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Enhancing the Climate Resilience of Africa's Infrastructure :

The Roads and Bridges Sector

Raffaello Cervigni, Andrew Losos,
Paul Chinowsky, and James E. Neumann,
Editors

WORLD BANK GROUP

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Preamble

The World Bank, in collaboration with the United Nations Economic Commission for Africa (UNECA), has undertaken a program of analytical work on "Enhancing the Climate Resilience of Africa Infrastructure" (ECRAI). The first major output of the program is a book on the power and water sector, launched in 2015 (Cervigni et al. 2015). This book is the second volume in the series, which focuses on the road and bridge transport sector.

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Abbreviations

ACPC	Africa Climate Policy Center
Afri-Res	Africa Climate Resilient Investment Facility
AICD	Africa Infrastructure Country Diagnostic
AfDB	African Development Bank
AFD	*Agence Française de Développement* (French Development Agency)
BNPP	Bank-Netherland Partnership Program
BCSD	Bias Correction and Spatial Disaggregation
DRC	Democratic Republic of the Congo
DfID	Department for International Development
ECRAI	Enhancing the Climate Resilience of Africa Infrastructure
GHCN	Global Historical Climatology Network
GHGs	Greenhouse Gases
ICT	Information and Communications Technology
IPSS	Infrastructure Planning Support System
ISRAMM	International Study of Road Asset Management and Models
KG	Köppen-Geiger
NEPAD	New Partnership for Africa's Development
NDF	Nordic Development Fund
PAP	Priority Action Plan
PIDA	Program for Infrastructure Development in Africa
RCP	Reference Concentration Pathway
SADC	Southern African Development Community
SSA	Sub-Saharan Africa
SSATP	Sub-Saharan Africa Transport Policy Program
TAH	Trans-African Highway
TICP	Tripartite and Intergovernmental Authority on Development
TFESSD	Trust Fund for Environmentally and Socially Sustainable Development
TDH	Turn Down the Heat
UN	United Nations
UNECA	United Nations Economic Commission for Africa

Key Messages

Roads are a key asset for Africa. They connect villages to economic centers, people to hospitals, children to schools and goods to markets facilitating trade. This report examines the implications of climate change for Africa's road connectivity, and practical steps that can be taken now to minimize the associated risks. The scope of the report includes 2.8 million km of roads throughout Sub-Saharan Africa, with a special focus on new road construction outlined in the Programme for Infrastructure Development in Africa (PIDA), an African Union facilitated initiative to enhance trans-boundary connectivity through the continent. The main conclusions of the report are:

Adequate road maintenance is the most critical and most efficient way of reducing the impact of a changing climate on the road system. In the absence of an adequate maintenance regime, the damage caused by climactic events is exacerbated. The uncertainty related to climate change further reinforces this dynamic. Thus, maintenance of pavements and sealing activities; regular maintenance of bridges, culverts and drainage structures to ensure they are functional and not obstructed; maintenance and improvement of slope protection works; and systematic assessments to identify and incrementally address vulnerable and critical road sections are the first defense to climate risks.

This report finds that even assuming adequate maintenance regimes (thereby standardizing the analysis across countries), climate change will cause substantial disruptions in network connectivity and increases in repairs and rehabilitation costs. In fact, most African countries are well below maintenance standards, which will make climate change impacts even more severe. This suggests that adequate, climate-resilient maintenance should be a key priority as countries operationalize their Nationally Determined Contributions (NDCs), and should be supported by climate finance when available.

Simply ignoring climate change is not an option. The report shows that climate change is likely to lead to a shortening of roads rehabilitation life-cycle, which, in addition to maintenance, usually entails resurfacing every 20 years. The shortened life-cycle is likely to lead to steep increases in maintenance and periodic rehabilitation costs. In the worst climate scenarios, stress imposed on the roads by precipitation can lead to rehabilitation costs 10 times higher (compared to historical climate conditions); stress imposed by flooding can lead to a 17 times increase.

In addition, climate change can lead to large increases in the disruption time of the network: in the worst climate scenarios, up to 2.5 times historic disruption due to extreme temperatures; for the temperature stressor; 76% higher due to precipitation; and 14 times higher due to flooding.

Proactive adaptation in response to temperature increase is a no regret option. Modifying the design in response to an anticipated higher temperature is a low or no-regret option for paved roads in virtually all countries and the vast majority of climate scenarios, including both the PIDA transboundary corridors and the planned expansion/upgrade of the national networks. The reason is that the savings accrued over the road life cycle more than offset the higher construction costs, even if the measures are adopted now, before significant temperature increases are experienced. In other words, the report shows that it is already appropriate to design road infrastructure for the higher temperatures that climate change will bring. Not doing so may cause the need to repair damages related to higher temperature.

The case for proactive adaptation in response to precipitation is not as clear cut, and needs to be assessed case by case. Because of the fundamental uncertainty regarding future climate, it is not possible to be as definite on how to proactively design for precipitation. Rainfall varies all over the continent, but in several countries (e.g. Angola, Nigeria, Botswana, Togo, South Sudan, Mozambique, Benin, and Cameroon), it is clear that even moderate changes in the climate will induce significant precipitation-related disruption. In these countries, it would be appropriate to start proactively adapting the road system. In other countries, more detailed analysis is needed to identify where, when and how to invest in resilience most appropriately. Some roads in some areas may well already benefit also from pro-active adaptation.

Better information on the benefits of avoiding climate-related disruption can inform decisions on proactive adaptation. This report develops a methodology to evaluate the merits of proactive adaptation in the context of an uncertain future climate. The methodology can be applied in a straightforward manner to decisions about specific investments, once more granular information is available on:

- the lifetime cost of road assets;
- the value of the freight and passenger traffic expected to use those assets,
- the criticality of the road segment on the one hand and the level of network redundancy on the other hand, and
- how climate stressors (precipitation, flooding, extreme temperatures) are likely to affect both the road asset and its use.

This study evaluated the economics of engineering solutions to build resilience (such as increasing the drainage capacity of a road; better crowning a road to enable water to the sides; hardening river banks to avoid flooding; using road binders better adapted to extreme temperatures). This focus is justified by the need to avoid locking road projects in climate-vulnerable engineering solutions that could be very costly to reverse later. Other adaptation options that African countries could assess, in terms of their cost-effectiveness of reducing climate risk, include:

- Sector and spatial planning - positioning roads where they are not likely to be harmed by climate; building-in redundancies, i.e., multiple ways to get to the same place
- Non-engineering solutions - traffic control, like restricting trucking on certain roads; rerouting traffic; regularly cleaning the drains and tunnels
- Enabling environment – policies and regulations that facilitate the professional management of road systems, including good contracting, regular maintenance, and inspection.

Overview

Africa's Road Infrastructure: A Vital but Vulnerable Asset

Economic growth is highly dependent on the quality, quantity, and accessibility of a country's infrastructure services. In sub-Saharan Africa (SSA), inadequate road infrastructure is increasingly seen as an obstacle to achieving poverty reduction and economic development goals. According to the Africa Infrastructure Country Diagnostic (AICD, Foster and Briceno-Garmendia, 2010), only one-third of rural inhabitants live within two kilometers of an all-season road – the lowest accessibility in the developing world (World Bank, 2010b).

In recognition of the urgent need to address SSA's infrastructure gap, the Program for Infrastructure Development in Africa (PIDA) was launched to provide a common framework for African stakeholders to build the infrastructure necessary for more integrated transport, energy, ICT, and trans-boundary water networks. Endorsed by African Heads of State in January 2012, PIDA aims to boost trade, spark growth, and create jobs. In the roads sector, PIDA aims to address the low density and poor condition of SSA's road networks to increase connectivity and reduce transport costs. The PIDA Priority Action Plan (PAP) identifies a subset of priority infrastructure programs designed to address the most urgent infrastructure deficits. The roads component as a subset of PIDA PAP makes up about half of the transport sector allocation, or $16.3 billion. Together with energy projects, PIDA transport investments represent approximately 95% of the total cost of the PIDA PAP, demonstrating the critical need for investment in these sectors.

In addition to the PIDA program, many SSA countries have their own road network investment plans. Research conducted for this study identified national road investment plans that include an additional 261 projects across 30 countries, with an estimated investment cost of US$45 billion. The combined "PIDA+" reference investment scenario, comprising PIDA and the national investment plans, therefore represents an approximate combined capital investment rate of US$4.6 billion per year, for a total of US$78 billion.

The PIDA program is a vital component of Africa's development strategy. Yet it is also essential that the forthcoming investment in SSA's roads take into account the very real risk of climate change. Roads are particularly vulnerable to climate stressors such as increased temperature and precipitation and flooding. For paved roads, increased temperature leads to accelerated aging of the pavement binder and rutting of asphalt. For paved and gravel roads, increased precipitation and flooding lead to reduced load-carrying capacity and overtopping of roads, among other impacts.

The effects of climate stressors on road infrastructure, which include both increased maintenance and a potentially shorter useful life between rehabilitation cycles, also give rise to indirect effects, such as disruption of unimpeded travel of people and goods, either because the road surface is damaged or destroyed, or because it is in the process of being repaired. These disruptions in turn affect economic activity and productivity.

Fortunately, there are effective ways of adapting new roads and modifying existing roads to make them more resilient to climate change. The challenge is in determining the most cost-effective and appropriate adaptation pathway given the high degree of uncertainty in climate projections. Although a vast body of scientific evidence indicates that the climate of the future will be very different from that of the past, climate models often disagree on the specific changes in temperature and precipitation at a given location. This uncertainty complicates adaptation planning, but as this book shows, the uncertainty can be managed, and steps necessary to achieve resilient roads can, and should, be taken as investments in these critical assets move forward.

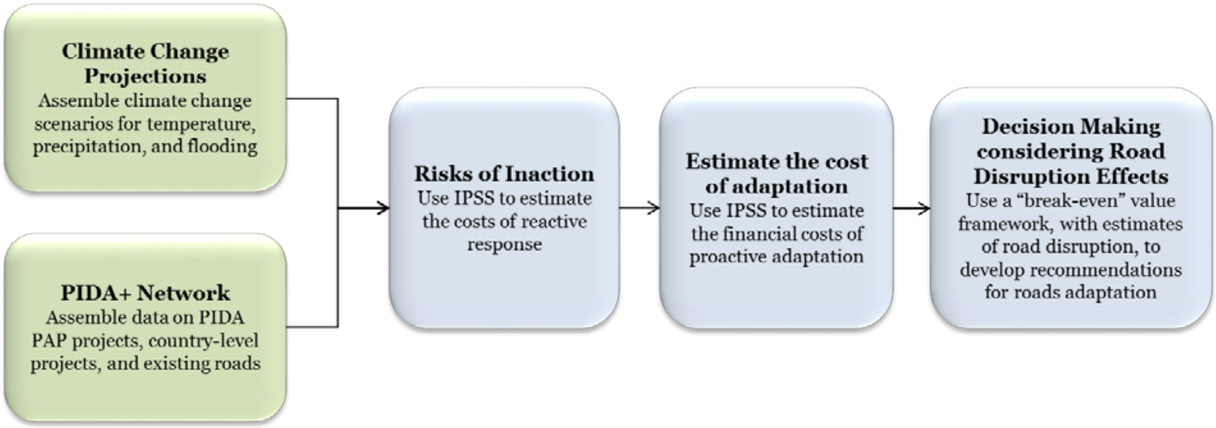
The key messages of the report at that enhancing maintenance of existing roads is vital priority, made more important by the risks that climate change may make these roads unpassable without a renewed commitment to maintaining roads as a vital asset in economic development; that new and many existing paved roads need to incorporate a new standard for achieving resilience to the effects of the forecast higher temperatures, because as this report shows such a new standard is cost-effective; and that country and local road planners need to carefully consider a strategic and targeted approach, on the most vulnerable and well-traveled roads in their systems, to further updating road construction and maintenance standards to address vulnerabilities to the effects of increased intensity of precipitation and flooding.

The goal of this study is first to quantify the cost of climate change to the African roads sector, and second to assist decision makers in identifying the most cost-effective adaptation approach. To this end, the study uses detailed analysis of climate impacts for each of a wide array of possible future climates, combined with decision analysis techniques, to identify how to maximize the cost-effectiveness of investing in infrastructure resilience plans in advance of knowing how the future climate will unfold.

How Should We Evaluate Adaptation Options for Africa’s Road Network?

The network of roads analyzed in this study is referred to as the “PIDA+” network, and includes both current road and planned projects from PIDA and country-level projects. Figure O.1 outlines the approach taken in the study, which consists of five main steps. The first steps include assembling the last two generations of United Nations, Intergovernmental Panel on Climate Change vetted climate change scenarios and compiling data on the PIDA+ network.

Figure O.1. Study approach



Next, the study uses the Infrastructure Planning Support System (IPSS – see Box O.1 below) to evaluate the climate change impacts to the PIDA+ network under the following scenarios:

- Reactive Response (Risks of Inaction): In this case, no proactive measures are taken to prepare the roads for climate change, and climate change and extreme events damage roads. Climate change impacts are quantified in terms of increased maintenance costs, relative to those that would be incurred under current climate, and incremental road disruption costs.
- Proactive Adaptation (Investments in Adaptation): Anticipatory measures are taken to mitigate the effects of climate change and take advantage of any opportunities. Climate change impacts are quantified in terms of up-front costs of design changes, reductions in subsequent needs for repeated repairs and maintenance, and reductions in road disruption.

The analysis assumes throughout that the timing, management and financing of periodic maintenance is adequate and in accordance with established engineering standards. While this may seem at odds with the reality of most of the region (where maintenance is substantially underfunded), the assumption is justified because it allows to standardize the modeling across countries, and to focus on the incremental maintenance cost caused by climate change. However, this does not imply that closing the current financing gap for maintenance is not important. To the contrary, mobilizing additional resources for maintenance will be a key, no-regret first step in reducing countries' vulnerability to climate change. The reason is that if countries continue to under-fund maintenance, they will be even more exposed to climate change than the present analysis concludes.

Comparing the lifetime cost of the road assets (construction, maintenance, repairs and rehabilitation) under the reactive and proactive response provides an assessment of the financial case for taking adaptation action. If the higher construction cost of adapting to climate change is more than offset by the lower annual cost for maintenance, rehabilitation and repairs, than adaptation makes financial sense.

However, the financial case for adaptation depends on the climate change scenario considered. The case will be stronger under scenarios of more severe climate change (as there will be higher cost savings over the lifecycle of the project); and weaker in scenarios of less pronounced change (smaller savings, relative to the upfront adaptation cost). For some road projects, there will be net financial savings over the assets' lifecycle in all climate scenarios. In these cases, the case for adaptation is unequivocal.

But considering only the perspective of life-time costs may be limited, as it leaves out the fact that more resilient road assets could shorten the down time of the transport network when climate stressors hit. A shorter downtime can reduce the disruption of supply chains, or restore the accessibility of schools and hospitals.

Therefore, the last step in the study is to consider both the financial benefits and the benefits of reduced disruption time in a decision-making context called a "breakeven analysis." This is particularly important in projects where the financial case for adaptation is sensitive to the climate scenario considered. In some of these cases, the time-saving benefits of adaptation may be more robust to different climate scenarios. In particular, for high-traffic roads, even milder climate change can cause important disruptions in the movement of people and goods. In these situations, the balance may be tilted again in favor of adopting more climate resilient engineering solutions, in spite of the higher construction costs incurred when following a proactive adaptation response.

Box O.1. The Infrastructure Planning Support System (IPSS)

The *Infrastructure Planning Support System* (IPSS) is a software model that integrates expertise from researchers in civil and environmental engineering, water resources, architecture, international development, and economics. It is a quantitative, engineering-based analysis tool to understand the impacts of climate change on current and future road, bridge, and other infrastructure (http://www.clicslab.org/ipss.html).

Costs are assessed based on two approaches. First, a reactive "no adaptation" approach which analyzes a changing future climate on existing road design standards. This is compared to a proactive "adaptation" approach which reduces future risk and damages by changing design standards at upgrades or re-construction. Both maintenance and new construction/re-construction costs are provided. Stressor-response relationships are based on based on a number of published sources including engineering research and materials studies.

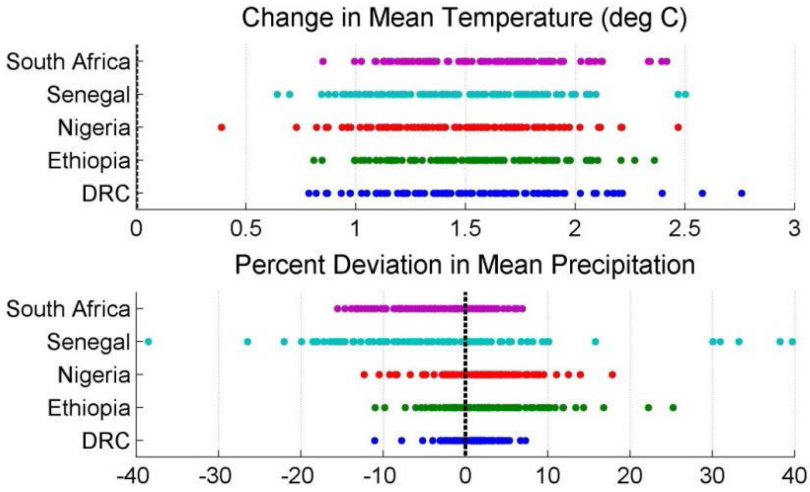
See Box O.2 below for a more detailed explanation of the stressor-response functions used in this study.

A similar analysis is conducted to assess climate impacts and adaptation options for Africa's bridges. Because no inventory of Africa's bridges exists, the study developed a new, "synthetic" inventory based on road crossings in the existing road and river networks of Sub-Saharan African countries. Because there is limited information on the size, construction material, and condition of these bridges, the bridge component of the study addresses risks of inaction and the potential for climate adaptation but does not assess disruption effects.

Climate Change Projections

Climate change is projected to bring about substantial changes across SSA in temperature and precipitation (see Figure O.2 for the projected change in five sample countries). The countries were selected based on their present-day climates, which represent the range of climates found across SSA. As shown in the figure, temperature is projected to rise uniformly across the climate models and countries. The projected change in mean precipitation is more uncertain, and varies substantially across countries.

Figure O.2. Projected changes in mean annual temperature and precipitation in SSA in 2050



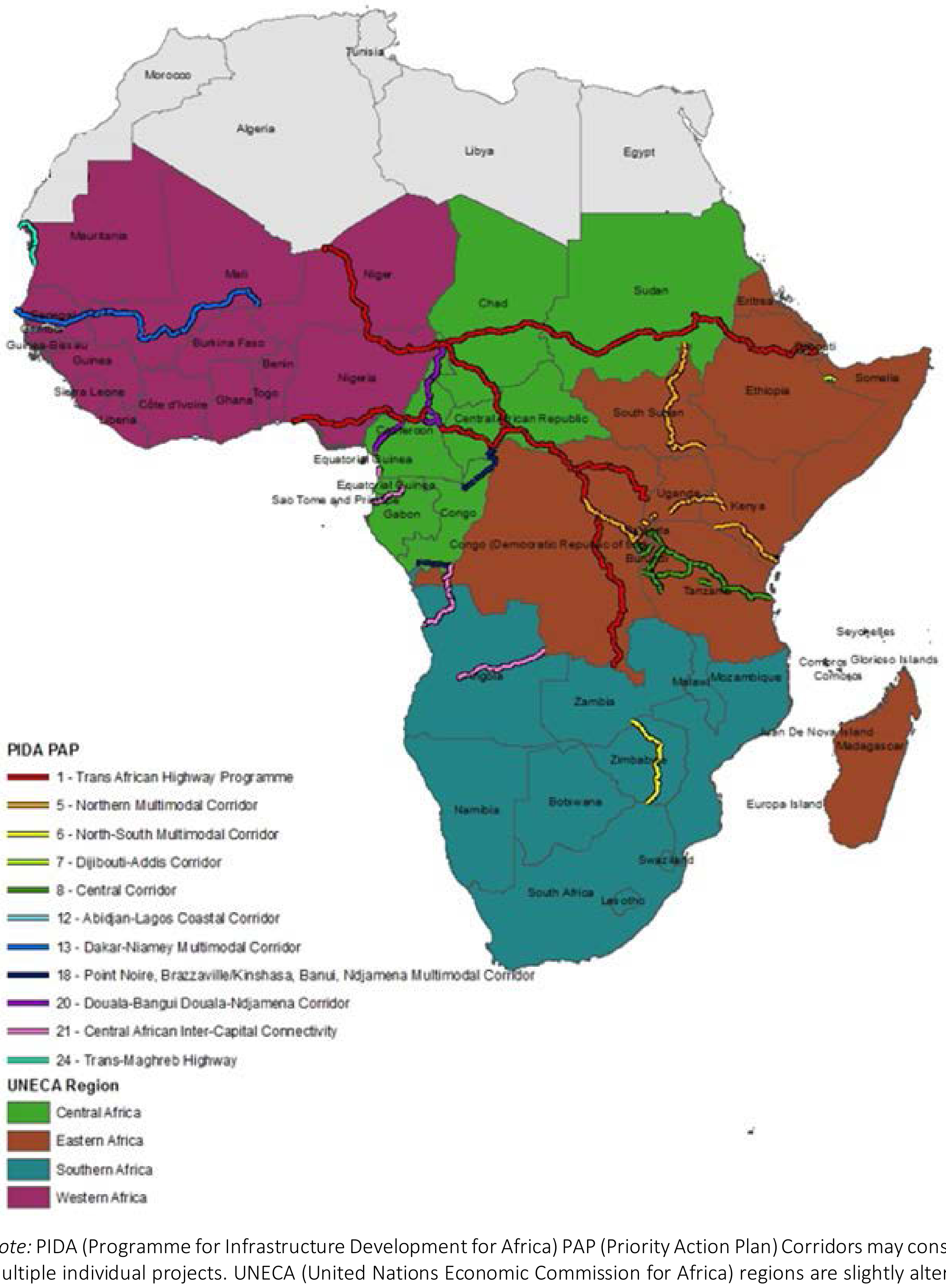
Note: In each country, each dot denotes an annual representation of climate. In the precipitation panel, the vertical zero line corresponds to current (recent historical) mean annual precipitation. Dots to the right of the historical value refer to projections of wetter climate; dots to the left indicate projections of drier climate.

The uncertainty in future climate is an important rationale for adopting the scenario-based analysis methods used in this study. Although considering many possible climate futures complicates the interpretation of our results, it is important to recognize that failure to consider a broad range of possible climate futures in planning climate-sensitive road infrastructure could lead to large over- or under-investments in climate resilience.

Characterizing Africa's Current and Future Roads – the PIDA+ Network

The PIDA+ network represents the planned roads investment in SSA through 2030, plus all current roads, totaling over 2.8 million km across the continent. The study draws on data from existing infrastructure investment plans (e.g., PIDA), as well as other regional initiatives and country-level master plans to characterize the scope of new road investments. But the PIDA+ network also includes existing roads. In total, the PIDA network evaluated in the study includes 11 trans-boundary road corridor projects, comprising 111 individual road segment investments, with a total projected investment of approximately US$16.3 billion. The “new” portion of the PIDA+ inventory includes an additional 261 projects across 30 countries, with an estimated investment cost of US$45 billion. Figure O.3 presents the PIDA PAP projects included in the study across the four SSA regions used by the United Nations Economic Commission for Africa (UNECA).

Figure O.3. PIDA PAP projects examined in the study across four UNECA multi-country regions



Note: PIDA (Programme for Infrastructure Development for Africa) PAP (Priority Action Plan) Corridors may constitute multiple individual projects. UNECA (United Nations Economic Commission for Africa) regions are slightly altered to reflect the Sub-Saharan Africa focus of this report. Mauritania and Sudan are actually part of the UNECA North Africa region.

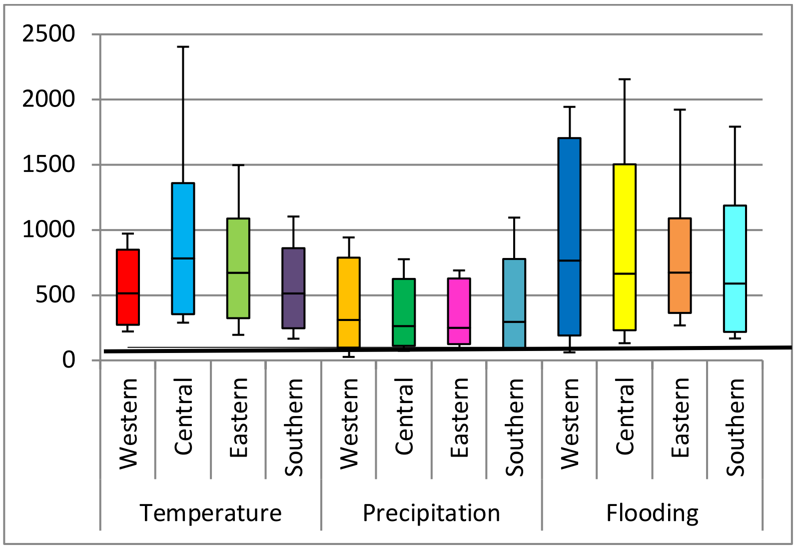
Risks of Inaction

The projected changes in temperature, precipitation, and flooding throughout SSA will have substantial effects on the PIDA+ network. Figure O.4 presents the estimated reactive response costs associated with each climate stressor (see Box O.2 for details of the climate effects modeled). Specifically, the figure shows the costs of conducting maintenance on the PIDA+ road network between major rehabilitation cycles in response to climate-induced damages, to restore roads to their pre-climate change condition. Periodic rehabilitation costs are included in the baseline, "historical climate" costs.

As shown, the flooding stressor leads to relatively higher increases in costs relative to historic costs across the regions for both the PIDA+ network and PIDA PAP projects. Cost increases are particularly high in the Central and Western regions.[1]

Figure O.4. Normalized net reactive response costs by region for the full PIDA+ network, 2015-50

(Historical (no-climate-change) costs = 100)



Note: The chart provides an indication of the impact of climate change relative to the optimal maintenance for a historic climate (because actual road maintenance is typically underfunded relative to the optimal maintenance cost, impacts are likely to be higher than indicated). The vertical axis is normalized (at 100) to the historic (no-climate-change) costs. Bars that are higher than the 100 line represent costs of climate change relative to the optimal costs of maintenance for current climate; bars below the line indicate potential savings. Box indicates the range of costs over the 25th to the 75th percentile of climate change scenarios; line in box represents the mean value; and whiskers extending from box refer to the 5th and 95th percentile of costs over climate change scenarios.

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[1] Note that recent global agreements to reduce greenhouse gas emissions might be expected to reduce these risks of inaction for the road network, when they are fully realized. But because it will take time for the reductions associated with GHG mitigation to take effect, those measures are less effective than might be expected, at least through the 2050 time horizon of the study. Adaptation action is likely to be needed, even if carbon emissions are dramatically reduced.

Box O.2. Summary Description of Impacts of Climate Change on Roads

In this study roads were analyzed for climate impacts from three specific climate stressors: temperature, precipitation, and flooding. The lifetime cost of each road segment was analyzed using a stressor-response method to evaluate, relative to a baseline of historical climate, the incremental cost attributable to climate change.

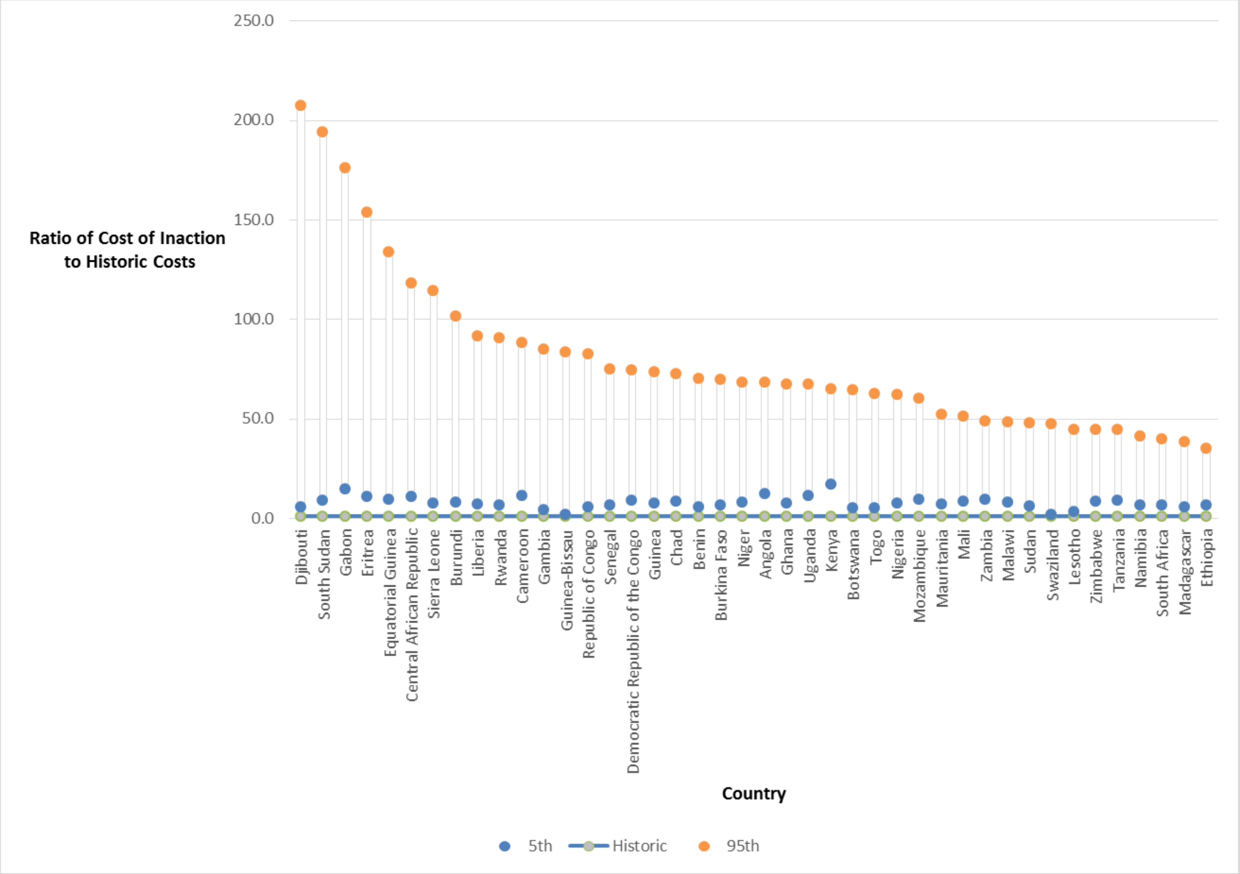
The basic impact estimate approach operates as follows. When a climate stressor reaches a level where it exceeds the climatic design parameters for the road, damage is incurred. In general, we assume that roads are built to historical climate standards. Where the historical standards are exceeded, damages are incurred through increased maintenance activities necessary to preserve the integrity of the road for its original design lifespan. A summary of how climate stressors affect paved and unpaved roads is provided in the table below. Note that each of the three climate stressors affects a different component of a road. For paved roads, for example, temperature affects the surface integrity, precipitation affects the subgrade, and flooding can wash away the entire road system. Because these impacts, and the reactive repairs and proactive adaptations options taken in response to the impacts, are independent, both the impacts and the adaptation strategies are analyzed separately throughout the book.

Roads were classified as "paved" or "gravel" surface, meaning bitumen surface or not, respectively. Additionally, roads were classified within the surface type as: *primary, secondary* or *tertiary* based upon design parameters, construction design and other characteristics; these distinctions imply construction scale, technique, and traffic volume, and therefore differences in baseline and climate response repair costs.

Road type	Climate stressor	Effect
Paved roads	Temperature	Increased temperature leads to accelerated aging of binder
		Increased temperature leads to rutting (of asphalt), and bleeding and flushing (of seals)
	Precipitation	Increased precipitation leads to increased average moisture content in subgrade layers and reduced load-carrying capacity
	Flooding (in excess of design flood)	Washaways and overtopping of road
Unpaved roads	Temperature	No effect
	Precipitation	Increased precipitation leads to increased roughness of the road surface, increased average moisture content in subgrade layers, and reduced load-carrying capacity
	Flooding (in excess of design flood)	Washaways and overtopping of road

Figure O.5 presents the reactive response costs at the country level, relative to the lifetime cost incurred under historical climate. Variation across countries is dependent on: the regional distribution of climate changes; the historical climate (because road infrastructure is assumed to be built to withstand current climate, making areas that are relatively cool or dry potentially more vulnerable as climate gets hotter and/or wetter), and the distribution of road types, with unpaved roads typically being more vulnerable.

Figure O.5. Risk of inaction for PIDA+ network for all countries, 2015-50

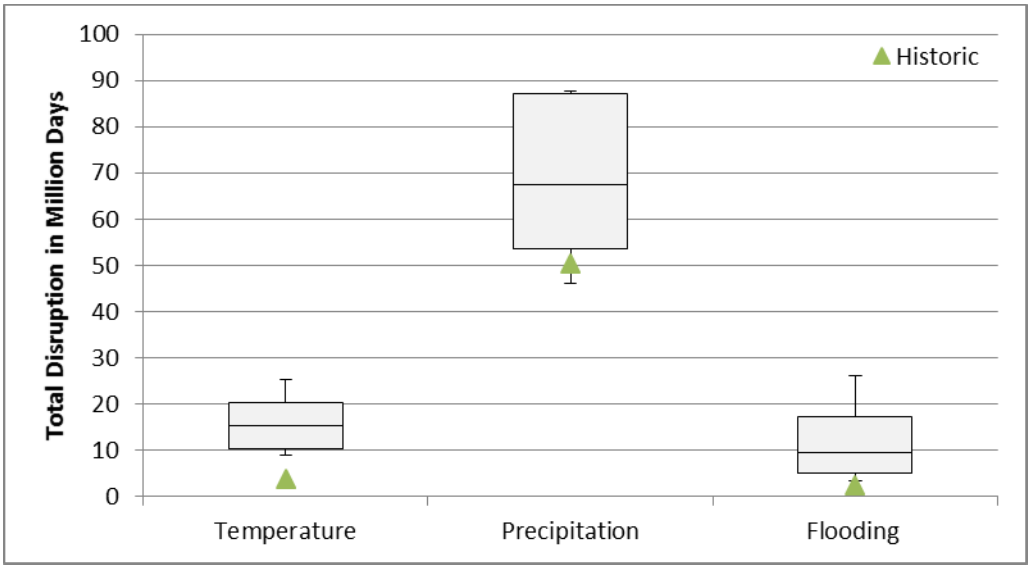


Note: The chart provides an indication of the impact of climate change relative to the optimal maintenance for a historic climate (because actual road maintenance is typically underfunded relative to the optimal maintenance cost, impacts are likely to be higher than indicated). The blue line shows the country-specific historic (no-climate-change) costs. Blue dot shows the 5th percentile (most benign) of costs over climate change scenarios; orange dot shows the result for the 95th percentile (most damaging) of costs.

In addition to increased maintenance costs, the reactive response approach is projected to result in a high degree of disruption to the PIDA+ network. The analysis quantifies disruption in terms of out-of-service days for roads in the network – roads must be out of service when climate change damages the road, to allow repair crews to fix the road and make them passable. The reactive response to changes in precipitation alone, for example, results in an estimated 46-88 million disruption days under different climate scenarios, compared to 50 million days for the historic climate. The increase in disruption for the reactive response mode for the worst expected future climate could be as much as 2.5 times historic climate disruption levels for the temperature stressor; 76% higher for the precipitation stressor; and 14 times higher for the flooding stressor (Figure O.6).

Disruption of the Africa road network clearly results in substantial economic costs, as goods and people are prevented from moving freely or engaging in economic activity. A single day of disruption likely restricts many person-days of activity, though this effect may be mitigated in places where there is a high degree of road network redundancy. The typical rule of thumb for valuation of traffic disruption is to use 50 percent of the daily wage as a proxy for the lost opportunity cost of time – using reasonable valuation estimates, then, disruption might lead to additional damages in the billions to tens of billions of dollars, associated with individual days of road closure for repairs.

Figure O.6. Disruption time for the PIDA+ network with reactive response, 2015-50



Note: The chart presents results for cumulative road disruption times across climates in million days of disruption, across all SSA. Green triangle indicates disruption estimated for a historic climate. Box indicates the range from the 25th to the 75th percentile of disruptions days over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range of disruption days over the 5th to the 95th percentile of climate change scenarios.

Even this value, however, excludes the broader macroeconomic implications of restricted travel and economic activity that extends to multiple economic sectors (e.g., associated with spoilage of agricultural products or lost tourism revenue). Two country scale examples support the importance of disruption to African economies. In Mozambique, analysts estimated that transport disruption associated with climate change could cost the economy roughly $2.5 billion/year over the 2010-2050 period, compared to a current annual GDP of $15.6 billion. (Arndt et al., 2012). In South Africa, a similar analysis found that transport disruption could cost 0.8% of GDP (with a range of 0.1 to 2.6% across climate futures) by 2050; South Africa's current GDP is over $350 billion. The cumulative cost over the 2015 to 2050 period (5% discount rate) would be $16 billion (mean across climate forecasts), with a range of $1.5 to $55 billion (Cullis et al., 2015).

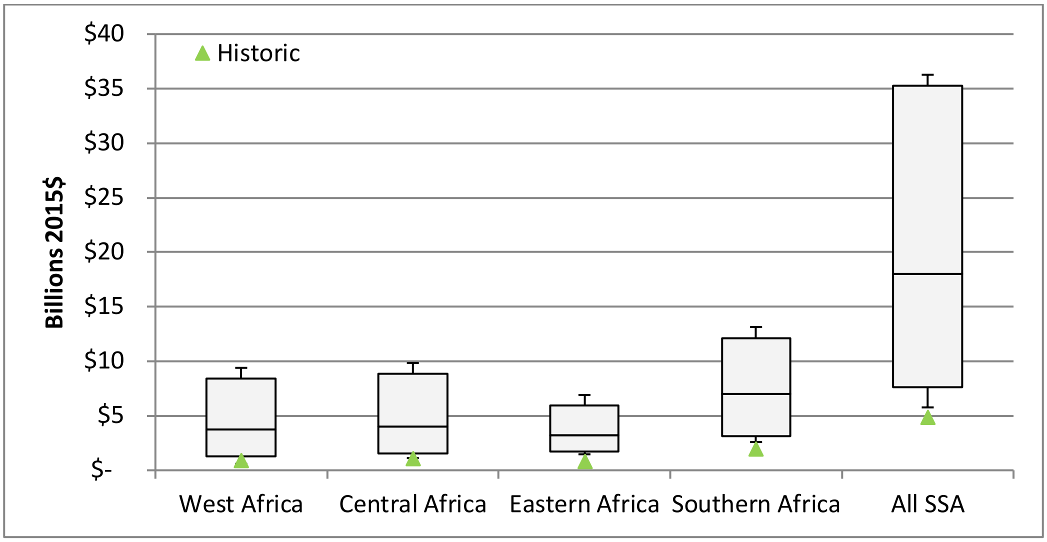
Effects of Climate Change on Bridges

Climate change also has significant impacts on Africa's bridge network. Although no comprehensive inventory of bridges exists for the continent, this study estimates there are approximately 330,000 bridges across SSA. Based on the size of their respective road crossings, approximately 230,000 (69%) of these bridges are small (associated with tertiary roads), 76,000 (23%) are medium sized (associated with secondary roads), and 26,000 (8%) are large (associated with primary roads).

The mean estimated cost for the PIDA+ bridge inventory associated with a climate change reactive response is $18 billion for 2015-50 (6% discount rate – corresponds to the mean cost over the distribution of climate change scenarios), which compares to a historical climate cost of about $5 billion (Figure O.7). Costs vary by climate scenario, however, with the 5th percentile climate showing costs of $7.6 billion, a 50% increase over historic costs, and the 95th percentile showing costs of just over $35 billion, 7 times the historic cost. Climate change therefore very clearly presents a substantial risk to Africa's bridges, across all projected future climates, and to the vital connectivity they provide for the transport network.

In some countries, bridge adaptation may also make good economic sense. The mean value of savings is slightly negative in several of the countries analyzed; however, disruption times are often much higher for bridges than for roads because of the critical nature of bridge crossings in road networks. So when the cost of disruption time is included in the analysis, it is reasonable to conclude that proactive fortifying of bridge construction will be cost effective, although this will need to be assessed on a case-by-case basis.

Figure O.7. Reactive response costs to SSA bridges by region, 2015-50 (6% discount rate)



Note: The chart provides an indication of the cost impact on bridges of climate change relative to the optimal maintenance under historic climate (green triangle). Box indicates the range of costs over the 25th to the 75th percentile of climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range of costs over the 5th to the 95th percentile of climate change scenarios.

