Flexible Pavement Performance and Life Cycle Assessment Incorporating Climate Change Impacts

Sheldon A. Blaauw[1]

Department of Civil Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

Email: sheldon.blaauw@arup.com

James W. Maina

Department of Civil Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

E-mail: james.maina@up.ac.za

Georges A.J. Mturi

Transport Infrastructure Engineering, Council for Scientific and Industrial Research (CSIR), Private Bag 395, Pretoria 0001, South Africa

E-mail: gmturi@csir.co.za

Alex T. Visser

Department of Civil Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

E-mail: alex.visser@up.ac.za

[1] Corresponding author

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Graphical Abstract

1. **Utilise High Resolution Regional Climate Projections (2021-2050)**
2. **Calculate Future Thornthwaite Moisture Index (2021-2050)**
3. **Analyse Pavement Deterioration with Highway Development and Management (HDM-4) for a Future Climate Using International Roughness Index**
4. **Translate Deterioration Trends to Road User Emissions**
5. **Complete Holistic Life Cycle Assessment of a Typical Pavement**

Abstract

Construction, maintenance and demolition of pavements are often considered the only activities impacting the environment. This paper shows that user emissions, influenced by factors such as road roughness and climate change, are also important measurements of pavement sustainability. The objective of this paper is to complete a life cycle assessment of a typical flexible pavement based on the climate change forecast by using road deterioration and user emissions analysed with the Highway Development and Management (HDM-4) package. Data from South Africa were used to prove the concept. Results showed that user emissions dominate life cycle environmental impacts, and that gradual warming and drying of the atmosphere attributed to climate change is beneficial to pavement deterioration and emissions alike. Although invariably debate about the impact of climate change has negative connotations, and the reality of many negative impacts, road authorities in South Africa are fortunate that less rainfall will be beneficial.

1. INTRODUCTION

Pavements are often considered as being static and passive, leading to the common notion that only construction, maintenance and demolition result in their overall environmental burden. However, the fuel consumption and resultant emissions of the road user, influenced by factors such as road roughness from use and pavement deterioration due to climate change, are important considerations for pavement sustainability.

This paper aims to present elements of life cycle assessment (LCA) results of a pavement, mainly in terms of the equivalent Carbon Dioxide (CO_2e) emissions. Background of the study and previously reported results are provided. This is followed by a summary of the important pavement deterioration and climate change parameters to be included in the analysis that was conducted using the Highway Development and Management 4 (HDM-4) package. Finally, conclusions and recommendations based on the effects of road user emissions on total life cycle emissions are provided.

Blaauw et al. (2020) and Blaauw and Maina (2021) have previously presented the main LCA results of pavement construction, maintenance and demolition. This paper builds on these previous documents and focuses on the road user emissions to complete a holistic LCA of a typical range of

South African pavements. The paper defines the contribution of pavement surface roughness deterioration exacerbated by the impacts of climate change on emissions. The importance of this topic lies mainly in the fact that surface roughness is a parameter that is specified for quality control in pavement construction. The quality, roughness or comfort of the pavement surface deteriorates during use and it is a parameter that is sensitive to climate changes but can be controlled by the selection of a proper maintenance strategy that can be applied to a pavement under certain climatic conditions. A visual illustration of the study is provided in Figure 1.

