COSTING AND IMPACT METHODOLOGY

DEVELOPMENT UNDER CLIMATE CHANGE RESEARCH PROJECT

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The Development Under Climate Change (DUCC) research effort provides a basis for determining quantitative impacts on infrastructure from climate change. This paper introduces the methodology for quantifying these impacts through engineering-based models that estimate the impact of climate stressors on individual infrastructure categories. Through these models, stressor-response functions quantify the cost impact of a specific stressor based on the intensity of the stressor and the type of infrastructure it is affecting. The findings of this approach are presented as a basis and first step towards the development of adaptation strategies within the overall DUCC research effort.

1.0 Introduction

The issue of climate change is one that dominates conversations in many contexts. Issues such as uncertainty in model forecasts, timeframe of impact and the influence of humans on climate change processes are all ones that continue to evoke debate around the world. However, much of the existing climate change literature examines the cost of policies to mitigate climate change (e.g., carbon taxes and cap-and-trade systems), but few studies address the costs of climate change adaptation (Stern 2007; Claussen et al 2001; Nordhaus 2008). Given that climate scientists put forth that the climate is likely to continue changing regardless of the success or failure of efforts to reduce emissions of greenhouse gases, adaptation represents an important tool for minimizing the adverse impacts of climate change. The development of efficient adaptation strategies requires sound information on the costs and benefits of different adaptation options to facilitate the allocation of scarce adaptation resources.

The challenge for public officials attempting to prepare for climate change is to anticipate the potential cost of climate change impact on public infrastructure (TRB 2008). While significant study has been done on the cost of natural disasters in various contexts, climate change presents a new challenge for public officials. The combination of the long-term nature of the event and the conflicting scenarios depicted for climate change create a significant amount of uncertainty in the planning process. This paper provides an initial step toward addressing one component of this uncertainty, the potential cost implications of climate change on infrastructure. Based on research previously completed by the authors for the World Bank (World Bank 2009), the State of Alaska (Larsen et al 2008), and on developing countries (Chinowsky et al 2011), the paper introduces a stressor-response methodology for calculating the cost impact of climate change on the road sector of infrastructure. The methodology lies at the core of the research being developed under the Development Under Climate Change (DUCC) program at WIDER.

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2.0 Background

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

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

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

In the context of Africa, the potential impact of climate change on infrastructure is beginning to receive increased attention. However, planning for climate change in the African context is complicated by the lack of existing infrastructure. In 1997, the continent of Africa (excluding South Africa) had 171,000 kilometers of paved roads, about 18% less than Poland, a country roughly the size of Zimbabwe. Despite continued investments, the stock of roads continues to lag behind the remainder of the world both in total roads and in paved roads. In 2008 only about 25% of sub-Saharan Africa's primary roads were paved, compared to a global rate of 50% and a

67% rate in North America. In terms of total roads compared to population, the paved road length in Sub-Saharan Africa of 0.79 kilometers per thousand inhabitants is less than half of that of South Asia and only about one fifth of the world average. In terms of road quality, there is significant variability in primary transport corridor quality with Central Africa having only 49% of primary roads in good condition, while South Africa has 100% of the roads in good condition (Gwilliam et al 2008). In terms of rural roads, which are the majority of the roads on the continent, more than 70% of rural roads are considered to be in fair or poor condition (Foster and Briceno-Garmendia 2010).

3.0 Methodology

The stressor-response methodology is based on the concept that exogenous factors, or stressors, have a direct affect on and subsequent response by, focal elements. In the context of climate change and infrastructure, the exogenous factors are the individual results of climate change including changes to precipitation levels, temperatures, storm frequency, and wind speeds. The focal elements are the individual infrastructure types including roads, railroads, water and power distribution, and public buildings among others. Therefore, a stressor-response value is the quantitative impact that a specific stressor has on a specific infrastructure element. The focus of the overall Development Under Climate Change (DUCC) research effort is the analysis of the cost impacts of climate change on overall development. In this specific component of the research effort, the impact on infrastructure is analyzed as it relates to the overall development effort. At the core of this analysis is a two-phase approach 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.

