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**Working Paper**

## Infrastructure and climate change: Impacts and adaptations for the Zambezi River Valley

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## WIDER Working Paper No. 2013/041

### Infrastructure and climate change

#### Impacts and adaptations for the Zambezi River Valley

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and Kenneth Strzepek<sup>2</sup>

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#### Abstract

The African Development Bank has called for US\$40 billion per year over the coming decades to be provided to African countries to address development issues directly related to climate change. The current study addresses a key component of these issues, the effect of climate change on the road infrastructure of Malawi, Mozambique, and Zambia, all located within the Zambezi River Basin. The study incorporates a stressor-response approach to estimate the effects of projected precipitation, temperature, and flooding changes on the .../

Keywords: climate change, roads, infrastructure, Mozambique, Malawi, Zambia  
JEL classification: Q54, O44, O55

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paved and unpaved road infrastructure of these countries. The paper highlights the result of running 425 climate scenarios for each road type and policy option from 2010-2050. Based on a resulting database of over 1.4 million data points, the three southern African countries are facing a potential US\$596 million price tag based on median climate scenarios to maintain and repair roads as a result of damages directly related to temperature and precipitation changes from potential climate change through 2050.

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## 1 Introduction

The African Development Bank has called for US\$40 billion per year over the coming decades to be provided to African countries to address development issues directly related to climate change (Kaberuka 2009). These costs are required to assist in the adaptation to and the mitigation from the effects of climate change. While costs are a concern for all countries, these costs are of particular concern in developing countries, where the additional funds needed to address climate change concerns are limited or non-existent. The limitations on these available funds are challenging developing countries to identify the threats that are posed by climate change, develop adaptation approaches to the predicted changes, incorporate changes into mid-range and long-term development plans, and secure funding for the proposed and necessary adaptations (UNFCCC 2009, 2010). The alternative to this proactive planning is the potential for climate change to significantly impact the social fabric of communities, where individuals may be required to consider change that will impact standards of living to an extent as to require relocation.

Earlier work by the UNFCCC, IPCC, World Bank and others, have attempted to quantify the impact of climate change on physical assets that will be affected in the coming decades. The current study extends these efforts by addressing the effect of climate change on the road infrastructure of three countries in the Southern African region as part of the UNU-WIDER Development under Climate Change (DUCC) research effort. The specific countries of interest are Malawi, Mozambique, and Zambia, all located within the Zambezi River Basin. Paved and unpaved road inventories were selected as the single infrastructure type to evaluate because of their economic, social, and development importance on the African continent. The study examines the extent to which climate change from global and country-specific climate scenarios will divert resources from the further development of road infrastructure to the maintenance and adaptation of the existing infrastructure. Roads are of specific importance for analysis in Africa because of the smaller existing networks that exist in the countries in comparison to other parts of the world.

In 1997, the continent of Africa (excluding South Africa) had 171,000 kilometers of paved roads, about 18% less than Poland, a country roughly the size of Zimbabwe. Despite continued investments, the stock of roads continues to lag behind the remainder of the world both in total roads and in paved roads. In 2008 only about 25% of Sub-Saharan Africa's primary roads were paved, compared to a global rate of 50% and a 67% rate in North America. In terms of the unpaved roads, which are the majority of the roads on the continent, more than 80% of unpaved roads are considered to be only in fair condition and 85% of rural feeder roads in poor condition and cannot be used during the wet season. The current study provides an overview of the potential damage to the Southern African countries in terms of climate change impacts on road infrastructure at individual country levels. Moving forward from the stressor-response methodology established in the Economics of Adaptation to Climate Change study, the current study introduces the use of multiple climate scenarios to develop a probabilistic conclusion of potential impact (World Bank 2009).

The following sections introduce the use of hybrid frequency distributions (HFDs) as the basis for developing a probabilistic projection of climate impact. Following this description, the paper introduces the specific stressor-response functions adopted for the individual road infrastructure elements. Finally, the paper summarizes the result of applying this methodology to the Zambezi River Valley countries of Malawi, Zambia, and Mozambique.