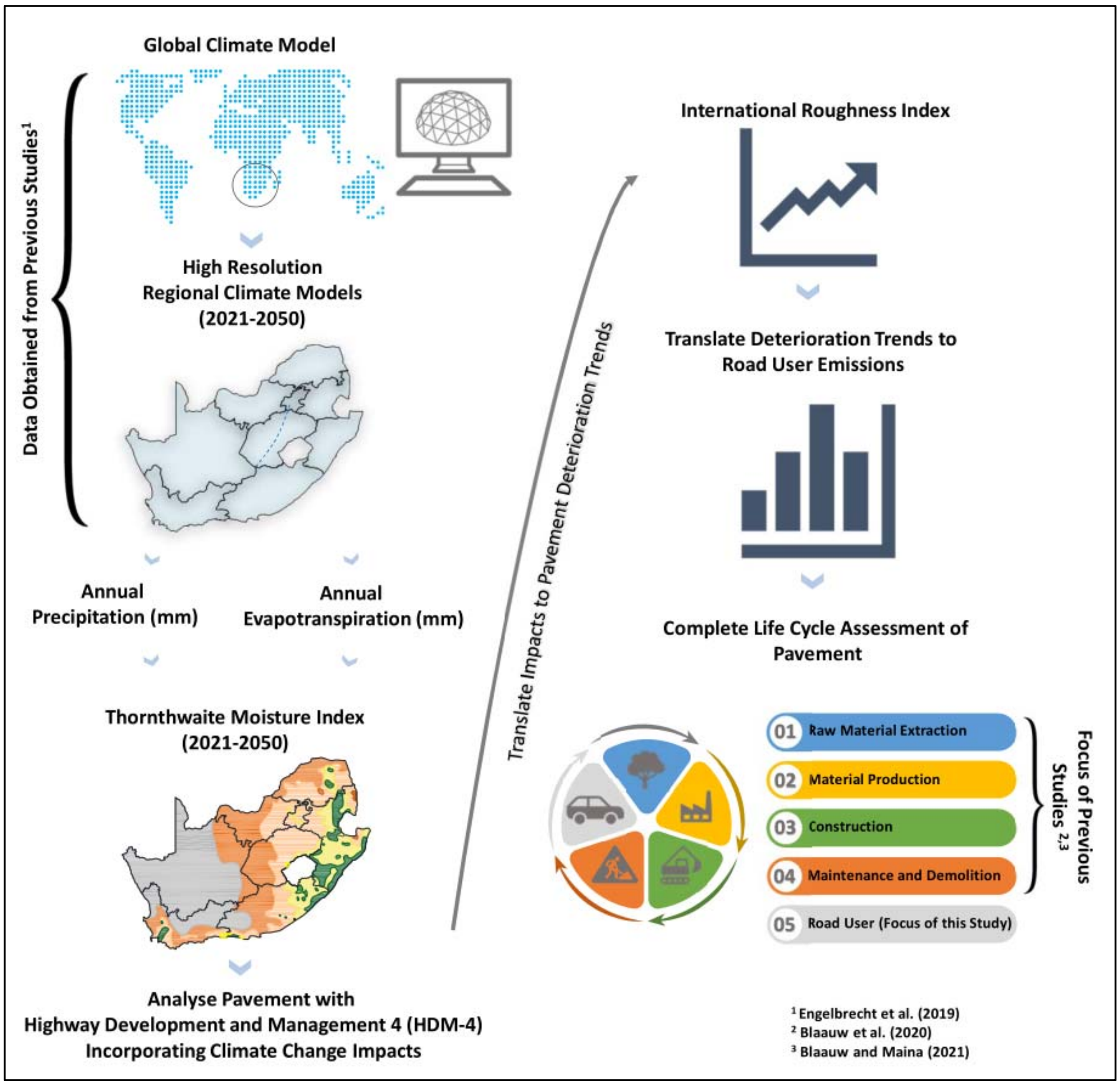

Figure 1: Study process

In this study, 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 article, 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 later sections 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.

2. BACKGROUND

For many years, South African road authorities have justified projects on an economic basis and have taken measures to reduce costs of road construction, vehicle operations as well as road fatalities while attempting to enhance the sustainability of the road network. However, efforts to address sustainability have been incomplete as environmental and social impacts are not holistically considered. To address the environmental impacts, Blaauw and Maina (2021) developed the first South African life cycle inventory for typical pavement materials and construction activities, allowing quantification of construction, maintenance and demolition. This inventory will be utilised to complement the road user impacts analysed in this study and provide a basis for a complete LCA of South African pavements.

Additionally, climate change has added to the risks of an increasing rate of pavement deterioration, a key factor affecting road user emissions and subsequent life cycle impacts. The Council for Scientific and Industrial Research (CSIR) has undertaken extensive climate change research for South Africa, producing some of the highest resolution projections globally (Engelbrecht et al., 2019). These data may be used to predict how climate will change the Thornthwaite Moisture Index (TMI) for South Africa. TMI is a leading climate variable utilised in pavement deterioration modelling. The 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 1 (Mather, 1974):

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

where:

Im is the Thornthwaite Moisture Index (unitless);

P is the annual precipitation (cm); and

PE is the annual potential evapotranspiration (cm).

As climate change is expected to manifest in a gradual increase in temperature, accompanied by the 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 deterioration (SAPEM, 2017). The climate change projections produced by the CSIR are evaluated in this study, 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 and intense storms, 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).

To determine road user emissions incorporating climate change impacts, a performance metric is required which is both climate-sensitive and correlated to road user fuel consumption. The International Roughness Index (IRI), developed by the World Bank in 1987, is generally used to define performance. Significant research has been done to develop performance models, which have been incorporated into Highways Development and Management Model 4 (HDM-4). HDM-4 ver 2.08 is the current version of the package and was used in this study to evaluate road user impacts. Performance calibration factors developed in South Africa and prescribed by the South African National Roads Agency SOC Ltd. (SANRAL) were used to relate the analysis to local conditions. The SANRAL unit cost figures, as well as the prescribed maintenance regime, were also used.

3. ANALYSIS INPUTS FOR HDM-4 MODELLING

3.1 Emissions

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

A Greenhouse Gas (GHG) is any gas in the atmosphere which adds to the greenhouse effect by absorbing and re-emitting heat from the earth's surface hence trapping it from leaving the atmosphere, increasing the temperature of the planet above what it would normally be. Carbon

Dioxide (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 GHGs 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, disposal and end of life aspects that make up the materials of a road pavement. The whole life carbon of road 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). Additional sources of pollution are associated with pavement infrastructure provisions, such as particulate matter, polycyclic aromatic hydrocarbons, volatile organic compounds, and so forth. These emissions may be viewed as socially-oriented emissions (Blaauw and Maina, 2021) and do not have a direct impact on climate change. As the focus of this paper is investigating the impacts of climate change on pavements and vice-versa, the socially-oriented emissions are omitted and CO_2e, the leading driver behind climate change, is focused on for simplicity.

3.2 Functional Unit and System Boundaries

The functional unit, representing the reference unit used to quantify road user emissions, is one kilometre, 7.4 m wide single carriageway with a 30-year analysis period. The 30-year analysis period reflects a standard 20-year pavement design life specified in South Africa, and the implementation of major maintenance and rehabilitation to extend the pavement life to 30 years. This analysis period is common in South Africa, and similar approaches are often seen in other countries such as the USA and UK. This study measures only the outputs related to the flexible pavement road user emissions as a function of roughness deterioration incorporating climate change effects. The study utilises CO_2e calculated by HDM-4 as the leading output indicator for the LCA. The analysis period selected for this study is 2021 to 2050.

3.3 Pavement Structures

For modelling, two design traffic classifications are utilised representing an ES1 and ES10 (1 and 10 million equivalent standard axles), for which two pavement structures are specified for each design traffic, one for a wet region (i.e. strong) and one for a dry region (i.e. weak). The equivalent standard axle, developed through the AASHO Road Test, is used to express a range of axle loads such as applied by mixed traffic, in terms of a common denominator (TRH16, 1991). In South Africa, an 80 kN axle is used as the standard axle load, and the damage caused by any other axle load relative to the standard axle is defined as the equivalent standard axle (E80).

The pavement structures analysed 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 1.

Table 1: Road structure inputs

Design Traffic	**AADT/ lane***	**AADTT/ lane****	**Pavement Structure – Strong**	**Pavement Structure - Weak**
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)

* AADT = Annual Average Daily Traffic
** AADTT = Annual Average Daily Truck Traffic
SNP = Adjusted Structural Number

The two pavement structure designations shown in Table 1 refer specifically to the climatic zones in which the structures are to be utilised, with ‘strong’ structures generally preferred in humid climates and ‘weak’ structures employed in more arid climates.