In the context of the first phase, the following section describes the multi-step process used to determine the climate impacts on the infrastructure inventory. Following this description, the paper introduces the specific stressor-response functions adopted for the individual road infrastructure elements. These 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 in the study are precipitation, temperature, and flooding as they are impact by climate change. 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 the focus on qualitative statements to an emphasis on quantitative estimates.

3.1 Climate and Inventory Determination

As illustrated in Figure 1, the overall stressor-response methodology involves seven steps which lead from determining the climate zones within each individual country to determining the appropriate Global Circulation Models (GCMs) to use for a given location and finally to determining climate impacts on an individual country level.

3.1.1 Climate Zones

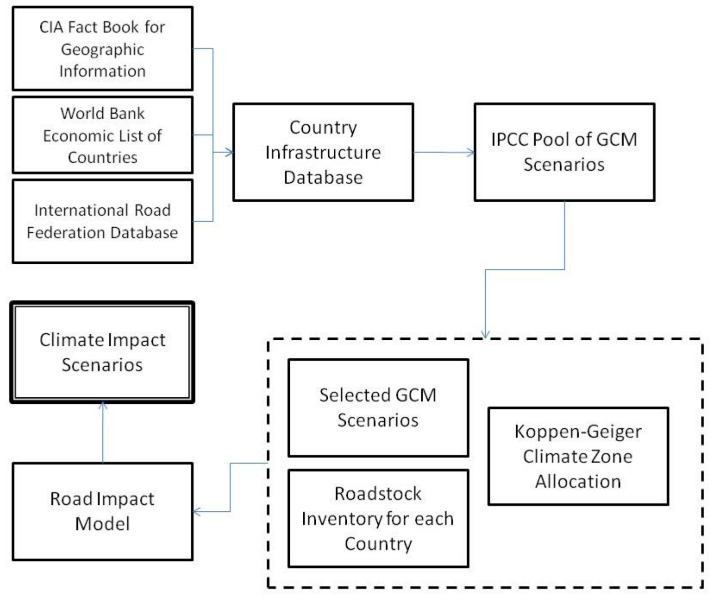

Figure 1: The process used to develop the climate scenarios and the impacts on each country.

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

Utilizing GIS maps, overlays will be created for each country to determine the percentage of each country that lies within a specific Koppen-Geiger climate zone. Depending on the country, this division generally ranges from 2 to 4 climate zones.

3.1.2 Division of Road Inventory

A primary analysis function of the DUCC infrastructure system is to provide cost information for a specific set of road parameters. In the start of this analysis, the system will adopt specific allocations of kilometres of road in each geographic area, the type of road, and the road surface type. However, during the analysis process, the system needs to provide benefit data of building such roads in the context of a specific location. From this perspective, the total road inventory of a geographic area is required. To allocate this road inventory within the country, the authors utilize a percentage allocation methodology. In this method, the authors obtain the total road inventory for each country through either direct data where it is available or through a commercial database of international road data (IRF 2009). Based on existing classifications, the roads are divided into three categories, primary, secondary, and tertiary. Further, roads are divided into paved and unpaved categories for each of the three classifications based on the percentage of paved roads provided by the data sources, thus giving each country the opportunity to have six distinct road classifications.

The total inventory of each road type for the country is subsequently divided into the climate zones based on the percentage of the country that the zone encompasses. This method is based on the assumption that geographic area is related to the number of roads in a given country. This provides a starting point from which to do the regional-level analysis. For example, if a country had two climate zones, Zone A which covered 65% of the country and Zone B which covered the remaining 35%, and 1,000 kilometers of primary paved roads, then 650 kilometers of primary paved road would be allocated to climate Zone A and 350 kilometers would be allocated to Zone B. In this same manner, each of the six types of road is allocated between the climate zones. This results in allocations of 12 to 24 total allocations depending on the number of climate zones within a country.