The Value of Adapting Africa’s Roads to Climate Change

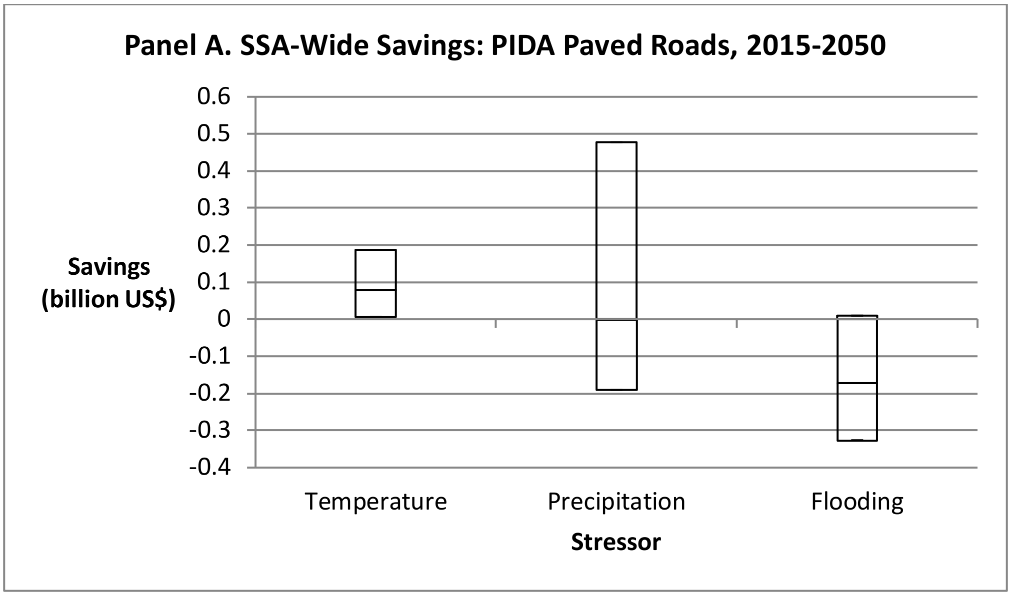
Adaptation has two major benefits: a potential reduction in lifetime road assets costs (construction, maintenance, and rehabilitation); and a reduction in disruption time (less time wasted in moving goods and people).

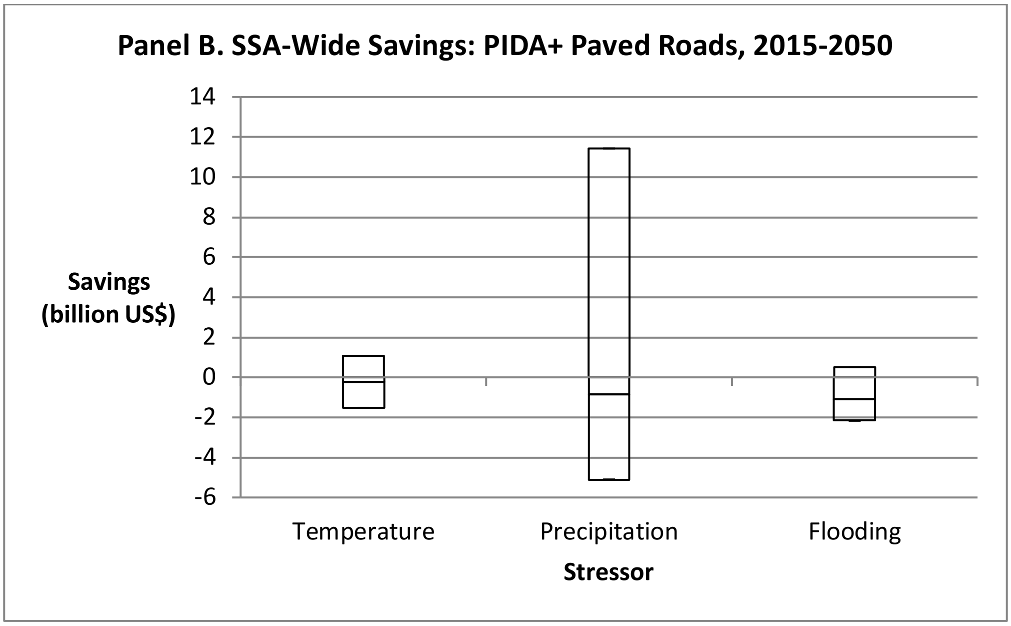
The saving in assets’ life-time cost is sometimes sufficient to support broad application of adaptation measures. For example, the adoption of temperature resistant road surfaces for the PIDA network makes sense on financial grounds alone, even without considering time disruption reduction co-benefits (Figure O.8, Panel A).

However, in other cases the lifetime cost savings argument alone is not sufficient to justify adaptation across the full spectrum of possible climate futures. This is the case for the precipitation and flooding stressors in the PIDA roads (Figure O.8, Panel A); and for all three stressors, for the PIDA+ paved roads (Figure O.8, Panel B). In these cases, in a considerable number of climate change scenarios adaptation would result in negative savings. In particular, in scenarios where climate change turns out to be relatively mild, the higher cost of construction would not be offset by reductions in maintenance, repair and rehabilitation costs.

In these cases, a closer look at the second type of adaptation benefits, namely the reduction in the down-time of the network, is warranted.

Figure O.8. The financial case for proactive adaptation for paved roads





Note: The chart provides an indication of the cost savings implied by proactive adaptation action for PIDA paved roads (Panel A) and PIDA+ paved roads (Panel B). Positive savings imply that the asset lifetime costs with adaptation is less than the costs incurred without adaptation; negative savings imply the opposite. Box indicates the range of savings from the 5th to the 95th percentile over climate change scenarios; line in box represents the mean value.

The Time-Saving Benefits of Adaptation

Adaptation invariably reduces traffic disruptions and the losses of productive time that these disruptions entail; i.e., it generates time saving benefits. How large should these benefits be in order to make adaptation worthwhile, irrespective of the climate scenario considered?

To address this question, this book uses a break-even analysis, illustrated in the charts (O.9 and O.10). This scenario-based analysis examines the “breakeven” point, where the value of disruption is large enough to justify the adoption of a proactive adaptation approach, and provides additional insights for adaptation planning. Low breakeven values should encourage proactive action, while higher breakeven values suggest proactive action is not warranted.

For any given road asset and climate stressor, there will not be a single breakeven value, but a distribution of values across climate scenarios. In scenarios of harsher future climate (e.g., more flooding, more frequent or intense precipitation), breakeven values will be lower, and the case for taking adaptation measures stronger, as the avoided disruption time will be higher. In scenarios of milder climate change, the value of avoided disruption time will need to be higher to justify adaptation, as there will be fewer disruption days avoided.

Because prior work provides some basic information on traffic volumes by country, for paved and unpaved roads, breakeven values in Figure O.9 below are expressed as the daily value, per vehicle, of time wasted due to the disruption of road. Put another way, this value is a threshold for action. If decision makers think that the value of time wasted every day (on average) as a result of climate change, per vehicle, is at least as large or higher than the breakeven value calculated here, then proactive action make sense. The larger the number of climate scenarios where the threshold for action is exceeded, the stronger the case for adaptation. A good benchmark value for comparison is the valuation of a day of traffic delays is one-half the daily wage rate. The average daily wage for most workers varies considerably across Sub-Saharan Africa, from roughly $30 per day in countries such as South Africa and Botswana, to as little as $3.50 per day in countries such as Ethiopia and Uganda, according to UN International Labor Organization data. For the purposes of this work, using $10 per day as a rough benchmark value of an avoided day of disruption, per vehicle, helps us to interpret the results (using the conservative assumption of one traveler per vehicle).

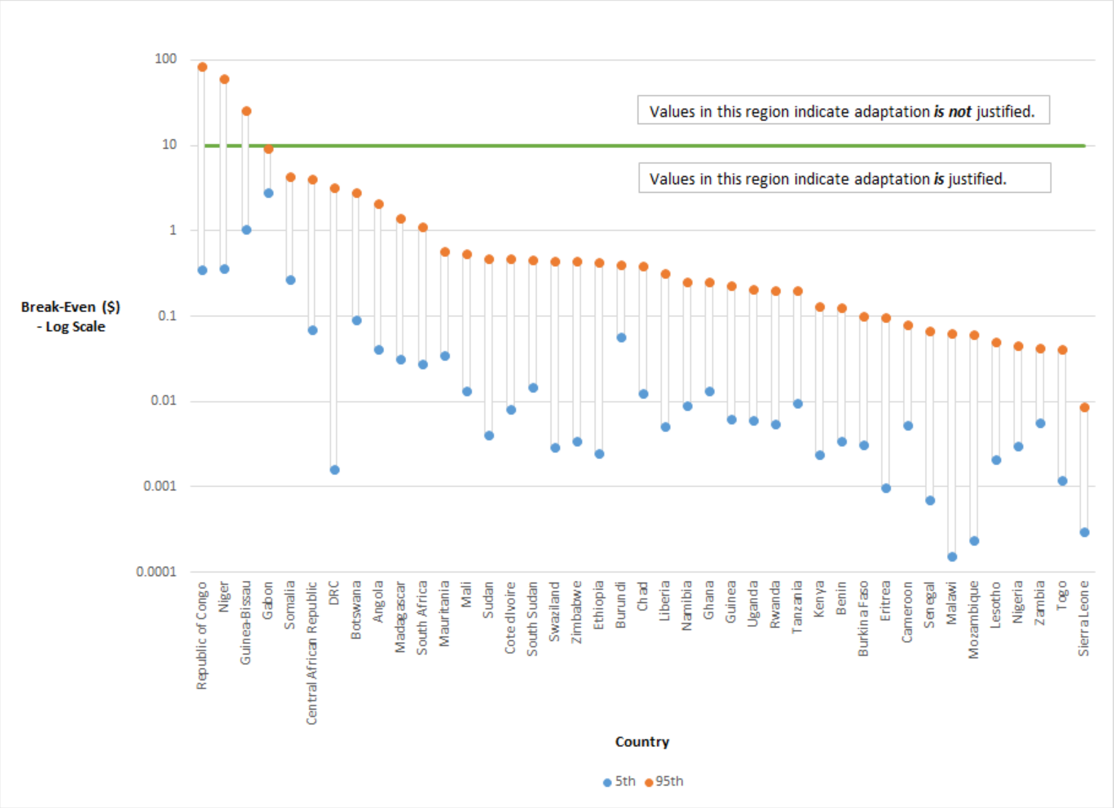
In Figure O.9 below, which presents breakeven values by country for the temperature stressor, it is clear that in all countries except for the few on the far left of the graphic, the breakeven values are less than $10 per day, per vehicle, for the 95th percentile climate scenario. That is, there are only 5% of the scenarios considered where climate change is so mild that the time savings generated do not justify adaptation.

The conclusion that follows for the other 95% of the climate scenarios considered is that, once disruption is considered, adaptation to the temperature stressor for all paved roads in these countries is justified. This reinforces, at the level of individual countries, the insight about the merit of proactive adaptation in response to temperature increases, already reported for the region as a whole (Figure O.8 above), but in this case extended to both new PIDA roads, and existing paved roads in the PIDA+ domain. In general, some of the more advantageous areas for proactive adaptation for paved roads are for countries in the warm temperate climates of Sub-Saharan Africa. These include Zambia, parts of Angola and Zimbabwe, the southern coast of Mozambique and north-eastern coast of South Africa, as well parts of Madagascar.

By looking at the higher end of the distribution of the breakeven values (e.g., the 95th percentile), road planners can have a simple tool to assess the merits of adaptation, despite climate uncertainty. That is, to compare the 95th percentile of the distribution of breakeven values, to a plausible estimate (discussed above) of the *value* of the avoided time lost.

The intuition is that the 95th percentile represent a high regret cost of adapting (since it refers to scenarios where climate change does not turn out to be as bad as feared). If even in that case, the value of the avoided disruption time is considered higher than the breakeven value, the case for adaptation will be even stronger for the scenarios of more pronounced climate change (the rest of the distribution of climate outcomes below the 95h percentile).

Figure O.9. Distribution of traffic normalized breakeven values across climate scenarios by country for all paved roads (PIDA and PIDA+), temperature stressor



Note: The chart provides an indication of the per-vehicle value of time required to justify proactive adaptation action (break-even value), considering both disruption time and financial cost implications. Higher break-even values imply action may not be justified – lower breakeven values imply action is justified. Blue dot is the 5th percentile (lowest break-even value) over climate change projections; orange dot is the 95th percentile (highest break-even value). Green line at $10 breakeven provides a reference point that corresponds to a per vehicle per disruption day value that is roughly consistent with daily wages in several African countries.

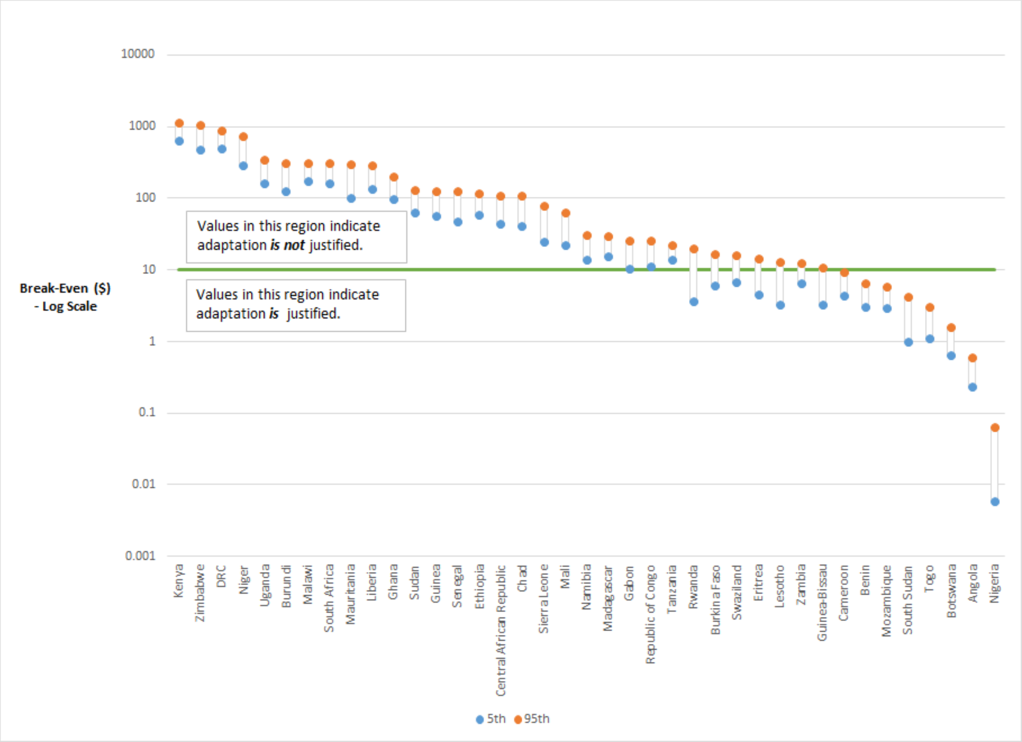
Results for the precipitation and flooding stressors for paved roads (not shown in the present overview) indicate higher break-even values, compared to the temperature stressor, so only a few countries have a breakeven value below $10 per person-day (see main report for more details). In general, proactive adaptation for paved roads in response to the flooding and precipitation stressors are evident in the equatorial steppe area, which occurs in Kenya and northern Gabon, and relatively large benefits are found in response to the precipitation stressor in some of the desert climatic zones, in large areas of the region across multiple countries.

Also, when disruption time is considered, a case can be made for adapting unpaved roads in several countries. Figure O.10 presents traffic-adjusted breakeven values for the flooding and precipitation stressors related to unpaved roads. While many countries have very high, worst case break-even values (i.e., high adaptation regrets when climate change turns out to be mild) for both stressors there are still a handful of countries where a worst-case breakeven value below $10 per person-day is seen for precipitation on the right of Figure O.10 (Panel A); and for flooding (Panel

B). In these countries, adaptation can generate large reduction in disruption time; and there are relatively high unpaved road traffic volumes (compared to other countries in the scope of the study). The combination of these two effects points to the importance of seriously considering adaptation, even for unpaved roads.

Figure O.10. Distribution of breakeven values across climate scenarios for unpaved PIDA+ roads

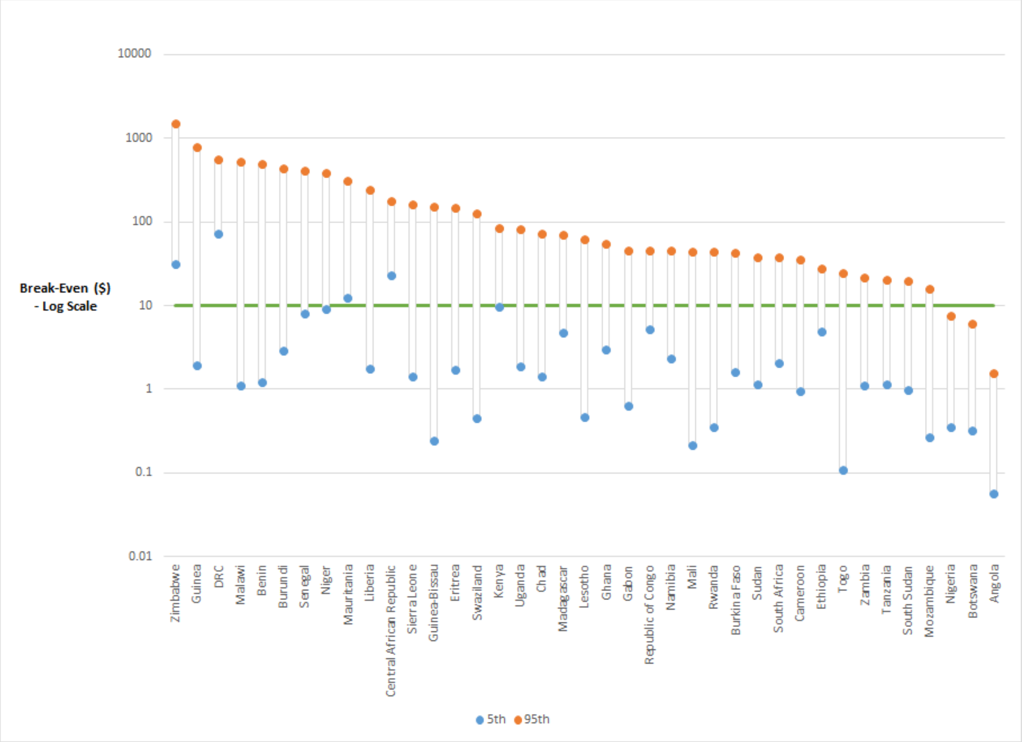
Panel A: Precipitation stressor, unpaved roads



Values in this region indicate adaptation ***is not*** justified.

Values in this region indicate adaptation ***is*** justified.

Panel B: Flooding stressor, unpaved roads



Note: The chart provides an indication of the per-vehicle value of time required to justify proactive adaptation action (break-even value), considering both disruption time and financial cost implications. Both charts refer to unpaved roads in PIDA+ network. Panel A addresses adaptation action in response to changes in precipitation; Panel B addresses adaptation action in response to changes in flooding. Higher break-even values imply action may not be justified – lower breakeven values imply action is justified. Blue dot shows the result for the 5th percentile (lowest break-even value) over climate change scenarios; orange dot shows the result for the 95th percentile (highest break-even value). Green line at $10 breakeven provides a reference point that corresponds to a per vehicle per disruption day value that is roughly consistent with daily wages in several African countries.

Road planners are likely to have more granular information, compared to what was possible to obtain for this study, on expected traffic volumes, redundancy at the road network level, and unit value of travel time applicable to their countries. Using such data, the approach proposed in this report enables planners to make more informed decisions on whether a proactive adaptation response is justified in any particular project, in anticipation of climate change.

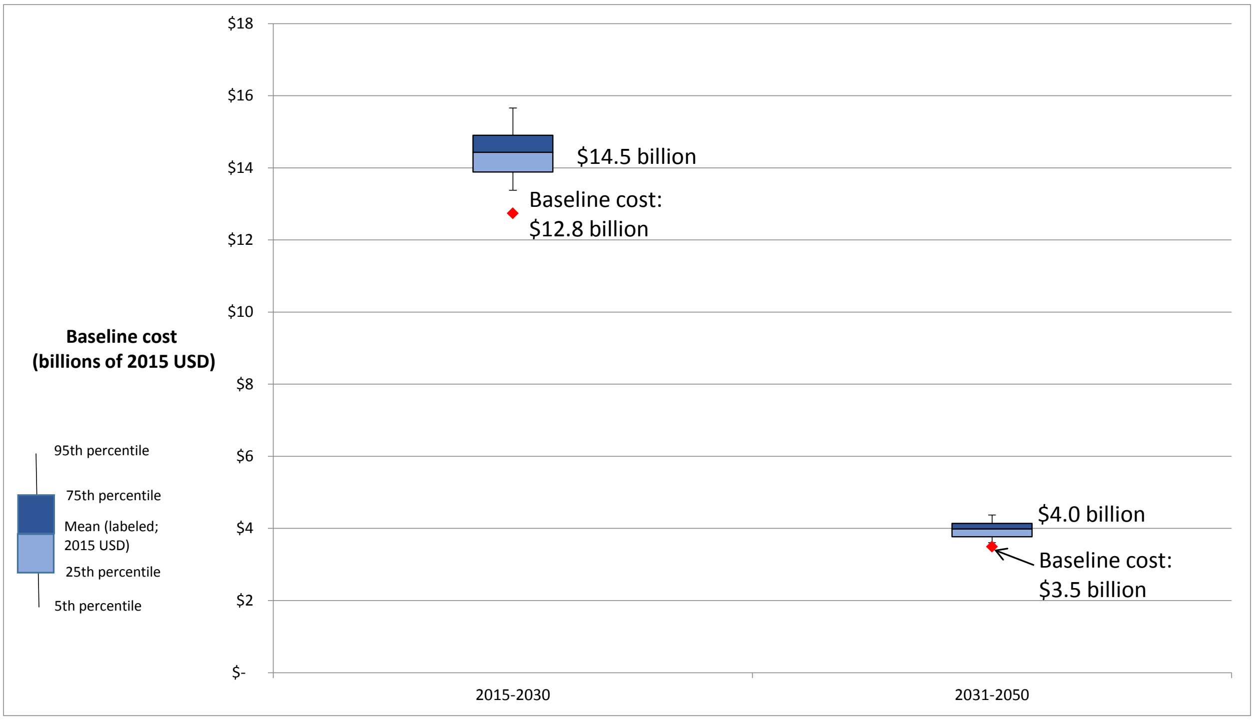
How Much Will It Cost to Proactively Adapt the PIDA Investments?

The savings in lifetime asset cost and the avoided disruption time represent deferred benefits, but the costs of adaptation must be financed upfront. Analysis of the incremental investment required to enhance the climate resilience of the PIDA roads investments suggests that only a relatively small additional investment is needed to achieve this goal (Figure O.11). This finding applies only to a portion of the total PIDA+ network – that is, only the PIDA component, which is 100 percent newly constructed paved roads. These relatively small incremental costs would not necessarily apply to unpaved roads or most existing paved roads.

Most of the PIDA investments analyzed here will occur by 2030 (many have projected construction completion dates in 2030), and the total construction cost without adaptation is estimated at $12.8 billion. Excluding climate outliers (the top and bottom 5%), construction costs with adaptation ranges between $13.3 and $15.7 billion (a 3% to 23% increase). The baseline costs in the later period are lower, $3.5 billion, but the range of incremental cost for adaptation is roughly proportional to the adaptation cost incurred in the prior period.

Figure O.11. Construction costs of proactive adaptation for the PIDA roads relative to baseline

(Undiscounted total costs by period)



Note: Chart provides a summary of the overall construction costs of proactive action for PIDA roads across all future climates, as compared to baseline (no adaptation) costs estimated in PIDA documents. Box indicates costs of 25th to the 75th percentiles over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentiles Number next to box is mean value. Left bar is for PIDA PAP projects scheduled to begin construction in the 2015 to 2030 period; right bar is for projects scheduled to begin construction in the 2031 to 2050 period.

Results that are disaggregated by stressor (see Chapter 6 of the main report) show that the incremental cost to achieve resilience to the temperature stressor is much lower, between 1% and 3% of the baseline cost, for the five largest cost PIDA corridors (that is, PIDA projects) considered in the study, but costs to achieve resilience to the precipitation and flooding stressors tend to be higher. These results suggest that a targeted approach to resilience, both over stressors and across PIDA corridors, is appropriate.

An Agenda for Action for Climate Resilience of Africa's Roads and Bridges

This book provides a framework for assessing climate related risks to road investments in Africa. A key finding is that, in the period from the present to 2050, climate change could cause:

- **Direct damages:** tens of billions of dollars in damages to roads, which will require additional maintenance to preserve basic serviceability; preliminary estimation of damage to bridges suggests costs may be even higher (in the order of $30 billion, mean estimate).
- **Substantial system disruption:** apart from increasing maintenance costs, climate changes will cause the disruption of road links, interrupting the flow of goods and people, to the tune of 100 million days of disrupted road links by 2050, all of which has a substantial economic cost.

A second important finding of this study is the fact that engineering solutions can be effective in addressing some impacts of climate change, through proactive action, depending on the context. These solutions can provide long-term resilience, with less disruption and lower lifetime maintenance costs, in exchange for a higher up-front investment. In particular, this study finds that that investing proactively in pavement improvements to resist increased temperature is economically justified under most climate projections *even without taking into account disruption costs*.

On the other hand, the study finds that in many situations proactive adaptation to precipitation and flooding events is unlikely to be justified solely on the grounds of reducing the lifetime expenditure on road assets (the sum total of construction, maintenance and rehabilitation costs).

Adaptation however, could be justified when the direct and indirect benefits of avoided disruptions are factored into the analysis. The merits of investing in adaptation, however, will have to be assessed on a case by case basis, considering the likely volume of the traffic disrupted in the absence of adaptation; and the opportunity cost of the time that would be lost because of disruption. The type of case-by-case analysis does not need to be complex – as outlined in Box O.3 below, the steps can be relatively simple.

Nonetheless, it is important to avoid blanket prescriptions for infrastructure adaptations, opting instead for specific interventions in resilient design according to the circumstances of each project and individual economic analyses, and explicitly acknowledges the need to balance the need for adaptation and resilience with the tendency to over-design.

Box O.3. What Does It Take to Integrate Climate Change into Road Project Design?

Implementing the approach proposed in this study is relatively straightforward. The modeling components required for a project- or country-level climate change adaptation analysis for roads consist of the following:

- A set of downscaled climate projections for the project's or country's relevant geographic region.

- Information on the baseline capital and maintenance costs for constructing roads to alternative design specifications.
- A simple project design and cost model that can reproduce existing cost estimates from pre-feasibility studies, and can estimate how costs would vary with alternative design specifications that incorporate adaptation. If the complexity of the design precludes the development of a simple design and cost model, several estimates of alternative designs could be developed using more detailed tools.

The requisite sets of climate projections have become increasingly available, including those used for this report. These data sets will soon be made available Africa-wide through a central data repository (http://sdwebx.worldbank.org/climateportal/). Appropriate road analysis tools have also become increasingly available and can be calibrated using the same data utilized in feasibility studies. Finally, this study has developed a relatively transparent set of adaptation measures for each climate stressor, that can be used as a template for a wide range of applications.

Assessing adaptation options when the financial and disruption implications are nuanced (for example, for unpaved roads, and for responses to changes in precipitation and flooding), will require assistance to local and national transportation planners. The need for this assistance is one reason the World Bank is pursuing support for an Africa Climate Resilient Investment Facility (Afri-Res) as described in Box O.4 below.

Box O.4. Africa Climate Resilient Investment Facility (AFRI-RES)

To develop Africa's capacity to systematically integrate climate change considerations into the planning and design of long-lived investments, the World Bank, the Africa Union Commission and the United Nation Economic Commission for Africa (UNECA) have teamed up to develop the Africa Climate Resilient Investment Facility (Afri-Res). The facility will develop guidelines, provide training, deliver on-demand advisory services, make data and knowledge tools more easily accessible, and ultimately help attract funding from sources of development and climate finance.

The facility is one of the components of the World Bank Group's $16 billion Africa Climate Business Plan that was presented at COP21 in Paris in November 2105:

(http://documents.worldbank.org/curated/en/2015/11/25481350/accelerating-climate-resilient-low-carbon-development-africa-climate-business-plan).

Seed funding in the amount of 4 Million Euros has been pledged by the Nordic Development Fund (NDF), and discussions are underway with other development partners to mobilize additional resources.

These findings provide a basis for making following recommendations for the consideration of regional or sub-regional organizations (e.g., Africa Union Commission, Regional Economic Communities), road sector ministries and agencies at the country level, along with ministries of finances and planning; and international development partners, as described in the table below:

Recommendations	Entities Encouraged to Act on the Recommendation	Supporting Information from the Study
PIDA road transport projects could include in the design stage provisions to include high temperature seals in the construction of the roads	The Africa Union Commission or NEPAD could develop overall guidelines/ recommendations on the PIDA program, to be implemented by country level project developers	Chapter 6 conclusions related to paved PIDA road adaptation
Evaluate the optimal timing for precipitation and flooding adaptations actions for the PIDA projects.	The Africa Union Commission or NEPAD could develop overall guidelines/ recommendations on the PIDA program, to be implemented by country level project developers	Chapter 6 conclusions related to paved PIDA road adaptation
Require that project developers carry out climate risk evaluations for road and bridge projects. Use the detailed data from this study, and then work collaboratively with the proposed AFRI-RES facility, when fully functional (see Box O.4) for initial screening. Follow-up using individual scenarios for climate projections, and more detailed engineering for project level analyses.	Donors and financiers of Sub-Saharan African road and bridge construction	Chapter 5 for risks and costs of inaction; Chapter 4 for details of the available daily downscaled climate projections.
Conduct financial analyses that examine the tradeoff between higher upfront costs and lower maintenance costs.	Ministries of Finance could provide overall guidelines to be implemented by Ministries of Transport/ Road Agencies	Chapter 6 for country level information comparing higher upfront costs (proactive adaptation) versus higher maintenance costs (reactive response to climate)
Identify critical road networks in existing system, including bridges, and establish priority status for climate risk and financial analyses for those infrastructure segments.	National Ministries of Transport/ Road Agencies	

Recommendations	Entities Encouraged to Act on the Recommendation	Supporting Information from the Study
Identify existing weather sensitive hotspots in the transport system – roads and bridges – and look across climate forecasts to identify trends of concern in temperature, precipitation, flooding, and river runoff scour or overtopping. Update construction norms to account for these factors. Mainstream vulnerability assessment into a range of road infrastructure project types. This could be done in a stepwise approach, extending the work from assessment, to design improvements, to adjustments in national construction standards as the case may warrant. Using multiple climate futures and a systematic approach to assessing additional maintenance and repair costs, as in this study, represents a rigorous approach to the needed vulnerability studies. The analysis of climate vulnerability should in particular focus on critical road segments including in particular bridge crossings. Assess the benefits of adaptation taking into account traffic volumes, and the opportunity cost of time lost because of road disruption. The merits of investing in adaptation will have to be assessed on a case by case basis, considering the likely volume of the traffic disrupted in the absence of adaptation; and a plausible range of unit values of the opportunity cost of the time that would be lost because of disruption. Integrate an assessment of how network redundancy, of the lack thereof, will affect priorities for resilience investments	National Ministries of Transport/ Road agencies	Chapter 5 information on risk of inaction by country; see Chapter 4 for description of available climate scenario information (detailed files available on project web site)
Learn basic techniques of climate risk assessment, and identify options in design, materials, and construction	Construction firms and suppliers, project engineers	Chapter 2 for climate risk assessment methodology and lists of categories of proactive

Recommendations	Entities Encouraged to Act on the Recommendation	Supporting Information from the Study
methods to improve resilience at lowest cost. Include as standard practice in all procurement responses costing of options to improve climate resilience, for consideration by project development clients.		adaptation engineering options to implement for individual projects.
Understand potential climate risks and identify alternative routes for freight transport across high climatic risk areas. Build capacity for understanding forecasts of damaging weather events.	Freight companies and their customers	Chapters 4 and 5 provide an initial identification of important climate risks to road and bridge infrastructure.

CHAPTER 1

Improving Africa’s Road Infrastructure to Sustainably Enhance Development

Raffaello Cervigni, Andrew Losos, and James E. Neumann

1.1 Understanding the Role of Road Infrastructure in Africa’s Development

Economic growth is highly dependent on the quality, quantity, and accessibility of a country’s infrastructure services. In sub-Saharan Africa (SSA), inadequate road infrastructure is increasingly seen as an obstacle to achieving poverty reduction and economic development goals. Lack of connectivity in rural areas, in particular, hampers progress toward improving SSA’s agriculture sector and rural economy, both of which are key to reducing poverty and promoting economic growth. In addition, transport costs in Africa are among the highest in the world, which increases the cost of trade and makes products uncompetitive on international markets (Teravaninthorn and Raballand, 2009). Recent studies have shown that expanding the road system and increasing the share of paved roads would yield high returns by lowering transport costs and expanding markets (World Bank, 2010a).

The Africa Infrastructure Country Diagnostic (AICD) was an unprecedented knowledge program prompted by the recognition that SSA’s weak infrastructure base is a crucial impediment to realizing the region’s full economic potential. AICD’s flagship report (World Bank, 2010b) contains detailed technical and economic data on network service infrastructures (including road transport) in 24 African countries, accounting for 85 percent of the SSA population. According to the report, although African governments have made progress in addressing the low density and poor condition of their road networks, there is still a great deal of work to be done. For example, only one-third of rural inhabitants live within two kilometers of an all-season road – the lowest accessibility in the developing world (World Bank, 2010b).

The AICD report also supports a widely accepted reality of the African road network – that maintenance is already underfunded. For example, modeling of optimal maintenance costs indicates that about 25% of countries are not spending enough on road maintenance to cover routine maintenance activity. Most countries spend around 2% of GDP on roads, and in general spend much more on capital investments than maintenance; lack of maintenance deteriorates overall quality of road networks and increases the amount that must be spent on rehabilitation, which usually cannot be adequately covered. Some countries are better prepared than others to bear the costs of maintaining their road networks. For example, establishment of road funds and fuel levies is correlated with a more even split (roughly 50/50) between capital and maintenance spending, while other countries spend 2/3 on capital, leaving maintenance seriously underfunded

(World Bank, 2010b). The main implication of this in responding to the new challenge of climate change is that few African countries are in a position to face the effects of climate change on roads, when higher temperatures, more variable precipitation, and more frequent flooding will increase the need for road maintenance. Clearly, the need for climate resilience planning starts with fully funding road maintenance needs before climatic events exacerbate the current situation.

Box 1.1 provides a summary of the AICD report's key findings related to financing gaps. Notably, an estimated $93 billion per year for the next decade will need to be invested if Africa is to fill the infrastructure gap.[2]

Box 1.1. AICD Key Findings

The AICD flagship report (World Bank, 2010b) describes the state of Africa's physical infrastructure and estimates the costs associated with its improvement. The study provides a baseline against which future improvements in infrastructure services can be measured, as well as a solid empirical foundation for prioritizing investments and designing policy reforms in the infrastructure sectors in Africa. AICD establishes both an overall economic rationale for this study, and the need to provide new insights on how best to design Africa's path to closing the infrastructure gap in the uncertain climate of the future. The report provides 10 key findings concerning the priorities of infrastructure investment in SSA. The findings most relevant for the roads sector are summarized below:

- *Finding 1:* Infrastructure Contributed over Half of Africa's Improved Growth Performance – the key implication being that infrastructure is critically important to Africa's development, now and in the future.
- *Finding 2:* Africa's Infrastructure Lags Well behind that of Other Developing Countries – re-establishing the importance of aggressive infrastructure investment plans to help close the gap, particularly for paved roads, telephone main lines, and power generation.
- *Finding 3:* Africa's Difficult Economic Geography Presents a Challenge for Infrastructure Development – Africa has low intraregional connectivity, and the intraregional road network is characterized by major discontinuities. Improving access is made difficult by the low overall population density, among other factors.
- *Finding 4:* Africa's Infrastructure Services are Twice as Expensive as Elsewhere – Road freight tariffs in Africa are high, but this has more to do with exceptionally high profit margins than high costs (the costs for trucking operators are not much higher than elsewhere).
- *Finding 6:* Africa's Infrastructure Spending Needs at $93 Billion a Year Are More than Double Previous Estimates by the Commission for Africa – providing a fresh look at infrastructure needs clarifies the magnitude and urgency of infrastructure investments.
- *Finding 7:* The Infrastructure Challenge Varies Greatly by Country Type – acknowledging the need to take a geographically oriented "bottom-up" approach; coincidentally, it is also necessary to evaluate climate risks and adaptation opportunities that also manifest differentially across space.

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[2] The gap is defined as the distance between the current quantity and quality of infrastructure, and a set of sector-specific targets that, if achieved, would enable Africa to catch up with the rest of the developing world. These include, for example, the Millennium Development Goal targets for water; connectivity between all key economic nodes; supply-demand balance for power, etc.

- *Finding 10:* Africa's Institutional, Regulatory, and Administrative Reform Process Is Only Halfway Along – countries have made progress, but much work remains to be done, particularly in the transport sector.

1.2 The Program for Infrastructure Development in Africa

Africa has experienced significant economic growth over the past decade of 5% per year, but in order to sustain this growth, investment in infrastructure is necessary. The Program for Infrastructure Development in Africa (PIDA) is a major effort, undertaken under the auspices of the Africa Union Commission, to improve and expand key infrastructure across the continent. Endorsed in 2012 by the continent's national leaders, PIDA lays out an ambitious long-term plan for closing Africa's infrastructure gap and enabling per-capita income to rise above US$10,000 in all countries of the continent by 2040. To enable such a substantial increase in the standard of living to happen, a rapid and major upgrade of the region's stock of infrastructure is required. The total estimated cost of implementing all of the projects identified in PIDA by 2040 is US$360 billion.

The PIDA Priority Action Plan (PAP) is a subset of 51 priority infrastructure programs in the energy, water, transport, and information and communications technology (ICT) sectors that are designed to address sector-specific priority infrastructure deficits. The PAP requires an investment of an estimated US$68 billion to be realized by 2020. Energy needs account for the largest portion of the needed investment (60%), followed by transport (37%).

For this report, we rely on the results of the PIDA process to characterize the extent of major trans-boundary road infrastructure development anticipated through mid-century. The transport component of PIDA focuses on connectivity improvements, corridor modernization, port and railway modernization, and air transport modernization. The benefits of such improvements in SSA's road infrastructure alone, however, could be substantial. Fostering better transport between inland areas and the coast could boost exports, while improving connectivity within Africa could substantially improve intra-African trade. In addition, PIDA stresses trans-boundary regional integration, with specific reference to building a road network that will facilitate the opening of trade corridors, and provide efficiency gains and advances in regional integration that will create a shift from overseas trade to trade between countries and within and across regions.

In addition to the PIDA projects, there are a number of country-level road projects that are included in master plans and regional plans. Collectively valued at approximately US$45 billion through 2030, the country-level infrastructure investment is significant. These high-priority projects are considered in this study along with the PIDA PAP projects; the full suite of projects examined in this study is referred to as the "PIDA+" investment scenario.

1.3 Vulnerability of Roads to Climate Change

Much of the investment in SSA's infrastructure will support the construction of long-lived infrastructure (e.g., dams, roads, power stations, etc.) that needs to be capable of delivering services under both current and future climates. Temperatures are projected to rise across the continent and very high temperatures can result in the softening and rutting of asphalt roads. Some parts of Africa will see an increase in precipitation, which can lead to reduced load-carrying capacity and lifespan of roads. Many parts of Africa will face more intense precipitation, which can increase flooding frequencies. These floods can overrun and erode roads, particularly unpaved roads (e.g., Niang et al., 2014).

Some recent literature also provides insights about the potential economy-wide implications of severe climate events that affect the road network, particularly implications for food security. For example, in Burkina Faso, maize price volatility is found to be greatest in remote (poorly connected) markets (Ndiaye, Maitre d'Hôtel, and Le Cotty, 2015). As climate change further reduces connectivity, this raises the potential for food shortages and economic shocks to vulnerable areas. In addition, after Tropical Storm Agatha struck Guatemala in 2010, per capita consumption fell 13 percent, raising poverty by 18 percent; in particular, food expenditures fell 10 percent, accounting for 40 percent of the total consumption drop (Baez et al., 2014). This stemmed from a major loss in food infrastructure and transport, resulting in a 17 percent increase in food prices 10 months after the storm. In this instance, the storm caused a logistical problem rather than a decline in domestic production, since it occurred in the middle of the first planting season, at a benign time with respect to local agricultural cycles.

