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Adaptation Advantage to Climate Change Impacts on Road Infra-structure in Africa through 2100

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Abstract

The African continent is facing the potential of a US$183.6 billion liability to repair and maintain roads damaged from temperature and precipitation changes related to climate change through 2100. As detailed, the central part of the continent faces the greatest impact from climate change with countries facing an average cost of US$22 million annually, if they adopt a proactive adaptation policy and a US$54 million annual average, if a reactive approach is adopted. Additionally, countries face an average loss of opportunity to expand road networks from a low of 22 per cent to a high of 235 per cent in the central region.

Keywords: infrastructure, climate change, roads, cost estimates

JEL classification: H54, L91, R42, R48

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Tables and figures appear at the end of the paper.

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1 Introduction

The African Development Bank has called for US$40 billionper 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 adaptation to and 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 pro-active 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 on the African continent as a whole.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 per cent 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 2008only about 25 per cent of Sub-Saharan Africa's (SSA) primary roads were paved, compared to a global rate of 50 per cent and a 67 per cent rate in North America. In terms of total roads compared to population, the paved road length in SSA of 0.79 kilometers per thousand population, is less than half of that of South Asia, and only about one fifth of the world average. In terms of road quality, there is significant variability in primary transport corridor quality with Central Africa having only 49 per cent of primary roads in good condition, while southern Africa has 100 per cent of the roads in good condition (Gwilliam et al. 2008). In terms of the unpaved roads, which are the majority of the roads on the continent, more than 80 per cent of unpaved roads are considered to be only in fair condition and 85 per cent of rural feeder roads in poor condition and cannot be used during the wet season. In Ethiopia, 70 per cent of the population has no access to all-weather roads (Mutume 2002).

The current study provides both an overview of the potential damage the African continent is facing as a whole in terms of climate change impacts on road infrastructure as well as a more detailed look at the impacts at regional perspectives and individual country levels.The study is designed to create a broader understanding of the effect climate change may have on facets of development including social, economic, and transport issues by analyzing the road infrastructure.This study expands upon the methodology established in the 'Economics of Adaptation to Climate Change' study conducted by the World Bank that introduced an engineering-based, stressor-response methodology to quantify the impact of climate change on specific physical assets (World Bank 2009). The analysis of paved and unpaved road networks as affected by precipitation and temperature is scaled up to analyze the road infrastructure impact on a continent-wide scale.

The concept of 'adaptive advantage' is introduced in the study to identify the benefits of adaptation for each country for the projected climatic changes.From this concept, the study provides a context for policy and decisionmakers to further understand the impacts of future climate change at multiple scales on the African continent through 2100.In summary, the study is designed to provide a larger context for policymakers to address, in part, the question of 'now or later?' Can the countries within Africa, or developed countries who may be subsidizing this development, afford to postpone adaptation to potential climate change effects on critical infrastructure?

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 focused on qualitative predictions concerning road impacts on both safety and road durability.Research completed by the Transportation Research Board in the United States, the Scottish Executive, and Austroads in Australia are notable efforts in this regard (TRB 2008; Galbraith et al. 2005; Austroads 2004).Within these reports, the authors compare past weather-based events with predicted climate change impacts to develop qualitative predictions.Typical of these findings are projections regarding the likelihood of reduced life spans for roads, increased erosion of unpaved roads, and potential effects of sea level rise on coastal roads.The TRB study concludes that the greatest impacts of climate change for North America's transportation systems will likely be the flooding of coastal roads, railways, transit systems, and runways because of global rising sea levels, coupled with storm surges and exacerbated in some locations by land subsidence.

The emphasis of these documents has primarily been awareness and the informing of public officials regarding policy implications for the infrastructure sector.For example, the TRB study presents detailed recommendations regarding potential changes to highway planning that should be considered during the next planning cycle.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.Mills and Andrey 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 last of these can arise from a variety of sources such as the climate effects on agriculture that may alter the location of agricultural production and, therefore, the need and mode for shipping agricultural products.

Complementing these broad policy studies has been the development of studies advocating the study of specific weather-based impacts on roads.For example, the US Climate Change Science Program takes a broad examination of the potential impacts of individual weather concerns including temperature, rain, snow and ice, wind, fog, and coastal flooding on roads in the Gulf Region (US Climate Change Science Program 2008).Similar 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).The particular concern in this context is the effect that rising temperatures will have on the durability of winter roads and the potential loss of economic viability of these roads.Similarly, increased freeze-thaw cycles in cold climates where warming is likely may result in increased degradation of the infrastructure (Jackson and Pucinelli 2006).

A specific study in the context of a limited climate focus was conducted by researchers at the University of Alaska, Fairbanks, which focused on the effects of climate on public infrastructure (Larsen et al. 2007; 2008).The study used three different GCM-based temperature and precipitation scenarios, which they characterize as ‘warm’, ‘warmer’, and ‘warmest’ based on their results for global circulation model (GCM) results for Alaska.The vulnerability of infrastructure is assessed based on location–infrastructure that is located in the presence of permafrost and in close proximity to a coast or a floodplain is considered potentially vulnerable to climate change.The scope of the Larsen study includes transportation infrastructure such as airports, bridges, harbors, major roads, and railroads.The net present value of maintenance and replacement costs for transportation infrastructure in the inventory through 2030 is approximately US$24.5 billion (in 2006 US$).

The limitation of these studies is that they focus on a narrow potential impact of climate change, and, with the exception of the Larsen study which the authors participated in, 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.The study illustrates both the potential real costs that countries may incur due to climate change scenarios as well as the potential opportunity costs of diverting infrastructure resources to climate change adaptation.Additionally, the 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.The potentially devastating economic effects from the combination of the lack of infrastructure and the potential impacts on this limited infrastructure is explored in recent studies by the World Bank on the Economics of Adaptation to Climate Change.In the African component of these studies, case studies of Ethiopia and Mozambique inform the current analysis of the overall economic impact of climate change.Highlighting one of these studies, the Ethiopia case, we see that climate change has the potential to result in US$3.1 billionof impact to roads when the effects of temperature, precipitation, and flooding increases are taken into consideration through 2100 (World Bank 2010).These costs could be reduced by 54 per cent if adaptation policies are adopted through policy changes by the government.However, even with these adaptations, the potential cost to Ethiopian roads from climate change could be as high as US$1.4 billion.