## 2 Background

The existing literature related to climate change adaptation in the infrastructure sector is primarily qualitative in nature with an emphasis on broad recommendations and warnings. These studies are primarily based on general weather studies, or focus on qualitative predictions. Research completed by the Transportation Research Board in the United States, the Scottish Executives, and Austroads in Australia are notable efforts in this regard (TRB 2008; Galbraith et al. 2005; AUSTROADS 2004). Within these reports, the authors compare weather-related disasters and their perceived severity with predicted climate change impacts. Further studies have advocated determining specific impacts of temperature, rain, snow and ice, wind, fog, and coastal flooding on roads (CCSP 2006). Additional studies have been undertaken in areas where specific climate change concerns threaten infrastructure that is unique to that locale. For example, ice and winter roads in Canada appear to be particularly vulnerable to rising temperatures (Industrial Economics 2010). Similarly, northern climates have the potential of increased infrastructure degradation due to increased freeze-thaw cycles (Jackson and Puccinelli 2006).

The emphasis of these documents has primarily been awareness and the informing of public officials regarding policy implications for the infrastructure sector. A comprehensive study in this regard was developed by Mills and Andrey (2002) that presents a general framework for the consideration of climate impacts on transportation. They enumerate baseline weather conditions and episodic weather-influenced hazards that make up the environment in which infrastructure is built, maintained, and used. Second, they note that the weather-related context will change with climate change, affecting the frequency, duration, and severity of the hazard. These hazards have the potential to affect the transportation infrastructure itself, its operation, and the demand for transportation.

The limitation of these studies is that they either focus on a narrow potential impact of climate change, or the studies fail to provide specific estimates of cost or damages that may result from potential climate change scenarios. In response to this gap in the climate change literature, the authors have been actively engaged in developing specific estimates of climate change impacts on infrastructure elements. Chinowsky et al. (2011) document the potential cost impacts of climate change on road infrastructure in ten countries that are geographically and economically diverse. Additionally, other authors have extended this response methodology to determine the potential impacts from climate change on bridges (Stratus 2010) and roads in northern climates (Industrial Economics 2010).

In the context of Africa, the potential impact of climate change on infrastructure is beginning to receive increased attention. However, planning for climate change in the African context is complicated by the lack of existing infrastructure. Despite continued investments, the stock of roads continues to lag behind the remainder of the world both in total roads and in paved roads. Similarly in terms of road quality, there is significant variability in primary transport corridor quality with Central Africa having only 49% of primary roads in good condition, while South Africa has 100% of the roads in good condition (Gwilliam et al. 2008). In terms of rural roads, which are the majority of the roads on the continent, more than 70% of rural roads are considered to be in fair or poor condition (Foster and Briceno-Garmendia 2010).

### **3 Methodology**

The stressor-response methodology is based on the concept that exogenous factors, or stressors, have a direct effect on and subsequent response by, focal elements. In the context of climate change and infrastructure, the exogenous factors are the individual results of climate change including changes to precipitation levels, temperatures, storm frequency, and wind speeds. The focal elements are the individual infrastructure types including roads, railroads, water and power distribution, and public buildings among others. Therefore, a stressor-response value is the quantitative impact that a specific stressor has on a specific infrastructure element.

#### **3.1 Hybrid frequency distributions**

In previous studies conducted by the authors, a set of four-to-six climate scenarios were adopted to determine a range of potential impact outcomes. In contrast, the current study employs the HFD approach developed by Schlosser et al. (2012). In this approach, 17 IPCC 4<sup>th</sup> Assessment (AR4) climate models are used as a basis for generating a suite of climate scenarios. To address the uncertainty associated with climate scenario projection including downscaling, economic, and policy issues, the HFD approach incorporates a set of 400 factors which are varied over the 17 climate models. The combination of these elements provides 6,800 discrete climate scenarios for each overall policy limit on climate change. The set of scenarios is shown by Schlosser et al. (2011) to provide an illustration of the likelihood that climate change impacts will occur in a given global zone. For the current study, an unconstrained policy is modeled to focus on the least restrictive projection of climate change scenarios. From this pool of 6,800 possible scenarios, a statistical sampling was employed to extract a set of 425 representative climate scenarios. The result of this extraction is a pool of 425 scenarios that are considered equally plausible outcomes from the unconstrained policy. Through the use of the large diversity of climate scenarios, the current study uses a broad basis for developing a set of potential climate impacts rather than focusing on a limited group of results.

