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Infrastructure and Climate Change

Impacts and Adaptations for South Africa

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Abstract

This paper presents the results of the current study on the impact of climate change on the road and building infrastructure within South Africa. The approach builds upon previous work associated with the UNU-WIDER Development under Climate Change effort emphasizing the impact of climate change on roads. The paper illustrates how climate change effects on both road and building structures can be evaluated with the application of a new analysis system—the infrastructure planning support system. The results of the study indicate that the national level climate change cost impact in South Africa will vary between US$141.0 million average annual costs in the median climate scenario under an adaptation policy, and US$210.0 million average annual costs under a no adaptation scenario. Similarly, the costs will vary between US$457.0 million average annual costs in the maximum climate scenario under an adaptation policy scenario, and US$522.0 million average annual costs under a no adaptation scenario. The paper presents these costs at a provincial impact level through the potential impacts of 54 climate scenarios. Decadal costs are detailed through 2100.

Keywords: climate change, infrastructure vulnerability, infrastructure maintenance

JEL classification: Q54, O44, O55

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1 Introduction

> 'The establishment of economically, physically, environmentally and socially integrated and sustainable built environments is one of the most important factors which will contribute to harnessing the full development potential of South Africa and addressing distortions of the past and the future needs of our growing population.' (CSIR 2005: 1).

South Africa is the largest economy in Sub-Saharan Africa and a member of several regional and international development organizations including the African Union, the UN Security Council, the G20 and others (DFID 2011). As the highest regional emitter of carbon dioxide and ranked 11th globally, they are taking a leading role in reducing and mitigating climate change impacts (DFID 2011). When compared to other Sub-Saharan African nations, South Africa has a highly developed infrastructure that is particularly vulnerable to potential changes in future climate. Still facing many challenges common to developing nations including further reduction of poverty, development of rural services, and continued economic growth, there are limited funds available to adequately address the threat climate change poses to the existing infrastructure. The limitations on these available funds are challenging developing countries to identify the threats that are posed by climate change, develop adaptation approaches to the predicted changes, incorporate changes into mid-range and long-term development plans, and secure funding for the proposed and necessary adaptations (UNFCCC 2009, 2010).

Earlier work by the UNFCCC, IPCC, World Bank, and others, have attempted to quantify the impact of climate change on physical assets that will be affected in the coming decades. The current study extends these efforts by addressing the effect of climate change on the road and building infrastructure of South Africa. Paved, gravel, and unpaved road inventories, as well as selected types of buildings, were selected as the infrastructure types evaluated in this study both because of their economic, social, and development importance and the long life-cycle these infrastructure elements normally have. The study examines the extent to which climate change from 54 IPCC-approved global circulation models (GCMs) climate scenarios will divert resources from the further development of infrastructure to the maintenance and adaptation of the existing infrastructure.

The following sections detail the climate scenarios used for analysis and the allocation and estimation methods used to determine the stock of infrastructure to be analyzed. Following this description, the paper introduces the specific stressor-response functions adopted for the individual road and building infrastructure elements. Finally, the paper summarizes the result of applying this methodology to South Africa.

2 Background

The limitation of existing impact studies on infrastructure is that they either focus on a narrow potential impact of climate change, or the studies fail to provide specific estimates of cost or damages that may result from potential climate change scenarios. In response to this gap in the climate change literature, the authors have been actively engaged in developing specific estimates of climate change impacts on infrastructure elements. Chinowsky et al. (2011) document the potential cost impacts of climate change on road infrastructure in ten countries that are geographically and economically diverse. The study illustrates both the potential real costs that countries may incur due to climate change scenarios as well as the potential opportunity costs of diverting infrastructure resources to climate change adaptation. Chinowsky and Arndt (2012) refine these results in the context of Southern Africa and the potential use of multiple climate scenarios in a probabilistic economic approach. The response methodology introduced in these efforts has been extended by additional researchers to analyze impacts from climate change on bridges (Stratus Consulting 2010) and roads in northern climates (Industrial Economics 2010).

In terms of buildings, an Economics of Adaptation to Climate Change Study (World Bank 2009) completed in 2009, estimated that urban housing costs could increase between US$23.3 billion (2005 USD) and US$41.1 billion per year in the period 2010–50 because of climate change impacts. This estimation does not include considerations such as slum areas. Buildings are an essential component of the built environment, the economy, and the daily lives in any area. A failure to properly incorporate climate change considerations could result in costly impacts including sick building syndrome, roof and drainage issues, cladding and exterior façade deterioration, and issues with the foundation of buildings, among many others. Additionally, a pro-active approach to understanding and addressing many of these issues may present an opportunity for buildings to be enhanced with alternative, green technologies which serve to reduce vulnerability to climate change impacts and reduce emissions and other negative environmental impacts.

However, unlike roads, the analysis of impacts on buildings requires a more segregated approach where different elements of the building are considered in addition to the overall building. Some of the critical potential impacts of climate change on components and sub-structures and whole buildings (with a focus on maintenance) that have been identified in the literature include: (i) damage to foundations and sub-structure concrete due to subsoil water; (ii) increased risk of cracking in structure/cladding/renders/roofing membranes due to differences in thermal or moisture movements, and (iv) the need to enhance lighting systems due to the reductions in natural light because of increased precipitation intervals (Graves and Phillipson 2000).

In addition to these impacts, two important additional considerations are: the impact that climate change may have on the performance of buildings and the impact that climate change may have on building materials. Material components are a key area for concern as any approach to mitigation is complicated by the fact that climate change may affect the degradation and durability of different building materials in opposite directions. Biodegradation (Adan 2003; Nijland et al. 2009), salt damage (Lubelli 2006; Koster et al. 2008), freeze-thaw damage (Van Hees et al. 2001), and increased solar radiation (Ross, Saunders, and Novakovic 2007) are all areas of concern that may be impacted by climate change factors.

3 Methodology

The methodology adopted for the current study to determine specific climate impacts is based on a stressor-response approach (Chinowsky and Arndt 2012). In this methodology, it is assumed that exogenous factors, or stressors, have a direct effect on focal elements. In the context of climate change and infrastructure, the exogenous factors are the individual results of climate change including changes to precipitation levels, temperatures, storm frequency, and wind speeds. Therefore, a stressor-response value is the quantitative impact that a specific stressor has on a specific infrastructure element. A two-phase approach is used based on the stressor-response methodology that first determines the appropriate climate effects on the given infrastructure inventory in the selected locations and then determines the cost impacts on this infrastructure based on a set of stressor-response functions. For this analysis, separate methodologies are applied to the roadstock and buildings analysis.

For roadstock, the stressors are examined in the context of paved, gravel, and dirt road infrastructure components to illustrate the impact of each stressor on the road infrastructure component based on the intensity of the stressor. The stressors of interest for roads are precipitation, temperature, and flooding. For example, the potential increase in precipitation levels is examined as a specific quantitative impact on unpaved roads in terms of the impact of lifespan based on the degree of increase in the precipitation. In this manner, the research diverges from a focus on qualitative summaries to an emphasis on quantitative estimates.

Similarly, the building stressor-response functions are defined based on the potential degradation or other impact that may be anticipated as a direct result of temperature or precipitation changes. As indicated above, the potential impact of climate change on buildings can be varied and extensive. The approach adopted for the current study isolates these potential impacts to ones that have been detailed in existing research as well as ones that have a mitigation path that can be accomplished through focused adaptation. Specifically, the areas of exterior cladding impact, roofing impact including drainage, and air flow impact including the mitigation of potential building contaminants are the focus of the current research effort.