3 Methodology

The methodology for the current study centers on the need to consistently analyze and apply projected climate variations to countries throughout Africa.The technique described in this section is derived from one previously developed by the authors to determine the impact of climate change on infrastructure in both developed and developing countries (Chinowsky et al. 2011).As illustrated in Figure 1, the methodology involves seven steps which lead from determining the climate zones within each individual country to determining the impacts on an individual country level and finally to aggregating the results to both regional and continent level findings.

3.1 Climate zones

The first requirement for conducting the impact study was to determine the climate zones that exist within each of the selected countries.The climate zone identification is necessary for two reasons:(1) to determine which climate models should be applied to which geographic locations within a country, and (2) to determine which infrastructure elements lie within specific climate zones, thus enabling the models to determine impacts from specific climate changes.The climate zone mapping process chosen for the study is the Koppen-Geiger classification.Established by Vladimir Koppen between 1884 and 1936, the Koppen method of climate zone classification focused on the annual temperature and precipitation cycles throughout the world (Lohmann et al. 1993).Using these cycles as a basis, Koppen established five primary climate classifications, tropical, arid, temperate, cold, and polar.Further dividing these primary categories according to levels of humidity and precipitation, Koppen ultimately presented a map with 31 distinct climate zone classifications.These climate zone classifications were refined and formalized into a global map in 1961 by Rudolf Geiger.Together, this work is the basis of the Koppen–Geiger global classification maps used throughout the world today.

Utilizing GIS maps of the selected countries, overlays were created for each country to determine the percentage of each country that lay within a specific Koppen–Geiger climate zone.Depending on the country, this division ranged from two to four climate zones.It should be noted that in countries with greater geographic areas such as China, or countries with diverse geographic landscapes, such as Tanzania, this total can reach ten or more distinct climate zones.

3.2 Division of road inventory

To allocate the road inventory within each country, the authors adopted a percentage allocation methodology.In this method, the authors obtained the total road inventory for each country through either direct data where it was available or through a commercial database of international road data (IRF 2009).Based on existing classifications, the roads were divided into three categories, primary, secondary, and tertiary.The authors did not attempt to validate the classifications that were established by the individual countries.Further, roads were divided into paved and unpaved categories for each of the three classifications based on the percentage of paved roads provided by the data sources, thus giving each country the opportunity to have six distinct road classifications.

The total inventory of each road type for the country was subsequently divided into the climate zones based on the percentage of the country that the zone encompassed.This method is based on the assumption that geographic area is related to the number of roads in a given country.As discussed below, exceptions to this rule exist, however, this provided a starting point from which to do the regionallevel analysis.For example, if a country had two climate zones, Zone A which covered 65 per cent of the country and Zone B which covered the remaining 35 per cent, and 1,000 kilometers of primary paved roads, then 650 kilometers of primary paved road would be allocated to climate Zone A and 350 kilometers would be allocated to Zone B.In this same manner, each of the six types of road was allocated between the climate zones.This resulted in allocations of 12 to 24 total allocations depending on the number of climate zones within a country.

3.3 Comparison of population centers to climate zones

Although the majority of the selected countries have a comparable population distribution to the climate zones, this is not the case in every circumstance.In certain geographic areas such as North Africa or northern Europe, population centers can differ significantly from the overall physical definitions of the climate zones.For example, in North Africa, the geographic zone delineation is dominated by arid desert climates.However, the population densities are dominant within the narrow bands of temperate climate found along the coast of the Mediterranean Sea.This impacts the geographic allocation method of road inventory division by placing roads in proportions which are different than the physical zone allocations.

The authors determined, if such a population imbalance existed within the selected countries by overlaying existing GIS population distribution maps over the climate zones (ESRI 2010).Where population distributions differed from the climate zone allocations, the authors modified the road allocations to reflect the general population imbalance within the country.For example, if a climate zone that encompassed only 20 per cent of the country contained 40 per cent of the country's population, the road inventory allocation would be adjusted to reflect the 40 per cent distribution rather than the 20 per cent physical distribution.This method was adopted based on the assumption that greater population levels require greater levels of infrastructure development and thus a greater density of roads within those areas.

3.4 GCM models

Once the allocations of the road inventories were completed, a determination was required as to what climate models should be used for each country.The climate models were selected from the pool approved by the IPCC and represent both a variance in projected precipitation increases as well as a variance in scenarios of how a given country may pursue industrial development (Pachauri and Reisinger 2007).Each of these climate models contains annual predicted precipitation and maximum temperatures.In an effort to get a broad picture of the potential effects of climate change and to avoid focusing on extreme possibilities, three different climate scenarios were chosen, a global effect, a maximum country effect, and a median country effect.The global perspective is adopted from earlier work by the authors for the World Bank and represents a global wet NCAR_ccsm3-A2 and a global dry CSIRO_mk3-A2 scenario based on soil moisture effects (World Bank 2009).These two models were run for each country as a baseline global climate model.

In contrast to the global model, the country models were selected based on the impact that the climate model indicated for a specific country.Focusing on the effects of climate on infrastructure, the wet and hot properties of the 22 accepted models were focused upon in this selection process.Specifically, the effects of each model were analyzed in terms of precipitation and temperature averages for each decade from 2010 through 2100.For precipitation, the annual precipitation for each decade was used to determine the total precipitation increase through 2100 in the specific country.Based on this total, models were selected based on the maximum annual precipitation predicted and the median precipitation predicted for each country.Similarly, the maximum temperature was used to select the models which predicted the greatest temperature increase and the median temperature increase.The completion of the selection process provided six selected models for each country: a global wet and a global dry, a country maximum wet and a country maximum dry, as well as a country median wet and a country median dry.

3.5 Road impacts

The World Bank (2009) and Chinowsky et al. (2011) have previously detailed the authors' approach to determining impacts of climate change on paved and unpaved roads.However, to summarize this process, the methodology focuses upon the effects of precipitation and temperature (stressors) on paved and unpaved road surfaces.Specifically, the impacts are translated into stressorresponse values which are the quantitative impacts that a specific stressor has on a specific infrastructure element based on engineering data, materials analysis, and previous impact studies.For example, an increase in precipitation level is going to have a specific quantitative impact on an unpaved road in terms of decreased lifespan.These 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.In each of these categories, the underlying concept is to retain the design life span for the structure.This premise was established due to the preference for retaining infrastructure rather than replacing the infrastructure on a more frequent basis.