#### **3.2 Division of road inventory**

A primary analysis function of the DUCC infrastructure system is to provide cost information. Key to this analysis is data on the existing roadstock in each geographic area analysed. Where possible, existing roadstock information at a provincial level is extracted from government data. However, when only national roadstock information is available the authors use government or commercially available data for road inventory (IRF 2009). The national inventory is allocated to each province based on a geographic allocation algorithm previously developed by the authors for climate studies (Chinowsky et al. 2011). In this process, roadstock is allocated at a sub-national administrative unit based upon geographic size, population density, and adjusted for other factors where data is available (such as GIS information). For analysis purposes, it is assumed that once the roadstock is allocated to a province, the roadstock is evenly distributed throughout the province.

To ensure that the allocation of road inventory to administrative levels correctly correlates to the HFD data provided, the 2 degree latitude by 2 degree longitudinal HFD climate data and the provincial mapping of the countries are translated into a standard grid system based on latitude and longitude. In terms of the current study, Climate Research Unit (CRU) grid cells

of .5 degree latitude by .5 degree longitudinal (an approximately 250 km square area) are the basis of this data translation. The CRU dataset is an open source, global land surface time series of historical weather data. The information used in this analysis is CRU TS 2.1 (Climate Research Unit Time Series Version 2.1). Several data parameters are included; this analysis focuses on the reported precipitation and maximum temperature (Mitchell 2004).

## **4 Impact functions**

The stressor-response methodology is based on the concept that specific road materials and components will have specific responses to external stressors such as precipitation and temperature. The stressor-response factors introduced below have been developed based on the engineering and materials response affects that individual material and elements have based on the specific stressors. These effects are then applied to specific circumstances such as pavement or gravel where the stressors are applied based on the climate context. The development of these factors is based on multiple inputs. A combination of material science reports, usage studies, case studies, and historic data were used to develop response functions for the infrastructure categories. Where possible, data from material manufacturers was combined with historical data to obtain an objective response function. However, when these data were not available, response functions were extrapolated based on performance data and case studies from sources such as departments of transportation or government ministries.

The stressor-response factors are divided into two general categories: impacts on new construction costs and impacts on maintenance costs. New construction cost factors focus on the additional cost required to adapt the design and construction when rehabilitating an asset to changes in climate expected to occur over the asset's lifespan. Maintenance cost effects are those maintenance costs, either increases or decreases that are anticipated to be incurred due to climate change to achieve the design lifespan if construction standards have not been adjusted. In each of these categories, the underlying concept is to retain the design life span for the structure.

### **4.1 Stressor-response values for new construction costs**

The derivation of the stressor-response values for new construction costs encompasses two general approaches. Each approach retains the focus of building a new infrastructure component to a standard that enables it to withstand projected climate changes over its design lifespan. The first approach estimates stressor-response values based on the cost associated with the change in material requirements, while the second emphasizes adaptation to an alternate infrastructure type. The materials approach is used to generate stressor-response values for paved roads and gravel roads.

The materials methodology is based on the premise that roads should be constructed to a level that anticipates the future changes in climate conditions and the accompanying changes in material requirements. Following this concept, this methodology determines if new structures such as paved roads will be subject to material changes if it is anticipated that a significant climate change stressor will occur during their projected lifespan. Similarly, the second option for adaptation for new construction is to alter the type of infrastructure being constructed to one that has the capacity to handle the anticipated climate change. For example, if climate change is anticipated for dirt roads, then a consideration has to be made for either increasing maintenance costs as described below or altering these roads to be gravel

roads. For the gravel road option, the cost of adaptation is based on the need to strengthen the road with a crushed gravel mix. The benefit with this approach is that basic maintenance as well as climate induced maintenance is eliminated on the road during the design life span of the road.