In both the roads and buildings applications, the overall approach for determining potential impacts involves three steps of analysis: (i) climate model projections, (ii) existing infrastructure stock estimation, and (iii) the analysis of climate change impact on the infrastructure components.

3.1 Global circulation models

The current analysis has been carried out using climate change projections analyzed by GCMs at the resolution of 0.5° grid squares, which were then aggregated to the level of province/region. The GCMs selected are the models that have complete datasets appropriate for making temperature and precipitation projections through 2100 (Schlosser et al. 2012). For each model, historical monthly climate data is used from the Climate Research Unit (CRU) for 1951–2000 to produce a baseline 'no climate change' scenario for each geographic region analyzed. The baseline scenario assumes that future weather patterns will retain the characteristics of historical climate variability. Taking the baseline scenario, a 10-year moving average of the monthly deviations in temperature and precipitation are used to establish average deltas that are applied to the new projected baselines in each GCM. The application of these deltas to the baselines in each of the future decades provides the climate scenarios that are used as the basis for the specific impact analyzes.

3.2 Division of road inventory

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

To ensure that the allocation of road inventory to administrative levels correctly correlates to the GCM data provided, the 2 degree latitude by 2 degree longitudinal GCM climate data and the provincial mapping of the countries are translated into a standard grid system based on latitude and longitude. In terms of the current study, CRU grid cells of 0.5 degree latitude by 0.5 degree longitudinal (an approximately 250 km^2 area) are the basis of this data translation. The CRU dataset is an open source, global land surface time series of historical weather data. The information used in this analysis is CRU TS 2.1 (Climate Research Unit Time Series Version 2.1). Several data parameters are included; this analysis focuses on the reported precipitation and maximum temperature (Mitchell et al. 2004).

3.3 Estimation of buildings inventory

The methodology for incorporating building stocks into the analysis incorporates a dual approach to building stock quantification. The first and more desired approach is to gather actual building stock data from sources such as Ministries and NGOs that track actual data for building stocks in South Africa. However, these accurate counts are not always available, in which case a methodology is required to estimate the number of buildings based upon country characteristics and population. In both approaches, the building stock is divided into urban and rural categories for primary and secondary schools, public administrative buildings, and hospitals.

An initial approach to this case when actual data is not available was developed for a previous study conducted by the Asian Development Bank. This approach was modified using South African specific information. Where specific data was not available, design specifications were adapted from a recent publication by the Council for Scientific and Industrial Research (CSIR), a South African research and development organization.

The process for estimating input data for determination of building stock in South Africa can be summarized as:

- Schools: number of primary and secondary schools (Lehohla 2004). CSIR guidelines used for average size
- Public administrative buildings: building guidelines of one administrative building per 50,000 people (CSIR); number of municipal administrative levels (assumed one administrative building per (see, www.statoids.com)
- Hospitals: total population; number of hospital beds per 1,000 people; average number of beds per hospital (see: www.globalhealthfacts.org/data/topic/map.aspx?ind=78)

The conclusion of this process provides a building stock inventory from which the IPSS system can be used to estimate the total cost impact of climate change within a given country and its sub-administrative units.

4 Impact functions

The stressor-response methodology is based on the concept that materials and components in roads and buildings will have specific responses to external stressors such as precipitation and temperature. The stressor-response factors introduced below were developed by analyzing specific material and system responses to the effects of each stressor. These effects are then applied to specific types of road and building systems based on the appropriate climate context. This process utilizes multiple baseline data inputs. A combination of material science reports, usage studies, case studies, and historic data were used for each infrastructure category. Where possible, data from material manufacturers was combined with historical data to obtain an objective response function. When these data were not available, response functions were extrapolated based on performance data and case studies from sources such as departments of transportation or government ministries.

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

4.1 Stressor-response values for new construction costs: roads

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

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

4.2 Stressor-response values for maintenance costs on roads

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

For gravel and dirt roads, maintenance impacts are induced by changes in maximum monthly precipitation rates. The result of increased precipitation is increased erosion, creating a need to increase maintenance to retain the original design life. To estimate the changes in road maintenance costs, the amount of erosion is used as a basis for determining the percentage of maintenance increase required. The calculation of the erosion rates for dirt and gravel roads is based on three factors: (1) precipitation amount, (2) traffic levels, and (3) slope of the road. In terms of precipitation, studies indicate that a 1 per cent increase results in an approximate 1 per cent impact on the design life in a minimal slope condition with low traffic levels (Dube et al. 2004). This is used as the base condition for maintenance calculations. However, this base case is augmented as traffic rates and slope percentages increase, resulting in significantly greater erosion rates.

4.3 Stressor-response values for new construction costs: buildings

The determination of building stress-response values is similar to roads as it is based on specific impacts of precipitation and temperature. However, as introduced previously, the focus on buildings incorporates an additional calculation: the concept of incurred costs. Incurred costs are defined as those costs that a building is assumed to incur that cannot be ignored or delayed until a later time. This includes climate impacts on components such as heating, ventilation and air conditioning (HVAC) systems which have specific design guidelines based upon factors such as air quality and health of the occupants.

Based on the types of building analyzed for this study and known construction techniques, the methodology for determining building impacts focuses on non-wooden structures. Buildings made of non-wooden materials including steel, masonry, and concrete are more resistant to climate impacts. Thus, the authors evaluated climate impacts on internal building systems (mechanical and electrical equipment) with the assumption that the impact on external cladding will be minimal due to climate effects. When evaluating the impacts to HVAC systems, it is assumed that if the airflow systems in the building need to be upgraded due to potential health implications then this upgrade will be undertaken. In addition to the incurred costs described above, the building methodology incorporates the 'Adapt' or 'No Adapt' options available in the roads analysis.

Incurred costs for non-wood structures are calculated using the MEWS Index, which determines climate impacts on HVAC systems (Cornick et al. 2001). The MEWS Index is an approach adopted by the MEWS consortium and is fully documented by Cornick et al. (2002). It utilizes a moisture index, defined by a wetting index and drying index to calculate the amount of moisture that a building will be subjected to under varying climate conditions. Using this moisture index as a basis, the MEWS Index defines the climate region that a structure exists within based on the conditions that it is subjected to during given periods of time. This index is then normalized to provide an indication of the changes in precipitation or temperature that are sufficient enough to change the climate condition under which the structure was designed. If the humidity rises above a threshold, the building codes for HVAC load mandate an upgrade of the system to handle airflow for health of the occupants.

For each geographic region, a baseline historic MEWS index is calculated and compared to a future climate change MEWS index developed from climate information. If the threshold is passed, a cost is applied based on the cost per m^2 of upgrading HVAC for a specific building type.

Climate change cost = 5.4% * construction cost * number of thresholds exceeded

where

Climate change cost = total cost applied to each building

Construction cost = average cost for construction of a building based on cost per m^2 and average size of building (1)

In this analysis, 5.4 per cent is the estimated cost of total construction costs that are directly attributed to HVAC components. This is based on the cost of the system components that would need to be replaced (boilers and fan units) as a percentage of the overall HVAC system, which is in turn a percentage of the overall building costs.

Stressor-response values for roofing adaptation: A second focus of the building analysis is on the potential damage to roofing materials on flat-roofed (typically public) buildings such as hospitals and schools. For these structures, roofing design, specifically drainage systems, is based on projected amounts of water that will exist on the roof from rain events. A failure to adequately size the roofing drain will result in water pooling on the roof. This pooling will result in failure of the roofing material as excessive moisture and standing water will ultimately lead to both material and sealant failure.