The stressor-response values for new construction costs encompasses two general approaches.The first approach estimates stressor-response values for paved roads based on the cost associated with a change in building code updates, while the second more directly estimates the incremental costs for unpaved roads based on design changes.The building code methodology focuses on the concept that new structures such as paved roads will be subject to material or building method changes if it is anticipated that a significant climate change stressor will occur during their projected lifespan.The readily available data from pavement specialists suggest that such updates would occur with every ten centimeter increase in precipitation or six degree Celsius maximum pavement temperature increase (Lea 1995; AASHTO 2000). It should be noted that these thresholds are a key assumption in this study and further refinement of these thresholds is a primary focus of continuing work in this area.

For unpaved roads, a direct approach is used for estimating the cost impact of changes in climate stressors.Under this approach, the stressor-response relationship for unpaved roads associates the change in construction and maintenance costs with a 1 per cent change in maximum monthly precipitation.Research findings have demonstrated that 80 per cent of unpaved road degradation during its lifetime can be attributed to precipitation (Ramos-Scharron and MacDonald 2007).The remaining 20 per cent is attributed to factors such as the tonnage of traffic and traffic rates.Given this 80 per cent attribution to precipitation, we assume that the base construction costs for unpaved roads increase by 80 per cent of the total percentage increase in maximum monthly precipitation.The readily available data suggests no relationship between temperature and the cost of building unpaved roads.

Both approaches assume perfect foresight with respect to climate change.Therefore, these stressor-response values represent the relationship between infrastructure construction costs at the time of construction and the changes in climate projected during the infrastructure’s lifespan.

Similar to the development of stressor-response values for new construction costs, two basic methodologies were adopted for maintenance costs.The first approach, used for paved roads, is based on the cost of preventing a reduction in lifespan that may result from changes in climate-related stress.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.After estimating the potential reduction in lifespan associated with a given climate stressor, the costs of avoiding this reduction in lifespan is calculated by the product of (1) the potential percent reduction in lifespan and (2) the base construction costs of the asset.

Utilizing these approaches for determining cost impacts on rehabilitation and maintenance over the lifetime of a road asset, the annual maintenance and rehabilitation cost impacts were calculated through 2100 based on each of the six model scenarios. As noted in the limitations section at the end of this paper, the authors make assumptions in calculating these costs which affect the overall quantitative outputs. Specifically, the authors adopt existing material impact studies for paved and unpaved roads. Although these studies do not reflect the condition found in every physical location, they provide an initial starting point for the current work. However, it must be noted that estimates will differ if local conditions and materials are analyzed in specific location contexts. Additionally, the impacts from the GCM models selected are based on specific decisions to adopt those models. Alternative models and uncertainty in modeling future climate scenarios will affect specific quantitative results.

3.6 Determination of opportunity cost

The final challenge in setting the methodology for the current study was establishing a common evaluation metric that could be used for each of the countries.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 was required that reflects the relative impact on the country while not overly weighting the total cost of climate change on the country.The solution to this issue was the establishment of an opportunity cost associated with each country.In quantitative terms, the opportunity cost is defined as

$$OC_x = (CC_x / SRC_x) / PR_x$$

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 2100

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.In this manner, opportunity cost is the degree to which a country could enhance its road infrastructure if climate change would not be impacting the road expenditures. The opportunity cost is based on existing road inventory numbers. It is intended to provide a reflection of climate change impact based on current circumstances. Since the majority of countries in Africa already have a low road density factor, the opportunity cost emphasizes the impact on projected plans to increase this density and meet projected development targets in terms of road infrastructure.

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. The focus on development advantage is inherent in these measures because roads, specifically those that are accessible year-round, have a significant impact upon communities. Indicators such as maternal health, level of education, poverty, gender equity, economic development, and transport are higher in areas where the rural areas have greater accessibility to developed urban centers and there is greater connectivity between communities. (Roberts et al. 2006).Therefore, the opportunity cost measurement is intended to have an underlying economic component that reflects the need to enhance economic development within a country.

4 Study results

The African continent as a whole is facing the potential of a US$183.6 billion price tag to repair and maintain roads as a result of damages directly related to temperature and precipitation changes from potential climate change through 2100. 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. As detailed in Table 1, if 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 2100 could be as high as US$183.6 billionor US$2.3 billionper year.Although uncertainties in the climate model projections insert variability in this total, even the median models suggest a potentialcumulative cost of US$73.2 billionthrough 2100 or US$915 millionper year.Although adaptation policies can significantly reduce this impact, the numbers remain notable for the continent. At the higher end of projections, a pro-active policy may still result in an annual cost of US$670 million per year.

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 kilometers of paved roads that cannot be built, or the kilometers of unpaved roads that cannot be upgraded, due to reallocation of funds to react to climate change damage. Utilizing this measure, the African continent is facing a potential opportunity costaveraging 436 per cent per country if no pre-emptive action is taken.This opportunity cost translates into a lost potential of expanding the existing paved road network on the continent either with new roads or with upgrades to existing unpaved roads by approximately 700,000 kilometers of paved road. In contrast, if adaptation policies are put in place, the opportunity costs are lowered to an average of 143 per cent per country. This translates to a road network increase in excess of 210,000 kilometers of paved roads. Although this is a 71 per cent decrease in the number of roads that are lost due to reallocation of funds, this number represents an overall increase of 36 per cent over the existing paved road inventory on the continent.

In these estimates, SSA is affected to a much greater degree when compared with northern Africa. This is due to the degree of projected climate effects and the lack of existing paved road infrastructure.Additionally, the opportunity cost for sub-Saharan countries, specifically those bordering the Sahel and in Central Africa, is high because of the large projected damage to unpaved roads as well as a very limited existing infrastructure.Unpaved roads are extremely susceptible to degradation by increased precipitation and thus require a greater level of maintenance in response to projected increases in precipitation.

Although projected impacts and costs vary between countries based on projected effects, existing infrastructure, and percentage of paved roads, every African nation will be affected by climate change.This reality is outlined in the following sections that refine these overall numbers into both regional and country perspectives.