While there is widespread scientific consensus that the climate of the next few decades will be significantly different from today's climate, and the current trajectory of increasing temperatures is likely to accelerate over the next several decades, there remains large uncertainty about whether dryer or wetter conditions will prevail in SSA's various sub-regions and countries. The challenge, therefore, is in understanding the range of climate impacts that may occur, and making decisions about infrastructure investments that minimize risks and maximize opportunities.

1.4 Integrating Climate Change in Road Investment Planning

The goal of this study is to promote climate-smart investment in road infrastructure by evaluating planned investments in light of future climate change. Specifically, the study evaluates the potential for adapting roads to reduce potential damages that result from inaction. The approach used in this study parallels the effort documented in Cervigni et al. (2015), which examined adaptation options for the power, irrigation, and water supply sectors.

1.4.1 Scope of the study

This study evaluates climate change impacts and adaptation options for planned road investments in SSA through 2030, including 11 transport projects from the PIDA PAP, comprising 111 individual road segment investments and 261 country-level road segment projects. The full suite of infrastructure investments analyzed in the study is referred to as the "PIDA+" network and is detailed in Appendix A.

1.4.2 Value added from the study

This is the first study to comprehensively examine climate change impacts and adaptation for the roads sector of SSA. Subject to the methodological limitations discussed in chapter 2, specific elements of novelty and value added of the study include:

- A comprehensive climate vulnerability assessment of all primary and secondary roads in SSA, including impacts from higher temperatures, changes in precipitation, and increases in flooding.
- An analysis of the costs and benefits of adaptation of PIDA+ roads. The adaptations include changing materials to better withstand heat, improving drainage or thickening roads to offset increased precipitation, and increasing culvert size to reduce flood risks. The benefits include reduction in maintenance costs (which would otherwise increase with climate change), and reduction in road disruption times.
- A clear set of recommendations for project financiers, country-level Ministries of Transport and Finance, and firms engaged in road design, construction, and maintenance, to address the effects of climate change on Africa's road and bridge network, acknowledging the deep uncertainty on how climate change will manifest itself in Sub-Saharan Africa.

1.4.3 Book structure

The remainder of the book is organized as follows:

- Chapter 2 describes the methods used in the study;
- Chapter 3 describes the reference investment scenario (i.e., the PIDA+ network);
- Chapter 4 presents the climate change projections that are used in the study to estimate the vulnerability of the PIDA+ network and assess the costs and benefits of adaptation;
- Chapter 5 presents the results of the reactive response analysis for roads and bridges, which assumes no proactive steps are taken to anticipate the impacts of climate change.
- Chapter 6 describes the results of the analysis of proactive adaptation and the financial costs compared to reactive response strategies for roads and bridges, as well as analysis of the effect of proactive adaptation on disruption times for roads. The scenario-based analysis provides conclusions about whether it is better to prepare for climate change (proactive adaptation) or address climate change impacts as they happen (reactive response).
- Chapter 7 provides policy recommendations with a particular focus on key actionable insights from the study, and specific recommendations for project financiers, national governments, and firms engaged in road design, construction, and maintenance.

- In addition, Appendix A presents the PIDA+ network by country; Appendix B presents the PIDA PAP projects included in the study; Appendix C presents the country-level projects included in the study; and Appendix D presents the AICD dataset sources by country.

CHAPTER 2

Methodology

Kenneth M. Strzepek, James E. Neumann, Paul Chinowsky, and Raffaello Cervigni

2.1 Framework

This study assesses the vulnerability to climate change of planned road investments in SSA in light of future climate change, and evaluates adaptation options that could be taken to minimize damages. The approach includes the development of three distinct scenarios for roads investment in SSA (Table 2.1):

1. **Reference scenario**: the reference scenario represents the planned roads investment in SSA through 2030. It includes projects from the PIDA PAP as well as country-level road projects; these two sets of projects are referred to as the "PIDA+" investment scenario (described in detail in Chapter 3). No climate impacts or adaptations are modeled in this scenario.
2. **Climate change, reactive response**: in this scenario, the full range of climate futures is estimated, and their impacts quantified as the costs of reactively responding to climate stressors after they have occurred, mainly through increased maintenance activity. This scenario illustrates the vulnerability of the PIDA+ network to future climate impacts.
3. **Climate change, proactive adaptation**: in this scenario, anticipatory measures are taken to mitigate the effects of climate change and take advantage of any opportunities. Climate change impacts are quantified in terms of up-front costs of design changes, reductions in subsequent needs for repeated repairs and maintenance, and reductions in road disruption.

Comparison of the road assets' lifetime costs (i.e., construction, maintenance, rehabilitation, repairs) under the reactive and proactive scenarios provides an assessment of the financial case for adaptation. In some cases, the financial case (i.e. net lifetime savings under adaptation) is sufficient to justify investments in proactive adaptation measures. However, although the financial perspective is informative, it does not account for the potential for climate change to result in disruptions in the use of the road network. As a result, the study separately evaluates the impacts of climate change on disruption time and evaluates the benefits of adaptation in reducing these effects. Importantly, although the tools used in the analysis allow disruption to be quantified, it is not currently possible to reliably monetize disruption. The study therefore considers both the financial benefits and the disruption benefits of adaptation in a decision-making context, called a "break-even analysis," which identifies climatic conditions and road types for which the benefit of reduced disruption time are likely to justify adaptation when the financial analysis alone of lifetime asset costs cannot.

Table 2.1. Framework for evaluating the impacts of climate change and adaptations in the road sector

Scenario	Investment strategy	Climate change assumptions	Adaptation strategy	Cost of climate change impacts
Reference scenario	PIDA+	No climate change (historical climate)	None	Zero (baseline maintenance and rehabilitation costs)
Climate change, reactive response	PIDA+	Full range of climate futures	None	For each climate future, climate impacts on roads resulting in increased maintenance costs (note that only historical climate rehabilitation is conducted)
Climate change, proactive adaptation	PIDA+ reflecting climate change (adaptation action varies across climate scenarios)	Full range of climate futures	Adjust PIDA+ in order to respond to anticipated changes in climate stressors (for each climate scenario considered)	Zero cost of climate change, but each scenario has higher construction costs

The analysis assumes throughout that the timing, management and financing of periodic maintenance is adequate and in accordance with established engineering standards. While this may seem at odds with the reality of most of the region (where maintenance is substantially underfunded), the assumption is justified because it allows to standardize the modeling across countries, and to focus on the incremental maintenance cost caused by climate change. However, this does not imply that closing the current financing gap for maintenance is not important. To the contrary, mobilizing additional resources for maintenance will be a key, no-regret first step in reducing countries' vulnerability to climate change. The reason is that if countries continue to under-fund maintenance, they will be even more exposed to climate change than the present analysis concludes.

The study uses the Infrastructure Planning Support System (IPSS) – described in Box 2.1 – to model future climate impacts and quantify the costs and benefits associated with each scenario.

Box 2.1. The Infrastructure Planning Support System (IPSS)

The *Infrastructure Planning Support System* (IPSS) is a software model that integrates expertise from researchers in civil and environmental engineering, water resources, architecture, international development, and economics. It is a quantitative, engineering-based analysis tool to understand the impacts of climate change on current and future roads, bridges, and other infrastructure.

IPSS models existing vulnerabilities to future weather, and specific adaptation options to respond to changed climate. Elements of analysis include: changes in temperature (maximum temperatures and freeze-thaw), changes in precipitation (drainage, flooding, and degradation rates), and changes in flood return times. The model is spatially disaggregated, usually at the resolution of climate forecast grid cells, and the basic structure incorporates climate inputs, baseline infrastructure cost and management information, an extensive database of stressor-response functions, and flexible post-processing and results aggregation options.

Costs are assessed based on two approaches. First, a reactive “no adaptation” approach which analyzes a changing future climate on existing road design standards. This is compared to a proactive “adaptation” approach which reduces future risk and damages by changing design standards at upgrades or re-construction. Both maintenance and new construction/re-construction costs are provided. The model incorporates flexibility and customized analysis for application to multiple contexts, including baseline cost information, degradation rates, historic flood data, and specific adaptation budgets. Stressor-response relationships are based on based on a number of sources including engineering research, materials studies, and published US Dept. of Transportation and Federal Highway Administration.

2.2 Development of the PIDA+ Road Inventory

The road inventory used in this study (referred to as the “PIDA+” network) includes both existing and new roads. The new roads include PIDA PAP projects and country-level road projects. The inventory was compiled from four main sources:

1. Country-sourced datasets (e.g., data from stakeholders, government websites, and transport master plans);
2. AICD road inventory datasets;
3. Published road inventory datasets (e.g., International Road Federation, 2012); and
4. The DeLorme 2012 Digital Atlas of the Earth (hereafter, DAE 2012).

In compiling the PIDA+ network, the team endeavored to use country-sourced data wherever possible, because it is considered to be the most reliable. Country-sourced data were used for a total of 22 out of the 49 countries included in the study (approximately 45%). The gaps in these data were filled using a combination of the remaining three sources. The AICD dataset provided the lengths of primary roads and road functional classes and surface types. The DAE 2012 dataset provided total road lengths by country, and these data were cross-checked against the International Road Federation data. In some cases, road segments could not be included in the network due to insufficient information. Chapter 3 provides a detailed discussion of each source, including strengths and limitations.

After the PIDA+ network was compiled in GIS, the data were overlaid with a half-degree grid cell network (the geographic scale at which we project climate change – approximately 50km by 50 km per cell) for further processing. The final dataset includes approximately 2.8 million km of roads, compared to the 371,000 km included in the AICD dataset. Appendix A presents a table with the complete PIDA+ inventory organized by country, functional class (primary, secondary, tertiary, and unknown/other), and surface type (paved, unpaved, and unknown).

2.3 Analysis of Reactive Response (Vulnerability Analysis)

This analysis examines the impacts of climate change assuming that no proactive, anticipatory measures are taken to protect the PIDA+ network against the impacts of climate change. Impacts are quantified as the increased maintenance costs for the roadways that are incurred as a result of climate stressors, including changes in precipitation, temperature, and flooding (see Chapter 4 for more details on the climate change projections used in the study). The study models adaptation responses based on stressor-response rules. Table 2.2 presents the adaptation measures associated with each climate stressor, including a set of reactive measures that do not require major capital or rehabilitation expense, and proactive measures that involve an upfront capital cost with the benefit of much reduced maintenance expense. The costs associated with these adaptations are based on figures provided by roadway design and management practitioners and reflect local construction and maintenance costs. Costs of adaptations on a per kilometer basis are compiled for each grid cell for each climate scenario.

Table 2.2. Reactive road measures and proactive adaptations included in the study

Road type	Climate stressor	Effect	Reactive measures	Proactive adaptation measure
Paved roads	Temperature	Increased temperature leads to accelerated aging of binder	Additional sealing required on a more frequent basis due to faster degradation of road quality	Construct dense seals (e.g., Sand Seal, Otta Seal, Cape Seal). Typically, Cape Seals are used on heavily trafficked roads.
		Increased temperature leads to rutting (of asphalt), and bleeding and flushing (of seals)	Additional patching required each year to fill cracks resulting from pavement weakening	Adoption of base bitumen binders with higher softening points (including polymer modification) for surface seals and asphalt.
	Precipitation	Increased precipitation leads to increased average moisture content in subgrade layers and reduced load-carrying capacity	Increase patching to address cracking from surface failure	Add wider paved shoulders to improve surface drainage.
			Fill subbase where erosion has occurred due to water	Increase base strength (thickness and/or quality) to

Road type	Climate stressor	Effect	Reactive measures	Proactive adaptation measure
			infiltration. Follow with additional patching	increase protection of subgrade layers.
	Flooding (in excess of design flood)	Washaways and overtopping of road	Repair of localized washouts including cleaning culverts, replacing culverts, replacing subbase, and replacing asphalt surface	Increase flood design return period by increasing the size of culverts (in most cases will require raising the road to allow larger culvert to fit).
Unpaved roads	Temperature	Not applicable		
	Precipitation	Increased precipitation leads to increased average moisture content in subgrade layers, and reduced load-carrying capacity	Regrade road localized to precipitation, fill subbase and reapply gravel top layer.	Increase gravel wearing course thickness to increase cover and protect subgrade layers. Upgrade road to paved.
	Flooding (in excess of design flood)	Washaways and overtopping of road	Same as for paved except application of gravel top layer rather than application of asphalt layer.	Increase flood design return period by increasing the size of culverts (in most cases will require raising the road to allow the culvert to fit underneath).

As shown in Table 2.2, paved and unpaved roads have distinct proactive adaptation approaches that reflect differences in construction and vulnerabilities. For paved roads, adaptations to temperature focus on changing the design mix as well as the design of the seals to protect the road from further damage. For precipitation, adaptations include both increasing the road thickness and expanding the width of the road to allow for improved drainage of surface water away from the road. Flooding adaptations focus on culvert design changes.

Temperature does not affect unpaved roads, so adaptation to this stressor is not needed. However, higher precipitation requires increases in base layer thickness of unpaved roads to enable greater carrying capacity and drainage. In addition, there is an option to upgrade to a paved road where appropriate. The design of culverts is changed to adapt to increased flooding.

2.4 Analysis of Proactive Adaptation

Under the second scenario, IPSS estimates the changes in costs assuming adaptations are made in response to each climate change scenario. For example, if a gravel road is projected to be washed out under a climate change scenario, the road bed may be thickened or paved road as the road is being built in anticipation of the climate events. The specific proactive actions assessed are described in Table 2.2.

The costs are calculated in present value 2015 US$ with a 6% discount rate, with a sensitivity analysis using a 3% discount rate. Costs are calculated on a total and per-kilometer basis and compiled for ½ degree by ½ degree grid cells (about 50 km x 50 km), consistent with the resolution of the climate projections (see Chapter 4).

Adaptation of the road and bridge system to climate change should ideally reflect the age and construction vintage of the roads and bridges analyzed, with specific estimates of when rehabilitation and replacement cycles occur. For the PIDA component of the road inventory, the expected build date provides information to trigger the start of a maintenance cycle, followed by a rehabilitation action when the useful life of the road is effectively exhausted. The rehabilitation action is less costly than a full new corridor build, but more costly than periodic maintenance. For existing roads, the road vintage is unknown, so IPSS assigns a vintage assuming a uniform vintage distribution across the road type lifespan (e.g., 20 years) within each ½ degree by ½ degree climate grid cell, and a similar maintenance and rehabilitation cycled is triggered.[3] The approach therefore follows a conventional rehabilitation cycle, albeit optimized compared to likely current maintenance practice in Africa.

In the case where a road is completed after 2030, the impact of climate change on the road is modeled and accounted for only through the study limit of 2050. Thus, for roads constructed in 2045, climate impacts are considered only through 2050. In the proactive adaptation scenario, the full costs of adaptation are accounted for, but the benefits (i.e., reduced maintenance costs) are only included through 2050. As a result, the analysis may estimate relatively higher costs associated with a proactive approach for that subset of roads.

2.5 Disruption Analysis

The disruption analysis evaluates the time that each road in the PIDA+ network is estimated to be "out of service" as a result of climate change. It relies on historical estimates of the time required to conduct road maintenance and rehabilitation, derived from the World Bank ROCKS Worldwide Database. The ROCKS database was selected due to its broad representation of relevant road maintenance and construction project data, collected by the World Bank for 65 developing countries.

The analysis estimates disruption time for the PIDA+ network in terms of the number of days per kilometer of disruption that will occur for each maintenance task. The duration of each disruption event is determined based on both the amount of time required for the maintenance and rehabilitation activities (derived from the ROCKS database) and the severity of the event. For

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[3] The assignment of a uniform distribution of capital stock vintage to existing roads is a compromise that reflects data limitations.

example, a 100-year flooding event would result in a longer period of disruption compared to a 10-year flooding event because it would likely result in a greater extent of damage.

Table 2.3 presents disruption estimates for specific events. If the events in the reactive and proactive components of the table were to occur with the same frequency, then it would be reasonable to assume that proactive action leads to more disruption, because the values in the right column for disruption days are generally higher for proactive compared to reactive activities. It is important to keep in mind, however, that proactive activities are designed for application only at the beginning of a rehabilitation cycle, and greatly reduce if not eliminate the need for reactive responses during the cycle. As a result, when this information is combined in the IPSS model with the number of reactive actions that climate change, it is generally (though not always) true that proactive action reduces disruption days.

Table 2.3. Disruption for each maintenance type

Reactive Response			
Paved	Maintenance Type	Construction Crew Production Rates (km/month)	Estimated Disruption (days/km)
Precipitation Damage	*Pothole patching/drainage works*	11.49	1.74
Temperature Damage	*Resurfacing/reseal*	2.36	8.47
Flooding Damage	*Reconstruction bituminous*	1.19	16.87
Unpaved/Gravel			
Precipitation Damage	*Regraveling*	3.38	5.91
Flooding Damage	*Reconstruction unpaved*	1.47	13.60
Proactive Adaptation			
Paved	Adaptation Type	Construction Crew Production Rates (km/month)	Base Disruption (days/km)
Precipitation Damage	*Widen Shoulder*	3.74	5.35
Temperature Damage	*Resurface*	1.33	15.08
Flooding Damage	*Upgrade Culverts*	1.25	16.05
Unpaved/Gravel			
Precipitation Damage	*Upgrade to Paved*	1.25	16.05
Flooding Damage	*Upgrade Culverts*	1.63	12.25

The disruption rates for specific events are then multiplied by the corresponding number of kilometers of road inventory within the PIDA+ network to obtain a total disruption number. Under the proactive adaptation scenario, however, certain roads avoid the disruption impact because they were proactively maintained or rehabilitated. This scenario is described in greater detail in Chapter 6.

2.6 Breakeven Analysis

For roads, a breakeven analysis is conducted to determine whether the combined benefits of reduced maintenance costs, denominated in dollars, and reduced disruption time, denominated in days, may be sufficient to justify proactive action. Note that the level of disruption days differs for each climate scenario, just as the reactive and proactive costs differ by scenario. As a result, each climate scenario generates a different breakeven value, so a distribution of breakeven values can be provided for each road type and climate stressor, by country and climate zone.

Valuation of disruption days is highly uncertain, and likely to be very context specific, reflecting the level of traffic on the road (a scalar which could convert days of disruption due to disruption to person-days of disruption), the redundancy of the network (a scalar which would reflect opportunities to avoid disruption by re-routing), and individual value of lost time in a transport context. Literature exists on the value of time in Africa, and generic rules of thumb are often used, such as application of 50% of the daily wage to avoid lost wait time, but comprehensive wage data is missing for many parts of Sub-Saharan Africa. Amidst these substantial uncertainties and data limitations, it is nonetheless possible to estimate the value of disruption that, if applied to lost disruption days, and when combined with the net cost of proactive measures, is sufficient to justify proactive action.

For each climate scenario, including the historical scenario, the breakeven analysis starts by calculating the savings in road assets lifetime costs (in net present value terms) when adapting to climate change, compared to the reactive response of not adapting. Where the savings are positive, proactive response is already justified. Where the savings are negative, the analysis proceeds to identify the reduction in disruption days that occurs under the proactive adaptation scenario, relative to the reactive response scenario. The breakeven value is then calculated as the net financial cost of proactive action divided by the reduced disruption days. If the unit value of the time saved as a result of adaptation is equal to, or higher than, the breakeven value, then adaptation will be justified.

The analysis is conducted independently for each climate scenario and stressor, at various scales of spatial aggregation and road categories (PIDA and PIDA+), and is then presented as a distribution of breakeven values over the range of climate change scenarios. This makes it possible to make decisions in spite of uncertainty on future climate change. In particular, the maximum breakeven value corresponds to the scenario of mildest climate change, under which adaptation may be difficult to justify. If even in that case, the opportunity cost of time saved thanks to adaptation is deemed higher than the break-even value, proactive adaptation is justified, and the case for undertaking it will be even stronger in other climate scenarios. Some decision makers, however, may be comfortable knowing that in 95% or 75% of the climate scenarios, proactive action is justified.

2.7 Bridges Analysis

Recent analysis in Mozambique suggests that some of the worst effects of flooding are on the bridge component of road transport networks, rather than road surfaces and culverts. Analyzing the effect of climate change on bridges in SSA is complicated, however, by the fact that there is no inventory of bridges for this region. As a result, the study developed a synthetic inventory by intersecting the road network with water crossings in GIS. The method was calibrated using the same technique for a U.S. land area where a comprehensive bridge inventory exists, and yielded approximately 90% to 95% accuracy with some variation across regions. Google Earth inspection of a subset of the identified bridges indicates that the method slightly over-identifies bridges.

The inventory was coupled with the climate-related flood risk results generated for the road analyses, to generate a first estimate of the vulnerability of bridges to climate stress. The estimates of vulnerability are based on comparison of current to future return periods for flooding at the bridge location. Vulnerability in physical terms is measured by a bridge count using the 100-year, 75-year, and 50-year flood exposure as signature events. The estimate addresses all of SSA, with an indicator of whether the bridge supports a primary, secondary, or tertiary road, and whether the bridge supports a current or planned road corridor. As described in Wright et al. (2012), bridges are mainly vulnerable to bank erosion and scour related to flood events. In the U.S., these effects are comparable in economic terms to those on the full road network (Neumann et al., 2014). While it is not possible to develop a full economic impact estimate, owing to the lack of bridge condition data, the study provides an initial “screening level” estimate for bridges.

The analysis estimates impacts by first assuming that all current bridges are resilient to the current 50-year flood. Flood flow analyses provide an estimate of the current 50-year flood by grid cell. Then, using the climate scenarios and a simple water routing model, the study forecasts how often and by how much this threshold will be exceeded. Minor damage is assumed based on a change from 50-year design to existing 75-year flood. This level of threat triggers a cost to add diversionary measures to base of bridge piers. Major damage involves exposure to a flood consistent with the existing 100-year interval. This level of flood exposure triggers action to strengthen bridge piers and abutments with additional concrete. The costs of these events, coupled with the estimated future exposure of bridges to flood risk, provides the basis for the reactive cost estimates for bridges.

Other adaptations might be considered for project scale analyses. For example, in addition to the bridge support vulnerability assessed here, failure of a bridge as a result of climate change can occur from wash-outs of soils at abutments or piers. Also, decks and piers themselves can fail if lack of maintenance has resulted in a build-up of debris, reducing the waterway area, and/or substantially increasing the lateral forces on the structure. Lack of regular maintenance is a key issue in these failures. There is generally some factor of safety built into design of this type of infrastructure, so small increases in run-off may not be of concern, as much as a lack of maintenance. This analysis, the first of its kind at the continental scale, necessarily focuses on the potential for larger changes in runoff to substantially impact the African bridge network, but at a project scale, these other vulnerabilities could also be assessed using local hydrological data.

2.8 Limitations

In general, the purpose of this analysis was to gain an understanding of the potential magnitude of climate change impacts on Africa's road networks and, in particular, on planned investments in road improvements and network expansion. The adaptation analysis provides insight as to whether proactive adaptations (those done in anticipation of potential future changes in climate) would have benefits over the timeframe considered, through 2050, both in terms of cost savings and reduced disruption time.

The main limitation of this study is that it uses, by necessity, a "top-down" approach. For example, rather than using location-specific information for road maintenance and repair costs and practices, the study applies uniform unit costs for all of SSA. In addition, the analysis is not able to comprehensively consider specific road conditions such as topography. As a result, the results should be interpreted with caution, and should not be used for specific design purposes. Rather, the results are intended to assist in identifying broad policy insights at a continental, regional, and national scale, and in a few instances, subnational by climate zone. In particular, key limitations of the analysis include:

- *Partial treatment of uncertainty*. The IPSS model is deterministic in nature and a choice was made that the first order uncertainty to be addressed in this study, as a contribution to the understanding of the road asset management problem in Africa, was to examine uncertainty in the risk of inaction and options to increase capital investments (proactive action) across a range of climate futures. Uncertainty in other divers of lifetime road asset costs is not considered
- *Limited calibration of cost estimates.* (IPSS) is a simulation engine which can be used to compare the results of alternative simulation scenarios to identify a least-cost approach (reactive response or proactive adaptation). The study team made an effort to calibrate the maintenance cost results to those of the RONET model used in the AICD report – this effort confirmed that the input parameters used were within 25% of those used by RONET. However, there remains sparse information and significant uncertainty concerning the actual cost required to achieve road maintenance activities in Africa. As noted in Chapter 7, the World Bank continues to undertake new efforts to better characterize these costs for use in a road asset management decision support system.
- *Optimal Maintenance Assumption*. An important inherent limitation in examining the annual maintenance versus capital cost tradeoff using continental scale assumptions is the need to model a standardized, and optimized, maintenance schedule. Optimal maintenance departs from the reality in Africa of fairly systematic and widespread underinvestment in maintenance. However, with limited information on the current and future expenditure in maintenance across African countries, optimal maintenance is the

only feasible modeling option at this time. The likely impact of this assumption is that we underestimate the impacts of climate change on roads, because less than optimal maintenance would be expected to reduce the useful life of roads, and more than proportionately increase both the disruption expected from impassible roads, and the cost to bring them back to a usable state.

- *Disruption analyses*. The disruption analysis is based on limited data on the opportunity cost of usable roads that are able to carry freight and passenger traffic. The true cost of disruption should take into account road traffic volumes, the value of the trip, and options for alternative routings. For this analysis, some data are available on road volumes, but very sparse data are available on the value of the trip or options for alternative transit routes. The breakeven analysis is designed to reflect these limitations, effectively asking policy-makers to consider whether the value of keeping roads passable exceeds the one calculated as the "breakeven." A particular difficulty in the analysis is quantifying the differential value of disruption that is planned (such as that for routine maintenance or for proactive adaptation) versus unplanned disruption. Unplanned disruption requires unanticipated mobilization of a road repair crew, and in some cases can also wipe out road network redundancies (for example, an area that is flooded can disable all roads in the area, not only those planned for rehabilitation or repair). As outlined in Section 2.7, the study includes some limited sensitivity analyses to assess the impact of placing a higher value on unplanned disruptions.
- *Flooding analysis*. The flooding analysis was conducted using assumptions about how the frequency peak runoff and flooding might change. Due to data and resource limitations, it was not possible to consider topography or hydraulics in these estimates, nor was it possible to consider the specific geography of roads relative to river beds. As a result, the analysis may overestimate flooding damage in some areas where buffer zones exist in the area between rivers beds and roads, and underestimate flooding in areas of where topography or geography do not allow for flood buffer zones, thereby potentially amplifying floods. Also, flash floods, which occur on the temporal scale of hours, were not considered as the climate projections used employ a daily time scale.
- *Impacts analysis*. The estimation of climate change effects on roads was conducted using uniform cost and impact assumptions across countries and regions. Specific impacts will vary on a site-by-site basis. Such factors as topography, soils, use of specific materials, road building, and maintenance practices will likely vary considerably.
- *Adaptation analysis*. A limited set of adaptations were analyzed using uniform engineering and cost assumptions for all of SSA. Most of the adaptations characterized reflect changes in engineering. Other adaptations that might be assessed in future work include: land use planning for roads (to avoid building them in areas exposed to floods or other climate hazards); non-engineering solutions such as more frequent clearing of debris from drainage canals and culverts; and in particular, changes to maintenance funding and institutionalization that could serve to reduce climate change impacts to road function.

CHAPTER 3

Reference Investment Scenario

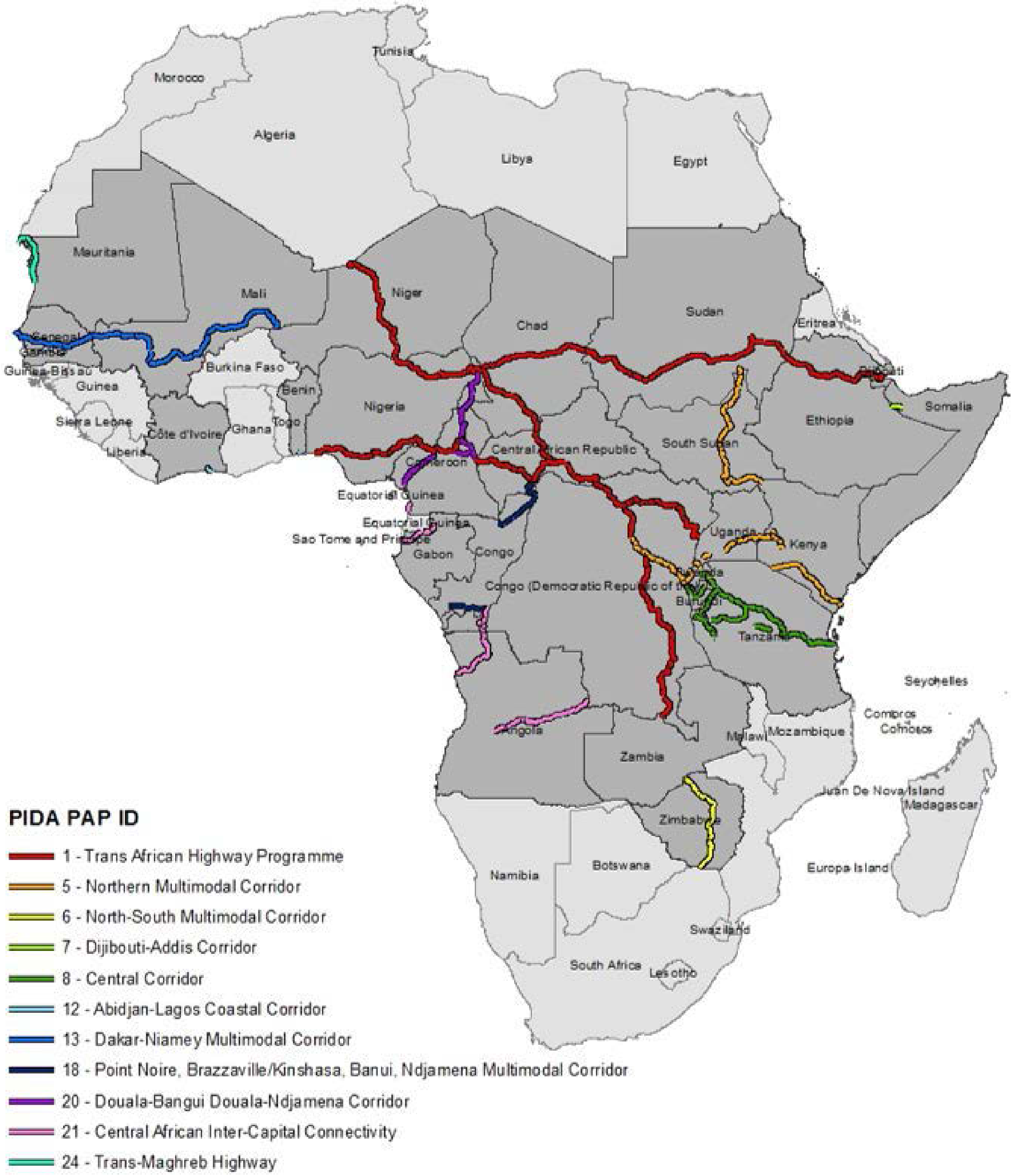
Gordon Robertson and Joel B. Smith

The reference investment scenario represents the planned roads investment in SSA through 2030. Rather than using models to generate this scenario, the study draws on data from existing infrastructure investment plans (e.g., PIDA), as well as other regional initiatives and country-level master plans. The reference scenario also includes the existing road network.

3.1 PIDA PAP Road Projects

As discussed in Chapter 1, the PIDA program is an ambitious effort to improve key infrastructure across the continent. The PIDA PAP is the agreed-upon set of priority projects and programs in the energy, information and communications technology, transport, and water sectors. This study includes 11 transport projects from the PIDA PAP, comprising 111 individual road segment investments (Figure 3.1). Appendix B provides detailed information on the projects. PIDA programs and projects that do not focus on improving connectivity through the provision, or improvement, of road infrastructure are not included in this analysis. Examples of omitted projects include improvements to border posts or airport facilities. In addition, projects without sufficient, readily-available data were not included.

Figure 3.1. PIDA Priority Action Plan (PAP) projects examined in the study



3.2 Sources of Information on Country-Level Road Projects

The PIDA+ inventory builds on the PIDA PAP inventory to incorporate 261 country-level road projects planned for SSA through 2030. Appendix C provides detailed information on the country-level projects included in the study. The inventory includes projects from country-level and regional transport plans, identified through stakeholder outreach and an extensive review of existing datasets.

3.2.1 Stakeholder Outreach

Much of the data on country-level and regional transport projects were obtained through the 2013 Sub-Saharan Africa Transport Policy Program (SSATP) Forum in Dakar. The study team consulted with stakeholders at the forum and requested data on road investment plans for use in the study. Of the 18 stakeholders who participated in the forum, nine provided project data and investment plans. To supplement these data, an extensive desktop search was undertaken to identify country-specific transport master plans and road network statistics.

In general, country-sourced datasets represent a more complete and current status quo compared to other sources. Therefore, every effort was made to get the best coverage from these sources. Country-sourced data were used for a total of 22 out of the 49 countries included in the study (approximately 45%). The country data used in this study generally include all functional road classes, including lower-order (i.e., tertiary) roads. One limitation with these data is that they are generally unavailable in spatial format.

A number of regionally coordinated investment plans were also consulted, including:

- Tripartite and Intergovernmental Authority on Development, or IGAD, Corridor Programme (TICP)
- East African Trade and Transport Facilitation Project
- AU/New Partnership for Africa's Development (NEPAD) African Action Plan: Strategic Overview and Revised Plan, 2010–2015
- The Southern African Development Community (SADC) Regional Infrastructure Development Master Plan
- African Development Bank (AfDB) Project Portfolio.

3.2.2 AICD Datasets

The PIDA+ inventory also incorporates road inventory data developed under the AICD project. The AICD spatial roads datasets contain high-quality attribute data, which allow for the characterization of functional class and surface type for country-road inventories. However, a number of limitations exist, including:

- the datasets are focused on the primary road networks in SSA and significant gaps in coverage of secondary and tertiary roads exist;

- a total of nine countries also have no coverage in the AICD road datasets;
- the AICD project collected data for the 2001–2006 period and have not been updated since; and
- the total road network coverage in these datasets represent only approximately 371,000 km of roads for the entire SSA.

Appendix D provides the AICD dataset sources by country.

3.2.3 DeLorme Dataset

Finally, the inventory draws on the DeLorme world dataset (DAE 2012). The DAE 2012 is a spatial atlas that provides an unprecedented level of detail in worldwide map data, and allowed for the identification of the following five functional road classes in SSA:

1. Primary (federal interstate highways)
2. Secondary (state or provincial highways)
3. Connector (major thoroughfares)
4. Local connector
5. Minor local road

The DAE 2012 is the most complete of the datasets, covering approximately 2.1 million km of roads in SSA (a coverage that is almost six-fold larger than that of the AICD datasets). The dataset is limited, however, because it does not contain high-quality attribute data, such as road surface type.

3.3 PIDA+ Road Network

The inventory of PIDA+ network resulting from the consolidation of the above sources contains approximately 2.8 million km of existing roadways across the 49 countries of SSA. Figure 3.2 presents a map that highlights the African countries included in the study, organized into four regions used by the United Nations Economic Commission for Africa (UNECA).[4] Of the approximately 2.8 million km of roads, approximately 35% are located in Southern Africa, 30% in Eastern Africa, 23% in Western Africa, and 12% in Central Africa (Table 3.1). The projected 2050 network contains an additional 51,795 km, the bulk of which (93%) are located in Eastern Africa. The graphs in Figure 3.3 display the breakdown of the existing network and 2050 network by region and country. In Central Africa, which contains the smallest portion of the overall PIDA+ network, most of the roadways are located in Sudan and Chad. In Eastern Africa, the bulk of the roadways are located in Kenya and Ethiopia. Ethiopia is the country where the bulk of the new projects are projected to occur by 2050. South Africa contains the largest portion of the network in Southern Africa, and in Sub-Saharan Africa overall (approximately 608,000 km). Lastly, in Western Africa, Nigeria contains the largest portion of the network. The 2050 network contains

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[4] Sudan and Mauritania are in UNECA's North Africa region but for the purposes of this study are included in Central Africa and Western Africa, respectively.

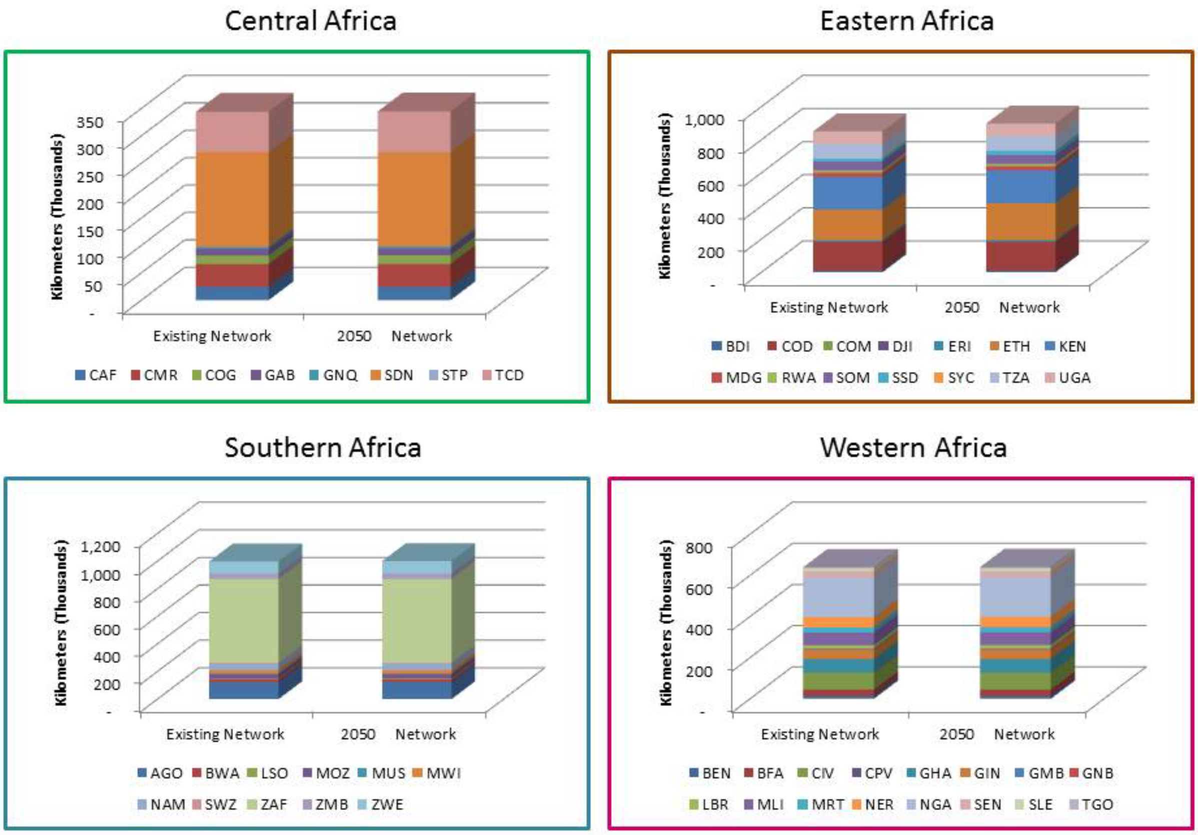
15% paved roads and 72% unpaved roads; 13% of the roads are of unknown type. All of the PIDA PAP projects included in the PIDA+ network are paved roads; the country-level projects and existing road network are mostly unpaved. Appendix A provides a detailed breakdown of the inventory by country and road type.

Figure 3.2. Countries of Sub-Saharan Africa with geographic classification to UNECA multi-country regions

Table 3.1. Existing and projected PIDA+ road networks by geographic area

UNECA Region	Existing Network (km) (% Total)	Projected Network in 2050 (km) (% Total)
Central Africa	344,083 (12%)	344,583 (12%)
Eastern Africa	850,710 (30%)	898,661 (31%)
Southern Africa	998,334 (35%)	1,000,816 (35%)
Western Africa	638,982 (23%)	639,845 (22%)
TOTAL	**2,832,110**	**2,883,905**

Figure 3.3. Geographic distribution of existing and projected PIDA+ networks



The PIDA PAP projects accounted for in this study reflect 11 multi-country transport projects, comprising 111 individual road segment investments, with a total investment of approximately US$33 billion. The PIDA+ inventory includes an additional 261 projects across 30 countries, with an estimated investment cost of US$45 billion. The combined "PIDA+" reference investment scenario therefore represents an approximate combined capital investment rate of US$4.6 billion per year, for a total of US$78 billion.