This stressor-response factor is included within the current study based on the design parameter of maximum monthly precipitation in a given location. Where the maximum monthly precipitation is anticipated to increase by more than 10 cm, it is determined that a greater precipitation drainage capacity is required. For the Adapt scenario, a larger drainage system is placed on the building with a resulting increase in cost of 0.05 per cent of the construction cost. This value represents the cost of changing the drainage system within a building prior to construction. For the No Adapt scenario, 0.3 per cent of total construction cost is incurred for additional maintenance. This represents the cost of repairing roofing materials that are damaged during precipitation events when the system is not initially upgraded.

Climate change cost (Adapt) = 0.05% * Construction cost

Climate change cost (No Adapt) = 0.3% * Construction cost

where

Climate change cost = total cost applied to each building

Construction cost = average cost for construction of a building based on cost per m^2 and average size of building (2)

Although precipitation increases can have additional impacts on exterior building components such as windows and doors, the effects on these components are individualized to the building and the conditions in which the building exists. Therefore, these impacts are not included in the current study.

5 Additional metrics used

5.1 Determination of opportunity cost

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

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

where

X: A specific country

OC: Opportunity cost for a country in percentage

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

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

PR: Current paved road inventory within a country in kilometers (3)

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

5.2 Net adaptation cost: roads

Net adaptation cost is the adaptation cost with maintenance savings incorporated. Because adaptation for unpaved and gravel road infrastructure requires upgrading vulnerable roads to gravel and paved roads, respectively, there is a savings in annual required maintenance costs. These are normal maintenance costs that are no longer required.

In many cases, adaptation costs are high due to higher construction costs for paved or gravel road infrastructure when compared with gravel or unpaved road infrastructure. The savings in routine maintenance costs often offsets these costs, in some cases completely.

5.3 Adaptive advantage: roads

Adaptive advantage is the benefit of adapting road infrastructure. It is the difference in cost between the No Adapt cost and the Net Adapt cost. It is designed to highlight the savings that may be incurred by a pro-active policy to climate change.

6 Study results

For this study, all results are presented below in terms of costs to roads or buildings. Because the life-cycle of the infrastructure components is different and the responsibility of adapting and maintaining the infrastructure falls on different authority, the results are detailed separately after an initial national summary. All results are presented in 2011 US$ and no discounting is used.

At a summary level, the national impact in South Africa of climate change on buildings and roads is summarized below. As illustrated in Table 1, the average annual cost at a national level for the Adapt policy for the median projected climate scenario is US$141 million.[1] This equates to a total impact of US$11,295 million. Similarly, for the maximum climate scenario, the average annual cost at a national level for the Adapt policy is US$457. This equates to a total impact of US$36,531. However, as illustrated, these costs rise significantly when the No Adapt policy is chosen. The following section details these impacts for both roads and buildings at national and provincial levels. Although the study analyzes these impacts through the year 2100, the following sections focus on three representative decades, the 2030s, 2050s, and 2090s. This approach allows both representative summaries as well as overall impacts.

Table 1: Selected national level results

	Total cost roads US$ millions		Total cost buildings US$ millions	Total costs US$ millions		Average annual costs US$ millions	
	Adapt	No Adapt	Incurred	Adapt	No Adapt	Adapt	No Adapt
Median GCM	7,876	13,358	3,419	11,295	16,777	141	210
Maximum GCM	19,385	24,639	17,146	36,531	41,785	457	522

Source: authors' calculations.

6.1 National level results: buildings

The potential impact of climate change on South Africa's public buildings is divided between hospitals, schools, and public buildings. Each of the three categories is based on the methodology above, but is divided to focus on the three distinct building categories reflecting the different administrative centers that oversee structures. Given the three categories, the total impact varies between median and maximum scenarios with schools being the focus of the majority of costs. For buildings, the projected climate change scenarios do not result in threats to the roof structures that fall under the Adapt and No Adapt scenarios. However, the changes do affect the building systems, resulting in incurred costs for the buildings. Therefore, the results presented here are all incurred costs which need to be addressed to avoid health and safety issues. From this perspective, using the median scenario, total costs increase steadily from US$112 annually in the 2030 decade to over a US billion dollars annually by the 2090 decade (Table 2).

The maximum climate scenario is notable for buildings in the difference in impact from the median scenarios. As documented in Table 2, the maximum scenario is an order of magnitude greater in impact in the 2030s. Although the difference in magnitude decreases in the 2050s and

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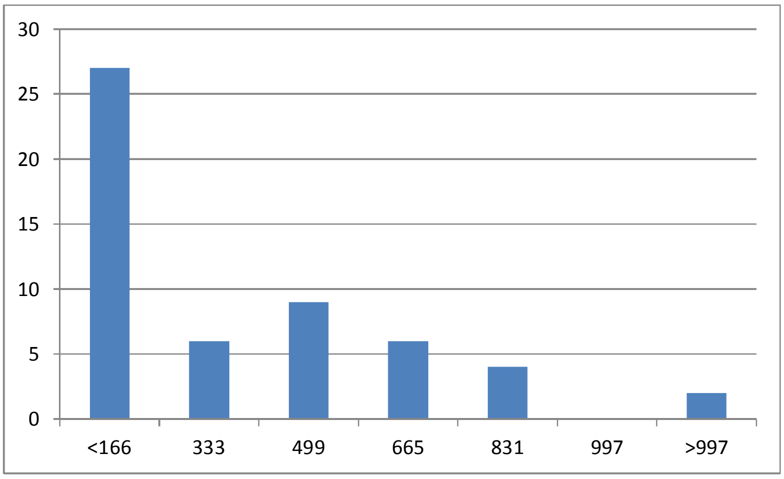
1 Note that the costs for roads are given as average annually since roads may need to be maintained on an annual basis. In contrast, buildings have a single cost for the decade since an adaptation or repair is anticipated to have a greater lifespan.

2090s, the actual dollars of difference continue to increase. By the 2090s, the maximum scenarios present a US$4 billion per year difference in incurred costs. This difference leads to the issue of variance in the results. Specifically, what is the trend from the different climate scenarios in terms of projected impact?

Figures 1a–1c address this issue based on the projected variance in impact on buildings from climate change. As illustrated, it is predicted that the impact will be on the lower end of the variance when the total number of estimates are considered. The lower classification of costs contains 50 per cent, 44 per cent, and 39 per cent of the total number of estimates in the 2030, 2050, and 2090 decades respectively. Although each scenario is equally likely, from a planning perspective, the skew towards a lower number may provide guidance to consider a lower estimate as a planning tool.

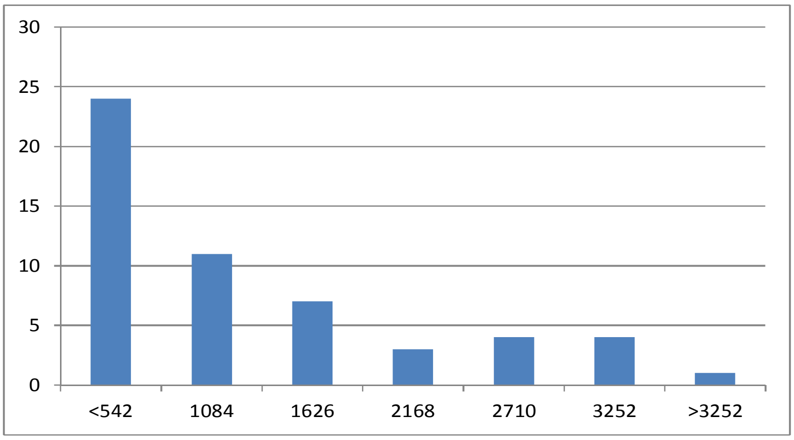
Figure 1a: Building impact distribution estimates – 2030 decade



Note: Maximum values are labeled in interim histogram categories

Source: authors' calculations.