4.1 Regional perspective

Although a continent-wide perspective is useful in understanding the overall impact of climate change, the reality for Africa is that the impact on roads will vary between regions.Specifically, the continent can be divided in terms of potential impacts into five regions: northern, western, east central, south central, and southern (see Figure 2).To illustrate these regional differences, two countries from each region are highlighted to provide a quantitative comparison between the regions. As detailed in the methodology section, three different climate scenarios are presented for each country.Country maximum represents the hottest and wettest scenarios for each country based on the GCM model projections. Country median is the median value of precipitation and temperature changes in each country, respectively.Maximum effect is a 'worst-case' scenario representing the highest effect per decade from the six climate scenarios run for the analysis (Table 2). Figure 3 illustrates the relative effect from this scenario throughout the continent. Maximum effect is often requested by policymakers to plan for contingencies in understanding the greatest threat posed by climate change.

4.1.1 Northern region

The northern Africa region includes the nations of Algeria, Libya, Morocco, and Tunisia. Due to inconsistency of climate data, Egypt and the territory of western Sahara were not included in this study. At a regional level, northern Africa sees a relatively lower impact from climate change than the rest of the continent (Table 2).While the total dollar costs from climate change impacts vary, the nations of north Africa face the lowest average cost per country under the maximum effect, adaptation scenario of US$15.4 million per year. This equates to a cumulative opportunity cost for each country of 22 per cent on average.The total cumulative cost for the region is US$1.2 billionor US$61.6 millionper year.The combination of this lower opportunity cost and the higher GDP and income in the region when compared to SSA (excluding South Africa and Equatoreal Guinea), affords the countries of this region a greater ability to make the necessary adaptations to potential climate change impacts.

Although the region as a whole absorbs the lowest relative impact from climate change, variations exist in the region as illustrated by the two countries in the table.The high dollar cost of climate change in Algeria results from the relatively greater amount of paved road infrastructure that currently exists in the country.Much of the climatic change predicted for northern Africa is a rise in temperature which has a greater potential effect on paved roads than precipitation. Algeria, a lower middle income country with a higher income and GDP than many SSAn countries, has over 70 per cent of their road network comprised of paved roads.Due to this large percentage of paved roads, the country incurs significant impact costs due to projected temperature changes. Morocco, also a lower middle income country, is susceptible to similar paved road impacts due to a similar road inventory profile.However, since Morocco has a smaller overall road inventory, the total cost impact of climate change is noticeably lower than Algeria.This illustrates the necessity of the opportunity cost parameter as total cost is not always the most appropriate measure of comparison between countries.Although the total costs are higher in Algeria, the relative effect is greater in Morocco with opportunity costs of 22 per cent and 34 per cent, respectively.This contrast between total costs and opportunity costs will be seen repeatedly in the current study.In summary, while the larger paved network incurs larger dollar costs of adaptation, the overall impact of climate change on road infrastructure in the northern region countries is lower than the remaining African regions.

4.1.2 Western region

The western African region in this study includes the countries of Benin, Burkina Faso, Côte d'Ivoire, the Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Senegal, Sierra Leone, and Togo. The western African region differs from the northern region described previously in that countries in this region incur a significant opportunity cost due to climate change impacts.As illustrated in Table 2, the western region is similar to the costs seen in the east central region (described below), and higher than both the northern and southern African regions. The cumulative opportunity cost for this region is 153 per cent on average under the maximum effect, adaptation scenario.Illustrating the advantage of adopting an adaptation policy, the average adaptive advantage for western Africa countries is 71 per cent when the effects are considered through 2100, or an equivalent total of US$333 millionper year of savings for the region.In contrast to the northern region, the countries in this region have a lower average annual cost under the maximum effect, adaptation scenario with an average projected cost of US$9.8 million USD. This lower amount is due to the smaller road inventory that is typical in the countries within the region.

The countries in this region predominantly lie on the border of the Sahel region and thus see an increase in both temperature and precipitation.In contrast to the high percentage of paved roads in the inventories of the northern region, the western Africa region countries have a combined inventory that encompasses 85 per cent unpaved roads.This inventory is vulnerable to the effects of increased precipitation.As detailed previously, the costs of adapting to climate change are costly in these scenarios due to the cost of increased maintenance on these roads, or upgrading an unpaved road to gravel or paved road, which is the primary weather-proofing option for mitigating the increased precipitation effects of climate change.

As illustrated in Table 2, the countries of Mali and Côte d'Ivoire illustrate the potential advantages of adaptation with adaptive advantages of 73 per cent and 83 per cent, respectively. While upgrading unpaved roads to gravel or paved surfaces, depending on slope and traffic levels, is costly, the long-term benefits and lower maintenance costs should influence adaptation decisions.The transition to paved roads has additional development benefits that need to be considered in this scenario, including increased traffic and freight haulage thresholds.These additional benefits are not quantified in the adaptive advantage, but should be considered in development planning for their economic and social benefits.

4.1.3 The east central region

The east central Africa region includes the countries of Cameroon, Central African Republic, Chad, Djibouti, Ethiopia, Niger, Nigeria, Somalia, and Sudan. Without adaptation, east central Africa sees the highest climate change impacts of the entire continent.Located along the Sahel and in the ecologically diverse region of central Africa, these countries experience significant impacts from climate scenarios. Similar to the western region, the large percentage of unpaved roads in this region incur repeated impacts from increases in precipitation through 2100.The result of these continuous impacts is the highest opportunity cost prior to adaptation in Africa with a cumulative value of 536 per cent average per country.Of particular concern in this respect are the countries of Niger, Chad, and Sudan which have large unpaved road networks that are vulnerable over extended period of time.

Given these large unpaved road networks, adaptation has a potential to reduce impact throughout the region.If adaptation strategies were adopted throughout the region, the overall climate impact can be reduced by an average adaptive advantage of 66 per cent per country and an equivalent total of US$3.6 billionfor the region through 2100.However, although adaptation provides a reduction in the potential impact costs in this region, challenges remain in terms of potential costs to the individual countries.For example, Niger is still affected because of the large area of the country and the large road network that exists which will require continuous adaptation through 2100. Similarly, Ethiopia has a high cost of climate change because of the large network of unpaved roads, projected precipitation increases, and sloping, mountainous terrain that exacerbate precipitation damages to roads.