3.4 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, HDM-4 selects the appropriate maintenance strategy to follow for the analysis period. These two maintenance regimes are used for modelling the deterioration of the pavements for incorporating the impacts of climate change.

Table 2: 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

3.5 Climate-Related Inputs

For modelling the road scenario, series of climatic data are required as input to HDM-4. The climatic inputs required are detailed in Table 2. Performance calibration factors developed in South Africa and prescribed by SANRAL are also used to relate the analysis to local conditions.

4. CLIMATE CHANGE FOR SOUTH AFRICA

The projections produced by the CSIR using Equation 1 were used to predict the locations of climatic zones for South Africa. Figure 2 shows the proposed revised TMI boundaries for the period 2021-2050 compared to the previous boundaries currently utilised by SAPEM (2017).

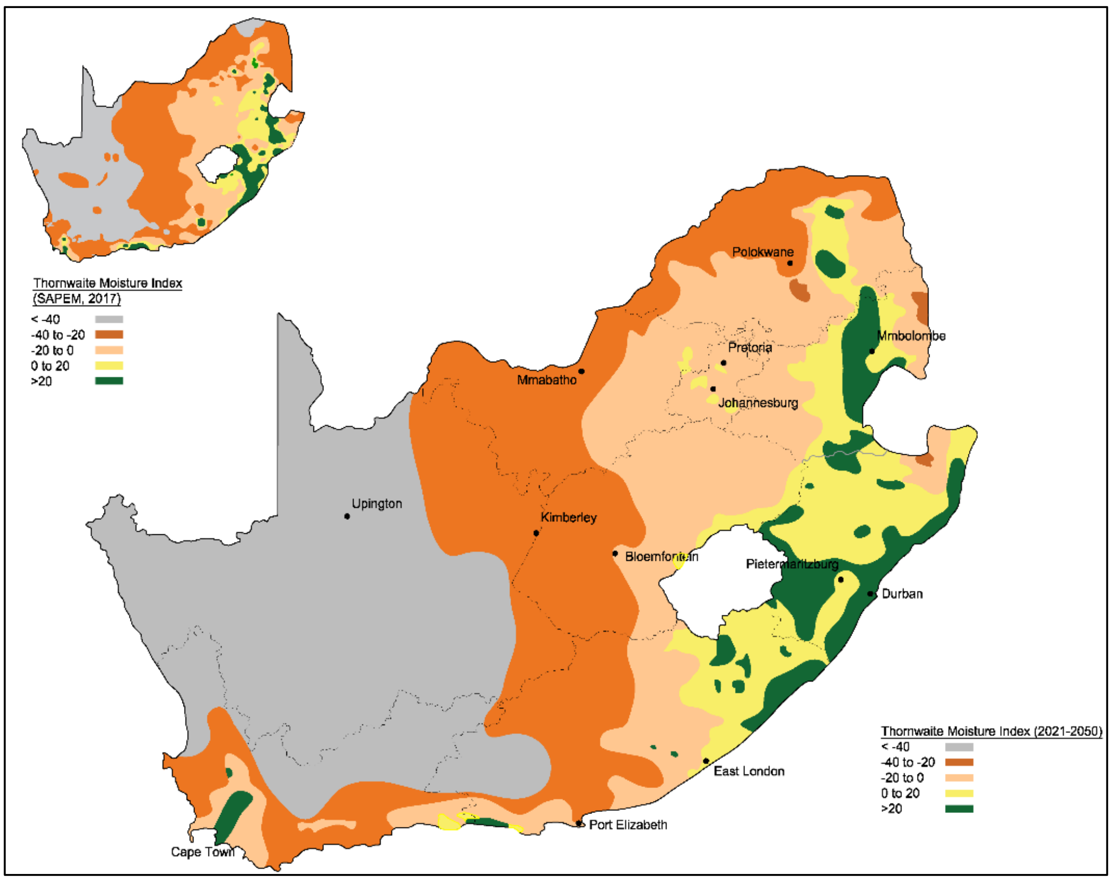

Figure 2: TMI changes for South Africa (2021-2050)

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 3.