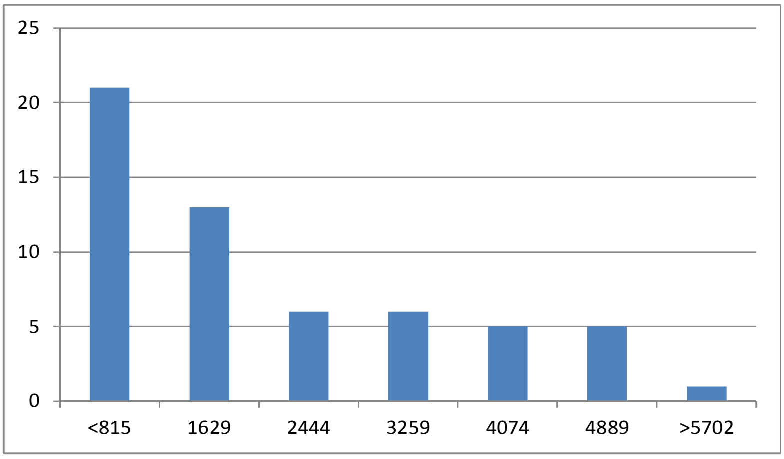
Figure 1b: Building impact distribution estimates – 2050 decade



Note: Maximum values are labeled in interim histogram categories

Source: authors' calculations.

Figure 1c: Building impact distribution estimates – 2090 decade



Note: Maximum values are labeled in interim histogram categories

Source: authors' calculations.

Table 2: Decadal incurred costs for building infrastructure, US$ million

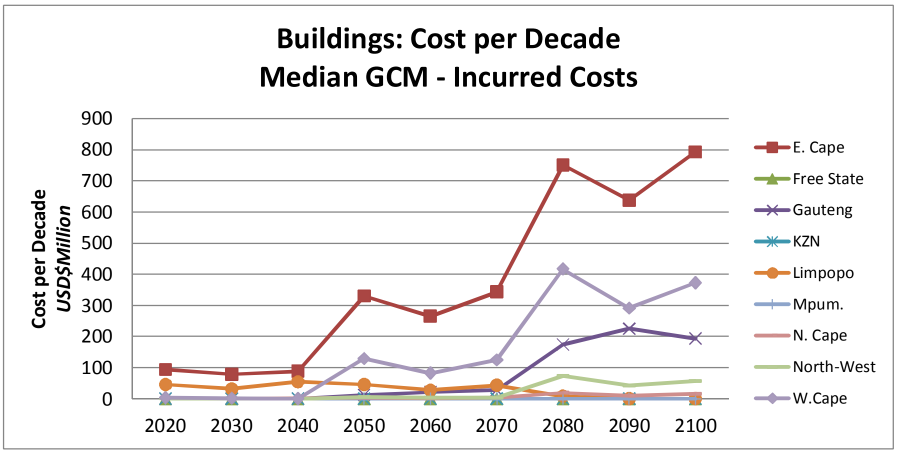
'Mandatory' incurred costs		Hospitals	Schools (urban and rural)	Public buildings (urban and rural)	Total
	Median	2.4	110.0	0.2	112.6
2030	Maximum	33.9	1,101.2	0.5	1,135.5
	Median	14.0	511.3	0.5	525.8
2050	Maximum	106.4	3,719.5	0.9	3,826.8
	Median	39.0	1,167.1	0.6	1,206.8
2090	Maximum	161.8	5,493.5	1.1	5,656.5

Source: authors' calculations.

6.2 Provincial level results: buildings

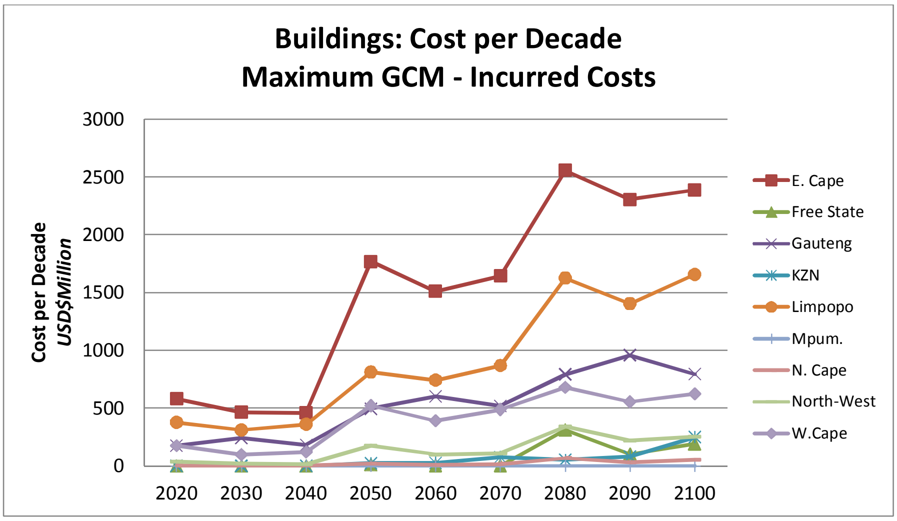
At the provincial level, there is significant variation between the provinces in terms of projected impacts. Figures 2a and 2b illustrate the decadal costs (the total cost for that decade) for each province for both the median and maximum climate scenarios. From the median perspective, the Eastern Cape province is the dominant province in terms of impacts with a notable increase beginning in 2060. The Western Cape province also shows a notable impact when compared with the remaining provinces. From the maximum impact scenario, the Eastern Cape is once again the dominant province with the impacts. However, in this scenario, the Limpopo province emerges as the second greatest impact area in the country.

Figure 2a: Decadal incurred costs for building infrastructure, median GCM



Source: authors' calculations.

Figure 2b: Decadal incurred costs for building infrastructure, maximum GCM



Source: authors' calculations.

Table 3 shows a detailed look at the maximum impact on the provinces in one specific decade, the 2050s, divided into the three categories of buildings analyzed in the study. As illustrated, the primary category of impact is on schools. The reason for this impact is the number of schools located in each province in comparison with the other two categories. As illustrated, the Eastern and Western Cape provinces as well as the Limpopo province absorb the greatest impact. However, at the opposite end of the spectrum, the Free State and the Mpumalanga provinces absorb very little impacts.

Of particular concern in these results are the impacts on hospitals in the impact-sensitive provinces. In these provinces, there needs to be a focused attention on the hospitals as the incurred costs can be directly associated with potential health effects in these facilities. Detailed results can be seen in Appendix Table 1.

6.3 National level results: road infrastructure

The potential impact of climate change on South Africa's national road network could be as high as US$198, US$308, and US$361 million annually in 2030, 2050, and 2090 respectively if no adaptation measures are taken (Table 4). This cost is increasingly reduced in the later decades if a pro-active adaptation strategy is taken. The benefits from adapting road infrastructure pro-actively including savings from decreased maintenance on unpaved road infrastructure, decreased vulnerability to climate change impacts, and a more robust and reliable road infrastructure system.

Table 3: Incurred costs for building infrastructure, 2050 maximum GCM scenario

'Mandatory' incurred costs	Hospitals	Schools (urban and rural)	Public buildings (urban and rural)	Total
	US$ million	US$ million	US$ million	US$ million
Eastern Cape	32.0	1,737.1	0.1	1,769.3
Free State	0.3	7.7	0.1	8.1
Gauteng	28.7	465.3	0.2	494.1
KwaZulu-Natal	0.6	22.9	0.1	23.6
Limpopo	16.1	796.6	0.1	812.8
Mpumalanga	0.0	0.0	0.0	0.0
Northern Cape	0.9	21.2	0.1	22.2
North West	4.8	170.5	0.1	175.5
Western Cape	23.0	498.2	0.1	521.3

Source: authors' calculations.

