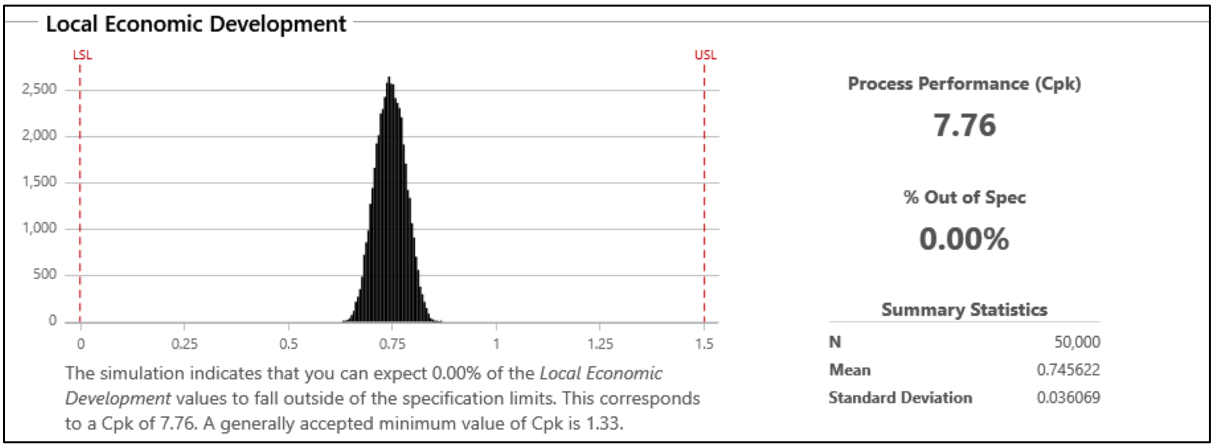
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.811622
Standard Deviation	0.036069

Figure B-13: Fundamental Economic Transformation



Process Performance (Cpk)

7.76

% Out of Spec

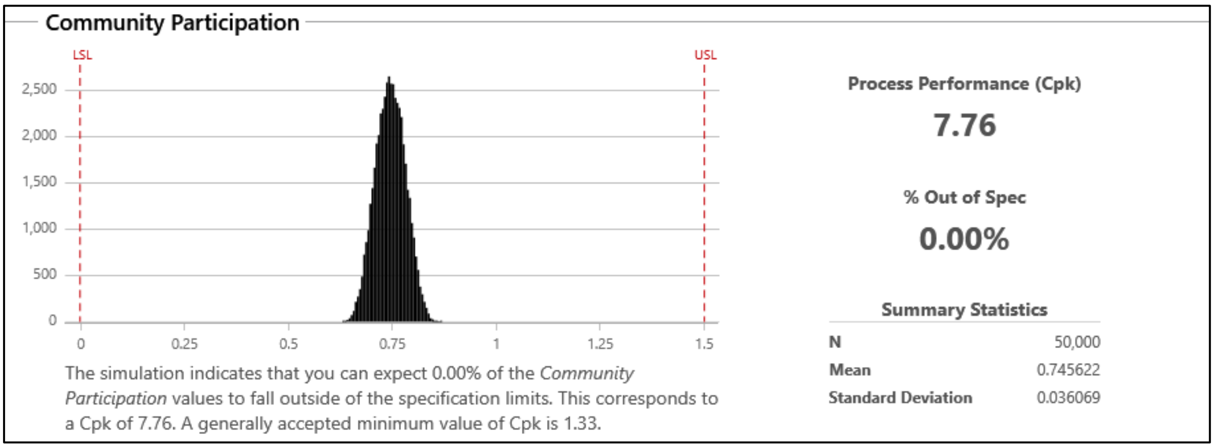
0.00%

Summary Statistics

N	50,000
Mean	0.745622
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Local Economic Development* values to fall outside of the specification limits. This corresponds to a Cpk of 7.76. A generally accepted minimum value of Cpk is 1.33.

Figure B-14: Local Economic Development



Process Performance (Cpk)

7.76

% Out of Spec

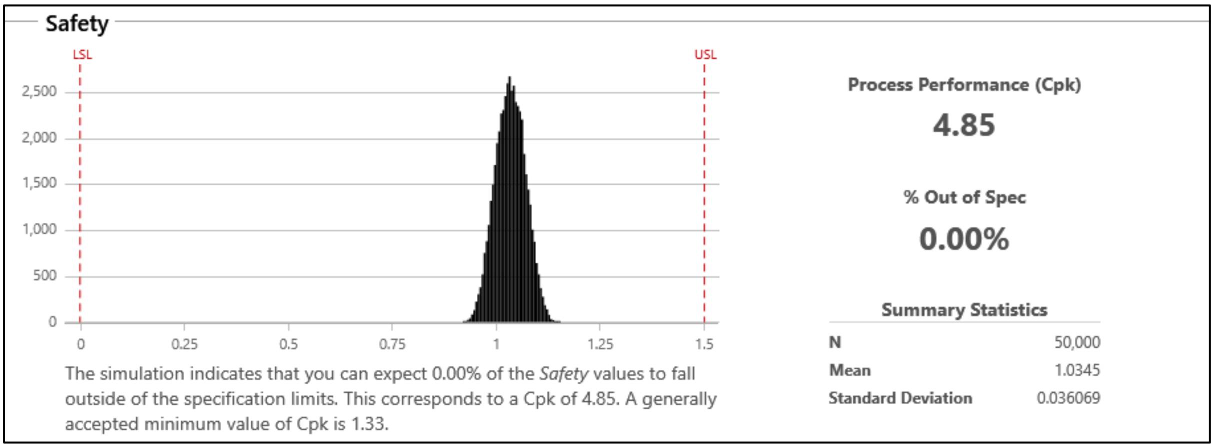
0.00%

Summary Statistics

N	50,000
Mean	0.745622
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Community Participation* values to fall outside of the specification limits. This corresponds to a Cpk of 7.76. A generally accepted minimum value of Cpk is 1.33.

Figure B-15: Community Participation



Process Performance (Cpk)

4.85

% Out of Spec

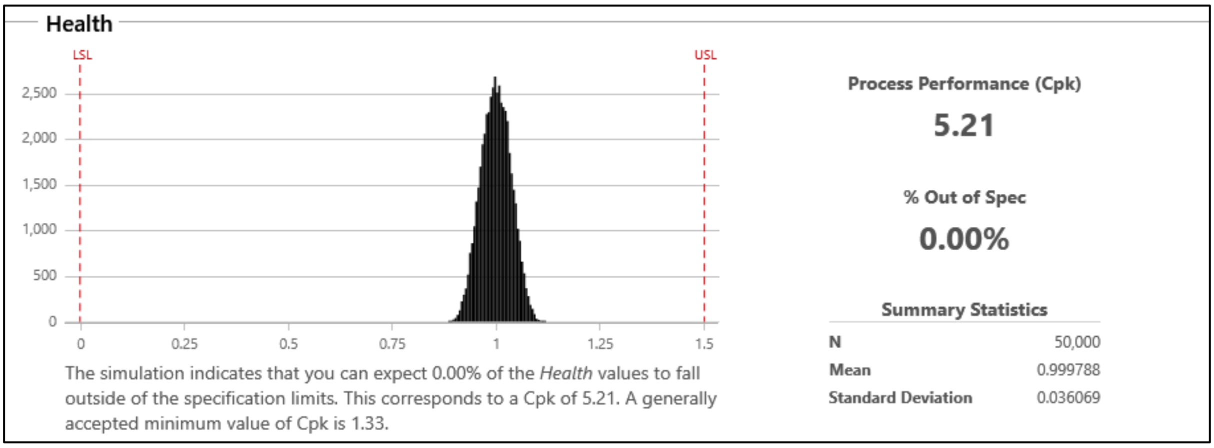
0.00%

Summary Statistics

N	50,000
Mean	1.0345
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Safety* values to fall outside of the specification limits. This corresponds to a Cpk of 4.85. A generally accepted minimum value of Cpk is 1.33.

Figure B-16: Safety



The simulation indicates that you can expect 0.00% of the *Health* values to fall outside of the specification limits. This corresponds to a Cpk of 5.21. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

5.21

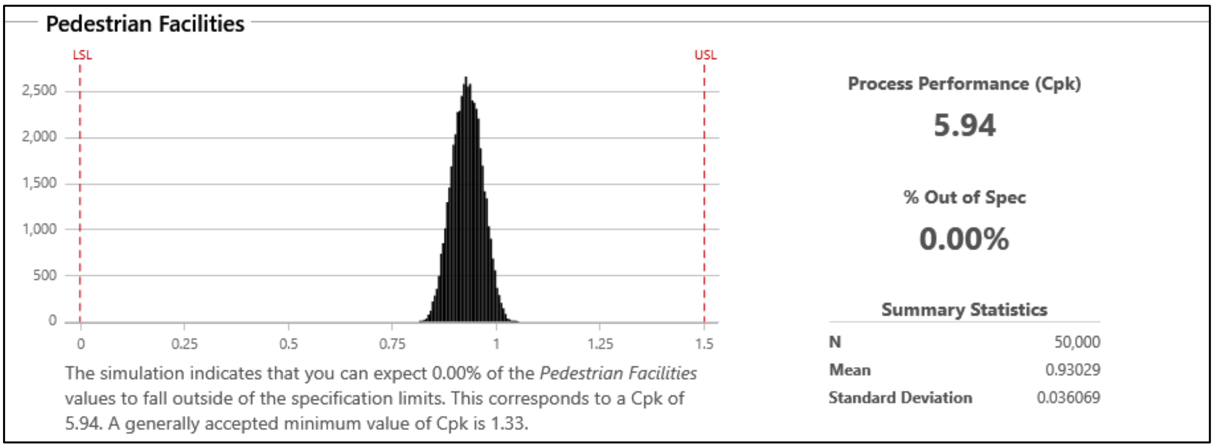
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.999788
Standard Deviation	0.036069

Figure B-17: Health



The simulation indicates that you can expect 0.00% of the *Pedestrian Facilities* values to fall outside of the specification limits. This corresponds to a Cpk of 5.94. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

5.94

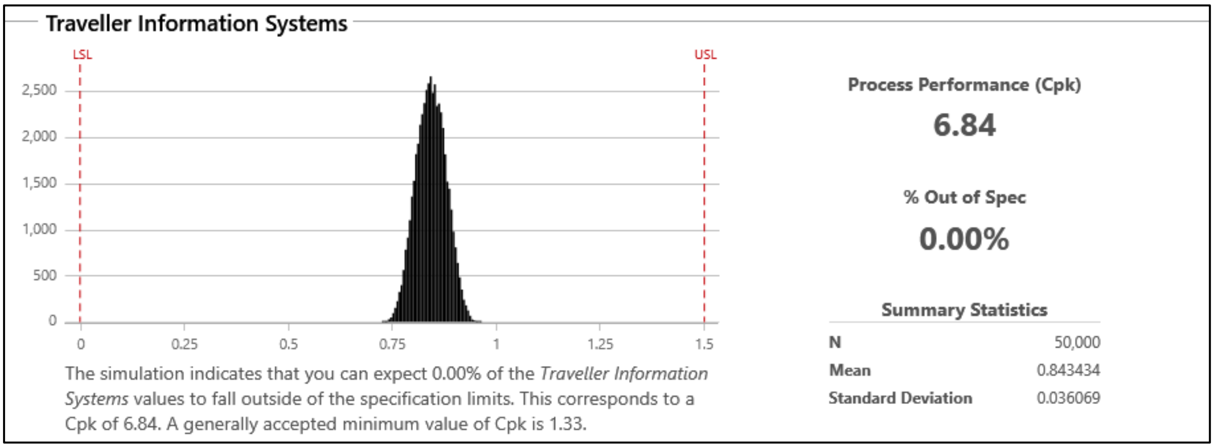
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.93029
Standard Deviation	0.036069

Figure B-18: Pedestrian Facilities



The simulation indicates that you can expect 0.00% of the *Traveller Information Systems* values to fall outside of the specification limits. This corresponds to a Cpk of 6.84. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

6.84

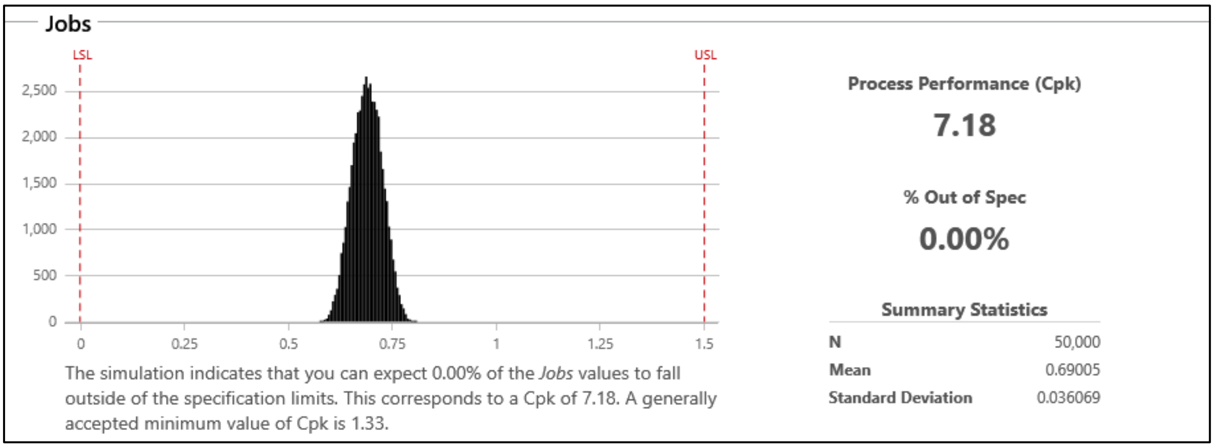
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.843434
Standard Deviation	0.036069

Figure B-19: Traveller Information Systems



Process Performance (Cpk)

7.18

% Out of Spec

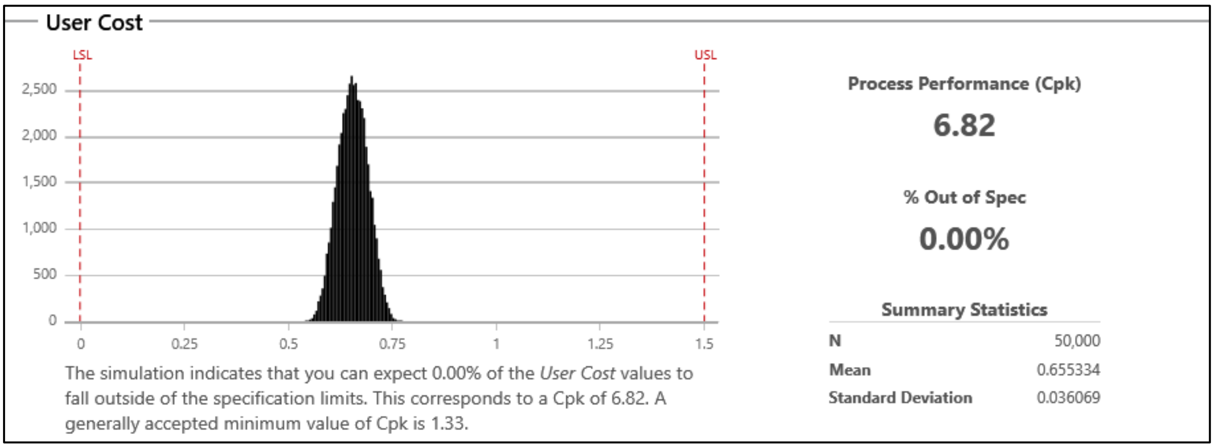
0.00%

Summary Statistics

N	50,000
Mean	0.69005
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Jobs* values to fall outside of the specification limits. This corresponds to a Cpk of 7.18. A generally accepted minimum value of Cpk is 1.33.

Figure B-20: Jobs



Process Performance (Cpk)

6.82

% Out of Spec

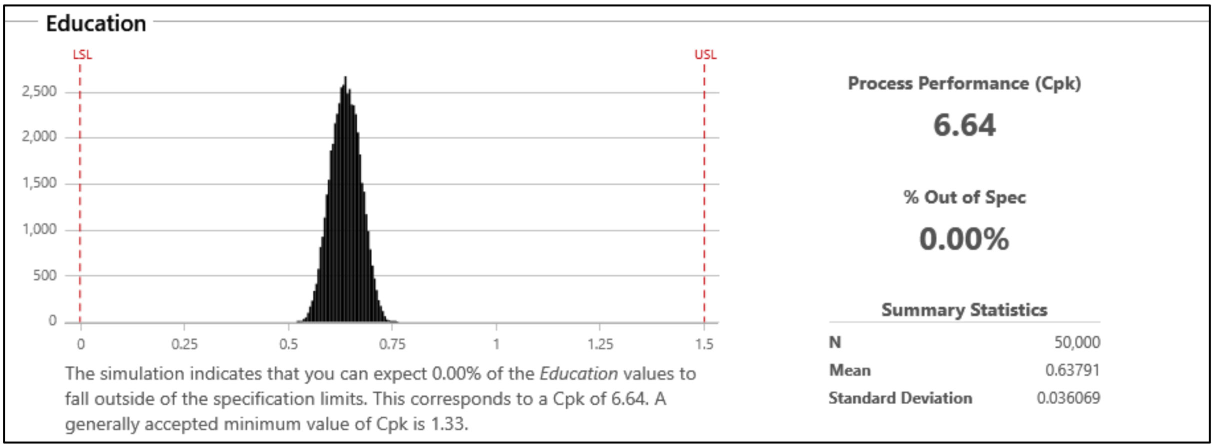
0.00%

Summary Statistics

N	50,000
Mean	0.655334
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *User Cost* values to fall outside of the specification limits. This corresponds to a Cpk of 6.82. A generally accepted minimum value of Cpk is 1.33.

Figure B-21: User Cost



Process Performance (Cpk)

6.64

% Out of Spec

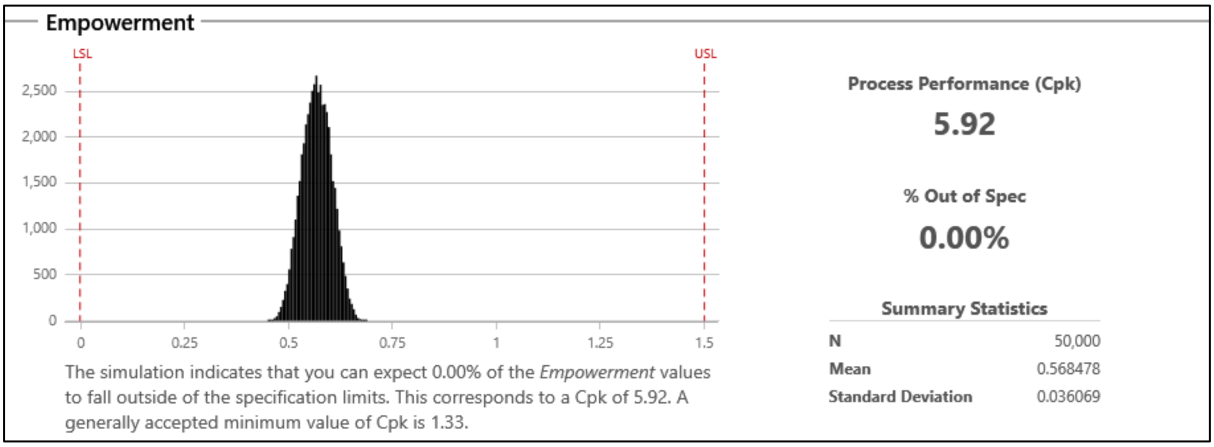
0.00%

Summary Statistics

N	50,000
Mean	0.63791
Standard Deviation	0.036069

The simulation indicates that you can expect 0.00% of the *Education* values to fall outside of the specification limits. This corresponds to a Cpk of 6.64. A generally accepted minimum value of Cpk is 1.33.

Figure B-22: Education



The simulation indicates that you can expect 0.00% of the *Empowerment* values to fall outside of the specification limits. This corresponds to a Cpk of 5.92. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

5.92

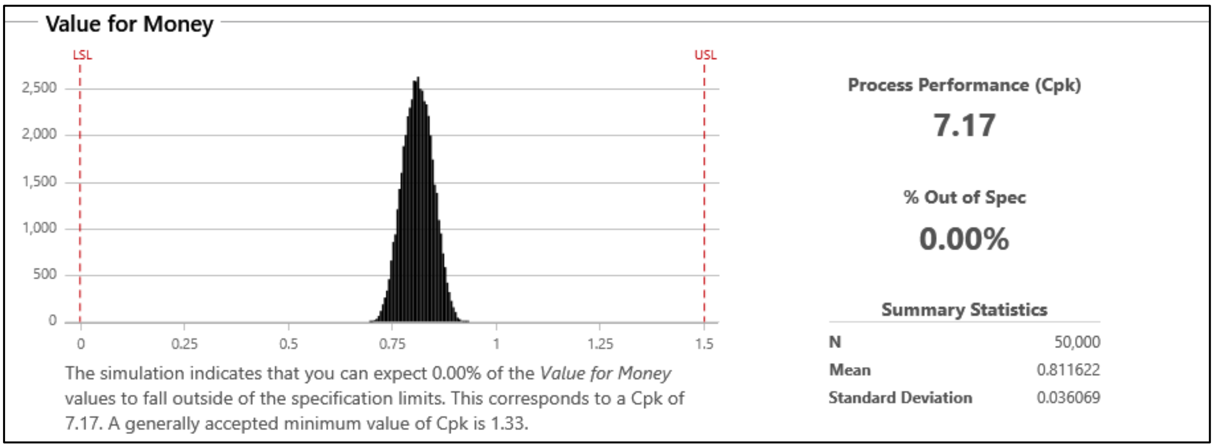
% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.568478
Standard Deviation	0.036069

Figure B-23: Empowerment



The simulation indicates that you can expect 0.00% of the *Value for Money* values to fall outside of the specification limits. This corresponds to a Cpk of 7.17. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

7.17

% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.811622
Standard Deviation	0.036069

Figure B-24: Value for Money

APPENDIX C

CLIMATE CHANGE PAVEMENT DETERIORATION DETAILED RESULTS

Table C-1: Pavement Deterioration Results – ES10 Strong

Section: **ES10 Strong Arid**
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.13	1.76	0	0	0	0	0	0	0.0	0	2.9	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.13	1.79	0	0	0	0	0	0	0.0	0	3.1	1.8	0.68	0.60
2023	10930	0.27	AMGB	4.13	1.81	0	0	0	0	0	0	0.0	0	3.3	1.9	0.67	0.60
2024	11149	0.28	AMGB	4.13	1.84	0	0	0	0	0	0	0.0	0	3.5	2.0	0.67	0.60
2025	11372	0.28	AMGB	4.13	1.87	0	0	0	0	0	0	0.0	0	3.7	2.1	0.67	0.60
2026	11599	0.29	AMGB	4.13	1.90	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.13	1.93	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.13	1.96	0	0	1	1	0	0	0.0	0	4.4	2.4	0.67	0.60
2029	12309	0.31	AMGB	4.13	1.99	1	0	1	1	0	0	0.0	0	4.6	2.5	0.67	0.60
2030	12556	0.31	AMGB	4.13	2.03	1	0	1	2	0	0	0.0	0	4.8	2.6	0.67	0.60
2031	12807	0.32	AMGB	4.13	2.06	1	0	1	3	1	0	0.0	0	5.0	2.7	0.67	0.60
2032	13063	0.32	AMGB	4.13	2.10	2	0	1	3	1	0	0.0	0	5.2	2.8	0.67	0.60
2033	13324	0.33	AMGB	4.13	2.13	3	0	2	4	2	0	0.0	0	5.4	3.0	0.67	0.60
2034	13591	0.34	AMGB	4.12	2.17	4	0	2	6	3	0	0.0	0	5.6	3.0	0.67	0.60
2035	13862	0.34	AMGB	4.12	2.21	5	0	2	7	4	0	0.0	0	5.8	3.2	0.67	0.60
2036	14140	0.35	AMGB	4.12	2.25	6	0	2	8	6	0	0.0	0	6.1	3.3	0.67	0.60
2037	14422	0.36	AMGB	4.12	2.29	7	1	2	9	8	0	0.0	0	6.3	3.3	0.67	0.60
2038	14711	0.36	AMGB	4.12	2.33	7	1	3	10	10	0	0.0	0	6.5	3.5	0.67	0.60
2039	15005	0.37	AMGB	4.12	2.36	7	1	3	10	13	0	0.0	0	6.7	3.5	0.67	0.60
2040	15305	0.38	AMGB	4.12	2.40	7	1	3	10	16	0	0.0	0	6.9	3.6	0.67	0.59
2041	15611	0.39	AMGB	4.12	2.43	7	1	3	10	19	0	0.0	0	7.1	3.7	0.67	0.59
2042	15924	0.39	AMGB	4.12	2.47	7	1	3	11	24	0	0.0	0	7.4	3.8	0.67	0.59
2043	16242	0.40	AMGB	4.12	2.50	7	1	4	11	28	0	0.0	0	7.6	3.9	0.67	0.59
2044	16567	0.41	AMGB	4.12	2.54	7	1	4	11	33	0	0.0	0	7.8	4.0	0.67	0.59
2045	16898	0.42	AMGB	4.12	3.00	7	1	4	11	39	108	0.1	0	8.0	4.1	0.67	0.59

2046	17236	0.43	AMGB	4.12	2.62	7	1	4	12	45	135	0.2	0	8.2	4.2	0.67	0.59
2047	17581	0.44	AMGB	4.12	2.66	7	1	4	12	50	31	0.0	0	8.4	4.3	0.67	0.59
2048	17933	0.44	AMGB	4.12	2.69	7	1	5	12	56	36	0.0	0	8.7	4.4	0.67	0.59
2049	18291	0.45	AMGB	4.12	2.73	7	1	5	12	60	40	0.1	0	8.9	4.4	0.67	0.59
2050	18657	0.46	AMGB	4.12	2.77	7	1	5	12	65	45	0.1	0	9.1	4.5	0.67	0.59

Section: ES10 Strong Arid
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.13	1.76	0	0	0	0	0	0	0.0	0	2.9	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.13	1.79	0	0	0	0	0	0	0.0	0	3.1	1.8	0.68	0.60
2023	10930	0.27	AMGB	4.13	1.81	0	0	0	0	0	0	0.0	0	3.3	1.9	0.67	0.60
2024	11149	0.28	AMGB	4.13	1.84	0	0	0	0	0	0	0.0	0	3.5	2.0	0.67	0.60
2025	11372	0.28	AMGB	4.13	1.87	0	0	0	0	0	0	0.0	0	3.7	2.1	0.67	0.60
2026	11599	0.29	AMGB	4.13	1.90	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.13	1.93	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.13	1.96	0	0	1	1	0	0	0.0	0	4.4	2.4	0.67	0.60
2029	12309	0.31	AMAP	4.84	1.62	0	0	0	0	0	0	0.0	0	0.2	2.5	0.68	0.52
2030	12556	0.31	AMAP	4.84	1.64	0	0	0	0	0	0	0.0	0	0.3	2.6	0.68	0.52
2031	12807	0.32	AMAP	4.84	1.67	0	0	0	0	0	0	0.0	0	0.5	2.8	0.67	0.52
2032	13063	0.32	AMAP	4.84	1.69	0	0	0	0	0	0	0.0	0	0.7	2.9	0.67	0.52
2033	13324	0.33	AMAP	4.84	1.71	0	0	0	0	0	0	0.0	0	0.9	3.0	0.67	0.52
2034	13591	0.34	AMAP	4.84	1.74	0	0	0	0	0	0	0.0	0	1.1	3.1	0.67	0.52
2035	13862	0.34	AMAP	4.84	1.76	0	0	0	0	0	0	0.0	0	1.2	3.2	0.67	0.52
2036	14140	0.35	AMAP	4.84	1.79	0	0	1	1	0	0	0.0	0	1.4	3.3	0.67	0.52
2037	14422	0.36	AMAP	5.54	1.62	0	0	0	0	0	0	0.0	0	0.2	3.4	0.68	0.52
2038	14711	0.36	AMAP	5.54	1.64	0	0	0	0	0	0	0.0	0	0.3	3.5	0.68	0.52
2039	15005	0.37	AMAP	5.54	1.66	0	0	0	0	0	0	0.0	0	0.5	3.6	0.67	0.52
2040	15305	0.38	AMAP	5.54	1.68	0	0	0	0	0	0	0.0	0	0.6	3.7	0.67	0.52
2041	15611	0.39	AMAP	5.54	1.70	0	0	0	0	0	0	0.0	0	0.8	3.8	0.67	0.52

2042	15924	0.39	AMAP	5.54	1.72	0	0	0	0	0	0	0.0	0	0.9	3.9	0.67	0.52
2043	16242	0.40	AMAP	5.54	1.74	0	0	0	0	0	0	0.0	0	1.1	4.0	0.67	0.52
2044	16567	0.41	AMAP	5.54	1.76	0	0	1	1	0	0	0.0	0	1.2	4.1	0.67	0.52
2045	16898	0.42	AMAP	6.25	1.62	0	0	0	0	0	0	0.0	0	0.1	4.2	0.68	0.52
2046	17236	0.43	AMAP	6.25	1.63	0	0	0	0	0	0	0.0	0	0.3	4.3	0.67	0.52
2047	17581	0.44	AMAP	6.25	1.65	0	0	0	0	0	0	0.0	0	0.4	4.3	0.67	0.52
2048	17933	0.44	AMAP	6.25	1.67	0	0	0	0	0	0	0.0	0	0.6	4.4	0.67	0.52
2049	18291	0.45	AMAP	6.25	1.69	0	0	0	0	0	0	0.0	0	0.7	4.5	0.67	0.52
2050	18657	0.46	AMAP	6.25	1.70	0	0	0	0	0	0	0.0	0	0.8	4.6	0.67	0.52

Section: ES10 strong semi arid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.20	1.76	0	0	0	0	0	0	0.0	0	2.8	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.19	1.80	0	0	0	0	0	0	0.0	0	3.0	1.7	0.68	0.60
2023	10930	0.27	AMGB	4.18	1.83	0	0	0	0	0	0	0.0	0	3.3	1.8	0.67	0.60
2024	11149	0.28	AMGB	4.18	1.86	0	0	0	0	0	0	0.0	0	3.5	2.0	0.67	0.60
2025	11372	0.28	AMGB	4.17	1.90	0	0	0	0	0	0	0.0	0	3.7	2.1	0.67	0.60
2026	11599	0.29	AMGB	4.16	1.93	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.16	1.97	0	0	0	0	0	0	0.0	0	4.1	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.16	2.01	1	0	0	1	0	0	0.0	0	4.3	2.4	0.67	0.60
2029	12309	0.31	AMGB	4.15	2.05	1	0	0	1	0	0	0.0	0	4.5	2.5	0.67	0.60
2030	12556	0.31	AMGB	4.15	2.09	2	0	0	2	0	0	0.0	0	4.7	2.6	0.67	0.60
2031	12807	0.32	AMGB	4.15	2.14	3	0	1	4	1	0	0.0	0	4.9	2.7	0.67	0.60
2032	13063	0.32	AMGB	4.14	2.19	5	0	1	5	2	0	0.0	0	5.1	2.8	0.67	0.60
2033	13324	0.33	AMGB	4.14	2.24	6	0	1	7	5	0	0.0	0	5.3	2.9	0.67	0.60
2034	13591	0.34	AMGB	4.13	2.29	8	1	1	9	8	0	0.0	0	5.6	3.0	0.67	0.60
2035	13862	0.34	AMGB	4.12	2.34	9	1	1	10	12	0	0.0	0	5.8	3.1	0.67	0.60
2036	14140	0.35	AMGB	4.12	2.39	10	1	2	11	17	0	0.0	0	6.0	3.2	0.67	0.60
2037	14422	0.36	AMGB	4.12	2.44	11	1	2	12	24	0	0.0	0	6.2	3.3	0.67	0.60
2038	14711	0.36	AMGB	4.11	2.49	12	1	2	14	31	0	0.0	0	6.4	3.4	0.67	0.60