Of particular concern in this region are the low road densities that exist in the region in relation to population and land area. This increases the value of each road as each road becomes more essential for transportation purposes and thus has a greater impact if it becomes unusable (Manahan 2010).Niger, Ethiopia, and Sudan have three of the lowest road densities in Africa, in relation to both population and land area and thus are highlighted in terms of this concern.

4.1.4 South central region

The south central Africa region includes the nations of Burundi, Democratic Republic of Congo, Equatorial Guinea, Gabon, Kenya, Republic of Congo, Rwanda, Tanzania, and Uganda. The Central Africa region sees some of the highest impact factors from climate change in the current study.With no adaptation policies put in place, the region is the second most affected in Africa with an average opportunity cost of 449 per cent per country—trailing only the effects on the east central region.Of particular concern in this region are the projected increases in precipitation seen in all climate scenarios. With 88 per cent of the road inventory comprised of unpaved roads, the effect of climate change is witnessed throughout the time period of the study.

Highlighting the potential climate impact in this region, Tanzania and the Democratic Republic of the Congo incur opportunity costs of 241 per cent and 375 per cent, respectively, after adaptation policies are put in place.The reason for these large impact factors is that many Central African countries have ‘large’ or ‘very large’ land areas and populations which are connected by predominantly unpaved roads.In these cases, the need for adaptation is highlighted by the potential adaptive advantage of 47 per cent per country on average, a difference of US$19.9 million per year or US$1.6 billionthrough 2100.

One anomaly in this region is Equatorial Guinea, an OECD high-income country with 75 per cent paved roads. The high paved road percentage and high-income classification in this country result in both an opportunity cost (33 per cent) and a total cost (US$106 million) that are lower than other nations in the south central region.

4.1.5 Southern region

The southern Africa region is comprised of the nations of Angola, Botswana, Lesotho, Madagascar, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, and Zimbabwe.Overall, southern Africa is less affected by climate change than the central swath of the continent.With adaptation, the region faces a US$7.5 million annual cost on average per country. The adaptation policy results in anaverage adaptive advantage of 75 per cent per country, equivalent to US$23.7 millionper year, or a total of US$1.9 billionper country through 2100.The average opportunity cost of 52 per cent per country is the second lowest of the regions, behind northern Africa.

The southern African nation of Botswana is representative of the low cumulative opportunity costsin the region through 2100 at 15 per cent. This is because of its flat land, low climate change projections, and 50 per cent paved road network, making it more resilient to increases in precipitation than the unpaved road networks.For the country of South Africa, the dollar costs of adaptation are high at US$14.6 million annually because of the large road network, but relative to the existing road network and current expenditures, the opportunity cost is reduced to only 12 per cent.

Namibia and Mozambique represent the average impacts in the southern Africa region with adaptive advantages of 68 per cent and 25 per cent respectively.Although outside the country of South Africa the road networks are similar to many other areas on the continent, the reduced precipitation and temperature increases mitigate the impact of climate change on the road infrastructure.

4.2 Maximum effect analysis on countries

The regional analysis provided the indicator that regional similarities exist within Africa based on climate scenarios and road inventories.However, regional similarities can mask individual variations within a region.In this last results section, a country level overview is provided based on the maximum effect scenario.This scenario is selected as it emphasizes the potential impact that can be incurred at individual locations.Although the actual impact may be higher in this scenario than that found in the median scenarios, the relative effects on the countries remain consistent.

As illustrated in Figures 4 and 5, the top ten countries in greatest opportunity cost and total cost differ between these measures.As discussed previously, the two measurements of impact can vary within a country due to the number of kilometers of roads within an inventory and the types of roads in the inventory. Countries with the largest road networks tend to have the largest total costs resulting from climate impacts due to maintenance requirements.In contrast, countries with a lower number of roads and a high climate impact tend to have a higher opportunity cost due to the opportunity that is lost because of resource reallocations away from increasing the existing network. For example, Algeria and Morocco in northern Africa rank in the top ten countries for highest total dollar cost of adaptation to climate change. These countries have larger road networks than the average of sub-Saharan countries. Because of the incurred costs of upgrading and maintaining paved roads and the overall large road inventories, the total costs are high. However, the size of the existing road networks in these countries in comparison to the total climate change impact costs results in a lower opportunity cost since the funds that are required for climate change do not result in a significant increase in the existing paved road inventory.

Concurrently, the countries that rank at the top in the opportunity costs measurement are almost all located in the central and south central African regions.The countries in this category are similar in that they have limited paved road networks and a high percentage of unpaved roads in the inventories.These countries also receive projected precipitation impacts in the climate scenarios through many of the decades.In particular, the decades beginning at 2040 incur a notable increase in projected precipitation.When combined with the percentage of unpaved roads that exist in these countries and the low road density factors that exist in comparison with the population and area, the result is a high opportunity cost as each damaged road requires funds that could be placed toward expanding a limited paved road network.The result of this potential loss in additional inventory is that the countries in this category see a much higher adaptive advantage than other countries in Africa.

In contrast to these single measurement countries, Niger and Chad rank in the top ten for both total cost and opportunity cost. Niger and Chad are characterized by having medium-large sized road networks and are highly affected by climate change in all scenarios.Chad has 34,000 kilometers of road, and less than 1 per centare paved. Niger has 20 per cent paved roads in a network of 18,950 kilometers. Both countries are located in the Sahel and see climate change impacts in both temperature and precipitation, affecting both the unpaved and paved components of their road inventories.The combination of climate impacts combined with the size of the road inventory creates the scenario where both cost and opportunity emerge as factors for these countries.

These measurements reflect the potential negative effects of climate change, however, it is important to recognize the difference in results between adaptation and no adaptation policies.The adaptation policy results in an average savings of 74 per cent in total costs than the no-adaptation policy, an average savings of US$43.1 millionper country annually.Put in a specific measure that emphasizes the potential benefits of adaptation, the average opportunity cost is reduced from 363 per cent to 121 per cent.The underlying message here is that climate change will impact road infrastructure, but failing to pro-actively adapt to these potential changes results in a significantly greater impact than the pro-active adaptation approach.