Where available, this allocation distribution will be compared to GIS data to ensure appropriate distribution through the country. In particular, this comparison will be focused on urban versus rural areas where the allocation of road inventory can be greatly skewed in some countries. For example, in North Africa, the geographic zone delineation is dominated by arid desert climates. However, the population densities are dominant within the narrow bands of temperate climate found along the coast of the Mediterranean Sea. This impacts the geographic allocation method of road inventory division by placing roads in proportions which are different than the physical zone allocations.

3.2 GCM Models

Once the allocations of the road inventories are completed, a determination is required as to what climate models should be used for each country. In the current study one of two processes will be used to select models depending on the progress of concurrent research being conducted at the Massachusetts Institute of Technology (MIT). In this work, the researchers are developing a probabilistic model of climate change scenarios where probabilistic distribution functions (PDFs) are being developed based on the array of Global Circulation Models (GCMs) available today. In this preferred model, the research team will incorporate the PDFs to develop output based on the probability that a scenario is likely to occur in a certain climate zone. In this manner, the results will provide a likelihood in terms of potential impact. This method has the additional advantage of directly addressing the uncertainty element of the climate projections. While this would be a preferred advance to the current methodology, the availability of the PDFs will be the determinant of whether this option will be adopted.

If the new probabilistic method is not available, the team will adopt the GCM selection previously utilized in existing efforts. In this method, the climate models will be selected from the pool approved by the IPCC and represent both a variance in projected precipitation increases as well as a variance in scenarios of how a given country may pursue industrial development (IPCC 2007). Each of these climate models contains annual predicted precipitation and maximum temperatures. In an effort to get a broad picture of the potential effects of climate change and to avoid focusing on extreme possibilities, three different climate scenarios will be chosen, a global effect, a maximum country effect, and a median country effect. The global perspective is adopted from earlier work by the authors for the World Bank and represents a global wet, NCAR_ccsm3-A2, and a global dry, CSIRO_mk3-A2, scenario based on soil moisture effects (World Bank 2009). These two models will be run for each country as a baseline global climate model.

In contrast to the global model, the country models are selected based on the impact that the climate model indicates for a specific country. Focusing on the effects of climate on infrastructure, the wet and hot properties of the 22 accepted models are focused upon in this selection process. Specifically, the effects of each model are analyzed in terms of precipitation and temperature averages for each decade from 2010 through 2100. For precipitation, the annual precipitation for each decade is used to determine the total precipitation increase through 2100 in the specific country. Based on this total, models are selected based on the maximum annual precipitation predicted and the median precipitation predicted for each country. Similarly, the maximum temperature is used to select the models which predict the greatest temperature increase and the median temperature increase. The completion of the selection process will provide six models for each country; a global wet and a global dry, a country maximum wet and a country maximum dry, and a country median wet and a country median dry. These six models can then be averaged into three groups using a weighting factor as determined by the user to compensate for the uncertainty of the models in predicting climate change impact.

4.0 Impact Functions

Once the appropriate GCM scenarios are selected, it is possible to determine the costs and impacts on the individual infrastructure elements based on the stress-response methodology. In this section, the current stressor-response functions are introduced for precipitation, temperature and flooding in the context of road infrastructure. During the next stage of the research, stressor-response functions will be developed for sea level rise as well as specific concerns for coastal infrastructure.

In this study, the stressor-response factors have been developed based on multiple inputs. A combination of material science reports, usage studies, case studies, and historic data were used to develop response functions for the infrastructure categories. Where possible, data from material manufacturers was combined with historical data to obtain an objective response function. However, when these data were not available, response functions were extrapolated based on performance data and case studies from sources such as Departments of Transportation or government Ministries. Cost data for the general study was determined based on both commercial cost databases and specific country data where available. Where in-country cost data is not available, costs are based on the cost of building and maintaining infrastructure in the United States. To develop stressor-response values specific to individual countries, the U.S.-based cost estimates are scaled using an inter-country construction cost index published by Compass International Consultants Inc. (2009). The country-specific values that make up this index represent average construction costs for each country relative to costs in the United States.