2039	15005	0.37	AMGB	4.11	2.94	13	1	2	15	41	102	0.1	0	6.6	3.5	0.67	0.60
2040	15305	0.38	AMGB	4.10	2.60	14	1	2	17	51	131	0.2	0	6.8	3.6	0.67	0.59
2041	15611	0.39	AMGB	4.10	2.66	16	1	3	18	60	36	0.0	0	7.1	3.7	0.67	0.59
2042	15924	0.39	AMGB	4.09	2.72	17	1	3	20	68	43	0.1	0	7.3	3.8	0.67	0.59
2043	16242	0.40	AMGB	4.08	2.78	19	1	3	22	74	49	0.1	0	7.5	3.9	0.67	0.59
2044	16567	0.41	AMGB	4.07	2.84	21	1	3	24	76	55	0.1	0	7.7	4.0	0.67	0.59
2045	16898	0.42	AMGB	4.06	2.91	23	1	3	26	74	57	0.1	0	8.0	4.1	0.67	0.59
2046	17236	0.43	AMGB	4.06	2.98	25	1	4	28	71	57	0.1	0	8.2	4.2	0.67	0.59
2047	17581	0.44	AMGB	4.04	3.05	27	1	4	31	69	56	0.1	0	8.4	4.3	0.67	0.59
2048	17933	0.44	AMGB	4.03	3.12	30	1	4	34	66	55	0.1	0	8.6	4.4	0.67	0.59
2049	18291	0.45	AMGB	4.02	3.19	32	1	4	37	63	54	0.1	0	8.9	4.4	0.67	0.59
2050	18657	0.46	AMGB	4.01	3.27	35	1	4	40	60	53	0.1	0	9.1	4.5	0.67	0.59

Section: ES10 strong semi arid
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.20	1.76	0	0	0	0	0	0	0.0	0	2.8	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.19	1.80	0	0	0	0	0	0	0.0	0	3.0	1.7	0.68	0.60
2023	10930	0.27	AMGB	4.18	1.83	0	0	0	0	0	0	0.0	0	3.3	1.8	0.67	0.60
2024	11149	0.28	AMGB	4.18	1.86	0	0	0	0	0	0	0.0	0	3.5	2.0	0.67	0.60
2025	11372	0.28	AMGB	4.17	1.90	0	0	0	0	0	0	0.0	0	3.7	2.1	0.67	0.60
2026	11599	0.29	AMGB	4.16	1.93	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.16	1.97	0	0	0	0	0	0	0.0	0	4.1	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.16	2.01	1	0	0	1	0	0	0.0	0	4.3	2.4	0.67	0.60
2029	12309	0.31	AMAP	4.85	1.63	0	0	0	0	0	0	0.0	0	0.2	2.5	0.68	0.52
2030	12556	0.31	AMAP	4.85	1.66	0	0	0	0	0	0	0.0	0	0.3	2.6	0.68	0.52
2031	12807	0.32	AMAP	4.85	1.68	0	0	0	0	0	0	0.0	0	0.5	2.7	0.67	0.52
2032	13063	0.32	AMAP	4.85	1.71	0	0	0	0	0	0	0.0	0	0.7	2.8	0.67	0.52
2033	13324	0.33	AMAP	4.85	1.74	0	0	0	0	0	0	0.0	0	0.9	3.0	0.67	0.52
2034	13591	0.34	AMAP	4.85	1.77	0	0	0	0	0	0	0.0	0	1.1	3.1	0.67	0.52
2035	13862	0.34	AMAP	4.85	1.80	0	0	0	0	0	0	0.0	0	1.2	3.2	0.67	0.52

2036	14140	0.35	AMAP	4.85	1.83	0	0	0	0	0	0	0.0	0	1.4	3.3	0.67	0.52
2037	14422	0.36	AMAP	5.54	1.62	0	0	0	0	0	0	0.0	0	0.2	3.4	0.68	0.52
2038	14711	0.36	AMAP	5.54	1.65	0	0	0	0	0	0	0.0	0	0.3	3.5	0.68	0.52
2039	15005	0.37	AMAP	5.54	1.68	0	0	0	0	0	0	0.0	0	0.5	3.6	0.67	0.52
2040	15305	0.38	AMAP	5.54	1.70	0	0	0	0	0	0	0.0	0	0.6	3.7	0.67	0.52
2041	15611	0.39	AMAP	5.54	1.73	0	0	0	0	0	0	0.0	0	0.8	3.8	0.67	0.52
2042	15924	0.39	AMAP	5.54	1.75	0	0	0	0	0	0	0.0	0	0.9	3.9	0.67	0.52
2043	16242	0.40	AMAP	5.54	1.78	0	0	0	0	0	0	0.0	0	1.1	4.0	0.67	0.52
2044	16567	0.41	AMAP	5.54	1.81	0	0	0	0	0	0	0.0	0	1.2	4.1	0.67	0.52
2045	16898	0.42	AMAP	6.23	1.62	0	0	0	0	0	0	0.0	0	0.1	4.1	0.68	0.52
2046	17236	0.43	AMAP	6.23	1.65	0	0	0	0	0	0	0.0	0	0.3	4.2	0.67	0.52
2047	17581	0.44	AMAP	6.23	1.67	0	0	0	0	0	0	0.0	0	0.4	4.3	0.67	0.52
2048	17933	0.44	AMAP	6.23	1.69	0	0	0	0	0	0	0.0	0	0.6	4.4	0.67	0.52
2049	18291	0.45	AMAP	6.23	1.72	0	0	0	0	0	0	0.0	0	0.7	4.5	0.67	0.52
2050	18657	0.46	AMAP	6.23	1.74	0	0	0	0	0	0	0.0	0	0.8	4.6	0.67	0.52

Section: ES10strong subhumid dry
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.18	1.78	0	0	0	0	0	0	0.0	0	2.9	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.17	1.83	0	0	0	0	0	0	0.0	0	3.1	1.7	0.68	0.60
2023	10930	0.27	AMGB	4.15	1.89	0	0	0	0	0	0	0.0	0	3.3	1.8	0.67	0.60
2024	11149	0.28	AMGB	4.14	1.94	0	0	0	0	0	0	0.0	0	3.5	2.0	0.67	0.60
2025	11372	0.28	AMGB	4.12	2.00	0	0	0	0	0	0	0.0	0	3.7	2.1	0.67	0.60
2026	11599	0.29	AMGB	4.11	2.06	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.11	2.12	1	0	0	1	0	0	0.0	0	4.1	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.10	2.19	1	0	0	1	0	0	0.0	0	4.3	2.4	0.67	0.60
2029	12309	0.31	AMGB	4.10	2.26	3	0	0	3	0	0	0.0	0	4.5	2.5	0.67	0.60
2030	12556	0.31	AMGB	4.09	2.34	4	0	0	4	0	0	0.0	0	4.7	2.6	0.67	0.60
2031	12807	0.32	AMGB	4.08	2.42	6	0	0	6	1	0	0.0	0	5.0	2.7	0.67	0.60
2032	13063	0.32	AMGB	4.07	2.51	9	2	0	9	3	0	0.0	0	5.2	2.8	0.67	0.60

2033	13324	0.33	AMGB	4.06	2.59	10	2	0	10	6	0	0.0	0	5.4	2.9	0.67	0.60
2034	13591	0.34	AMGB	4.05	2.67	11	2	0	11	11	0	0.0	0	5.6	3.0	0.67	0.60
2035	13862	0.34	AMGB	4.04	2.76	13	2	0	13	17	0	0.0	0	5.8	3.2	0.67	0.60
2036	14140	0.35	AMGB	4.03	2.85	15	2	0	15	24	0	0.0	0	6.1	3.3	0.67	0.60
2037	14422	0.36	AMGB	4.02	2.94	17	2	0	17	34	0	0.0	0	6.3	3.3	0.67	0.60
2038	14711	0.36	AMGB	4.01	3.50	19	2	0	19	46	114	0.2	0	6.5	3.5	0.67	0.60
2039	15005	0.37	AMGB	3.99	3.16	21	2	0	21	58	148	0.2	0	6.7	3.6	0.67	0.60
2040	15305	0.38	AMGB	3.98	3.26	24	2	0	24	68	42	0.1	0	6.9	3.7	0.67	0.59
2041	15611	0.39	AMGB	3.96	3.38	27	2	0	27	73	50	0.1	0	7.2	3.8	0.67	0.59
2042	15924	0.39	AMGB	3.94	3.50	30	2	0	30	70	54	0.1	0	7.4	3.9	0.67	0.59
2043	16242	0.40	AMGB	3.91	3.62	34	2	0	34	66	53	0.1	0	7.7	4.0	0.67	0.59
2044	16567	0.41	AMGB	3.89	3.76	37	2	0	37	63	51	0.1	0	7.9	4.1	0.67	0.59
2045	16898	0.42	AMGB	3.86	3.89	42	2	0	42	58	49	0.1	0	8.1	4.2	0.67	0.59
2046	17236	0.43	AMGB	3.83	4.04	46	2	0	46	54	47	0.1	0	8.4	4.3	0.67	0.59
2047	17581	0.44	AMGB	3.79	4.19	51	2	0	51	49	44	0.1	0	8.6	4.3	0.67	0.59
2048	17933	0.44	AMGB	3.76	4.34	55	2	0	55	45	41	0.1	0	8.9	4.4	0.67	0.59
2049	18291	0.45	AMGB	3.73	4.50	59	2	0	59	41	38	0.1	0	9.1	4.5	0.67	0.59
2050	18657	0.46	AMGB	3.70	4.66	62	2	0	62	38	36	0.0	0	9.4	4.6	0.67	0.59

Section: ES10strong subhumid dry
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.18	1.78	0	0	0	0	0	0	0.0	0	2.9	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.17	1.83	0	0	0	0	0	0	0.0	0	3.1	1.7	0.68	0.60
2023	10930	0.27	AMGB	4.15	1.89	0	0	0	0	0	0	0.0	0	3.3	1.8	0.67	0.60
2024	11149	0.28	AMGB	4.14	1.94	0	0	0	0	0	0	0.0	0	3.5	2.0	0.67	0.60
2025	11372	0.28	AMGB	4.12	2.00	0	0	0	0	0	0	0.0	0	3.7	2.1	0.67	0.60
2026	11599	0.29	AMGB	4.11	2.06	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.11	2.12	1	0	0	1	0	0	0.0	0	4.1	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.10	2.19	1	0	0	1	0	0	0.0	0	4.3	2.4	0.67	0.60
2029	12309	0.31	AMAP	4.78	1.65	0	0	0	0	0	0	0.0	0	0.2	2.5	0.68	0.52

2030	12556	0.31	AMAP	4.78	1.69	0	0	0	0	0	0	0.0	0	0.4	2.6	0.68	0.52
2031	12807	0.32	AMAP	4.78	1.74	0	0	0	0	0	0	0.0	0	0.5	2.7	0.67	0.52
2032	13063	0.32	AMAP	4.78	1.79	0	0	0	0	0	0	0.0	0	0.7	2.8	0.67	0.52
2033	13324	0.33	AMAP	4.78	1.84	0	0	0	0	0	0	0.0	0	0.9	3.0	0.67	0.52
2034	13591	0.34	AMAP	4.78	1.89	0	0	0	0	0	0	0.0	0	1.1	3.1	0.67	0.52
2035	13862	0.34	AMAP	4.78	1.94	0	0	0	0	0	0	0.0	0	1.3	3.2	0.67	0.52
2036	14140	0.35	AMAP	4.78	2.00	1	0	0	1	0	0	0.0	0	1.4	3.3	0.67	0.52
2037	14422	0.36	AMAP	5.46	1.64	0	0	0	0	0	0	0.0	0	0.2	3.4	0.68	0.52
2038	14711	0.36	AMAP	5.46	1.69	0	0	0	0	0	0	0.0	0	0.3	3.5	0.68	0.52
2039	15005	0.37	AMAP	5.46	1.73	0	0	0	0	0	0	0.0	0	0.5	3.6	0.67	0.52
2040	15305	0.38	AMAP	5.46	1.78	0	0	0	0	0	0	0.0	0	0.6	3.7	0.67	0.52
2041	15611	0.39	AMAP	5.46	1.82	0	0	0	0	0	0	0.0	0	0.8	3.8	0.67	0.52
2042	15924	0.39	AMAP	5.46	1.87	0	0	0	0	0	0	0.0	0	0.9	3.9	0.67	0.52
2043	16242	0.40	AMAP	5.46	1.92	0	0	0	0	0	0	0.0	0	1.1	4.0	0.67	0.52
2044	16567	0.41	AMAP	5.46	1.97	0	0	0	0	0	0	0.0	0	1.3	4.1	0.67	0.52
2045	16898	0.42	AMAP	6.13	1.64	0	0	0	0	0	0	0.0	0	0.1	4.2	0.68	0.52
2046	17236	0.43	AMAP	6.13	1.68	0	0	0	0	0	0	0.0	0	0.3	4.3	0.67	0.52
2047	17581	0.44	AMAP	6.13	1.72	0	0	0	0	0	0	0.0	0	0.4	4.3	0.67	0.52
2048	17933	0.44	AMAP	6.13	1.77	0	0	0	0	0	0	0.0	0	0.6	4.4	0.67	0.52
2049	18291	0.45	AMAP	6.13	1.81	0	0	0	0	0	0	0.0	0	0.7	4.5	0.67	0.52
2050	18657	0.46	AMAP	6.13	1.85	0	0	0	0	0	0	0.0	0	0.8	4.6	0.67	0.52

Section: ES10 strong Subhumidwet
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.21	1.77	0	0	0	0	0	0	0.0	0	2.8	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.19	1.82	0	0	0	0	0	0	0.0	0	3.0	1.7	0.68	0.60
2023	10930	0.27	AMGB	4.17	1.87	0	0	0	0	0	0	0.0	0	3.2	1.8	0.67	0.60
2024	11149	0.28	AMGB	4.15	1.92	0	0	0	0	0	0	0.0	0	3.5	1.9	0.67	0.60
2025	11372	0.28	AMGB	4.13	1.97	0	0	0	0	0	0	0.0	0	3.7	2.0	0.67	0.60
2026	11599	0.29	AMGB	4.11	2.02	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60

2027	11831	0.29	AMGB	4.11	2.08	1	0	0	1	0	0	0.0	0	4.1	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.10	2.15	3	0	0	3	0	0	0.0	0	4.3	2.4	0.67	0.60
2029	12309	0.31	AMGB	4.09	2.22	5	0	0	5	0	0	0.0	0	4.5	2.5	0.67	0.60
2030	12556	0.31	AMGB	4.07	2.30	9	2	0	9	0	0	0.0	0	4.7	2.6	0.67	0.60
2031	12807	0.32	AMGB	4.05	2.37	10	3	0	10	2	0	0.0	0	4.9	2.7	0.67	0.60
2032	13063	0.32	AMGB	4.04	2.44	12	3	0	12	5	0	0.0	0	5.2	2.8	0.67	0.60
2033	13324	0.33	AMGB	4.03	2.52	14	3	0	14	11	0	0.0	0	5.4	2.9	0.67	0.60
2034	13591	0.34	AMGB	4.01	2.61	17	3	0	17	21	0	0.0	0	5.6	3.0	0.67	0.60
2035	13862	0.34	AMGB	3.98	2.69	20	3	0	20	34	0	0.0	0	5.8	3.1	0.67	0.60
2036	14140	0.35	AMGB	3.96	3.28	24	3	0	24	52	118	0.2	0	6.0	3.3	0.67	0.60
2037	14422	0.36	AMGB	3.92	2.90	28	3	0	28	69	157	0.2	0	6.3	3.4	0.67	0.60
2038	14711	0.36	AMGB	3.88	3.01	33	3	0	33	67	50	0.1	0	6.5	3.5	0.67	0.60
2039	15005	0.37	AMGB	3.84	3.13	39	3	0	39	61	50	0.1	0	6.8	3.6	0.67	0.60
2040	15305	0.38	AMGB	3.78	3.26	45	3	0	45	55	47	0.1	0	7.0	3.7	0.67	0.59
2041	15611	0.39	AMGB	3.72	3.39	52	3	0	52	48	43	0.1	0	7.3	3.8	0.67	0.59
2042	15924	0.39	AMGB	3.66	3.53	58	3	0	58	42	38	0.1	0	7.5	3.9	0.67	0.59
2043	16242	0.40	AMGB	3.59	3.67	64	3	0	64	36	34	0.0	0	7.8	4.0	0.67	0.59
2044	16567	0.41	AMGB	3.54	3.81	69	3	0	69	31	30	0.0	0	8.1	4.1	0.67	0.59
2045	16898	0.42	AMGB	3.48	3.95	73	3	0	73	27	26	0.0	0	8.4	4.2	0.67	0.59
2046	17236	0.43	AMGB	3.44	4.10	77	3	0	77	23	23	0.0	0	8.6	4.4	0.67	0.59
2047	17581	0.44	AMGB	3.40	4.25	81	3	0	81	19	20	0.0	0	8.9	4.5	0.67	0.59
2048	17933	0.44	AMGB	3.36	4.40	83	3	0	83	17	17	0.0	0	9.2	4.6	0.67	0.59
2049	18291	0.45	AMGB	3.33	4.55	86	3	0	86	14	15	0.0	0	9.5	4.7	0.67	0.59
2050	18657	0.46	AMGB	3.30	4.71	88	3	0	88	12	13	0.0	0	9.9	4.8	0.67	0.59

Section: ES10 strong Subhumidwet
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.21	1.77	0	0	0	0	0	0	0.0	0	2.8	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.19	1.82	0	0	0	0	0	0	0.0	0	3.0	1.7	0.68	0.60
2023	10930	0.27	AMGB	4.17	1.87	0	0	0	0	0	0	0.0	0	3.2	1.8	0.67	0.60

2024	11149	0.28	AMGB	4.15	1.92	0	0	0	0	0	0	0.0	0	3.5	1.9	0.67	0.60
2025	11372	0.28	AMGB	4.13	1.97	0	0	0	0	0	0	0.0	0	3.7	2.0	0.67	0.60
2026	11599	0.29	AMGB	4.11	2.02	0	0	0	0	0	0	0.0	0	3.9	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.11	2.08	1	0	0	1	0	0	0.0	0	4.1	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.10	2.15	3	0	0	3	0	0	0.0	0	4.3	2.4	0.67	0.60
2029	12309	0.31	AMAP	4.77	1.64	0	0	0	0	0	0	0.0	0	0.2	2.5	0.68	0.52
2030	12556	0.31	AMAP	4.77	1.68	0	0	0	0	0	0	0.0	0	0.4	2.6	0.68	0.52
2031	12807	0.32	AMAP	4.77	1.73	0	0	0	0	0	0	0.0	0	0.5	2.7	0.67	0.52
2032	13063	0.32	AMAP	4.77	1.77	0	0	0	0	0	0	0.0	0	0.7	2.8	0.67	0.52
2033	13324	0.33	AMAP	4.77	1.81	0	0	0	0	0	0	0.0	0	0.9	3.0	0.67	0.52
2034	13591	0.34	AMAP	4.77	1.86	0	0	0	0	0	0	0.0	0	1.1	3.1	0.67	0.52
2035	13862	0.34	AMAP	4.77	1.90	0	0	0	0	0	0	0.0	0	1.3	3.2	0.67	0.52
2036	14140	0.35	AMAP	4.77	1.96	1	0	0	1	0	0	0.0	0	1.4	3.3	0.67	0.52
2037	14422	0.36	AMAP	5.44	1.64	0	0	0	0	0	0	0.0	0	0.2	3.4	0.68	0.52
2038	14711	0.36	AMAP	5.44	1.68	0	0	0	0	0	0	0.0	0	0.3	3.5	0.68	0.52
2039	15005	0.37	AMAP	5.44	1.72	0	0	0	0	0	0	0.0	0	0.5	3.6	0.67	0.52
2040	15305	0.38	AMAP	5.44	1.75	0	0	0	0	0	0	0.0	0	0.6	3.7	0.67	0.52
2041	15611	0.39	AMAP	5.44	1.80	0	0	0	0	0	0	0.0	0	0.8	3.8	0.67	0.52
2042	15924	0.39	AMAP	5.44	1.84	0	0	0	0	0	0	0.0	0	0.9	3.9	0.67	0.52
2043	16242	0.40	AMAP	5.44	1.88	0	0	0	0	0	0	0.0	0	1.1	4.0	0.67	0.52
2044	16567	0.41	AMAP	5.44	1.92	1	0	0	1	0	0	0.0	0	1.3	4.1	0.67	0.52
2045	16898	0.42	AMAP	6.10	1.64	0	0	0	0	0	0	0.0	0	0.1	4.2	0.68	0.52
2046	17236	0.43	AMAP	6.10	1.67	0	0	0	0	0	0	0.0	0	0.3	4.3	0.67	0.52
2047	17581	0.44	AMAP	6.10	1.71	0	0	0	0	0	0	0.0	0	0.4	4.3	0.67	0.52
2048	17933	0.44	AMAP	6.10	1.75	0	0	0	0	0	0	0.0	0	0.6	4.4	0.67	0.52
2049	18291	0.45	AMAP	6.10	1.78	0	0	0	0	0	0	0.0	0	0.7	4.5	0.67	0.52
2050	18657	0.46	AMAP	6.10	1.82	0	0	0	0	0	0	0.0	0	0.8	4.6	0.67	0.52
2047	17581	0.44	AMGB	3.18	8.51	80	3	0	80	20	22	0.0	0	9.1	4.5	0.67	0.59
2048	17933	0.44	AMGB	3.14	9.08	83	3	0	83	17	19	0.0	0	9.4	4.7	0.67	0.59
2049	18291	0.45	AMGB	3.10	9.69	86	3	0	86	14	17	0.0	0	9.8	4.8	0.67	0.59
2050	18657	0.46	AMGB	3.06	10.35	88	3	0	88	12	15	0.0	0	10.1	4.9	0.67	0.59

Section: ES10 strong humid
Alternative: Full maintenance
Sensitivity: No Sensitivity Analysis Conducted

End of Year Condition

Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	4.24	1.82	0	0	0	0	0	0	0.0	0	2.8	1.6	0.68	0.60
2022	10716	0.27	AMGB	4.21	1.92	0	0	0	0	0	0	0.0	0	3.0	1.7	0.68	0.60
2023	10930	0.27	AMGB	4.17	2.03	0	0	0	0	0	0	0.0	0	3.2	1.8	0.67	0.60
2024	11149	0.28	AMGB	4.14	2.14	0	0	0	0	0	0	0.0	0	3.4	1.9	0.67	0.60
2025	11372	0.28	AMGB	4.11	2.25	0	0	0	0	0	0	0.0	0	3.6	2.0	0.67	0.60
2026	11599	0.29	AMGB	4.11	2.38	0	0	0	0	0	0	0.0	0	3.8	2.2	0.67	0.60
2027	11831	0.29	AMGB	4.11	2.51	1	0	0	1	0	0	0.0	0	4.0	2.3	0.67	0.60
2028	12068	0.30	AMGB	4.10	2.66	3	0	0	3	0	0	0.0	0	4.3	2.4	0.67	0.60
2029	12309	0.31	AMAP	4.76	1.69	0	0	0	0	0	0	0.0	0	0.2	2.5	0.68	0.52
2030	12556	0.31	AMAP	4.76	1.78	0	0	0	0	0	0	0.0	0	0.4	2.6	0.68	0.52
2031	12807	0.32	AMAP	4.76	1.87	0	0	0	0	0	0	0.0	0	0.5	2.7	0.67	0.52
2032	13063	0.32	AMAP	4.76	1.98	0	0	0	0	0	0	0.0	0	0.7	2.8	0.67	0.52
2033	13324	0.33	AMAP	4.76	2.08	0	0	0	0	0	0	0.0	0	0.9	2.9	0.67	0.52
2034	13591	0.34	AMAP	4.76	2.19	0	0	0	0	0	0	0.0	0	1.1	3.0	0.67	0.52
2035	13862	0.34	AMAP	4.76	2.31	0	0	0	0	0	0	0.0	0	1.3	3.2	0.67	0.52
2036	14140	0.35	AMAP	4.76	2.43	1	0	0	1	0	0	0.0	0	1.4	3.3	0.67	0.52
2037	14422	0.36	AMAP	5.41	1.68	0	0	0	0	0	0	0.0	0	0.2	3.4	0.68	0.52
2038	14711	0.36	AMAP	5.41	1.77	0	0	0	0	0	0	0.0	0	0.3	3.5	0.68	0.52
2039	15005	0.37	AMAP	5.41	1.86	0	0	0	0	0	0	0.0	0	0.5	3.6	0.67	0.52
2040	15305	0.38	AMAP	5.41	1.96	0	0	0	0	0	0	0.0	0	0.6	3.7	0.67	0.52
2041	15611	0.39	AMAP	5.41	2.06	0	0	0	0	0	0	0.0	0	0.8	3.8	0.67	0.52
2042	15924	0.39	AMAP	5.41	2.17	0	0	0	0	0	0	0.0	0	0.9	3.9	0.67	0.52
2043	16242	0.40	AMAP	5.41	2.28	0	0	0	0	0	0	0.0	0	1.1	4.0	0.67	0.52
2044	16567	0.41	AMAP	5.41	2.40	1	0	0	1	0	0	0.0	0	1.3	4.1	0.67	0.52
2045	16898	0.42	AMAP	6.06	1.68	0	0	0	0	0	0	0.0	0	0.1	4.2	0.68	0.52
2046	17236	0.43	AMAP	6.06	1.77	0	0	0	0	0	0	0.0	0	0.3	4.2	0.67	0.52
2047	17581	0.44	AMAP	6.06	1.86	0	0	0	0	0	0	0.0	0	0.4	4.3	0.67	0.52

Table C-2: Pavement Deterioration Results – ES10 Weak

Section: ES10weak Arid **Alternative:** Base Alternative																	
				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.49	1.79	0	0	0	0	0	0	0.0	0	3.5	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.49	1.83	0	0	0	0	0	0	0.0	0	3.7	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.49	1.87	0	0	0	0	0	0	0.0	0	4.0	2.2	0.67	0.60
2024	11149	0.28	AMGB	3.49	1.91	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.49	1.95	0	0	0	0	0	0	0.0	0	4.5	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.49	1.99	0	0	0	0	0	0	0.0	0	4.8	2.6	0.67	0.60
2027	11831	0.29	AMGB	3.49	2.04	1	0	0	1	0	0	0.0	0	5.0	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.49	2.08	1	0	1	1	0	0	0.0	0	5.3	2.8	0.67	0.60
2029	12309	0.31	AMGB	3.49	2.13	1	0	1	2	0	0	0.0	0	5.5	2.9	0.67	0.60
2030	12556	0.31	AMGB	3.48	2.18	2	0	1	3	0	0	0.0	0	5.8	3.1	0.67	0.60
2031	12807	0.32	AMGB	3.48	2.23	3	0	1	4	1	0	0.0	0	6.0	3.2	0.67	0.60
2032	13063	0.32	AMGB	3.48	2.28	4	0	1	5	1	0	0.0	0	6.3	3.3	0.67	0.60
2033	13324	0.33	AMGB	3.48	2.33	5	0	2	6	2	0	0.0	0	6.6	3.4	0.67	0.60
2034	13591	0.34	AMGB	3.48	2.39	6	0	2	8	3	0	0.0	0	6.8	3.5	0.67	0.60
2035	13862	0.34	AMGB	3.47	2.44	7	1	2	9	4	0	0.0	0	7.1	3.7	0.67	0.60
2036	14140	0.35	AMGB	3.47	2.49	7	1	2	9	6	0	0.0	0	7.3	3.8	0.67	0.60
2037	14422	0.36	AMGB	3.47	2.54	7	1	2	10	8	0	0.0	0	7.6	3.9	0.67	0.60
2038	14711	0.36	AMGB	3.47	2.59	7	1	3	10	10	0	0.0	0	7.8	4.0	0.67	0.60
2039	15005	0.37	AMGB	3.47	2.64	7	1	3	10	12	0	0.0	0	8.1	4.1	0.67	0.60
2040	15305	0.38	AMGB	3.47	2.70	7	1	3	10	16	0	0.0	0	8.4	4.2	0.67	0.59
2041	15611	0.39	AMGB	3.47	2.75	7	1	3	10	19	0	0.0	0	8.6	4.3	0.67	0.59

2042	15924	0.39	AMGB	3.47	2.80	7	1	3	11	23	0	0.0	0	8.9	4.4	0.67	0.59
2043	16242	0.40	AMGB	3.47	2.85	7	1	4	11	28	0	0.0	0	9.2	4.5	0.67	0.59
2044	16567	0.41	AMGB	3.47	2.91	7	1	4	11	33	0	0.0	0	9.4	4.6	0.67	0.59
2045	16898	0.42	AMGB	3.47	3.38	7	1	4	11	38	106	0.1	0	9.7	4.7	0.67	0.59
2046	17236	0.43	AMGB	3.47	3.03	7	1	4	12	44	133	0.2	0	10.0	4.8	0.67	0.59
2047	17581	0.44	AMGB	3.47	3.09	7	1	4	12	50	31	0.0	0	10.2	4.9	0.67	0.59
2048	17933	0.44	AMGB	3.47	3.14	7	1	5	12	55	35	0.0	0	10.5	5.0	0.67	0.59
2049	18291	0.45	AMGB	3.47	3.20	8	1	5	12	60	40	0.1	0	10.8	5.1	0.67	0.59
2050	18657	0.46	AMGB	3.47	3.27	8	1	5	13	64	44	0.1	0	11.0	5.1	0.67	0.59

Section: ES10weak Arid
Alternative: Heavy maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.49	1.79	0	0	0	0	0	0	0.0	0	3.5	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.49	1.83	0	0	0	0	0	0	0.0	0	3.7	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.49	1.87	0	0	0	0	0	0	0.0	0	4.0	2.2	0.67	0.60
2024	11149	0.28	AMGB	3.49	1.91	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.49	1.95	0	0	0	0	0	0	0.0	0	4.5	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.49	1.99	0	0	0	0	0	0	0.0	0	4.8	2.6	0.67	0.60
2027	11831	0.29	AMGB	3.49	2.04	1	0	0	1	0	0	0.0	0	5.0	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.49	2.08	1	0	1	1	0	0	0.0	0	5.3	2.8	0.67	0.60
2029	12309	0.31	AMAP	4.19	1.63	0	0	0	0	0	0	0.0	0	0.2	3.0	0.68	0.52
2030	12556	0.31	AMAP	4.19	1.66	0	0	0	0	0	0	0.0	0	0.4	3.1	0.68	0.52
2031	12807	0.32	AMAP	4.19	1.69	0	0	0	0	0	0	0.0	0	0.6	3.2	0.67	0.52
2032	13063	0.32	AMAP	4.19	1.72	0	0	0	0	0	0	0.0	0	0.8	3.3	0.67	0.52
2033	13324	0.33	AMAP	4.19	1.75	0	0	0	0	0	0	0.0	0	1.0	3.5	0.67	0.52

2034	13591	0.34	AMAP	4.19	1.78	0	0	0	0	0	0	0.0	0	1.3	3.6	0.67	0.52
2035	13862	0.34	AMAP	4.19	1.81	0	0	0	0	0	0	0.0	0	1.5	3.7	0.67	0.52
2036	14140	0.35	AMAP	4.19	1.84	0	0	1	1	0	0	0.0	0	1.7	3.8	0.67	0.52
2037	14422	0.36	AMAP	4.90	1.62	0	0	0	0	0	0	0.0	0	0.2	4.0	0.68	0.52
2038	14711	0.36	AMAP	4.90	1.65	0	0	0	0	0	0	0.0	0	0.3	4.1	0.68	0.52
2039	15005	0.37	AMAP	4.90	1.67	0	0	0	0	0	0	0.0	0	0.5	4.2	0.67	0.52
2040	15305	0.38	AMAP	4.90	1.69	0	0	0	0	0	0	0.0	0	0.7	4.3	0.67	0.52
2041	15611	0.39	AMAP	4.90	1.72	0	0	0	0	0	0	0.0	0	0.9	4.4	0.67	0.52
2042	15924	0.39	AMAP	4.90	1.74	0	0	0	0	0	0	0.0	0	1.1	4.5	0.67	0.52
2043	16242	0.40	AMAP	4.90	1.77	0	0	0	0	0	0	0.0	0	1.2	4.6	0.67	0.52
2044	16567	0.41	AMAP	4.90	1.79	0	0	1	1	0	0	0.0	0	1.4	4.8	0.67	0.52
2045	16898	0.42	AMAP	5.61	1.62	0	0	0	0	0	0	0.0	0	0.2	4.8	0.68	0.52
2046	17236	0.43	AMAP	5.61	1.64	0	0	0	0	0	0	0.0	0	0.3	4.9	0.67	0.52
2047	17581	0.44	AMAP	5.61	1.66	0	0	0	0	0	0	0.0	0	0.5	5.0	0.67	0.52
2048	17933	0.44	AMAP	5.61	1.68	0	0	0	0	0	0	0.0	0	0.6	5.1	0.67	0.52
2049	18291	0.45	AMAP	5.61	1.70	0	0	0	0	0	0	0.0	0	0.8	5.2	0.67	0.52
2050	18657	0.46	AMAP	5.61	1.72	0	0	0	0	0	0	0.0	0	0.9	5.3	0.67	0.52