As a benchmark to this investment scenario, the AICD study concluded that road infrastructure spending needs for SSA amount to an average of 1.5% of GDP per year (US$5.98 billion/year in capital costs, plus US$3.65 billion/year in operations and maintenance costs; Carruthers et al., 2008). We therefore estimate that this study's reference investment scenario represents 77% of the AICD-identified capital investment needs for SSA.

3.4 Estimates of Traffic Volumes in the SSA Road Network

Information on traffic volumes for the SSA road network is only sparsely available. In particular, there is no comprehensive dataset available to characterize road volumes that might be useful in interpreting the road disruption results presented in Chapter 6. There is, however, a source of attributed traffic volume data that relies on expert judgments of traffic volumes by road class (primary, secondary, and tertiary) and type (paved and unpaved) (Gwilliam, 2011). The Project Team employed the attributed data on traffic volumes by road class, with the inventory data by road class, to estimate traffic volumes by country for the paved and unpaved road categories. The results are presented in Table 3.2 below, and are also used in Chapter 6 to understand the likely range of values that might be appropriate for avoid disruption times. Two methods were used to develop these estimates, which could be interpreted as a range of values. Method 1 uses estimates of the road distribution by class and length from Gwilliam (2011), and Method 2 relies on estimates of the road distribution by class and length from this study.

Table 3.2. Estimates of traffic volumes by country and major road category

Country	Classified Roads from Gwilliam (2011) (km)		Estimated Traffic Volumes (vehicles/day)			
			Method 1		Method 2	
	Paved	Unpaved	Paved	Unpaved	Paved	Unpaved
Angola	14428	7758	377	378	632	88
Benin	1775	11646	1627	112	1627	179
Botswana	7892	12316	970	353	931	119
Burkina Faso	2643	4061	401	401	397	156
Burundi	1586	9625	215	34	305	85
Cameroon	4544	37048	751	132	750	225
Central African Republic	0	0	55	19	55	25
Chad	6500	75496	N/A	N/A	149	47
Cote d'Ivoire	842	3520	397	84	618	151
Democratic Republic of the Congo	8562	176306	48	22	48	35
Eritrea	2322	24599	385	180	385	130
Ethiopia	8938	188153	387	105	503	133
Gabon	1527	4217	266	150	267	94
Ghana	754	15847	1917	113	843	198
Guinea	5953	19686	586	61	585	106
Kenya	4517	29492	729	58	723	128
Lesotho	1936	22983	1363	369	1560	482

Country	Classified Roads from Gwilliam (2011) (km)		Estimated Traffic Volumes (vehicles/day)			
			Method 1		Method 2	
	Paved	Unpaved	Paved	Unpaved	Paved	Unpaved
Liberia	2635	0	275	47	276	79
Madagascar	3812	6990	483	68	599	95
Malawi	6432	38954	557	62	532	115
Mali	3637	9791	170	98	288	66
Mauritania	23773	169427	247	44	247	113
Mauritius	1060	6929	484	N/A	3556	N/A
Mozambique	1171	12829	1053	353	837	127
Namibia	4057	25449	1150	96	1199	87
Niger	951	11048	405	57	405	57
Nigeria	154723	453260	1845	57	1720	355
Republic of the Congo	2527	169953	172	85	172	65
Rwanda	1610	4632	913	141	913	65
Senegal	512	2177	978	63	979	88
Sierra Leone	2907	74254	458	77	482	117
South Africa	19204	69134	966	56	3395	47
South Sudan	14428	7758	N/A	N/A	1031	228
Sudan	1775	11646	260	21	265	112
Swaziland	7892	12316	1431	287	1866	417
Tanzania	2643	4061	1016	189	1031	228
The Gambia	1586	9625	375	75	375	16
Togo	4544	37048	2042	238	2041	391
Uganda	653	23693	653	25	870	108
Zambia	0	0	995	115	800	77
Zimbabwe	6500	75496	376	34	915	64

Notes: Method 1 uses estimates of the road distribution by class and length from Gwilliam (2011). Method 2 relies on estimates of the road distribution by class and length from this study.

CHAPTER 4

Climate Change Projections in Africa

Brent Boehlert, Kenneth M. Strzepek, and James E. Neumann

This chapter describes the methods used to develop the broad set of climate projections that are used in this study, which are used as inputs in the impacts and adaptation analyses in the subsequent chapters. The methods generated 95 individual representations of climate futures through 2050 that span a wide range of GHG emissions scenarios and GCMs applied in the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) recent Fourth and Fifth assessment reports (AR4 and AR5). This chapter also discusses how the approach to climate change projection used here complements the one used in the World Bank's "Turn Down the Heat" (TDH) series of reports.

Figuring out how exactly infrastructure development should be modified to take climate change into account is difficult because of the large uncertainty in climate projections. Since no consensus has yet emerged in the climate science community on how to assign probabilities to alternative climate futures, approaches have been suggested to identify "robust decisions" (i.e., those that perform well compared to the alternatives over a wide range of plausible futures). The first step toward applying such an approach is to define the "uncertainty domain" (i.e., define across the continent a range of climate projections that adequately capture uncertainty about climate processes and is reflected in the wide range of GCMs, as well as uncertainty about future GHG emissions pathways). This chapter reviews methods for developing such a range of climate futures and presents the climate change scenarios used in this assessment.

4.1 Developing Climate Change Projections

The process of developing climate change projections generally includes four elements:

1. ***Characterize history***: Select a representation of the historical climate that will be used to relate the projection to existing conditions. This step also involves selecting the spatial and temporal scales for the analysis.
2. ***Characterize the principal climate change drivers***: Select a GHG emissions pathway that represents a reasonable projection of the phenomenon believed to drive future climate change.
3. ***Process the emissions data in a climate model***: Use one or more GCMs to process the emissions projection to develop trajectories of climate indicators (such as temperature and precipitation).
4. ***Relate the model projections to historical data***: Relate the projections to historical information on temporal and spatial variability of current climate, while also taking into

account information from climate models about how these patterns could change in the future.

At each step of the above process, there are both choices and uncertainties, and while some consensus exists concerning how to complete each step, multiple valid alternatives exist. As a result, there are many reasonable projections of future climate for a given location and time period. It is significant, however, that climate scientists have not reached consensus about the relative likelihood of these multiple projections.

In light of this circumstance, the study team has chosen to employ climate information from several emissions scenarios and climate models, as well as multiple bias correction and spatial downscaling techniques. Bias correction is a process of using measured historical climate information to normalize the outputs from the models – effectively ensuring that what we take from each climate model is a representation of the modeled differences they imply between historical and future climate conditions. Spatial downscaling (and/or spatial disaggregation) is a process of enhancing the spatial resolution of the relatively crude spatial projections from climate models, through judicious use of historical information. Both bias correction and spatial disaggregation (BCSD), as well as downscaling processes, derive from the conclusion that it would be inappropriate to use the results of climate models directly; instead, it is better to use historical climate information to ground the results. Each of the approaches used for developing disaggregated or downscaled future climate projections is defensible scientifically and provides information on different possible realizations of future climates. Box 4.1 provides technical details on the procedures applied.

The result of this approach is a characterization of the historical climate for SSA, which is necessary to provide a clear representation of natural variability in climate systems, and a total of 95 alternative representations of the climate future, each of which can be used to estimate the impacts of climate change on infrastructure performance, and the adaptation options that can be deployed to respond to those impacts. The approach utilized in this study to develop climate projections complements the one adopted by the Turn Down the Heat (TDH) series of reports (World Bank, 2012; Potsdam Institute, 2013), as discussed in detail in Box 4.2.

Box 4.1. A Technical Summary of the Methods for Developing Climate Futures

Historical climate sequences. This analysis uses data from the Terrestrial Hydrology Research Group at Princeton University; the data are organized in a grid at a 0.5 degree resolution (approximately 50 km) covering Africa for the 1948–2008 time period. This dataset merges what is currently one of the most comprehensive collections of daily observed records from the Global Historical Climatology Network (GHCN) with a number of re-analysis and satellite or satellite/station merged gridded datasets.

Disaggregated global ***climate projections*** of future climate using the BCSD method. The BCSD method is a development of pattern scaling, incorporating quantile mapping to account for GCM biases in rainfall-intensity distributions. The strengths of this method are that the projections show strong agreement with GCM projected changes at the large scale, and that the method produces a de-biased future projected time series, which greatly eases the application to impact modeling, particularly hydrology.

The Track I, basin, and power-pool scale analyses use results of ***two classes of climate models***, which were supported as part of IPCC's two most recent assessments: AR4 and AR5, published in 2007 and 2013, respectively. For this study, daily results for the 2001–2050 time period are needed. The IPCC AR4 provided data from 22 GCMs, which were evaluated across three emissions scenarios. Because not all models were deployed for all three emissions scenarios, this yields a total of 56 emissions-GCM combinations for our use. These results were processed using the BCSD method to produce a daily time series for a 50-year period, representing 2001–2050 at a 0.5 by 0.5 degree resolution grid across Africa for rainfall and temperature.

The IPCC AR5 provides suitable data from 9 GCMs, and the study team employed results for ***two emissions pathways***, labeled Reference Concentration Pathway (RCP) 4.5 and RCP 8.5, corresponding to a "medium" and "high" emissions scenario, respectively. RCP 8.5 corresponds to the emissions pathway often emphasized in characterizations of the World Bank's recent report, *Turn Down the Heat: Why a 4°C Warmer World Must Be Avoided*. Combining the GCMs and emissions scenarios yields a total of 17 additional emissions-GCM combinations (9 driven by RCP 4.5 and 8 driven by RCP 8.5 emissions), which were also downscaled using the BCSD method.

An ***additional 22 climate futures*** (11 GCMs driven by the 4.5 and 8.5 RCP emissions pathways) were produced using an alternative downscaling technique, the Empirical-Statistical Downscaling Methods developed at the Climate Systems Analysis Group at the University of Cape Town. This method relies on different outputs from the GCMs in the downscaling process, focusing on the atmospheric pressure results, which are then related to precipitation outcomes, rather than using the precipitation outcomes directly from the GCMs.

Box 4.2. Comparison of Climate Projections in this Study to Those of the TDH Series of Reports

The projections used in this study reflect the broad base of climate science that underlies the last two IPCC Assessment Reports – AR4 and AR5. One prominent recent World Bank-supported effort, the "Turn Down the Heat" (TDH) series of reports (World Bank, 2012; Potsdam Institute, 2013), relies on the most recent IPCC climate science base, the AR5, as well. The TDH reports use the same AR5 emissions scenarios (i.e., RCPs) and the same set of AR5 GCMs as this report. Differences between the climate projections presented in the TDH reports and this report come mainly from three sources:

- *How the GCMs are used.* Rather than using the GCM results as they are provided by the IPCC, the TDH reports present ensemble results by running a climate model ensemble of 600 realizations for each GHG emissions scenario. In the simulations, each ensemble member is driven by a different set of climate-model parameters that define the climate-system response, including parameters determining climate sensitivity, carbon cycle characteristics, and many others. Some filtering is then conducted, so that randomly drawn parameter sets that do not allow the climate model to reproduce a set of observed climate variables over the past centuries (within certain tolerable "accuracy" levels) are filtered out and not used for the projections, leaving the 600 realizations that are assumed to have adequate predictive skill. The current study, by contrast, uses the results of GCMs directly, and then conducts downscaling and bias-correction calculations for each of the individual GCM-emissions scenario combinations. In short, the TDH reports tend to focus on aggregate ensemble results, and this study tends to focus on ensemble members.
- *How the emissions scenarios are used.* The TDH reports rely mostly on two RCPs – 3.0 and 8.5. RCP 3.0 is a mitigation scenario, while RCP 8.5 is largely acknowledged to be a non-mitigation scenario. This study also uses RCP 8.5, but for the mitigation scenario relies on RCP 4.5, which reflects recent thinking that the failure to date to reach an international climate agreement on GHG emissions reductions makes the realization of RCP 3.0 less likely. This study also uses other emissions projections from the older AR4.
- *How the time period of interest is defined.* For most of their results, the TDH reports present outcomes for the mid-century, centered on 2050, and for the end of century, reflecting the 2080–2100 period. The use of "eras" to present mid-century and end-century results is appropriate for illustrating the temperature, precipitation, sea level rise, and extreme event endpoints that are the focus of the TDH reports, but results for eras typically are not used as inputs to biophysical and economic models of climate impacts. This study focuses on the period from the present to mid-century, or year 2050, which is relevant for decision-making for new infrastructure in the next 15–20 years. A daily time series of climate projections is used to drive impact and adaptation models of the road sector.

The cumulative effect of these differences is that the climate scenarios used in this study span a broader range of discrete climate model and emissions scenario outcomes than the TDH reports, which is appropriate for the purposes of the current study, which is focused on methods for addressing uncertainty in climate futures.

4.2 Temperature and Precipitation Forecasts in SSA

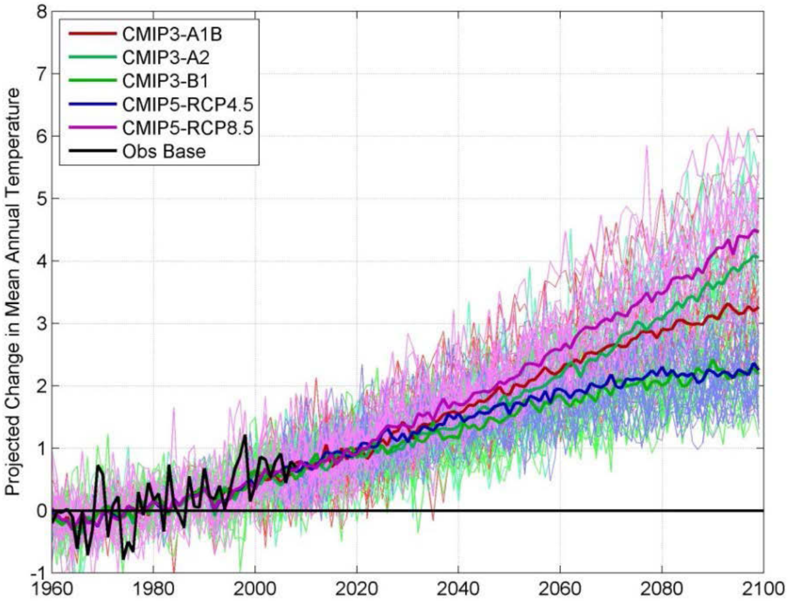
The results of our broad characterization of climate futures resulting from the above methods indicates that a wide range of temperature and precipitation outcomes are possible across SSA. Figure 4.1, Panel A, shows the temperature results (spatially-averaged) for Senegal, in West Africa, both for the historical period and for the projection through 2100. Senegal was chosen simply as an example of the types of climate information that are typically used in impact analysis, and to illustrate several points that apply to climate analyses throughout SSA. As indicated in the figure, all temperature forecasts show increases over time, but the magnitude of the increase for any single projected trajectory can differ markedly, with estimates for the end of the century ranging from a one-degree increase to a six-degree increase. Note also that estimates for the highest GHG emissions scenario, the CMIP5-RCP8.5, show the highest degree of warming over time. These patterns are similar throughout SSA.

Panel B of Figure 4.1 shows the comparable results for precipitation forecasts, also for Senegal. In the case of precipitation, however, the overall results show almost no discernable trend, even when the end of the century is considered. Instead, they are marked by a very high degree of both year-to-year variability and cross-GCM variability. In addition, the higher-emissions scenarios (e.g., CMIP5-RCP8.5) tend to show more drying than the lower-emissions scenarios, at least at the end of the century. Also note that the results shown are for the full 21st century, while in this study our time horizon extends only to 2050.

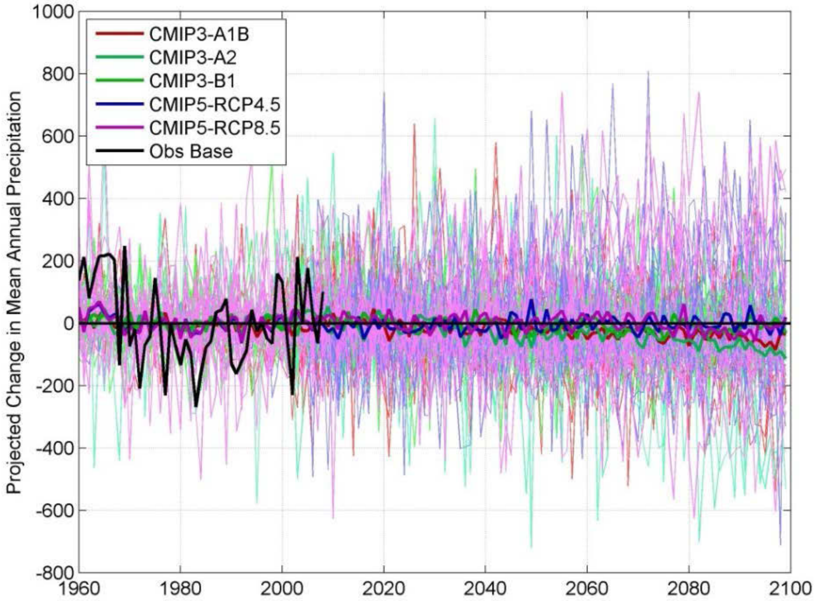
A key point from this example is that in most all parts of Africa, there exists a particular historical pattern, with areas within the Congo River Basin generally the wettest and areas in Southern Africa the driest in SSA, but the projections show both drier and wetter futures than historical. For example, comparable results for precipitation outcomes in the DRC and South Africa are shown in Panels A and B, respectively, in Figure 4.2. These results support the point that the range of alternative climate futures cannot be readily summarized as either wetter or drier than the historical climate. Further, the dark lines for CMIP3 and CMIP5 in Figures 4.1 and 4.2 show that averages across GCMs clearly underestimate the variability that can result from a large portion of individual GCM/emissions combinations. This finding reinforces the need to consider a framework such as RDM (described in more detail in Chapter 2), which allows the analyst to consider a broad range of individual future outcomes when making infrastructure planning decisions. With uncertainty in the pattern of future climate, the possibility to over- or under-design climate sensitive transport infrastructure is considerable; a wiser course of action is to consider the outcomes of alternative infrastructure plans across the broadest feasible set of futures.

Figure 4.1. Illustration of model variation for temperature and precipitation futures in Senegal

Panel A: Temperature futures



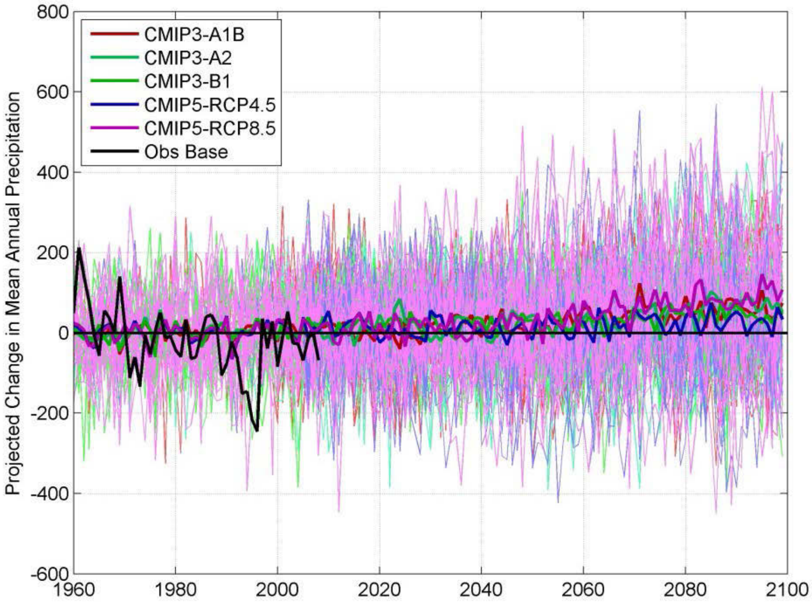
Panel B: Precipitation futures



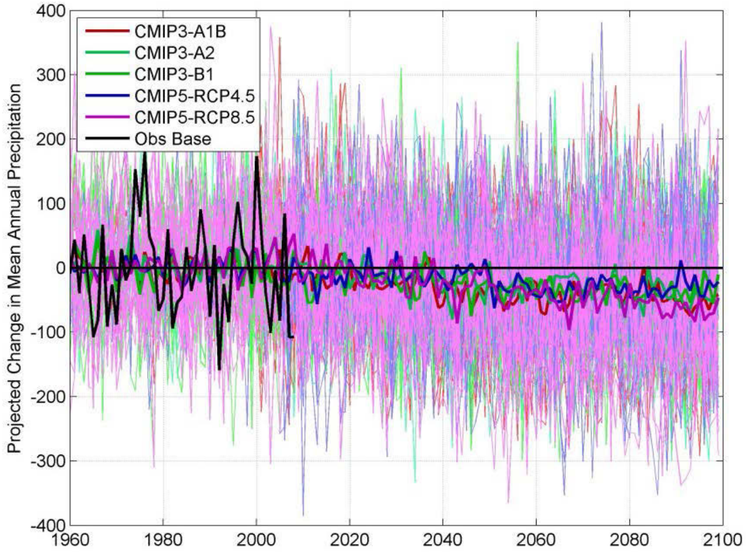
Note: CMIP3 corresponds to IPCC AR4 GCM results, CMIP5 corresponds to IPCC AR5 GCM results. Observed (Obs) Base reflects only the measured (Princeton) dataset base.

Figure 4.2. Illustration of model variation for precipitation futures in two countries, DRC and South Africa

Panel A: Precipitation futures in the DRC



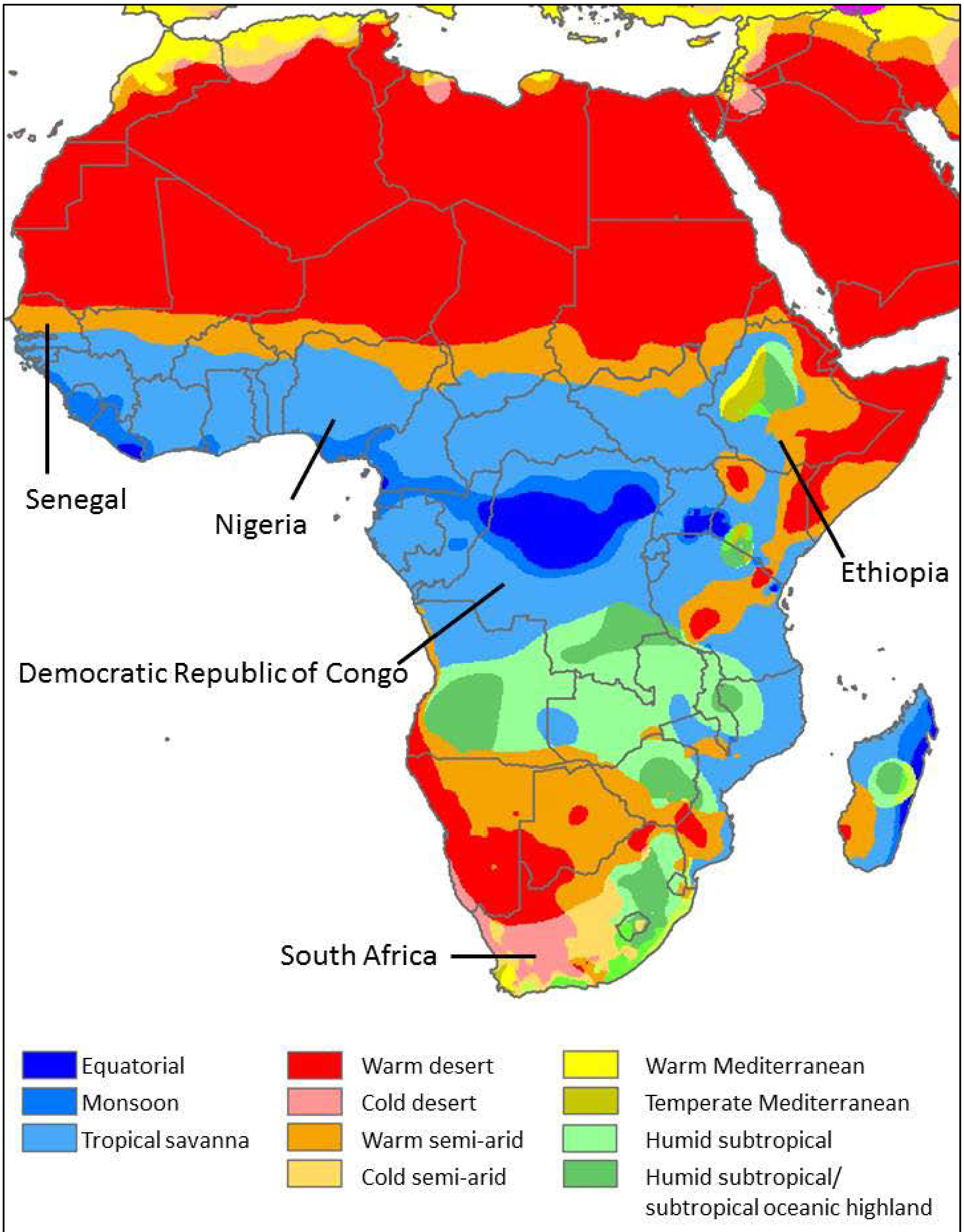
Panel B: Precipitation futures in South Africa



Notes: CMIP3 corresponds to IPCC AR4 GCM results, CMIP5 corresponds to IPCC AR5 GCM results. Observed (Obs) Base reflects only the measured (Princeton) dataset base.

Below we present the results of the temperature and precipitation forecasting for five countries in SSA: South Africa, Senegal, Nigeria, Ethiopia, and the DRC. These countries contain a variety of climates that are representative of the range of climates across SSA. Figure 4.3 presents the Köppen-Geiger climate classifications in Africa, highlighting the variety of zones found within the five sample countries.

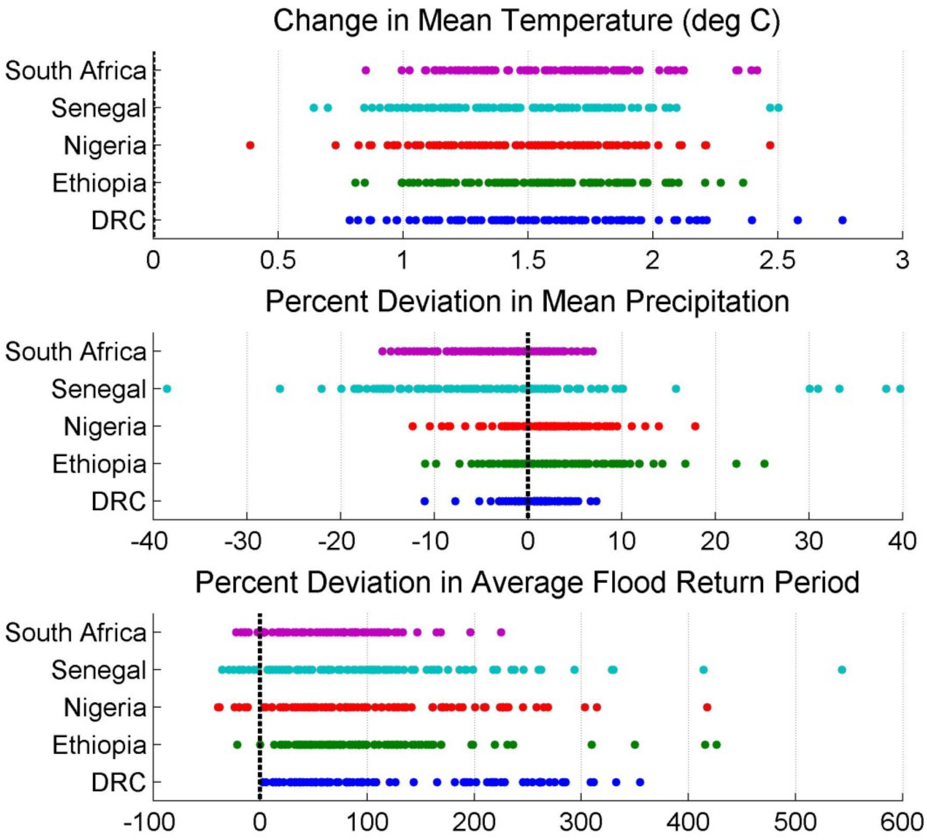
Figure 4.3. Köppen-Geiger climate classifications in Africa



Source: Peel, M. C. and Finlayson, B. L and McMahon, T. A. (2007). "Updated world map of the Köppen-Geiger climate classification". *Hydrol. Earth Syst. Sci.* **11**: 1633-1644.

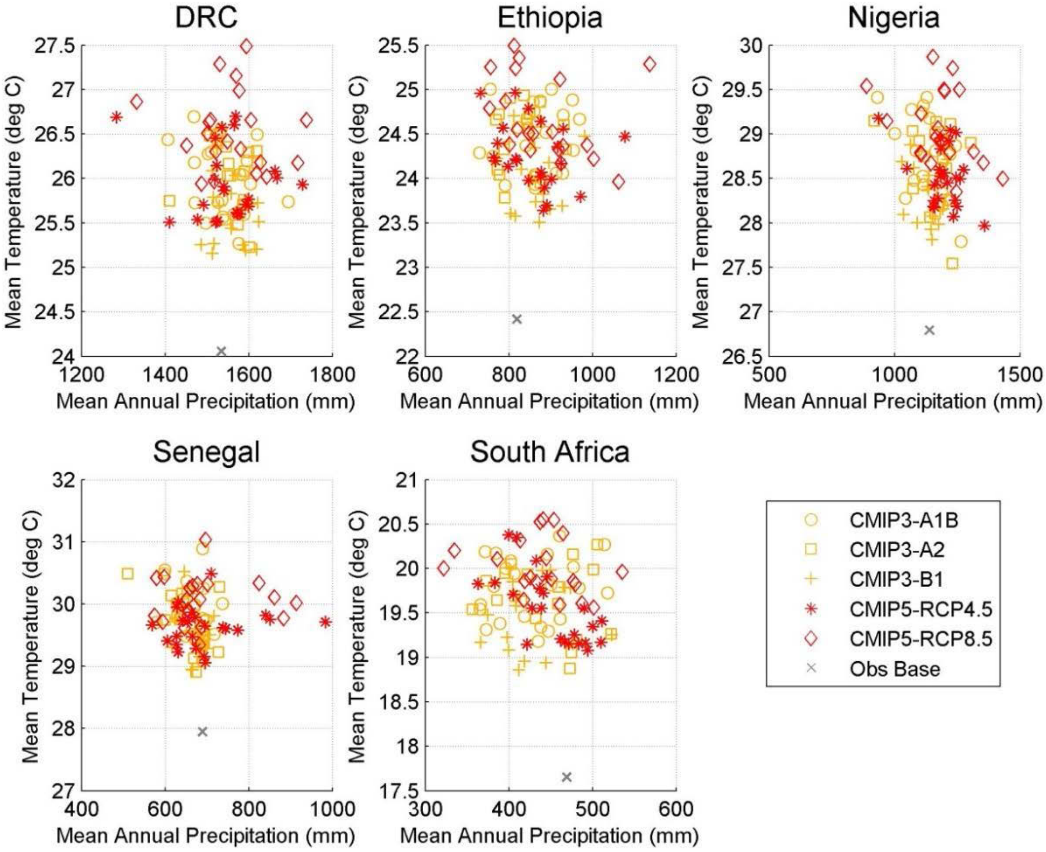
Figure 4.4 shows summary results in box and whisker form for the five example countries. The temperature outcomes are most consistent across these five countries, and center on about 1.5°C to 2°C. Precipitation outcomes, as noted above, vary more substantially across countries, as can be seen in the center panel of Figure 4.4. In addition, the bottom panel provides a measure of changes in flood risk, showing changes in the magnitude of the maximum daily precipitation event in 2050 compared to the average 24-hour event for years in the baseline period. The interesting result is that, even in situations where average annual precipitation may decline, changes in the daily variation of precipitation volumes imply that flood risks could increase. This finding is important for the design of culverts to carry runoff beneath road surfaces.

Figure 4.4. Comparison of temperature, precipitation, and flood risk forecasts for 2050 for five example countries throughout SSA



Another way to view the climate scenarios is shown in Figure 4.5, presented for the same five sample countries of the DRC, Ethiopia, Nigeria, Senegal, and South Africa. Here the vertical axis is average mean temperature for the country, and the horizontal axis is average mean annual precipitation. The X's shown toward the bottom of the graphics show the historical climate, corresponding to the measured Princeton historical baseline. Orange and red symbols indicate CMIP3 and CMIP5 projections, respectively, and the various symbols in the legend provide an indication of the emissions scenario. Observation of the range of red (CMIP5) versus orange (CMIP3) precipitation outcomes in all five countries suggests that even with the most recent advances in climate science implied by the progression from CMIP3 to CMIP5, the result does not narrow uncertainty but reflects an increase in uncertainty. The conclusion provides another important rationale for adopting the RDM methods used in this study in planning climate-sensitive infrastructure deployment.

Figure 4.5. Climate futures in 2050 for five SSA countries



Notes: CMIP3 corresponds to IPCC AR4 GCM results, CMIP5 corresponds to IPCC AR5 GCM results. Baseline reflects the measured (Princeton) dataset.

In general, the results presented in this chapter demonstrate that the historical temperatures are lower than all of the temperature futures, but the historical precipitations generally sit in the middle of the range of precipitation futures. The newer CMIP5 projections tend to represent the more extreme temperature and precipitation projections (to the top and right of Figure 4.5, respectively), particularly those for RCP 8.5, the "high-end" emissions scenario, shown as red diamonds.

Looking across the countries, the relative positions of the historical results to the left or right of the cluster of future climate projections give some indication of whether the study team can expect a largely drier or largely wetter future in these basins. For example, the Ethiopia results suggest more wetter than drier futures, while the South Africa results suggest there is some possibility of a much drier basin. As noted above, however, there is no way to assign probabilities to the 95 climate futures, so readers should not interpret likelihoods from these results. Rather, it is useful to think of the climate futures as indicating a range of possibilities for each country that are supported by the best current IPCC climate science, and therefore provide an initially plausible space for thinking about the range of possible climate impacts (as outlined in Chapter 5), and the range of climate futures that can be considered in future adaptation planning and design (as presented in Chapter 6).

In addition, it is important to note that "drier" can ultimately be a combination of both temperature and precipitation, as higher temperatures lead to higher evaporation from surface waters, higher evapotranspiration from plants, and, as a result, lower runoff in rivers, all else equal – this is most important in assessing flood risks. Finally, these figures provide a sense of the annual mean values, but the impact and adaptation results presented in later chapters make use of daily results for each country the study team considers. The monthly patterns of temperature, and especially precipitation, vary considerably across SSA, and the more refined temporal patterns have the most influence on impacts for road infrastructure.

4.3 Flooding Projections

For the roads analysis, the study forecasts the change in precipitation events within grid cells, on a daily basis. The change in flood risk is characterized as the change in high daily precipitation events. A distribution of high daily precipitation events is established for the historical climate case, and the fifty-year baseline historical period is then use to calculate return periods for flood events, as characterized by high daily precipitation events. The analysis then considers each changed climate, and provides a daily time series of the changed occurrence of daily precipitation events, which are in turn used in the IPSS model to characterize changes in the damage associated with flooding. The road component does not consider the routing of water from one grid cell to another.

Because bridges cross rivers, the flow in rivers is critically important to the effect on bridge footings and/or overtopping. Therefore, a water flow routing analysis was conducted at the major basin scale to capture the effect of precipitation events in multiple upstream grid cells, since these affect flow in downstream grid cells that might contain bridges. At noted in Chapter 2, the bridges analysis estimates impacts by first assuming that all current bridges are resilient to the current 50-year flood, and then a damage function is applied for river flow events corresponding to the 75-year and 100-year flood in future climates. The flood flow analysis provides an estimate of the current 50-year, 75-year, and 100-year flood events by grid cell. The logic for the extra effort required to estimate river flow for the bridges analysis is that the effect of flooding on bridges is related to scouring of the bridge footings, which sit in the river itself. As described in Wright et al. (2012), bridges are mainly vulnerable to bank erosion and scour related to flood events.

CHAPTER 5

Risks of Inaction

Paul Chinowsky, Xavier Espinet, and Jacob Helman

This chapter presents the results of the “reactive response” analysis. This analysis examines a scenario in which no proactive measures are taken to protect infrastructure from climate change impacts, and instead measures are taken after the impacts have occurred. In this scenario, the costs of climate change are the costs of the response, which include incremental maintenance and repairs between major rehabilitation cycles to restore the roads to their pre-climate change condition, as well as the costs of disruption when the roads are out of service. The reactive response analysis illustrates the “risks of inaction” or the vulnerability of the infrastructure to climate change.

As described in Chapter 2, the analysis relies on the IPSS tool to analyze the impacts of three specific climate stressors: temperature, precipitation, and flooding. Each road segment is analyzed using a stressor-response method and compared with a baseline of historical climate data. The analysis then quantifies the incremental costs of the reactive responses, presented in Table 5.1 (repeated from Chapter 2, to remind readers of the specific reactive response measures that are considered in the risks of inaction analysis). The reactive strategies are based on specific thresholds for each stressor and road type. For the reactive response analysis, roads are built based on historic climate standards, and assuming, for the comparability reasons discussed in chapter 2, full maintenance routines. When climate change stressors exceed thresholds, damages are incurred through increased maintenance activities necessary to preserve the integrity of the road for its original design lifespan. The costs associated with these responses are based on figures provided by roadway design and management practitioners and reflect local construction and maintenance costs.

Table 5.1. Reactive responses included in the study

Road type	Climate stressor	Effect	Reactive response
Paved roads	Temperature	Increased temperature leads to accelerated aging of binder	Additional sealing required on a more frequent basis due to faster degradation of road quality
		Increased temperature leads to rutting (of asphalt), and bleeding and flushing (of seals)	Additional patching required each year to fill cracks resulting from pavement weakening
	Precipitation	Increased precipitation leads to increased average moisture content in subgrade layers and reduced load-carrying capacity	Increase patching to address cracking from surface failure Fill subbase where erosion has occurred due to water infiltration. Follow with additional patching
	Flooding (in excess of design flood)	Washaways and overtopping of road	Repair of localized washouts including cleaning culverts, replacing culverts, replacing subbase, and replacing asphalt surface
Unpaved roads	Temperature	Not applicable	No response
	Precipitation	Increased precipitation leads to increased average moisture content in subgrade layers, and reduced load-carrying capacity	Regrade road localized to precipitation, fill subbase and reapply gravel top layer.
	Flooding (in excess of design flood)	Washaways and overtopping of road	Same as for paved except application of gravel top layer rather than application of asphalt layer.

5.1 Risk to SSA of a Reactive Response to Climate Change

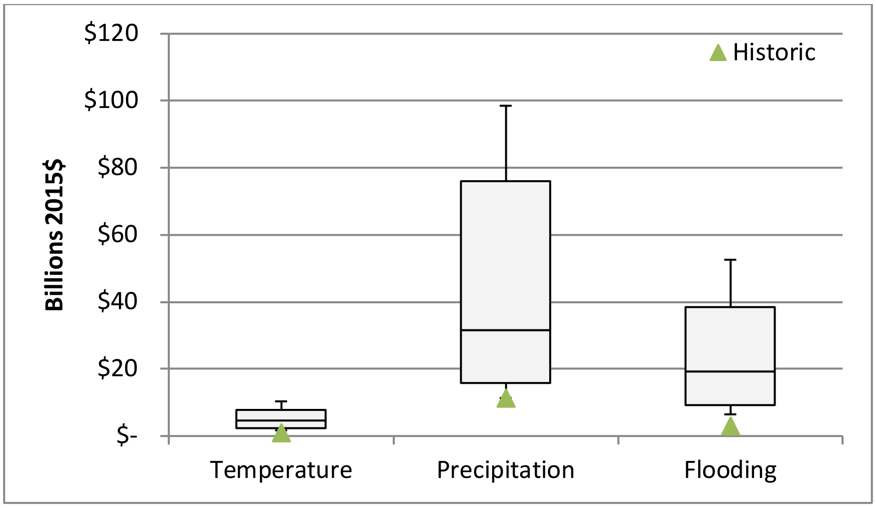
Across SSA, the mean costs (across climate scenarios) of climate change for the PIDA+ network associated with the reactive response scenario are estimated at $56 billion for 2015-50 (6% discount rate), compared to historic climate costs of about $15 billion. The uncertainty across climates is very substantial, however, with the 95th percentile values as much as three times larger than the mean, and the 5th percentile values almost indistinguishable from the baseline, no climate change costs. Figure 5.1 presents the reactive response costs associated with each climate stressor (temperature, precipitation, and flooding), and also includes historical costs for reference. Specifically, the figure shows the costs of conducting maintenance on the PIDA+ road network between major rehabilitation cycles in response to climate-induced damages to restore roads to their pre-climate change condition. Periodic rehabilitation costs are included in the baseline.