Finally, the stressor-response factors presented below are divided into two general categories; impacts on new construction costs and impacts on maintenance costs. New construction cost factors are focused on the additional cost required to adapt the design and construction of a new infrastructure asset, or rehabilitating the asset, to changes in climate expected to occur over the asset's lifespan. Maintenance cost effects are maintenance costs, either increases or decreases, which are anticipated to be incurred due to climate change to achieve the design lifespan. In each of these categories, the underlying concept is to retain the design life span for the structure. This premise was established as a baseline requirement in the study due to the preference for retaining infrastructure for as long as possible rather than replacing the infrastructure on a more frequent basis. Achieving this goal may require a change in the construction standard for new construction or an increase in maintenance for existing infrastructure. As documented, this strategy is realized individually for the various infrastructure categories.

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

4.1 Stressor-Response Values for New Construction Costs

The derivation of the stressor-response values for new construction costs encompasses two general approaches. Each approach retains the focus of building a new infrastructure component to a standard that enables it to withstand projected climate changes over its design lifespan. The first approach estimates dose-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.

4.1.1 Materials Methodology

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 with those changes the accompanying changes in material requirements. Following this concept, this methodology determine 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. The readily available data suggest that such changes would occur with every 10 centimeter (cm) increase in maximum monthly precipitation for both paved and gravel roads, or 6 degree Celsius maximum pavement temperature increase for paved roads (AASHTO 2001; NOAA 2009; Lea 1995).

The general stressor-response relationship for these specific types of infrastructure is expressed as follows:

(1) $\mathrm{Cp} = (\mathrm{NTHRESH} * \mathrm{SCI}) * \mathrm{BPG}$

Where C_P = change in construction costs for paved and gravel roads associated with a climate stressor,

N_{THRESH} = Number of precipitation or temperature thresholds exceeded

SCI = Stressor Cost Increase per threshold increase, and

B_{PG} = base construction costs for paved or gravel roads.

The specific stressor cost increase for precipitation is based on the degradation that increased precipitation causes on a paved or gravel roadway. Specifically, for paved roads, the increased precipitation results in an increase in rutting and thus a reduced amount of time until resurfacing is required. The resultant degradation in the road surface is dependent on climactic conditions, with dry climates absorbing a 1% loss and wet climates absorbing a 1.7% decrease for each 10 cm increase. The mitigation of this effect is to change the sealant that is used for the road, or increase the interval that sealing is completed on the road. The cost of these changes is dependent on the solution selected for the individual infrastructure element.

Concurrently, the specific stressor cost increase for temperature is based on predicted maximum pavement temperatures during the design life of the paved roads. Based on pavement binder requirements, for every 6 degree projected pavement increase, a new asphalt binder must be selected. This change results in a 3.5% cost increase over base construction costs to the overall project. Temperature does not have a tangible effect on gravel roads and thus the increase is not appropriate for these roads.

4.1.2 Alternate Infrastructure

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. This is the method adopted for dirt roads where minimal options exist to offset anticipated climate changes. For new construction of unpaved roads, the impact of concern from climate change is precipitation. However, the challenge with precipitation is that no direct adaptation for dirt roads is generally feasible to reduce degradation. Thus, 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. The general benefit relationship from this adaptation is as follows:

(2) $BR_G = CC_G - (MC_D + CCMC_D + RC_D)$

Where:

BR_G = Benefit to change to a gravel road

CC_G = Construction Cost for the Gravel Road

MC_D = Standard maintenance cost for the dirt road

$CCMC_D$ = Climate induced maintenance cost for the dirt road

RC_D = Intermittent cost of rehabilitating the dirt road

This benefit is presented as a decision point for consideration at the construction phase. If the benefit is positive, then the gravel road alternative is recommended if funds are available. However, if the benefit is negative, then it may be more appropriate to focus on anticipating increased maintenance costs.