Section: ES10weak semi arid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.54	1.79	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.54	1.84	0	0	0	0	0	0	0.0	0	3.7	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.53	1.88	0	0	0	0	0	0	0.0	0	3.9	2.1	0.67	0.60
2024	11149	0.28	AMGB	3.53	1.93	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.52	1.98	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60

2026	11599	0.29	AMGB	3.51	2.02	0	0	0	0	0	0	0.0	0	4.7	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.51	2.08	1	0	0	1	0	0	0.0	0	4.9	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.51	2.13	1	0	0	1	0	0	0.0	0	5.2	2.8	0.67	0.60
2029	12309	0.31	AMGB	3.50	2.19	2	0	0	2	0	0	0.0	0	5.4	2.9	0.67	0.60
2030	12556	0.31	AMGB	3.50	2.25	4	0	0	4	0	0	0.0	0	5.7	3.0	0.67	0.60
2031	12807	0.32	AMGB	3.49	2.31	5	0	1	5	1	0	0.0	0	5.9	3.1	0.67	0.60
2032	13063	0.32	AMGB	3.49	2.38	7	0	1	7	2	0	0.0	0	6.2	3.3	0.67	0.60
2033	13324	0.33	AMGB	3.48	2.45	9	1	1	9	5	0	0.0	0	6.4	3.4	0.67	0.60
2034	13591	0.34	AMGB	3.48	2.51	9	1	1	11	8	0	0.0	0	6.7	3.5	0.67	0.60
2035	13862	0.34	AMGB	3.47	2.58	10	1	1	12	12	0	0.0	0	7.0	3.6	0.67	0.60
2036	14140	0.35	AMGB	3.47	2.64	11	1	2	13	17	0	0.0	0	7.2	3.7	0.67	0.60
2037	14422	0.36	AMGB	3.47	2.71	13	1	2	14	23	0	0.0	0	7.5	3.8	0.67	0.60
2038	14711	0.36	AMGB	3.46	2.78	14	1	2	16	31	0	0.0	0	7.8	4.0	0.67	0.60
2039	15005	0.37	AMGB	3.46	3.24	15	1	2	17	40	101	0.1	0	8.0	4.1	0.67	0.60
2040	15305	0.38	AMGB	3.45	2.94	17	1	2	19	50	130	0.2	0	8.3	4.2	0.67	0.59
2041	15611	0.39	AMGB	3.44	3.02	18	1	3	21	59	35	0.0	0	8.6	4.3	0.67	0.59
2042	15924	0.39	AMGB	3.44	3.10	20	1	3	23	67	42	0.1	0	8.8	4.4	0.67	0.59
2043	16242	0.40	AMGB	3.43	3.19	22	1	3	25	74	49	0.1	0	9.1	4.5	0.67	0.59
2044	16567	0.41	AMGB	3.42	3.27	24	1	3	27	72	55	0.1	0	9.4	4.6	0.67	0.59
2045	16898	0.42	AMGB	3.41	3.37	27	1	3	30	70	55	0.1	0	9.6	4.7	0.67	0.59
2046	17236	0.43	AMGB	3.40	3.46	29	1	4	33	67	54	0.1	0	9.9	4.8	0.67	0.59
2047	17581	0.44	AMGB	3.39	3.56	32	1	4	35	64	53	0.1	0	10.2	4.9	0.67	0.59
2048	17933	0.44	AMGB	3.38	3.66	35	1	4	39	61	52	0.1	0	10.5	5.0	0.67	0.59
2049	18291	0.45	AMGB	3.36	3.76	38	1	4	42	58	50	0.1	0	10.8	5.1	0.67	0.59
2050	18657	0.46	AMGB	3.35	3.87	41	1	4	45	55	49	0.1	0	11.0	5.1	0.67	0.59

Section: ES10weak semi arid
Alternative: Heavy maintenance

				Bituminous Pavement													
				End of Year Condition													
Year		ESAL				Cracking Area (%)					Potholes			Rutting			SFC50

	MT AADT		Pavement Type	Average Structural Number SNPK	IRI (m/km)	ACA	ACW	CT	ACRA	ARV (%)	NPT (km)	APOT (%)	AEB (m/km)	Mean Rut Depth (mm)	RDS	TD (mm)	
2021	10506	0.26	AMGB	3.54	1.79	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.54	1.84	0	0	0	0	0	0	0.0	0	3.7	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.53	1.88	0	0	0	0	0	0	0.0	0	3.9	2.1	0.67	0.60
2024	11149	0.28	AMGB	3.53	1.93	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.52	1.98	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.51	2.02	0	0	0	0	0	0	0.0	0	4.7	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.51	2.08	1	0	0	1	0	0	0.0	0	4.9	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.51	2.13	1	0	0	1	0	0	0.0	0	5.2	2.8	0.67	0.60
2029	12309	0.31	AMAP	4.20	1.63	0	0	0	0	0	0	0.0	0	0.2	2.9	0.68	0.52
2030	12556	0.31	AMAP	4.20	1.67	0	0	0	0	0	0	0.0	0	0.4	3.0	0.68	0.52
2031	12807	0.32	AMAP	4.20	1.71	0	0	0	0	0	0	0.0	0	0.6	3.2	0.67	0.52
2032	13063	0.32	AMAP	4.20	1.74	0	0	0	0	0	0	0.0	0	0.8	3.3	0.67	0.52
2033	13324	0.33	AMAP	4.20	1.78	0	0	0	0	0	0	0.0	0	1.0	3.4	0.67	0.52
2034	13591	0.34	AMAP	4.20	1.81	0	0	0	0	0	0	0.0	0	1.3	3.6	0.67	0.52
2035	13862	0.34	AMAP	4.20	1.85	0	0	0	0	0	0	0.0	0	1.5	3.7	0.67	0.52
2036	14140	0.35	AMAP	4.20	1.89	1	0	0	1	0	0	0.0	0	1.7	3.8	0.67	0.52
2037	14422	0.36	AMAP	4.89	1.63	0	0	0	0	0	0	0.0	0	0.2	3.9	0.68	0.52
2038	14711	0.36	AMAP	4.89	1.66	0	0	0	0	0	0	0.0	0	0.3	4.0	0.68	0.52
2039	15005	0.37	AMAP	4.89	1.69	0	0	0	0	0	0	0.0	0	0.5	4.2	0.67	0.52
2040	15305	0.38	AMAP	4.89	1.72	0	0	0	0	0	0	0.0	0	0.7	4.3	0.67	0.52
2041	15611	0.39	AMAP	4.89	1.75	0	0	0	0	0	0	0.0	0	0.9	4.4	0.67	0.52
2042	15924	0.39	AMAP	4.89	1.78	0	0	0	0	0	0	0.0	0	1.1	4.5	0.67	0.52
2043	16242	0.40	AMAP	4.89	1.81	0	0	0	0	0	0	0.0	0	1.3	4.6	0.67	0.52
2044	16567	0.41	AMAP	4.89	1.84	0	0	0	0	0	0	0.0	0	1.4	4.7	0.67	0.52
2045	16898	0.42	AMAP	5.58	1.63	0	0	0	0	0	0	0.0	0	0.2	4.8	0.68	0.52
2046	17236	0.43	AMAP	5.58	1.65	0	0	0	0	0	0	0.0	0	0.3	4.9	0.67	0.52
2047	17581	0.44	AMAP	5.58	1.68	0	0	0	0	0	0	0.0	0	0.5	5.0	0.67	0.52

2048	17933	0.44	AMAP	5.58	1.70	0	0	0	0	0	0	0.0	0	0.6	5.1	0.67	0.52
2049	18291	0.45	AMAP	5.58	1.73	0	0	0	0	0	0	0.0	0	0.8	5.2	0.67	0.52
2050	18657	0.46	AMAP	5.58	1.76	0	0	0	0	0	0	0.0	0	0.9	5.3	0.67	0.52

Section: ES10weak subhumid dry
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.53	1.81	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.52	1.88	0	0	0	0	0	0	0.0	0	3.7	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.51	1.94	0	0	0	0	0	0	0.0	0	3.9	2.1	0.67	0.60
2024	11149	0.28	AMGB	3.49	2.01	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.48	2.08	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.47	2.16	1	0	0	1	0	0	0.0	0	4.7	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.46	2.24	1	0	0	1	0	0	0.0	0	4.9	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.46	2.33	3	0	0	3	0	0	0.0	0	5.2	2.8	0.67	0.60
2029	12309	0.31	AMGB	3.45	2.42	4	0	0	4	0	0	0.0	0	5.5	2.9	0.67	0.60
2030	12556	0.31	AMGB	3.44	2.52	6	0	0	6	0	0	0.0	0	5.7	3.0	0.67	0.60
2031	12807	0.32	AMGB	3.43	2.63	9	2	0	9	1	0	0.0	0	6.0	3.2	0.67	0.60
2032	13063	0.32	AMGB	3.42	2.72	10	2	0	10	3	0	0.0	0	6.2	3.3	0.67	0.60
2033	13324	0.33	AMGB	3.42	2.83	11	2	0	11	6	0	0.0	0	6.5	3.4	0.67	0.60
2034	13591	0.34	AMGB	3.41	2.93	13	2	0	13	10	0	0.0	0	6.8	3.5	0.67	0.60
2035	13862	0.34	AMGB	3.40	3.04	15	2	0	15	16	0	0.0	0	7.0	3.6	0.67	0.60
2036	14140	0.35	AMGB	3.39	3.16	17	2	0	17	24	0	0.0	0	7.3	3.8	0.67	0.60
2037	14422	0.36	AMGB	3.38	3.28	19	2	0	19	34	0	0.0	0	7.6	3.9	0.67	0.60
2038	14711	0.36	AMGB	3.36	3.87	21	2	0	21	46	113	0.2	0	7.8	4.0	0.67	0.60
2039	15005	0.37	AMGB	3.35	3.56	24	2	0	24	58	146	0.2	0	8.1	4.1	0.67	0.60

2040	15305	0.38	AMGB	3.33	3.70	27	2	0	27	68	41	0.1	0	8.4	4.2	0.67	0.59
2041	15611	0.39	AMGB	3.31	3.85	30	2	0	30	70	49	0.1	0	8.7	4.3	0.67	0.59
2042	15924	0.39	AMGB	3.29	4.01	34	2	0	34	66	52	0.1	0	9.0	4.4	0.67	0.59
2043	16242	0.40	AMGB	3.27	4.18	37	2	0	37	63	50	0.1	0	9.3	4.5	0.67	0.59
2044	16567	0.41	AMGB	3.25	4.36	42	2	0	42	58	48	0.1	0	9.6	4.6	0.67	0.59
2045	16898	0.42	AMGB	3.22	4.54	46	2	0	46	54	46	0.1	0	9.9	4.7	0.67	0.59
2046	17236	0.43	AMGB	3.19	4.73	51	2	0	51	49	43	0.1	0	10.1	4.8	0.67	0.59
2047	17581	0.44	AMGB	3.16	4.94	55	2	0	55	45	40	0.1	0	10.5	4.9	0.67	0.59
2048	17933	0.44	AMGB	3.13	5.14	59	2	0	59	41	38	0.1	0	10.8	5.1	0.67	0.59
2049	18291	0.45	AMGB	3.10	5.36	62	2	0	62	38	35	0.0	0	11.1	5.2	0.67	0.59
2050	18657	0.46	AMGB	3.08	5.58	66	2	0	66	34	33	0.0	0	11.4	5.3	0.67	0.59

Section: ES10weak subhumid dry
Alternative: Heavy maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.53	1.81	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.52	1.88	0	0	0	0	0	0	0.0	0	3.7	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.51	1.94	0	0	0	0	0	0	0.0	0	3.9	2.1	0.67	0.60
2024	11149	0.28	AMGB	3.49	2.01	0	0	0	0	0	0	0.0	0	4.2	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.48	2.08	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.47	2.16	1	0	0	1	0	0	0.0	0	4.7	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.46	2.24	1	0	0	1	0	0	0.0	0	4.9	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.46	2.33	3	0	0	3	0	0	0.0	0	5.2	2.8	0.67	0.60
2029	12309	0.31	AMAP	4.14	1.65	0	0	0	0	0	0	0.0	0	0.2	2.9	0.68	0.52
2030	12556	0.31	AMAP	4.14	1.71	0	0	0	0	0	0	0.0	0	0.4	3.1	0.68	0.52
2031	12807	0.32	AMAP	4.14	1.76	0	0	0	0	0	0	0.0	0	0.6	3.2	0.67	0.52

2032	13063	0.32	AMAP	4.14	1.82	0	0	0	0	0	0	0.0	0	0.8	3.3	0.67	0.52
2033	13324	0.33	AMAP	4.14	1.88	0	0	0	0	0	0	0.0	0	1.0	3.5	0.67	0.52
2034	13591	0.34	AMAP	4.14	1.94	0	0	0	0	0	0	0.0	0	1.3	3.6	0.67	0.52
2035	13862	0.34	AMAP	4.14	2.00	1	0	0	1	0	0	0.0	0	1.5	3.7	0.67	0.52
2036	14140	0.35	AMAP	4.14	2.07	1	0	0	1	0	0	0.0	0	1.7	3.8	0.67	0.52
2037	14422	0.36	AMAP	4.81	1.65	0	0	0	0	0	0	0.0	0	0.2	4.0	0.68	0.52
2038	14711	0.36	AMAP	4.81	1.69	0	0	0	0	0	0	0.0	0	0.4	4.1	0.68	0.52
2039	15005	0.37	AMAP	4.81	1.74	0	0	0	0	0	0	0.0	0	0.5	4.2	0.67	0.52
2040	15305	0.38	AMAP	4.81	1.79	0	0	0	0	0	0	0.0	0	0.7	4.3	0.67	0.52
2041	15611	0.39	AMAP	4.81	1.85	0	0	0	0	0	0	0.0	0	0.9	4.4	0.67	0.52
2042	15924	0.39	AMAP	4.81	1.90	0	0	0	0	0	0	0.0	0	1.1	4.5	0.67	0.52
2043	16242	0.40	AMAP	4.81	1.95	0	0	0	0	0	0	0.0	0	1.3	4.6	0.67	0.52
2044	16567	0.41	AMAP	4.81	2.01	1	0	0	1	0	0	0.0	0	1.5	4.8	0.67	0.52
2045	16898	0.42	AMAP	5.49	1.64	0	0	0	0	0	0	0.0	0	0.2	4.8	0.68	0.52
2046	17236	0.43	AMAP	5.49	1.69	0	0	0	0	0	0	0.0	0	0.3	4.9	0.67	0.52
2047	17581	0.44	AMAP	5.49	1.73	0	0	0	0	0	0	0.0	0	0.5	5.1	0.67	0.52
2048	17933	0.44	AMAP	5.49	1.78	0	0	0	0	0	0	0.0	0	0.6	5.2	0.67	0.52
2049	18291	0.45	AMAP	5.49	1.83	0	0	0	0	0	0	0.0	0	0.8	5.3	0.67	0.52
2050	18657	0.46	AMAP	5.49	1.87	0	0	0	0	0	0	0.0	0	0.9	5.3	0.67	0.52

Section: ES10weak subhumid wet
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.56	1.81	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.54	1.86	0	0	0	0	0	0	0.0	0	3.6	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.52	1.92	0	0	0	0	0	0	0.0	0	3.9	2.1	0.67	0.60

2024	11149	0.28	AMGB	3.50	1.99	0	0	0	0	0	0	0.0	0	4.1	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.48	2.05	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.47	2.13	1	0	0	1	0	0	0.0	0	4.7	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.46	2.21	3	0	0	3	0	0	0.0	0	4.9	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.45	2.30	6	0	0	6	0	0	0.0	0	5.2	2.8	0.67	0.60
2029	12309	0.31	AMGB	3.43	2.39	9	2	0	9	0	0	0.0	0	5.4	2.9	0.67	0.60
2030	12556	0.31	AMGB	3.42	2.48	11	3	0	11	0	0	0.0	0	5.7	3.0	0.67	0.60
2031	12807	0.32	AMGB	3.40	2.57	13	3	0	13	2	0	0.0	0	5.9	3.2	0.67	0.60
2032	13063	0.32	AMGB	3.39	2.67	16	3	0	16	5	0	0.0	0	6.2	3.3	0.67	0.60
2033	13324	0.33	AMGB	3.37	2.78	18	3	0	18	11	0	0.0	0	6.5	3.4	0.67	0.60
2034	13591	0.34	AMGB	3.35	2.89	22	3	0	22	21	0	0.0	0	6.8	3.5	0.67	0.60
2035	13862	0.34	AMGB	3.32	3.01	26	3	0	26	34	0	0.0	0	7.0	3.6	0.67	0.60
2036	14140	0.35	AMGB	3.29	3.61	31	3	0	31	51	116	0.2	0	7.3	3.8	0.67	0.60
2037	14422	0.36	AMGB	3.25	3.29	36	3	0	36	64	154	0.2	0	7.6	3.9	0.67	0.60
2038	14711	0.36	AMGB	3.21	3.43	42	3	0	42	58	47	0.1	0	7.9	4.0	0.67	0.60
2039	15005	0.37	AMGB	3.16	3.60	49	3	0	49	51	44	0.1	0	8.2	4.1	0.67	0.60
2040	15305	0.38	AMGB	3.10	3.76	55	3	0	55	45	39	0.1	0	8.5	4.3	0.67	0.59
2041	15611	0.39	AMGB	3.05	3.94	61	3	0	61	39	35	0.0	0	8.8	4.4	0.67	0.59
2042	15924	0.39	AMGB	2.99	4.12	66	3	0	66	33	31	0.0	0	9.2	4.5	0.67	0.59
2043	16242	0.40	AMGB	2.94	4.30	71	3	0	71	29	27	0.0	0	9.5	4.6	0.67	0.59
2044	16567	0.41	AMGB	2.90	4.49	75	3	0	75	25	24	0.0	0	9.9	4.8	0.67	0.59
2045	16898	0.42	AMGB	2.86	4.69	79	3	0	79	21	21	0.0	0	10.2	4.9	0.67	0.59
2046	17236	0.43	AMGB	2.83	4.90	82	3	0	82	18	18	0.0	0	10.6	5.0	0.67	0.59
2047	17581	0.44	AMGB	2.80	5.11	85	3	0	85	15	16	0.0	0	10.9	5.1	0.67	0.59
2048	17933	0.44	AMGB	2.78	5.33	87	3	0	87	13	14	0.0	0	11.3	5.2	0.67	0.59
2049	18291	0.45	AMGB	2.76	5.56	89	3	0	89	11	12	0.0	0	11.6	5.3	0.67	0.59
2050	18657	0.46	AMGB	2.74	5.80	90	3	0	90	10	10	0.0	0	12.0	5.4	0.67	0.59

Section: ES10weak subhumid wet
Alternative: Heavy maintenance

Bituminous Pavement

				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.56	1.81	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.54	1.86	0	0	0	0	0	0	0.0	0	3.6	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.52	1.92	0	0	0	0	0	0	0.0	0	3.9	2.1	0.67	0.60
2024	11149	0.28	AMGB	3.50	1.99	0	0	0	0	0	0	0.0	0	4.1	2.3	0.67	0.60
2025	11372	0.28	AMGB	3.48	2.05	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.47	2.13	1	0	0	1	0	0	0.0	0	4.7	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.46	2.21	3	0	0	3	0	0	0.0	0	4.9	2.7	0.67	0.60
2028	12068	0.30	AMGB	3.45	2.30	6	0	0	6	0	0	0.0	0	5.2	2.8	0.67	0.60
2029	12309	0.31	AMAP	4.13	1.65	0	0	0	0	0	0	0.0	0	0.2	2.9	0.68	0.52
2030	12556	0.31	AMAP	4.13	1.70	0	0	0	0	0	0	0.0	0	0.4	3.0	0.68	0.52
2031	12807	0.32	AMAP	4.13	1.75	0	0	0	0	0	0	0.0	0	0.6	3.2	0.67	0.52
2032	13063	0.32	AMAP	4.13	1.80	0	0	0	0	0	0	0.0	0	0.8	3.3	0.67	0.52
2033	13324	0.33	AMAP	4.13	1.85	0	0	0	0	0	0	0.0	0	1.0	3.4	0.67	0.52
2034	13591	0.34	AMAP	4.13	1.91	1	0	0	1	0	0	0.0	0	1.3	3.6	0.67	0.52
2035	13862	0.34	AMAP	4.12	1.97	1	0	0	1	0	0	0.0	0	1.5	3.7	0.67	0.52
2036	14140	0.35	AMAP	4.12	2.03	2	0	0	2	0	0	0.0	0	1.7	3.8	0.67	0.52
2037	14422	0.36	AMAP	4.79	1.64	0	0	0	0	0	0	0.0	0	0.2	3.9	0.68	0.52
2038	14711	0.36	AMAP	4.79	1.69	0	0	0	0	0	0	0.0	0	0.4	4.1	0.68	0.52
2039	15005	0.37	AMAP	4.79	1.73	0	0	0	0	0	0	0.0	0	0.5	4.2	0.67	0.52
2040	15305	0.38	AMAP	4.79	1.77	0	0	0	0	0	0	0.0	0	0.7	4.3	0.67	0.52
2041	15611	0.39	AMAP	4.79	1.82	0	0	0	0	0	0	0.0	0	0.9	4.4	0.67	0.52
2042	15924	0.39	AMAP	4.79	1.87	0	0	0	0	0	0	0.0	0	1.1	4.5	0.67	0.52
2043	16242	0.40	AMAP	4.79	1.92	1	0	0	1	0	0	0.0	0	1.3	4.6	0.67	0.52
2044	16567	0.41	AMAP	4.78	1.97	1	0	0	1	0	0	0.0	0	1.5	4.7	0.67	0.52
2045	16898	0.42	AMAP	5.45	1.64	0	0	0	0	0	0	0.0	0	0.2	4.8	0.68	0.52

2046	17236	0.43	AMAP	5.45	1.68	0	0	0	0	0	0	0.0	0	0.3	4.9	0.67	0.52
2047	17581	0.44	AMAP	5.45	1.72	0	0	0	0	0	0	0.0	0	0.5	5.0	0.67	0.52
2048	17933	0.44	AMAP	5.45	1.76	0	0	0	0	0	0	0.0	0	0.6	5.1	0.67	0.52
2049	18291	0.45	AMAP	5.45	1.80	0	0	0	0	0	0	0.0	0	0.8	5.2	0.67	0.52
2050	18657	0.46	AMAP	5.45	1.84	0	0	0	0	0	0	0.0	0	0.9	5.3	0.67	0.52

Section: ES10weak humid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.58	1.85	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.55	1.96	0	0	0	0	0	0	0.0	0	3.6	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.52	2.08	0	0	0	0	0	0	0.0	0	3.8	2.1	0.67	0.60
2024	11149	0.28	AMGB	3.49	2.21	0	0	0	0	0	0	0.0	0	4.1	2.2	0.67	0.60
2025	11372	0.28	AMGB	3.47	2.35	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.47	2.50	1	0	0	1	0	0	0.0	0	4.6	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.46	2.66	3	0	0	3	0	0	0.0	0	4.9	2.6	0.67	0.60
2028	12068	0.30	AMGB	3.44	2.84	6	0	0	6	0	0	0.0	0	5.1	2.8	0.67	0.60
2029	12309	0.31	AMGB	3.41	3.04	9	2	0	9	0	0	0.0	0	5.4	2.9	0.67	0.60
2030	12556	0.31	AMGB	3.40	3.23	11	3	0	11	0	0	0.0	0	5.7	3.0	0.67	0.60
2031	12807	0.32	AMGB	3.38	3.44	13	3	0	13	2	0	0.0	0	5.9	3.1	0.67	0.60
2032	13063	0.32	AMGB	3.37	3.66	15	3	0	15	5	0	0.0	0	6.2	3.3	0.67	0.60
2033	13324	0.33	AMGB	3.34	3.90	18	3	0	18	11	0	0.0	0	6.5	3.4	0.67	0.60
2034	13591	0.34	AMGB	3.32	4.17	22	3	0	22	21	0	0.0	0	6.7	3.5	0.67	0.60
2035	13862	0.34	AMGB	3.28	4.45	26	3	0	26	34	0	0.0	0	7.0	3.6	0.67	0.60
2036	14140	0.35	AMGB	3.24	5.30	30	3	0	30	51	128	0.2	0	7.3	3.8	0.67	0.60
2037	14422	0.36	AMGB	3.19	5.12	36	3	0	36	64	170	0.2	0	7.6	3.9	0.67	0.60

2038	14711	0.36	AMGB	3.14	5.48	42	3	0	42	58	52	0.1	0	7.9	4.0	0.67	0.60
2039	15005	0.37	AMGB	3.07	5.88	48	3	0	48	52	48	0.1	0	8.2	4.1	0.67	0.60
2040	15305	0.38	AMGB	3.00	6.31	55	3	0	55	45	44	0.1	0	8.6	4.3	0.67	0.59
2041	15611	0.39	AMGB	2.93	6.78	61	3	0	61	39	39	0.1	0	8.9	4.4	0.67	0.59
2042	15924	0.39	AMGB	2.86	7.29	66	3	0	66	34	34	0.0	0	9.3	4.5	0.67	0.59
2043	16242	0.40	AMGB	2.80	7.84	71	3	0	71	29	30	0.0	0	9.6	4.7	0.67	0.59
2044	16567	0.41	AMGB	2.74	8.44	75	3	0	75	25	26	0.0	0	10.0	4.8	0.67	0.59
2045	16898	0.42	AMGB	2.69	9.09	79	3	0	79	21	23	0.0	0	10.4	4.9	0.67	0.59
2046	17236	0.43	AMGB	2.65	9.81	82	3	0	82	18	20	0.0	0	10.8	5.1	0.67	0.59
2047	17581	0.44	AMGB	2.61	10.58	85	3	0	85	15	17	0.0	0	11.2	5.2	0.67	0.59
2048	17933	0.44	AMGB	2.57	11.42	87	3	0	87	13	15	0.0	0	11.6	5.3	0.67	0.59
2049	18291	0.45	AMGB	2.55	12.33	89	3	0	89	11	13	0.0	0	12.0	5.4	0.67	0.59
2050	18657	0.46	AMGB	2.52	13.32	90	3	0	90	10	12	0.0	0	12.4	5.6	0.67	0.59

Section: ES10weak humid
Alternative: Heavy maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	10506	0.26	AMGB	3.58	1.85	0	0	0	0	0	0	0.0	0	3.4	1.9	0.68	0.60
2022	10716	0.27	AMGB	3.55	1.96	0	0	0	0	0	0	0.0	0	3.6	2.0	0.68	0.60
2023	10930	0.27	AMGB	3.52	2.08	0	0	0	0	0	0	0.0	0	3.8	2.1	0.67	0.60
2024	11149	0.28	AMGB	3.49	2.21	0	0	0	0	0	0	0.0	0	4.1	2.2	0.67	0.60
2025	11372	0.28	AMGB	3.47	2.35	0	0	0	0	0	0	0.0	0	4.4	2.4	0.67	0.60
2026	11599	0.29	AMGB	3.47	2.50	1	0	0	1	0	0	0.0	0	4.6	2.5	0.67	0.60
2027	11831	0.29	AMGB	3.46	2.66	3	0	0	3	0	0	0.0	0	4.9	2.6	0.67	0.60
2028	12068	0.30	AMGB	3.44	2.84	6	0	0	6	0	0	0.0	0	5.1	2.8	0.67	0.60
2029	12309	0.31	AMAP	4.11	1.69	0	0	0	0	0	0	0.0	0	0.2	2.9	0.68	0.52

2030	12556	0.31	AMAP	4.11	1.79	0	0	0	0	0	0	0.0	0	0.4	3.0	0.68	0.52
2031	12807	0.32	AMAP	4.11	1.90	0	0	0	0	0	0	0.0	0	0.6	3.2	0.67	0.52
2032	13063	0.32	AMAP	4.11	2.01	0	0	0	0	0	0	0.0	0	0.8	3.3	0.67	0.52
2033	13324	0.33	AMAP	4.11	2.12	0	0	0	0	0	0	0.0	0	1.0	3.4	0.67	0.52
2034	13591	0.34	AMAP	4.11	2.25	1	0	0	1	0	0	0.0	0	1.3	3.5	0.67	0.52
2035	13862	0.34	AMAP	4.11	2.38	1	0	0	1	0	0	0.0	0	1.5	3.7	0.67	0.52
2036	14140	0.35	AMAP	4.10	2.52	2	0	0	2	0	0	0.0	0	1.7	3.8	0.67	0.52
2037	14422	0.36	AMAP	4.76	1.69	0	0	0	0	0	0	0.0	0	0.2	3.9	0.68	0.52
2038	14711	0.36	AMAP	4.76	1.78	0	0	0	0	0	0	0.0	0	0.4	4.0	0.68	0.52
2039	15005	0.37	AMAP	4.76	1.88	0	0	0	0	0	0	0.0	0	0.5	4.2	0.67	0.52
2040	15305	0.38	AMAP	4.76	1.98	0	0	0	0	0	0	0.0	0	0.7	4.3	0.67	0.52
2041	15611	0.39	AMAP	4.76	2.09	0	0	0	0	0	0	0.0	0	0.9	4.4	0.67	0.52
2042	15924	0.39	AMAP	4.76	2.20	0	0	0	0	0	0	0.0	0	1.1	4.5	0.67	0.52
2043	16242	0.40	AMAP	4.76	2.32	1	0	0	1	0	0	0.0	0	1.3	4.6	0.67	0.52
2044	16567	0.41	AMAP	4.76	2.45	1	0	0	1	0	0	0.0	0	1.5	4.7	0.67	0.52
2045	16898	0.42	AMAP	5.41	1.68	0	0	0	0	0	0	0.0	0	0.2	4.8	0.68	0.52
2046	17236	0.43	AMAP	5.41	1.77	0	0	0	0	0	0	0.0	0	0.3	4.9	0.67	0.52
2047	17581	0.44	AMAP	5.41	1.87	0	0	0	0	0	0	0.0	0	0.5	5.0	0.67	0.52
2048	17933	0.44	AMAP	5.41	1.96	0	0	0	0	0	0	0.0	0	0.6	5.1	0.67	0.52
2049	18291	0.45	AMAP	5.41	2.07	0	0	0	0	0	0	0.0	0	0.8	5.2	0.67	0.52
2050	18657	0.46	AMAP	5.41	2.17	0	0	0	0	0	0	0.0	0	1.0	5.3	0.67	0.52

