Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 78 (2014) 306 – 316

Procedia Engineering

www.elsevier.com/locate/procedia

Humanitarian Technology: Science, Systems and Global Impact 2014, HumTech2014

Climate change and infrastructure impacts: comparing the impact on roads in ten countries through 2100

Amy Schweikert*, Paul Chinowsky, Xavier Espinet, Michael Tarbert

Institute of Climate and Civil Systems, 428 UCB, Boulder, Colorado, 80303

Abstract

Climate change poses a critical threat to future development, particularly in areas where poverty is widespread and key assets such as infrastructure are underdeveloped for even current needs. The focus of this study includes ten geographically and economically diverse countries and the impact of 54 distinct AR4 Global Circulation Model (GCM) scenarios of future climate change on their existing road networks. The analysis is completed using a software tool which uses engineering and materials-based stressor-response functions to determine the impact of climate on maintenance, repair and construction. This study represents an update to a previous study conducted by the authors in 2011. The key updates include methodological advances, policy-oriented results presentation and the use of a new software tool developed by the authors.

For nine out of ten countries in the study, pro-active adaptation measures result in lower fiscal costs and higher connectivity rates as early as 2025. The results through 2100 are presented and the costs of climate change present clear findings for these countries in terms of road maintenance, construction, and adaptation policy.

In rural areas, particularly those in low-income countries, roads represent a lifeline for economic and agricultural livelihood, as well as a number of indirect benefits including access to healthcare, education, credit, political participation, and more. Roads may be sparse through geographic locations, making each road critical. Extreme events pose a costly hazard to roads in terms of degradation, necessary maintenance, and potential decrease in lifespan due to climatic impacts.

Climate change poses costly impacts in terms of maintenance, repairs and lost connectivity; yet many of these impacts can be mitigated and avoided by pro-active adaptation measures. It is a crucial consideration for protecting current and future infrastructure investments and the economic, social, and other functions they serve.

The Infrastructure Planning Support System (IPSS) is a software tool designed to quantify the impacts of both extreme events and incremental climatic changes on road infrastructure in any geographic location throughout the world. The system identifies the financial cost on a yearly basis through 2100 and allows users to compare proactive adaptation measures and reactive non-adaptation measures. IPSS compares a ‘no climate change’ scenario as a baseline to provide information on the ‘regret’ that may occur if a predicted outcome of climate change model does not manifest as projected. Infrastructure impacts are determined based on civil engineering materials research, field studies of actual impacts on roads and buildings, and additional data. These resources are combined into stressor-response equations which are implemented to provide specific cost estimates. Additionally,

---

* Corresponding author. Email: amy@clicslab.org

Selection and peer-review under responsibility of the Organizing Committee of HumTech2014
doi:10.1016/j.proeng.2014.07.072

the program can be customized to a specific location where data is available on stressor-response impacts on the infrastructure elements being analyzed.

This paper focuses on the methodology and application of the IPSS tool to countries representing a range of incomes including low-income, middle, and upper income countries. The IPSS tool is used to compare costs of adaptation and opportunity cost for each country. The results indicate that higher income countries face significant dollar costs due to the extensive road networks, with very high costs in Japan and Italy, in particular. Bolivia, Ethiopia, and Cameroon all show extremely high advantages to adaptation, yet the costs required to simply maintain existing networks are equivalent to funding equal to doubling or tripling the existing paved road inventory. These results can help policy makers at the national and international levels decide where and how to invest; and show that climate change represents a significant and urgent threat to transportation throughout the world.

Selection and peer-review under responsibility of the Organizing Committee of HumTech2014

Keywords: Road infrastructure; climate change; adaptation; risk; developing countries; developed countries;

1. Introduction

Much of the recent literature on climate change focuses on the impacts on human life, economic activity, physical assets and the environment, and the need to address these impacts proactively to minimize the damages in current and future development. In many of these studies the issue of climate change and the impacts it may present are termed a ‘disaster’ which must be integrated into current planning perspectives [1, 2, 3, 4, 5, 11, 12, 13, 17, 18, 19, 22, 24, 25, 27, 29, 33, 37, 38]. However, there is often a gap between the assessment of impacts and tangible, actionable results that allow decision makers to invest in key areas to mitigate and adapt to the climate change impacts.

This paper is an update to a study conducted by the authors in 2011: *Climate Change as Disaster: Comparative Impact on Developing and Developed Countries* [10]. This past represented one of the first studies to compare climate change impacts across geographic regions with a quantitative measure on a single, comparable asset: road infrastructure. It sought to answer the question: does climate change impact have a greater relative impact on developing or developed nations? One metric used in the study was ‘opportunity cost’: a metric which related the cost of climate change impacts to the country’s existing road infrastructure. This was introduced in the original study as a way to compare findings across countries with widely different income levels and road infrastructure networks. The findings showed that while developed countries, including Japan and Italy, face significant fiscal costs, the relative impact is small compared to overall road network; the opportunity costs for these countries ranged from 1-7%. For developing countries including Bolivia and Ethiopia, the opportunity costs ranged from 33% - 200%, depending on the climate scenario used for analysis. Overall, this initial study showed that developing countries bear a dis-proportionate burden of climate change impacts and that the future costs could be detrimental not only to future expansion but also current battles against poverty, isolation, and economic growth initiatives.