5 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 the World Climate Research Programme’s (WCRP’s) coupled model intercomparison project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007). The dataset represents current approaches to modelling potential climate change, but is still based on probabilistic modelling. Thus, a degree of uncertainty is introduced in terms of climate impacts. This is one reason why the current study utilizes multiple climate models to arrive at conclusions. Additionally, as stated previously, 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.'

6 Discussion and conclusion

The African continent continues to lag behind global averages in road density based on both kilometers of road per population and density of roads compared to area covered. In an economic environment where expanding infrastructure is increasingly difficult to accomplish, the African countries are facing a potential cost of US$183.6 billion price tag to repair and maintain roads as a result of damages directly related to temperature and precipitation changes from potential climate change through 2100. The potential degradation of roads from these impacts presents a significant economic threat throughout the continent, but to countries with lower GDPs in particular. Roads are a lifeline to alleviating poverty since investment in access to rural areas and transport improves the living conditions of the poor (Khandker and Koolwal 2010).Consequently roads, which have a powerful effect on mobility and choice, continue to merit priority by national governments.

The importance of roads to development and long-term growth 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 study illustrates that based on the impact of predicted temperature and precipitation changes, the opportunity cost to African countries is notable throughout the continent.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 regional level, the central part of the continent faces the greatest impact from climate change with countries facing an average cost of US$22 million annually if they adopt a pro-active adaptation policy and a US$54 million annual average if a reactive approach is adopted. 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 in the central part of the continent face a potential cumulative opportunity cost of over 180 per cent with adaptation policies in effect. Although this represents the maximum effect that may occur, a conservative, median climate scenario results in a 135 per cent cumulative opportunity cost of no adaptation is put in place and a 25 per cent cumulative opportunity cost if a pro-active approach is adopted.

These numbers establish a basis from which African countries need to approach the climate change challenge. The opportunity costs associated with potential climate change impacts have the potential to further delay infrastructure development plans.Associated with these delays is the potential for social development to be impaired as access to critical services and expansion of economic ties is delayed. The challenge to governmental organizations is how to incorporate the multitude of conflicting requirements associated with the potential impacts 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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Table 1: Overall continent values for each climate scenario: values based on 47 countries

	Adaptation policy Total cost Annual average Country Cost/average Annual continent Cost (Millions US$)	Adaptation policy Opportunity cost Averageper country– Cumulative through 2100 %	No adaptation policy Total cost Annual average Country Cost/average Annual continent cost (Millions US$)	No adaptation policy Opportunity cost Averageper country– Cumulative through 2100 %
Maximum effect	15.7/663.8	121	59.4/2790.7	363
Country average	12.3/579.1	63	44.3/2080.5	264
Country median average	3.5/165.1	14	28.7/1347.8	101

Table 2: The regional perspective on climate impacts including the adaptation and no adaptation policies as well as adaptation advantages.Two countries from each region are included as representative examples

Region	Selected country	Opportunity cost in %			Total cost, annual (Millions US$)			Opportunity cost in %			Total cost, annual (Millions US$)			Adaptive advantage in %		
		Adapt			Adapt			No Adapt			No Adapt					
		Max	Country max	Median	Max	Country max	Median	Max	Country max	Median	Max	Country max	Median	Max	Country max	Median
Northern	Morocco	34	23	4	22.0	7.4	4.4	110	99	30	70.1	U60.5	35.9	69	88	88
	Algeria	22	11	4	29.3	3.6	28.6	160	86	83	216.0	101.5	216.0	86	96	87
	Region total				61.7	16.3	34.8				488.4	289.3	355.5	87	94	90
Western	Mali	114	70	3	7.2	6.7	0.2	421	355	190	26.6	23.3	15.1	73	71	99
	Côte d'Ivoire	72	29	6	8.8	6.7	1.2	415	339	34	50.5	43.9	8.0	83	85	85
	Region total				137.1	117.3	10.5				468.0	419.1	141.7	71	72	93
East central	Niger	233	169	17	17.1	12.1	2.4	955	731	137	70.1	51.0	4.4	76	76	46
	Ethiopia	138	49	33	18.1	8.2	6.4	302	136	41	39.5	29.8	8.5	54	72	25
	Region total				203.4	183.5	32.6				605.2	558.8	188.3	66	67	83
South central	DRC	375	182	91	19.6	16.0	5.3	483	334	186	25.3	22.5	10.1	22	29	47
	Tanzania	241	153	35	30.7	30.7	7.5	498	397	104	63.6	53.5	9.0	52	43	17
	Region total				159.3	155.7	25.3				298.5	278.8	70.1	47	44	64
Southern	Mozambique	25	12	2	2.6	2.1	0.3	332	169	101	35.4	2.7	0.5	93	23	40
	Namibia	68	40	14	6.9	6.7	2.5	380	228	119	38.5	9.5	23.7	82	29	90
	Region total				102.4	83.7	11.7				434.7	215.7	159.5	76	61	93
Continent total	*Continent total*				663.9	422.9	114.9				2,294.6	1,761.7	915.1	71	76	87%

Figure 1: The process used to develop the climate scenarios and the impacts on each country