## **4.2 Stressor-response values for maintenance costs**

Similar to the stressor-response functions for new construction, the functions for estimating maintenance differs between paved, gravel, and unpaved roads. For paved roads, an approach is adopted that bases the cost of maintenance on the cost of preventing a reduction in lifespan. The implementation of this approach involves two basic steps: (1) estimating the lifespan decrement that would result from a unit change in climate stress and (2) estimating the costs of avoiding this reduction in lifespan. To estimate the reduction in lifespan that could result from an incremental change in climate stress, it is assumed that such a reduction is equal to the percent change in climate stress, scaled for the stressor's effect on maintenance costs.

For gravel and dirt roads, maintenance impacts are induced by changes in maximum monthly precipitation rates. The result of increased precipitation is increased erosion, creating a need to increase maintenance to retain the original design life. To estimate the changes in road maintenance costs, the amount of erosion is used as a basis for determining the percentage of maintenance increase required. The calculation of the erosion rates for dirt and gravel roads is based on three factors: precipitation amount, traffic levels, and slope of the road. In terms of precipitation, studies indicate that a 1% increase results in an approximate 1% impact on the design life in a minimal slope condition with low traffic levels (Dubé et al. 2004). This is used as the base condition for maintenance calculations. However, this base case is augmented as traffic rates and slope percentages increase, resulting in significantly greater erosion rates.

## **5 Flooding**

Similar to precipitation and temperature, flooding damage is calculated through stressor-response functions. Specifically, road losses are calculated based on monthly runoff estimates and a custom damage function that generates loss estimates based on the return period of the precipitation intensities. The damage function is derived by assuming damage begins at the 2-year frequency and grows linearly to 100% damage at the 100-year event. While this is valid for road culvert damage, it does not consider other damages that may be incurred beyond culvert washout. These other damages include damages in riverside floodplains, other washouts, etc. These damages typically occur as a result of infrequent events. Therefore, this basis is used for events with recurrence intervals 20 years or less. For events greater than 20 years, and less than or equal to 50 years, it is assumed that an increase in the fraction of roadway damages would occur.

Translating the runoff and damage curve estimates into damage costs requires two steps: determining the amount of road kilometers damaged and the specific costs implied by these damages. The first of these steps requires translating information on floods into actual kilometers of road that will be damaged. This determination is dependent on two factors; the intensity of the flood and how many roads have had climate-resilient adaptations applied to them. For paved roads, the accomplishment of this task is based on the type of roads that are being damaged and the standard maintenance costs these roads incur. For example, annual



maintenance costs for primary roads are estimated at 15% of construction cost, while 29% and 35% are used for secondary and tertiary roads, respectively. The primary roads number is lower due to the roads being built to a higher standard at original construction (COWI 2009).

## 6 Determination of opportunity cost

The final element required for the current study is to establish a common evaluation metric that can be used for each of the countries being studied. The difficulty in this determination is the variation in the countries in terms of amount of current road inventory, annual expenditures on roads, the GDP of the country, and the projected cost of climate change for each country. Given these variances, a metric is required that reflects the relative impact on the country while not overly weighting the total cost of climate change on the country. The current solution to this issue is the adoption of the opportunity cost metric established by the authors in previous studies. In quantitative terms, the opportunity cost is defined as

$$OC_x = (CC_x / SRC_x) / PR \quad (1)$$

where:

X: a specific country

OC: opportunity cost for a country in percentage

CC: total estimated climate change cost for a country including both maintenance and new costs through 2050

SRC: cost of constructing a kilometer of new, secondary paved road

PR: current paved road inventory within a country in kilometers

The equation indicates that the opportunity cost for a country is equal to the total percentage increase in the paved road network that could have been achieved if the money was not being diverted to climate change adaptation. The percentage reduction in the opportunity cost percentage between the non-adaptation approach and the adaptation approach is referred to in this study as the adaptive advantage.

## 7 Study results

The result of running the 425 HFD-based scenarios within the stressor-response framework for each road type and policy option from 2010- 2050 provided a database of over 1.4 million data points from which to extract the study conclusions. Based on this data, the three southern African countries examined in this paper are facing a potential US\$596 million price tag based on median climate scenarios to maintain and repair roads as a result of damages directly related to temperature and precipitation changes from potential climate change through 2050.<sup>1</sup> This cost is strictly to retain the current road inventory. This cost does not include any costs associated with impacts to critically needed new roads or to rehabilitate roads that may exist below design standard currently. As detailed in Table 1, if these African countries focus on a reactive response to climate change, where the repair of additional climate change damage is completed on an annual basis with no adaptive changes to infrastructure elements the total cost projections through 2050 could increase to US\$772 million at the 75<sup>th</sup> percentile level.