As shown, costs associated with all three stressors are projected to increase relative to historic costs, particularly costs associated with flooding. Across the PIDA+ network, the highest reactive response costs are associated with projected changes in precipitation (the mean estimated cost is $32 billion for 2015-50, 6% discount rate). This is due to the fact that changes in precipitation have serious impacts on unpaved roads, which represent the majority of the PIDA+ network (72%). The effect of the temperature stressor is more modest because temperature does not affect unpaved roads and because there are already high temperatures across SSA, so the incremental effect of additional temperature increases due to climate change is relatively small. As noted by the green diamond in the figure, costs based on historical climate are at or near the bottom of the range estimated with forecasted climate change. The estimated costs can be as much as 10 times higher than historical costs for the temperature and precipitation stressors, and as much as 17 times higher for the flooding stressor. The maximum risks of inaction are clearly very much larger than historical maintenance costs.

Figure 5.2 shows the reactive response costs for the PIDA PAP projects only. As shown, the relative effect of the precipitation stressor is reduced because the PIDA PAP projects include only paved roads.

Figure 5.1. Reactive response costs for the PIDA+ network, 2015-50

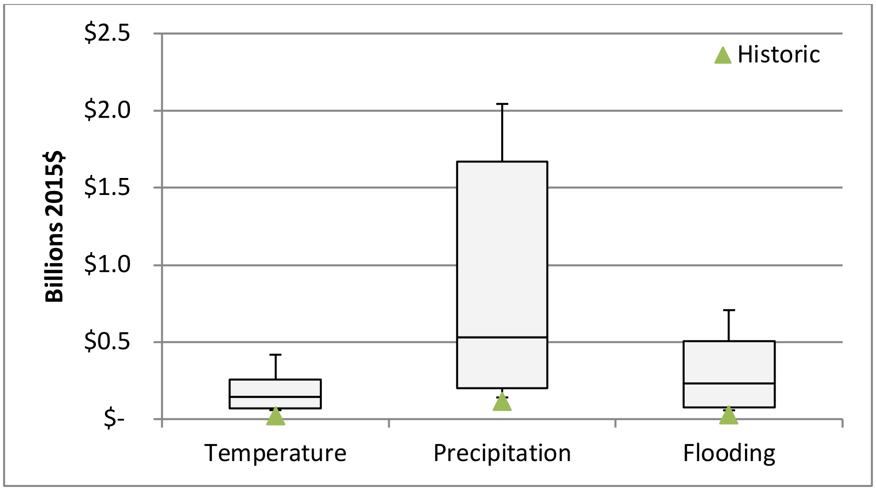
(Present value, 6% discount rate)



Note: Green triangle indicates lifetime road asset costs for historic climate. Box indicates the range of costs from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range of costs from the 5th to the 95th percentile of climate scenarios.

Figure 5.2. Reactive response costs for PIDA PAP projects only, 2015-50

(Present value, 6% discount rate)

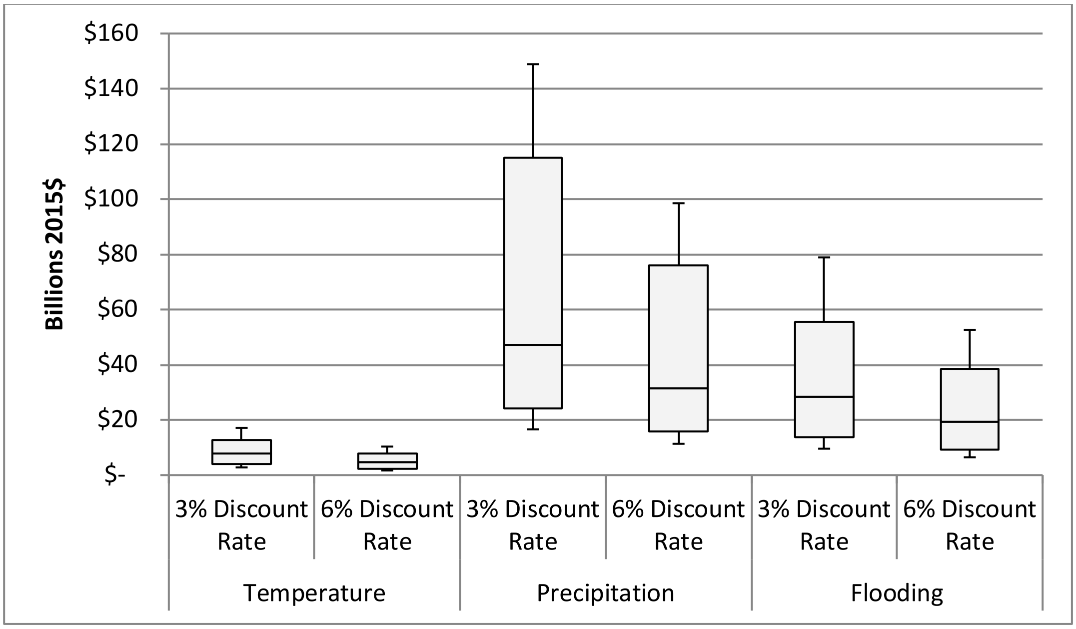


Note: Green triangle indicates lifetime road asset costs for historic climate. Box indicates the range of costs from the 25th to the 75th percentile, over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range of costs from the 5th to the 95th percentile of climate scenarios.

Figure 5.3 illustrates the effect of the choice of discount rate on the reactive response costs for the PIDA+ network. As shown, costs are substantially higher when using a 3% discount rate compared to a 6% discount rate. This is because the majority of the impacts are expected to occur later in the time period.

Figure 5.3. Reactive response costs for the PIDA+ network, for alternative discount rates, 2015-50

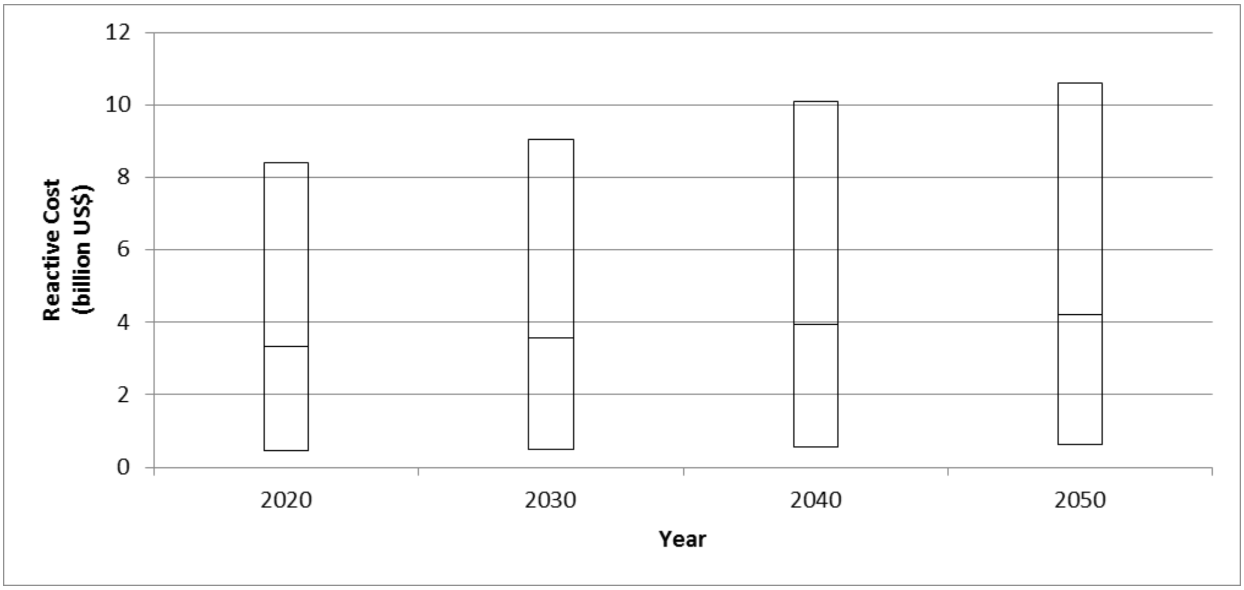
(Present value)



Note: Box indicates the range of lifetime costs from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile of costs over climate scenarios.

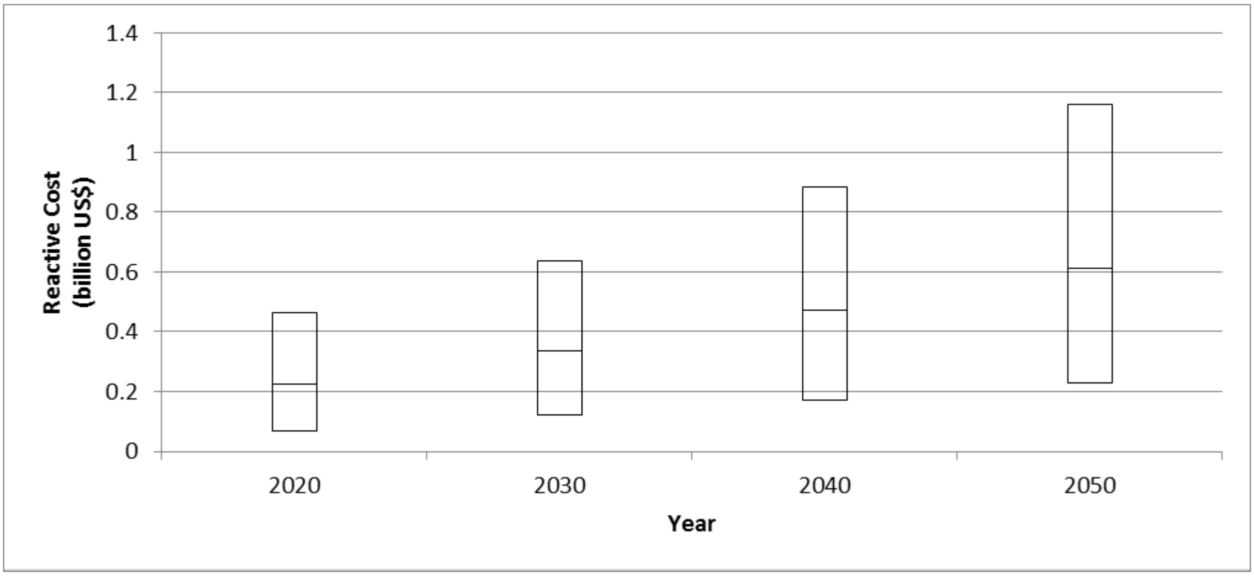
The discount rate effect is closely related to the timing of these impacts, which are in turn linked to the timing of the climate changes which cause the impacts. The top panel of Figure 5.4 provides an indication of the incidence of reactive costs by decade, using an aggregate measure for all climate stressors and all regions; the lower panel shows the same measure for all regions, but for the temperature stressor only. The lower end of the box shows the 5th percentile climate result, the top shows the 95th, and the middle line shows the mean. The results indicate the increasing trend in the timing of reactive costs over the course of the study period, with a relatively large increase in the early period and a shallow trend line for the mean result over time. The trajectory of costs for the temperature stressor, though, is steeper. The reasons for these trends are that costs for all stressors are dominated by the precipitation results; that costs for the precipitation stressor include an early component that reflects “catch-up” investments, which close the current climate adaptation gap; and that, as indicated in Chapter 4, the precipitation changes at the SSA level show relatively small changes from the mean, with relatively larger changes in variance over time (note that the trend in the 5th percentile results shows nearly no increase over time). For temperature, as indicated in Chapter 4, there is a more pronounced upward trend across all climate scenarios.

Figure 5.4a. Timing of reactive costs for PIDA+ roads – all stressors, all regions



Note: Box indicates the range of costs from the 5th to the 95th percentile over climate change scenarios; line in box represents the mean value.

Figure 5.4b. Timing of reactive costs for PIDA+ roads – all regions, temperature only



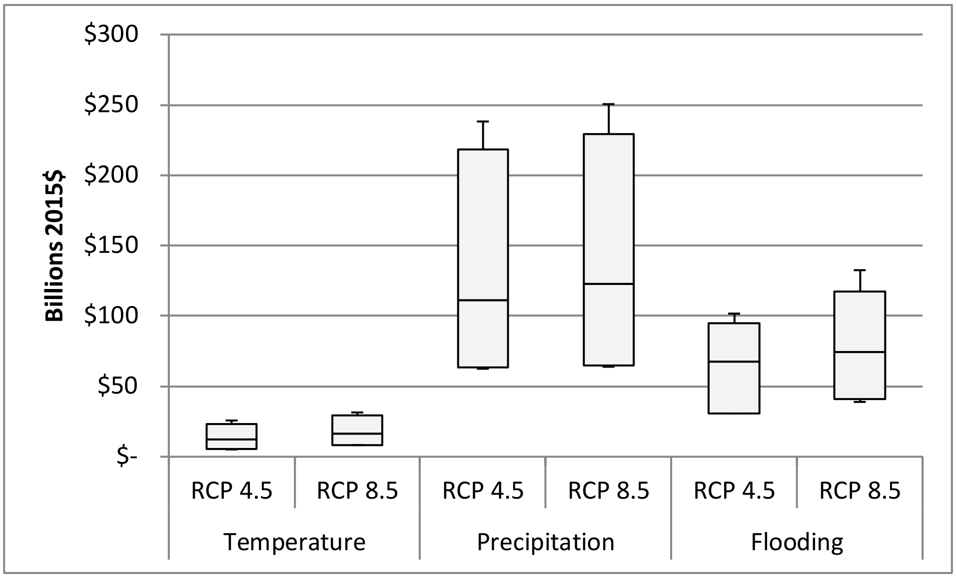
Note: Box indicates the range of costs from the 5th to the 95th percentile of climate change scenarios; line in box represents the mean value.

Recent global agreements to reduce greenhouse gas emissions might be expected to reduce these risks of inaction for the road network, when they are fully realized, but the reduction associated with GHG mitigation are much less effective than might be expected, at least through the 2050 time horizon of the study. Figure 5.5 shows the estimated reactive response costs for the PIDA+ network for two greenhouse gas concentration trajectories: RCP 8.5 and RCP 4.5. RCP 8.5 is a scenario of comparatively high greenhouse gas concentrations, resulting from a continued increase in emissions throughout the 21st century. RCP 4.5 is a scenario in which emissions peak around 2040 and then decline and level off due to mitigation efforts. As shown in the figure, costs are projected to increase under both scenarios relative to historical costs. The estimated costs of inaction for the road network under RCP 4.5 are reduced compared to RCP 8.5, but not as much as may be expected. This suggests that mitigation at the RCP 4.5 level, which does not guarantee a specific limit on temperature increases for all locations or in all climate change projections, would not substantially lower impacts to the SSA road network.

One reason underlying this finding is the 2050 time horizon. The differences in emissions between RCP8.5 and RCP4.5 are relatively modest through 2040, and differences in outcomes in SSA are most pronounced after 2050. Greenhouse gas mitigation remains an important priority for African countries for multiple sectors, and if the study considered a longer time horizon it would likely demonstrate the importance of mitigation for the road transport sector as well. However, a key lesson from this study is that mitigation alone is not sufficient to alleviate impacts in this sector, which puts yet more emphasis on the urgency for robust adaptation planning.

Figure 5.5. Reactive response costs for the PIDA+ network by RCP, 2015-50 (6% discount rate)

(Present value)

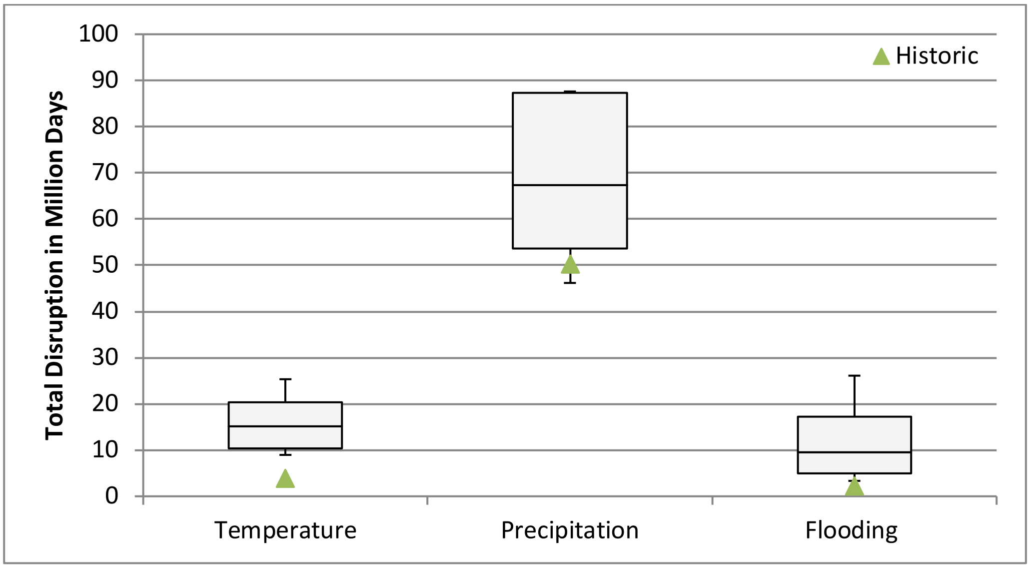


Note: Box indicates the range of costs from the 5th to the 95th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile of costs over climate scenarios.

In addition to increased maintenance costs, the reactive response approach is projected to result in a high degree of disruption to the PIDA+ network. As described in Chapter 2, disruption is the time out-of-service for the PIDA+ roads during the maintenance and repair activities resulting from climate change impacts. The analysis quantifies disruption in terms of out-of-service days for roads in the network.

As shown in Figure 5.6, a reactive response to the precipitation stressor results in an estimated 46-88 million disruption days, compared to 50 million days historically. The increase in disruption for the reactive response mode, associated with an increase in the need for repair of road surfaces and sub-grades, is in the worst climate up to 2.5 times historic disruption for the temperature stressor; 76% higher for the precipitation stressor; and 14 times higher for the flooding stressor.

Figure 5.6. Disruption time for the PIDA+ network with reactive response, 2015-50



Note: The chart presents results for cumulative road disruption times across climates in million days of disruption, across all SSA. Green triangle indicates disruption estimated for a historic climate. Box indicates the range of disruption days from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range of days from the 5th to the 95th percentile over climate scenarios.

Disruption of the Africa road network clearly results in substantial economic costs, as goods and people are prevented from moving freely or engaging in economic activity. Unfortunately, data on traffic volumes, effective network redundancy (allowing for alternative routing), or the economic value of avoiding disruptions is not available for most parts of SSA. A single day of disruption likely restricts many person-days of activity, though this effect may be mitigated in places where there is a high degree of road network redundancy. The typical rule of thumb for valuation of traffic disruption is to use 50 percent of the daily wage as a proxy for the lost opportunity cost of time – using reasonable valuation estimates, then, disruption might lead to additional damages in the billions to tens of billions of dollars, associated with individual days of road closure for repairs.

Even this value, however, excludes the broader macroeconomic implications of restricted travel and economic activity that extends to multiple economic sectors (e.g., associated with spoilage of agricultural products or lost tourism revenue). Two country-level examples provide insights on the possible magnitude of transportation disruption effects. In Mozambique, analysts estimated that transport disruption associated with climate change could cost the economy roughly $2.5 billion per year from 2010 to 2050, compared to a current annual GDP of $15.6 billion (Arndt and Thurlow, 2015). In South Africa, a similar analysis found that transport disruption could cost 0.8% of GDP (with a range of 0.1 to 2.6% across climate futures) by 2050; South Africa's current GDP is over $350 billion. The cumulative cost over the 2015 to 2050 period (5% discount rate) would be $16 billion (mean across climate forecasts), with a range of $1.5 to $55 billion (Cullis et al., 2015).

5.2 Regional Impacts of a Reactive Response

The effects of climate change on roads vary considerably by region.[5] Reactive response costs for the PIDA+ network are estimated to be highest in the Southern Africa region, but costs for the PIDA PAP projects are highest in Eastern and Central Africa. This is due to the fact that there are relatively few PIDA PAP projects in Southern Africa compared to the Eastern and Central regions. Again, the highest estimated costs in both cases are those associated with the precipitation stressor, which has the largest impact on the vast existing unpaved road network throughout SSA.

It is useful to consider how reactive response costs vary across climate stressors and regions. Figure 5.7 (panel a) presents such an evaluation for the PIDA+ network, and Figure 5.7 (panel b) for the PIDA PAP projects only. In both figures, the vertical axis is normalized (at 100) to the historic (no-climate-change) costs. Bars that are higher than the 100 line represent costs of climate change and bars below the line indicate potential savings. As shown, the flooding stressor leads to relatively higher increases in costs relative to historic across the regions for both the PIDA+ network and PIDA PAP projects. Cost increases are particularly high in the Central and Western regions.

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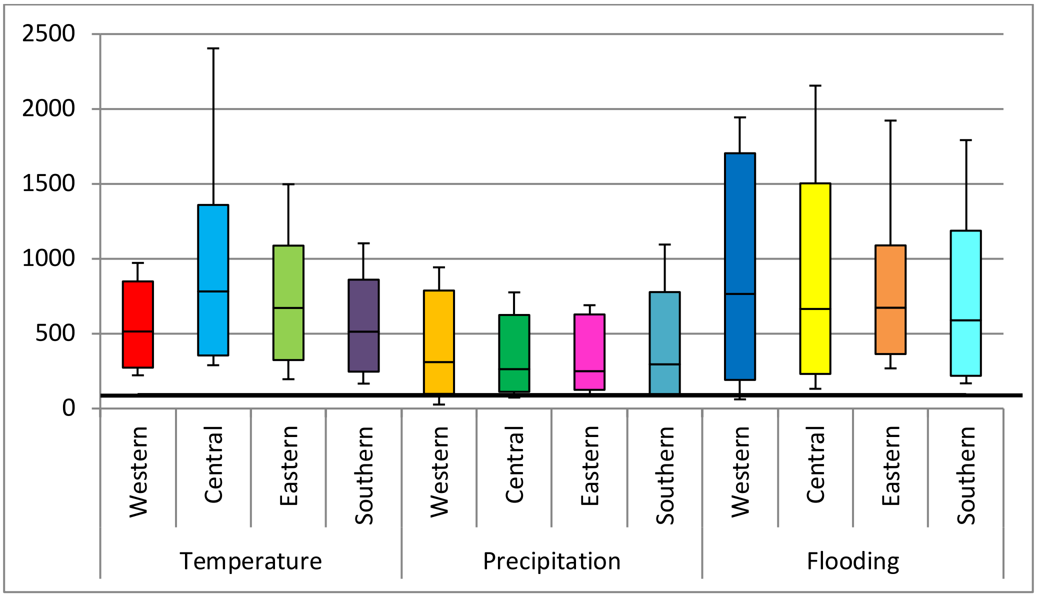
[5] A map of the regions is presented in Figure 3.2. The regions are based on the regions used by the United Nations Economic Commission for Africa (UNECA). Sudan and Mauritania are in UNECA's North Africa region but for the purposes of this study are included in Central Africa and Western Africa, respectively.

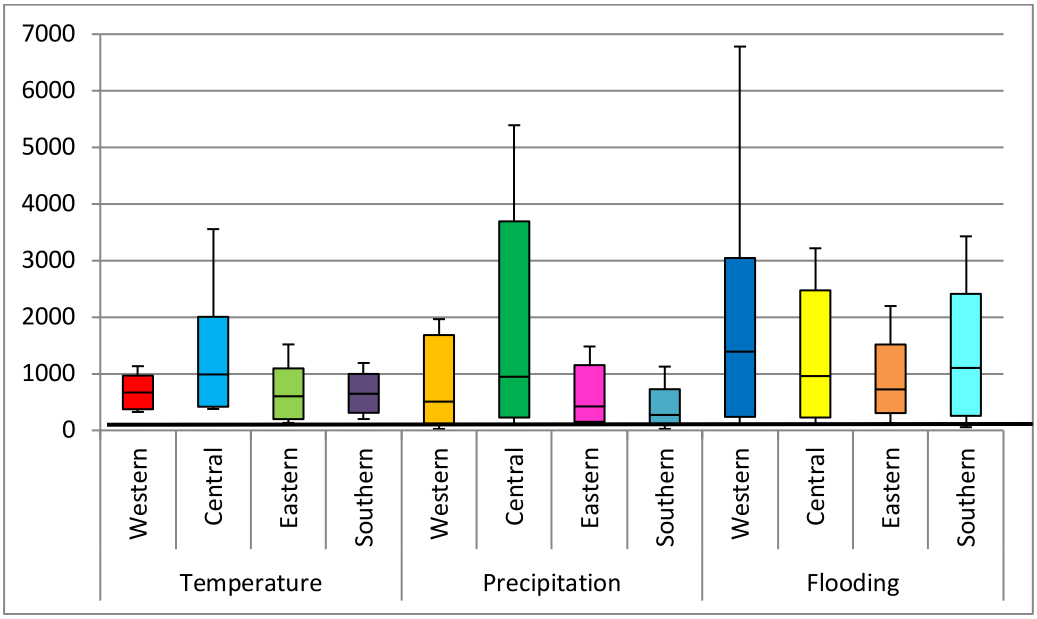
Figure 5.7. Normalized net reactive response costs by region, 2015-50

(Present value, 6% discount rate)

Panel A: Costs for the PIDA+ network



Panel B: Costs for PIDA PAP projects only



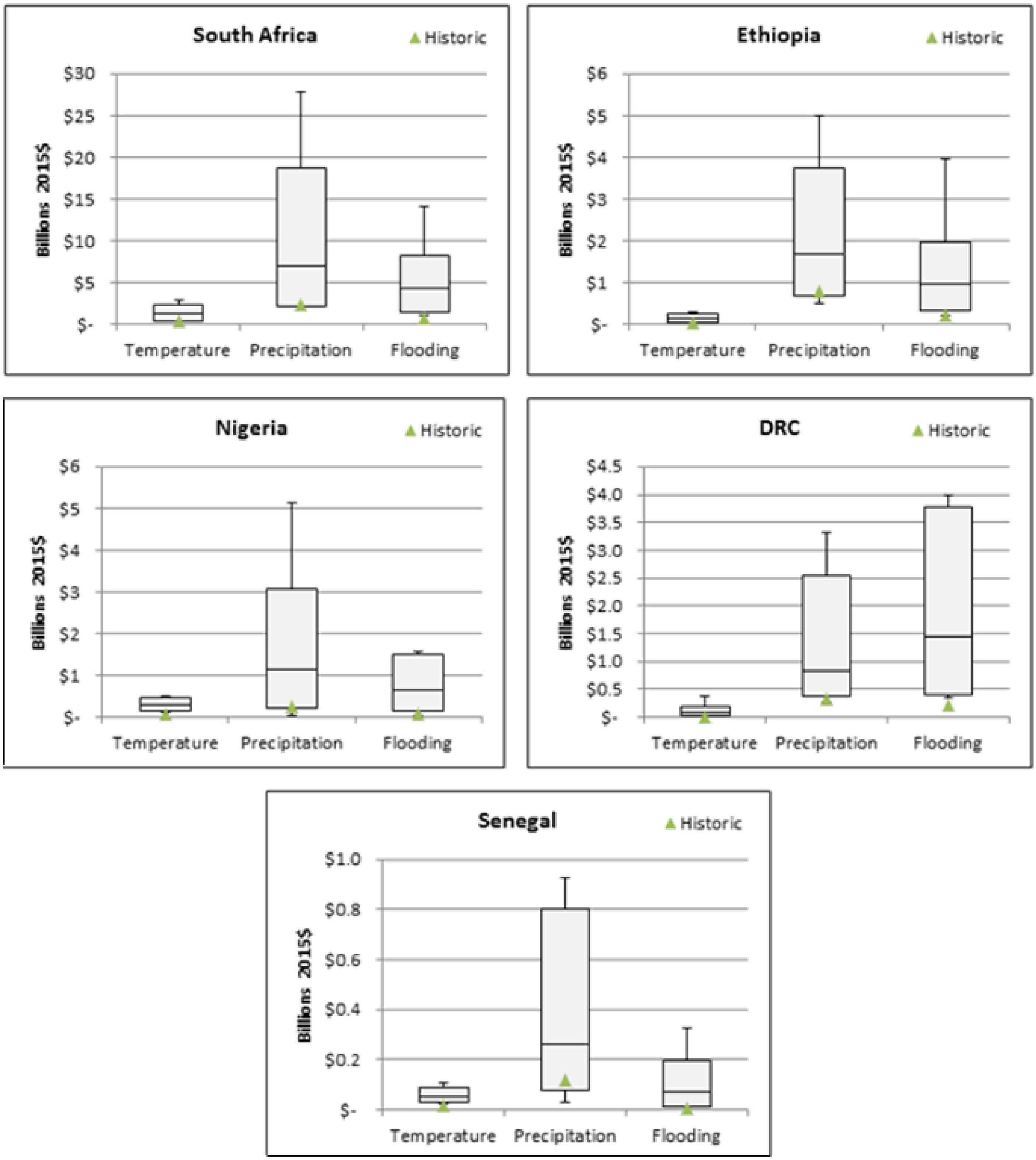
Note: The chart provides an indication of the impact of climate change relative to the optimal maintenance for a historic climate – because actual road maintenance is typically underfunded relative to the optimal maintenance cost, impacts are likely to be higher than indicated. The vertical axis is normalized (at 100) to the historic (no-climate-change) costs. Bars that are higher than the 100 line represent costs of climate change relative to the optimal costs of maintenance for current climate; bars below the line indicate potential savings. Box indicates the range of cost from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range of costs from the 5th to the 95th percentile over climate change scenarios.

5.3 Reactive Response Costs by Country

The analysis examines reactive response costs for the five representative SSA countries highlighted in other areas of the report (DRC, Ethiopia, Nigeria, Senegal, and South Africa). The relative results by stressor vary across the five countries (Figure 5.8), consistent with variation in historical and forecast climates across SSA. For example, the highest estimated costs for DRC ($4 billion) are associated with the flooding stressor, while the highest estimated costs for Senegal ($16 million) are associated with the precipitation stressor. It is interesting to note that for Senegal the historical costs associated with the precipitation stressor are slightly higher than the minimum estimated reactive response costs – suggesting that while some climate futures could be more benign than the historical climate, and lead to lower costs of road maintenance, this effect is small and effectively inconsequential.

Overall, costs are highest in South Africa due to the fact that it contains 21% of the 2050 PIDA+ network, while the other countries contain only 1-8%. In addition, within South Africa the majority of the network (74%) is unpaved, making it particularly vulnerable to precipitation and flooding stressors.

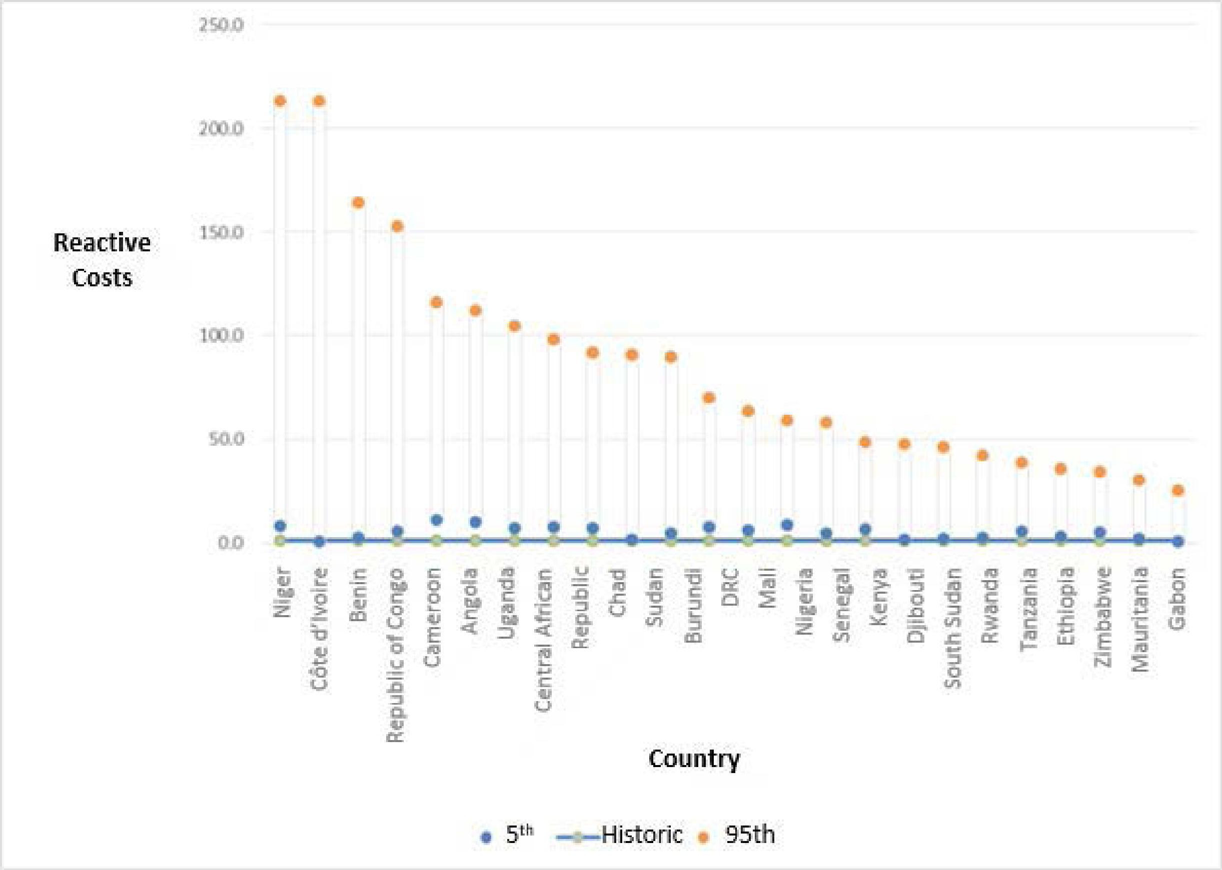
Figure 5.8. Reactive response costs for the PIDA+ network in five representative SSA countries, 2015-50 (6% discount rate)



Note: Green triangle indicates costs estimated for a historic climate. Box indicates the range of costs from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile over climate change scenarios.

Results for the PIDA network for all countries are presented in Figure 5.9 below, using a logarithmic vertical scale, normalized to historic climate costs. Results vary by country but show the potential for a very large increase in reactive costs for the 95th percentile of climate scenarios (shown in orange), with countries on the left side of the graph showing potential for costs over 100 times the current climate maintenance requirements. Costs for the 5th percentile climate (shown in blue) indicate that under scenarios of mild climate change, costs could be close to historic costs in most countries.

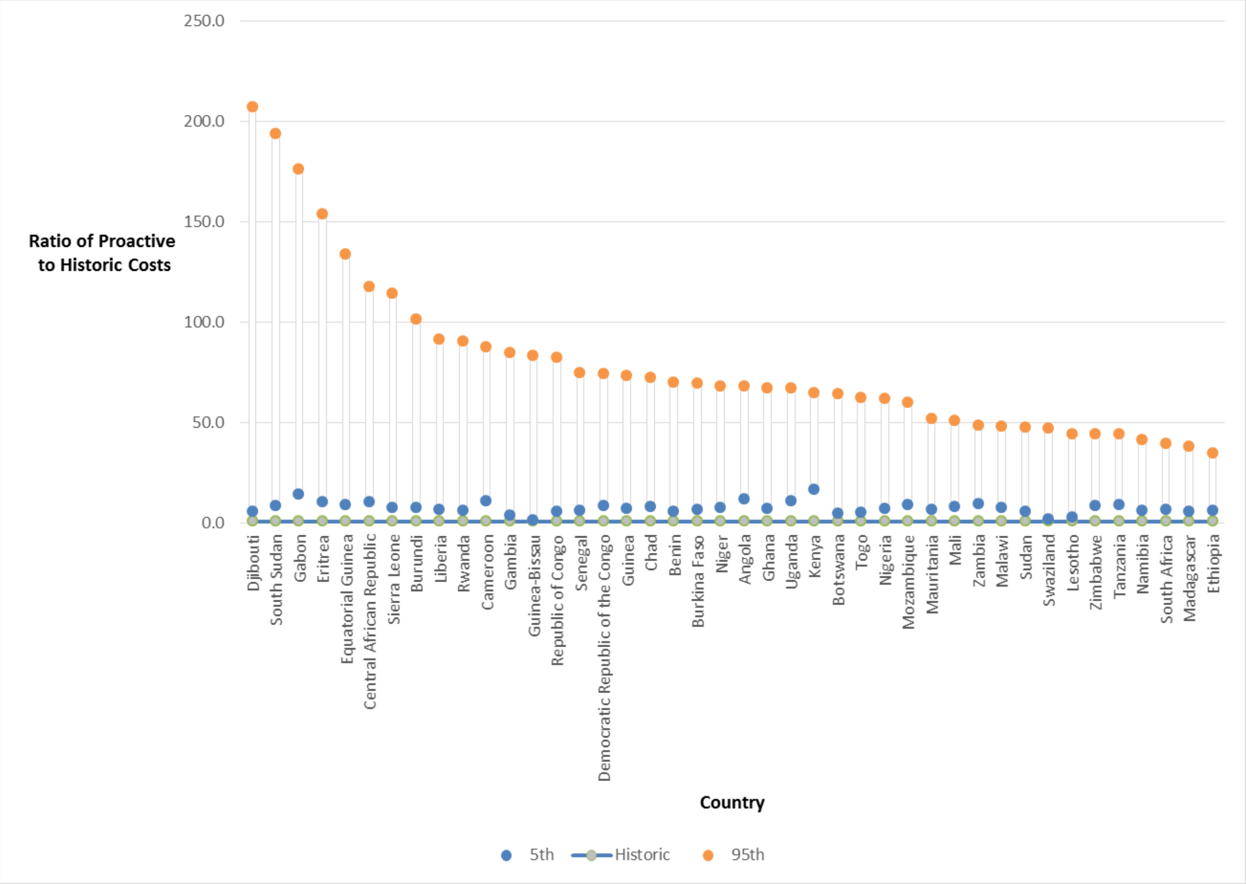
Figure 5.9. Reactive costs, NPV for PIDA roads by country, all stressors, normalized by historic costs, with a 6% discount rate



Note: The chart provides an indication of the impact of climate change relative to the optimal maintenance for a historic climate – because actual road maintenance is typically underfunded relative to the optimal maintenance cost, impacts are likely to be higher than indicated. The blue line shows the country-specific historic (no-climate-change) costs. Blue dot shows the result for the 5th percentile (mildest) climate change scenarios; orange dot shows the result for the 95th percentile (most damaging) scenario. Somalia was removed from this figure since it has fewer than 100 km of PIDA roads.

Figure 5.10 below provides a summary of reactive costs for the PIDA+ network, paved and unpaved roads, for all countries, aggregated across all stressors, with the results scaled by the historic climate reactive response costs. Variation across countries is dependent on the regional distribution of climate changes; the starting climate (as road infrastructure is assumed to be built to withstand current climate, making areas that are relatively cool or dry potentially more vulnerable as climate gets hotter and/or wetter), and the distribution of road types, with unpaved roads typically being more vulnerable.