4.2 Stressor-Response Values for Maintenance Costs

Similar to the stressor-response functions for new construction, the functions for maintenance differ between paved, gravel, and unpaved roads. In terms of paved roads, an approach is adopted that bases the cost of maintenance on the cost of preventing a reduction in lifespan. As indicated by Equation 3, implementation of this approach involves two basic steps: (1) estimating the lifespan decrement that would result from a unit change in climate stress and (2) estimating the costs of avoiding this reduction in lifespan.

$$MT_{ERB} = (L_{ERB})(C_{ERB}) \tag{3}$$

Where MT_{ERB} = Change in maintenance costs for existing paved roads associated with a unit change in climate stress

L_{ERB} = Potential percent change in lifespan for existing paved roads associated with a unit change in climate stress

C_{ERB} = Cost of preventing a given lifespan decrement for existing paved roads

To estimate the reduction in lifespan that could result from an incremental change in climate stress (L_{ERB}), 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, as shown in Equation 4.

$$L_{ERB} = \frac{\Delta S}{BaseS}(SMT)(SDR) \tag{4}$$

Where L_{ERB} = Potential percent change in lifespan for existing paved roads associated with a unit change in climate stress

ΔS = Change in climate stress (i.e., precipitation or temperature)

$BaseS$ = Base level of climate stress with no climate change

SDR = Standard road degradation rate

SMT = Standard maintenance costs for the road type

As indicated in Equation 4, the potential change in lifespan is dependent on the change in climate stress. For precipitation effects, a potential reduction in lifespan is incorporated for existing paved roads for every 10 cm increase in annual rainfall. Specifically, the increased degradation of the pavement based on the increased precipitation is the basis for estimating the climate change effect. In the case of temperature, a similar lifespan reduction occurs when a change in maximum pavement temperature occurs for existing paved roads. In this scenario, increased cracking occurs in the pavement and an increased sealant schedule is required.

After estimating the potential reduction in lifespan associated with the given climate stressors, the next step in the process is estimating the costs of avoiding this reduction in lifespan. To estimate these costs, the change in maintenance costs is set to the product of (1) the potential percent reduction in lifespan (L_{ERB}) and (2) the base construction costs of the asset. Therefore, a 10 percent potential reduction in lifespan has an estimated increase in maintenance costs of 10 percent of base construction costs.

For gravel and dirt roads, maintenance impacts are induced by changes in maximum monthly precipitation rates. Specifically, increases in maximum precipitation result in increased erosion of the road surfaces. The result of this increased erosion is the 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. This increase is illustrated by Equation 5.

$$MT_{URR} = M \times B_{URR} \tag{5}$$

Where MT_{URR} = Change in maintenance costs for unpaved or gravel roads associated with a unit change in climate stress

M = Cost multiplier

B_{URR} = Baseline maintenance

The calculation of the erosion rates for dirt and gravel roads is based on three factors, precipitation amount, traffic levels, and slope of the road. In terms of precipitation, studies indicate that a 1% increase results in an approximate 1% impact on the design life in a minimal slope condition with low traffic levels. This is used as the base condition for maintenance calculations. However, this base case is augmented as per the table multipliers in the following table. As illustrated in the following chart, as traffic rates and slope percentages increase, the impact gets significantly greater. Once the appropriate modifiers are taken into account, the total cost can be calculated for the specific climate scenario.

	Low Slope (< 5%)	Med Slope (5% - 10%)	High Slope
Low Traffic	1	5	13
Med Traffic	2	10	25
High Traffic	3	15	36
	Low Slope (< 5%)	Med Slope (5% - 10%)	High Slope
Low Traffic	1	5	10
Med Traffic	2	10	25
High Traffic	3	15	36

5.0 FLOODING

Similar to precipitation and temperature, flooding damage is calculated through stressor-response functions. Specifically, road losses are calculated based on monthly runoff estimates and a custom damage function that generates loss estimates based on the return period of the precipitation intensities. The damage function is derived by assuming damage begins at the 2 year frequency and grows linearly to 100% damage at the 100 year event. Under this assumption, the linear damage relationship as a function of recurrence interval is:

(6) $\% \text{ Damage} = 0.043(R)-0.0906$

Where "R" = Recurrence Interval

While this equation, based on these assumptions, is valid for road culvert damage, it does not consider other damages that may be incurred beyond culvert washout. These damages include damages in riverside floodplains, other non-culvert washouts, etc. These damages typically occur as a result of infrequent events. Therefore, equation 6 is used for events with recurrence intervals 20 years or less. For events greater than 20 years, and less than or equal to 50 years, it is assumed that an increase in the fraction of roadway damages would occur. A point is taken to estimate the effect of these increased damages, and is assumed to double the fraction found by equation 6 at the 50 year event. Equation 6 gives 2.2% at 50 years, so the revised formula should result in 4.4% damages at 50 years. Therefore, for events greater than 20 years and less than or equal to 50 years, equation 7 is used:

(7) $\% \text{ Damage} = 0.117(R)-1.53$

Using the same logic, it is assumed that at the 100 year event, 50% more damage would occur than that estimated using equation 7. Equation 7 would result in 10.2% damage therefore equation 7 should result in 15.3% damage. Equation 7 is used for events with recurrence intervals greater than 50 years.

(8) $\% \text{ Damage} = 0.2202(R)-6.66$

The linear functions for these three equations are illustrated in Figure 2.

5.1 Cost Estimates

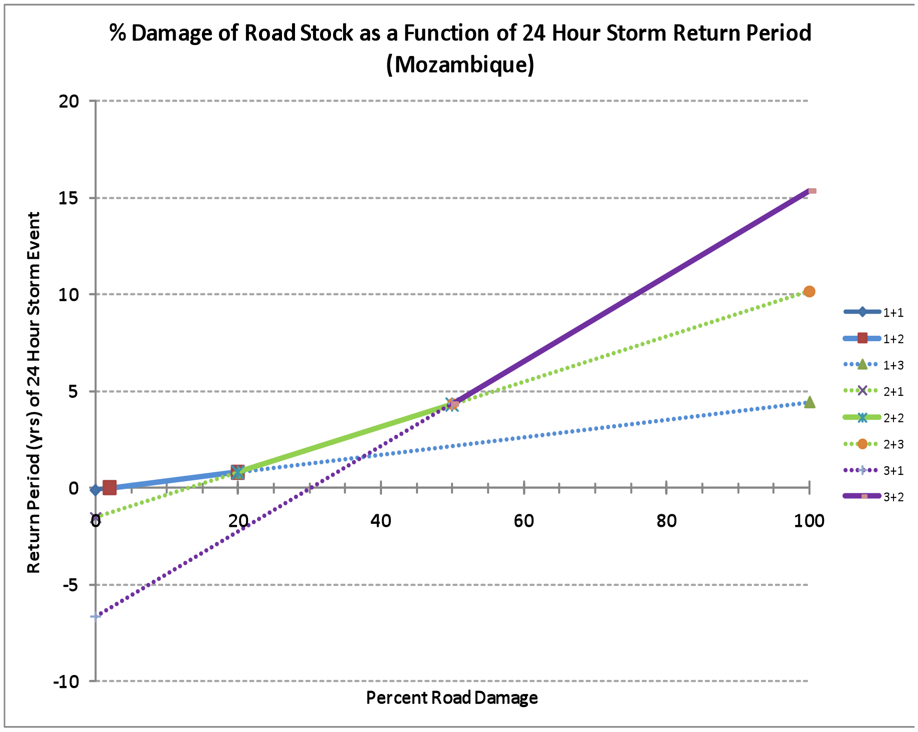

Figure 2: Step-wise damage functions for flood intensities.

Translating the runoff and damage curve estimates into damage costs requires two steps: determining the amount of road kilometers damaged and the specific costs implied by these damages. The first of these steps requires translating information on floods into actual kilometers of road that will be damaged. This determination is dependent on two factors; the intensity of the flood and how many roads have had adaptations applied to them. In terms of the former, the intensity of the flood impacts the degree to which a road is damaged and thus the total kilometers of road that are damaged by a flood in a specific region. As documented by Wright (2011), the flood intensity results in a step-wise damage function with the rate of damage increasing at the 20-year and 50-year flood intensities. These increases raise the damage from a low of 2.2% below 20-year levels to 4.4% between 20 and 50-year levels to a low of 15.3% for floods above the 50 year stage (Figure 2).