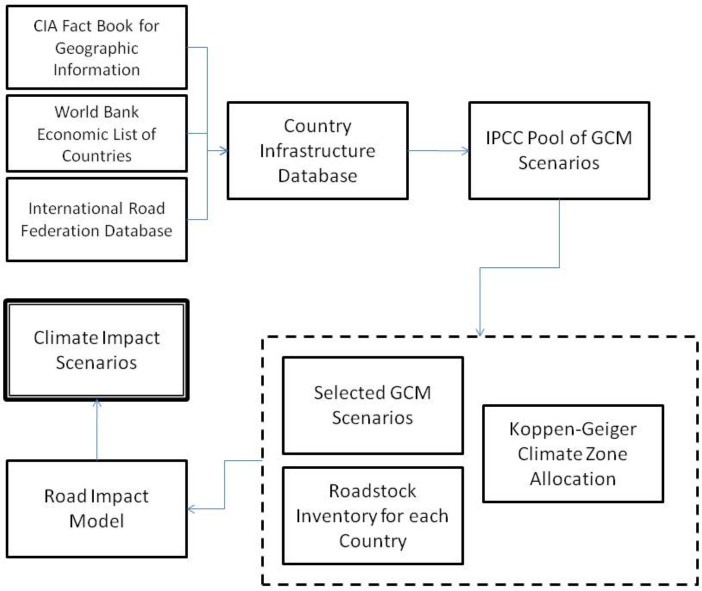


Figure 2: Regional cumulative annual costs for adapt and no-adapt policies

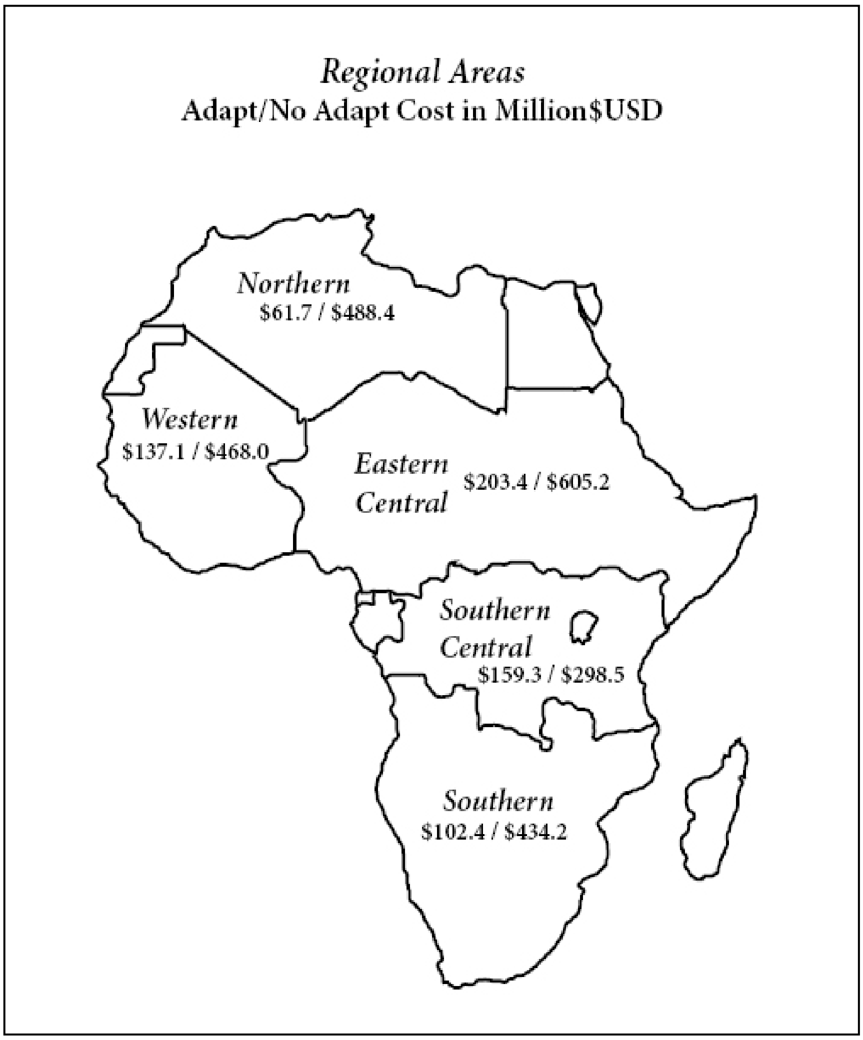
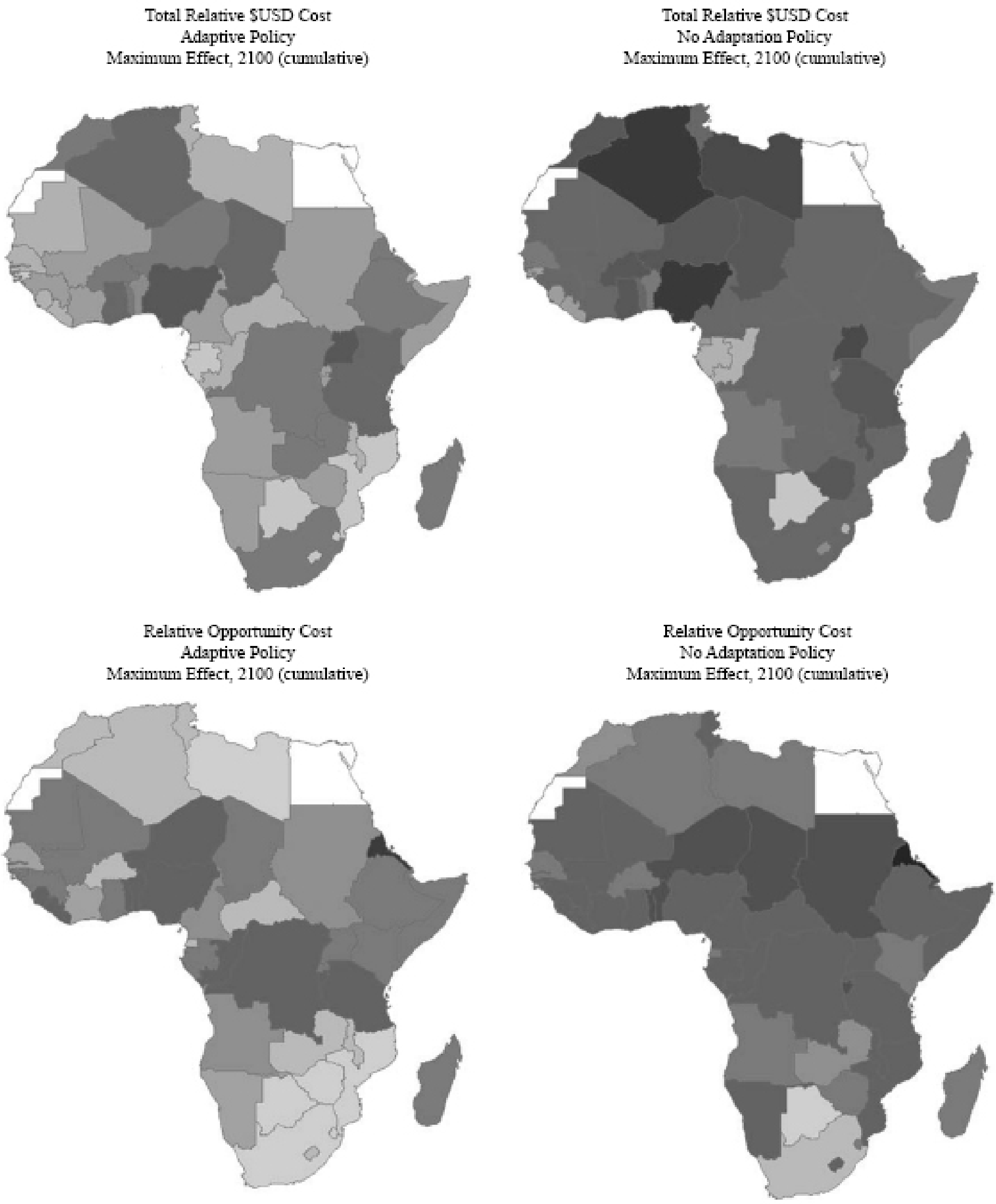