Table C-3: Pavement Deterioration Results – ES1 Strong

Section: ES1 strong Arid **Alternative:** Base Alternative																	
				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.72	1.78	0	0	0	0	0	0	0.0	0	3.5	1.9	0.71	0.60
2022	1072	0.03	STGB	2.72	1.80	0	0	0	0	0	0	0.0	0	3.8	2.1	0.65	0.60
2023	1093	0.03	STGB	2.72	1.83	0	0	0	0	0	0	0.0	0	4.0	2.2	0.61	0.60
2024	1115	0.03	STGB	2.72	1.85	0	0	0	0	0	0	0.0	0	4.3	2.3	0.58	0.60
2025	1137	0.03	STGB	2.72	1.88	0	0	0	0	0	0	0.0	0	4.6	2.5	0.56	0.60
2026	1160	0.03	STGB	2.72	1.90	0	0	0	0	0	0	0.0	0	4.8	2.6	0.54	0.60
2027	1183	0.03	STGB	2.72	1.93	0	0	0	0	0	0	0.0	0	5.1	2.7	0.52	0.60
2028	1207	0.03	STGB	2.72	1.95	0	0	0	0	0	0	0.0	0	5.3	2.9	0.50	0.60
2029	1231	0.03	STGB	2.72	1.98	0	0	0	0	0	0	0.0	0	5.6	3.0	0.49	0.60
2030	1256	0.03	STGB	2.72	2.00	0	0	0	0	0	0	0.0	0	5.9	3.1	0.47	0.60
2031	1281	0.03	STGB	2.72	2.03	0	0	0	0	1	0	0.0	0	6.1	3.2	0.46	0.60
2032	1306	0.03	STGB	2.72	2.05	0	0	0	0	1	0	0.0	0	6.4	3.3	0.45	0.60
2033	1332	0.03	STGB	2.72	2.08	0	0	0	0	1	0	0.0	0	6.7	3.5	0.44	0.60
2034	1359	0.03	STGB	2.72	2.10	0	0	0	0	2	0	0.0	0	6.9	3.6	0.43	0.60
2035	1386	0.03	STGB	2.71	2.13	0	0	0	0	2	0	0.0	0	7.2	3.7	0.42	0.60
2036	1414	0.04	STGB	2.71	2.15	0	0	0	0	3	0	0.0	0	7.5	3.8	0.41	0.60
2037	1442	0.04	STGB	2.71	2.18	0	0	0	0	4	0	0.0	0	7.8	3.9	0.40	0.60
2038	1471	0.04	STGB	2.71	2.21	1	0	0	1	5	0	0.0	0	8.0	4.0	0.39	0.60
2039	1501	0.04	STGB	2.71	2.23	1	0	0	1	6	0	0.0	0	8.3	4.2	0.38	0.60
2040	1531	0.04	STGB	2.71	2.26	2	0	0	2	7	0	0.0	0	8.6	4.3	0.37	0.60
2041	1561	0.04	STGB	2.71	2.30	2	0	0	2	9	0	0.0	0	8.8	4.4	0.37	0.60

2042	1592	0.04	STGB	2.71	2.33	3	0	0	3	10	0	0.0	0	9.1	4.5	0.36	0.60
2043	1624	0.04	STGB	2.71	2.36	4	0	0	4	12	0	0.0	0	9.4	4.6	0.35	0.60
2044	1657	0.04	STGB	2.71	2.40	6	0	0	6	14	0	0.0	0	9.6	4.7	0.35	0.60
2045	1690	0.04	STGB	2.71	2.43	7	0	0	7	16	0	0.0	0	9.9	4.8	0.34	0.60
2046	1724	0.04	STGB	2.71	2.47	9	0	0	9	19	0	0.0	0	10.2	4.9	0.33	0.60
2047	1758	0.04	STGB	2.71	2.51	11	0	0	11	22	0	0.0	0	10.5	4.9	0.33	0.60
2048	1793	0.04	STGB	2.71	2.56	14	0	0	14	25	0	0.0	0	10.8	5.0	0.32	0.60
2049	1829	0.05	STGB	2.71	2.60	16	0	0	16	28	0	0.0	0	11.0	5.1	0.31	0.60
2050	1866	0.05	STGB	2.70	2.65	19	0	0	19	32	0	0.0	0	11.3	5.2	0.31	0.60

Section: ES1 strong Arid
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.72	1.78	0	0	0	0	0	0	0.0	0	3.5	1.9	0.71	0.60
2022	1072	0.03	STGB	2.72	1.80	0	0	0	0	0	0	0.0	0	3.8	2.1	0.65	0.60
2023	1093	0.03	STGB	2.72	1.83	0	0	0	0	0	0	0.0	0	4.0	2.2	0.61	0.60
2024	1115	0.03	STGB	2.72	1.85	0	0	0	0	0	0	0.0	0	4.3	2.3	0.58	0.60
2025	1137	0.03	STGB	2.72	1.88	0	0	0	0	0	0	0.0	0	4.6	2.5	0.56	0.60
2026	1160	0.03	STGB	2.72	1.90	0	0	0	0	0	0	0.0	0	4.8	2.6	0.54	0.60
2027	1183	0.03	STGB	2.72	1.93	0	0	0	0	0	0	0.0	0	5.1	2.7	0.52	0.60
2028	1207	0.03	STGB	2.72	1.95	0	0	0	0	0	0	0.0	0	5.3	2.9	0.50	0.60
2029	1231	0.03	STGB	2.72	1.98	0	0	0	0	0	0	0.0	0	5.6	3.0	0.49	0.60
2030	1256	0.03	STGB	2.72	2.00	0	0	0	0	0	0	0.0	0	5.9	3.1	0.47	0.60
2031	1281	0.03	STGB	2.72	2.03	0	0	0	0	1	0	0.0	0	6.1	3.2	0.46	0.60
2032	1306	0.03	STGB	2.72	2.05	0	0	0	0	1	0	0.0	0	6.4	3.3	0.45	0.60
2033	1332	0.03	STGB	2.72	2.08	0	0	0	0	1	0	0.0	0	6.7	3.5	0.44	0.60

2034	1359	0.03	STGB	2.72	2.10	0	0	0	0	2	0	0.0	0	6.9	3.6	0.43	0.60
2035	1386	0.03	STGB	2.71	2.13	0	0	0	0	2	0	0.0	0	7.2	3.7	0.42	0.60
2036	1414	0.04	STGB	2.71	2.15	0	0	0	0	3	0	0.0	0	7.5	3.8	0.41	0.60
2037	1442	0.04	STGB	2.71	2.18	0	0	0	0	4	0	0.0	0	7.8	3.9	0.40	0.60
2038	1471	0.04	STGB	2.86	2.21	0	0	0	0	0	0	0.0	0	1.4	4.1	0.75	0.52
2039	1501	0.04	STGB	2.86	2.23	0	0	0	0	0	0	0.0	0	1.7	4.2	0.66	0.52
2040	1531	0.04	STGB	2.86	2.26	0	0	0	0	0	0	0.0	0	1.9	4.4	0.60	0.52
2041	1561	0.04	STGB	2.86	2.29	0	0	0	0	0	0	0.0	0	2.2	4.5	0.57	0.52
2042	1592	0.04	STGB	2.86	2.32	0	0	0	0	0	0	0.0	0	2.4	4.7	0.54	0.52
2043	1624	0.04	STGB	2.86	2.35	0	0	0	0	0	0	0.0	0	2.7	4.8	0.51	0.52
2044	1657	0.04	STGB	2.86	2.38	0	0	0	0	0	0	0.0	0	3.0	5.0	0.49	0.52
2045	1690	0.04	STGB	2.86	2.41	0	0	0	0	0	0	0.0	0	3.2	5.1	0.47	0.52
2046	1724	0.04	STGB	2.86	2.44	0	0	0	0	0	0	0.0	0	3.5	5.3	0.45	0.52
2047	1758	0.04	STGB	2.86	2.47	0	0	0	0	0	0	0.0	0	3.7	5.4	0.44	0.52
2048	1793	0.04	STGB	2.86	2.49	0	0	0	0	1	0	0.0	0	4.0	5.5	0.43	0.52
2049	1829	0.05	STGB	2.86	2.52	0	0	0	0	1	0	0.0	0	4.3	5.7	0.41	0.52
2050	1866	0.05	STGB	2.86	2.55	0	0	0	0	2	0	0.0	0	4.5	5.8	0.40	0.52

Section: ES1 strong semi arid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.76	1.78	0	0	0	0	0	0	0.0	0	3.4	1.9	0.71	0.60
2022	1072	0.03	STGB	2.76	1.81	0	0	0	0	0	0	0.0	0	3.7	2.0	0.65	0.60
2023	1093	0.03	STGB	2.75	1.84	0	0	0	0	0	0	0.0	0	4.0	2.2	0.61	0.60
2024	1115	0.03	STGB	2.75	1.87	0	0	0	0	0	0	0.0	0	4.2	2.3	0.58	0.60
2025	1137	0.03	STGB	2.74	1.91	0	0	0	0	0	0	0.0	0	4.5	2.4	0.56	0.60

2026	1160	0.03	STGB	2.74	1.94	0	0	0	0	0	0	0.0	0	4.7	2.6	0.54	0.60
2027	1183	0.03	STGB	2.73	1.97	0	0	0	0	0	0	0.0	0	5.0	2.7	0.52	0.60
2028	1207	0.03	STGB	2.73	2.00	0	0	0	0	0	0	0.0	0	5.3	2.8	0.50	0.60
2029	1231	0.03	STGB	2.73	2.03	0	0	0	0	0	0	0.0	0	5.5	2.9	0.49	0.60
2030	1256	0.03	STGB	2.73	2.06	0	0	0	0	0	0	0.0	0	5.8	3.1	0.47	0.60
2031	1281	0.03	STGB	2.73	2.10	0	0	0	0	1	0	0.0	0	6.0	3.2	0.46	0.60
2032	1306	0.03	STGB	2.73	2.13	0	0	0	0	1	0	0.0	0	6.3	3.3	0.45	0.60
2033	1332	0.03	STGB	2.73	2.16	0	0	0	0	2	0	0.0	0	6.6	3.4	0.44	0.60
2034	1359	0.03	STGB	2.73	2.20	0	0	0	0	3	0	0.0	0	6.8	3.5	0.43	0.60
2035	1386	0.03	STGB	2.73	2.23	0	0	0	0	4	0	0.0	0	7.1	3.7	0.42	0.60
2036	1414	0.04	STGB	2.73	2.27	1	0	0	1	6	0	0.0	0	7.4	3.8	0.41	0.60
2037	1442	0.04	STGB	2.73	2.31	1	0	0	1	8	0	0.0	0	7.6	3.9	0.40	0.60
2038	1471	0.04	STGB	2.73	2.35	2	0	0	2	10	0	0.0	0	7.9	4.0	0.39	0.60
2039	1501	0.04	STGB	2.73	2.39	3	0	0	3	13	0	0.0	0	8.2	4.1	0.38	0.60
2040	1531	0.04	STGB	2.72	2.44	5	0	0	5	16	0	0.0	0	8.4	4.2	0.37	0.60
2041	1561	0.04	STGB	2.72	2.49	8	0	0	8	20	0	0.0	0	8.7	4.3	0.37	0.60
2042	1592	0.04	STGB	2.72	2.55	10	0	0	10	25	0	0.0	0	9.0	4.4	0.36	0.60
2043	1624	0.04	STGB	2.71	2.61	14	0	0	14	30	0	0.0	0	9.3	4.5	0.35	0.60
2044	1657	0.04	STGB	2.70	2.71	18	1	0	18	36	28	0.0	0	9.5	4.6	0.35	0.60
2045	1690	0.04	STGB	2.69	2.73	21	1	0	21	42	36	0.0	0	9.8	4.7	0.34	0.60
2046	1724	0.04	STGB	2.69	2.80	25	1	0	25	49	9	0.0	0	10.1	4.8	0.33	0.60
2047	1758	0.04	STGB	2.68	2.87	30	1	0	30	56	10	0.0	0	10.4	4.9	0.33	0.60
2048	1793	0.04	STGB	2.67	2.94	35	1	0	35	62	12	0.0	0	10.6	5.0	0.32	0.60
2049	1829	0.05	STGB	2.65	3.02	40	1	0	40	60	13	0.0	0	10.9	5.1	0.31	0.60
2050	1866	0.05	STGB	2.64	3.11	47	1	0	47	53	13	0.0	0	11.2	5.2	0.31	0.60

Section: ES1 strong semi arid
Alternative: Full maintenance
Sensitivity: No Sensitivity Analysis Conducted

				Bituminous Pavement													
				End of Year Condition													
Year		ESAL				Cracking Area (%)					Potholes			Rutting			SFC50

	MT AADT		Pavement Type	Average Structural Number SNPK	IRI (m/km)	ACA	ACW	CT	ACRA	ARV (%)	NPT (km)	APOT (%)	AEB (m/km)	Mean Rut Depth (mm)	RDS	TD (mm)	
2021	1051	0.03	STGB	2.76	1.78	0	0	0	0	0	0	0.0	0	3.4	1.9	0.71	0.60
2022	1072	0.03	STGB	2.76	1.81	0	0	0	0	0	0	0.0	0	3.7	2.0	0.65	0.60
2023	1093	0.03	STGB	2.75	1.84	0	0	0	0	0	0	0.0	0	4.0	2.2	0.61	0.60
2024	1115	0.03	STGB	2.75	1.87	0	0	0	0	0	0	0.0	0	4.2	2.3	0.58	0.60
2025	1137	0.03	STGB	2.74	1.91	0	0	0	0	0	0	0.0	0	4.5	2.4	0.56	0.60
2026	1160	0.03	STGB	2.74	1.94	0	0	0	0	0	0	0.0	0	4.7	2.6	0.54	0.60
2027	1183	0.03	STGB	2.73	1.97	0	0	0	0	0	0	0.0	0	5.0	2.7	0.52	0.60
2028	1207	0.03	STGB	2.73	2.00	0	0	0	0	0	0	0.0	0	5.3	2.8	0.50	0.60
2029	1231	0.03	STGB	2.73	2.03	0	0	0	0	0	0	0.0	0	5.5	2.9	0.49	0.60
2030	1256	0.03	STGB	2.73	2.06	0	0	0	0	0	0	0.0	0	5.8	3.1	0.47	0.60
2031	1281	0.03	STGB	2.73	2.10	0	0	0	0	1	0	0.0	0	6.0	3.2	0.46	0.60
2032	1306	0.03	STGB	2.73	2.13	0	0	0	0	1	0	0.0	0	6.3	3.3	0.45	0.60
2033	1332	0.03	STGB	2.73	2.16	0	0	0	0	2	0	0.0	0	6.6	3.4	0.44	0.60
2034	1359	0.03	STGB	2.73	2.20	0	0	0	0	3	0	0.0	0	6.8	3.5	0.43	0.60
2035	1386	0.03	STGB	2.73	2.23	0	0	0	0	4	0	0.0	0	7.1	3.7	0.42	0.60
2036	1414	0.04	STGB	2.73	2.27	1	0	0	1	6	0	0.0	0	7.4	3.8	0.41	0.60
2037	1442	0.04	STGB	2.73	2.31	1	0	0	1	8	0	0.0	0	7.6	3.9	0.40	0.60
2038	1471	0.04	STGB	2.87	2.34	0	0	0	0	0	0	0.0	0	1.4	4.0	0.75	0.52
2039	1501	0.04	STGB	2.87	2.38	0	0	0	0	0	0	0.0	0	1.6	4.2	0.66	0.52
2040	1531	0.04	STGB	2.87	2.42	0	0	0	0	0	0	0.0	0	1.9	4.3	0.60	0.52
2041	1561	0.04	STGB	2.87	2.46	0	0	0	0	0	0	0.0	0	2.2	4.5	0.57	0.52
2042	1592	0.04	STGB	2.87	2.50	0	0	0	0	0	0	0.0	0	2.4	4.6	0.54	0.52
2043	1624	0.04	STGB	2.87	2.54	0	0	0	0	0	0	0.0	0	2.7	4.8	0.51	0.52
2044	1657	0.04	STGB	2.87	2.57	0	0	0	0	0	0	0.0	0	2.9	4.9	0.49	0.52
2045	1690	0.04	STGB	2.87	2.61	0	0	0	0	0	0	0.0	0	3.2	5.1	0.47	0.52
2046	1724	0.04	STGB	2.87	2.65	0	0	0	0	0	0	0.0	0	3.4	5.2	0.45	0.52
2047	1758	0.04	STGB	2.87	2.69	0	0	0	0	0	0	0.0	0	3.7	5.3	0.44	0.52

2048	1793	0.04	STGB	2.87	2.74	0	0	0	0	1	0	0.0	0	4.0	5.5	0.43	0.52
2049	1829	0.05	STGB	2.87	2.78	0	0	0	0	1	0	0.0	0	4.2	5.6	0.41	0.52
2050	1866	0.05	STGB	2.87	2.82	0	0	0	0	3	0	0.0	0	4.5	5.8	0.40	0.52

Section: ES1 strong subhumid dry
Alternative: Base Alternative
Sensitivity: No Sensitivity Analysis Conducted

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.75	1.80	0	0	0	0	0	0	0.0	0	3.5	1.9	0.71	0.60
2022	1072	0.03	STGB	2.74	1.85	0	0	0	0	0	0	0.0	0	3.7	2.0	0.65	0.60
2023	1093	0.03	STGB	2.73	1.90	0	0	0	0	0	0	0.0	0	4.0	2.2	0.61	0.60
2024	1115	0.03	STGB	2.72	1.95	0	0	0	0	0	0	0.0	0	4.2	2.3	0.58	0.60
2025	1137	0.03	STGB	2.71	2.01	0	0	0	0	0	0	0.0	0	4.5	2.4	0.56	0.60
2026	1160	0.03	STGB	2.70	2.06	0	0	0	0	0	0	0.0	0	4.8	2.6	0.54	0.60
2027	1183	0.03	STGB	2.70	2.12	0	0	0	0	0	0	0.0	0	5.0	2.7	0.52	0.60
2028	1207	0.03	STGB	2.70	2.17	0	0	0	0	0	0	0.0	0	5.3	2.8	0.50	0.60
2029	1231	0.03	STGB	2.70	2.23	0	0	0	0	0	0	0.0	0	5.6	3.0	0.49	0.60
2030	1256	0.03	STGB	2.70	2.29	0	0	0	0	0	0	0.0	0	5.8	3.1	0.47	0.60
2031	1281	0.03	STGB	2.70	2.35	0	0	0	0	1	0	0.0	0	6.1	3.2	0.46	0.60
2032	1306	0.03	STGB	2.70	2.41	0	0	0	0	2	0	0.0	0	6.3	3.3	0.45	0.60
2033	1332	0.03	STGB	2.70	2.48	0	0	0	0	4	0	0.0	0	6.6	3.5	0.44	0.60
2034	1359	0.03	STGB	2.70	2.55	1	0	0	1	7	0	0.0	0	6.9	3.6	0.43	0.60
2035	1386	0.03	STGB	2.70	2.62	3	0	0	3	11	0	0.0	0	7.2	3.7	0.42	0.60
2036	1414	0.04	STGB	2.69	2.71	6	0	0	6	16	0	0.0	0	7.4	3.8	0.41	0.60
2037	1442	0.04	STGB	2.68	2.81	11	0	0	11	22	0	0.0	0	7.7	3.9	0.40	0.60
2038	1471	0.04	STGB	2.66	2.93	17	3	0	17	30	0	0.0	0	8.0	4.0	0.39	0.60
2039	1501	0.04	STGB	2.65	3.08	23	3	0	23	39	27	0.0	0	8.3	4.1	0.38	0.60

2040	1531	0.04	STGB	2.62	3.17	31	3	0	31	50	35	0.0	0	8.5	4.3	0.37	0.60
2041	1561	0.04	STGB	2.59	3.32	41	3	0	41	59	10	0.0	0	8.8	4.4	0.37	0.60
2042	1592	0.04	STGB	2.55	3.48	53	3	0	53	47	12	0.0	0	9.1	4.5	0.36	0.60
2043	1624	0.04	STGB	2.50	3.64	63	3	0	63	37	10	0.0	0	9.4	4.6	0.35	0.60
2044	1657	0.04	STGB	2.46	3.78	71	3	0	71	29	8	0.0	0	9.8	4.7	0.35	0.60
2045	1690	0.04	STGB	2.42	3.92	78	3	0	78	22	6	0.0	0	10.1	4.8	0.34	0.60
2046	1724	0.04	STGB	2.40	4.06	83	3	0	83	17	5	0.0	0	10.4	4.9	0.33	0.60
2047	1758	0.04	STGB	2.37	4.19	86	3	0	86	14	4	0.0	0	10.8	5.1	0.33	0.60
2048	1793	0.04	STGB	2.35	4.32	89	3	0	89	11	3	0.0	0	11.1	5.2	0.32	0.60
2049	1829	0.05	STGB	2.34	4.45	92	3	0	92	8	2	0.0	0	11.4	5.3	0.31	0.60
2050	1866	0.05	STGB	2.33	4.57	93	3	0	93	7	2	0.0	0	11.8	5.4	0.31	0.60

Section: ES1 strong subhumid dry
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.75	1.80	0	0	0	0	0	0	0.0	0	3.5	1.9	0.71	0.60
2022	1072	0.03	STGB	2.74	1.85	0	0	0	0	0	0	0.0	0	3.7	2.0	0.65	0.60
2023	1093	0.03	STGB	2.73	1.90	0	0	0	0	0	0	0.0	0	4.0	2.2	0.61	0.60
2024	1115	0.03	STGB	2.72	1.95	0	0	0	0	0	0	0.0	0	4.2	2.3	0.58	0.60
2025	1137	0.03	STGB	2.71	2.01	0	0	0	0	0	0	0.0	0	4.5	2.4	0.56	0.60
2026	1160	0.03	STGB	2.70	2.06	0	0	0	0	0	0	0.0	0	4.8	2.6	0.54	0.60
2027	1183	0.03	STGB	2.70	2.12	0	0	0	0	0	0	0.0	0	5.0	2.7	0.52	0.60
2028	1207	0.03	STGB	2.70	2.17	0	0	0	0	0	0	0.0	0	5.3	2.8	0.50	0.60
2029	1231	0.03	STGB	2.70	2.23	0	0	0	0	0	0	0.0	0	5.6	3.0	0.49	0.60
2030	1256	0.03	STGB	2.70	2.29	0	0	0	0	0	0	0.0	0	5.8	3.1	0.47	0.60
2031	1281	0.03	STGB	2.70	2.35	0	0	0	0	1	0	0.0	0	6.1	3.2	0.46	0.60

2032	1306	0.03	STGB	2.70	2.41	0	0	0	0	2	0	0.0	0	6.3	3.3	0.45	0.60
2033	1332	0.03	STGB	2.70	2.48	0	0	0	0	4	0	0.0	0	6.6	3.5	0.44	0.60
2034	1359	0.03	STGB	2.70	2.55	1	0	0	1	7	0	0.0	0	6.9	3.6	0.43	0.60
2035	1386	0.03	STGB	2.70	2.62	3	0	0	3	11	0	0.0	0	7.2	3.7	0.42	0.60
2036	1414	0.04	STGB	2.69	2.71	6	0	0	6	16	0	0.0	0	7.4	3.8	0.41	0.60
2037	1442	0.04	STGB	2.84	2.78	0	0	0	0	0	0	0.0	0	1.4	4.0	0.68	0.55
2038	1471	0.04	STGB	2.84	2.86	0	0	0	0	0	0	0.0	0	1.6	4.1	0.67	0.55
2039	1501	0.04	STGB	2.84	2.93	0	0	0	0	0	0	0.0	0	1.9	4.3	0.67	0.55
2040	1531	0.04	STGB	2.84	3.01	0	0	0	0	0	0	0.0	0	2.1	4.4	0.67	0.55
2041	1561	0.04	STGB	2.84	3.08	0	0	0	0	0	0	0.0	0	2.4	4.6	0.67	0.55
2042	1592	0.04	STGB	2.84	3.16	0	0	0	0	0	0	0.0	0	2.7	4.7	0.67	0.55
2043	1624	0.04	STGB	2.84	3.24	0	0	0	0	0	0	0.0	0	2.9	4.8	0.67	0.55
2044	1657	0.04	STGB	2.84	3.32	0	0	0	0	0	0	0.0	0	3.2	5.0	0.67	0.55
2045	1690	0.04	STGB	2.84	3.41	0	0	0	0	0	0	0.0	0	3.4	5.1	0.67	0.55
2046	1724	0.04	STGB	2.84	3.50	1	0	0	1	0	0	0.0	0	3.7	5.3	0.67	0.55
2047	1758	0.04	STGB	2.84	3.61	4	0	0	4	0	0	0.0	0	3.9	5.4	0.67	0.55
2048	1793	0.04	STGB	2.82	3.74	10	0	0	10	0	0	0.0	0	4.2	5.6	0.67	0.55
2049	1829	0.05	STGB	2.98	3.83	0	0	0	0	0	0	0.0	0	0.9	5.7	0.68	0.55
2050	1866	0.05	STGB	2.98	3.93	0	0	0	0	0	0	0.0	0	1.1	5.9	0.67	0.55

Section: ES1 strong subhumid wet
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.77	1.79	0	0	0	0	0	0	0.0	0	3.4	1.9	0.71	0.60
2022	1072	0.03	STGB	2.76	1.84	0	0	0	0	0	0	0.0	0	3.7	2.0	0.65	0.60
2023	1093	0.03	STGB	2.74	1.88	0	0	0	0	0	0	0.0	0	3.9	2.2	0.61	0.60

2024	1115	0.03	STGB	2.73	1.93	0	0	0	0	0	0	0.0	0	4.2	2.3	0.58	0.60
2025	1137	0.03	STGB	2.71	1.98	0	0	0	0	0	0	0.0	0	4.4	2.4	0.56	0.60
2026	1160	0.03	STGB	2.70	2.02	0	0	0	0	0	0	0.0	0	4.7	2.5	0.54	0.60
2027	1183	0.03	STGB	2.70	2.07	0	0	0	0	0	0	0.0	0	5.0	2.7	0.52	0.60
2028	1207	0.03	STGB	2.70	2.12	0	0	0	0	0	0	0.0	0	5.2	2.8	0.50	0.60
2029	1231	0.03	STGB	2.70	2.17	0	0	0	0	0	0	0.0	0	5.5	2.9	0.49	0.60
2030	1256	0.03	STGB	2.70	2.22	0	0	0	0	0	0	0.0	0	5.8	3.1	0.47	0.60
2031	1281	0.03	STGB	2.70	2.28	0	0	0	0	1	0	0.0	0	6.0	3.2	0.46	0.60
2032	1306	0.03	STGB	2.70	2.33	0	0	0	0	2	0	0.0	0	6.3	3.3	0.45	0.60
2033	1332	0.03	STGB	2.70	2.38	0	0	0	0	4	0	0.0	0	6.6	3.4	0.44	0.60
2034	1359	0.03	STGB	2.70	2.44	1	0	0	1	7	0	0.0	0	6.8	3.5	0.43	0.60
2035	1386	0.03	STGB	2.70	2.51	3	0	0	3	11	0	0.0	0	7.1	3.7	0.42	0.60
2036	1414	0.04	STGB	2.69	2.59	6	0	0	6	16	0	0.0	0	7.4	3.8	0.41	0.60
2037	1442	0.04	STGB	2.67	2.68	10	0	0	10	22	0	0.0	0	7.6	3.9	0.40	0.60
2038	1471	0.04	STGB	2.65	2.79	17	3	0	17	30	0	0.0	0	7.9	4.0	0.39	0.60
2039	1501	0.04	STGB	2.63	2.93	23	3	0	23	39	29	0.0	0	8.2	4.1	0.38	0.60
2040	1531	0.04	STGB	2.60	3.00	31	3	0	31	50	37	0.1	0	8.5	4.2	0.37	0.60
2041	1561	0.04	STGB	2.56	3.14	41	3	0	41	59	11	0.0	0	8.8	4.4	0.37	0.60
2042	1592	0.04	STGB	2.50	3.29	52	3	0	52	47	13	0.0	0	9.1	4.5	0.36	0.60
2043	1624	0.04	STGB	2.44	3.43	63	3	0	63	37	10	0.0	0	9.4	4.6	0.35	0.60
2044	1657	0.04	STGB	2.38	3.57	71	3	0	71	29	8	0.0	0	9.8	4.7	0.35	0.60
2045	1690	0.04	STGB	2.33	3.69	77	3	0	77	23	7	0.0	0	10.1	4.8	0.34	0.60
2046	1724	0.04	STGB	2.29	3.82	83	3	0	83	17	5	0.0	0	10.5	4.9	0.33	0.60
2047	1758	0.04	STGB	2.26	3.93	86	3	0	86	14	4	0.0	0	10.8	5.1	0.33	0.60
2048	1793	0.04	STGB	2.23	4.05	89	3	0	89	11	3	0.0	0	11.2	5.2	0.32	0.60
2049	1829	0.05	STGB	2.21	4.16	92	3	0	92	8	3	0.0	0	11.6	5.3	0.31	0.60
2050	1866	0.05	STGB	2.20	4.27	93	3	0	93	7	2	0.0	0	12.0	5.4	0.31	0.60
Section: ES1 strong subhumid wet **Alternative:** Full maintenance																	
				Bituminous Pavement													

				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.77	1.79	0	0	0	0	0	0	0.0	0	3.4	1.9	0.71	0.60
2022	1072	0.03	STGB	2.76	1.84	0	0	0	0	0	0	0.0	0	3.7	2.0	0.65	0.60
2023	1093	0.03	STGB	2.74	1.88	0	0	0	0	0	0	0.0	0	3.9	2.2	0.61	0.60
2024	1115	0.03	STGB	2.73	1.93	0	0	0	0	0	0	0.0	0	4.2	2.3	0.58	0.60
2025	1137	0.03	STGB	2.71	1.98	0	0	0	0	0	0	0.0	0	4.4	2.4	0.56	0.60
2026	1160	0.03	STGB	2.70	2.02	0	0	0	0	0	0	0.0	0	4.7	2.5	0.54	0.60
2027	1183	0.03	STGB	2.70	2.07	0	0	0	0	0	0	0.0	0	5.0	2.7	0.52	0.60
2028	1207	0.03	STGB	2.70	2.12	0	0	0	0	0	0	0.0	0	5.2	2.8	0.50	0.60
2029	1231	0.03	STGB	2.70	2.17	0	0	0	0	0	0	0.0	0	5.5	2.9	0.49	0.60
2030	1256	0.03	STGB	2.70	2.22	0	0	0	0	0	0	0.0	0	5.8	3.1	0.47	0.60
2031	1281	0.03	STGB	2.70	2.28	0	0	0	0	1	0	0.0	0	6.0	3.2	0.46	0.60
2032	1306	0.03	STGB	2.70	2.33	0	0	0	0	2	0	0.0	0	6.3	3.3	0.45	0.60
2033	1332	0.03	STGB	2.70	2.38	0	0	0	0	4	0	0.0	0	6.6	3.4	0.44	0.60
2034	1359	0.03	STGB	2.70	2.44	1	0	0	1	7	0	0.0	0	6.8	3.5	0.43	0.60
2035	1386	0.03	STGB	2.70	2.51	3	0	0	3	11	0	0.0	0	7.1	3.7	0.42	0.60
2036	1414	0.04	STGB	2.69	2.59	6	0	0	6	16	0	0.0	0	7.4	3.8	0.41	0.60
2037	1442	0.04	STGB	2.84	2.65	0	0	0	0	0	0	0.0	0	1.4	3.9	0.68	0.55
2038	1471	0.04	STGB	2.84	2.71	0	0	0	0	0	0	0.0	0	1.6	4.1	0.67	0.55
2039	1501	0.04	STGB	2.84	2.77	0	0	0	0	0	0	0.0	0	1.9	4.2	0.67	0.55
2040	1531	0.04	STGB	2.84	2.84	0	0	0	0	0	0	0.0	0	2.1	4.4	0.67	0.55
2041	1561	0.04	STGB	2.84	2.90	0	0	0	0	0	0	0.0	0	2.4	4.5	0.67	0.55
2042	1592	0.04	STGB	2.84	2.97	0	0	0	0	0	0	0.0	0	2.6	4.7	0.67	0.55
2043	1624	0.04	STGB	2.84	3.04	0	0	0	0	0	0	0.0	0	2.9	4.8	0.67	0.55
2044	1657	0.04	STGB	2.84	3.10	0	0	0	0	0	0	0.0	0	3.2	5.0	0.67	0.55
2045	1690	0.04	STGB	2.84	3.17	0	0	0	0	0	0	0.0	0	3.4	5.1	0.67	0.55

2046	1724	0.04	STGB	2.84	3.25	1	0	0	1	0	0	0.0	0	3.7	5.3	0.67	0.55
2047	1758	0.04	STGB	2.83	3.34	4	0	0	4	0	0	0.0	0	3.9	5.4	0.67	0.55
2048	1793	0.04	STGB	2.82	3.46	10	0	0	10	0	0	0.0	0	4.2	5.5	0.67	0.55
2049	1829	0.05	STGB	2.98	3.53	0	0	0	0	0	0	0.0	0	0.9	5.7	0.68	0.55
2050	1866	0.05	STGB	2.98	3.61	0	0	0	0	0	0	0.0	0	1.1	5.8	0.67	0.55