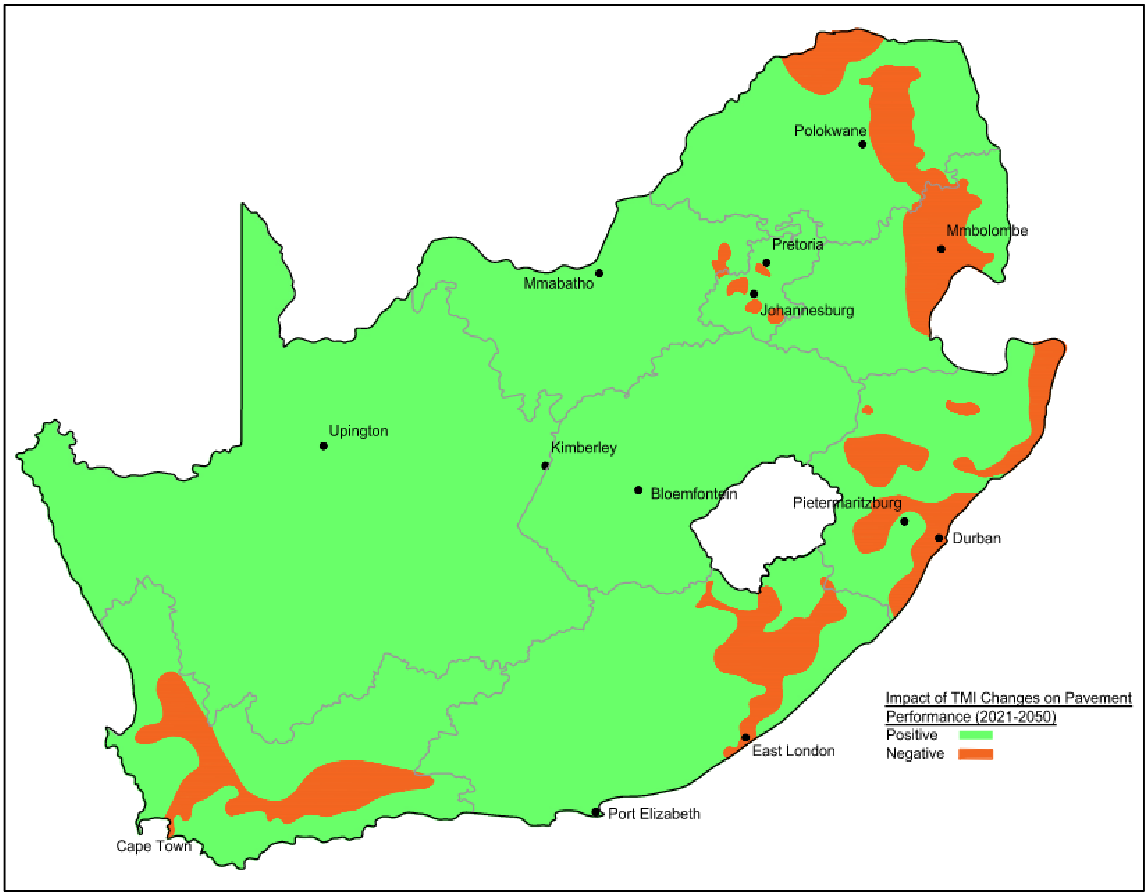

Figure 3: Impact of TMI changes on pavement performance

Figure 3 shows 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, reducing the aggravating moisture-related circumstances which accelerate pavement deterioration.

5. 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 Figure 4 to Figure 7 and are summarised in Table 3.