Figure 5.10. Reactive costs, net present value for PIDA+ paved and unpaved roads by country, all stressors, with 6% discount rate

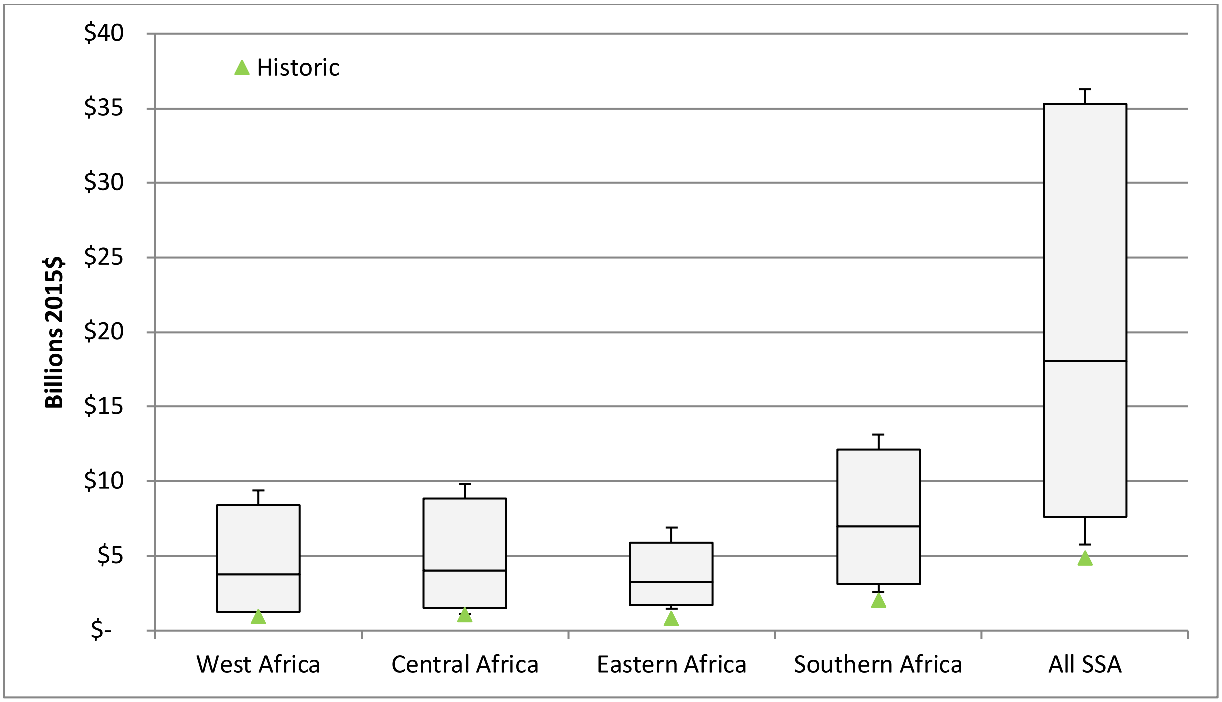


Note: The chart provides an indication of the impact of climate change relative to the optimal maintenance for a historic climate – because actual road maintenance is typically underfunded relative to the optimal maintenance cost, impacts are likely to be higher than indicated. The blue line shows the country-specific historic (no-climate-change) costs. Blue dot shows the result for the 5th percentile (mildest) climate change scenario; orange dot shows the result for the 95th percentile (most damaging) scenario.

5.4 Risks of Inaction for SSA Bridges

Climate change also has significant impacts on Africa’s bridge network. Although no comprehensive inventory of bridges exists for the continent, this study estimates there are approximately 330,000 bridges across SSA (see Section 2.6 for a description of the methods used to develop the study’s bridge inventory). Based on the size of their respective road crossings, approximately 230,000 (69%) of these bridges are small (associated with tertiary roads), 76,000 (23%) are medium sized (associated with secondary roads), and 26,000 (8%) are large (associated with primary roads). In the reactive response scenario, the mean estimated cost for the PIDA+ bridge inventory is $18 billion for 2015-50 (6% discount rate), [6] compared to a historical cost of about $5 billion (see Figure 5.11 below). Costs vary by climate scenario, however, with the 5th percentile climate showing costs of $7.6 billion, a 50% increase over historic costs, and the 95th percentile showing costs of just over $35 billion, 7 times the historic cost. Climate change therefore very clearly presents a substantial risk to Africa's bridges, across all projected future climates, and to the vital connectivity they provide for the transport network.

Figure 5.11. Reactive response costs to SSA bridges by region, 2015-50 (6% discount rate)



Note: Green triangle indicates costs estimated for a historic climate. Box indicates the range of costs from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range of costs from the 5th to the 95th over climate change scenarios.

Figure 5.12 presents the reactive response costs for bridges in five representative SSA countries for small, medium, and large bridges, to provide an illustration of how costs vary by country. The main driver of costs by country in this analysis, which due to data limitations relies on a synthetically produced inventory, is the extent of the road network coupled with the number of crossings of the road network with in-country river system.

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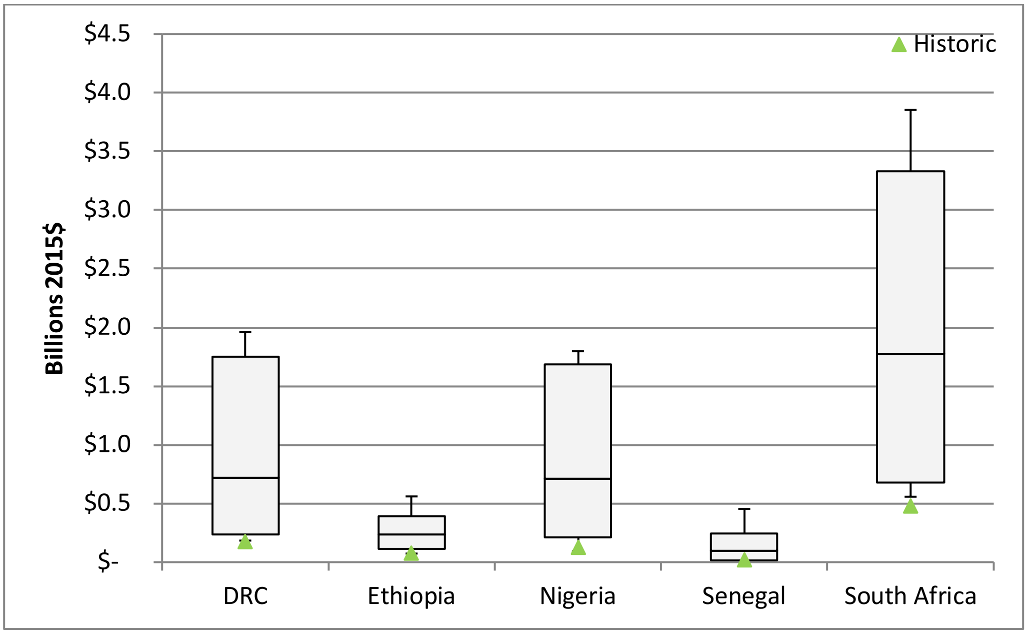
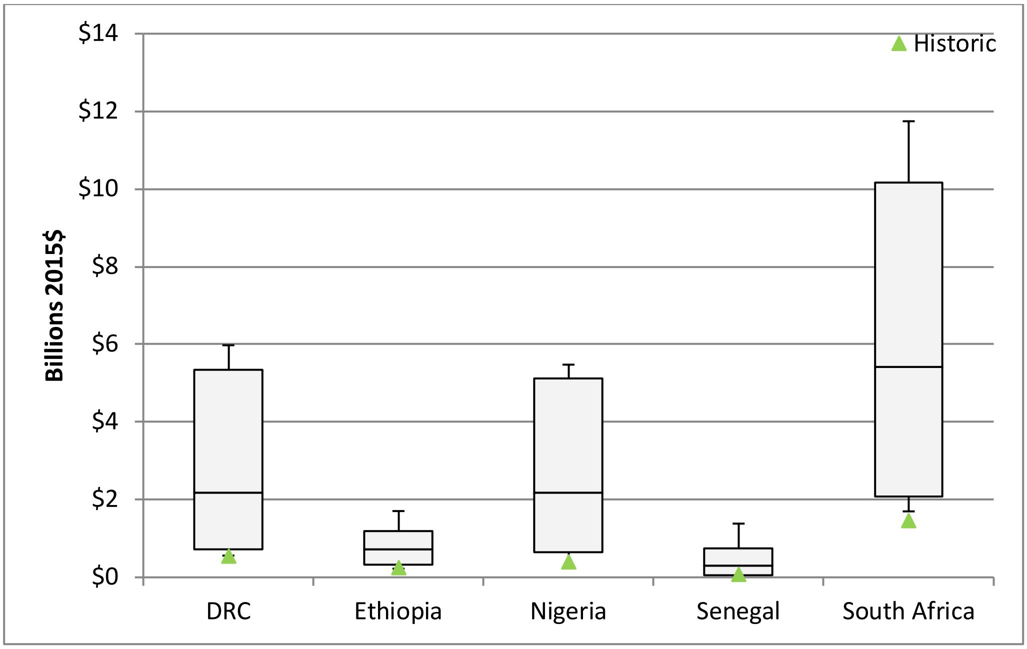
[6] Corresponding to the mean cost across the distribution of climate futures analyzed.

Figure 5.12. Reactive response costs for bridges in five representative SSA countries, 2015-50 (6% discount rate)

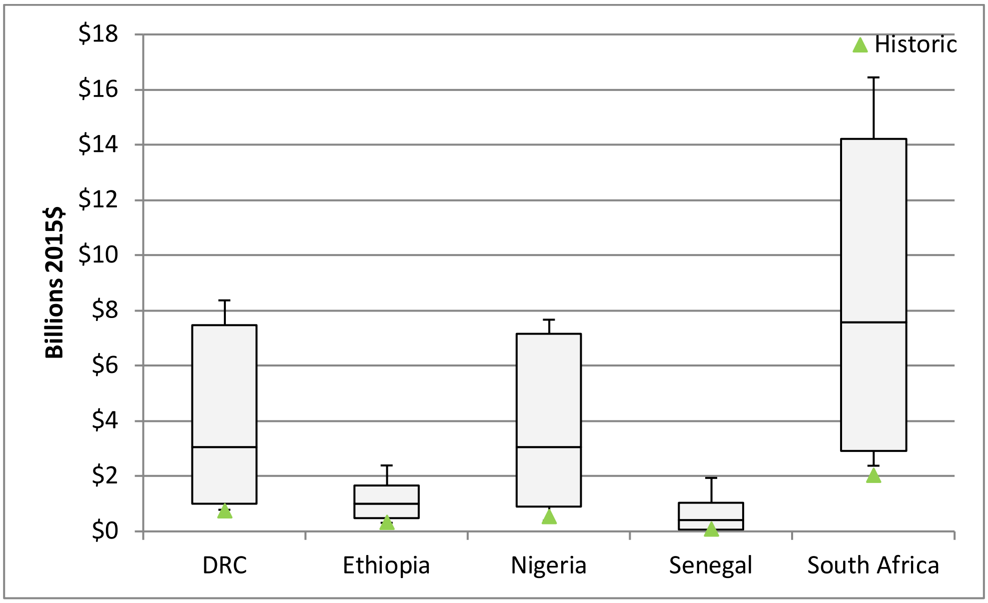
Panel A: Costs for small bridges



Panel B: Costs for medium bridges



Panel C: Costs for large bridges



Note: Green triangle indicates costs estimated for a historic climate. Box indicates the range from the 25th to the 75th percentile future climate outcome; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile climate outcome.

The risks of inaction to the PIDA+ road and bridge network presented in this chapter highlight the need to consider an alternate course of action in the face of climate change risks – one that makes use of climate forecasts and strategically enhances the resiliency of infrastructure to potential future impacts through preventative adaptation measures. Chapter 6 presents the results of the proactive adaptation analysis and examines the potential savings of this approach compared to the reactive response strategy.

CHAPTER 6

Adaptation Analysis

Paul Chinowsky, Andrew Losos, James E. Neumann, Kenneth M. Strzepek, and Raffaello Cervigni

The objective of the adaptation analysis is to determine where and under what conditions it is advantageous to enhance the resiliency of infrastructure to potential future impacts through proactive adaptation, and where and under what conditions is it more cost-effective to take a reactive response. The analysis compares costs under the proactive adaptation scenario to costs under the reactive response scenario for the PIDA and PIDA+ networks, for a near-term time period (2015-2030) and a long-term time period (2015-2050).[7] We first examine the results at the continental (SSA-wide) level to determine what key messages emerge for SSA as a whole. We then look at the results at the country level.

In addition, the analysis compares disruption (quantified as the time out-of-service resulting from climate-induced impacts) under the proactive adaptation and reactive response scenarios. To determine whether proactive adaptation can be financially justified when taking into considering the costs of disruption, we examine the "breakeven point" where the value of time lost because of disruption is large enough to justify the adoption of a proactive approach. This analysis provides additional insights for adaptation planning.

6.1 Assessment of Proactive Adaptation across SSA

Across SSA, the mean costs of climate change for the PIDA+ network associated with the reactive response scenario are estimated at $56 billion for 2015-50 (6% discount rate), 10 times the historical costs, and range, across climate scenarios, from about 50% higher to 7 times higher than historical costs. Proactive action has the potential to reduce those impacts, if properly focused. Figure 6.1 below shows the savings from proactive adaptation in response to the three climate stressors (temperature, precipitation, and flooding) for the PIDA paved roads (panel a) and the

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[7] Adaptation of the road and bridge system to climate change should ideally reflect the vintage of the roads and bridges analyzed, with specific estimates of when the rehabilitation and replacement cycles occur. For the PIDA component of the road inventory, the expected build date provides information to trigger the start of a maintenance cycle, followed a rehabilitation action when useful life of the road is effectively exhausted. With useful life of 20 to 30 years, many roads in the inventory will undergo major rehabilitation twice during the full study period, perhaps once prior to 2030, and once after 2030 – and in the meantime, climate change will be progressing. This reality provides the logic for looking at the two periods. Data limitations on the actual vintage of existing roads, however, require a statistical approach to determining the age of capital for the non-PIDA portion of the inventory. As a result, there are limitations on the ability to look more carefully at distinct rehabilitation cycles in the pre-2030 versus post-2030 periods.

PIDA+ paved (panel b) and unpaved (panel c) roads.[8] The results are for 2015-50 (6% discount rate). For the PIDA roads (panel a), proactive adaptation in response to the temperature stressor results in mean savings of approximately $80 million. For the precipitation and flooding stressors, however, broad application of proactive action leads to negative savings (i.e. losses) in several climate scenarios, suggesting that a blanket approach to invest in resilience to precipitation and flooding stressors across all PIDA projects is not cost-effective.

For the PIDA+ paved roads (panel b), proactive adaptation results in savings only in certain climates, but the mean savings are negative (losses), suggesting that here, too, more analysis is needed to determine when and where to take proactive action. For unpaved roads (panel c), proactive adaptation in response to both the precipitation and flooding stressors leads to losses, with particularly large losses for the precipitation stressor.[9] In the PIDA+ network, which has a high percentage of existing unpaved, gravel roads, proactive adaptation to increase resilience to the precipitation stressor largely involves adding pavement, which proves to be prohibitively costly and does not adequately reduce periodic maintenance costs.

There are, however, arguments for investing in proactive adaptation in response to the precipitation and flooding stressors for both the PIDA and PIDA+ road inventories. The following sections explore the circumstances under which this investment is justified for certain geographic scales and/or to avoid disruption impacts. In addition, we examine the costs of proactive adaptation within the context of overall PIDA investment costs.

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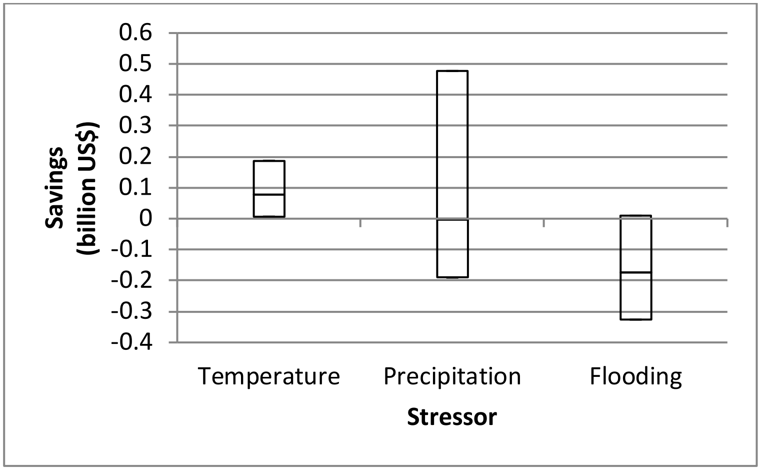
[8] There are only paved roads in the PIDA network, but the PIDA+ network includes both paved and unpaved roads.

[9] Temperature is not a stressor for unpaved roads.

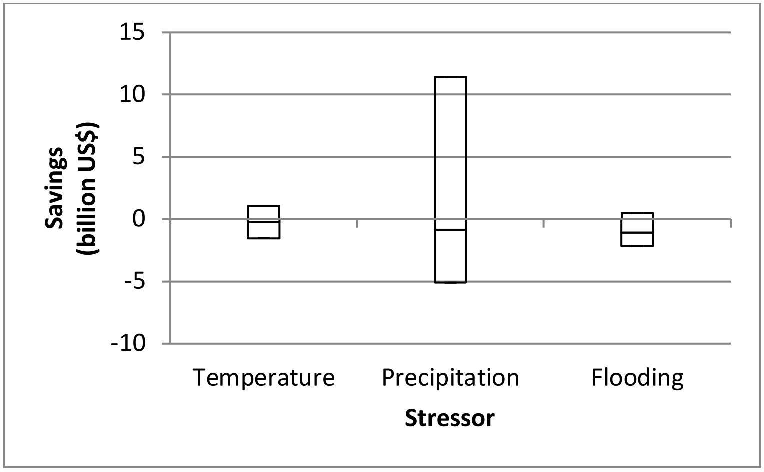
Figure 6.1. Savings from proactive adaptation across SSA, 2015-2050 (6% discount rate)

Panel A: PIDA paved roads



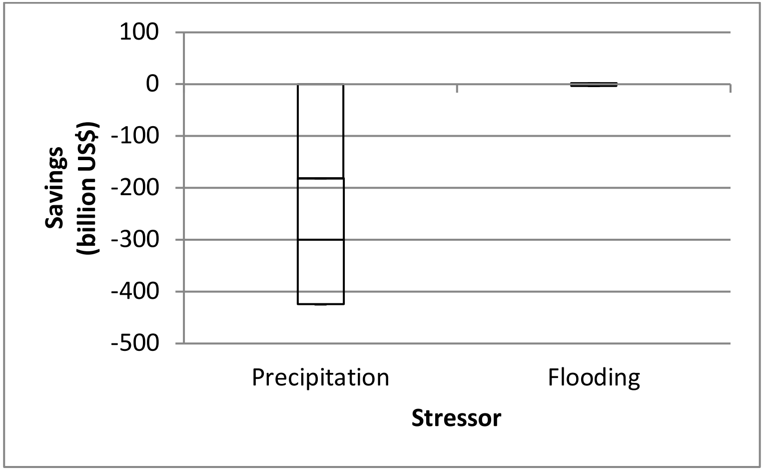
Note: Boxes show the 5th-95th percentile of savings across climate scenarios; break in box is the mean.

Panel B: PIDA+ paved roads



Note: Boxes show the 5th-95th percentile of savings across climate scenarios; break in box is the mean.

Panel C: PIDA+ unpaved roads



Note: Boxes show the 5th-95th percentile of savings across climate scenarios; break in box is the mean.

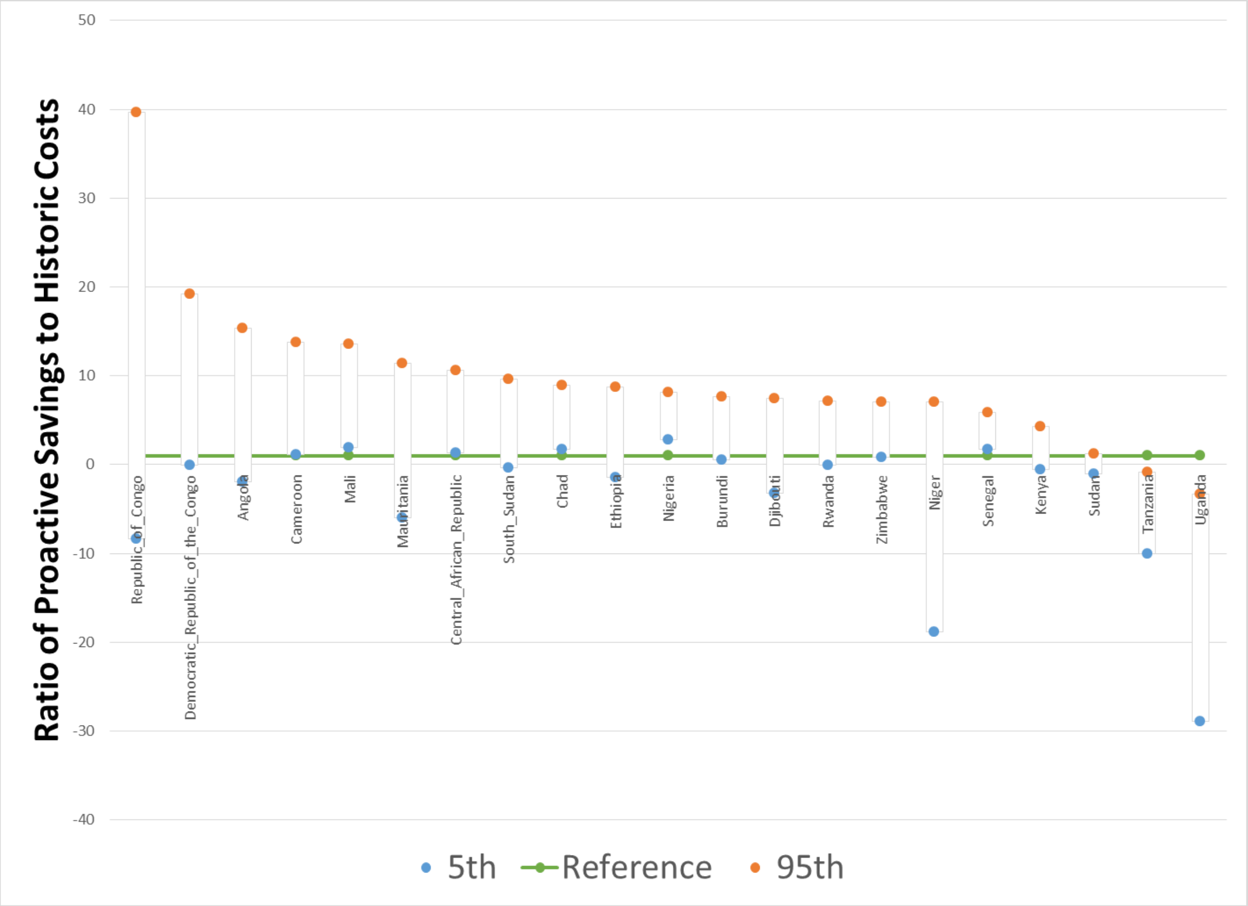
6.2 Assessment of Proactive Adaptation at the Country Level

In this section, we examine the country-level results of the proactive adaptation analysis. We focus on the PIDA+ road network, where proactive adaptation is not always financially justified at the national level, as described in Figure 6.1. Figure 6.2 shows the 5th and 95th percentile of cost savings under the proactive adaptation scenario for the PIDA+ network by country for the period 2015-2015 (6% discount rate) in response to temperature (panel a and b), precipitation (panels c and d), and flooding (panels e and f). A comparison of the country-level results suggests the following conclusions:

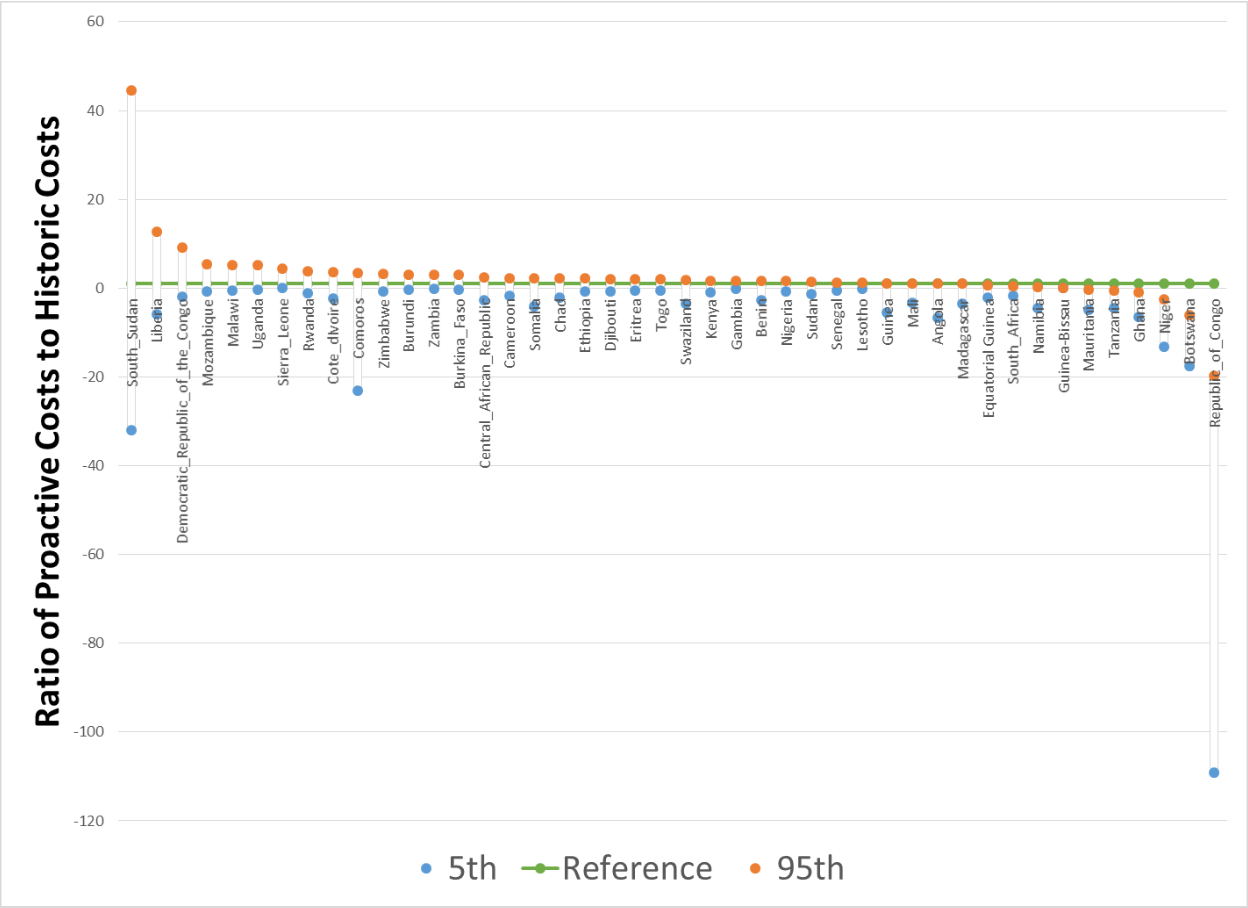
- In many countries, proactive adaptation in response to the temperature stressor is often financially justified for paved roads (panel a and b), particularly when focused on the new PIDA paved roads (panel a). Even in the milder scenarios of climate change (approximated by the 5th percentile of the distribution of climate outcomes, represented by the blue dot in the graphs), proactive adaptation is financially justified for many countries where the blue dot is above or close to the green line, which represents historic costs. For these countries, proactive adaptation of paved roads presents low or no regrets, because savings are nearly guaranteed. The case for proactive adaptation for the mostly existing (PIDA+) paved roads (panel b) is more mixed.
- Proactive adaptation in response to the precipitation stressor results in losses for the majority of countries for both paved and unpaved roads (panels c and d, respectively). This is particularly true for unpaved roads, where the only adaptation available is to pave the roads, which is very costly. For roads that are currently paved, there are many countries for which the 95th percentile climate outcome shows positive savings. Where the 5th percentile shows relatively small losses, there is a good chance that consideration of disruption costs may tilt the balance toward proactive action (see Figure 6.4).
- For the flooding stressor, the financial savings potential across climate outcomes appears to be larger for unpaved (panel f) than for paved roads (panel e), because of the lower costs associated with modifying unpaved roads to accept a larger culvert beneath the road bed (that is, there are higher costs for the proactive action to raise a paved road than an unpaved road so a larger culvert can be placed beneath it).

Figure 6.2. Savings from proactive adaptation by country, normalized by historical costs

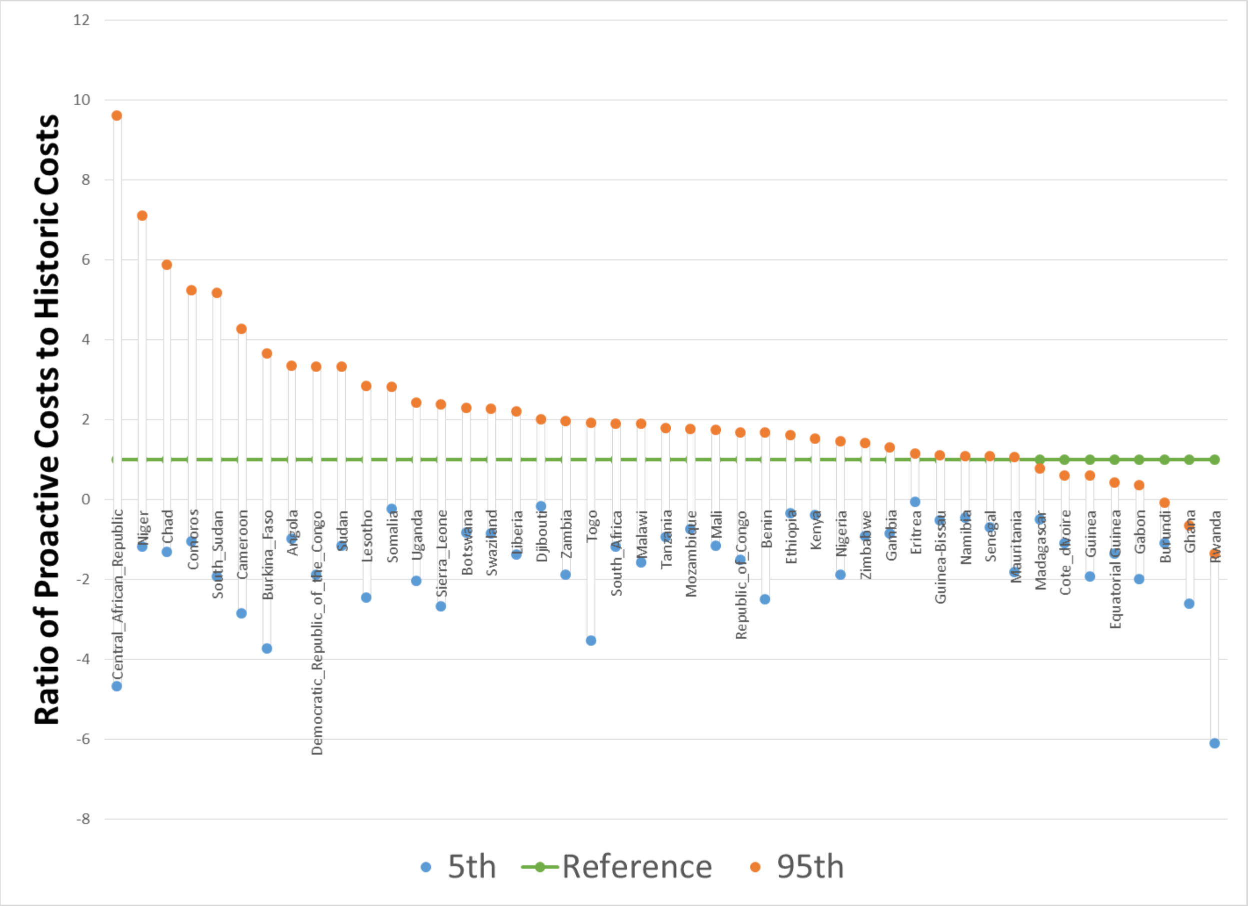
Panel A: In response to the temperature stressor (PIDA new paved roads only)



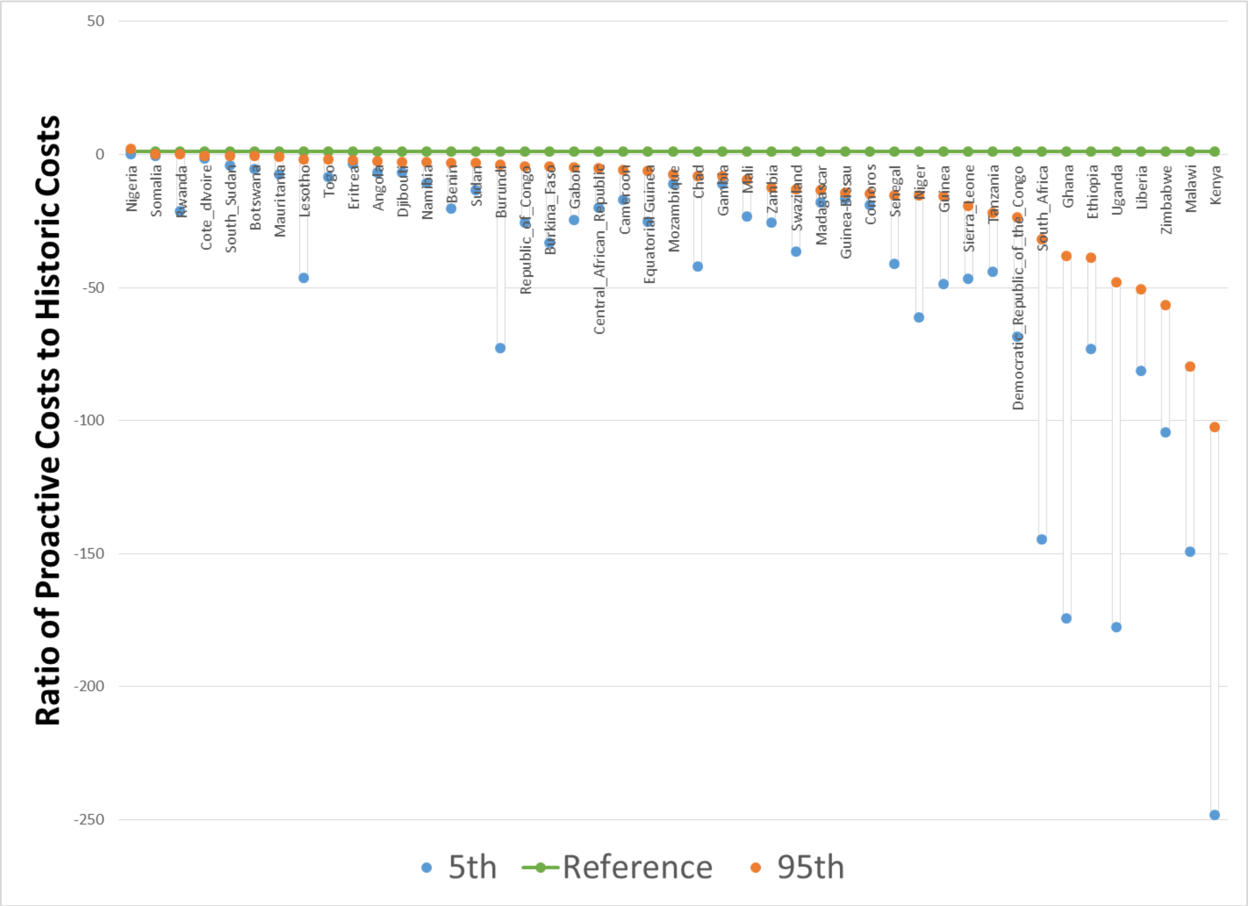
Panel B: In response to the temperature stressor (PIDA+ paved roads only)



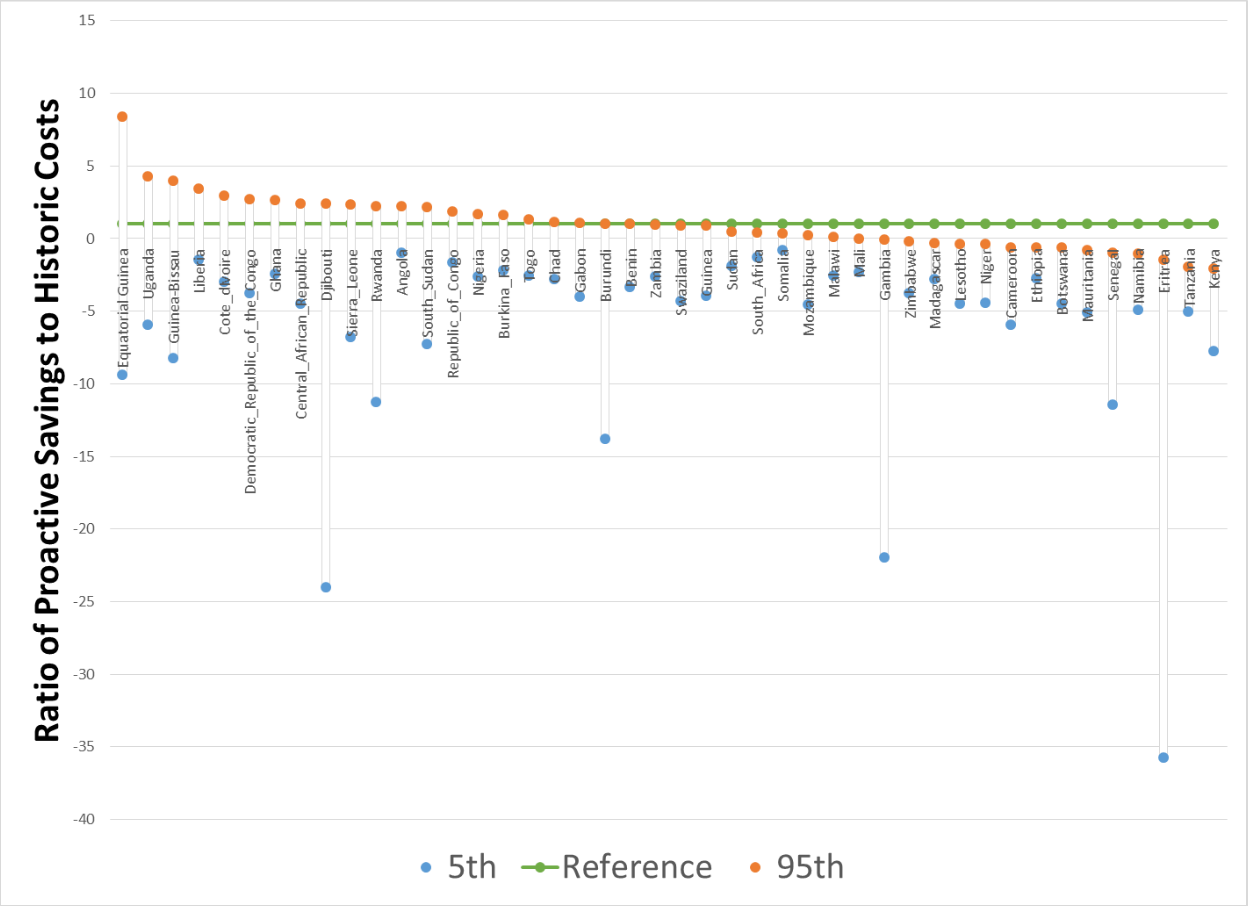
Panel C: In response to the precipitation stressor for paved roads



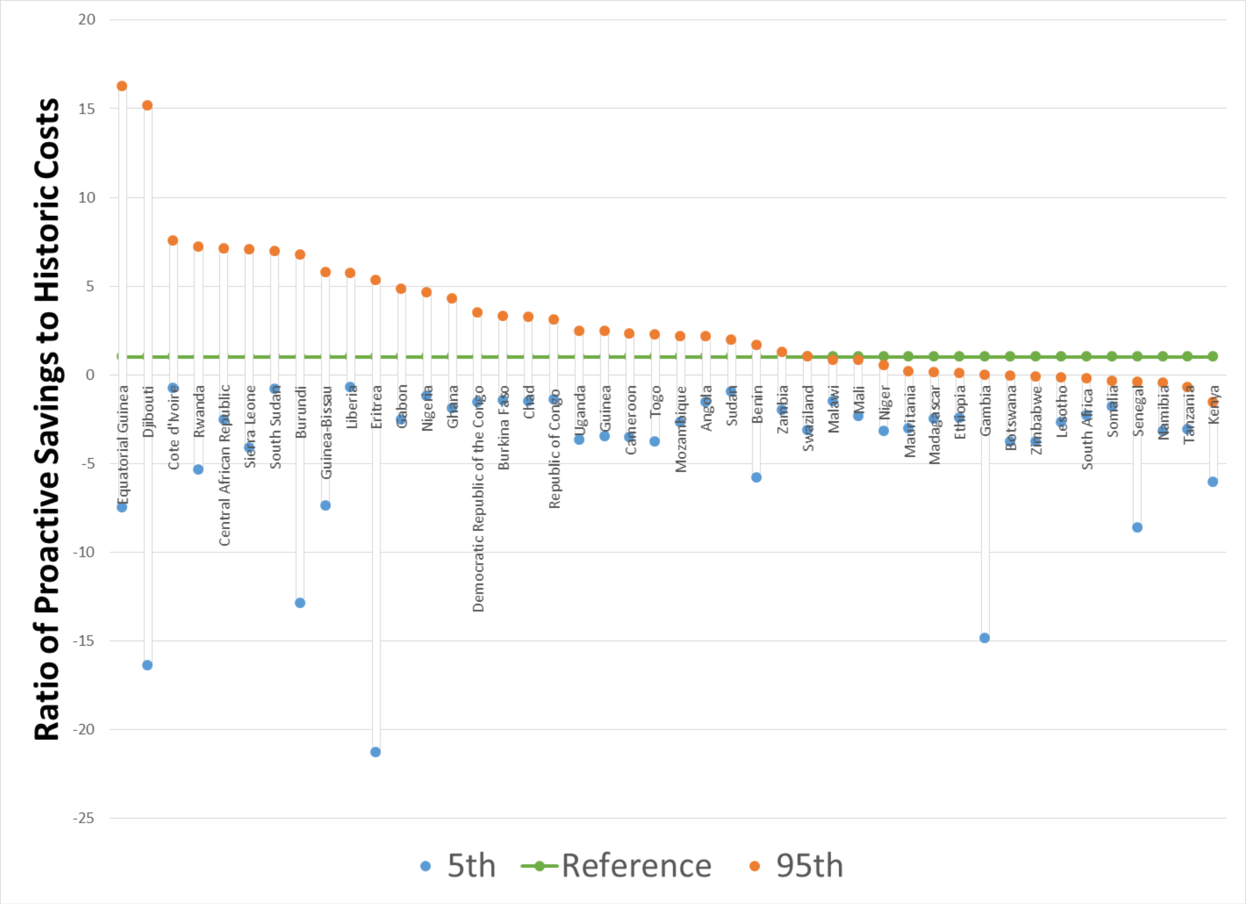
Panel D: In response to the precipitation stressor for unpaved roads



Panel E: In response to the flooding stressor for paved roads



Panel F: In response to the flooding stressor for unpaved roads

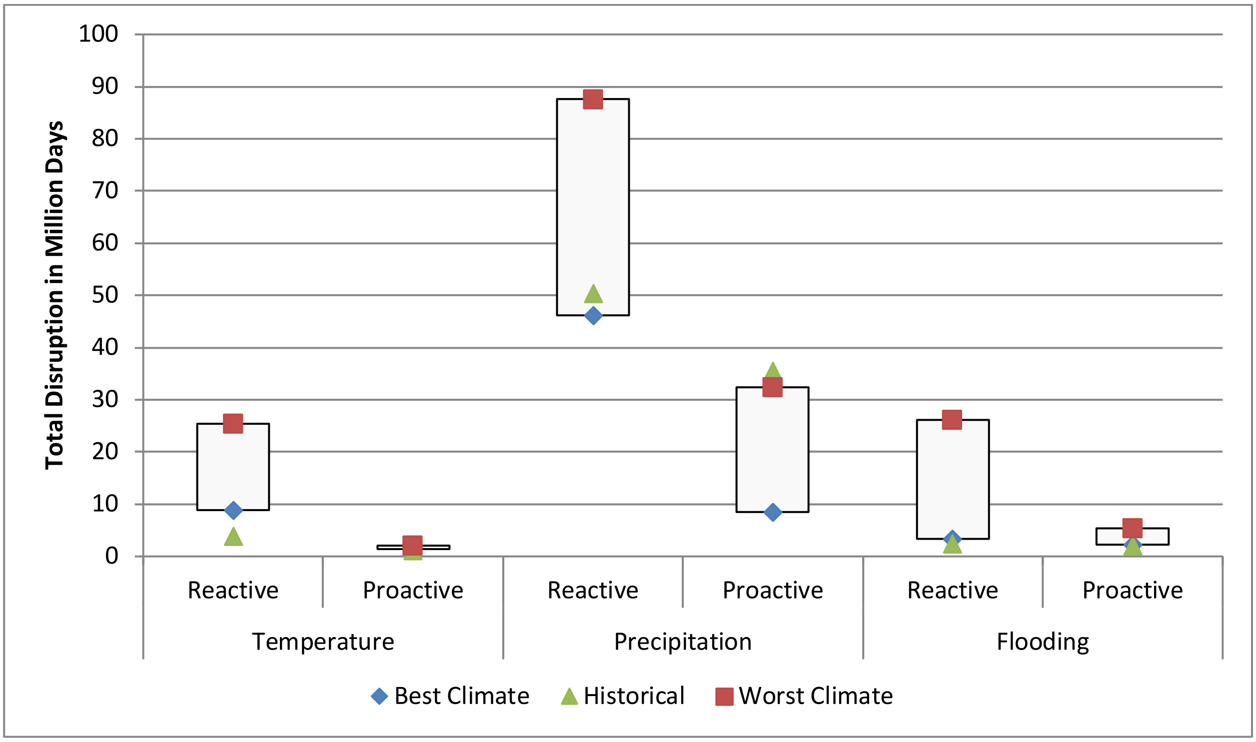


Note: Blue dot shows the result for the 5th percentile future climate outcome; orange dot shows the result for the 95th percentile future climate outcome. Green line corresponds to historic costs, values on y-axis are multiples of proactive savings to historic costs (savings can be negative if proactive costs exceed reactive costs).