Section: ES1 strong humid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.79	1.84	0	0	0	0	0	0	0.0	0	3.4	1.9	0.71	0.60
2022	1072	0.03	STGB	2.77	1.94	0	0	0	0	0	0	0.0	0	3.6	2.0	0.65	0.60
2023	1093	0.03	STGB	2.74	2.04	0	0	0	0	0	0	0.0	0	3.9	2.1	0.61	0.60
2024	1115	0.03	STGB	2.72	2.15	0	0	0	0	0	0	0.0	0	4.1	2.3	0.58	0.60
2025	1137	0.03	STGB	2.70	2.26	0	0	0	0	0	0	0.0	0	4.4	2.4	0.56	0.60
2026	1160	0.03	STGB	2.70	2.38	0	0	0	0	0	0	0.0	0	4.7	2.5	0.54	0.60
2027	1183	0.03	STGB	2.70	2.50	0	0	0	0	0	0	0.0	0	4.9	2.7	0.52	0.60
2028	1207	0.03	STGB	2.70	2.63	0	0	0	0	0	0	0.0	0	5.2	2.8	0.50	0.60
2029	1231	0.03	STGB	2.70	2.77	0	0	0	0	0	0	0.0	0	5.4	2.9	0.49	0.60
2030	1256	0.03	STGB	2.70	2.91	0	0	0	0	0	0	0.0	0	5.7	3.0	0.47	0.60
2031	1281	0.03	STGB	2.70	3.06	0	0	0	0	1	0	0.0	0	6.0	3.2	0.46	0.60
2032	1306	0.03	STGB	2.70	3.22	0	0	0	0	2	0	0.0	0	6.2	3.3	0.45	0.60
2033	1332	0.03	STGB	2.70	3.38	0	0	0	0	4	0	0.0	0	6.5	3.4	0.44	0.60
2034	1359	0.03	STGB	2.70	3.56	1	0	0	1	7	0	0.0	0	6.8	3.5	0.43	0.60
2035	1386	0.03	STGB	2.69	3.75	3	0	0	3	11	0	0.0	0	7.0	3.7	0.42	0.60
2036	1414	0.04	STGB	2.68	3.96	6	0	0	6	16	0	0.0	0	7.3	3.8	0.41	0.60
2037	1442	0.04	STGB	2.66	4.19	10	0	0	10	22	0	0.0	0	7.6	3.9	0.40	0.60

2038	1471	0.04	STGB	2.63	4.44	17	3	0	17	30	0	0.0	0	7.9	4.0	0.39	0.60
2039	1501	0.04	STGB	2.61	4.75	23	3	0	23	39	32	0.0	0	8.1	4.1	0.38	0.60
2040	1531	0.04	STGB	2.56	5.00	31	3	0	31	50	41	0.1	0	8.4	4.2	0.37	0.60
2041	1561	0.04	STGB	2.51	5.32	41	3	0	41	59	12	0.0	0	8.8	4.3	0.37	0.60
2042	1592	0.04	STGB	2.44	5.67	52	3	0	52	48	14	0.0	0	9.1	4.5	0.36	0.60
2043	1624	0.04	STGB	2.35	6.03	63	3	0	63	37	11	0.0	0	9.4	4.6	0.35	0.60
2044	1657	0.04	STGB	2.27	6.40	71	3	0	71	29	9	0.0	0	9.8	4.7	0.35	0.60
2045	1690	0.04	STGB	2.20	6.79	77	3	0	77	23	7	0.0	0	10.2	4.9	0.34	0.60
2046	1724	0.04	STGB	2.15	7.19	82	3	0	82	18	6	0.0	0	10.6	5.0	0.33	0.60
2047	1758	0.04	STGB	2.11	7.61	86	3	0	86	14	4	0.0	0	11.0	5.1	0.33	0.60
2048	1793	0.04	STGB	2.07	8.05	89	3	0	89	11	4	0.0	0	11.4	5.3	0.32	0.60
2049	1829	0.05	STGB	2.05	8.51	92	3	0	92	8	3	0.0	0	11.8	5.4	0.31	0.60
2050	1866	0.05	STGB	2.03	8.99	93	3	0	93	7	2	0.0	0	12.2	5.5	0.31	0.60

Section: ES1 strong humid
Alternative: Full maintenance
Sensitivity: No Sensitivity Analysis Conducted

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.79	1.84	0	0	0	0	0	0	0.0	0	3.4	1.9	0.71	0.60
2022	1072	0.03	STGB	2.77	1.94	0	0	0	0	0	0	0.0	0	3.6	2.0	0.65	0.60
2023	1093	0.03	STGB	2.74	2.04	0	0	0	0	0	0	0.0	0	3.9	2.1	0.61	0.60
2024	1115	0.03	STGB	2.72	2.15	0	0	0	0	0	0	0.0	0	4.1	2.3	0.58	0.60
2025	1137	0.03	STGB	2.70	2.26	0	0	0	0	0	0	0.0	0	4.4	2.4	0.56	0.60
2026	1160	0.03	STGB	2.70	2.38	0	0	0	0	0	0	0.0	0	4.7	2.5	0.54	0.60
2027	1183	0.03	STGB	2.70	2.50	0	0	0	0	0	0	0.0	0	4.9	2.7	0.52	0.60
2028	1207	0.03	STGB	2.70	2.63	0	0	0	0	0	0	0.0	0	5.2	2.8	0.50	0.60
2029	1231	0.03	STGB	2.70	2.77	0	0	0	0	0	0	0.0	0	5.4	2.9	0.49	0.60

2030	1256	0.03	STGB	2.70	2.91	0	0	0	0	0	0	0.0	0	5.7	3.0	0.47	0.60
2031	1281	0.03	STGB	2.70	3.06	0	0	0	0	1	0	0.0	0	6.0	3.2	0.46	0.60
2032	1306	0.03	STGB	2.70	3.22	0	0	0	0	2	0	0.0	0	6.2	3.3	0.45	0.60
2033	1332	0.03	STGB	2.70	3.38	0	0	0	0	4	0	0.0	0	6.5	3.4	0.44	0.60
2034	1359	0.03	STGB	2.70	3.56	1	0	0	1	7	0	0.0	0	6.8	3.5	0.43	0.60
2035	1386	0.03	STGB	2.69	3.75	3	0	0	3	11	0	0.0	0	7.0	3.7	0.42	0.60
2036	1414	0.04	STGB	2.68	3.96	6	0	0	6	16	0	0.0	0	7.3	3.8	0.41	0.60
2037	1442	0.04	STGB	2.84	4.16	0	0	0	0	0	0	0.0	0	1.4	3.9	0.68	0.55
2038	1471	0.04	STGB	2.84	4.36	0	0	0	0	0	0	0.0	0	1.6	4.1	0.67	0.55
2039	1501	0.04	STGB	2.84	4.58	0	0	0	0	0	0	0.0	0	1.9	4.2	0.67	0.55
2040	1531	0.04	STGB	2.84	4.81	0	0	0	0	0	0	0.0	0	2.1	4.4	0.67	0.55
2041	1561	0.04	STGB	2.84	5.05	0	0	0	0	0	0	0.0	0	2.4	4.5	0.67	0.55
2042	1592	0.04	STGB	2.84	5.31	0	0	0	0	0	0	0.0	0	2.6	4.7	0.67	0.55
2043	1624	0.04	STGB	2.84	5.57	0	0	0	0	0	0	0.0	0	2.9	4.8	0.67	0.55
2044	1657	0.04	STGB	2.84	5.85	0	0	0	0	0	0	0.0	0	3.1	4.9	0.67	0.55
2045	1690	0.04	STGB	2.84	6.14	0	0	0	0	0	0	0.0	0	3.4	5.1	0.67	0.55
2046	1724	0.04	STGB	2.84	6.45	1	0	0	1	0	0	0.0	0	3.7	5.2	0.67	0.55
2047	1758	0.04	STGB	2.83	6.79	4	0	0	4	0	0	0.0	0	3.9	5.4	0.67	0.55
2048	1793	0.04	STGB	2.81	7.16	10	0	0	10	0	0	0.0	0	4.2	5.5	0.67	0.55
2049	1829	0.05	STGB	2.97	6.45	0	0	0	0	0	0	0.0	0	0.9	5.7	0.68	0.55
2050	1866	0.05	STGB	2.97	6.77	0	0	0	0	0	0	0.0	0	1.1	5.8	0.67	0.55

Table C-4: Pavement Deterioration Results – ES1 Weak

Section: ES1 weak Arid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.52	1.80	0	0	0	0	0	0	0.0	0	3.9	2.1	0.71	0.60
2022	1072	0.03	STGB	2.52	1.82	0	0	0	0	0	0	0.0	0	4.2	2.2	0.65	0.60
2023	1093	0.03	STGB	2.52	1.85	0	0	0	0	0	0	0.0	0	4.5	2.4	0.61	0.60
2024	1115	0.03	STGB	2.52	1.88	0	0	0	0	0	0	0.0	0	4.8	2.5	0.58	0.60
2025	1137	0.03	STGB	2.52	1.90	0	0	0	0	0	0	0.0	0	5.1	2.7	0.56	0.60
2026	1160	0.03	STGB	2.52	1.93	0	0	0	0	0	0	0.0	0	5.3	2.8	0.54	0.60
2027	1183	0.03	STGB	2.52	1.96	0	0	0	0	0	0	0.0	0	5.6	2.9	0.52	0.60
2028	1207	0.03	STGB	2.52	1.99	0	0	0	0	0	0	0.0	0	5.9	3.1	0.50	0.60
2029	1231	0.03	STGB	2.52	2.01	0	0	0	0	0	0	0.0	0	6.2	3.2	0.49	0.60
2030	1256	0.03	STGB	2.52	2.04	0	0	0	0	0	0	0.0	0	6.5	3.3	0.47	0.60
2031	1281	0.03	STGB	2.52	2.07	0	0	0	0	1	0	0.0	0	6.8	3.5	0.46	0.60
2032	1306	0.03	STGB	2.52	2.10	0	0	0	0	1	0	0.0	0	7.1	3.6	0.45	0.60
2033	1332	0.03	STGB	2.52	2.12	0	0	0	0	1	0	0.0	0	7.3	3.7	0.44	0.60
2034	1359	0.03	STGB	2.52	2.15	0	0	0	0	2	0	0.0	0	7.7	3.8	0.43	0.60
2035	1386	0.03	STGB	2.52	2.18	0	0	0	0	2	0	0.0	0	7.9	4.0	0.42	0.60
2036	1414	0.04	STGB	2.52	2.21	0	0	0	0	3	0	0.0	0	8.2	4.1	0.41	0.60
2037	1442	0.04	STGB	2.52	2.24	0	0	0	0	4	0	0.0	0	8.5	4.2	0.40	0.60
2038	1471	0.04	STGB	2.52	2.27	1	0	0	1	5	0	0.0	0	8.8	4.3	0.39	0.60
2039	1501	0.04	STGB	2.51	2.30	1	0	0	1	6	0	0.0	0	9.1	4.4	0.38	0.60
2040	1531	0.04	STGB	2.51	2.33	2	0	0	2	7	0	0.0	0	9.4	4.5	0.37	0.60
2041	1561	0.04	STGB	2.51	2.37	2	0	0	2	9	0	0.0	0	9.7	4.6	0.37	0.60

2042	1592	0.04	STGB	2.51	2.40	3	0	0	3	10	0	0.0	0	10.0	4.7	0.36	0.60
2043	1624	0.04	STGB	2.51	2.44	4	0	0	4	12	0	0.0	0	10.3	4.8	0.35	0.60
2044	1657	0.04	STGB	2.51	2.48	6	0	0	6	14	0	0.0	0	10.6	4.9	0.35	0.60
2045	1690	0.04	STGB	2.51	2.52	7	0	0	7	16	0	0.0	0	10.9	5.0	0.34	0.60
2046	1724	0.04	STGB	2.51	2.56	9	0	0	9	19	0	0.0	0	11.2	5.1	0.33	0.60
2047	1758	0.04	STGB	2.51	2.60	11	0	0	11	22	0	0.0	0	11.5	5.2	0.33	0.60
2048	1793	0.04	STGB	2.51	2.65	14	0	0	14	25	0	0.0	0	11.8	5.3	0.32	0.60
2049	1829	0.05	STGB	2.51	2.70	16	0	0	16	28	0	0.0	0	12.1	5.4	0.31	0.60
2050	1866	0.05	STGB	2.50	2.75	19	0	0	19	32	0	0.0	0	12.4	5.5	0.31	0.60

Section: ES1 weak Arid
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.52	1.80	0	0	0	0	0	0	0.0	0	3.9	2.1	0.71	0.60
2022	1072	0.03	STGB	2.52	1.82	0	0	0	0	0	0	0.0	0	4.2	2.2	0.65	0.60
2023	1093	0.03	STGB	2.52	1.85	0	0	0	0	0	0	0.0	0	4.5	2.4	0.61	0.60
2024	1115	0.03	STGB	2.52	1.88	0	0	0	0	0	0	0.0	0	4.8	2.5	0.58	0.60
2025	1137	0.03	STGB	2.52	1.90	0	0	0	0	0	0	0.0	0	5.1	2.7	0.56	0.60
2026	1160	0.03	STGB	2.52	1.93	0	0	0	0	0	0	0.0	0	5.3	2.8	0.54	0.60
2027	1183	0.03	STGB	2.52	1.96	0	0	0	0	0	0	0.0	0	5.6	2.9	0.52	0.60
2028	1207	0.03	STGB	2.52	1.99	0	0	0	0	0	0	0.0	0	5.9	3.1	0.50	0.60
2029	1231	0.03	STGB	2.52	2.01	0	0	0	0	0	0	0.0	0	6.2	3.2	0.49	0.60
2030	1256	0.03	STGB	2.52	2.04	0	0	0	0	0	0	0.0	0	6.5	3.3	0.47	0.60
2031	1281	0.03	STGB	2.52	2.07	0	0	0	0	1	0	0.0	0	6.8	3.5	0.46	0.60
2032	1306	0.03	STGB	2.52	2.10	0	0	0	0	1	0	0.0	0	7.1	3.6	0.45	0.60
2033	1332	0.03	STGB	2.52	2.12	0	0	0	0	1	0	0.0	0	7.3	3.7	0.44	0.60

2034	1359	0.03	STGB	2.52	2.15	0	0	0	0	2	0	0.0	0	7.7	3.8	0.43	0.60
2035	1386	0.03	STGB	2.52	2.18	0	0	0	0	2	0	0.0	0	7.9	4.0	0.42	0.60
2036	1414	0.04	STGB	2.52	2.21	0	0	0	0	3	0	0.0	0	8.2	4.1	0.41	0.60
2037	1442	0.04	STGB	2.52	2.24	0	0	0	0	4	0	0.0	0	8.5	4.2	0.40	0.60
2038	1471	0.04	STGB	2.66	2.27	0	0	0	0	0	0	0.0	0	1.5	4.4	0.75	0.52
2039	1501	0.04	STGB	2.66	2.30	0	0	0	0	0	0	0.0	0	1.8	4.5	0.66	0.52
2040	1531	0.04	STGB	2.66	2.33	0	0	0	0	0	0	0.0	0	2.1	4.7	0.60	0.52
2041	1561	0.04	STGB	2.66	2.36	0	0	0	0	0	0	0.0	0	2.4	4.9	0.57	0.52
2042	1592	0.04	STGB	2.66	2.39	0	0	0	0	0	0	0.0	0	2.7	5.0	0.54	0.52
2043	1624	0.04	STGB	2.66	2.43	0	0	0	0	0	0	0.0	0	2.9	5.2	0.51	0.52
2044	1657	0.04	STGB	2.66	2.46	0	0	0	0	0	0	0.0	0	3.2	5.3	0.49	0.52
2045	1690	0.04	STGB	2.66	2.49	0	0	0	0	0	0	0.0	0	3.5	5.5	0.47	0.52
2046	1724	0.04	STGB	2.66	2.52	0	0	0	0	0	0	0.0	0	3.8	5.6	0.45	0.52
2047	1758	0.04	STGB	2.66	2.56	0	0	0	0	0	0	0.0	0	4.1	5.8	0.44	0.52
2048	1793	0.04	STGB	2.66	2.59	0	0	0	0	1	0	0.0	0	4.3	5.9	0.43	0.52
2049	1829	0.05	STGB	2.66	2.62	0	0	0	0	1	0	0.0	0	4.6	6.1	0.41	0.52
2050	1866	0.05	STGB	2.66	2.66	0	0	0	0	2	0	0.0	0	4.9	6.2	0.40	0.52

Section: ES1 weak semi arid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.56	1.80	0	0	0	0	0	0	0.0	0	3.8	2.0	0.71	0.60
2022	1072	0.03	STGB	2.55	1.83	0	0	0	0	0	0	0.0	0	4.1	2.2	0.65	0.60
2023	1093	0.03	STGB	2.55	1.86	0	0	0	0	0	0	0.0	0	4.4	2.3	0.61	0.60
2024	1115	0.03	STGB	2.54	1.90	0	0	0	0	0	0	0.0	0	4.7	2.5	0.58	0.60
2025	1137	0.03	STGB	2.54	1.93	0	0	0	0	0	0	0.0	0	4.9	2.6	0.56	0.60

2026	1160	0.03	STGB	2.54	1.97	0	0	0	0	0	0	0.0	0	5.2	2.8	0.54	0.60
2027	1183	0.03	STGB	2.53	2.00	0	0	0	0	0	0	0.0	0	5.5	2.9	0.52	0.60
2028	1207	0.03	STGB	2.53	2.03	0	0	0	0	0	0	0.0	0	5.8	3.0	0.50	0.60
2029	1231	0.03	STGB	2.53	2.07	0	0	0	0	0	0	0.0	0	6.1	3.2	0.49	0.60
2030	1256	0.03	STGB	2.53	2.10	0	0	0	0	0	0	0.0	0	6.4	3.3	0.47	0.60
2031	1281	0.03	STGB	2.53	2.14	0	0	0	0	1	0	0.0	0	6.7	3.4	0.46	0.60
2032	1306	0.03	STGB	2.53	2.18	0	0	0	0	1	0	0.0	0	6.9	3.5	0.45	0.60
2033	1332	0.03	STGB	2.53	2.21	0	0	0	0	2	0	0.0	0	7.2	3.7	0.44	0.60
2034	1359	0.03	STGB	2.53	2.25	0	0	0	0	3	0	0.0	0	7.5	3.8	0.43	0.60
2035	1386	0.03	STGB	2.53	2.29	0	0	0	0	4	0	0.0	0	7.8	3.9	0.42	0.60
2036	1414	0.04	STGB	2.53	2.33	1	0	0	1	6	0	0.0	0	8.1	4.0	0.41	0.60
2037	1442	0.04	STGB	2.53	2.37	1	0	0	1	8	0	0.0	0	8.4	4.2	0.40	0.60
2038	1471	0.04	STGB	2.53	2.41	2	0	0	2	10	0	0.0	0	8.7	4.3	0.39	0.60
2039	1501	0.04	STGB	2.53	2.46	3	0	0	3	13	0	0.0	0	9.0	4.4	0.38	0.60
2040	1531	0.04	STGB	2.52	2.51	5	0	0	5	16	0	0.0	0	9.3	4.5	0.37	0.60
2041	1561	0.04	STGB	2.52	2.57	8	0	0	8	20	0	0.0	0	9.6	4.6	0.37	0.60
2042	1592	0.04	STGB	2.52	2.62	10	0	0	10	25	0	0.0	0	9.9	4.7	0.36	0.60
2043	1624	0.04	STGB	2.51	2.69	14	0	0	14	30	0	0.0	0	10.1	4.8	0.35	0.60
2044	1657	0.04	STGB	2.50	2.79	18	1	0	18	36	28	0.0	0	10.4	4.9	0.35	0.60
2045	1690	0.04	STGB	2.50	2.82	21	1	0	21	42	36	0.0	0	10.8	5.0	0.34	0.60
2046	1724	0.04	STGB	2.49	2.89	25	1	0	25	49	9	0.0	0	11.1	5.1	0.33	0.60
2047	1758	0.04	STGB	2.48	2.96	29	1	0	29	56	10	0.0	0	11.4	5.2	0.33	0.60
2048	1793	0.04	STGB	2.47	3.04	34	1	0	34	62	12	0.0	0	11.7	5.3	0.32	0.60
2049	1829	0.05	STGB	2.46	3.12	40	1	0	40	60	13	0.0	0	12.0	5.4	0.31	0.60
2050	1866	0.05	STGB	2.44	3.21	46	1	0	46	54	13	0.0	0	12.3	5.5	0.31	0.60

Section: ES1 weak semi arid
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year		ESAL				Cracking Area (%)					Potholes			Rutting			SFC50

	MT AADT		Pavement Type	Average Structural Number SNPK	IRI (m/km)	ACA	ACW	CT	ACRA	ARV (%)	NPT (km)	APOT (%)	AEB (m/km)	Mean Rut Depth (mm)	RDS	TD (mm)	
2021	1051	0.03	STGB	2.56	1.80	0	0	0	0	0	0	0.0	0	3.8	2.0	0.71	0.60
2022	1072	0.03	STGB	2.55	1.83	0	0	0	0	0	0	0.0	0	4.1	2.2	0.65	0.60
2023	1093	0.03	STGB	2.55	1.86	0	0	0	0	0	0	0.0	0	4.4	2.3	0.61	0.60
2024	1115	0.03	STGB	2.54	1.90	0	0	0	0	0	0	0.0	0	4.7	2.5	0.58	0.60
2025	1137	0.03	STGB	2.54	1.93	0	0	0	0	0	0	0.0	0	4.9	2.6	0.56	0.60
2026	1160	0.03	STGB	2.54	1.97	0	0	0	0	0	0	0.0	0	5.2	2.8	0.54	0.60
2027	1183	0.03	STGB	2.53	2.00	0	0	0	0	0	0	0.0	0	5.5	2.9	0.52	0.60
2028	1207	0.03	STGB	2.53	2.03	0	0	0	0	0	0	0.0	0	5.8	3.0	0.50	0.60
2029	1231	0.03	STGB	2.53	2.07	0	0	0	0	0	0	0.0	0	6.1	3.2	0.49	0.60
2030	1256	0.03	STGB	2.53	2.10	0	0	0	0	0	0	0.0	0	6.4	3.3	0.47	0.60
2031	1281	0.03	STGB	2.53	2.14	0	0	0	0	1	0	0.0	0	6.7	3.4	0.46	0.60
2032	1306	0.03	STGB	2.53	2.18	0	0	0	0	1	0	0.0	0	6.9	3.5	0.45	0.60
2033	1332	0.03	STGB	2.53	2.21	0	0	0	0	2	0	0.0	0	7.2	3.7	0.44	0.60
2034	1359	0.03	STGB	2.53	2.25	0	0	0	0	3	0	0.0	0	7.5	3.8	0.43	0.60
2035	1386	0.03	STGB	2.53	2.29	0	0	0	0	4	0	0.0	0	7.8	3.9	0.42	0.60
2036	1414	0.04	STGB	2.53	2.33	1	0	0	1	6	0	0.0	0	8.1	4.0	0.41	0.60
2037	1442	0.04	STGB	2.53	2.37	1	0	0	1	8	0	0.0	0	8.4	4.2	0.40	0.60
2038	1471	0.04	STGB	2.67	2.41	0	0	0	0	0	0	0.0	0	1.5	4.3	0.75	0.52
2039	1501	0.04	STGB	2.67	2.45	0	0	0	0	0	0	0.0	0	1.8	4.5	0.66	0.52
2040	1531	0.04	STGB	2.67	2.49	0	0	0	0	0	0	0.0	0	2.1	4.7	0.60	0.52
2041	1561	0.04	STGB	2.67	2.53	0	0	0	0	0	0	0.0	0	2.4	4.8	0.57	0.52
2042	1592	0.04	STGB	2.67	2.58	0	0	0	0	0	0	0.0	0	2.6	5.0	0.54	0.52
2043	1624	0.04	STGB	2.67	2.62	0	0	0	0	0	0	0.0	0	2.9	5.1	0.51	0.52
2044	1657	0.04	STGB	2.67	2.66	0	0	0	0	0	0	0.0	0	3.2	5.3	0.49	0.52
2045	1690	0.04	STGB	2.67	2.70	0	0	0	0	0	0	0.0	0	3.5	5.4	0.47	0.52
2046	1724	0.04	STGB	2.67	2.75	0	0	0	0	0	0	0.0	0	3.7	5.6	0.45	0.52
2047	1758	0.04	STGB	2.67	2.79	0	0	0	0	0	0	0.0	0	4.0	5.7	0.44	0.52

2048	1793	0.04	STGB	2.67	2.84	0	0	0	0	1	0	0.0	0	4.3	5.9	0.43	0.52
2049	1829	0.05	STGB	2.67	2.88	0	0	0	0	1	0	0.0	0	4.6	6.0	0.41	0.52
2050	1866	0.05	STGB	2.67	2.93	0	0	0	0	3	0	0.0	0	4.9	6.2	0.40	0.52

Section: ES1 weak subhumid dry
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.55	1.82	0	0	0	0	0	0	0.0	0	3.8	2.0	0.71	0.60
2022	1072	0.03	STGB	2.54	1.87	0	0	0	0	0	0	0.0	0	4.1	2.2	0.65	0.60
2023	1093	0.03	STGB	2.53	1.92	0	0	0	0	0	0	0.0	0	4.4	2.3	0.61	0.60
2024	1115	0.03	STGB	2.52	1.98	0	0	0	0	0	0	0.0	0	4.7	2.5	0.58	0.60
2025	1137	0.03	STGB	2.51	2.03	0	0	0	0	0	0	0.0	0	5.0	2.6	0.56	0.60
2026	1160	0.03	STGB	2.50	2.09	0	0	0	0	0	0	0.0	0	5.3	2.8	0.54	0.60
2027	1183	0.03	STGB	2.50	2.15	0	0	0	0	0	0	0.0	0	5.5	2.9	0.52	0.60
2028	1207	0.03	STGB	2.50	2.21	0	0	0	0	0	0	0.0	0	5.8	3.0	0.50	0.60
2029	1231	0.03	STGB	2.50	2.27	0	0	0	0	0	0	0.0	0	6.1	3.2	0.49	0.60
2030	1256	0.03	STGB	2.50	2.34	0	0	0	0	0	0	0.0	0	6.4	3.3	0.47	0.60
2031	1281	0.03	STGB	2.50	2.40	0	0	0	0	1	0	0.0	0	6.7	3.5	0.46	0.60
2032	1306	0.03	STGB	2.50	2.47	0	0	0	0	2	0	0.0	0	7.0	3.6	0.45	0.60
2033	1332	0.03	STGB	2.50	2.53	0	0	0	0	4	0	0.0	0	7.3	3.7	0.44	0.60
2034	1359	0.03	STGB	2.50	2.61	1	0	0	1	7	0	0.0	0	7.6	3.8	0.43	0.60
2035	1386	0.03	STGB	2.50	2.69	3	0	0	3	11	0	0.0	0	7.9	4.0	0.42	0.60
2036	1414	0.04	STGB	2.49	2.79	7	0	0	7	15	0	0.0	0	8.2	4.1	0.41	0.60
2037	1442	0.04	STGB	2.48	2.90	12	1	0	12	22	0	0.0	0	8.5	4.2	0.40	0.60
2038	1471	0.04	STGB	2.46	3.02	20	4	0	20	29	0	0.0	0	8.8	4.3	0.39	0.60
2039	1501	0.04	STGB	2.45	3.17	25	3	0	25	39	27	0.0	0	9.1	4.4	0.38	0.60

2040	1531	0.04	STGB	2.42	3.27	33	3	0	33	50	34	0.0	0	9.4	4.5	0.37	0.60
2041	1561	0.04	STGB	2.39	3.43	43	3	0	43	57	10	0.0	0	9.7	4.7	0.37	0.60
2042	1592	0.04	STGB	2.35	3.60	55	3	0	55	45	11	0.0	0	10.0	4.8	0.36	0.60
2043	1624	0.04	STGB	2.31	3.76	64	3	0	64	36	9	0.0	0	10.4	4.9	0.35	0.60
2044	1657	0.04	STGB	2.27	3.91	72	3	0	72	28	7	0.0	0	10.7	5.0	0.35	0.60
2045	1690	0.04	STGB	2.24	4.06	79	3	0	79	21	6	0.0	0	11.1	5.1	0.34	0.60
2046	1724	0.04	STGB	2.21	4.20	83	3	0	83	17	5	0.0	0	11.4	5.2	0.33	0.60
2047	1758	0.04	STGB	2.19	4.34	87	3	0	87	13	4	0.0	0	11.8	5.3	0.33	0.60
2048	1793	0.04	STGB	2.17	4.48	90	3	0	90	10	3	0.0	0	12.2	5.4	0.32	0.60
2049	1829	0.05	STGB	2.16	4.61	92	3	0	92	8	2	0.0	0	12.6	5.5	0.31	0.60
2050	1866	0.05	STGB	2.15	4.75	93	3	0	93	7	2	0.0	0	12.9	5.6	0.31	0.60

Section: ES1 weak subhumid dry
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.55	1.82	0	0	0	0	0	0	0.0	0	3.8	2.0	0.71	0.60
2022	1072	0.03	STGB	2.54	1.87	0	0	0	0	0	0	0.0	0	4.1	2.2	0.65	0.60
2023	1093	0.03	STGB	2.53	1.92	0	0	0	0	0	0	0.0	0	4.4	2.3	0.61	0.60
2024	1115	0.03	STGB	2.52	1.98	0	0	0	0	0	0	0.0	0	4.7	2.5	0.58	0.60
2025	1137	0.03	STGB	2.51	2.03	0	0	0	0	0	0	0.0	0	5.0	2.6	0.56	0.60
2026	1160	0.03	STGB	2.50	2.09	0	0	0	0	0	0	0.0	0	5.3	2.8	0.54	0.60
2027	1183	0.03	STGB	2.50	2.15	0	0	0	0	0	0	0.0	0	5.5	2.9	0.52	0.60
2028	1207	0.03	STGB	2.50	2.21	0	0	0	0	0	0	0.0	0	5.8	3.0	0.50	0.60
2029	1231	0.03	STGB	2.50	2.27	0	0	0	0	0	0	0.0	0	6.1	3.2	0.49	0.60
2030	1256	0.03	STGB	2.50	2.34	0	0	0	0	0	0	0.0	0	6.4	3.3	0.47	0.60
2031	1281	0.03	STGB	2.50	2.40	0	0	0	0	1	0	0.0	0	6.7	3.5	0.46	0.60

2032	1306	0.03	STGB	2.50	2.47	0	0	0	0	2	0	0.0	0	7.0	3.6	0.45	0.60
2033	1332	0.03	STGB	2.50	2.53	0	0	0	0	4	0	0.0	0	7.3	3.7	0.44	0.60
2034	1359	0.03	STGB	2.50	2.61	1	0	0	1	7	0	0.0	0	7.6	3.8	0.43	0.60
2035	1386	0.03	STGB	2.50	2.69	3	0	0	3	11	0	0.0	0	7.9	4.0	0.42	0.60
2036	1414	0.04	STGB	2.58	2.76	0	0	0	0	0	0	0.0	0	8.1	4.1	0.63	0.55
2037	1442	0.04	STGB	2.58	2.84	0	0	0	0	0	0	0.0	0	8.4	4.2	0.59	0.55
2038	1471	0.04	STGB	2.58	2.91	0	0	0	0	0	0	0.0	0	8.7	4.3	0.56	0.55
2039	1501	0.04	STGB	2.58	2.98	0	0	0	0	0	0	0.0	0	9.0	4.4	0.53	0.55
2040	1531	0.04	STGB	2.58	3.06	0	0	0	0	0	0	0.0	0	9.3	4.5	0.51	0.55
2041	1561	0.04	STGB	2.58	3.14	0	0	0	0	0	0	0.0	0	9.6	4.6	0.49	0.55
2042	1592	0.04	STGB	2.58	3.22	0	0	0	0	0	0	0.0	0	9.9	4.7	0.47	0.55
2043	1624	0.04	STGB	2.58	3.30	0	0	0	0	0	0	0.0	0	10.1	4.8	0.45	0.55
2044	1657	0.04	STGB	2.58	3.38	0	0	0	0	0	0	0.0	0	10.4	4.9	0.44	0.55
2045	1690	0.04	STGB	2.58	3.47	0	0	0	0	0	0	0.0	0	10.7	5.0	0.43	0.55
2046	1724	0.04	STGB	2.58	3.56	0	0	0	0	1	0	0.0	0	11.0	5.1	0.41	0.55
2047	1758	0.04	STGB	2.58	3.65	0	0	0	0	3	0	0.0	0	11.3	5.2	0.40	0.55
2048	1793	0.04	STGB	2.58	3.74	1	0	0	1	6	0	0.0	0	11.6	5.3	0.39	0.55
2049	1829	0.05	STGB	2.71	3.84	0	0	0	0	0	0	0.0	0	2.0	5.4	0.72	0.52
2050	1866	0.05	STGB	2.71	3.94	0	0	0	0	0	0	0.0	0	2.3	5.6	0.63	0.52