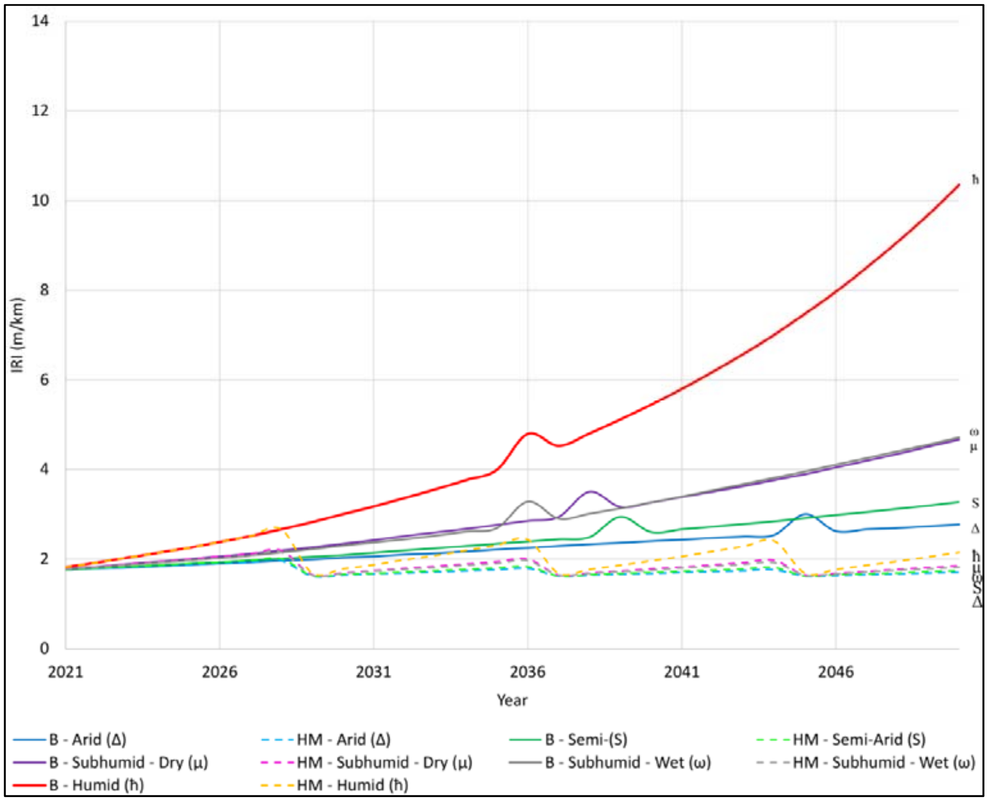

Figure 4: ES10 Strong Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

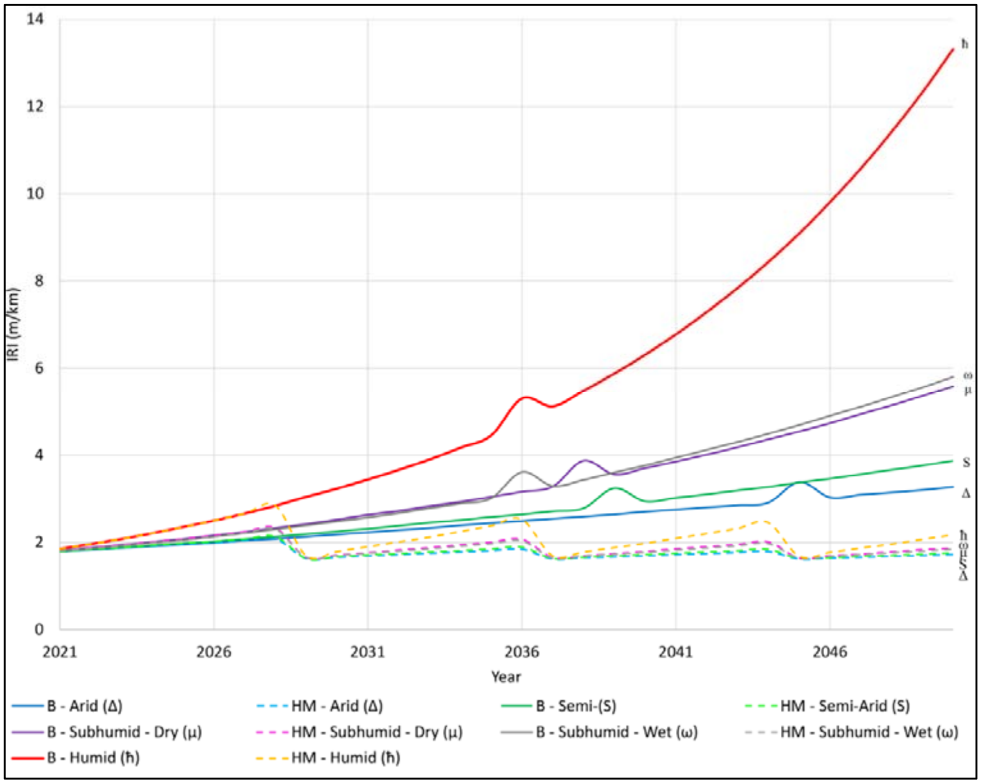

Figure 5: ES10 Weak Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

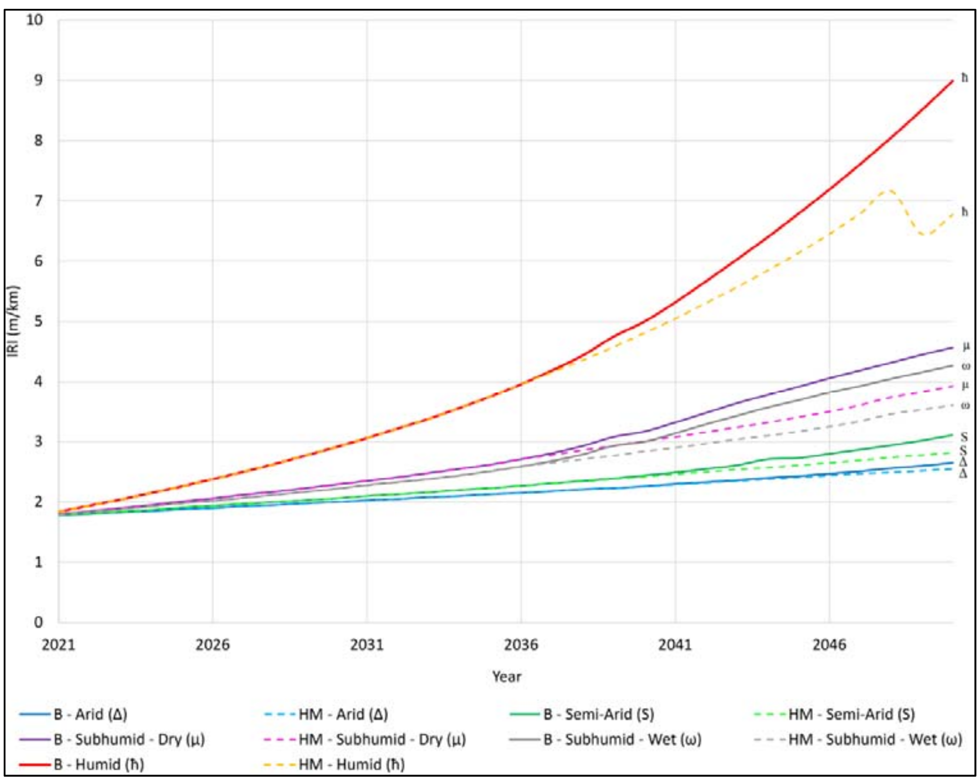

Figure 6: ES1 Strong Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

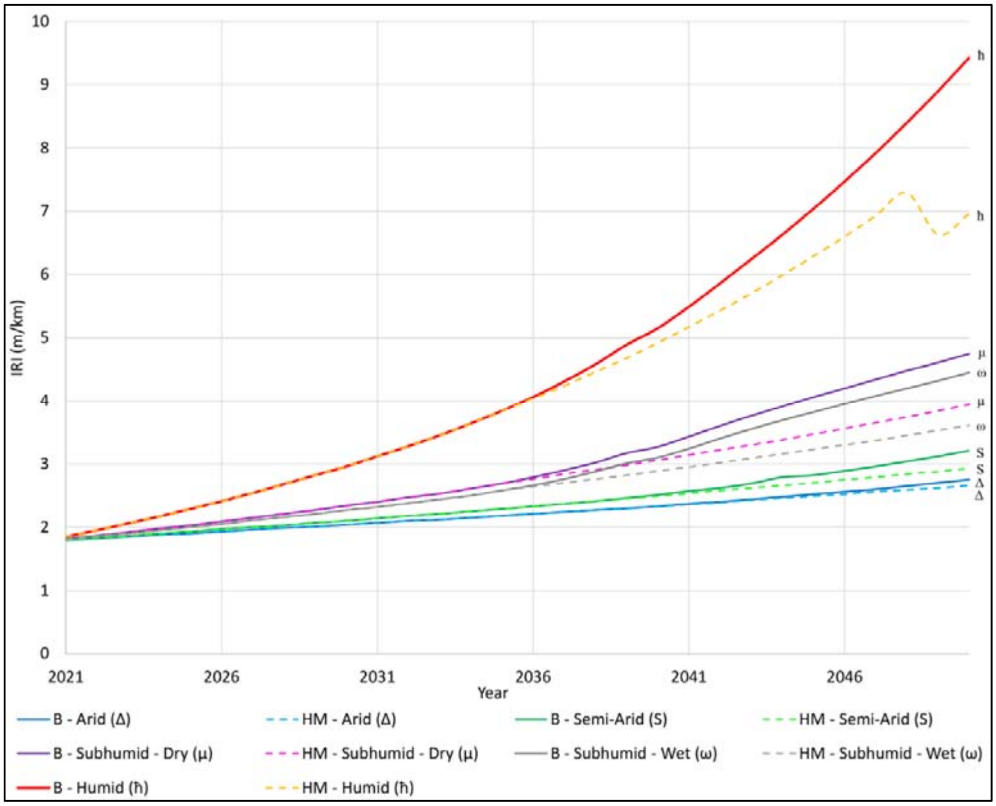

Figure 7: ES1 Weak Pavement Deterioration (B = Baseline, HM = Heavy Maintenance)

Table 3: 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	3.00	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	2.70	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	5.80	2.78	4.27	2.86	4.45
HM - Subhumid - Wet	1.82	2.15	1.86	2.30	2.60	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	2.10	2.84	4.13	7.16*	4.21	7.29*

(*exceeds the critical 6 m/km threshold)

From the pavement deterioration results summarised in Table 3, 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 as would be expected. 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.