Figure 3:The relative effect of the maximum effect climate scenario on road infrastructure within the African countries



Note: Total costs and opportunity cost are illustrated with cumulative costs for both the adaptation and no adaptation policies cumulative through 2100. Darker shades indicate greater impacts.

Figure 4: Cumulative opportunity cost for each country under the maximum effect scenario, sorted by opportunity cost with adaptation policy

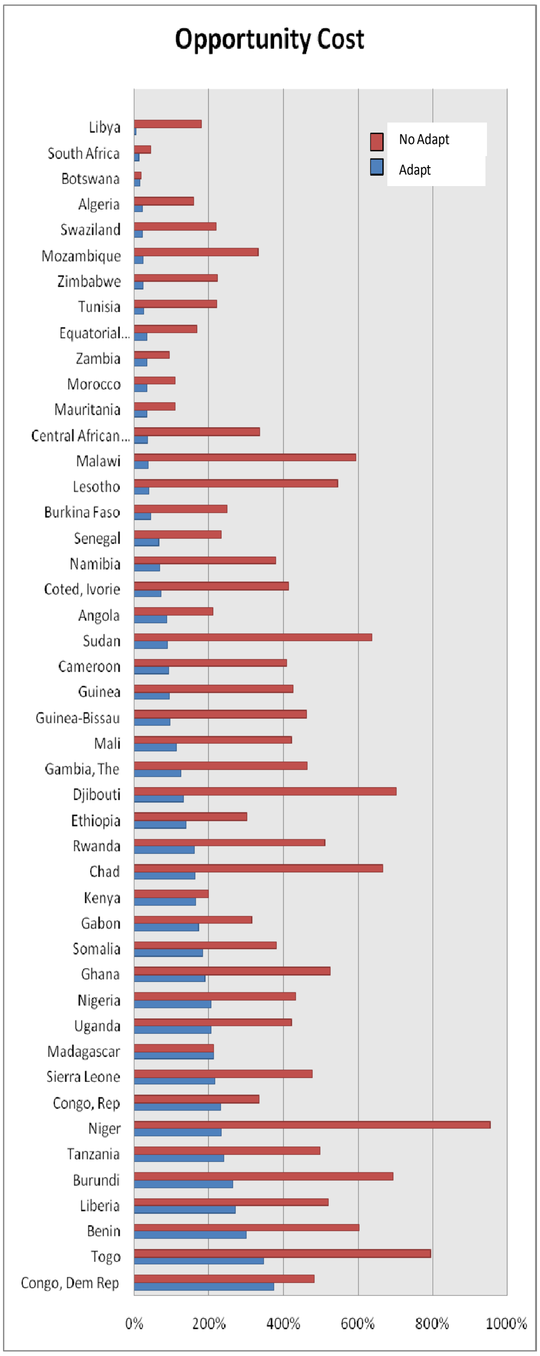
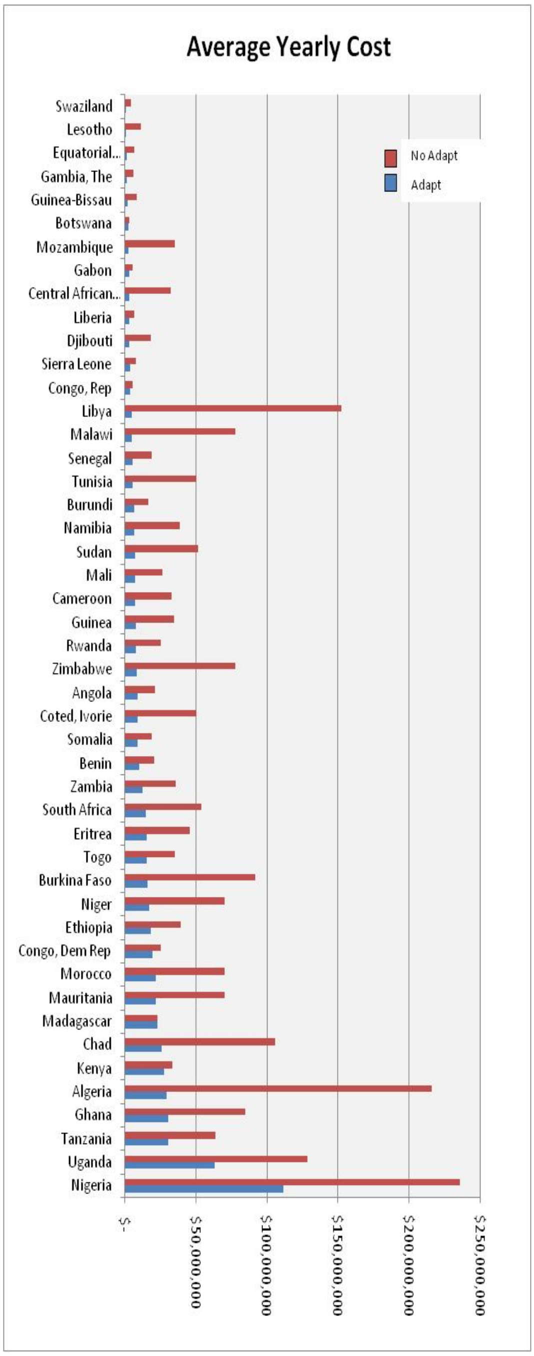


Figure 5: Average yearly cost for each country under the maximum effect scenario, sorted by annual cost with adaptation policy



Source: all tables and figures are authors' compilations.