Section: ES1 weak subhumid wet
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.57	1.81	0	0	0	0	0	0	0.0	0	3.8	2.0	0.71	0.60
2022	1072	0.03	STGB	2.55	1.86	0	0	0	0	0	0	0.0	0	4.1	2.2	0.65	0.60
2023	1093	0.03	STGB	2.54	1.90	0	0	0	0	0	0	0.0	0	4.3	2.3	0.61	0.60

2024	1115	0.03	STGB	2.53	1.95	0	0	0	0	0	0	0.0	0	4.6	2.5	0.58	0.60
2025	1137	0.03	STGB	2.51	2.00	0	0	0	0	0	0	0.0	0	4.9	2.6	0.56	0.60
2026	1160	0.03	STGB	2.50	2.05	0	0	0	0	0	0	0.0	0	5.2	2.8	0.54	0.60
2027	1183	0.03	STGB	2.50	2.11	0	0	0	0	0	0	0.0	0	5.5	2.9	0.52	0.60
2028	1207	0.03	STGB	2.50	2.16	0	0	0	0	0	0	0.0	0	5.8	3.0	0.50	0.60
2029	1231	0.03	STGB	2.50	2.21	0	0	0	0	0	0	0.0	0	6.1	3.2	0.49	0.60
2030	1256	0.03	STGB	2.50	2.27	0	0	0	0	0	0	0.0	0	6.3	3.3	0.47	0.60
2031	1281	0.03	STGB	2.50	2.32	0	0	0	0	1	0	0.0	0	6.6	3.4	0.46	0.60
2032	1306	0.03	STGB	2.50	2.38	0	0	0	0	2	0	0.0	0	6.9	3.5	0.45	0.60
2033	1332	0.03	STGB	2.50	2.44	0	0	0	0	4	0	0.0	0	7.2	3.7	0.44	0.60
2034	1359	0.03	STGB	2.50	2.50	1	0	0	1	7	0	0.0	0	7.5	3.8	0.43	0.60
2035	1386	0.03	STGB	2.50	2.58	3	0	0	3	11	0	0.0	0	7.8	3.9	0.42	0.60
2036	1414	0.04	STGB	2.49	2.66	7	0	0	7	15	0	0.0	0	8.1	4.1	0.41	0.60
2037	1442	0.04	STGB	2.47	2.76	12	1	0	12	22	0	0.0	0	8.4	4.2	0.40	0.60
2038	1471	0.04	STGB	2.45	2.88	20	4	0	20	29	0	0.0	0	8.7	4.3	0.39	0.60
2039	1501	0.04	STGB	2.43	3.01	25	3	0	25	39	29	0.0	0	9.0	4.4	0.38	0.60
2040	1531	0.04	STGB	2.40	3.10	33	3	0	33	50	37	0.0	0	9.3	4.5	0.37	0.60
2041	1561	0.04	STGB	2.36	3.24	43	3	0	43	57	10	0.0	0	9.6	4.6	0.37	0.60
2042	1592	0.04	STGB	2.31	3.40	55	3	0	55	45	12	0.0	0	10.0	4.8	0.36	0.60
2043	1624	0.04	STGB	2.25	3.55	64	3	0	64	36	10	0.0	0	10.4	4.9	0.35	0.60
2044	1657	0.04	STGB	2.19	3.69	72	3	0	72	28	8	0.0	0	10.7	5.0	0.35	0.60
2045	1690	0.04	STGB	2.15	3.82	79	3	0	79	21	6	0.0	0	11.1	5.1	0.34	0.60
2046	1724	0.04	STGB	2.11	3.95	83	3	0	83	17	5	0.0	0	11.5	5.2	0.33	0.60
2047	1758	0.04	STGB	2.08	4.08	87	3	0	87	13	4	0.0	0	11.9	5.3	0.33	0.60
2048	1793	0.04	STGB	2.06	4.20	90	3	0	90	10	3	0.0	0	12.3	5.5	0.32	0.60
2049	1829	0.05	STGB	2.05	4.32	92	3	0	92	8	2	0.0	0	12.7	5.6	0.31	0.60
2050	1866	0.05	STGB	2.03	4.45	93	3	0	93	7	2	0.0	0	13.1	5.7	0.31	0.60

Section: ES1 weak subhumid wet
Alternative: Full maintenance

Bituminous Pavement

				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.57	1.81	0	0	0	0	0	0	0.0	0	3.8	2.0	0.71	0.60
2022	1072	0.03	STGB	2.55	1.86	0	0	0	0	0	0	0.0	0	4.1	2.2	0.65	0.60
2023	1093	0.03	STGB	2.54	1.90	0	0	0	0	0	0	0.0	0	4.3	2.3	0.61	0.60
2024	1115	0.03	STGB	2.53	1.95	0	0	0	0	0	0	0.0	0	4.6	2.5	0.58	0.60
2025	1137	0.03	STGB	2.51	2.00	0	0	0	0	0	0	0.0	0	4.9	2.6	0.56	0.60
2026	1160	0.03	STGB	2.50	2.05	0	0	0	0	0	0	0.0	0	5.2	2.8	0.54	0.60
2027	1183	0.03	STGB	2.50	2.11	0	0	0	0	0	0	0.0	0	5.5	2.9	0.52	0.60
2028	1207	0.03	STGB	2.50	2.16	0	0	0	0	0	0	0.0	0	5.8	3.0	0.50	0.60
2029	1231	0.03	STGB	2.50	2.21	0	0	0	0	0	0	0.0	0	6.1	3.2	0.49	0.60
2030	1256	0.03	STGB	2.50	2.27	0	0	0	0	0	0	0.0	0	6.3	3.3	0.47	0.60
2031	1281	0.03	STGB	2.50	2.32	0	0	0	0	1	0	0.0	0	6.6	3.4	0.46	0.60
2032	1306	0.03	STGB	2.50	2.38	0	0	0	0	2	0	0.0	0	6.9	3.5	0.45	0.60
2033	1332	0.03	STGB	2.50	2.44	0	0	0	0	4	0	0.0	0	7.2	3.7	0.44	0.60
2034	1359	0.03	STGB	2.50	2.50	1	0	0	1	7	0	0.0	0	7.5	3.8	0.43	0.60
2035	1386	0.03	STGB	2.50	2.58	3	0	0	3	11	0	0.0	0	7.8	3.9	0.42	0.60
2036	1414	0.04	STGB	2.58	2.64	0	0	0	0	0	0	0.0	0	8.1	4.0	0.63	0.55
2037	1442	0.04	STGB	2.58	2.70	0	0	0	0	0	0	0.0	0	8.4	4.2	0.59	0.55
2038	1471	0.04	STGB	2.58	2.76	0	0	0	0	0	0	0.0	0	8.6	4.3	0.56	0.55
2039	1501	0.04	STGB	2.58	2.82	0	0	0	0	0	0	0.0	0	8.9	4.4	0.53	0.55
2040	1531	0.04	STGB	2.58	2.89	0	0	0	0	0	0	0.0	0	9.2	4.5	0.51	0.55
2041	1561	0.04	STGB	2.58	2.95	0	0	0	0	0	0	0.0	0	9.5	4.6	0.49	0.55
2042	1592	0.04	STGB	2.58	3.02	0	0	0	0	0	0	0.0	0	9.8	4.7	0.47	0.55
2043	1624	0.04	STGB	2.58	3.09	0	0	0	0	0	0	0.0	0	10.1	4.8	0.45	0.55
2044	1657	0.04	STGB	2.58	3.16	0	0	0	0	0	0	0.0	0	10.4	4.9	0.44	0.55
2045	1690	0.04	STGB	2.58	3.23	0	0	0	0	0	0	0.0	0	10.7	5.0	0.43	0.55

2046	1724	0.04	STGB	2.58	3.30	0	0	0	0	1	0	0.0	0	10.9	5.1	0.41	0.55
2047	1758	0.04	STGB	2.58	3.37	0	0	0	0	3	0	0.0	0	11.2	5.2	0.40	0.55
2048	1793	0.04	STGB	2.58	3.45	1	0	0	1	6	0	0.0	0	11.5	5.3	0.39	0.55
2049	1829	0.05	STGB	2.71	3.53	0	0	0	0	0	0	0.0	0	2.0	5.4	0.72	0.52
2050	1866	0.05	STGB	2.71	3.61	0	0	0	0	0	0	0.0	0	2.3	5.6	0.63	0.52

Section: ES1 weak humid
Alternative: Base Alternative

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.58	1.85	0	0	0	0	0	0	0.0	0	3.7	2.0	0.71	0.60
2022	1072	0.03	STGB	2.56	1.95	0	0	0	0	0	0	0.0	0	4.0	2.2	0.65	0.60
2023	1093	0.03	STGB	2.54	2.06	0	0	0	0	0	0	0.0	0	4.3	2.3	0.61	0.60
2024	1115	0.03	STGB	2.52	2.17	0	0	0	0	0	0	0.0	0	4.6	2.5	0.58	0.60
2025	1137	0.03	STGB	2.50	2.29	0	0	0	0	0	0	0.0	0	4.9	2.6	0.56	0.60
2026	1160	0.03	STGB	2.50	2.41	0	0	0	0	0	0	0.0	0	5.2	2.7	0.54	0.60
2027	1183	0.03	STGB	2.50	2.54	0	0	0	0	0	0	0.0	0	5.4	2.9	0.52	0.60
2028	1207	0.03	STGB	2.50	2.68	0	0	0	0	0	0	0.0	0	5.7	3.0	0.50	0.60
2029	1231	0.03	STGB	2.50	2.82	0	0	0	0	0	0	0.0	0	6.0	3.1	0.49	0.60
2030	1256	0.03	STGB	2.50	2.96	0	0	0	0	0	0	0.0	0	6.3	3.3	0.47	0.60
2031	1281	0.03	STGB	2.50	3.12	0	0	0	0	1	0	0.0	0	6.6	3.4	0.46	0.60
2032	1306	0.03	STGB	2.50	3.28	0	0	0	0	2	0	0.0	0	6.9	3.5	0.45	0.60
2033	1332	0.03	STGB	2.50	3.45	0	0	0	0	4	0	0.0	0	7.2	3.7	0.44	0.60
2034	1359	0.03	STGB	2.50	3.64	1	0	0	1	7	0	0.0	0	7.4	3.8	0.43	0.60
2035	1386	0.03	STGB	2.49	3.84	3	0	0	3	11	0	0.0	0	7.7	3.9	0.42	0.60
2036	1414	0.04	STGB	2.48	4.06	7	0	0	7	15	0	0.0	0	8.0	4.0	0.41	0.60
2037	1442	0.04	STGB	2.46	4.31	12	1	0	12	22	0	0.0	0	8.3	4.2	0.40	0.60

2038	1471	0.04	STGB	2.43	4.58	20	4	0	20	29	0	0.0	0	8.6	4.3	0.39	0.60
2039	1501	0.04	STGB	2.41	4.89	24	3	0	24	39	32	0.0	0	9.0	4.4	0.38	0.60
2040	1531	0.04	STGB	2.37	5.15	33	3	0	33	50	40	0.1	0	9.3	4.5	0.37	0.60
2041	1561	0.04	STGB	2.31	5.49	43	3	0	43	57	11	0.0	0	9.6	4.6	0.37	0.60
2042	1592	0.04	STGB	2.24	5.86	54	3	0	54	46	13	0.0	0	10.0	4.8	0.36	0.60
2043	1624	0.04	STGB	2.16	6.24	64	3	0	64	36	11	0.0	0	10.4	4.9	0.35	0.60
2044	1657	0.04	STGB	2.09	6.63	72	3	0	72	28	9	0.0	0	10.8	5.0	0.35	0.60
2045	1690	0.04	STGB	2.03	7.04	78	3	0	78	22	7	0.0	0	11.2	5.1	0.34	0.60
2046	1724	0.04	STGB	1.98	7.47	83	3	0	83	17	5	0.0	0	11.6	5.3	0.33	0.60
2047	1758	0.04	STGB	1.94	7.92	87	3	0	87	13	4	0.0	0	12.0	5.4	0.33	0.60
2048	1793	0.04	STGB	1.91	8.40	90	3	0	90	10	3	0.0	0	12.5	5.5	0.32	0.60
2049	1829	0.05	STGB	1.89	8.90	92	3	0	92	8	3	0.0	0	13.0	5.7	0.31	0.60
2050	1866	0.05	STGB	1.87	9.43	93	3	0	93	7	2	0.0	0	13.4	5.8	0.31	0.60

Section: ES1 weak humid
Alternative: Full maintenance

				Bituminous Pavement													
				End of Year Condition													
Year	MT AADT	ESAL	Pavement Type	Average Structural Number SNPK	IRI (m/km)	Cracking Area (%)				ARV (%)	Potholes		AEB (m/km)	Rutting		TD (mm)	SFC50
						ACA	ACW	CT	ACRA		NPT (km)	APOT (%)		Mean Rut Depth (mm)	RDS		
2021	1051	0.03	STGB	2.58	1.85	0	0	0	0	0	0	0.0	0	3.7	2.0	0.71	0.60
2022	1072	0.03	STGB	2.56	1.95	0	0	0	0	0	0	0.0	0	4.0	2.2	0.65	0.60
2023	1093	0.03	STGB	2.54	2.06	0	0	0	0	0	0	0.0	0	4.3	2.3	0.61	0.60
2024	1115	0.03	STGB	2.52	2.17	0	0	0	0	0	0	0.0	0	4.6	2.5	0.58	0.60
2025	1137	0.03	STGB	2.50	2.29	0	0	0	0	0	0	0.0	0	4.9	2.6	0.56	0.60
2026	1160	0.03	STGB	2.50	2.41	0	0	0	0	0	0	0.0	0	5.2	2.7	0.54	0.60
2027	1183	0.03	STGB	2.50	2.54	0	0	0	0	0	0	0.0	0	5.4	2.9	0.52	0.60
2028	1207	0.03	STGB	2.50	2.68	0	0	0	0	0	0	0.0	0	5.7	3.0	0.50	0.60
2029	1231	0.03	STGB	2.50	2.82	0	0	0	0	0	0	0.0	0	6.0	3.1	0.49	0.60

2030	1256	0.03	STGB	2.50	2.96	0	0	0	0	0	0	0.0	0	6.3	3.3	0.47	0.60
2031	1281	0.03	STGB	2.50	3.12	0	0	0	0	1	0	0.0	0	6.6	3.4	0.46	0.60
2032	1306	0.03	STGB	2.50	3.28	0	0	0	0	2	0	0.0	0	6.9	3.5	0.45	0.60
2033	1332	0.03	STGB	2.50	3.45	0	0	0	0	4	0	0.0	0	7.2	3.7	0.44	0.60
2034	1359	0.03	STGB	2.50	3.64	1	0	0	1	7	0	0.0	0	7.4	3.8	0.43	0.60
2035	1386	0.03	STGB	2.49	3.84	3	0	0	3	11	0	0.0	0	7.7	3.9	0.42	0.60
2036	1414	0.04	STGB	2.57	4.04	0	0	0	0	0	0	0.0	0	8.0	4.0	0.63	0.55
2037	1442	0.04	STGB	2.57	4.24	0	0	0	0	0	0	0.0	0	8.3	4.1	0.59	0.55
2038	1471	0.04	STGB	2.57	4.46	0	0	0	0	0	0	0.0	0	8.6	4.2	0.56	0.55
2039	1501	0.04	STGB	2.57	4.68	0	0	0	0	0	0	0.0	0	8.9	4.3	0.53	0.55
2040	1531	0.04	STGB	2.57	4.92	0	0	0	0	0	0	0.0	0	9.1	4.5	0.51	0.55
2041	1561	0.04	STGB	2.57	5.17	0	0	0	0	0	0	0.0	0	9.4	4.6	0.49	0.55
2042	1592	0.04	STGB	2.57	5.43	0	0	0	0	0	0	0.0	0	9.7	4.7	0.47	0.55
2043	1624	0.04	STGB	2.57	5.70	0	0	0	0	0	0	0.0	0	10.0	4.8	0.45	0.55
2044	1657	0.04	STGB	2.57	5.99	0	0	0	0	0	0	0.0	0	10.3	4.9	0.44	0.55
2045	1690	0.04	STGB	2.57	6.29	0	0	0	0	0	0	0.0	0	10.6	5.0	0.43	0.55
2046	1724	0.04	STGB	2.57	6.60	0	0	0	0	1	0	0.0	0	10.9	5.1	0.41	0.55
2047	1758	0.04	STGB	2.57	6.93	0	0	0	0	3	0	0.0	0	11.2	5.2	0.40	0.55
2048	1793	0.04	STGB	2.57	7.29	1	0	0	1	6	0	0.0	0	11.4	5.2	0.39	0.55
2049	1829	0.05	STGB	2.70	6.63	0	0	0	0	0	0	0.0	0	2.0	5.4	0.72	0.52
2050	1866	0.05	STGB	2.70	6.96	0	0	0	0	0	0	0.0	0	2.3	5.6	0.63	0.52

APPENDIX D

PAVEMENT USE PHASE DETAILED RESULTS

Table D-1: Road User Emission Results – ES10 Strong

Section: ES10strong Arid **Alternative:** Base Alternative							
Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.18	6.19	0.12	829.52	0.59	0.09
2022	0.88	3.23	6.31	0.12	845.11	0.60	0.09
2023	0.89	3.28	6.42	0.13	860.96	0.62	0.09
2024	0.91	3.33	6.54	0.13	877.09	0.63	0.10
2025	0.92	3.38	6.66	0.13	893.50	0.64	0.10
2026	0.94	3.44	6.79	0.13	910.20	0.65	0.10
2027	0.96	3.49	6.91	0.14	927.21	0.66	0.10
2028	0.97	3.55	7.04	0.14	944.53	0.68	0.10
2029	0.99	3.60	7.17	0.14	962.15	0.69	0.11
2030	1.01	3.66	7.30	0.14	980.09	0.70	0.11
2031	1.03	3.72	7.44	0.15	998.36	0.72	0.11
2032	1.04	3.77	7.57	0.15	1,016.96	0.73	0.11
2033	1.06	3.83	7.71	0.15	1,035.89	0.74	0.11
2034	1.08	3.89	7.85	0.16	1,055.16	0.76	0.12
2035	1.10	3.95	8.00	0.16	1,074.78	0.77	0.12
2036	1.12	4.01	8.14	0.16	1,094.75	0.79	0.12
2037	1.14	4.07	8.29	0.16	1,114.82	0.80	0.12
2038	1.15	4.12	8.44	0.17	1,135.20	0.82	0.12
2039	1.17	4.18	8.59	0.17	1,155.93	0.83	0.13
2040	1.19	4.24	8.74	0.17	1,177.00	0.85	0.13
2041	1.21	4.30	8.90	0.18	1,198.45	0.87	0.13
2042	1.23	4.36	9.05	0.18	1,220.26	0.88	0.13
2043	1.25	4.42	9.21	0.18	1,242.46	0.90	0.14
2044	1.27	4.48	9.38	0.19	1,265.04	0.92	0.14
2045	1.30	4.55	9.56	0.19	1,289.62	0.94	0.14
2046	1.32	4.61	9.73	0.20	1,313.05	0.95	0.14
2047	1.34	4.67	9.88	0.20	1,335.22	0.97	0.15
2048	1.36	4.73	10.06	0.20	1,359.43	0.99	0.15
2049	1.38	4.79	10.23	0.21	1,384.06	1.01	0.15
2050	1.40	4.85	10.41	0.21	1,409.13	1.03	0.15
Section: ES10strong Arid **Alternative:** Full maintenance							
Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.18	6.19	0.12	829.52	0.59	0.09
2022	0.88	3.23	6.31	0.12	845.11	0.60	0.09
2023	0.89	3.28	6.42	0.13	860.96	0.62	0.09
2024	0.91	3.33	6.54	0.13	877.09	0.63	0.10
2025	0.92	3.38	6.66	0.13	893.50	0.64	0.10

2026	0.94	3.44	6.79	0.13	910.20	0.65	0.10
2027	0.96	3.49	6.91	0.14	927.21	0.66	0.10
2028	0.97	3.55	7.04	0.14	944.53	0.68	0.10
2029	0.99	3.59	7.16	0.14	960.64	0.69	0.11
2030	1.00	3.65	7.28	0.14	977.78	0.70	0.11
2031	1.02	3.70	7.41	0.15	995.94	0.71	0.11
2032	1.04	3.76	7.55	0.15	1,014.41	0.73	0.11
2033	1.06	3.82	7.69	0.15	1,033.21	0.74	0.11
2034	1.08	3.87	7.83	0.15	1,052.34	0.76	0.12
2035	1.09	3.93	7.97	0.16	1,071.82	0.77	0.12
2036	1.11	3.99	8.11	0.16	1,091.64	0.79	0.12
2037	1.13	4.05	8.25	0.16	1,111.03	0.80	0.12
2038	1.15	4.10	8.39	0.17	1,130.41	0.81	0.12
2039	1.17	4.16	8.54	0.17	1,150.94	0.83	0.13
2040	1.18	4.21	8.69	0.17	1,171.83	0.84	0.13
2041	1.20	4.27	8.85	0.18	1,193.07	0.86	0.13
2042	1.22	4.33	9.01	0.18	1,214.68	0.88	0.13
2043	1.24	4.39	9.16	0.18	1,236.66	0.89	0.14
2044	1.26	4.45	9.33	0.19	1,259.03	0.91	0.14
2045	1.28	4.51	9.49	0.19	1,281.42	0.93	0.14
2046	1.30	4.56	9.64	0.19	1,303.56	0.94	0.14
2047	1.32	4.62	9.81	0.20	1,327.04	0.96	0.15
2048	1.34	4.69	9.98	0.20	1,350.92	0.98	0.15
2049	1.37	4.75	10.16	0.20	1,375.23	1.00	0.15
2050	1.39	4.81	10.33	0.21	1,399.96	1.02	0.15

Section: ES10 strong semi arid
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.18	6.20	0.12	830.83	0.59	0.09
2022	0.88	3.24	6.32	0.12	846.47	0.61	0.09
2023	0.90	3.29	6.44	0.13	862.38	0.62	0.10
2024	0.91	3.34	6.56	0.13	878.56	0.63	0.10
2025	0.93	3.39	6.68	0.13	895.05	0.64	0.10
2026	0.94	3.45	6.80	0.13	911.82	0.65	0.10
2027	0.96	3.50	6.93	0.14	928.89	0.67	0.10
2028	0.98	3.56	7.05	0.14	946.28	0.68	0.10
2029	0.99	3.61	7.18	0.14	964.00	0.69	0.11
2030	1.01	3.67	7.32	0.14	982.04	0.71	0.11
2031	1.03	3.73	7.45	0.15	1,000.42	0.72	0.11
2032	1.05	3.79	7.59	0.15	1,019.13	0.73	0.11
2033	1.06	3.84	7.73	0.15	1,038.19	0.75	0.11
2034	1.08	3.90	7.87	0.16	1,057.60	0.76	0.12
2035	1.10	3.96	8.02	0.16	1,077.32	0.78	0.12
2036	1.12	4.02	8.16	0.16	1,097.40	0.79	0.12

2037	1.14	4.08	8.31	0.17	1,117.57	0.81	0.12
2038	1.16	4.14	8.46	0.17	1,138.12	0.82	0.13
2039	1.18	4.21	8.62	0.17	1,160.35	0.84	0.13
2040	1.20	4.27	8.78	0.18	1,181.66	0.85	0.13
2041	1.22	4.32	8.93	0.18	1,201.98	0.87	0.13
2042	1.24	4.38	9.09	0.18	1,224.01	0.89	0.13
2043	1.26	4.44	9.25	0.19	1,246.44	0.90	0.14
2044	1.28	4.50	9.41	0.19	1,269.27	0.92	0.14
2045	1.30	4.56	9.58	0.19	1,292.51	0.94	0.14
2046	1.32	4.63	9.75	0.20	1,316.16	0.96	0.14
2047	1.34	4.69	9.93	0.20	1,340.23	0.97	0.15
2048	1.37	4.75	10.10	0.20	1,364.74	0.99	0.15
2049	1.39	4.82	10.28	0.21	1,389.68	1.01	0.15
2050	1.41	4.88	10.47	0.21	1,415.07	1.03	0.16

Section: ES10 strong semi arid
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.18	6.20	0.12	830.83	0.59	0.09
2022	0.88	3.24	6.32	0.12	846.47	0.61	0.09
2023	0.90	3.29	6.44	0.13	862.38	0.62	0.10
2024	0.91	3.34	6.56	0.13	878.56	0.63	0.10
2025	0.93	3.39	6.68	0.13	895.05	0.64	0.10
2026	0.94	3.45	6.80	0.13	911.82	0.65	0.10
2027	0.96	3.50	6.93	0.14	928.89	0.67	0.10
2028	0.98	3.56	7.05	0.14	946.28	0.68	0.10
2029	0.99	3.60	7.17	0.14	962.17	0.69	0.11
2030	1.01	3.65	7.29	0.14	979.37	0.70	0.11
2031	1.02	3.71	7.43	0.15	997.60	0.72	0.11
2032	1.04	3.77	7.56	0.15	1,016.14	0.73	0.11
2033	1.06	3.83	7.70	0.15	1,035.02	0.74	0.11
2034	1.08	3.89	7.84	0.16	1,054.23	0.76	0.12
2035	1.10	3.94	7.99	0.16	1,073.78	0.77	0.12
2036	1.12	4.00	8.13	0.16	1,093.68	0.79	0.12
2037	1.13	4.06	8.27	0.16	1,112.81	0.80	0.12
2038	1.15	4.11	8.41	0.17	1,132.27	0.82	0.12
2039	1.17	4.17	8.56	0.17	1,152.87	0.83	0.13
2040	1.19	4.23	8.71	0.17	1,173.84	0.85	0.13
2041	1.21	4.28	8.87	0.18	1,195.17	0.86	0.13
2042	1.23	4.34	9.02	0.18	1,216.87	0.88	0.13
2043	1.25	4.40	9.18	0.18	1,238.94	0.90	0.14
2044	1.27	4.46	9.35	0.19	1,261.40	0.91	0.14
2045	1.29	4.52	9.50	0.19	1,283.48	0.93	0.14
2046	1.31	4.58	9.66	0.19	1,305.70	0.95	0.14
2047	1.33	4.64	9.83	0.20	1,329.28	0.96	0.15

2048	1.35	4.70	10.00	0.20	1,353.26	0.98	0.15
2049	1.37	4.76	10.18	0.21	1,377.67	1.00	0.15
2050	1.39	4.82	10.36	0.21	1,402.50	1.02	0.15

Section: ES10strong subhumid dry
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.19	6.21	0.12	832.18	0.59	0.09
2022	0.88	3.25	6.33	0.12	847.95	0.61	0.09
2023	0.90	3.30	6.45	0.13	864.00	0.62	0.10
2024	0.91	3.35	6.57	0.13	880.34	0.63	0.10
2025	0.93	3.41	6.69	0.13	896.98	0.64	0.10
2026	0.95	3.46	6.82	0.13	913.93	0.66	0.10
2027	0.96	3.52	6.95	0.14	931.19	0.67	0.10
2028	0.98	3.57	7.08	0.14	948.79	0.68	0.10
2029	1.00	3.63	7.21	0.14	966.73	0.69	0.11
2030	1.02	3.69	7.34	0.15	985.02	0.71	0.11
2031	1.03	3.75	7.48	0.15	1,003.66	0.72	0.11
2032	1.05	3.80	7.62	0.15	1,022.65	0.74	0.11
2033	1.07	3.86	7.76	0.15	1,041.95	0.75	0.11
2034	1.09	3.93	7.91	0.16	1,061.60	0.77	0.12
2035	1.11	3.99	8.05	0.16	1,081.61	0.78	0.12
2036	1.13	4.05	8.20	0.16	1,102.00	0.80	0.12
2037	1.15	4.11	8.35	0.17	1,122.50	0.81	0.12
2038	1.17	4.17	8.52	0.17	1,144.64	0.83	0.13
2039	1.19	4.23	8.67	0.17	1,165.85	0.84	0.13
2040	1.21	4.29	8.82	0.18	1,186.29	0.86	0.13
2041	1.23	4.35	8.98	0.18	1,208.25	0.88	0.13
2042	1.25	4.41	9.14	0.18	1,230.56	0.89	0.14
2043	1.27	4.47	9.31	0.19	1,253.23	0.91	0.14
2044	1.29	4.53	9.47	0.19	1,276.20	0.93	0.14
2045	1.31	4.58	9.64	0.19	1,299.47	0.95	0.14
2046	1.33	4.64	9.81	0.20	1,322.98	0.97	0.14
2047	1.35	4.69	9.98	0.20	1,346.68	0.98	0.15
2048	1.37	4.74	10.15	0.21	1,370.50	1.00	0.15
2049	1.39	4.79	10.32	0.21	1,394.38	1.02	0.15
2050	1.41	4.83	10.49	0.21	1,418.21	1.04	0.16

Section: ES10strong subhumid dry
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.19	6.21	0.12	832.18	0.59	0.09
2022	0.88	3.25	6.33	0.12	847.95	0.61	0.09
2023	0.90	3.30	6.45	0.13	864.00	0.62	0.10

2024	0.91	3.35	6.57	0.13	880.34	0.63	0.10
2025	0.93	3.41	6.69	0.13	896.98	0.64	0.10
2026	0.95	3.46	6.82	0.13	913.93	0.66	0.10
2027	0.96	3.52	6.95	0.14	931.19	0.67	0.10
2028	0.98	3.57	7.08	0.14	948.79	0.68	0.10
2029	0.99	3.61	7.18	0.14	963.74	0.69	0.11
2030	1.01	3.67	7.31	0.14	981.09	0.70	0.11
2031	1.03	3.72	7.44	0.15	999.46	0.72	0.11
2032	1.04	3.78	7.58	0.15	1,018.18	0.73	0.11
2033	1.06	3.84	7.72	0.15	1,037.23	0.75	0.11
2034	1.08	3.90	7.86	0.16	1,056.62	0.76	0.12
2035	1.10	3.96	8.01	0.16	1,076.37	0.77	0.12
2036	1.12	4.02	8.16	0.16	1,096.49	0.79	0.12
2037	1.14	4.07	8.28	0.16	1,114.64	0.80	0.12
2038	1.15	4.12	8.43	0.17	1,134.25	0.82	0.12
2039	1.17	4.18	8.58	0.17	1,155.04	0.83	0.13
2040	1.19	4.24	8.73	0.17	1,176.19	0.85	0.13
2041	1.21	4.30	8.89	0.18	1,197.73	0.86	0.13
2042	1.23	4.36	9.05	0.18	1,219.64	0.88	0.13
2043	1.25	4.42	9.21	0.18	1,241.94	0.90	0.14
2044	1.27	4.48	9.37	0.19	1,264.63	0.92	0.14
2045	1.29	4.53	9.52	0.19	1,285.59	0.93	0.14
2046	1.31	4.59	9.68	0.19	1,308.01	0.95	0.14
2047	1.33	4.65	9.85	0.20	1,331.79	0.97	0.15
2048	1.35	4.71	10.03	0.20	1,355.99	0.98	0.15
2049	1.37	4.78	10.20	0.21	1,380.63	1.00	0.15
2050	1.40	4.84	10.38	0.21	1,405.71	1.02	0.15

Section: ES10 strong Subhumidwet
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.20	6.22	0.12	833.03	0.60	0.09
2022	0.88	3.25	6.34	0.12	848.79	0.61	0.09
2023	0.90	3.30	6.46	0.13	864.82	0.62	0.10
2024	0.91	3.36	6.58	0.13	881.14	0.63	0.10
2025	0.93	3.41	6.70	0.13	897.76	0.64	0.10
2026	0.95	3.46	6.82	0.13	914.69	0.66	0.10
2027	0.96	3.52	6.95	0.14	931.94	0.67	0.10
2028	0.98	3.58	7.08	0.14	949.54	0.68	0.10
2029	1.00	3.63	7.21	0.14	967.50	0.69	0.11
2030	1.02	3.69	7.35	0.15	985.82	0.71	0.11
2031	1.03	3.75	7.49	0.15	1,004.40	0.72	0.11
2032	1.05	3.81	7.63	0.15	1,023.34	0.74	0.11
2033	1.07	3.87	7.77	0.15	1,042.64	0.75	0.11
2034	1.09	3.93	7.91	0.16	1,062.31	0.77	0.12