In the 2090 decade, there is a net savings of over US$40 million compared to current road expenditure if the adapt approach is taken. This is largely because the adapted road infrastructure is more resilient to climate impacts, including upgrading unpaved road infrastructure to gravel and paved roads, reducing the annual maintenance requirements. In 2090, the adaptive advantage is over US$260 million. The opportunity cost of climate change on South African road infrastructure is fairly low at 1–4 per cent depending on the GCM scenario and decade analyzed. South Africa has a large existing road network of over 360,000 km. However, only 20 per cent of this roadstock is paved (IRF 2012). By adapting unpaved road infrastructure to paved infrastructure, there are fiscal savings as well as additional benefits including less maintenance from extreme events, increased connectivity of roads year-round, and higher traffic and freight volumes.

6.4 Provincial level results: road infrastructure

At the provincial level, there is an adaptive advantage for nearly all of the provinces in each decade. As Figures 3 and 4 illustrate, the costs for adaptation are higher in the earlier parts of the century, particularly Eastern Cape, but by 2070, the costs become more consistent and are much lower than the No Adapt costs. This is because of the large unpaved road network that is impacted by increases in precipitation and the existing paved road network that needs to be adapted to projected increases in temperature. As seen in the median and maximum GCM scenarios, the adaptive advantage is particularly high for Northern Cape, North West Province, and Limpopo.

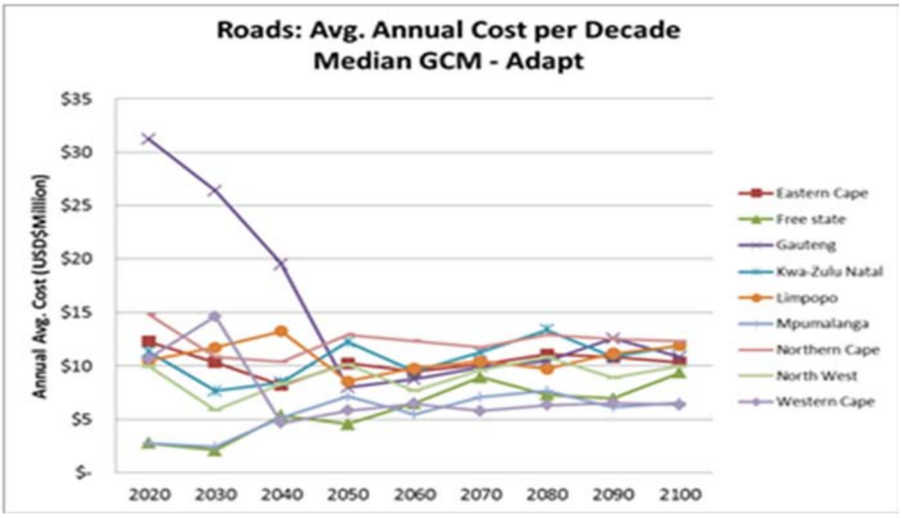
For all provinces, the No Adapt scenarios see an upward trend in average annual cost for both the median and maximum GCM scenarios.

Table 4: Decadal annual average road costs, national level

Decade	Scenario	Annual avg. cost US$ million No Adapt	Annual avg. cost US$ million Adapt	Maintenance savings US$ million Adapt	Net adapt cost US$ million Adapt	Adaptive advantage US$ million	Opp. cost % Adapt	Opp. cost % No Adapt	Equiv. KM Adapt	Equiv. KM No Adapt
2030	Median	59.6	76.8	55.1	21.7	37.9	0.8	0.6	512	397
	Maximum	197.5	202.1	17.1	184.9	12.6	2.1	2.1	1,347	1,317
2050	Median	143.8	81.7	76.9	4.8	138.9	0.9	1.5	545	958
	Maximum	307.6	179.2	20.6	158.6	149.0	1.9	3.2	1,194	2,051
2090	Median	218.9	73.0	119.5	-46.6	265.5	0.8	2.3	486	1,459
	Maximum	360.6	172.5	29.8	142.7	217.9	1.8	3.8	1,150	2,404

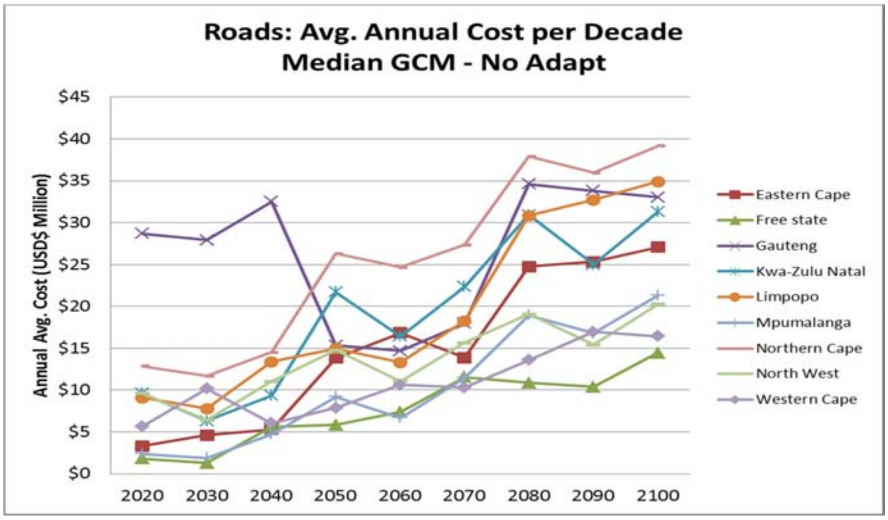
Source: authors' calculations.

Figure 3a: Decadal costs for road infrastructure, median GCM, Adapt



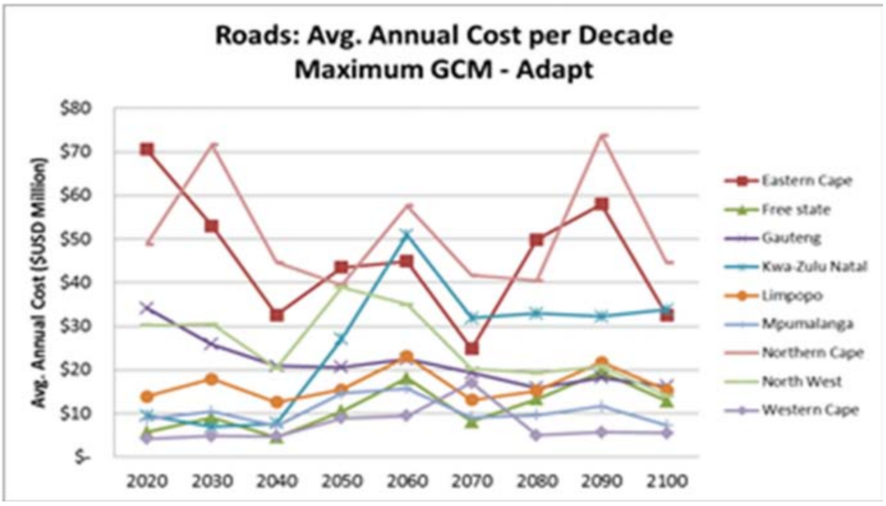
Source: authors' calculations.