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<sup>1</sup> All costs are provided in US\$ using a 5% discount rate to 2010 dollars.

Table 1: The Cumulative Adapt and No Adapt potential costs (discounted to 2010) from climate change for the three countries in the study

Country	Total cumulative cost (million US\$) Adapt policy			Total cumulative cost (million US\$) No Adapt policy		
	25 <sup>th</sup> percentile	Median	75 <sup>th</sup> percentile	25 <sup>th</sup> percentile	Median	75 <sup>th</sup> percentile
	Malawi	118	133	146	100	132
Mozambique	299	321	341	92	123	162
Zambia	587	638	690	242	341	445

Source: authors' calculations.

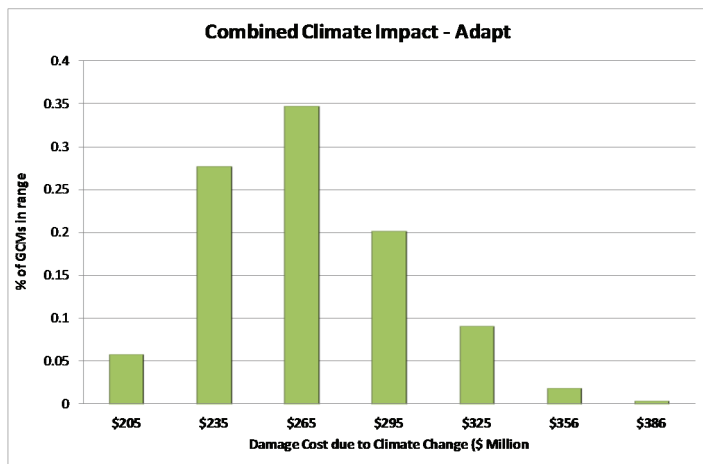
These same numbers can be put in the perspective of *opportunity cost* to determine the relative effect of climate change on the continent based on the kilometres of paved roads that cannot be built, or the kilometres of unpaved roads that cannot be upgraded, due to reallocation of funds to react to climate change damage. Utilizing this measure, Malawi, Mozambique, and Zambia are facing a potential opportunity cost of 51%, 57%, and 44%, respectively if no pre-emptive action is taken based on the median climate scenarios. This opportunity cost translates into a lost potential of expanding the existing paved road network in the countries either with new roads or with upgrades to existing unpaved roads by 3,530, 3,213, and 8,760 kilometres of paved road, respectively.

These results are modified if a proactive adaptation response is implemented. As described previously, if adaptation options are implemented such as changing dirt roads to gravel surfaces, or increasing the base depth of gravel roads, the impact of climate change can be reduced. When these adaptations are put in place in scenarios where climate impacts are anticipated, the total impact costs are changed (Table 1). As illustrated, the total costs for the three countries under the median and 75<sup>th</sup> percentile scenarios are changed to US\$1.09 billion and US\$1.17 billion, respectively. Although as a group this represents an increase in total costs, the benefits vary between countries. Malawi sees a distinct benefit from adaptation while Mozambique and Zambia incur a net increase in cost from adaptation.