2035	1.11	3.99	8.06	0.16	1,082.36	0.78	0.12
2036	1.13	4.06	8.22	0.16	1,104.25	0.80	0.12
2037	1.15	4.12	8.37	0.17	1,124.83	0.81	0.12
2038	1.17	4.17	8.51	0.17	1,144.40	0.83	0.13
2039	1.19	4.23	8.67	0.17	1,165.75	0.84	0.13
2040	1.21	4.29	8.83	0.18	1,187.48	0.86	0.13
2041	1.23	4.36	8.99	0.18	1,209.58	0.88	0.13
2042	1.25	4.42	9.15	0.18	1,232.00	0.89	0.14
2043	1.27	4.47	9.32	0.19	1,254.73	0.91	0.14
2044	1.29	4.53	9.49	0.19	1,277.73	0.93	0.14
2045	1.31	4.59	9.65	0.19	1,300.98	0.95	0.14
2046	1.33	4.65	9.82	0.20	1,324.44	0.97	0.15
2047	1.35	4.70	9.99	0.20	1,348.07	0.99	0.15
2048	1.38	4.75	10.16	0.21	1,371.81	1.00	0.15
2049	1.39	4.79	10.33	0.21	1,395.60	1.02	0.15
2050	1.41	4.83	10.50	0.21	1,419.34	1.04	0.16

Section: ES10 strong Subhumidwet
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.20	6.22	0.12	833.03	0.60	0.09
2022	0.88	3.25	6.34	0.12	848.79	0.61	0.09
2023	0.90	3.30	6.46	0.13	864.82	0.62	0.10
2024	0.91	3.36	6.58	0.13	881.14	0.63	0.10
2025	0.93	3.41	6.70	0.13	897.76	0.64	0.10
2026	0.95	3.46	6.82	0.13	914.69	0.66	0.10
2027	0.96	3.52	6.95	0.14	931.94	0.67	0.10
2028	0.98	3.58	7.08	0.14	949.54	0.68	0.10
2029	0.99	3.62	7.19	0.14	964.73	0.69	0.11
2030	1.01	3.67	7.32	0.14	982.06	0.70	0.11
2031	1.03	3.73	7.45	0.15	1,000.43	0.72	0.11
2032	1.05	3.79	7.59	0.15	1,019.13	0.73	0.11
2033	1.06	3.84	7.73	0.15	1,038.15	0.75	0.11
2034	1.08	3.90	7.87	0.16	1,057.53	0.76	0.12
2035	1.10	3.96	8.02	0.16	1,077.26	0.78	0.12
2036	1.12	4.03	8.16	0.16	1,097.35	0.79	0.12
2037	1.14	4.07	8.29	0.16	1,115.79	0.80	0.12
2038	1.15	4.13	8.44	0.17	1,135.38	0.82	0.12
2039	1.17	4.19	8.59	0.17	1,156.16	0.83	0.13
2040	1.19	4.25	8.74	0.17	1,177.30	0.85	0.13
2041	1.21	4.30	8.90	0.18	1,198.81	0.87	0.13
2042	1.23	4.37	9.06	0.18	1,220.69	0.88	0.13
2043	1.25	4.43	9.22	0.18	1,242.97	0.90	0.14
2044	1.27	4.49	9.38	0.19	1,265.64	0.92	0.14
2045	1.29	4.54	9.53	0.19	1,286.93	0.93	0.14

2046	1.31	4.60	9.69	0.19	1,309.33	0.95	0.14
2047	1.33	4.66	9.86	0.20	1,333.09	0.97	0.15
2048	1.35	4.72	10.04	0.20	1,357.27	0.98	0.15
2049	1.38	4.78	10.21	0.21	1,381.88	1.00	0.15
2050	1.40	4.85	10.39	0.21	1,406.94	1.02	0.15

Section: ES10 strong humid
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.21	6.24	0.12	835.33	0.60	0.09
2022	0.89	3.27	6.36	0.12	851.39	0.61	0.09
2023	0.90	3.32	6.48	0.13	867.78	0.62	0.10
2024	0.92	3.38	6.61	0.13	884.50	0.63	0.10
2025	0.94	3.43	6.73	0.13	901.55	0.65	0.10
2026	0.95	3.49	6.86	0.14	918.94	0.66	0.10
2027	0.97	3.55	6.99	0.14	936.69	0.67	0.10
2028	0.99	3.61	7.13	0.14	954.82	0.69	0.11
2029	1.01	3.67	7.26	0.14	973.32	0.70	0.11
2030	1.03	3.73	7.40	0.15	992.19	0.71	0.11
2031	1.05	3.79	7.55	0.15	1,011.34	0.73	0.11
2032	1.07	3.85	7.69	0.15	1,030.79	0.74	0.11
2033	1.08	3.91	7.84	0.16	1,050.51	0.76	0.12
2034	1.10	3.96	7.98	0.16	1,070.42	0.77	0.12
2035	1.12	4.02	8.13	0.16	1,090.40	0.79	0.12
2036	1.14	4.04	8.26	0.17	1,109.12	0.81	0.12
2037	1.15	4.07	8.39	0.17	1,127.03	0.82	0.12
2038	1.17	4.12	8.54	0.17	1,147.47	0.84	0.13
2039	1.18	4.13	8.65	0.17	1,164.17	0.85	0.13
2040	1.19	4.10	8.74	0.18	1,178.71	0.86	0.13
2041	1.18	4.05	8.81	0.18	1,190.55	0.87	0.13
2042	1.18	3.96	8.84	0.18	1,199.67	0.88	0.13
2043	1.17	3.84	8.85	0.18	1,206.83	0.89	0.13
2044	1.15	3.71	8.85	0.19	1,213.61	0.90	0.13
2045	1.14	3.57	8.86	0.19	1,221.47	0.91	0.13
2046	1.13	3.44	8.87	0.19	1,232.16	0.92	0.13
2047	1.12	3.32	8.90	0.19	1,247.39	0.94	0.14
2048	1.12	3.22	8.97	0.20	1,268.83	0.95	0.14
2049	1.12	3.15	9.08	0.20	1,297.92	0.98	0.14
2050	1.14	3.10	9.25	0.21	1,335.80	1.01	0.14

Section: ES10 strong humid
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.21	6.24	0.12	835.33	0.60	0.09

2022	0.89	3.27	6.36	0.12	851.39	0.61	0.09
2023	0.90	3.32	6.48	0.13	867.78	0.62	0.10
2024	0.92	3.38	6.61	0.13	884.50	0.63	0.10
2025	0.94	3.43	6.73	0.13	901.55	0.65	0.10
2026	0.95	3.49	6.86	0.14	918.94	0.66	0.10
2027	0.97	3.55	6.99	0.14	936.69	0.67	0.10
2028	0.99	3.61	7.13	0.14	954.82	0.69	0.11
2029	1.00	3.63	7.21	0.14	967.40	0.69	0.11
2030	1.02	3.69	7.34	0.14	985.09	0.71	0.11
2031	1.03	3.75	7.48	0.15	1,003.84	0.72	0.11
2032	1.05	3.81	7.62	0.15	1,022.97	0.74	0.11
2033	1.07	3.87	7.76	0.15	1,042.48	0.75	0.11
2034	1.09	3.93	7.91	0.16	1,062.37	0.77	0.12
2035	1.11	3.99	8.06	0.16	1,082.64	0.78	0.12
2036	1.13	4.06	8.21	0.16	1,103.33	0.80	0.12
2037	1.14	4.09	8.32	0.17	1,118.88	0.81	0.12
2038	1.16	4.15	8.47	0.17	1,138.89	0.82	0.13
2039	1.18	4.21	8.62	0.17	1,160.13	0.84	0.13
2040	1.20	4.27	8.78	0.18	1,181.77	0.85	0.13
2041	1.22	4.33	8.94	0.18	1,203.82	0.87	0.13
2042	1.24	4.40	9.10	0.18	1,226.29	0.89	0.13
2043	1.26	4.46	9.27	0.19	1,249.20	0.90	0.14
2044	1.28	4.52	9.44	0.19	1,272.56	0.92	0.14
2045	1.30	4.56	9.56	0.19	1,290.53	0.93	0.14
2046	1.32	4.62	9.73	0.20	1,313.40	0.95	0.14
2047	1.34	4.68	9.90	0.20	1,337.69	0.97	0.15
2048	1.36	4.75	10.08	0.20	1,362.45	0.99	0.15
2049	1.38	4.81	10.26	0.21	1,387.69	1.01	0.15
2050	1.41	4.88	10.45	0.21	1,413.43	1.03	0.15

Table D-2: Road User Emission Results – ES10 Weak

Section: ES10 weak Arid **Alternative:** Base Alternative							
Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.18	6.19	0.12	829.61	0.59	0.09
2022	0.88	3.23	6.31	0.12	845.32	0.60	0.09
2023	0.89	3.28	6.43	0.13	861.23	0.62	0.09
2024	0.91	3.33	6.55	0.13	877.44	0.63	0.10
2025	0.93	3.39	6.67	0.13	893.92	0.64	0.10
2026	0.94	3.44	6.79	0.13	910.71	0.65	0.10
2027	0.96	3.50	6.92	0.14	927.81	0.66	0.10
2028	0.98	3.55	7.05	0.14	945.22	0.68	0.10
2029	0.99	3.61	7.18	0.14	962.94	0.69	0.11
2030	1.01	3.66	7.31	0.14	980.99	0.70	0.11
2031	1.03	3.72	7.44	0.15	999.37	0.72	0.11
2032	1.05	3.78	7.58	0.15	1,018.08	0.73	0.11
2033	1.06	3.84	7.72	0.15	1,037.13	0.75	0.11
2034	1.08	3.90	7.86	0.16	1,056.52	0.76	0.12
2035	1.10	3.96	8.01	0.16	1,076.27	0.78	0.12
2036	1.12	4.02	8.15	0.16	1,096.32	0.79	0.12
2037	1.14	4.08	8.30	0.17	1,116.47	0.81	0.12
2038	1.16	4.13	8.45	0.17	1,136.98	0.82	0.12
2039	1.18	4.19	8.60	0.17	1,157.84	0.84	0.13
2040	1.20	4.25	8.76	0.17	1,179.06	0.85	0.13
2041	1.22	4.31	8.91	0.18	1,200.65	0.87	0.13
2042	1.24	4.37	9.07	0.18	1,222.61	0.89	0.13
2043	1.26	4.43	9.24	0.19	1,244.96	0.90	0.14
2044	1.28	4.49	9.40	0.19	1,267.70	0.92	0.14
2045	1.30	4.56	9.58	0.19	1,292.20	0.94	0.14
2046	1.32	4.62	9.75	0.20	1,315.75	0.96	0.14
2047	1.34	4.68	9.91	0.20	1,338.36	0.97	0.15
2048	1.36	4.74	10.09	0.20	1,362.73	0.99	0.15
2049	1.39	4.80	10.26	0.21	1,387.53	1.01	0.15
2050	1.41	4.87	10.45	0.21	1,412.76	1.03	0.15
Section: ES10 weak Arid **Alternative:** Heavy maintenance							
Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.18	6.19	0.12	829.61	0.59	0.09
2022	0.88	3.23	6.31	0.12	845.32	0.60	0.09
2023	0.89	3.28	6.43	0.13	861.23	0.62	0.09
2024	0.91	3.33	6.55	0.13	877.44	0.63	0.10
2025	0.93	3.39	6.67	0.13	893.92	0.64	0.10

2026	0.94	3.44	6.79	0.13	910.71	0.65	0.10
2027	0.96	3.50	6.92	0.14	927.81	0.66	0.10
2028	0.98	3.55	7.05	0.14	945.22	0.68	0.10
2029	0.99	3.59	7.16	0.14	960.66	0.69	0.11
2030	1.00	3.65	7.28	0.14	977.85	0.70	0.11
2031	1.02	3.70	7.42	0.15	996.05	0.71	0.11
2032	1.04	3.76	7.55	0.15	1,014.56	0.73	0.11
2033	1.06	3.82	7.69	0.15	1,033.41	0.74	0.11
2034	1.08	3.88	7.83	0.15	1,052.59	0.76	0.12
2035	1.09	3.93	7.97	0.16	1,072.12	0.77	0.12
2036	1.11	3.99	8.12	0.16	1,092.00	0.79	0.12
2037	1.13	4.05	8.25	0.16	1,111.05	0.80	0.12
2038	1.15	4.10	8.39	0.17	1,130.45	0.81	0.12
2039	1.17	4.16	8.54	0.17	1,151.02	0.83	0.13
2040	1.19	4.21	8.70	0.17	1,171.93	0.85	0.13
2041	1.20	4.27	8.85	0.18	1,193.22	0.86	0.13
2042	1.22	4.33	9.01	0.18	1,214.87	0.88	0.13
2043	1.24	4.39	9.17	0.18	1,236.88	0.89	0.14
2044	1.26	4.45	9.33	0.19	1,259.28	0.91	0.14
2045	1.28	4.51	9.49	0.19	1,281.43	0.93	0.14
2046	1.30	4.56	9.64	0.19	1,303.59	0.94	0.14
2047	1.32	4.62	9.81	0.20	1,327.09	0.96	0.15
2048	1.35	4.69	9.98	0.20	1,351.00	0.98	0.15
2049	1.37	4.75	10.16	0.20	1,375.34	1.00	0.15
2050	1.39	4.81	10.34	0.21	1,400.10	1.02	0.15

Section: ES10 weak semi arid
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.19	6.20	0.12	830.92	0.59	0.09
2022	0.88	3.24	6.32	0.12	846.68	0.61	0.09
2023	0.90	3.29	6.44	0.13	862.65	0.62	0.10
2024	0.91	3.34	6.56	0.13	878.91	0.63	0.10
2025	0.93	3.40	6.68	0.13	895.46	0.64	0.10
2026	0.94	3.45	6.81	0.13	912.32	0.65	0.10
2027	0.96	3.51	6.93	0.14	929.48	0.67	0.10
2028	0.98	3.56	7.06	0.14	946.98	0.68	0.10
2029	1.00	3.62	7.19	0.14	964.80	0.69	0.11
2030	1.01	3.67	7.33	0.14	982.96	0.71	0.11
2031	1.03	3.73	7.46	0.15	1,001.45	0.72	0.11
2032	1.05	3.79	7.60	0.15	1,020.28	0.73	0.11
2033	1.07	3.85	7.74	0.15	1,039.47	0.75	0.11
2034	1.09	3.91	7.88	0.16	1,058.96	0.76	0.12
2035	1.10	3.97	8.03	0.16	1,078.81	0.78	0.12
2036	1.12	4.03	8.18	0.16	1,099.02	0.79	0.12

2037	1.14	4.09	8.33	0.17	1,119.34	0.81	0.12
2038	1.16	4.15	8.48	0.17	1,140.01	0.82	0.13
2039	1.18	4.21	8.64	0.17	1,162.25	0.84	0.13
2040	1.20	4.27	8.80	0.18	1,183.68	0.86	0.13
2041	1.22	4.33	8.95	0.18	1,204.32	0.87	0.13
2042	1.24	4.39	9.11	0.18	1,226.49	0.89	0.13
2043	1.26	4.45	9.27	0.19	1,249.06	0.91	0.14
2044	1.28	4.51	9.44	0.19	1,272.02	0.92	0.14
2045	1.31	4.58	9.61	0.19	1,295.37	0.94	0.14
2046	1.33	4.64	9.78	0.20	1,319.11	0.96	0.14
2047	1.35	4.70	9.95	0.20	1,343.24	0.98	0.15
2048	1.37	4.76	10.13	0.20	1,367.77	1.00	0.15
2049	1.39	4.82	10.31	0.21	1,392.68	1.02	0.15
2050	1.42	4.88	10.49	0.21	1,417.96	1.04	0.16

Section: ES10 weak semi arid
Alternative: Heavy maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.86	3.19	6.20	0.12	830.92	0.59	0.09
2022	0.88	3.24	6.32	0.12	846.68	0.61	0.09
2023	0.90	3.29	6.44	0.13	862.65	0.62	0.10
2024	0.91	3.34	6.56	0.13	878.91	0.63	0.10
2025	0.93	3.40	6.68	0.13	895.46	0.64	0.10
2026	0.94	3.45	6.81	0.13	912.32	0.65	0.10
2027	0.96	3.51	6.93	0.14	929.48	0.67	0.10
2028	0.98	3.56	7.06	0.14	946.98	0.68	0.10
2029	0.99	3.60	7.17	0.14	962.19	0.69	0.11
2030	1.01	3.66	7.29	0.14	979.44	0.70	0.11
2031	1.02	3.71	7.43	0.15	997.70	0.72	0.11
2032	1.04	3.77	7.57	0.15	1,016.29	0.73	0.11
2033	1.06	3.83	7.70	0.15	1,035.22	0.74	0.11
2034	1.08	3.89	7.85	0.16	1,054.49	0.76	0.12
2035	1.10	3.95	7.99	0.16	1,074.09	0.77	0.12
2036	1.12	4.01	8.13	0.16	1,094.06	0.79	0.12
2037	1.13	4.06	8.27	0.16	1,112.83	0.80	0.12
2038	1.15	4.11	8.41	0.17	1,132.31	0.82	0.12
2039	1.17	4.17	8.56	0.17	1,152.95	0.83	0.13
2040	1.19	4.23	8.71	0.17	1,173.95	0.85	0.13
2041	1.21	4.29	8.87	0.18	1,195.32	0.86	0.13
2042	1.23	4.34	9.03	0.18	1,217.06	0.88	0.13
2043	1.25	4.40	9.19	0.18	1,239.17	0.90	0.14
2044	1.27	4.46	9.35	0.19	1,261.67	0.91	0.14
2045	1.29	4.52	9.50	0.19	1,283.49	0.93	0.14
2046	1.31	4.58	9.66	0.19	1,305.75	0.95	0.14
2047	1.33	4.64	9.83	0.20	1,329.34	0.96	0.15

2048	1.35	4.70	10.00	0.20	1,353.35	0.98	0.15
2049	1.37	4.76	10.18	0.21	1,377.78	1.00	0.15
2050	1.39	4.82	10.36	0.21	1,402.65	1.02	0.15

Section: ES10 weak subhumid dry
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.19	6.22	0.12	832.27	0.59	0.09
2022	0.88	3.25	6.33	0.12	848.16	0.61	0.09
2023	0.90	3.30	6.45	0.13	864.28	0.62	0.10
2024	0.91	3.35	6.57	0.13	880.69	0.63	0.10
2025	0.93	3.41	6.70	0.13	897.42	0.64	0.10
2026	0.95	3.46	6.82	0.13	914.47	0.66	0.10
2027	0.96	3.52	6.95	0.14	931.85	0.67	0.10
2028	0.98	3.58	7.08	0.14	949.57	0.68	0.10
2029	1.00	3.63	7.22	0.14	967.63	0.70	0.11
2030	1.02	3.69	7.35	0.15	986.04	0.71	0.11
2031	1.04	3.75	7.49	0.15	1,004.82	0.72	0.11
2032	1.05	3.81	7.63	0.15	1,023.89	0.74	0.11
2033	1.07	3.87	7.77	0.15	1,043.31	0.75	0.11
2034	1.09	3.93	7.92	0.16	1,063.09	0.77	0.12
2035	1.11	3.99	8.07	0.16	1,083.23	0.78	0.12
2036	1.13	4.06	8.22	0.16	1,103.72	0.80	0.12
2037	1.15	4.11	8.37	0.17	1,124.32	0.81	0.12
2038	1.17	4.17	8.53	0.17	1,146.11	0.83	0.13
2039	1.19	4.23	8.68	0.17	1,167.19	0.85	0.13
2040	1.21	4.29	8.83	0.18	1,188.07	0.86	0.13
2041	1.23	4.35	8.99	0.18	1,209.85	0.88	0.13
2042	1.25	4.40	9.15	0.18	1,231.83	0.90	0.14
2043	1.27	4.45	9.31	0.19	1,253.94	0.91	0.14
2044	1.29	4.50	9.47	0.19	1,276.06	0.93	0.14
2045	1.31	4.54	9.63	0.19	1,298.07	0.95	0.14
2046	1.32	4.58	9.78	0.20	1,319.80	0.97	0.14
2047	1.34	4.60	9.93	0.20	1,341.08	0.98	0.15
2048	1.35	4.62	10.07	0.21	1,361.72	1.00	0.15
2049	1.37	4.62	10.20	0.21	1,381.59	1.02	0.15
2050	1.37	4.61	10.32	0.21	1,400.55	1.03	0.15

Section: ES10 weak subhumid dry
Alternative: Heavy maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.19	6.22	0.12	832.27	0.59	0.09
2022	0.88	3.25	6.33	0.12	848.16	0.61	0.09
2023	0.90	3.30	6.45	0.13	864.28	0.62	0.10

2024	0.91	3.35	6.57	0.13	880.69	0.63	0.10
2025	0.93	3.41	6.70	0.13	897.42	0.64	0.10
2026	0.95	3.46	6.82	0.13	914.47	0.66	0.10
2027	0.96	3.52	6.95	0.14	931.85	0.67	0.10
2028	0.98	3.58	7.08	0.14	949.57	0.68	0.10
2029	0.99	3.61	7.18	0.14	963.76	0.69	0.11
2030	1.01	3.67	7.31	0.14	981.16	0.70	0.11
2031	1.03	3.72	7.44	0.15	999.58	0.72	0.11
2032	1.05	3.78	7.58	0.15	1,018.34	0.73	0.11
2033	1.06	3.84	7.72	0.15	1,037.45	0.75	0.11
2034	1.08	3.90	7.87	0.16	1,056.91	0.76	0.12
2035	1.10	3.96	8.01	0.16	1,076.73	0.78	0.12
2036	1.12	4.02	8.16	0.16	1,096.93	0.79	0.12
2037	1.14	4.07	8.28	0.16	1,114.65	0.80	0.12
2038	1.15	4.12	8.43	0.17	1,134.30	0.82	0.12
2039	1.17	4.18	8.58	0.17	1,155.12	0.83	0.13
2040	1.19	4.24	8.73	0.17	1,176.31	0.85	0.13
2041	1.21	4.30	8.89	0.18	1,197.89	0.87	0.13
2042	1.23	4.36	9.05	0.18	1,219.85	0.88	0.13
2043	1.25	4.42	9.21	0.18	1,242.19	0.90	0.14
2044	1.27	4.48	9.38	0.19	1,264.95	0.92	0.14
2045	1.29	4.53	9.52	0.19	1,285.60	0.93	0.14
2046	1.31	4.59	9.68	0.19	1,308.05	0.95	0.14
2047	1.33	4.65	9.85	0.20	1,331.85	0.97	0.15
2048	1.35	4.71	10.03	0.20	1,356.09	0.98	0.15
2049	1.37	4.78	10.20	0.21	1,380.76	1.00	0.15
2050	1.40	4.84	10.38	0.21	1,405.87	1.02	0.15

Section: ES10 weak subhumid wet
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.20	6.22	0.12	833.12	0.60	0.09
2022	0.88	3.25	6.34	0.12	849.00	0.61	0.09
2023	0.90	3.30	6.46	0.13	865.09	0.62	0.10
2024	0.92	3.36	6.58	0.13	881.49	0.63	0.10
2025	0.93	3.41	6.70	0.13	898.19	0.64	0.10
2026	0.95	3.47	6.83	0.13	915.23	0.66	0.10
2027	0.97	3.52	6.96	0.14	932.62	0.67	0.10
2028	0.98	3.58	7.09	0.14	950.36	0.68	0.10
2029	1.00	3.64	7.22	0.14	968.46	0.70	0.11
2030	1.02	3.70	7.36	0.15	986.84	0.71	0.11
2031	1.04	3.76	7.50	0.15	1,005.57	0.72	0.11
2032	1.06	3.82	7.64	0.15	1,024.65	0.74	0.11
2033	1.07	3.88	7.78	0.15	1,044.11	0.75	0.11
2034	1.09	3.94	7.93	0.16	1,063.94	0.77	0.12

2035	1.11	4.00	8.08	0.16	1,084.14	0.78	0.12
2036	1.13	4.07	8.24	0.16	1,105.90	0.80	0.12
2037	1.15	4.12	8.39	0.17	1,126.51	0.82	0.12
2038	1.17	4.18	8.53	0.17	1,146.53	0.83	0.13
2039	1.19	4.24	8.69	0.17	1,167.88	0.85	0.13
2040	1.21	4.30	8.85	0.18	1,189.49	0.86	0.13
2041	1.23	4.35	9.01	0.18	1,211.28	0.88	0.13
2042	1.25	4.40	9.16	0.18	1,233.17	0.90	0.14
2043	1.27	4.45	9.32	0.19	1,255.06	0.92	0.14
2044	1.29	4.49	9.48	0.19	1,276.83	0.93	0.14
2045	1.31	4.53	9.63	0.20	1,298.32	0.95	0.14
2046	1.32	4.56	9.77	0.20	1,319.35	0.97	0.14
2047	1.34	4.57	9.91	0.20	1,339.73	0.98	0.15
2048	1.35	4.58	10.04	0.21	1,359.27	1.00	0.15
2049	1.36	4.57	10.16	0.21	1,377.85	1.01	0.15
2050	1.36	4.54	10.26	0.21	1,395.45	1.03	0.15

Section: ES10 weak subhumid wet
Alternative: Heavy maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.20	6.22	0.12	833.12	0.60	0.09
2022	0.88	3.25	6.34	0.12	849.00	0.61	0.09
2023	0.90	3.30	6.46	0.13	865.09	0.62	0.10
2024	0.92	3.36	6.58	0.13	881.49	0.63	0.10
2025	0.93	3.41	6.70	0.13	898.19	0.64	0.10
2026	0.95	3.47	6.83	0.13	915.23	0.66	0.10
2027	0.97	3.52	6.96	0.14	932.62	0.67	0.10
2028	0.98	3.58	7.09	0.14	950.36	0.68	0.10
2029	0.99	3.62	7.19	0.14	964.75	0.69	0.11
2030	1.01	3.67	7.32	0.14	982.13	0.70	0.11
2031	1.03	3.73	7.45	0.15	1,000.55	0.72	0.11
2032	1.05	3.79	7.59	0.15	1,019.29	0.73	0.11
2033	1.06	3.85	7.73	0.15	1,038.38	0.75	0.11
2034	1.08	3.91	7.87	0.16	1,057.83	0.76	0.12
2035	1.10	3.97	8.02	0.16	1,077.65	0.78	0.12
2036	1.12	4.03	8.17	0.16	1,097.83	0.79	0.12
2037	1.14	4.07	8.29	0.16	1,115.80	0.80	0.12
2038	1.15	4.13	8.44	0.17	1,135.43	0.82	0.12
2039	1.17	4.19	8.59	0.17	1,156.24	0.83	0.13
2040	1.19	4.25	8.74	0.17	1,177.43	0.85	0.13
2041	1.21	4.31	8.90	0.18	1,198.97	0.87	0.13
2042	1.23	4.37	9.06	0.18	1,220.91	0.88	0.13
2043	1.25	4.43	9.22	0.18	1,243.24	0.90	0.14
2044	1.27	4.49	9.38	0.19	1,265.98	0.92	0.14
2045	1.29	4.54	9.53	0.19	1,286.95	0.93	0.14

2046	1.31	4.60	9.69	0.19	1,309.37	0.95	0.14
2047	1.33	4.66	9.86	0.20	1,333.15	0.97	0.15
2048	1.35	4.72	10.04	0.20	1,357.37	0.98	0.15
2049	1.38	4.78	10.21	0.21	1,382.02	1.00	0.15
2050	1.40	4.85	10.39	0.21	1,407.10	1.02	0.15
Section: ES10 weak humid **Alternative:** Base Alternative							
Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.21	6.24	0.12	835.41	0.60	0.09
2022	0.89	3.27	6.36	0.12	851.60	0.61	0.09
2023	0.90	3.32	6.48	0.13	868.07	0.62	0.10
2024	0.92	3.38	6.61	0.13	884.87	0.63	0.10
2025	0.94	3.44	6.74	0.13	902.03	0.65	0.10
2026	0.96	3.49	6.87	0.14	919.54	0.66	0.10
2027	0.97	3.55	7.00	0.14	937.44	0.67	0.10
2028	0.99	3.61	7.13	0.14	955.71	0.69	0.11
2029	1.01	3.67	7.27	0.14	974.35	0.70	0.11
2030	1.03	3.73	7.41	0.15	993.25	0.72	0.11
2031	1.05	3.79	7.56	0.15	1,012.43	0.73	0.11
2032	1.07	3.85	7.70	0.15	1,031.81	0.75	0.11
2033	1.09	3.90	7.84	0.16	1,051.28	0.76	0.12
2034	1.10	3.95	7.98	0.16	1,070.63	0.78	0.12
2035	1.12	3.99	8.12	0.16	1,089.51	0.79	0.12
2036	1.13	3.97	8.22	0.17	1,104.02	0.80	0.12
2037	1.13	3.95	8.30	0.17	1,117.83	0.82	0.12
2038	1.15	3.98	8.43	0.17	1,136.16	0.83	0.12
2039	1.14	3.91	8.48	0.17	1,146.02	0.84	0.13
2040	1.13	3.80	8.49	0.17	1,152.47	0.85	0.13
2041	1.11	3.66	8.48	0.18	1,156.70	0.85	0.13
2042	1.10	3.50	8.45	0.18	1,160.85	0.86	0.13
2043	1.08	3.34	8.43	0.18	1,167.18	0.87	0.13
2044	1.07	3.19	8.43	0.18	1,178.04	0.88	0.13
2045	1.06	3.06	8.47	0.19	1,195.84	0.90	0.13
2046	1.06	2.97	8.57	0.19	1,222.65	0.92	0.13
2047	1.07	2.92	8.72	0.20	1,260.04	0.95	0.14
2048	1.09	2.90	8.96	0.20	1,309.16	0.98	0.14
2049	1.12	2.92	9.27	0.21	1,370.88	1.03	0.15
2050	1.16	2.98	9.67	0.22	1,445.96	1.08	0.16
Section: ES10 weak humid **Alternative:** Heavy maintenance							
Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.87	3.21	6.24	0.12	835.41	0.60	0.09

2022	0.89	3.27	6.36	0.12	851.60	0.61	0.09
2023	0.90	3.32	6.48	0.13	868.07	0.62	0.10
2024	0.92	3.38	6.61	0.13	884.87	0.63	0.10
2025	0.94	3.44	6.74	0.13	902.03	0.65	0.10
2026	0.96	3.49	6.87	0.14	919.54	0.66	0.10
2027	0.97	3.55	7.00	0.14	937.44	0.67	0.10
2028	0.99	3.61	7.13	0.14	955.71	0.69	0.11
2029	1.00	3.63	7.21	0.14	967.42	0.69	0.11
2030	1.02	3.69	7.34	0.14	985.16	0.71	0.11
2031	1.03	3.75	7.48	0.15	1,003.97	0.72	0.11
2032	1.05	3.81	7.62	0.15	1,023.16	0.74	0.11
2033	1.07	3.87	7.77	0.15	1,042.73	0.75	0.11
2034	1.09	3.93	7.91	0.16	1,062.71	0.77	0.12
2035	1.11	4.00	8.06	0.16	1,083.09	0.78	0.12
2036	1.13	4.06	8.22	0.16	1,103.89	0.80	0.12
2037	1.14	4.09	8.32	0.17	1,118.90	0.81	0.12
2038	1.16	4.15	8.47	0.17	1,138.95	0.82	0.13
2039	1.18	4.21	8.62	0.17	1,160.22	0.84	0.13
2040	1.20	4.27	8.78	0.18	1,181.90	0.85	0.13
2041	1.22	4.33	8.94	0.18	1,204.01	0.87	0.13
2042	1.24	4.40	9.11	0.18	1,226.54	0.89	0.13
2043	1.26	4.46	9.27	0.19	1,249.52	0.91	0.14
2044	1.29	4.53	9.44	0.19	1,272.96	0.92	0.14
2045	1.30	4.56	9.56	0.19	1,290.54	0.93	0.14
2046	1.32	4.62	9.73	0.20	1,313.44	0.95	0.14
2047	1.34	4.68	9.90	0.20	1,337.77	0.97	0.15
2048	1.36	4.75	10.08	0.20	1,362.56	0.99	0.15
2049	1.39	4.81	10.26	0.21	1,387.84	1.01	0.15
2050	1.41	4.88	10.45	0.21	1,413.62	1.03	0.15