Figure 3b: Decadal costs for road infrastructure, median GCM, No Adapt



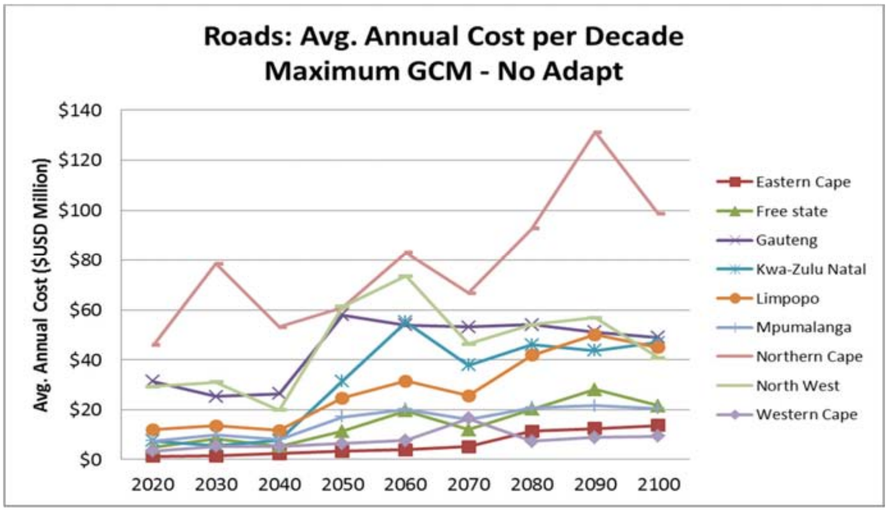
Source: authors' calculations.

Figure 4a: Decadal costs for road infrastructure, maximum GCM, Adapt



Source: authors' calculations.

Figure 4b: Decadal costs for road infrastructure, maximum GCM, No Adapt



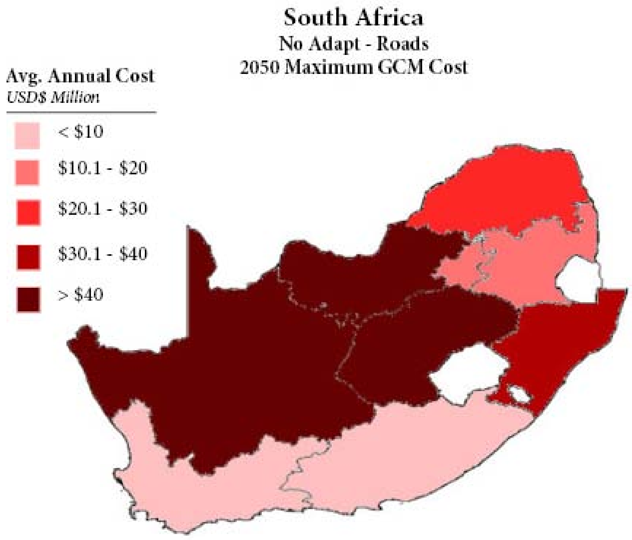
Source: authors' calculations.

For Gauteng province, the adaptive advantage is small. However, total cost is not the only metric that should be considered when deciding between an Adapt and No Adapt policy approach. Proactive adaptation strategy minimizes vulnerability of road infrastructure to climate impacts and reduces the need for extra maintenance costs, increased disruption of traffic, and other impacts associated with damages to road infrastructure.

Northern Cape and Eastern Cape both have higher costs than the other provinces in most decades. This is due to both the projected climate impacts and the high amounts of road infrastructure compared to other provinces (second and third, respectively). Detailed results can be seen in Appendix Table 2.

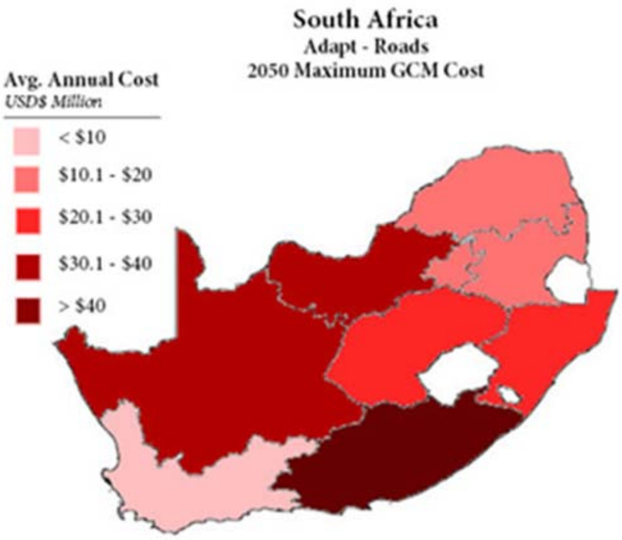
Figures 5a and 5b show the differences between provinces for the Adapt and No Adapt maximum GCM Scenario. In the 2050 decade, it is not always fiscally beneficial to adapt (Table 5).

Figure 5a: Map of annual costs for 2050 decade for road impacts, maximum GCM, No Adapt



Source: authors' calculations.

Figure 5b: Map of annual costs for 2050 decade for road impacts, maximum GCM, Adapt



Source: authors' calculations.

Table 5: 2050 annual average road costs, provincial level

Province	GCM Scenario	Annual avg. cost US$ million No Adapt	Annual avg. cost US$ million Adapt	Maintenance savings US$ million Adapt	Net adapt cost US$ million Adapt	Opp. cost Adapt, in %	Opp. cost No Adapt	Equiv. KM Adapt	Equiv. KM No Adapt
Eastern Cape	Median	13.8	10.2	4.5	5.8	0.8	1.0	68	92
	Maximum	3.3	43.5	6.7	36.8	3.2	0.2	290	22
Free State	Median	15.4	8.0	0.6	7.4	0.8	1.5	53	102
	Maximum	57.9	20.6	0.0	20.6	2.1	5.8	138	386
Gauteng	Median	5.8	4.5	3.6	0.9	0.6	0.7	30	39
	Maximum	11.3	10.5	4.0	6.5	1.3	1.4	70	75
Northern Cape	Median	26.3	12.9	5.3	7.7	0.9	1.8	86	175
	Maximum	61.1	39.4	5.0	34.4	2.6	4.1	263	408
North West	Median	14.8	10.1	5.3	4.8	1.2	1.8	67	98
	Maximum	61.5	39.0	2.0	37.0	4.6	7.3	260	410
Mpumalanga	Median	9.2	7.1	1.0	6.1	1.1	1.4	47	61
	Maximum	17.1	14.6	0.5	14.0	2.3	2.7	97	114
Limpopo	Median	15.0	8.6	2.3	6.3	0.8	1.4	57	100
	Maximum	24.7	15.4	2.1	13.4	1.5	2.4	103	165
KwaZulu-Natal	Median	21.7	12.3	2.7	9.5	0.9	1.6	82	145
	Maximum	31.5	27.1	0.3	26.7	2.	2.3	180	210
Western Cape	Median	7.9	5.8	5.8	0.1	0.6	0.8	39	52
	Maximum	6.4	8.9	4.7	4.1	0.9	0.7	59	43

Source: authors' calculations.

7 Limitations

The current study is based on several key components which introduce uncertainty into the quantitative analysis within the study. The climate data used for this analysis comes from a collection of 54 different GCMs with acknowledged variability and uncertainty. These projections are also performed at a global scale, which necessitates down-scaling for application to country and region-specific analysis. Additionally, the study relies on existing material studies to derive the impact stressors. Although the study bases its findings on recognized authorities and studies, the quantitative cost estimates are dependent on the findings from these and similar studies. Issues such as specific pavement types, local conditions, construction, and maintenance techniques can all combine to affect specific cost impacts. Therefore, the quantitative cost results may differ based on alternative studies.