6. 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.

7. ROAD USER EMISSIONS

To determine the road user emissions, the pavement deterioration trends were assessed with HDM-4. The results of this assessment are shown in Figures 8 to 11.

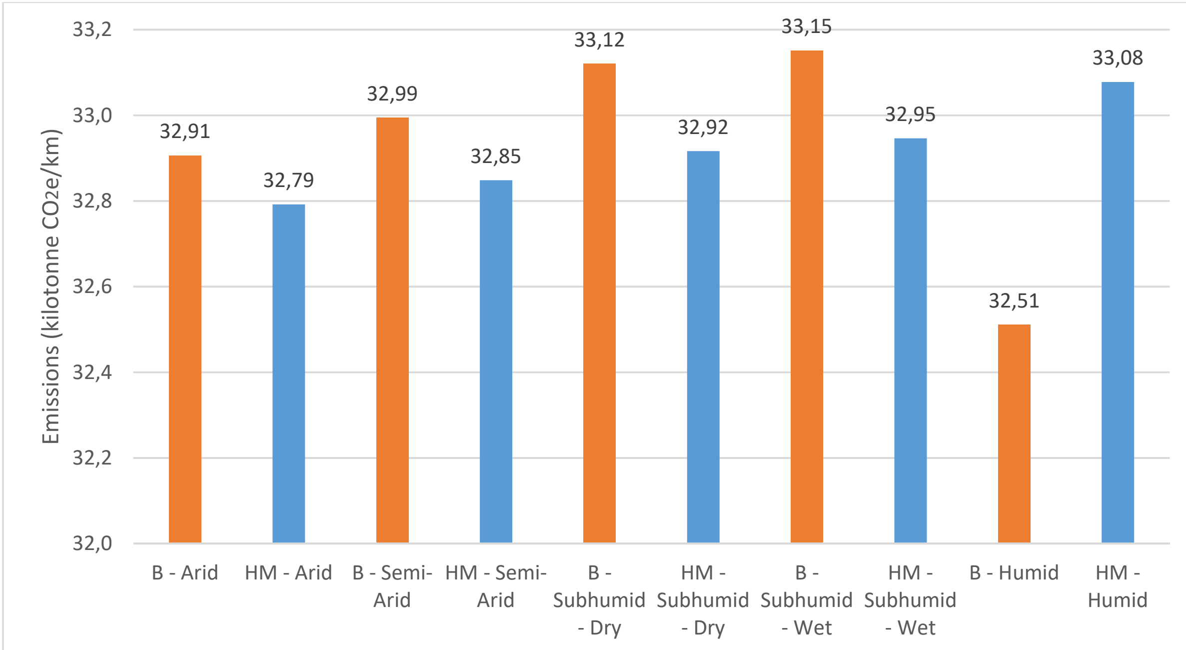

Figure 8: ES10 Strong Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

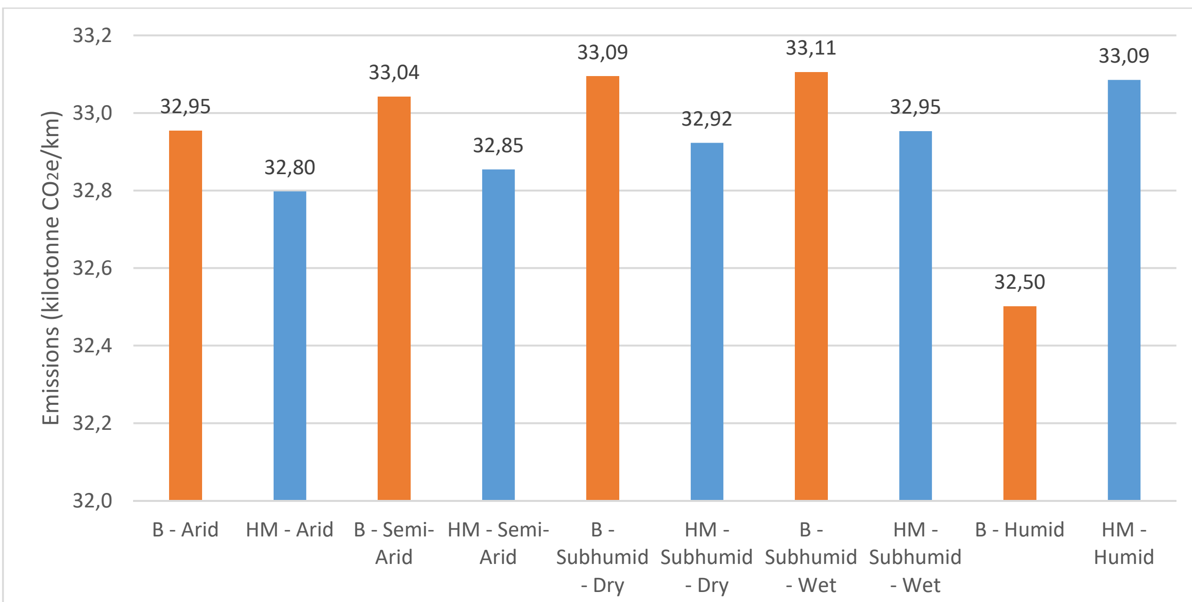

Figure 9: ES10 Weak Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

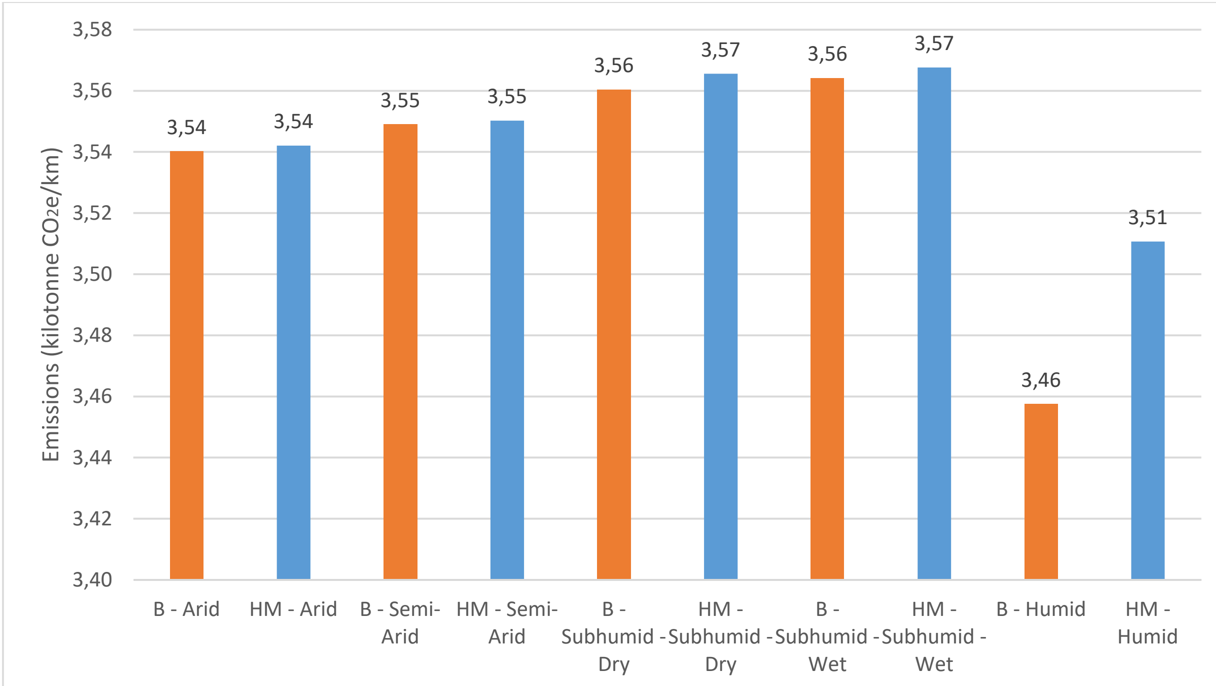

Figure 10: ES1 Strong Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

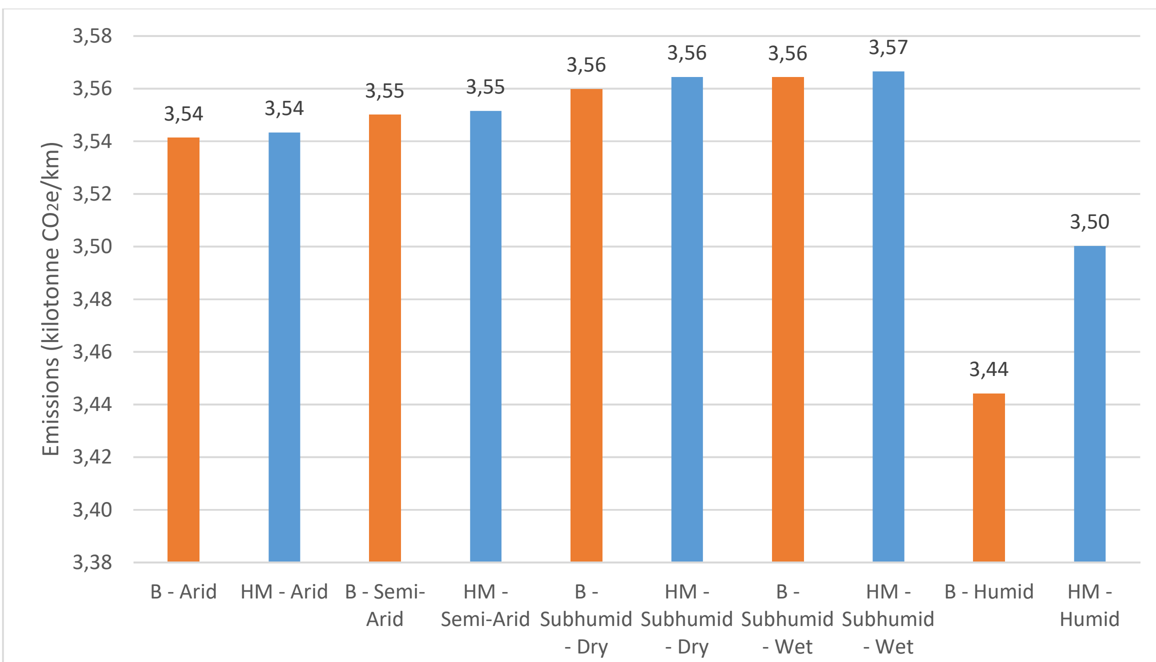

Figure 11: ES1 Weak Pavement Road User Emissions (B = Baseline, HM = Heavy Maintenance)

Similar to the pavement deterioration trends previously observed, pavements in the arid climate zones tend to perform better compared to those in the more 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) perform 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.

Another notable outlier is observed in the data, where the Baseline – Humid scenario for all traffic classes, 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 and 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). Figure 12 shows the decrease in the operating speeds for the typical 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, simply attributed to reduced operating speeds for the baseline options.