6.3 Reducing Disruption Time through Proactive Adaptation

This section examines how proactive adaptation affects disruption of the PIDA+ road network (quantified as the time out-of-service resulting from climate-induced damages). Figure 6.3 shows the total disruption days under the reactive and proactive approaches for the three stressors. As shown, the reactive response approach results in greater disruption than proactive adaptation. Because this cumulative physical effects measure is difficult to reliably monetize, the key question is therefore whether savings in maintenance costs, plus avoided disruption, is sufficient to justify a proactive adaptation approach for roads; this is discussed in the next section.

Figure 6.3. Disruption benefits of adaptation for the PIDA+ network, 2015-50



Note: The blue and red data points refer to the disruption time under the mildest/ best climate scenario, and the strongest/ worst climate scenarios, respectively. Green triangle shows result for historic climate.

6.4 Evaluating the Combined Financial and Time Benefits of adaptation

In addition to the financial analysis presented in Sections 6.1 and 6.2, it is also important for decision makers to take into consideration the effect of proactive adaptation on disruption time. Due to the fact that it is difficult to monetize disruption, this analysis instead identifies for each climate scenario the "breakeven" point at which the value of the avoided disruption time is large enough to justify the incremental construction costs of adaptation. Disruption is measured using a measure of a road's days out of service – but a better measure of disruption needs to consider traffic volumes – i.e., the number of trips that are disrupted, not the number of days the road is impassable. When interpreting the results of a break-even analysis, a low breakeven value implies the economic value of disrupted trips does not need to be very high to make up for the incremental construction cost resulting from adaptation. In these cases, proactive adaptation may be justified. Conversely, if a breakeven value is high, proactive adaptation may not be justified to the extent that the value of disrupted trips must is not high enough to justify the incremental construction costs.

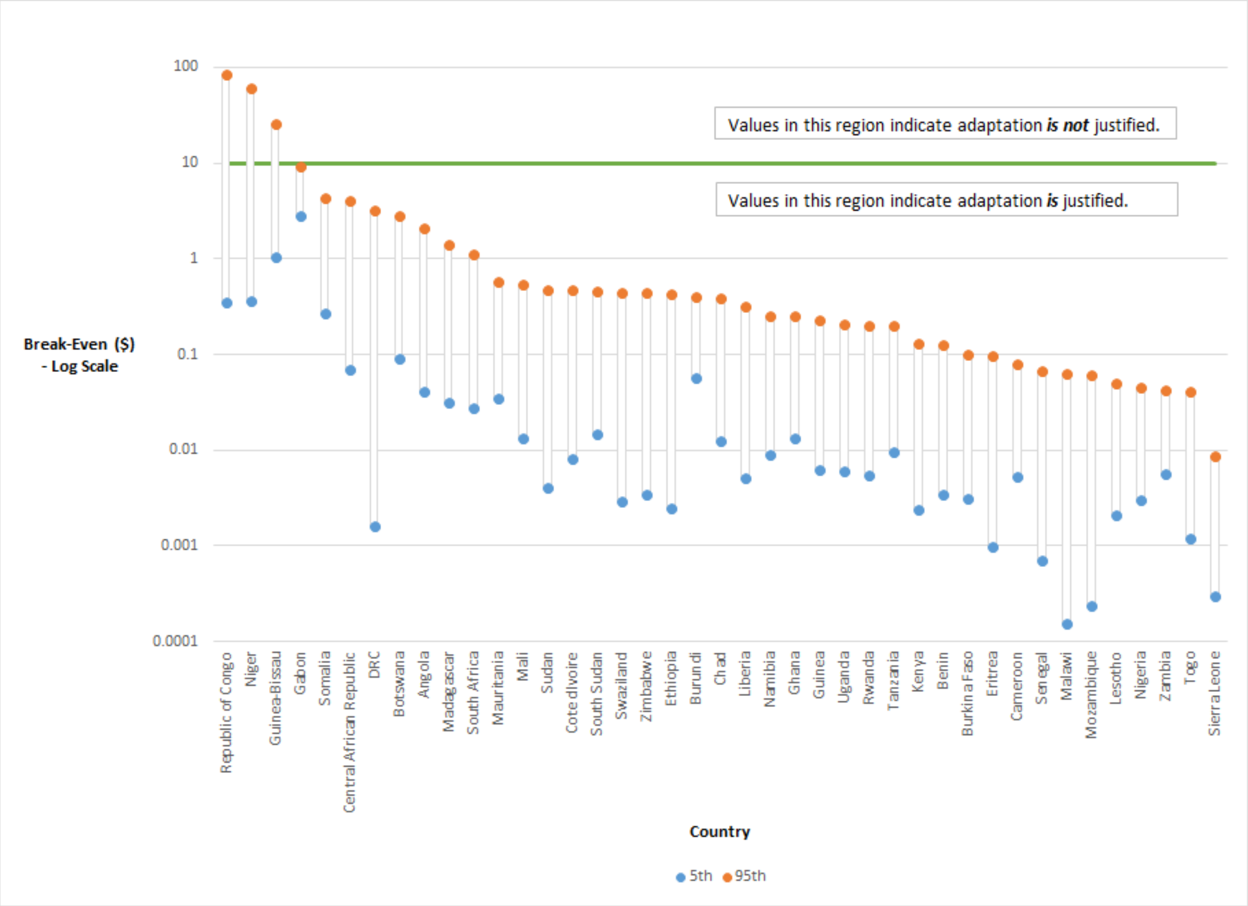
By comparing the breakeven values to a plausible estimate of the value of avoided time lost, road planners can better assess the merits of adaptation. Where breakeven values are higher than the estimated value of avoided time lost, proactive adaptation is not justified. However, breakeven values vary, depending on the climate change scenario considered. A simple way to deal with the resulting uncertainty is to look at scenarios of relatively mild climate change, where breakeven values will be higher (e.g. the 95th percentile of the distribution).

If the opportunity cost of time lost because of disruption is deemed higher than the high-end breakeven value, then proactive adaptation will be justified since the time benefits will be even higher in scenarios of more severe climate change.

Figures 6.4, 6.5, and 6.6 present the per-person, per-day breakeven values, adjusted for the distribution of traffic volume, by country, for the three climate stressors. In all three cases, the analysis uses an estimate of the value of a day of disruption per vehicle of $10. The average daily wage for most workers varies considerably across Sub-Saharan Africa, from roughly $30 per day in countries such as South Africa and Botswana, to as little as $3.50 per day in countries such as Ethiopia and Uganda, according to UN International Labor Organization data. Unfortunately, the ILO data address only a few of the countries in the study scope. For our purposes, using $10 per day as a rough benchmark value of an avoided day of disruption, per vehicle (a vehicle which may include multiple travelers), helps us to interpret the results.

In Figure 6.4, which refers to the temperature stressor, it is clear that in all countries except for the few on the far left of the graphic, the high-end breakeven values (approximated by the 95th percentile of the distribution) are less than $10 per day. The conclusion that follows is that, once disruption is considered, adaptation to the temperature stressor for all paved roads in these countries is justified. Consideration of disruption, when compared to the conclusions for the financial analysis alone, provides a justification not only for the new PIDA roads, but also for the rest of the existing and planned road network. Further, with deeper, in country analysis, the results could yield information about the optimal timing of these adaptations for the existing road network, through examination of the current climate, current road condition, and use of spatial projections of climate change available in the study dataset (at the 50 km by 50 km level).

Figure 6.4. Distribution of traffic normalized breakeven values across climate scenarios by country for PIDA+ paved roads, temperature stressor



Values in this region indicate adaptation ***is not*** justified.

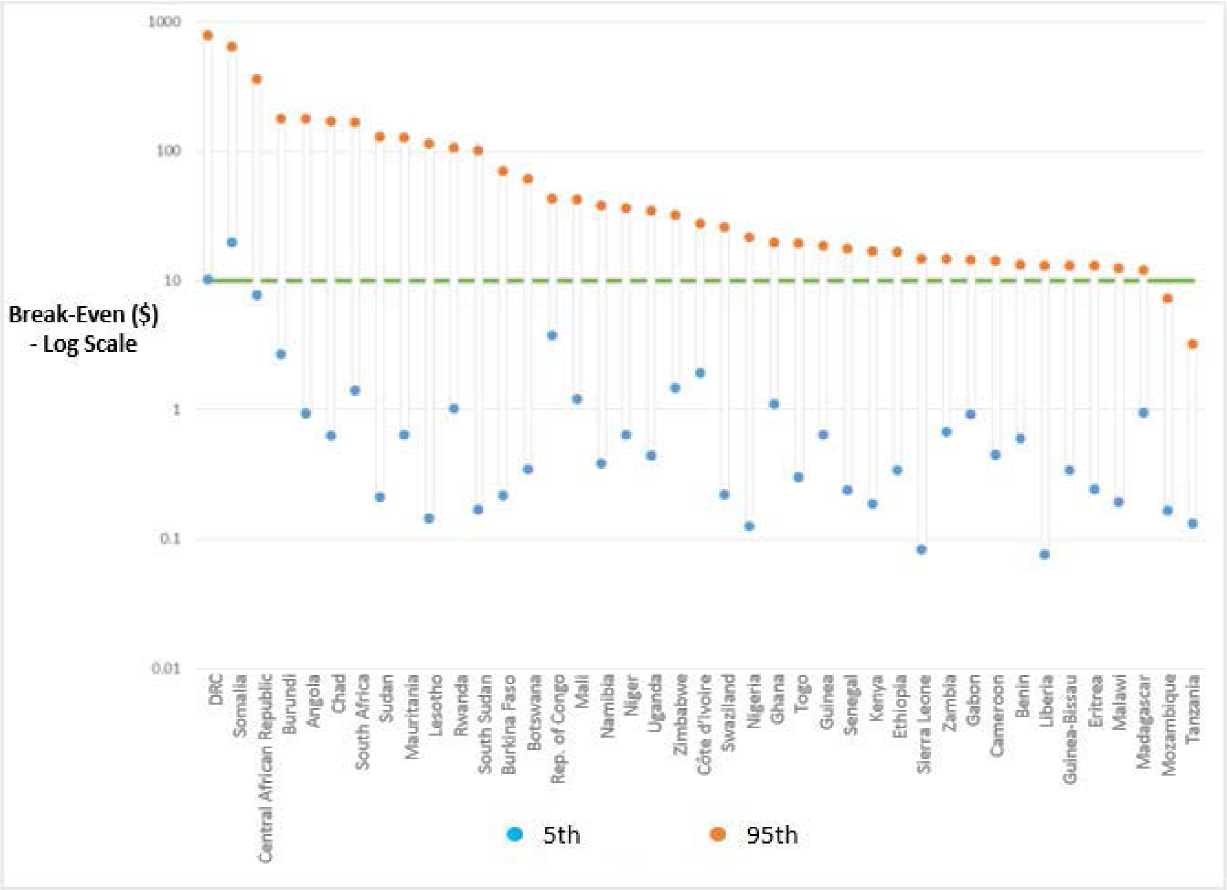
Values in this region indicate adaptation ***is*** justified.

Note: The chart provides an indication of the per-vehicle value of time required to justify proactive adaptation action (break-even value), considering both disruption time and financial cost implications. Higher break-even values imply action may not be justified – lower breakeven values imply action is justified. Blue dot shows the result for the 5th percentile (lowest break-even value) over climate change scenarios; orange dot shows the result for the 95th percentile (highest break-even value).

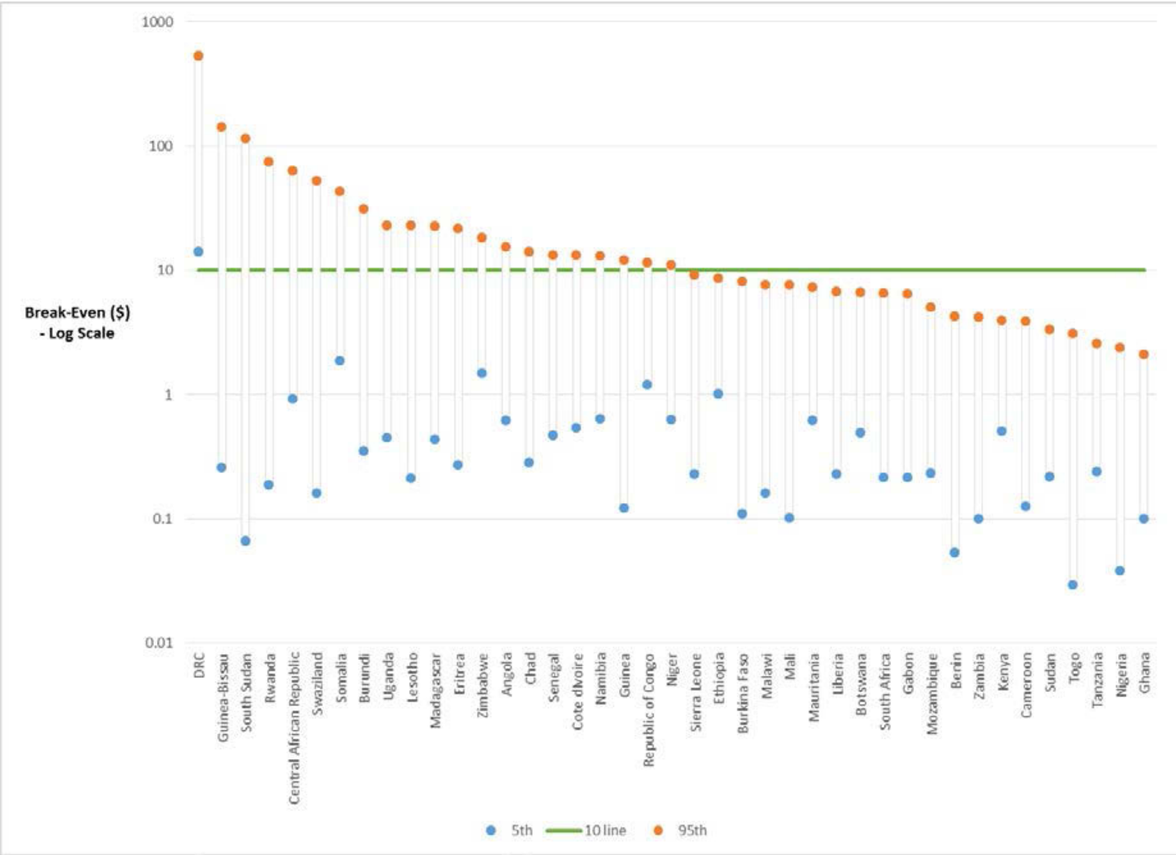
Figure 6.5 presents the same information, but for the flooding and precipitation stressors as applied to paved roads. Results for the precipitation and flooding stressors show higher break-even values for disruption, compared to the temperature stressor, so only a few countries have a high-end breakeven value (95th percentile of climate scenarios) below $10 per vehicle-day, on the right of the graphic.

Figure 6.5. Distribution of breakeven values across climate scenarios, Sub-Saharan Africa for paved PIDA+ roads

Panel A: Precipitation stressor, paved roads



Panel B: Flooding stressor, paved roads

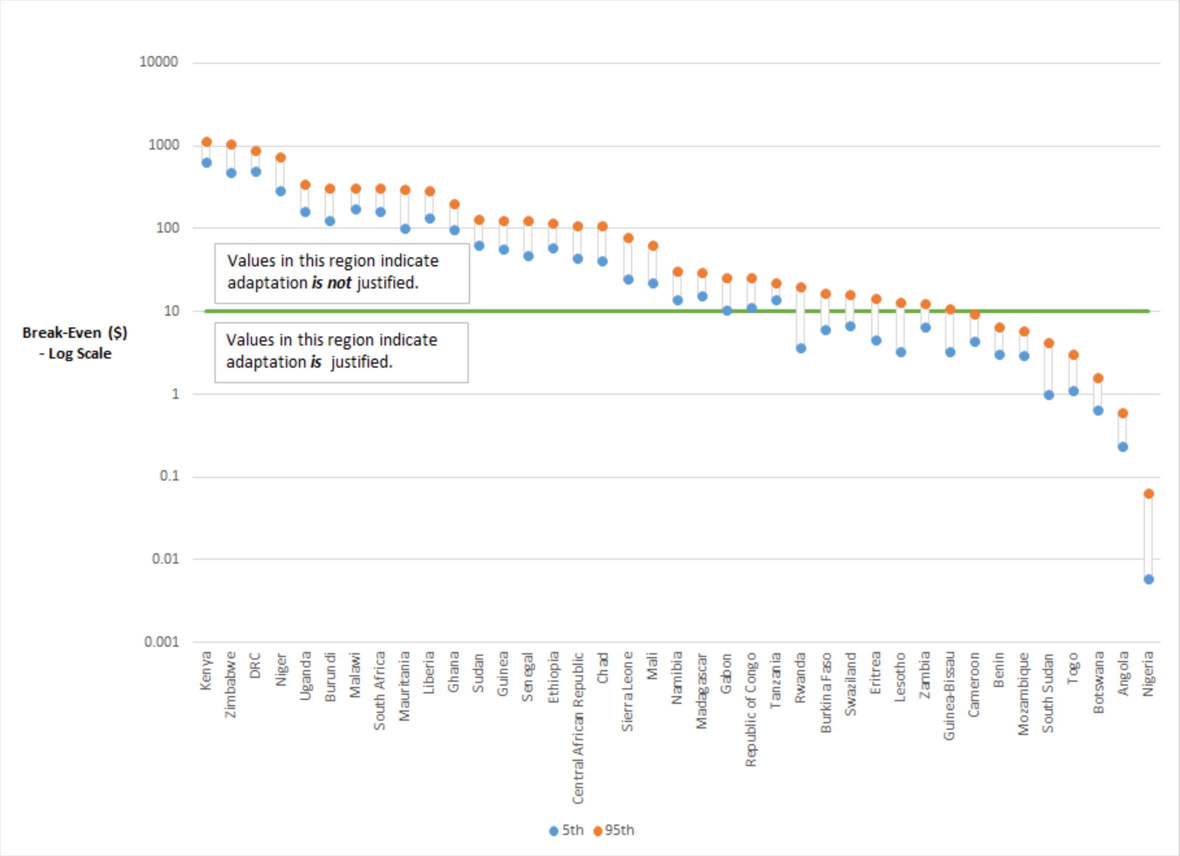


Note: The chart provides an indication of the per-vehicle value of time required to justify proactive adaptation action (break-even value), considering both disruption time and financial cost implications. Higher break-even values imply adaptation may not be justified – lower breakeven values imply adaptation is justified. Blue dot shows the result for the 5th percentile (lowest break-even value) over climate change scenarios; orange dot shows the result for the 95th percentile (highest break-even value).

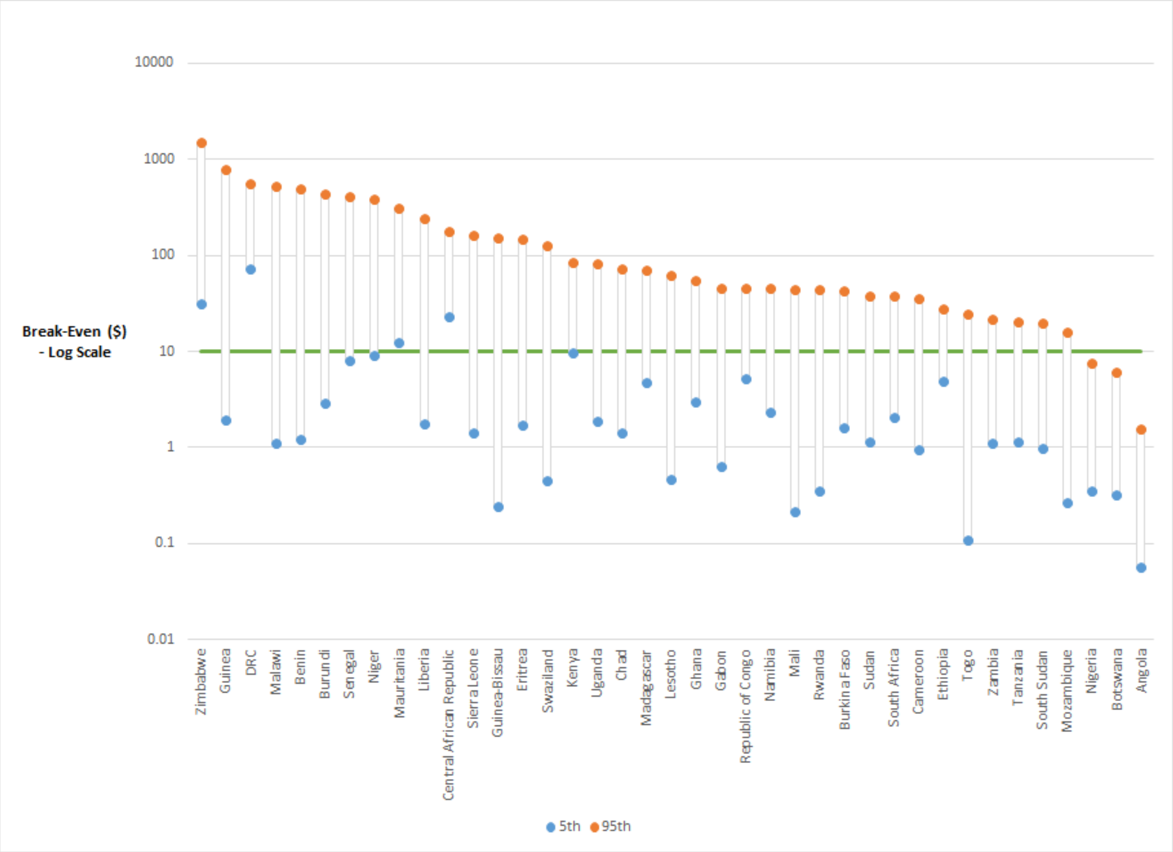
Figure 6.6 presents traffic-adjusted breakeven values for the flooding and precipitation stressors but as applied to unpaved roads. Results for both stressors applied to unpaved roads show the highest break-even values for disruption, but there remain a handful of countries where a high-end (approximated by the 95th percentile) breakeven value below $10 per vehicle-day is seen for all climate stressors, on the right of the graphics. These countries have both a high avoided disruption associated with adaptation, and relatively high unpaved road traffic volumes, relative to other countries in the scope of the study.

Figure 6.6. Distribution of breakeven values across climate scenarios, Sub-Saharan Africa for unpaved PIDA+ roads

Panel A: Precipitation stressor, unpaved roads



Panel B: Flooding stressor, unpaved roads



Note: The chart provides an indication of the per-vehicle value of time required to justify proactive adaptation action (break-even value), considering both disruption time and financial cost implications. Higher break-even values imply adaptation may not be justified – lower breakeven values imply adaptation is justified. Blue dot shows the result for the 5th percentile (lowest break-even value) over climate change scenarios; orange dot shows the result for the 95th percentile (highest break-even value).

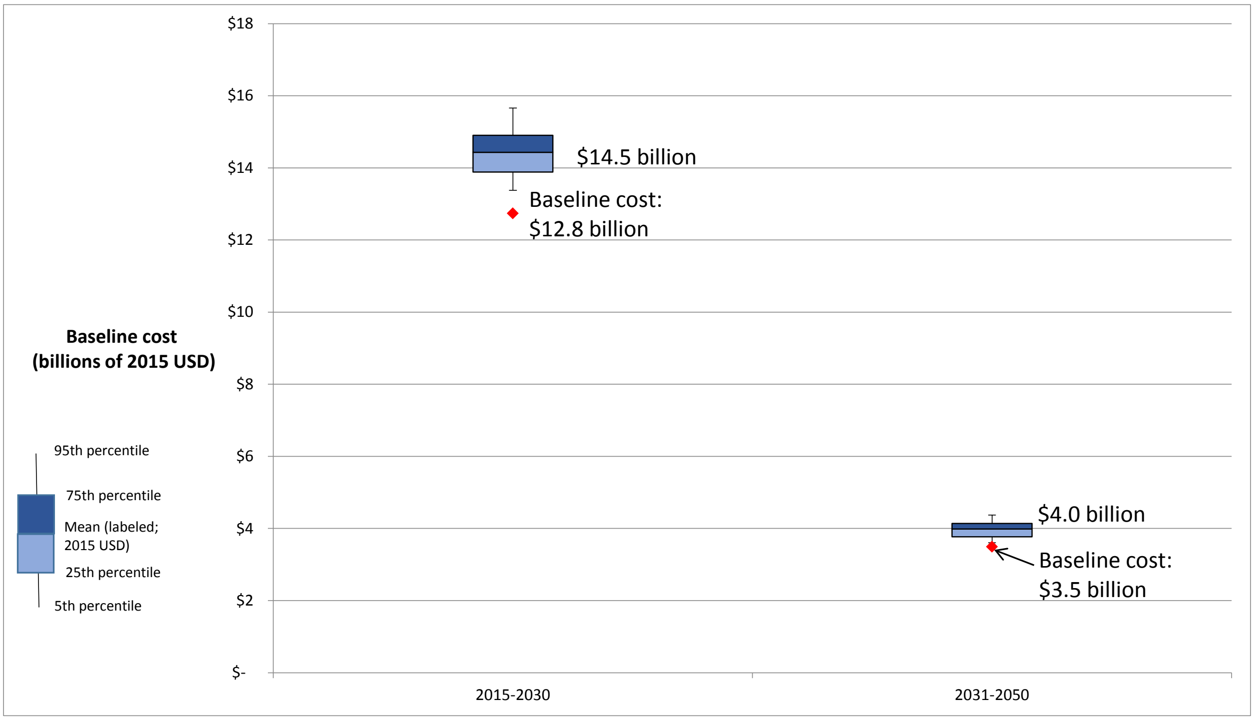
Road planners are likely to have more granular information, compared to what was possible to obtain for this study, on expected traffic volumes, redundancy at the road network level, and unit value of travel time. Using such data, the approach proposed in this report enables planners to make more informed decisions on whether a proactive adaptation response is justified in any particular project, in anticipation to climate change.

6.5 Costs of Proactive Adaptation for the PIDA Investments Across SSA

Analysis of the incremental investment required for proactive adaptation of the PIDA roads investments finds that only a relatively small additional investment is needed to achieve this goal (Figure 6.7). Most of the PIDA investments analyzed here are planned to occur by 2030 (many have projected construction completion dates in 2030), and the total baseline cost (i.e., with no adaptation) is estimated at $12.8 billion. For 50% of the future climates (between the 25th and 75th percentiles), resilience investments for all stressors would cost between $13.9 and $15 billion, with a mean cost of $14.5 billion (13% higher than the baseline). The 5th to 95th percentile range in the first period is $13.3 to $15.7 billion. The baseline costs in the later period are lower, at $3.5 billion, but the incremental cost is roughly proportional to that in the prior period.

Figure 6.7. Capital costs of proactive adaptation for the PIDA roads relative to baseline

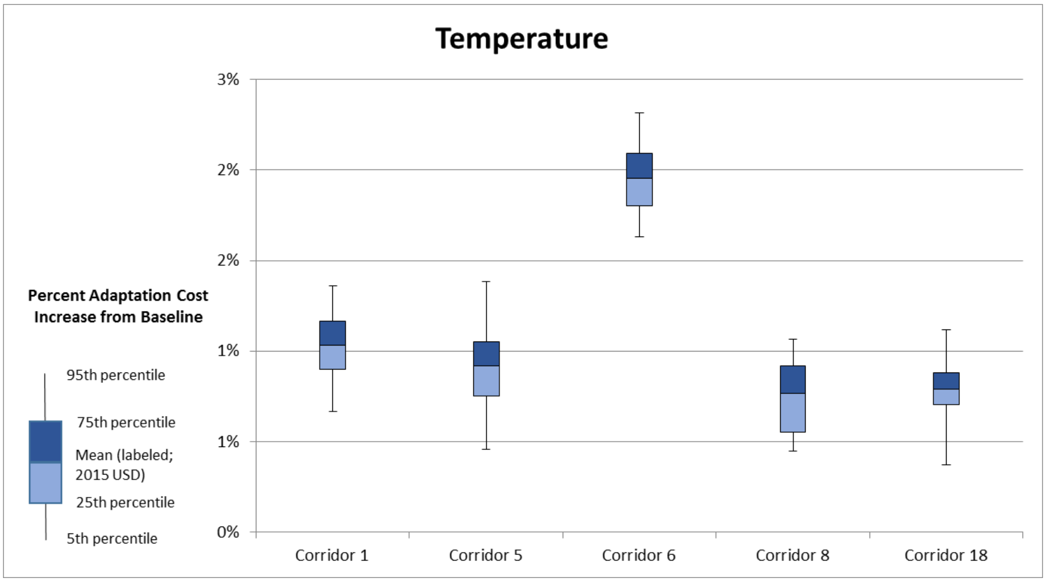
(Undiscounted total costs by period)

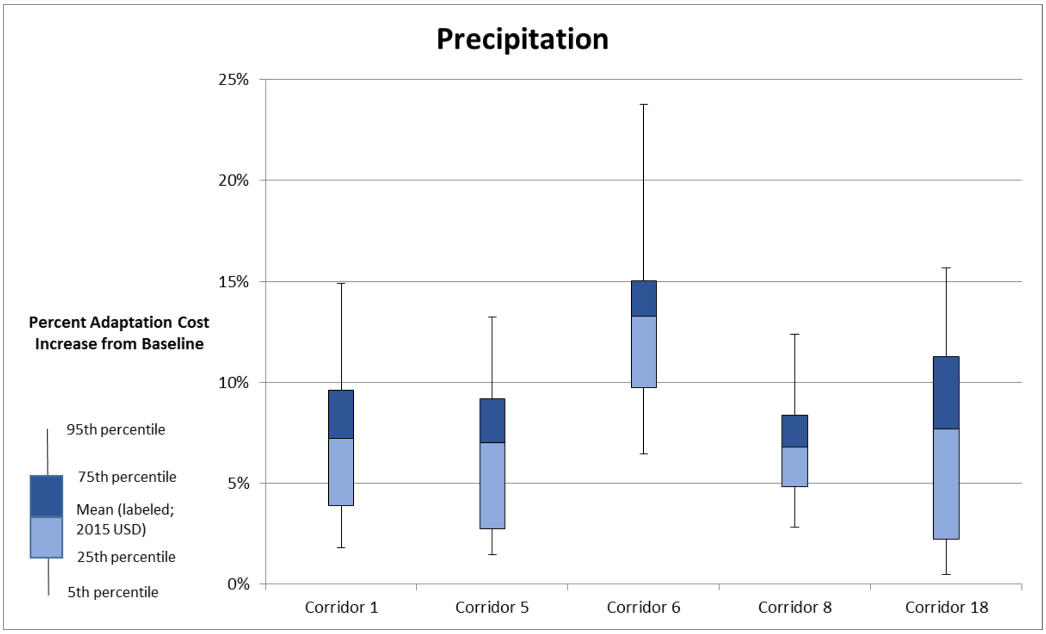


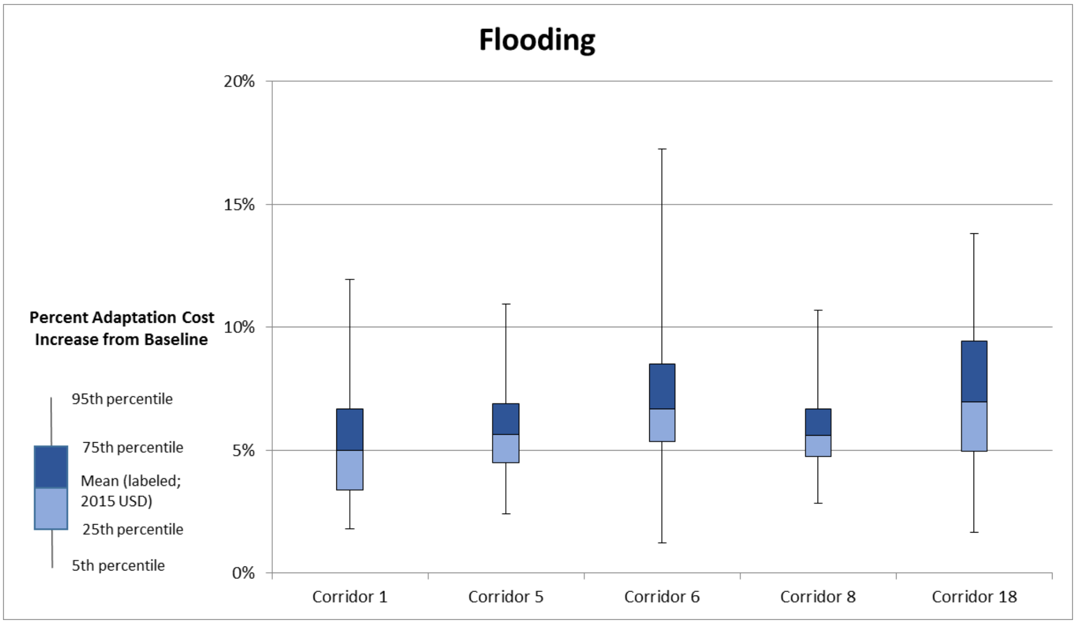
Note: Chart provides a summary of the overall costs of proactive action for PIDA roads across all future climates, as compared to baseline (no climate change adaptation) costs estimated in PIDA documents. Box indicates the range from the 25th to the 75th percentile future climate outcome; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile climate outcome. Number next to box is mean value. Left bar is for PIDA PAP projects scheduled to begin construction in the 2015 to 2030 period; right bar is for projects scheduled to begin construction in the 2031 to 2050 period.

These incremental costs of adaptation can also be assessed by stressor, and by corridor, as shown in the three panels of Figure 6.8. The results show that the incremental cost to achieve resilience to the temperature stressor is much lower, between 1% and 3% of the baseline cost, for the five largest cost PIDA corridors in our scope, but costs to achieve resilience to the precipitation and flooding stressors are higher. For example, in Corridor 6, mean costs across climate scenarios to achieve resilience to precipitation are about 13% of construction costs, but for the 95th percentile climate they could be as high as 23%. These results suggest that a targeted approach to resilience, over both stressors and corridors, may be appropriate.

Figure 6.8. Capital costs of proactive adaptation for the PIDA roads relative to baseline, by stressor and PIDA corridor





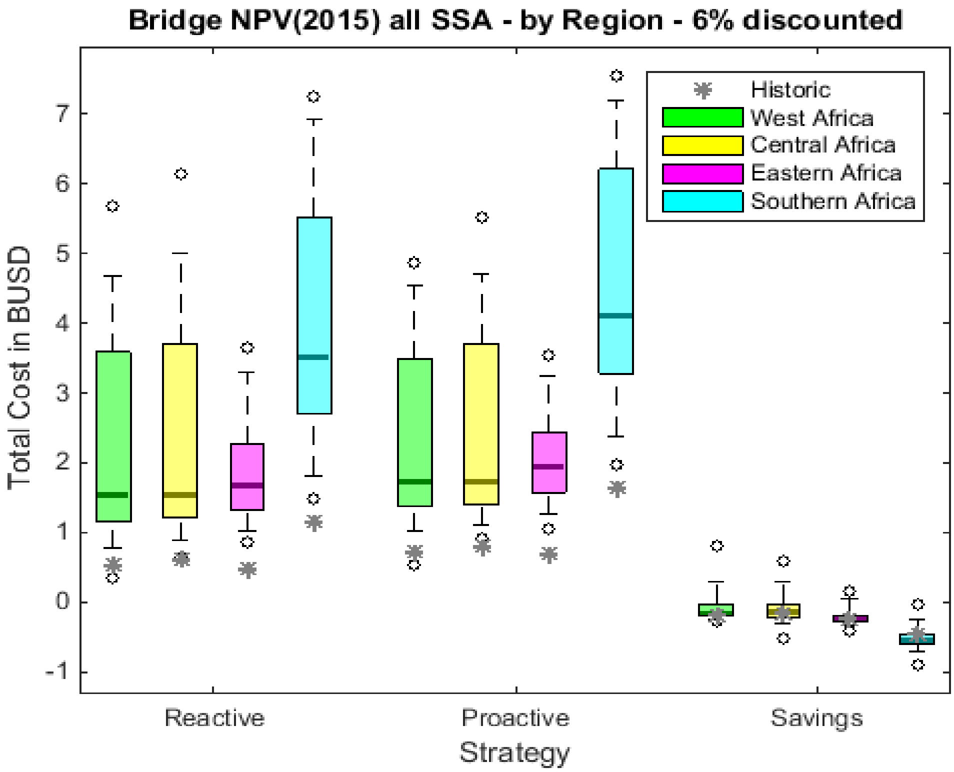


Note: Chart provides a summary of the overall costs of proactive action for PIDA roads across all future climates, as compared to baseline (no climate change adaptation) costs estimated in PIDA documents. Box indicates the range from the 25th to the 75th percentile future climate outcome; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile climate outcome. Bars correspond to costs for PIDA corridors, which are collections of projects. See Chapter 3 and Appendix B for more detail on locations of PIDA PAP corridors.