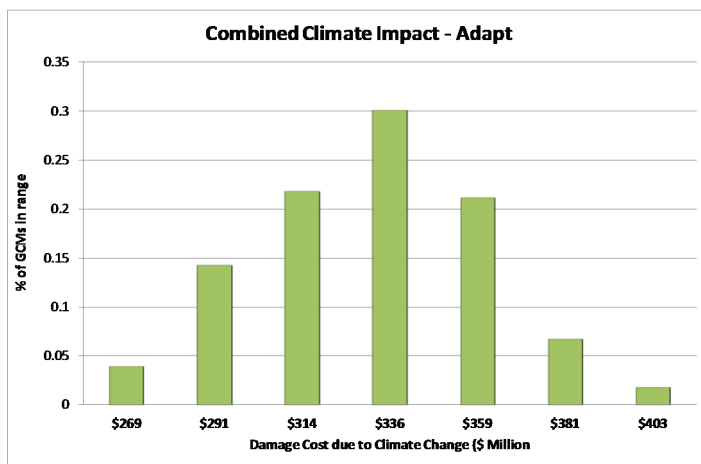
The reason for a net increase resulting from adaptation resides in a combination of using foresight to determine adaptation and the length of life of roads. If perfect foresight anticipates that at some point in the future life of the road that climate change may impact the road, then the adaptation policy requires the road to be adapted through an appropriate upgrade at the time of construction or rehabilitation. Given that the impact may not occur for 15 years after the adaptation is put in place, discounting will minimize the long-term benefit versus the short-term cost increase.

In addition to this variance that occurs with the implementation of an adaptation policy, variance must be examined in terms of the distribution of the potential impacts based on the climate scenarios. In the current study incorporating the 425 HFD climate scenarios, the three countries have distinct distributions of potential impacts (Figure 1). As illustrated, the adapt scenarios produce the greatest balance of potential impacts in Mozambique. Malawi and Zambia both display a slight skew of the distribution to the left of center. However, Malawi and Zambia differ slightly with Malawi having 35% of its scenarios falling in the main group and 27% falling in the second group. In contrast, Zambia is slightly more focused on the main grouping with 40% of the scenarios falling in the main group and 24% of the scenarios falling in the second group. Of particular interest for Malawi and Zambia are the minimal number of

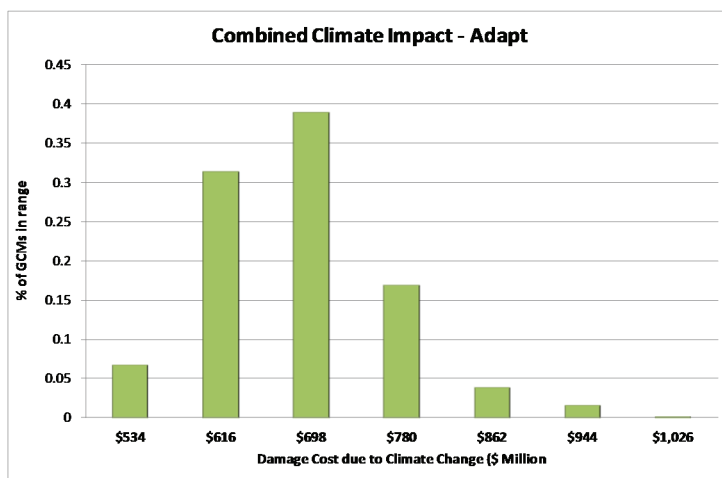
Figure 1: Distribution of cost impacts for each country under the adapt policy



(a) Malawi



(b) Mozambique



(c) Zambia

scenarios that occur in the highest two groupings. Only 3% and 4% of the scenarios are included in these groups, respectively, indicating that these scenarios may occur, but are far less likely than a lower impact scenario.

## 7.1 Malawi

At a country level, Malawi lies in the middle of the three countries in terms of national impact under the no adaptation policy. As illustrated in Table 2, Malawi is the only country that sees an economic benefit from adaptation prior to any other considerations being put in place. This savings is increased when maintenance savings are incorporated into the analysis.

Maintenance savings are included in the current study in terms of adapting unpaved roads. Since unpaved roads are susceptible to increases in precipitation as well as traffic increases, when precipitation increases are anticipated that exceed the maximum monthly threshold, unpaved roads are altered to be gravel surfaces. This adaptation is a front-end expense, however, it concurrently provides longer life for the road and eliminates 90% of the annual maintenance associated with the road since gravel surfaces require significantly less maintenance than dirt surfaces. This savings is reflected in the ‘maintenance savings’ entry in Tables 2, 4, and 6 associated with each country.