In terms of the potential number of kilometers of damage that may occur to a specific flood area, this number is reduced if the roads have had adaptation measures applied to them. These measures—which include increased drainage, increased road thickness, or a change in asphalt mix—provide resistance to additional flooding levels induced by climate change. Thus, the potential number of roads that can be damaged is equal to the total number of roads that are within the flood area, less the number of kilometer of roads in that area that have been adapted to reduce flood vulnerability. The formula reflecting this determination is as follows:

(9) $\square\square\square=\sum\square\square*\square\square+(\sum\square\square*\square\square)$

Where: PDR = Potential Damaged Roads

PR = Paved Roads

DE = Damage Estimate

UR = Unpaved Roads

The second step for cost estimation in flooding is to determine the cost-per-kilometer effect of floods on the roads. For paved roads, the accomplishment of this task is based on the type of roads that are being damaged and the standard maintenance costs these roads incur. For example, annual maintenance costs for primary roads are estimated at 15 percent of construction cost, while 29 percent and 35 percent are used for secondary and tertiary roads respectively. The primary roads number is lower due to the roads being built to a higher standard at original construction. For example, primary roads have a thicker base to accommodate greater traffic densities and thus gain additional resiliency to flood effects.

Unpaved roads differ in that they are based on the severity of the flood rather than the road type, since the impact focuses on the road surface rather than the road base or the type of pavement, as is the case for paved or gravel roads. Therefore, the dirt surfaces on these roads will erode based on the amount of floodwater rather than the type of road that is constructed. Given this relationship to water rather than construction materials, the impact percentage for unpaved roads does not vary according to whether they are primary, secondary, or tertiary roads. Specifically, the cost to rehabilitate unpaved roads after flood damage is set to 60% of the original cost (COWI 2009). Therefore, if the original cost of constructing a secondary unpaved road is USD$75,000 per kilometer, then the cost to rehabilitate that same road after a flood is USD$45,000.

For both paved and unpaved roads, it is assumed that the repairs can be completed in a single year. Using these maintenance ratios, the potential roads that could be damaged each year, as described above, are then multiplied by the cost per kilometer to obtain a total maintenance rate required for that particular year in the time series. The general form for both paved and unpaved roads is as follows:

$$FDC = (CC * MR) * PDR \quad (10)$$

Where:

FDC = Flood Damage Cost

CC = Construction Cost

MR = Maintenance Ratio

PDR = Potential Damaged Roads

6.0 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,

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

Where:

X: A specific country

OC: Opportunity cost for a country in percentage

CC: Total estimated climate change cost for a country including both maintenance and new costs through 2100

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

PR: Current paved road inventory within a country in kilometers

The equation indicates that the opportunity cost for a country is equal to the total percentage increase in the paved road network that could have been achieved if the money was not being diverted to climate change adaptation. In this manner, opportunity cost is the degree to which a country could enhance its road infrastructure if climate change would not be impacting the road expenditures. The opportunity cost is based on existing road inventory numbers. It is intended to provide a reflection of climate change impact based on current circumstances. Since the majority of countries in Africa already have a low road density factor, the opportunity cost emphasizes the impact on projected plans to increase this density and meet projected development targets in terms of road infrastructure.

7.0 Conclusion

This paper introduces a methodology for estimating the cost impact of climate change on infrastructure based on the integration of existing material-based studies. At the core of the methodology is a quantitative basis in engineering and material science. Through a combination of material studies, historical records, and individual case studies, a series of stressor-response variables have been developed for paved, gravel, and dirt roads. The variables have been developed for both new construction and maintenance values in response to temperature, precipitation, and flooding stressors.

The developed stressor-response functions illustrate the potential to integrate the predicted temperature, flooding, and precipitation changes resulting from climate change with traditional costing methods to anticipate cost impacts in specific locations. Additionally, using existing expenditures, road inventories, and the calculated cost impacts, it is possible to determine base opportunity costs for each location. Although the gross dollar impact is the number that attracts the greatest attention, it is the relative impact of climate change on specific economies that illustrates the real impact of climate change on infrastructure development. From this perspective, the adopted methodology will spotlight the relative impact for each country under study.

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

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