6.6 Assessment of Proactive Adaptation for Bridges

The previous chapter established that the cost of inaction for bridges is high for most parts of SSA. The cost of adaptation is likely to be high too. Figure 6.9 shows the reactive cost, proactive cost, and cost savings for historic climate and the 91 climate forecasts across SSA, disaggregated by region. In all regions, proactive costs of bridge adaptation are higher than reactive costs, and with the exception of a few extreme scenarios, cost savings are negative (that is, proactive adaptation is financially detrimental). A sensitivity analysis using a 3% discount rate yields somewhat better results, but the mean savings from adaptation remain negative across all regions.

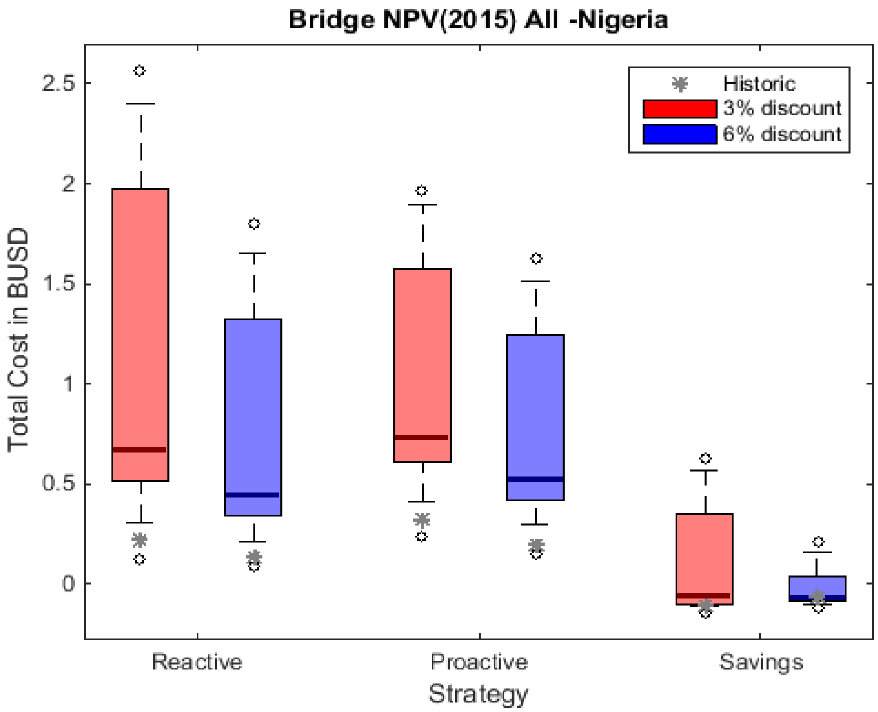
Figure 6.9. Reactive costs, proactive costs, and cost savings by region for bridges

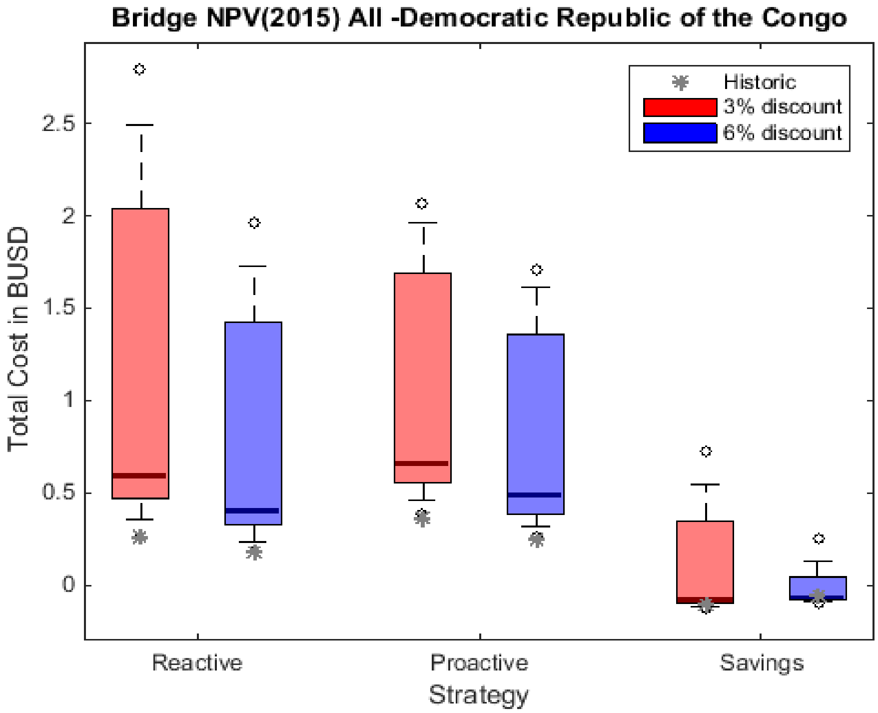


Note: Box indicates the range of costs from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile climate outcome. Circles represent maximum and minimum climate outcome. Asterisks provides values for historic climate.

In some countries, however, bridge adaptation may make good economic sense. In Nigeria and DRC, for example, the net present value of proactive costs is generally lower than the cost of the reactive response, as shown in Figure 6.10. The mean value of savings is slightly negative in both countries. However, when disruption times are included, which are often much higher for bridges than for roads because of the critical nature of bridge crossings in road networks, and the general lack of bridge network redundancy, it is reasonable to conclude that adaptation of bridges may be cost effective. The specific merits of the adaptation option will need to be assessed on a case-by-case basis.

Figure 6.10. Reactive costs, proactive costs, and cost savings for bridges in Nigeria and DRC





Note: Box indicates the range of results from the 25th to the 75th percentile over climate change scenarios; line in box represents the mean value; and whiskers extending from box indicate the range from the 5th to the 95th percentile. Circles represent maximum and minimum results. Asterisks provides values for historic climate.

CHAPTER 7

Conclusions and Recommendations

Raffaello Cervigni and Andrew Losos

7.1 Key Overall Insights from the Study

This book provides a framework for assessing climate related risks to road investments in Africa. A key finding is that, in the period from the present to 2050, climate change could cause:

- **Direct damages:** tens of billions of dollars in damages to roads, which will require additional maintenance to preserve basic serviceability; preliminary estimation of damage to bridges suggests costs may be even higher (in the order of $30 billion, mean estimate).
- **Substantial system disruption:** apart from increasing maintenance costs, climate changes will cause the disruption of road links, interrupting the flow of goods and people, to the tune of 100 million days of disrupted road links by 2050, all of which has a substantial economic cost.

As noted in Chapter 1, while road and bridge infrastructure is a critical element in the development of economies in Sub-Saharan Africa, many if not most African countries struggle to fund and execute the maintenance of their road and bridge networks. One implication of the findings of this study is that the prospect of climate change will increase the need for maintenance and rehabilitation for all types of roads and bridges, in virtually all climate contexts, putting continued pressure on an already stressed system.

A first key area of focus for transport sector authorities is therefore to incorporate climate change in road asset management, with a particular focus on institutionalizing regular road maintenance. Funding and adequately executing the regular functions of maintenance is a first key step towards increasing the climate resilience of roads and bridge assets. The World Bank is promoting a range of initiatives in this area, including a note on how to integrate climate change in road asset management, and a new generation of road asset management systems, the International Study of Road Asset Management and Models (ISRAMM). These efforts will help inform a consistent approach to planning for climate resiliency across countries.

The study also points to a second area of recommendations, concerning engineering design solutions as effective options to address the impacts of climate change. These solutions can provide long-term resilience, with less disruption and lower lifetime maintenance costs, in exchange for a higher up-front investment. In particular, this study finds that that investing proactively in pavement improvements to withstand increased temperature is economically justified under most climate projections, *even without taking into account the cost of increased disruption time*.

On the other hand, the study finds that proactive adaptation to precipitation and flooding events is more expensive, and is unlikely to be justified in the shorter term solely on the grounds of reducing the lifetime expenditure on road assets (the sum total of construction, maintenance and rehabilitation costs). For damage caused by these climate stressors, it is important to consider not just financial costs but disruption of traffic volume and critical economic links.

As more severe precipitation and flooding changes will manifest themselves closer to mid-century, and as the costs and risks of inaction grow larger over time, indications are the case for adaptation (based on both the financial and the avoided disruption time) will grow stronger as well. In the shorter term, it is important to avoid blanket prescriptions for infrastructure adaptations, opting instead for specific interventions on resilient design, according to the circumstances of each project and individual economic analyses.

7.2 Specific Recommendations

The framework of analysis developed in this study provide a basis for making recommendations for the consideration of regional or sub-regional organizations (e.g., Africa Union Commission, Regional Economic Communities), road sector ministries and agencies at the country level, along with ministries of finances and planning; and international development partners, as described in the table below.

Recommendations	Entities Encouraged to Act on the Recommendation	Supporting Information from the Study
PIDA road transport projects could include in the design stage provisions to include high temperature seals in the construction of the roads	The Africa Union Commission or NEPAD could develop overall guidelines/ recommendations on the PIDA program, to be implemented by country level project developers	Chapter 6 conclusions related to paved PIDA road adaptation
Evaluate the optimal timing for precipitation and flooding adaptations actions for the PIDA projects.	The Africa Union Commission or NEPAD could develop overall guidelines/ recommendations on the PIDA program, to be implemented by country level project developers	Chapter 6 conclusions related to paved PIDA road adaptation

Recommendations	Entities Encouraged to Act on the Recommendation	Supporting Information from the Study
Require that project developers carry out climate risk evaluations for road and bridge projects. Use the detailed data from this study, and then work collaboratively with the proposed AFRI-RES facility, when fully functional (see Box 7.1) for initial screening. Follow-up using individual scenarios for climate projections, and more detailed engineering for project level analyses.	Donors and financiers of Sub-Saharan African road and bridge construction	Chapter 5 for risks and costs of inaction; Chapter 4 for details of the available daily downscaled climate projections.
Conduct financial analyses that examine the tradeoff between higher upfront costs and lower maintenance costs.	Ministries of Finance could provide overall guidelines to be implemented by Ministries of Transport/ Road Agencies	Chapter 6 for country level information comparing higher upfront costs (proactive adaptation) versus higher maintenance costs (reactive response to climate)
Identify critical road networks in existing system, including bridges, and establish priority status for climate risk and financial analyses for those infrastructure segments.	National Ministries of Transport/ Road Agencies	
Identify existing weather sensitive hotspots in the transport system – roads and bridges – and look across climate forecasts to identify trends of concern in temperature, precipitation, flooding, and river runoff scour or overtopping. Update construction norms to account for these factors. Mainstream vulnerability assessment into a range of road infrastructure project types. This could be done in a stepwise approach, extending the work from assessment, to design improvements, to adjustments in national construction standards as the case may warrant. Using multiple climate futures and a systematic approach to assessing additional	National Ministries of Transport/ Road agencies	Chapter 5 information on risk of inaction by country; see Chapter 4 for description of available climate scenario information (detailed files available on project web site)

Recommendations	Entities Encouraged to Act on the Recommendation	Supporting Information from the Study
maintenance and repair costs, as in this study, represents a rigorous approach to the needed vulnerability studies. The analysis of climate vulnerability should in particular focus on critical road segments including in particular bridge crossings. Assess the benefits of adaptation taking into account traffic volumes, and the opportunity cost of time lost because of road disruption. The merits of investing in adaptation will have to be assessed on a case by case basis, considering the likely volume of the traffic disrupted in the absence of adaptation; and a plausible range of unit values of the opportunity cost of the time that would be lost because of disruption. Integrate an assessment of how network redundancy, of the lack thereof, will affect priorities for resilience investments		
Learn basic techniques of climate risk assessment, and identify options in design, materials, and construction methods to improve resilience at lowest cost. Include as standard practice in all procurement responses costing of options to improve climate resilience, for consideration by project development clients.	Construction firms and suppliers, project engineers	Chapter 2 for climate risk assessment methodology and lists of categories of proactive adaptation engineering options to implement for individual projects.
Understand potential climate risks and identify alternative routes for freight transport across high climatic risk areas. Build capacity for understanding forecasts of damaging weather events.	Freight companies and their customers	Chapters 4 and 5 provide an initial identification of important climate risks to road and bridge infrastructure.

Box 7.1. Africa Climate Resilient Investment Facility (AFRI-RES)

To develop Africa's capacity to systematically integrate climate change considerations into the planning and design of long-lived investments, the World Bank, the Africa Union Commission and the United Nation Economic Commission for Africa (UNECA) have teamed up to develop the Africa Climate Resilient Investment Facility (Afri-Res). The facility will develop guidelines, provide training, deliver on-demand advisory services, make data and knowledge tools more easily accessible, and ultimately help attract funding from sources of development and climate finance.

The facility is one of the components of the World Bank Group's $16 billion Africa Climate Business Plan that we have presented at COP21 in Paris in November 2015 (http://documents.worldbank.org/curated/en/2015/11/25481350/accelerating-climate-resilient-low-carbon-development-africa-climate-business-plan).

Seed funding in the amount of 4 Million Euros has been pledged by the Nordic Development Fund (NDF), and discussion are underway with other development partners to mobilize additional resources.

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Appendix A: PIDA+ Network Detail

Countries	Primary			Secondary			Tertiary			unknown/other			Subtotal			Grand Total
	paved	unpaved	unknown	paved	unpaved	unknown	paved	unpaved	unknown	paved	unpaved	unknown	paved	unpaved	unknown	
Angola	7 174	3 870		6 235	3 461	41 255	1 019	427	58 623				14 428	7 758	99 878	122 064
Benin	1 775	540			3 849			7 257					1 775	11 646	0	13 421
Botswana	4 656	0		3 157	11 145		79	1 171					7 892	12 316	0	20 208
Burkina Faso	2 643	4 061				4 654			19 699				2 643	4 061	24 353	31 057
Burundi	1 103	842		21	2 501		0	282		462	6 000		1 586	9 625	0	11 211
Cameroon	3 118	2 695		906	4 280		519	12 028				18 044	4 544	19 004	18 044	41 592
Cape Verde				152			443	268					595	268	0	863
Central African Republic	653	4 360			4 978			14 355					653	23 693	0	24 345
Chad			2 896			23 029			48 051				0	0	73 976	73 976
Comoros				260			165	131					425	131	0	556
Cote d'Ivoire	1 906	4 045		4 594	8 747			17 286			45 418		6 500	75 496	0	81 996
Democratic Republic of the Congo	2 255	17 173			8 851			9 314			133 000		2 255	168 338	0	170 593
Djibouti	420	273			436			1 445					420	2 155	0	2 574
Equatorial Guinea			970			601			2 080				0	0	3 651	3 651
Eritrea	815	1 344		28	2 176				4 643				842	3 520	4 643	9 006
Ethiopia	5 039	364		3 228	35 699		295	106 566			33 677		8 562	176 306	0	184 868
Gabon	951	1 818	191	168	1 239	320	35	1 180	6 238				1 154	4 237	6 749	12 140
Ghana	5 948				5 646				42 192			12 400	5 948	5 646	54 592	66 186
Guinea	2 091	1 638		231	2 347				17 427			20 614	2 322	3 985	38 041	44 348
Guinea-Bissau	363			602	1 796				668				965	1 796	668	3 429
Kenya	4 319	2 235		3 654	15 230		965	36 888			126 800	7 000	8 938	181 153	7 000	197 091
Lesotho	1 011	466		475	926		41	2 825					1 527	4 217	0	5 744
Liberia	652	1 734		2	2 158			198		101	11 756		754	15 846	0	16 600
Madagascar	2 366	328		2 141	2 753		366	13 092		1 080	3 513		5 953	19 686	0	25 639
Malawi	2 647	948		290	2 489		95	3 703			15 279		3 032	22 418	0	25 450
Mali	2 047	6 356		1 206	9 295		1 264	13 840	27 716				4 517	29 492	27 716	61 724
Mauritania	1 885	3 401		37	1 752		14	5 312			12 518		1 936	22 983	0	24 919
Mauritius	57			834			1 744						2 635	0	0	2 635
Mozambique	3 812	2 000				4 792			18 679			4 990	3 812	2 000	28 461	34 273
Namibia	4 238	471		1 899	9 271		295	29 212					6 432	38 954	0	45 386
Niger	3 536	461		70	1 967		31	7 364	36 999				3 637	9 791	36 999	50 427
Nigeria	16 820	962		6 707	962		246	120				167 382	23 773	2 045	167 382	193 200
Republic of the Congo	551	937	152	466	3 027	315	43	2 965	7 253				1 060	6 929	7 720	15 710
Rwanda	1 171	1 667			1 838							9 324	1 171	3 505	9 324	14 000
São Tomé and Príncipe						38			151				0	0	189	189
Senegal	2 679	216		1 194	674		184	10 707				13 853	4 057	11 596	13 853	29 506
Seychelles						28			184				0	0	212	212
Sierra Leone	860	1 307		28	1 827			4 533		63	444	2 937	951	8 111	2 937	11 999
Somalia	1 610			23 962			11 294	1 926				13 857	36 866	1 926	13 857	52 649
South Africa	21 117			67 094	136 640		66 512	316 620					154 723	453 260	0	607 983
South Sudan	194	6 602			4 162						7 720		194	18 485	0	18 679
Sudan	2 299	2 333		229	69 515			83 770			14 206	129	2 527	169 824	129	172 481
Swaziland	1 140	362		80	1 975		390	1 110			1 185		1 610	4 632	0	6 242
Tanzania	5 478	7 308		840	20 265		774	51 807					7 092	79 380	0	86 472
The Gambia	512	352			849			977					512	2 177	0	2 689
Togo	1 594	254		14	961			1 815				1 980	1 608	3 030	1 980	6 618
Uganda	2 155	174		547	29 671		205	39 609				4 800	2 907	69 454	4 800	77 161
Zambia	5 925	0		706	12 561		0	15 312		2 111	3 396		8 742	31 269	0	40 011
Zimbabwe	4 724			6 196	9 690		8 284	59 444					19 204	69 134	0	88 338
Grand Total	136 308	83 897	4 209	138 252	437 609	75 032	95 303	874 858	290 602	3 817	414 912	277 310	373 680	1 811 277	647 154	2 832 111

Appendix B: PIDA PAP Projects Included in the Study

Programme ID	Program name/ summary description	Country impacted	Estimated cost in US$ (millions)[a]	Estimated completion year
T.01	**Trans-African Highway (TAH) Program (completion of missing links by 2030)**			
T.01.1.2	TAH 6 Ndjamena – Djibouti: 1,582 km of earth track in Chad and Sudan (out of 4,200 km overall length)	Chad	1,327	2050
T.01.1.2	TAH 6 Ndjamena – Djibouti: 1,582 km of earth track in Chad and Sudan (out of 4,200 km overall length)	Djibouti	161	2050
T.01.1.2	TAH 6 Ndjamena – Djibouti: 1,582 km of earth track in Chad and Sudan (out of 4,200 km overall length)	Ethiopia	1,095	2050
T.01.1.2	TAH 6 Ndjamena – Djibouti: 1,582 km of earth track in Chad and Sudan (out of 4,200 km overall length)	Sudan	1,992	2050
T.01.2	TAH 2 Algiers – Lagos: 1,950 km of paved road construction and rehabilitation in Algeria and Niger (out of 4,500 km)	Niger	322	2030
T.01.2	TAH 2 Algiers – Lagos: 1,950 km of paved road construction and rehabilitation in Algeria and Niger (out of 4,500 km)	Nigeria	1,789	2030
T.01.3	TAH 3 Tripoli – Cape Town	Chad	872	2030
T.01.3	TAH 3 Tripoli – Cape Town	Central African Republic	1,336	2030
T.01.3	TAH 3 Tripoli – Cape Town	Cameroon	46	2030
T.01.3	TAH 3 Tripoli – Cape Town	South Africa	4	2030
T.01.3	TAH 3 Tripoli – Cape Town	DRC	3,441	2030
T.01.3	TAH 3 Tripoli – Cape Town	Niger	313	2030
T.01.3	TAH 3 Tripoli – Cape Town	Nigeria	519	2030
T.01.4.1	TAH 8 Lagos – Mombasa	Cameroon	883	2030
T.01.4.2	TAH 8 Lagos – Mombasa	Central African Republic	1,172	2030
T.01.4.3	TAH 8 Lagos – Mombasa	DRC	2,214	2030
T.01.4.3	TAH 8 Lagos – Mombasa	Nigeria	847	2030
T.01.4.3	TAH 8 Lagos – Mombasa	Uganda	443	2030
T.05	**Northern Multimodal Corridor Program**			
T.05.3.1.1	Road Toll along Northern Corridor (Mombasa-Nairobi)	Kenya	Unknown	2050
T.05.3.2.3	Nairobi Western Bypass Upgrading	Kenya	Unknown	2050
T.05.3.3	Mombasa Southern Bypass	Kenya	42	2020

Programme ID	Program name/ summary description	Country impacted	Estimated cost in US$ (millions)[a]	Estimated completion year
T.05.3.4	Molo-Eldoret Road Upgrading and Rehabilitation (11 km road section, adding 4.4 lane km)	Kenya	2	2015
T.05.3.5	Mombasa – Voi Road Upgrading and Rehabilitation (57 km road section, adding 28.5 lane km)	Kenya	11	2012
T.05.3.5.1	Bachuma Gate – Maji ya Chumvi	Kenya	61	2017
T.05.3.6	Voi-Athi River Road Rehabilitation (214 km road section, 428 lane km)	Kenya	118	2012
T.05.3.7	Juba-Torit-Kapoeta-Nadapal-multidal and OSBP Project (linked to Kenya/South Sudan border)	South Sudan	420	2022
T.05.3.8	Juba-Bor-Malakal-Renki-Sudan border Road-Rail and OSBP Project	South Sudan	1,840	2030
T.05.3.9	Mbarara-Ntungamo Road Capacity Upgrade	Uganda	24	2015
T.05.3.10	Tororo-Jinja Road Upgrading and Rehabilitation	Uganda	5	2030
T.05.3.11	Masaka-Malaba Road Reconstruction	Uganda	122	2012
T.05.3.12	Kampala-Mpinzi (Ntinzi) Road Upgrading	Uganda	Unknown	2012
T.05.3.13	Kampala-Wakiso Road Capacity Upgrade	Uganda	13	2012
T.05.3.14	Kabale-Kisoro Road (B153) Upgrading	Uganda	12	2012
T.05.3.15	Jinja-Kampala Road Upgrading (dualisation)	Uganda	65	2030
T.05.3.16	Eldoret-Kitale Road Upgrading [Lesseru (JnB2/A104) – Kitale] (52 km road section, adding 26 lane km)	Kenya	10	2015
T.05.3.17	Bungoma-Eldoret Road Capacity Upgrade (10 km road section, adding 4 lane km)	Kenya	2	2050
T.05.3.18	Kampala-Eldoret Road Upgrading	Kenya	62	2020
T.05.3.18	Kampala-Eldoret Road Upgrading	Uganda	89	2020
T.05.3.19	Katuna-Biumba Road Upgrading	Rwanda	11	2050
T.05.3.20	DRC National Road No. 2 (Goma-Kisangani) Construction	DRC	750	2034
T.06	**North-South Multimodal Corridor Program**			
T.06.3.1	Upgrading of the Kitwe – Chingola Dual Carriageway (45.5 km)	Zambia	76	2015
T.06.3.2	Beitbridge to Chirundu Road Upgrading (930 km) (+/-50% to be dualled)	Zimbabwe	775	2020
T.07	**Djibouti-Addis Corridor Program**			
T.07.4.1.1	Dobi-Galafi-Yakobi Road Upgrading [Project is to upgrade to bitumen standard a 72 km section of road between Dobi (Ethiopia) and Yakobi (Djibouti). This section of road is part of the Dakar- Ndjamena – Djibouti highway (TAH 6).]	Ethiopia	30	2012

Programme ID	Program name/ summary description	Country impacted	Estimated cost in US$ (millions)[a]	Estimated completion year
T.07.4.1.2	Dobi-Galafi-Yakobi Road Upgrading [Project is to upgrade to bitumen standard a 72 km section of road between Dobi (Ethiopia) and Yakobi (Djibouti). This section of road is part of the Dakar- Ndjamena – Djibouti highway (TAH 6).]	Djibouti	Unknown	2012
T.07.4.2	Tog Wajaale-Hargeysa Road Upgrading	Somalia	Unknown	Unknown
T.08	**Central Corridor Program**			
T.08.3.1	Dar es Salaam Port Access Roads Construction	Tanzania	Unknown	2012
T.08.3.2	Road to the Port of Kigoma Upgrading	Tanzania	Unknown	2030
T.08.3.3	RN 18 Upgrading	Burundi	100	2030
T.08.3.4	Bujumbura-Mugina (RN3) Road Upgrading	Burundi	77	2020
T.08.3.5.1	Mpanda-Nyakanazi Road Upgrading [Mpanda – Kanazi (252 km)]	Tanzania	185	2022
T.08.3.5.2	Mpanda-Nyakanazi Road Upgrading [Kidahwe – Kanazi – Kasulu (50 km)]	Tanzania	33	2022
T.08.3.5.3	Mpanda-Nyakanazi Road Upgrading [Kasulu – Kibondo-Nyakanazi (250 km)]	Tanzania	185	2022
T.08.3.6.1	Kigoma-Manyoni Road Upgrading [Kidoma – Kidahwe (30 km)]	Tanzania	26	2012
T.08.3.6.2	Kigoma-Manyoni Road Upgrading [Kidahwe – Uvinza (76.6 km)]	Tanzania	125	2015
T.08.3.6.3	Kigoma-Manyoni Road Upgrading [Uvinza – Ilunde – Malagarasi (51.1 km)]	Tanzania	171	2021
T.08.3.6.4	Kigoma-Manyoni Road Upgrading [Malagarasi – Chagu (48 km)]	Tanzania	80	2015
T.08.3.6.5	Kigoma-Manyoni Road Upgrading [Chagu – Kaliua section (81 km)]	Tanzania	135	2020
T.08.3.6.6	Kigoma-Manyoni Road Upgrading [Kaliua – Urambo (36 km)]	Tanzania	44	2015
T.08.3.6.7	Kigoma-Manyoni Road Upgrading Urambo – Tabora)	Tanzania	4	2015
T.08.3.6.8	Kigoma-Manyoni Road Upgrading [Tabora – Nyahua (85 km)]	Tanzania	58	2012
T.08.3.6.9	Kigoma-Manyoni Road Upgrading [Nyahua – Chaya (85 km)]	Tanzania	142	2021
T.08.3.6.10	Kigoma-Manyoni Road Upgrading [Chaya – Manyoni (89 km)]	Tanzania	183	2015
T.08.3.7	Nzega-Tabora Road Upgrading	Tanzania	193	2015
T.08.3.8	Kidahwe-Uvinza-Ilunde-Malagarasi-Kaliua-Urambo-Tabora Road Upgrading	Tanzania	125	2015

Programme ID	Program name/ summary description	Country impacted	Estimated cost in US$ (millions)[a]	Estimated completion year
T.08.3.9	Nyahua-Tabora Road Upgrading	Tanzania	142	2015
T.08.3.10	Kobero Bu Border Muyinga Road Upgrading	Burundi	84	2030
T.08.3.11	Gitega-Muyinga Road Upgrading	Burundi	153	2029
T.08.3.12	Kigali-Kibungo Road Upgrading	Rwanda	123	2030
T.08.3.13	Midpoint Sumbawanga Road Upgrading	Tanzania	395	2030
T.08.3.14	Bujumbura-Kayanza Road Upgrading	Burundi	65	2028
T.08.3.14.1	Kayanza-Bugarama Road Rehabilitation and Capacity Upgrade	Burundi	45	2028
T.08.3.14.2	Bugarama-Bujumbura Road Rehabilitation and Capacity Upgrade	Burundi	22	2028
T.08.3.15.1	Central Corridor Core Road Completion (Network in Tanzania and Rwanda): DSM – Manyoni – Isaka	Tanzania	857	2012
T.08.3.15.2	Rehabilitation of Lusahunga Isaka – Lusahunga (260 km)	Tanzania	21	2021
T.08.3.15.3	Rehabilitation of Lusahunga – Rusumo (91 km)	Tanzania	120	2021
T.10	**Lamu Gateway Development**			
T.10.2.1.1	Lamu Road Corridor (Lamu-Isiolo-Lodwar-Nadapal-Juba)	Kenya	63	2030
T.12	**Abidjan-Lagos Coastal Corridor Program**			
T.12.3.1	Abidjan-Grand Bassam Construction of Missing Links: 17 km	Cote d’Ivoire	28	2029
T.12.3.2	Agona Junction-Alubo Road Upgrading and Rehabilitation	Ghana	402	2029
T.12.3.3	Anejo-Hillakondji Road and Bridge Upgrading and Rehabilitation	Ghana	Unknown	2029
T.12.3.4	Godomey-Pahou Road Upgrading and Rehabilitation	Benin	14	2029
T.13	**Dakar-Bamako-Niamey Multimodal Corridor Program**			
T.13.3.1.1	Dakar-Bamako Northern Missing Links Construction: sections already completed (596 km)	Senegal	490	2012
T.13.3.1.2	Dakar-Bamako Northern Missing Links Construction: Mako – Dialocoto (117 km)	Senegal	195	2021
T.13.3.1.3	Dakar-Bamako Northern Missing Links Construction: Dialocoto – Tambacounda (145 km)	Senegal	242	2015
T.13.3.1.4	Dakar-Bamako Northern Missing Links Construction: Kaolack – Fatick (43 km)	Mali	72	2030
T.13.3.2.2	Burkina Faso Border-Niamey-Zinder-Chad Border Missing Links Construction: 55 km (sections only)	Niger	92	2050

Programme ID	Program name/ summary description	Country impacted	Estimated cost in US$ (millions)[a]	Estimated completion year
T.13.3.3.1	Bamako-Gao-Niamey Road Construction of Missing Links (Mali): 205 km	Mali	342	2050
T.13.3.3.2	Bamako-Gao-Niamey Road Construction of Missing Links (Mali): 205 km	Niger	57	2050
T.15	**Abidjan-Ouagadougou/ Bamako Multimodal Corridor Program**			
T.15.3.1.1	Bamako-Gao-Niamey Construction of Missing Links (sections) (Mali): Singrobo-Yamoussoukro (86 km)	Mali	143	2050
T.15.3.1.2	Bamako-Gao-Niamey Construction of Missing Links (sections) (Mali): Singrobo-Yamoussoukro (86 km)	Niger	17	2050
T.18	**Pointe Noire, Brazzaville/ Kinshasa, Bangui, N'Djamena Multimodal Corridor Program**			
T.18.4.1.1	Dolisie-Brazzaville road	Republic of the Congo	60	2015
T.18.4.1.2	Mambili-Ouesso road	Republic of the Congo	Unknown	2030
T.18.4.1.3.1	Ouesso-Pokola-Enyellé-Betou-Mongoumba-Mbaïki-Bangui road	Republic of the Congo	Unknown	2030
T.18.4.1.3.2	Ouesso-Pokola-Enyellé-Betou-Mongoumba-Mbaïki-Bangui road	Central African Republic	Unknown	2050
T.18.4.1.4	Bossembélé-Mbaïkoro road	Central African Republic	216	2050
T.20	**Douala-Bangui Douala-N'Djamena Corridor Programme**			
T.20.3.1.1	Douala-N'Gaoundéré-N'Djamena: Construction (sections only)	Cameroon	776	2050
T.20.3.1.2	Douala-N'Gaoundéré-N'Djamena: Construction (sections only)	Chad	Unknown	2050
T.20.3.2	Garoua Boulai-Ngaoundéré Section Bitumizing	Cameroon	405	2033
T.21	**Central African Inter-Capital Connectivity Programme**			
T.21.1.1	Yaounde-Bata (variation via Douala and Kribi): Kribi-Campo (70 km)	Cameroon	122	2015
T.21.1.2	Yaounde-Bata (variation via Douala and Kribi): Bridge over N'Tem River	Gabon	Unknown	2050
T.21.2.1.1	Libreville-Brazzaville: Doussala-Dolissie (236 km)	Gabon	464	2020
T.21.2.1.2	Libreville-Brazzaville: Doussala-Dolissie (236 km)	Republic of the Congo	804	2020
T.21.3.1	Lobito-Lubumbashi: Huambo-Kuito (81 km)	Angola	68	2050
T.21.3.2	Lobito-Lubumbashi: Kuito-Luena (184 km)	Angola	307	2050
T.21.3.3	Lobito-Lubumbashi: Luena-Luau-Dilolo (164 km)	Angola	273	2050
T.21.4.1	Libreville-Bata:	Gabon	523	2050

Programme ID	Program name/ summary description	Country impacted	Estimated cost in US$ (millions)[a]	Estimated completion year
T.21.4.2	Libreville-Bata:	Equatorial Guinea	37	2050
T.21.5.1	Kinshasa-Luanda:	DRC	151	2020
T.21.5.2	Kinshasa-Luanda:	Angola	477	2015
T.24	**Trans-Maghreb Highway (part of TAH 1) Program**			
T.24.3.1	Nouakchott-Nouadhibou Road Upgrading	Mauritania	90	2050

Note: The table does not include PIDA programs and projects that do not focus on improving connectivity through the provision, or improvement, of road infrastructure. Examples of omitted projects include improvements to border posts or airport facilities. The PAP is not static and will be updated regularly to reflect progress and make way for new priorities as Africa's needs continue to evolve.

In cases where cost estimates were not available from the PIDA data, these were estimated using Unit Rates for similar projects.

Appendix C: Country-level Projects Included in the Study

Country/summary project description	Data reference no.	Estimated cost in millions US$	Estimated completion year/period
Angola			
Trans African Highway Missing Links (Noqui-Mepala) (60 km gravel to paved)	40	97	2030
Trans African Highway Missing Links (Mepala-M'banza Congo) (79 km new road)	40	128	2030
Trans African Highway Missing Links (M'banza Congo-Negage) (294 km new road)	40	475	2030
Trans African Highway Missing Links (Dilolo-Luena) (334 km new road)	40	540	2030
Trans African Highway Missing Links (Luena-Kuito) (404 km gravel to paved)	40	653	2030
Botswana			
Dualling of road between Gaborone and Tlokweng (10 km)	Nat. Dev. Plan 10	16	2020
Letlhakeng-Kudumalapye-Khutse road (+/- 100 km)	Nat. Dev. Plan 10	88	2025
Ngoma-Kachikau road	Nat. Dev. Plan 10	7	2020
Mahalapye-Kalamre road	Nat. Dev. Plan 10	9	2015
Dutlwe-Morwamosi road	Nat. Dev. Plan 10	18	2015
Tsabong-Middlepits	Nat. Dev. Plan 10	18	2014
Middlepits-Bokspits road	Nat. Dev. Plan 10	35	2014
Burundi			
Gitega-Nyakararo upgrade to paved (56 km, 112 lane km)	22	30	2011
Mugina-Mabanda upgrade to paved (21-km road section, 42 lane km)	22	23	2018
Bururi-Makamba upgrade	24	37	2030
Makamba-Mabanda rehabilitation and widening	24	16	2030
Gashoho-Ngozi	24	38	2030
Ngozi-Kayanza	24	28	2030
Mweya-Mahwa	24	43	2030
Mweya-Mahwa	24	28	2030
Gitega-Bugarama (RN2)	24	57	2030
Muyinga-Gashoho	24	33	2030
Kobero-Muyinga road-capacity upgrade and rehabilitation (30 km)	24	84	2030

Nyakararo-Bujumbura road-capacity upgrade and rehabilitation	24	67	2035
Kanyaru-Kayanza road rehabilitation and capacity upgrade	24	13	2035
Gitega-Karuzi-Muying (RN12) road-capacity upgrade and rehabilitation	24	168	2035
Gitega-Nyakarar construction road	24	38	2035
Kayanza-Bugarama road rehabilitation and capacity upgrade	24	59	2030
Bugarama-Bujumbura road rehabilitation and capacity upgrade	24	26	2030
Bujumbura-Isare-Bugarama capacity upgrade	24	34	2030
Asphalting 20 km of road between Mabanda and Mugina (in Burundi)	49	32	2030
Cameroon			
Ketta-Djoum Road and Brazzaville-Yaoundé Corridor Transport Facilitation Project Phase I: Paving the Mintom-Djoum Section (83 km)	15	134	2014
Ketta-Djoum Road and Brazzaville-Yaoundé Corridor Transport Facilitation Project – Kumba-Mamfe Road Development Project	73	165	2018
Strategy Paper for Growth and Employment (330 km upgrade/year for next 10 years) – Years 1 to 10	41	397/annum	2015 to 2024
Cote d’Ivoire			
Trans-West Africa Coastal Highway – in Côte d’Ivoire a new section is needed from the Liberian border through Toulépleu to Blolekin, while the road from there through Yamoussoukro and Abidjan to the Ghanaian border is completed	14	81	2030
DRC			
Trans African Highway missing links (Likasi-Nguba) (120 km new road)	40	194	2030
Trans African Highway missing links (Nguba-Kolwezi) (65 km new road)	40	105	2030
Trans African Highway missing links (Kolwezi-Dilolo) (428 km new road)	40	692	2030
Toll fee paying – pedicle road through Zambia DRC	48	126	2030
Asphalting the Kananga/Mbuji-Mayi road section		60	2030
Tshikapa Tshikulela road (100 km)		162	2030
Development of a 56-km portion of the Batshamba-Tshikapa road between Lovua and Tshikapa on the National Road 1	60	105	2018
Batshamba-Tshikapa Road Improvement Project – Loange Bridge-Lovua Bridge Section	61	86	2015

Federal Roads Plan (upgrading trunk roads)	32	49	2014
Federal Roads Plan (upgrading trunk roads)	32	65	2015
Federal Roads Plan (upgrading link roads)	32	269	2014
Ethiopia			
Federal Roads Plan (upgrading link roads)	32	261	2015
Federal Roads Plan (construction of link roads)	32	379	2014
Federal Roads Plan (construction of link roads)	32	258	2015
Regional Roads Plan (construction of gravel roads)	32	155	2014
Regional Roads Plan (construction of gravel roads)	32	119	2015
Wereda Roads Plan (construction of track roads)	32	276	2014
Wereda Roads Plan (construction of track roads)	32	275	2015

Appendix D: AICD Dataset Sources

Country	Data source
Angola	Aurecon
Benin	World Bank
Botswana	Aurecon
Burkina Faso	World Bank
Burundi	World Bank
Cameroon	World Bank
Central African Republic	World Bank
Cote d'Ivoire	World Bank
Democratic Republic of the Congo (DRC)	World Bank
Djibouti	Aurecon
Eritrea	World Bank
Ethiopia	Aurecon
Gabon	World Bank
Ghana	World Bank
Guinea	World Bank
Kenya	Aurecon
Lesotho	Aurecon
Liberia	Aurecon
Madagascar	Aurecon
Malawi	Aurecon
Mali	World Bank
Mauritania	World Bank
Mauritius	Aurecon
Mozambique	World Bank
Namibia	Aurecon
Niger	World Bank
Nigeria	Aurecon
Republic of the Congo	World Bank
Rwanda	World Bank
Senegal	World Bank
Sierra Leone	Aurecon
South Africa	Aurecon
Sudan	Aurecon
Swaziland	Aurecon
Tanzania	Aurecon
The Gambia	Aurecon

Country	Data source
Togo	World Bank
Uganda	Aurecon
Zambia	Aurecon
Zimbabwe	Aurecon

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