When viewed through a decadal lens, the difference between an adaptation and a no adaptation policy becomes evident. The first decade between 2011 and 2020 reveals the front-end cost associated with adapting roads through the adaptation policy. However, as the decades progress, the long-term savings is reflected in the adaptation costs becoming increasingly lower than the no adaptation policy. As seen in Table 3, as the roadstock is adapted to mitigate future climate impacts, the number of kilometres that have not been adapted and are thus potentially susceptible to a greater impact by climate change is reduced. In contrast, the no adaptation policy does not reflect this reduction and shows a constant financial impact from the climate change scenarios.

The overall totals when divided between the decades reflect the narrow distribution of the climate scenarios. The difference between the 25<sup>th</sup> and 75<sup>th</sup> adapt scenarios is consistent between the first and fourth decades with a maximum of a 34% increase from the 25<sup>th</sup> to the 75<sup>th</sup> percentile impact values. Once again, this distribution is skewed towards the lower half of the distribution groupings.

Table 2: Country level climate impacts for Malawi

	Total cumulative cost (million US\$) Adapt policy			Total cumulative cost (million US\$) No Adapt policy		
	25 <sup>th</sup> Percentile	Median	75 <sup>th</sup> Percentile	25 <sup>th</sup> Percentile	Median	75 <sup>th</sup> Percentile
Temperature and precipitation	118	133	146	98	131	161
Maintenance savings	(15)	(16)	(18)			
Net total	103	117	128	98	131	161

Source: authors' calculations.

Table 3 Decadal analysis of impacts for adapt and No Adapt policies

	Total cumulative cost by decade (million US\$)				Total cumulative cost by decade (million US\$)			
	Adapt policy				No Adapt policy			
	2020	2030	2040	2050	2020	2030	2040	2050
25 <sup>th</sup> percentile	59	34	16	9	23	21	30	27
Median	68	38	16	10	33	29	38	34
75 <sup>th</sup> percentile	79	41	17	10	42	38	45	40

Source: authors' calculations.

## 7.2 Mozambique

Mozambique consistently incurs a higher economic cost through the adaptation policy when compared to a no adaptation policy (Table 4). However, Mozambique obtains a savings of 29% in the median scenario to only 13% for Malawi. This savings is a direct result of the larger percentage of unpaved roads that exist in Mozambique. The combination of the projected increase in precipitation with the large percentage of unpaved roads results in the greater percentage basis of maintenance savings.

The difference between an adaptation and a no adaptation policy becomes evident (Table 5). As illustrated, the adaptation scenario sees a continuing reduction in costs while the no adaptation scenario sees a consistent impact across the time series. The distribution of the decadal results illustrates a small variance between the potential scenarios. The maximum variance between the 25<sup>th</sup> and 75<sup>th</sup> adapt scenarios is only 18% and occurs in the first decade. This variance reflects the even distribution of the scenario results in a pattern that is close to a normal distribution.

Table 4: Country level climate impacts for Mozambique

	Total cumulative cost (million US\$)			Total cumulative cost (million US\$)		
	Adapt Policy			No Adapt Policy		
	25 <sup>th</sup> Percentil e	Median	75 <sup>th</sup> Percentil e	25 <sup>th</sup> Percentile	Median	75 <sup>th</sup> Percentile
Temperature and precipitation	299	321	341	92	123	158
Maintenance savings	(90)	(93)	(97)			
Net total	209	228	244	92	123	158

Source: authors' calculations.

Table 5: Decadal analysis of impacts for adapt and No Adapt policies

	Total cumulative cost by decade (million US\$)				Total cumulative cost by decade (million US\$)			
	Adapt policy				No Adapt policy			
	2020	2030	2040	2050	2020	2030	2040	2050
25 <sup>th</sup> percentile	177	72	34	16	22	21	24	23
Median	192	77	35	17	33	30	33	30
75 <sup>th</sup> percentile	206	81	37	18	43	41	41	37

Source: authors' calculations.

### 7.3 Zambia

At a country level, Zambia incurs more than double the potential economic impacts from climate change than either Malawi or Mozambique. This economic figure is a result of Zambia having over 20,000 kilometers of roads which is three times the amount of either of the other two countries. However, as illustrated in Table 6, the large number of roads translates to maintenance savings as Zambia contains a significant percentage of unpaved roads that are susceptible to climate change impacts.