Table D-3: Road User Emission Results – ES1 Strong

Section: ES1 strong Arid
Alternative: Base Alternative

Year	Annual Emission Quantities in tonnes						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.09	0.37	0.66	0.01	87.18	0.06	0.01
2022	0.10	0.38	0.67	0.01	88.94	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.70	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.51	0.06	0.01
2025	0.10	0.40	0.71	0.01	94.36	0.07	0.01
2026	0.10	0.41	0.72	0.01	96.25	0.07	0.01
2027	0.11	0.41	0.74	0.01	98.17	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.14	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.15	0.07	0.01
2030	0.11	0.44	0.78	0.01	104.20	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.29	0.07	0.01
2032	0.12	0.46	0.81	0.02	108.42	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.60	0.08	0.01
2034	0.12	0.48	0.85	0.02	112.82	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.09	0.08	0.01
2036	0.13	0.50	0.88	0.02	117.40	0.08	0.01
2037	0.13	0.51	0.90	0.02	119.76	0.08	0.01
2038	0.13	0.52	0.92	0.02	122.17	0.09	0.01
2039	0.14	0.53	0.94	0.02	124.63	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.14	0.09	0.01
2041	0.14	0.55	0.98	0.02	129.70	0.09	0.01
2042	0.14	0.56	0.99	0.02	132.31	0.09	0.01
2043	0.15	0.57	1.01	0.02	134.98	0.09	0.01
2044	0.15	0.58	1.04	0.02	137.70	0.10	0.02
2045	0.15	0.59	1.06	0.02	140.48	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.31	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.20	0.10	0.02
2048	0.16	0.63	1.12	0.02	149.16	0.10	0.02
2049	0.17	0.64	1.14	0.02	152.17	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.25	0.11	0.02

Section: ES1 strong Arid
Alternative: Full maintenance

Year	Annual Emission Quantities in tonnes						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.09	0.37	0.66	0.01	87.18	0.06	0.01
2022	0.10	0.38	0.67	0.01	88.94	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.70	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.51	0.06	0.01
2025	0.10	0.40	0.71	0.01	94.36	0.07	0.01

2026	0.10	0.41	0.72	0.01	96.25	0.07	0.01
2027	0.11	0.41	0.74	0.01	98.17	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.14	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.15	0.07	0.01
2030	0.11	0.44	0.78	0.01	104.20	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.29	0.07	0.01
2032	0.12	0.46	0.81	0.02	108.42	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.60	0.08	0.01
2034	0.12	0.48	0.85	0.02	112.82	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.09	0.08	0.01
2036	0.13	0.50	0.88	0.02	117.40	0.08	0.01
2037	0.13	0.51	0.90	0.02	119.76	0.08	0.01
2038	0.13	0.52	0.92	0.02	122.70	0.09	0.01
2039	0.14	0.53	0.94	0.02	124.88	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.34	0.09	0.01
2041	0.14	0.55	0.98	0.02	129.87	0.09	0.01
2042	0.14	0.56	1.00	0.02	132.46	0.09	0.01
2043	0.15	0.57	1.02	0.02	135.11	0.09	0.01
2044	0.15	0.58	1.04	0.02	137.82	0.10	0.02
2045	0.15	0.59	1.06	0.02	140.58	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.40	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.28	0.10	0.02
2048	0.16	0.63	1.12	0.02	149.21	0.10	0.02
2049	0.17	0.64	1.14	0.02	152.21	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.27	0.11	0.02

Section: ES1 strong semi arid
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.31	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.08	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.85	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.66	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.52	0.07	0.01
2026	0.10	0.41	0.72	0.01	96.41	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.35	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.32	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.34	0.07	0.01
2030	0.11	0.44	0.78	0.01	104.40	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.50	0.07	0.01
2032	0.12	0.46	0.82	0.02	108.64	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.83	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.06	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.34	0.08	0.01
2036	0.13	0.50	0.88	0.02	117.66	0.08	0.01

2037	0.13	0.51	0.90	0.02	120.04	0.08	0.01
2038	0.13	0.52	0.92	0.02	122.46	0.09	0.01
2039	0.14	0.53	0.94	0.02	124.93	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.46	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.04	0.09	0.01
2042	0.14	0.56	1.00	0.02	132.68	0.09	0.01
2043	0.15	0.57	1.02	0.02	135.37	0.10	0.02
2044	0.15	0.58	1.04	0.02	138.13	0.10	0.02
2045	0.15	0.60	1.06	0.02	140.93	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.78	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.69	0.10	0.02
2048	0.16	0.63	1.13	0.02	149.67	0.11	0.02
2049	0.17	0.65	1.15	0.02	152.72	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.82	0.11	0.02

Section: ES1 strong semi arid
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.31	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.08	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.85	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.66	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.52	0.07	0.01
2026	0.10	0.41	0.72	0.01	96.41	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.35	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.32	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.34	0.07	0.01
2030	0.11	0.44	0.78	0.01	104.40	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.50	0.07	0.01
2032	0.12	0.46	0.82	0.02	108.64	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.83	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.06	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.34	0.08	0.01
2036	0.13	0.50	0.88	0.02	117.66	0.08	0.01
2037	0.13	0.51	0.90	0.02	120.04	0.08	0.01
2038	0.13	0.52	0.93	0.02	122.99	0.09	0.01
2039	0.14	0.53	0.94	0.02	125.18	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.66	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.20	0.09	0.01
2042	0.14	0.56	1.00	0.02	132.80	0.09	0.01
2043	0.15	0.57	1.02	0.02	135.47	0.10	0.02
2044	0.15	0.59	1.04	0.02	138.19	0.10	0.02
2045	0.15	0.60	1.06	0.02	140.96	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.80	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.69	0.10	0.02

2048	0.16	0.63	1.13	0.02	149.64	0.11	0.02
2049	0.17	0.65	1.15	0.02	152.65	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.73	0.11	0.02

Section: ES1 strong subhumid dry
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.45	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.23	0.06	0.01
2023	0.10	0.39	0.68	0.01	91.02	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.85	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.72	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.63	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.59	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.58	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.62	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.70	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.82	0.08	0.01
2032	0.12	0.46	0.82	0.02	108.99	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.20	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.46	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.77	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.13	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.55	0.08	0.01
2038	0.13	0.52	0.93	0.02	123.02	0.09	0.01
2039	0.14	0.53	0.94	0.02	125.54	0.09	0.01
2040	0.14	0.54	0.96	0.02	128.11	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.72	0.09	0.01
2042	0.15	0.57	1.00	0.02	133.39	0.09	0.01
2043	0.15	0.58	1.02	0.02	136.09	0.10	0.02
2044	0.15	0.59	1.04	0.02	138.82	0.10	0.02
2045	0.15	0.60	1.07	0.02	141.57	0.10	0.02
2046	0.16	0.61	1.09	0.02	144.34	0.10	0.02
2047	0.16	0.62	1.11	0.02	147.14	0.10	0.02
2048	0.16	0.63	1.13	0.02	149.95	0.11	0.02
2049	0.17	0.64	1.15	0.02	152.78	0.11	0.02
2050	0.17	0.65	1.17	0.02	155.62	0.11	0.02

Section: ES1 strong subhumid dry
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.45	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.23	0.06	0.01
2023	0.10	0.39	0.68	0.01	91.02	0.06	0.01

2024	0.10	0.39	0.70	0.01	92.85	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.72	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.63	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.59	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.58	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.62	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.70	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.82	0.08	0.01
2032	0.12	0.46	0.82	0.02	108.99	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.20	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.46	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.77	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.13	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.87	0.09	0.01
2038	0.13	0.52	0.93	0.02	123.21	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.72	0.09	0.01
2040	0.14	0.54	0.97	0.02	128.27	0.09	0.01
2041	0.14	0.56	0.99	0.02	130.88	0.09	0.01
2042	0.15	0.57	1.01	0.02	133.54	0.09	0.01
2043	0.15	0.58	1.03	0.02	136.25	0.10	0.02
2044	0.15	0.59	1.05	0.02	139.01	0.10	0.02
2045	0.16	0.60	1.07	0.02	141.83	0.10	0.02
2046	0.16	0.61	1.09	0.02	144.69	0.10	0.02
2047	0.16	0.63	1.11	0.02	147.61	0.10	0.02
2048	0.16	0.64	1.13	0.02	150.57	0.11	0.02
2049	0.17	0.65	1.16	0.02	153.74	0.11	0.02
2050	0.17	0.66	1.18	0.02	156.63	0.11	0.02

Section: ES1 strong subhumid wet
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.54	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.32	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.10	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.93	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.80	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.71	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.66	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.65	0.07	0.01
2029	0.11	0.44	0.77	0.01	102.69	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.77	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.89	0.08	0.01
2032	0.12	0.46	0.82	0.02	109.05	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.26	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.51	0.08	0.01

2035	0.13	0.49	0.87	0.02	115.82	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.18	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.59	0.08	0.01
2038	0.13	0.52	0.93	0.02	123.06	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.59	0.09	0.01
2040	0.14	0.54	0.96	0.02	128.16	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.78	0.09	0.01
2042	0.15	0.57	1.00	0.02	133.46	0.09	0.01
2043	0.15	0.58	1.03	0.02	136.18	0.10	0.02
2044	0.15	0.59	1.05	0.02	138.94	0.10	0.02
2045	0.15	0.60	1.07	0.02	141.73	0.10	0.02
2046	0.16	0.61	1.09	0.02	144.56	0.10	0.02
2047	0.16	0.62	1.11	0.02	147.43	0.10	0.02
2048	0.16	0.63	1.13	0.02	150.32	0.11	0.02
2049	0.17	0.65	1.15	0.02	153.25	0.11	0.02
2050	0.17	0.66	1.18	0.02	156.21	0.11	0.02

Section: ES1 strong subhumid wet
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.54	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.32	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.10	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.93	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.80	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.71	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.66	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.65	0.07	0.01
2029	0.11	0.44	0.77	0.01	102.69	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.77	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.89	0.08	0.01
2032	0.12	0.46	0.82	0.02	109.05	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.26	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.51	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.82	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.18	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.92	0.09	0.01
2038	0.13	0.52	0.93	0.02	123.25	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.75	0.09	0.01
2040	0.14	0.54	0.97	0.02	128.31	0.09	0.01
2041	0.14	0.56	0.99	0.02	130.92	0.09	0.01
2042	0.15	0.57	1.01	0.02	133.58	0.09	0.01
2043	0.15	0.58	1.03	0.02	136.29	0.10	0.02
2044	0.15	0.59	1.05	0.02	139.05	0.10	0.02
2045	0.16	0.60	1.07	0.02	141.87	0.10	0.02

2046	0.16	0.61	1.09	0.02	144.75	0.10	0.02
2047	0.16	0.63	1.11	0.02	147.68	0.10	0.02
2048	0.16	0.64	1.13	0.02	150.68	0.11	0.02
2049	0.17	0.65	1.16	0.02	153.88	0.11	0.02
2050	0.17	0.66	1.18	0.02	156.81	0.11	0.02

Section: ES1 strong humid
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.78	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.59	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.41	0.06	0.01
2024	0.10	0.40	0.70	0.01	93.28	0.07	0.01
2025	0.10	0.40	0.72	0.01	95.19	0.07	0.01
2026	0.11	0.41	0.73	0.01	97.15	0.07	0.01
2027	0.11	0.42	0.75	0.01	99.15	0.07	0.01
2028	0.11	0.43	0.76	0.01	101.20	0.07	0.01
2029	0.11	0.44	0.78	0.01	103.29	0.07	0.01
2030	0.12	0.45	0.79	0.02	105.42	0.07	0.01
2031	0.12	0.46	0.81	0.02	107.59	0.08	0.01
2032	0.12	0.47	0.83	0.02	109.81	0.08	0.01
2033	0.12	0.48	0.84	0.02	112.05	0.08	0.01
2034	0.13	0.49	0.86	0.02	114.34	0.08	0.01
2035	0.13	0.49	0.88	0.02	116.64	0.08	0.01
2036	0.13	0.50	0.90	0.02	118.95	0.08	0.01
2037	0.13	0.51	0.91	0.02	121.24	0.09	0.01
2038	0.13	0.52	0.93	0.02	123.47	0.09	0.01
2039	0.14	0.52	0.95	0.02	125.56	0.09	0.01
2040	0.14	0.53	0.96	0.02	127.48	0.09	0.01
2041	0.14	0.53	0.97	0.02	129.17	0.09	0.01
2042	0.14	0.52	0.98	0.02	130.40	0.09	0.01
2043	0.14	0.51	0.98	0.02	131.19	0.09	0.01
2044	0.14	0.49	0.98	0.02	131.61	0.09	0.01
2045	0.13	0.47	0.98	0.02	131.77	0.10	0.01
2046	0.13	0.45	0.97	0.02	131.82	0.10	0.01
2047	0.13	0.43	0.97	0.02	131.95	0.10	0.01
2048	0.13	0.41	0.97	0.02	132.25	0.10	0.01
2049	0.12	0.40	0.97	0.02	132.87	0.10	0.01
2050	0.12	0.38	0.97	0.02	133.91	0.10	0.01

Section: ES1 strong humid
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.78	0.06	0.01

2022	0.10	0.38	0.67	0.01	89.59	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.41	0.06	0.01
2024	0.10	0.40	0.70	0.01	93.28	0.07	0.01
2025	0.10	0.40	0.72	0.01	95.19	0.07	0.01
2026	0.11	0.41	0.73	0.01	97.15	0.07	0.01
2027	0.11	0.42	0.75	0.01	99.15	0.07	0.01
2028	0.11	0.43	0.76	0.01	101.20	0.07	0.01
2029	0.11	0.44	0.78	0.01	103.29	0.07	0.01
2030	0.12	0.45	0.79	0.02	105.42	0.07	0.01
2031	0.12	0.46	0.81	0.02	107.59	0.08	0.01
2032	0.12	0.47	0.83	0.02	109.81	0.08	0.01
2033	0.12	0.48	0.84	0.02	112.05	0.08	0.01
2034	0.13	0.49	0.86	0.02	114.34	0.08	0.01
2035	0.13	0.49	0.88	0.02	116.64	0.08	0.01
2036	0.13	0.50	0.90	0.02	118.95	0.08	0.01
2037	0.13	0.51	0.92	0.02	121.59	0.09	0.01
2038	0.14	0.52	0.93	0.02	123.75	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.97	0.09	0.01
2040	0.14	0.53	0.96	0.02	128.10	0.09	0.01
2041	0.14	0.54	0.98	0.02	130.10	0.09	0.01
2042	0.14	0.54	0.99	0.02	131.91	0.09	0.01
2043	0.14	0.53	1.00	0.02	133.49	0.10	0.01
2044	0.14	0.53	1.01	0.02	134.82	0.10	0.01
2045	0.14	0.52	1.02	0.02	135.88	0.10	0.01
2046	0.14	0.51	1.02	0.02	136.67	0.10	0.02
2047	0.14	0.49	1.02	0.02	137.20	0.10	0.02
2048	0.14	0.47	1.02	0.02	137.50	0.10	0.02
2049	0.15	0.54	1.08	0.02	145.20	0.10	0.02
2050	0.15	0.52	1.08	0.02	145.68	0.11	0.02

Table D-4: Road User Emission Results – ES1 Weak

Section: ES1 weak Arid
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.09	0.37	0.66	0.01	87.18	0.06	0.01
2022	0.10	0.38	0.67	0.01	88.95	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.71	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.52	0.06	0.01
2025	0.10	0.40	0.71	0.01	94.37	0.07	0.01
2026	0.10	0.41	0.72	0.01	96.26	0.07	0.01
2027	0.11	0.41	0.74	0.01	98.19	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.16	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.17	0.07	0.01
2030	0.11	0.44	0.78	0.01	104.22	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.32	0.07	0.01
2032	0.12	0.46	0.82	0.02	108.45	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.63	0.08	0.01
2034	0.12	0.48	0.85	0.02	112.86	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.13	0.08	0.01
2036	0.13	0.50	0.88	0.02	117.44	0.08	0.01
2037	0.13	0.51	0.90	0.02	119.80	0.08	0.01
2038	0.13	0.52	0.92	0.02	122.21	0.09	0.01
2039	0.14	0.53	0.94	0.02	124.68	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.19	0.09	0.01
2041	0.14	0.55	0.98	0.02	129.75	0.09	0.01
2042	0.14	0.56	1.00	0.02	132.37	0.09	0.01
2043	0.15	0.57	1.02	0.02	135.03	0.09	0.01
2044	0.15	0.58	1.04	0.02	137.76	0.10	0.02
2045	0.15	0.59	1.06	0.02	140.54	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.38	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.28	0.10	0.02
2048	0.16	0.63	1.12	0.02	149.23	0.10	0.02
2049	0.17	0.64	1.14	0.02	152.25	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.33	0.11	0.02

Section: ES1 weak Arid
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.09	0.37	0.66	0.01	87.18	0.06	0.01
2022	0.10	0.38	0.67	0.01	88.95	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.71	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.52	0.06	0.01
2025	0.10	0.40	0.71	0.01	94.37	0.07	0.01

2026	0.10	0.41	0.72	0.01	96.26	0.07	0.01
2027	0.11	0.41	0.74	0.01	98.19	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.16	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.17	0.07	0.01
2030	0.11	0.44	0.78	0.01	104.22	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.32	0.07	0.01
2032	0.12	0.46	0.82	0.02	108.45	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.63	0.08	0.01
2034	0.12	0.48	0.85	0.02	112.86	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.13	0.08	0.01
2036	0.13	0.50	0.88	0.02	117.44	0.08	0.01
2037	0.13	0.51	0.90	0.02	119.80	0.08	0.01
2038	0.13	0.52	0.92	0.02	122.75	0.09	0.01
2039	0.14	0.53	0.94	0.02	124.93	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.39	0.09	0.01
2041	0.14	0.55	0.98	0.02	129.93	0.09	0.01
2042	0.14	0.56	1.00	0.02	132.52	0.09	0.01
2043	0.15	0.57	1.02	0.02	135.17	0.10	0.01
2044	0.15	0.58	1.04	0.02	137.88	0.10	0.02
2045	0.15	0.59	1.06	0.02	140.65	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.47	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.35	0.10	0.02
2048	0.16	0.63	1.12	0.02	149.29	0.11	0.02
2049	0.17	0.64	1.15	0.02	152.29	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.35	0.11	0.02

Section: ES1 weak semi arid
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.32	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.09	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.86	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.68	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.53	0.07	0.01
2026	0.10	0.41	0.72	0.01	96.43	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.37	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.34	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.36	0.07	0.01
2030	0.11	0.44	0.79	0.01	104.42	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.53	0.07	0.01
2032	0.12	0.46	0.82	0.02	108.67	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.86	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.10	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.38	0.08	0.01
2036	0.13	0.50	0.89	0.02	117.70	0.08	0.01

2037	0.13	0.51	0.90	0.02	120.08	0.08	0.01
2038	0.13	0.52	0.92	0.02	122.51	0.09	0.01
2039	0.14	0.53	0.94	0.02	124.98	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.51	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.09	0.09	0.01
2042	0.14	0.56	1.00	0.02	132.73	0.09	0.01
2043	0.15	0.57	1.02	0.02	135.42	0.10	0.02
2044	0.15	0.59	1.04	0.02	138.19	0.10	0.02
2045	0.15	0.60	1.06	0.02	140.99	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.84	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.76	0.10	0.02
2048	0.16	0.63	1.13	0.02	149.74	0.11	0.02
2049	0.17	0.65	1.15	0.02	152.78	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.88	0.11	0.02

Section: ES1 weak semi arid
Alternative: Full maintenance

Year	Annual Emission Quantities in tonnes						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.32	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.09	0.06	0.01
2023	0.10	0.38	0.68	0.01	90.86	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.68	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.53	0.07	0.01
2026	0.10	0.41	0.72	0.01	96.43	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.37	0.07	0.01
2028	0.11	0.42	0.75	0.01	100.34	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.36	0.07	0.01
2030	0.11	0.44	0.79	0.01	104.42	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.53	0.07	0.01
2032	0.12	0.46	0.82	0.02	108.67	0.08	0.01
2033	0.12	0.47	0.83	0.02	110.86	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.10	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.38	0.08	0.01
2036	0.13	0.50	0.89	0.02	117.70	0.08	0.01
2037	0.13	0.51	0.90	0.02	120.08	0.08	0.01
2038	0.13	0.52	0.93	0.02	123.04	0.09	0.01
2039	0.14	0.53	0.94	0.02	125.23	0.09	0.01
2040	0.14	0.54	0.96	0.02	127.71	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.25	0.09	0.01
2042	0.14	0.56	1.00	0.02	132.86	0.09	0.01
2043	0.15	0.57	1.02	0.02	135.53	0.10	0.02
2044	0.15	0.59	1.04	0.02	138.25	0.10	0.02
2045	0.15	0.60	1.06	0.02	141.03	0.10	0.02
2046	0.16	0.61	1.08	0.02	143.87	0.10	0.02
2047	0.16	0.62	1.10	0.02	146.76	0.10	0.02

2048	0.16	0.63	1.13	0.02	149.72	0.11	0.02
2049	0.17	0.65	1.15	0.02	152.73	0.11	0.02
2050	0.17	0.66	1.17	0.02	155.81	0.11	0.02

Section: ES1 weak subhumid dry
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.46	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.24	0.06	0.01
2023	0.10	0.39	0.68	0.01	91.03	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.86	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.73	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.65	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.60	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.60	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.64	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.72	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.85	0.08	0.01
2032	0.12	0.46	0.82	0.02	109.02	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.23	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.50	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.81	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.18	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.59	0.08	0.01
2038	0.13	0.52	0.93	0.02	123.07	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.59	0.09	0.01
2040	0.14	0.54	0.96	0.02	128.16	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.76	0.09	0.01
2042	0.15	0.56	1.00	0.02	133.42	0.09	0.01
2043	0.15	0.58	1.02	0.02	136.10	0.10	0.02
2044	0.15	0.59	1.04	0.02	138.80	0.10	0.02
2045	0.15	0.60	1.07	0.02	141.52	0.10	0.02
2046	0.16	0.61	1.09	0.02	144.26	0.10	0.02
2047	0.16	0.62	1.11	0.02	147.00	0.10	0.02
2048	0.16	0.63	1.13	0.02	149.76	0.11	0.02
2049	0.17	0.64	1.15	0.02	152.51	0.11	0.02
2050	0.17	0.64	1.17	0.02	155.25	0.11	0.02

Section: ES1 weak subhumid dry
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.46	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.24	0.06	0.01
2023	0.10	0.39	0.68	0.01	91.03	0.06	0.01

2024	0.10	0.39	0.70	0.01	92.86	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.73	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.65	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.60	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.60	0.07	0.01
2029	0.11	0.43	0.77	0.01	102.64	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.72	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.85	0.08	0.01
2032	0.12	0.46	0.82	0.02	109.02	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.23	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.50	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.81	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.36	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.73	0.09	0.01
2038	0.13	0.52	0.93	0.02	123.16	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.64	0.09	0.01
2040	0.14	0.54	0.96	0.02	128.18	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.76	0.09	0.01
2042	0.15	0.57	1.00	0.02	133.40	0.09	0.01
2043	0.15	0.58	1.02	0.02	136.09	0.10	0.02
2044	0.15	0.59	1.05	0.02	138.84	0.10	0.02
2045	0.15	0.60	1.07	0.02	141.63	0.10	0.02
2046	0.16	0.61	1.09	0.02	144.47	0.10	0.02
2047	0.16	0.62	1.11	0.02	147.36	0.10	0.02
2048	0.16	0.64	1.13	0.02	150.31	0.11	0.02
2049	0.17	0.65	1.16	0.02	153.96	0.11	0.02
2050	0.17	0.66	1.18	0.02	156.62	0.11	0.02

Section: ES1 weak subhumid wet
Alternative: Base Alternative

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.55	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.33	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.11	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.94	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.82	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.73	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.68	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.68	0.07	0.01
2029	0.11	0.44	0.77	0.01	102.71	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.79	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.91	0.08	0.01
2032	0.12	0.46	0.82	0.02	109.08	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.29	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.55	0.08	0.01

2035	0.13	0.49	0.87	0.02	115.86	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.22	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.64	0.08	0.01
2038	0.13	0.52	0.93	0.02	123.11	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.64	0.09	0.01
2040	0.14	0.54	0.96	0.02	128.21	0.09	0.01
2041	0.14	0.55	0.98	0.02	130.83	0.09	0.01
2042	0.15	0.57	1.00	0.02	133.50	0.09	0.01
2043	0.15	0.58	1.03	0.02	136.22	0.10	0.02
2044	0.15	0.59	1.05	0.02	138.96	0.10	0.02
2045	0.15	0.60	1.07	0.02	141.73	0.10	0.02
2046	0.16	0.61	1.09	0.02	144.54	0.10	0.02
2047	0.16	0.62	1.11	0.02	147.37	0.10	0.02
2048	0.16	0.63	1.13	0.02	150.23	0.11	0.02
2049	0.17	0.64	1.15	0.02	153.10	0.11	0.02
2050	0.17	0.65	1.17	0.02	156.00	0.11	0.02

Section: ES1 weak subhumid wet
Alternative: Full maintenance

Year	**Annual Emission Quantities in tonnes**						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.55	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.33	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.11	0.06	0.01
2024	0.10	0.39	0.70	0.01	92.94	0.07	0.01
2025	0.10	0.40	0.71	0.01	94.82	0.07	0.01
2026	0.11	0.41	0.73	0.01	96.73	0.07	0.01
2027	0.11	0.42	0.74	0.01	98.68	0.07	0.01
2028	0.11	0.43	0.76	0.01	100.68	0.07	0.01
2029	0.11	0.44	0.77	0.01	102.71	0.07	0.01
2030	0.11	0.44	0.79	0.02	104.79	0.07	0.01
2031	0.12	0.45	0.80	0.02	106.91	0.08	0.01
2032	0.12	0.46	0.82	0.02	109.08	0.08	0.01
2033	0.12	0.47	0.84	0.02	111.29	0.08	0.01
2034	0.12	0.48	0.85	0.02	113.55	0.08	0.01
2035	0.13	0.49	0.87	0.02	115.86	0.08	0.01
2036	0.13	0.50	0.89	0.02	118.41	0.08	0.01
2037	0.13	0.51	0.91	0.02	120.77	0.09	0.01
2038	0.13	0.52	0.93	0.02	123.20	0.09	0.01
2039	0.14	0.53	0.95	0.02	125.68	0.09	0.01
2040	0.14	0.54	0.96	0.02	128.21	0.09	0.01
2041	0.14	0.56	0.98	0.02	130.80	0.09	0.01
2042	0.15	0.57	1.00	0.02	133.44	0.09	0.01
2043	0.15	0.58	1.02	0.02	136.13	0.10	0.02
2044	0.15	0.59	1.05	0.02	138.88	0.10	0.02
2045	0.15	0.60	1.07	0.02	141.68	0.10	0.02

2046	0.16	0.61	1.09	0.02	144.54	0.10	0.02
2047	0.16	0.63	1.11	0.02	147.45	0.10	0.02
2048	0.16	0.64	1.13	0.02	150.42	0.11	0.02
2049	0.17	0.65	1.16	0.02	154.10	0.11	0.02
2050	0.17	0.66	1.18	0.02	156.81	0.11	0.02

Section: ES1 weak humid
Alternative: Base Alternative

Year	Annual Emission Quantities in tonnes						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.78	0.06	0.01
2022	0.10	0.38	0.67	0.01	89.60	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.42	0.06	0.01
2024	0.10	0.40	0.70	0.01	93.29	0.07	0.01
2025	0.10	0.40	0.72	0.01	95.21	0.07	0.01
2026	0.11	0.41	0.73	0.01	97.17	0.07	0.01
2027	0.11	0.42	0.75	0.01	99.17	0.07	0.01
2028	0.11	0.43	0.76	0.01	101.22	0.07	0.01
2029	0.11	0.44	0.78	0.01	103.31	0.07	0.01
2030	0.12	0.45	0.79	0.02	105.45	0.07	0.01
2031	0.12	0.46	0.81	0.02	107.62	0.08	0.01
2032	0.12	0.47	0.83	0.02	109.83	0.08	0.01
2033	0.12	0.48	0.84	0.02	112.08	0.08	0.01
2034	0.13	0.49	0.86	0.02	114.35	0.08	0.01
2035	0.13	0.49	0.88	0.02	116.64	0.08	0.01
2036	0.13	0.50	0.90	0.02	118.92	0.08	0.01
2037	0.13	0.51	0.91	0.02	121.17	0.09	0.01
2038	0.13	0.52	0.93	0.02	123.32	0.09	0.01
2039	0.14	0.52	0.94	0.02	125.31	0.09	0.01
2040	0.14	0.52	0.96	0.02	127.07	0.09	0.01
2041	0.14	0.52	0.97	0.02	128.56	0.09	0.01
2042	0.14	0.51	0.97	0.02	129.52	0.09	0.01
2043	0.14	0.49	0.97	0.02	130.03	0.09	0.01
2044	0.13	0.48	0.97	0.02	130.21	0.09	0.01
2045	0.13	0.46	0.96	0.02	130.18	0.09	0.01
2046	0.13	0.43	0.96	0.02	130.17	0.10	0.01
2047	0.13	0.41	0.96	0.02	130.31	0.10	0.01
2048	0.12	0.39	0.95	0.02	130.73	0.10	0.01
2049	0.12	0.38	0.95	0.02	131.58	0.10	0.01
2050	0.12	0.36	0.95	0.02	132.96	0.10	0.01

Section: ES1 weak humid
Alternative: Full maintenance

Year	Annual Emission Quantities in tonnes						
	Hydrocarbon HC	**Carbon monoxide CO**	**Nitrous oxide NOx**	**Sulphur dioxide SO2**	**Carbon dioxide CO2**	**Particulates Par**	**Lead Pb**
2021	0.10	0.37	0.66	0.01	87.78	0.06	0.01

2022	0.10	0.38	0.67	0.01	89.60	0.06	0.01
2023	0.10	0.39	0.69	0.01	91.42	0.06	0.01
2024	0.10	0.40	0.70	0.01	93.29	0.07	0.01
2025	0.10	0.40	0.72	0.01	95.21	0.07	0.01
2026	0.11	0.41	0.73	0.01	97.17	0.07	0.01
2027	0.11	0.42	0.75	0.01	99.17	0.07	0.01
2028	0.11	0.43	0.76	0.01	101.22	0.07	0.01
2029	0.11	0.44	0.78	0.01	103.31	0.07	0.01
2030	0.12	0.45	0.79	0.02	105.45	0.07	0.01
2031	0.12	0.46	0.81	0.02	107.62	0.08	0.01
2032	0.12	0.47	0.83	0.02	109.83	0.08	0.01
2033	0.12	0.48	0.84	0.02	112.08	0.08	0.01
2034	0.13	0.49	0.86	0.02	114.35	0.08	0.01
2035	0.13	0.49	0.88	0.02	116.64	0.08	0.01
2036	0.13	0.50	0.90	0.02	119.13	0.08	0.01
2037	0.13	0.51	0.91	0.02	121.37	0.09	0.01
2038	0.13	0.52	0.93	0.02	123.58	0.09	0.01
2039	0.14	0.52	0.95	0.02	125.72	0.09	0.01
2040	0.14	0.53	0.96	0.02	127.75	0.09	0.01
2041	0.14	0.53	0.97	0.02	129.63	0.09	0.01
2042	0.14	0.53	0.99	0.02	131.30	0.09	0.01
2043	0.14	0.53	1.00	0.02	132.72	0.10	0.01
2044	0.14	0.52	1.00	0.02	133.87	0.10	0.01
2045	0.14	0.51	1.01	0.02	134.76	0.10	0.01
2046	0.14	0.49	1.01	0.02	135.42	0.10	0.01
2047	0.14	0.48	1.01	0.02	135.92	0.10	0.01
2048	0.13	0.46	1.01	0.02	136.36	0.10	0.01
2049	0.15	0.53	1.07	0.02	144.22	0.10	0.02
2050	0.15	0.51	1.07	0.02	144.32	0.10	0.02