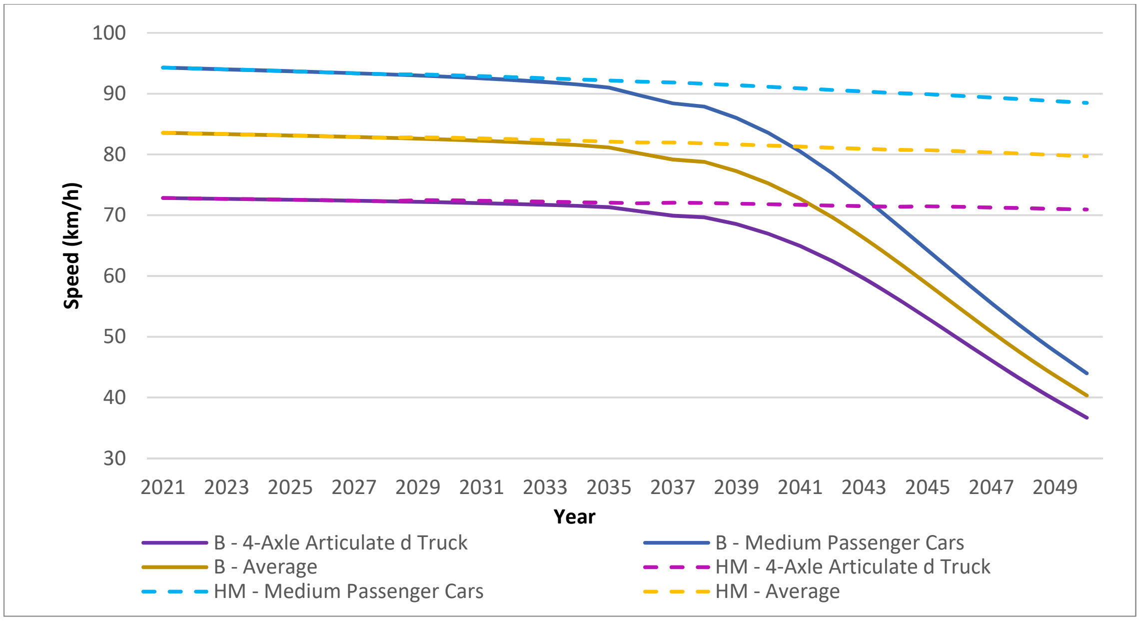

Figure 12: ES10 Weak Pavement Structure - Humid Operating Speeds (B = Baseline, HM = Heavy Maintenance)

8. CUMULATIVE DISCOUNTED AUTHORITY COSTS AND USER BENEFITS

For the comparative assessment, cumulative discounted authority costs (8% discount rate) related to the maintenance regimes were calculated, as well as the resultant net present value (NPV) which is summarised in Table 4. 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 2:

$$NPV = \sum(Cn \times q) = \sum_{n=1}^{p} \frac{Cn}{(1+d)^n} \qquad \text{Eq. 2}$$

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.

The results from Table 4 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 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.

Table 4: 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	-0.710	-0.328	-0.309	3.49
	Weak	Baseline	0.598	0.598	0.583	0.598	0.600
		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	0.310	0.310	0.310
		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

9. 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 Blaauw and Maina (2021) 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 13, focusing on the arid climate zones for simplicity. The relative comparison in results is similar for all climatic zones.

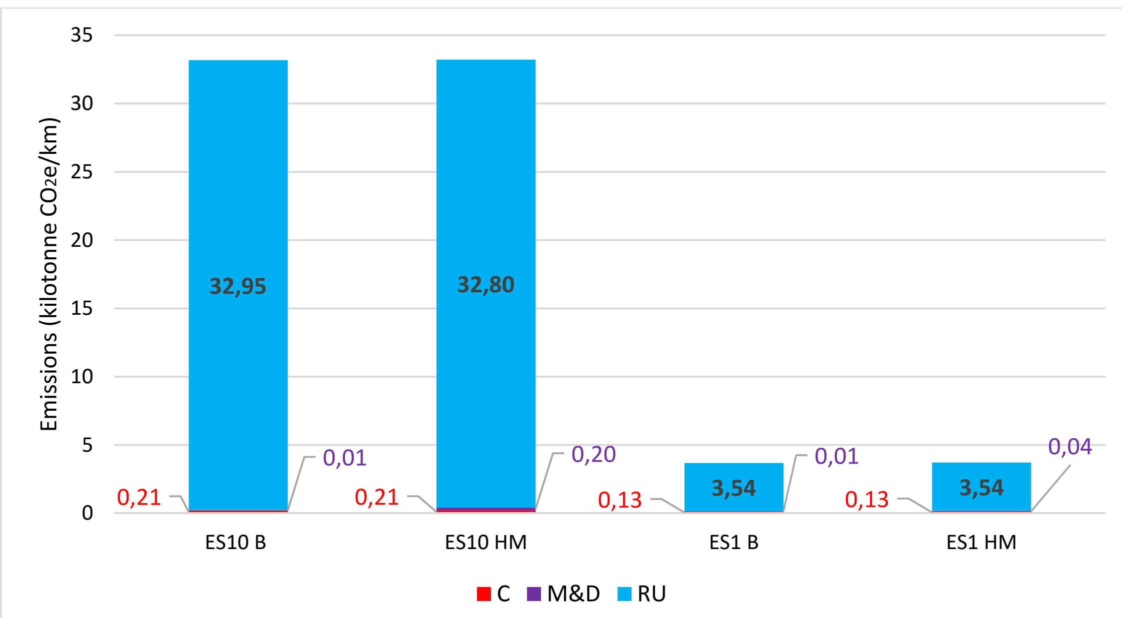

Figure 13: Life Cycle Assessment Results for Pavement Alternatives in Arid Region (ES1 = 1 million ESALs, ES10 = 10 million ESALs, B = baseline maintenance regime, HM = heavy maintenance regime, C = initial construction, M&D = maintenance and demolition, RU = road user)

Figure 13 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. 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 was not considered in the analysis, which could become important to the broader concept of sustainability where poor roads result in reduced operating speeds (Blaauw et al., 2021).

11. 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.

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.

12. 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.

13. CONCLUSIONS

In this paper, 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 12. 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 study 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 gradual drying of the atmosphere across the majority of South Africa will have positive contributions for pavement deterioration, user emissions and user benefits alike. The results presented in this study may enable road authorities to make more reliable decisions regarding maintenance actions designed to limit pavement roughness and associated emissions.

14. RECOMMENDATIONS

Based on the information provided in this paper 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.

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