Calculation of building stock quantities also has limitations based on limited data and the subsequent assumptions. Efforts were made to limit uncertainty by using known statistical data. However, these statistics are typically only available at the national level and detail is limited to rural versus urban areas. These data must then be proportionally applied to smaller regions for analysis with climate information. In this study, building stock and costs are estimated on the lower end of the probable stock and impacts.

Building impact estimates are acknowledged to be on the low side of estimations and further results including a sensitivity analysis should be done. Uncertainty in geographic location of particular building infrastructure and the specific impact of localized climate impacts, especially extreme events, necessitate further study.

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

8 Discussion and conclusion

In conclusion, the current study examines the potential effects of climate change on the road and building infrastructure of South Africa. The study focused on using an engineering approach to determining the specific effects of climate stressors on road surfaces and building systems. Based on a combination of actual and estimated totals for each province within South Africa, the study illustrates the variance in local effects as well as projections from differing climate scenarios. Overall, the study finds that total road impacts will vary between US$98.5 million average annual costs in the median Adapt scenario and US$167.0 million average annual costs in the No Adapt scenario. Similarly, the costs will vary between US$242.3 million average annual costs in the maximum Adapt scenario and US$308.0 million average annual costs in the No Adapt scenario.

For buildings, the same estimates vary between US$42.7 million average annual costs in the median scenario and US$214.3 million average annual costs in the maximum scenario.

When combined, the national level impact will vary between US$141.0 million average annual costs in the median Adapt scenario and US$210.0 million average annual costs in the No Adapt scenario. The costs will vary between US$457.0 million average annual costs in the maximum Adapt scenario and US$522.0 million average annual costs in the No Adapt scenario.

The results from this analysis are intended to inform the economic models that comprehensively analyze the effects of climate change on the economy of South Africa. The resulting challenge to local, regional, and national government agencies from the final results of this analysis is how to incorporate a multitude of conflicting requirements into a cohesive policy that achieves balance between short-term needs and the potential long-term effects of climate change on infrastructure.

Appendix

Appendix Table 1: Detailed building results, province level

Province	Decade	GCM		Climate-driven adaptation and damages ('Mandatory' incurred costs) Hospitals	Schools (urban and rural)	Public buildings (urban and rural)	Total
Eastern Cape	2030	Median	csiro_mk3_5_sresa1b	1.4	76.9	0.1	78.4
		Maximum	csiro_mk3_0_sresb1	8.5	457.8	0.1	466.4
	2050	Median	csiro_mk3_5_sresa1b	5.9	324.0	0.1	330.0
		Maximum	csiro_mk3_0_sresb1	32.0	1737.1	0.1	1769.3
	2090	Median	csiro_mk3_5_sresa1b	11.4	626.8	0.1	638.3
		Maximum	csiro_mk3_0_sresb1	42.0	2263.5	0.2	2305.8
Free State	2030	Median	inmcm3_0_sresa2	0.0	0.0	0.0	0.0
		Maximum	bccr_bcm2_0_sresb1	0.0	0.0	0.0	0.0
	2050	Median	inmcm3_0_sresa2	0.0	0.0	0.0	0.0
		Maximum	bccr_bcm2_0_sresb1	0.3	7.7	0.1	8.1
	2090	Median	inmcm3_0_sresa2	0.0	0.0	0.0	0.0
		Maximum	bccr_bcm2_0_sresb1	1.9	98.9	0.1	100.9
Gauteng	2030	Median	csiro_mk3_5_sresb1	0.0	0.0	0.0	0.0
		Maximum	csiro_mk3_0_sresb1	14.0	225.5	0.1	239.7
	2050	Median	csiro_mk3_5_sresb1	0.7	11.4	0.0	12.1
		Maximum	csiro_mk3_0_sresb1	28.7	465.3	0.2	494.1
	2090	Median	csiro_mk3_5_sresb1	12.8	212.1	0.1	225.0
		Maximum	csiro_mk3_0_sresb1	56.3	900.9	0.3	957.4
KwaZulu-Natal	2030	Median	ipsl_cm4_sresa2	0.0	0.0	0.0	0.0
		Maximum	ncar_ccsm3_0_sresb1	0.0	0.0	0.0	0.0
	2050	Median	ipsl_cm4_sresa2	0.0	0.0	0.0	0.0
		Maximum	ncar_ccsm3_0_sresb1	0.6	22.9	0.1	23.6
	2090	Median	ipsl_cm4_sresa2	0.0	0.0	0.0	0.0
		Maximum	ncar_ccsm3_0_sresb1	2.1	79.0	0.1	81.2
Limpopo	2030	Median	ukmo_hadgem1_sresa2	0.7	30.9	0.0	31.7
		Maximum	csiro_mk3_0_sresb1	6.2	304.9	0.1	311.2
	2050	Median	ukmo_hadgem1_sresa2	0.9	44.7	0.0	45.6
		Maximum	csiro_mk3_0_sresb1	16.1	796.6	0.1	812.8
	2090	Median	ukmo_hadgem1_sresa2	0.0	0.0	0.0	0.0
		Maximum	csiro_mk3_0_sresb1	27.7	1375.7	0.1	1403.5

Mpumalanga		Median		0.0	0.0	0.0	0.0
	2030	Maximum	All GCMs	0.0	0.0	0.0	0.0
		Median		0.0	0.0	0.0	0.0
	2050	Maximum	All GCMs	0.0	0.0	0.0	0.0
		Median		0.0	0.0	0.0	0.0
	2090	Maximum	All GCMs	0.0	0.0	0.0	0.0
Northern Cape		Median	gfdl_cm2_1_sresa1b	0.2	0.3	0.0	0.5
	2030	Maximum	csiro_mk3_0_sresb1	0.2	1.0	0.0	1.2
		Median	gfdl_cm2_1_sresa1b	0.5	3.1	0.1	3.7
	2050	Maximum	csiro_mk3_0_sresb1	0.9	21.2	0.1	22.2
		Median	gfdl_cm2_1_sresa1b	0.6	8.5	0.1	9.2
	2090	Maximum	csiro_mk3_0_sresb1	1.2	31.9	0.1	33.2
North West		Median	ncar_ccsm3_0_sresa1b	0.1	0.7	0.0	0.8
	2030	Maximum	bccr_bcm2_0_sresb1	0.6	18.8	0.1	19.5
		Median	ncar_ccsm3_0_sresa1b	0.3	4.8	0.1	5.2
	2050	Maximum	bccr_bcm2_0_sresb1	4.8	170.5	0.1	175.5
		Median	ncar_ccsm3_0_sresa1b	1.3	41.8	0.1	43.3
	2090	Maximum	bccr_bcm2_0_sresb1	6.2	213.5	0.1	219.8
Western Cape		Median	cccma_cgcm3_1_sresb1	0.1	1.2	0.0	1.3
	2030	Maximum	csiro_mk3_0_sresb1	4.3	93.1	0.0	97.4
		Median	cccma_cgcm3_1_sresb1	5.8	123.3	0.1	129.1
	2050	Maximum	csiro_mk3_0_sresb1	23.0	498.2	0.1	521.3
		Median	cccma_cgcm3_1_sresb1	13.0	277.9	0.1	291.0
	2090	Maximum	csiro_mk3_0_sresb1	24.5	530.1	0.1	554.7

Source: see text.