The decadal analysis illustrates the difference between an adaptation and a no adaptation policy (Table 7). The pattern is consistent in that it illustrates how the relative costs from the adaptation policy decrease as more roads are adapted over time. The savings are particularly apparent in the last decade as changes in climate increasingly cause damage to roads under the no adaptation policy. However, as the roadstock inventory is adapted to future impacts under the adaptation policy, the level of maintenance required to mitigate the damage is consistently reduced.

In terms of variance in the scenarios, the distribution pattern is clustered around the 2<sup>nd</sup> and 3<sup>rd</sup> groups in the overall distribution pattern resulting in a similar variance to Malawi between the 25<sup>th</sup> and 75<sup>th</sup> percentile impact numbers. The greatest variance for Zambia is in the first decade where the variance between the 25<sup>th</sup> and 75<sup>th</sup> percentile figures raises to 20%. However, this variance reduces as the discounting impacts the results and the decades progress to a variance of only 10% in the final decade.

Table 6: Country level climate impacts for Mozambique

	Total cumulative cost (million US\$)			Total cumulative cost (million US\$)		
	Adapt policy			No Adapt policy		
	25 <sup>th</sup> Percentile	Median	75 <sup>th</sup> Percentile	25 <sup>th</sup> Percentile	Median	75 <sup>th</sup> Percentile
Temperature and precipitation	587	638	690	236	329	424
Maintenance savings	(177)	(183)	(193)			
Net total	401	455	497	236	329	424

Source: authors' calculations.

Table 7: Decadal analysis of impacts for adapt and No Adapt policies

	Total cumulative cost by decade (million US\$)				Total cumulative cost by decade (million US\$)			
	Adapt policy				No Adapt policy			
	2020	2030	2040	2050	2020	2030	2040	2050
25 <sup>th</sup> percentile	350	127	69	39	57	52	67	61
Median	383	139	72	41	90	80	88	80
75 <sup>th</sup> percentile	420	152	75	43	129	109	119	98

Source: authors' calculations.

## 8 Limitations

The current study is based on several key components which introduce uncertainty into the quantitative analysis within the study. The climate data presented here is based on input from a single source, using an innovative new approach in HFD. Additionally, the study relies on existing material studies to derive the impact stressors. Although the study bases its findings on recognized authorities and studies, the quantitative cost estimates are dependent on the findings from these and similar studies. Issues such as specific pavement types, local conditions, construction and maintenance techniques can all combine to impact specific cost impacts. Therefore, the quantitative cost results may differ based on alternative studies.

These limitations should be considered when analyzing the quantitative results of this study. However, the qualitative relationships presented here will remain consistent even if the referenced studies are altered. Specifically, the relative impact on the countries in the study will remain consistent and the overall findings remain as stated.

## 9 Discussion and conclusion

The importance of roads to development and long-term growth in the Southern Africa region requires public officials to balance short-term needs versus long-term planning. The addition of potential climate change effects increases the requirement for balance as the potential benefit from a decision may not appear for several decades. The developed stressor-response functions illustrate the potential to integrate the predicted temperature, flooding, and precipitation changes resulting from climate change with traditional costing methods to anticipate cost impacts in specific locations.

Although the gross dollar impact varies between countries due to individual road inventories and climate impacts, the impacts will force every country to transfer a proportion of annual expenditures to offset the effects of climate change on road infrastructure. On a country level, potential cumulative costs for the countries in the study may exceed US\$923 million with a reactive approach to climate change. Zambia faces increased costs if adaptations are considered. However, total costs do not reflect the complete impact. Rather, it is the opportunity cost associated with these total costs that create the potential hardship for each country. As indicated in the study, individual countries face the prospect of losing the opportunity to expand current paved networks by 23,000 kilometers if a reactive approach is adopted and 20,500 kilometers if a proactive approach is adopted.

In conclusion, the developed methodology represents an evolutionary step toward developing an integrated and comprehensive economic evaluation of the effects of climate change on road infrastructure. The results from the analysis will inform the economic models that comprehensively analyze the effects of climate change on the economy of a country. The resulting challenge to governments from the final results of this analysis will be how to incorporate a multitude of conflicting requirements into a cohesive policy that achieves balance between short-term needs and the potential long-term effects of climate change on infrastructure.

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