Appendix Table 2: Detailed road infrastructure results, province level

Province	Decade	Scenario	GCM	Annual avg. cost US$ million	Annual avg. cost US$ million	Maintenance savings US$ million	Net adapt Cost (Adapt cost - maint. savings) US$ million	Opp. cost	Opp. cost	Equiv. KM	Equiv. KM
				No Adapt	Adapt	Adapt	Adapt	Adapt, in %	No Adapt, in %	Adapt	No Adapt
Eastern Cape	2030	Median	gfdl_cm2_0_sresa1b'	4.6	10.4	4.8	5.6	0.8	0.3	69	31
		Maximum	csiro_mk3_0_sresa1b'	1.5	53.0	3.6	49.4	4.0	0.1	354	10
	2050	Median	gfdl_cm2_0_sresa1b'	13.8	10.2	4.5	5.8	0.8	1.0	68	92
		Maximum	'csiro_mk3_0_sresa1b'	3.3	43.5	6.7	36.8	3.2	0.2	290	22
	2090	Median	gfdl_cm2_0_sresa1b'	25.3	10.8	5.8	5.0	0.8	1.9	72	169
		Maximum	'csiro_mk3_0_sresa1b'	12.5	58.1	8.6	49.5	4.3	0.9	387	83
Free State	2030	Median	gfdl_cm2_1_sresa2'	27.9	26.4	0.9	25.5	2.6	2.8	176	186
		Maximum	cccma_cgcm3_1_sresa1b'	25.4	25.8	0.0	25.8	2.6	2.5	172	169
	2050	Median	gfdl_cm2_1_sresa2'	15.4	8.0	0.6	7.4	0.8	1.5	53	102
		Maximum	cccma_cgcm3_1_sresa1b'	57.9	20.6	0.0	20.6	2.1	5.8	138	386
	2090	Median	gfdl_cm2_1_sresa2'	33.8	12.6	0.3	12.2	1.3	3.4	84	225
		Maximum	cccma_cgcm3_1_sresa1b'	51.1	18.2	1.0	17.2	1.8	5.1	121	341
Gauteng	2030	Median	gfdl_cm2_1_sresa1b'	1.3	2.1	2.3	-0.2	0.3	0.2	14	9
		Maximum	cccma_cgcm3_1_sresa2'	8.3	9.0	2.4	6.6	1.1	1.1	60	56

	2050	Median	'gfdl_cm2_1_sresa1b'	5.8	4.5	3.6	0.9	0.6	0.7	30	39
		Maximum	'cccma_cgcm3_1_sresa2'	11.3	10.5	4.0	6.5	1.3	1.4	70	75
	2090	Median	'gfdl_cm2_1_sresa1b'	10.4	6.9	4.6	2.3	0.9	1.3	46	69
		Maximum	'cccma_cgcm3_1_sresa2'	28.2	19.6	4.7	14.9	2.5	3.6	131	188
Northern Cape	2030	Median	csiro_mk3_5_sresa1b'	11.7	10.9	2.7	8.1	0.7	0.8	72	78
		Maximum	cnrm_cm3_sresa2'	78.6	71.7	2.9	68.7	4.8	5.3	478	524
	2050	Median	'csiro_mk3_5_sresa1b'	26.3	12.9	5.3	7.7	0.9	1.8	86	175
		Maximum	'cnrm_cm3_sresa2'	61.1	39.4	5.0	34.4	2.6	4.1	263	408
	2090	Median	'csiro_mk3_5_sresa1b'	36.0	12.5	9.0	3.5	0.8	2.4	84	240
		Maximum	'cnrm_cm3_sresa2'	131.3	73.8	4.9	68.9	4.9	8.8	492	875
North West	2030	Median	csiro_mk3_5_sresb1'	6.4	5.9	4.8	1.0	0.7	0.8	39	43
		Maximum	'cccma_cgcm3_1_sresa1b'	31.0	30.5	0.4	30.1	3.6	3.7	203	207
	2050	Median	'csiro_mk3_5_sresb1'	14.8	10.1	5.3	4.8	1.2	1.8	67	98
		Maximum	'cccma_cgcm3_1_sresa1b'	61.5	39.0	2.0	37.0	4.6	7.3	260	410
	2090	Median	'csiro_mk3_5_sresb1'	15.4	8.9	5.2	3.7	1.1	1.8	59	103
		Maximum	'cccma_cgcm3_1_sresa1b'	57.0	20.8	3.1	17.7	2.5	6.8	138	380
Mpulmalanga	2030	Median	ukmo_hadcm3_sresa1b'	1.9	2.4	1.3	1.1	0.4	0.3	16	13
		Maximum	cccma_cgcm3_1_sresa1b'	9.9	10.4	0.4	10.0	1.6	1.5	69	66
	2050	Median	'ukmo_hadcm3_sresa1b'	9.2	7.1	1.0	6.1	1.1	1.4	47	61
		Maximum	'cccma_cgcm3_1_sresa1b'	17.1	14.6	0.5	14.0	2.3	2.7	97	114
	2090	Median	'ukmo_hadcm3_sresa1b'	16.8	6.1	1.7	4.5	1.0	2.6	41	112
		Maximum	'cccma_cgcm3_1_sresa1b'	21.6	11.6	1.2	10.4	1.8	3.4	77	144
Limpopo	2030	Median	gfdl_cm2_1_sresa2'	7.8	11.7	1.2	10.5	1.1	0.8	78	52

		Maximum	cccma_cgcm3_1_sresa2'	13.6	17.9	0.6	17.3	1.7	1.3	119	91
	2050	Median	'gfdl_cm2_1_sresa2'	15.0	8.6	2.3	6.3	0.8	1.4	57	100
		Maximum	'cccma_cgcm3_1_sresa2'	24.7	15.4	2.1	13.4	1.5	2.4	103	165
	2090	Median	'gfdl_cm2_1_sresa2'	32.7	11.2	2.8	8.4	1.1	3.2	75	218
		Maximum	'cccma_cgcm3_1_sresa2'	50.2	21.7	3.2	18.5	2.1	4.8	145	334
KwaZulu-Natal	2030	Median	inmcm3_0_sresa1b'	6.3	7.6	2.8	4.8	0.6	0.5	51	42
		Maximum	cnrm_cm3_sresa1b'	5.7	6.9	7.5	-0.5	0.5	0.4	46	38
	2050	Median	'inmcm3_0_sresa1b'	21.7	12.3	2.7	9.5	0.9	1.6	82	145
		Maximum	'cnrm_cm3_sresa1b'	31.5	27.1	0.3	26.7	2.0	2.3	180	210
	2090	Median	'inmcm3_0_sresa1b'	25.0	10.8	8.1	2.7	0.8	1.8	72	167
		Maximum	'cnrm_cm3_sresa1b'	43.7	32.3	2.8	29.5	2.4	3.2	215	291
Western Cape	2030	Median	iap_fgoals1_0_g_sresa1b'	10.2	14.7	2.8	11.8	1.5	1.0	98	68
		Maximum	ncar_ccsm3_0_sresb1'	5.4	4.9	5.1	-0.3	0.5	0.5	32	36
	2050	Median	'iap_fgoals1_0_g_sresa1b'	7.9	5.8	5.8	0.1	0.6	0.8	39	52
		Maximum	'ncar_ccsm3_0_sresb1'	6.4	8.9	4.7	4.1	0.9	0.7	59	43
	2090	Median	'iap_fgoals1_0_g_sresa1b'	17.0	6.5	8.2	-1.7	0.7	1.7	43	113
		Maximum	'ncar_ccsm3_0_sresb1'	8.9	5.7	5.4	0.3	0.6	0.9	38	59

Source: see text.

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