The current study will address the same questions and compare road infrastructure impacts across the same countries; however this study focuses on operationalizing the findings and the usefulness of the results to policy and decision-makers. To this end, the current study has four major updates:

- *Analysis Tool:* The authors have developed a software tool designed to analyse a range of climate models on road, building, and other infrastructure assets globally. This tool, the Infrastructure Planning Support System (IPSS), is briefly introduced [see: 20, 32];
- *Methodological*: 54 AR4 GCM climate change scenarios are used for robust analysis of possible future impacts; 9 types of road inventory are analysed; and updated stressor-response methodologies are used to develop cost impacts;

- *Assessment Tools*: This study focuses on output measures which highlight risk assessment based on multiple policy approaches, climate scenarios, and regret spending metrics, and;
- *Discussion*: A focus on operationalizing the assessment tools by incorporating discussions at the international level (comparing countries), national level (costs per sub-administrative unit) and local level (criticality of roads in relation to connectivity).

2. Background

2.1 Climate change impacts and road infrastructure

In terms of climate change analysis, a large body of literature highlights the imperative to evaluate the impacts on infrastructure, including roads. One consistent finding in the literature is that climate change poses a threat to existing and future infrastructure, including high costs for adaptation, maintenance, and potential negative impacts on transit [15, 23, 29]. While the basis for considering climate change impacts on road infrastructure is well established, the quantification of these results in monetary terms or on a time-scale receives less attention [5, 12, 28].

Research completed by the Transportation Research Board in the United States and the Scottish Executives are notable efforts in bridging this research gap [13, 33]. 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 [22]. Additional studies have been undertaken in areas where specific climate change concerns threaten infrastructure that is unique to that locale.

The emphasis of these existing studies 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 [39] 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.

Another focus is sea level rise and flooding in coastal areas. Multiple studies present tools investigating the effects of sea level rise and flooding from climate change on transportation infrastructure [5, 12, 28, 30]. An extensive examination of risks to existing transportation infrastructure due to climate change along the Gulf Coast region of the United States is ongoing [30].

2.2 Infrastructure management tools and climate change

Many tools to increase pavement management, prioritize investment, and help build capacity in road agencies have been developed, including the World Bank’s HDM-4 model [16]. These models typically focus on monthly and annual management strategies and costing for existing and near-term planned roads. However, HDM-4 and other similar pavement management systems do not incorporate climate change considerations. In an effort to bridge this gap, specific tools have been designed to analyse climate change include the Climate Change Adaptation Tool for Transportation (CCATT) [28]. CCATT requires detailed input from local administrators. The MAGICC/SCENGEN [35] model focuses on changes in temperature, precipitation and other climate phenomena; however it is not designed to tie these changes to impacts on the built environment.

The limitation of these existing tools is that they either focus on a narrow potential impact of climate change, or they fail to provide specific estimates of cost or damages that may result from potential climate change scenarios.

Additionally, most climate change analysis tools are designed for use by scientists and researchers, making the translation to policy and integration into routine decision-making unlikely.

The IPSS tool diverges from these efforts by broadening the concept of road maintenance, resiliency, and development through a more holistic approach. Specifically, IPSS integrates technical decision making, climate change impacts, and a more comprehensive set of concerns including transportation, social, and financial considerations.

3. Methodology

There are two phases to this study: the selection of countries for analysis and the allocation of roadstock inventory and the analysis of climate impacts on the roadstock in the selected countries. As mentioned earlier, this study is an update of an earlier pilot study conducted by the authors in 2011 which was designed to explore the difference in real and relative climate impacts on developing and developed countries globally. The major methodological updates to this study include:

- Increasing the range of climate analysis by moving from 6 to 54 GCM models
- Increasing the resolution of modelling accuracy by moving from Köppen-Geiger climate zones to 0.5x0.5 degree CRU grid zones
- More robust analysis of the impact of specific climate stressors, including changes in temperature and precipitation. This is achieved by an additional three years of methodology refinement (see section 3.2 below). This includes an expansion of analysis from 6 types of roadstock to 9 types with the inclusion of gravel roads.

3.1 Selection of countries and roadstock determination

This study is an update of an earlier study by the authors that explored the difference in impact between developing and developed countries [10]. Therefore, this study uses the same countries, which were selected to represent a spectrum of national wealth, roadstock inventory, climate impacts, and other factors. The countries represent a global selection and countries are similar in geographic size. Table 1 is a summary of the countries and selected characteristics (Note: these numbers represent data from the original study in 2011; they were the criterion used for selection and thus the authors wanted to portray the original numbers for consistency of selection). The method for determining roadstock varied based upon available data, but where available published road inventory data was used and characteristics allowed it to be sorted to the correct analysis sectors for the IPSS system (see 3.2 below). Where direct road inventory information was not available, estimates were taken based on international road data [21].

3.2 Climate impact analysis tool: The Infrastructure Planning Support System (IPSS)

The climate impact analysis in this study is performed using a software tool designed by the authors: The Infrastructure Planning Support System (IPSS). It is a Matlab software with Excel interface and a range of provided outputs. IPSS is a software tool that incorporates the analysis on six different areas, including climate change, environment and social impact, providing a holistic and long term infrastructure planning approach (see: [32]). This section focuses on the brief methodology of IPSS climate impact component which is the focus of this study.

IPSS evaluates the cost of climate change based on two distinct strategies, or policy approaches: reactive and proactive. The proactive strategy, ”adapt”, is based on incorporating measures to make the road infrastructure resilient to climate impacts by changing specific elements during the design and construction. The adapt strategy performs upgrades on the design standards of the roads to increase resilience to stressor impacts. The reactive strategy, “no adapt” approach, does not consider the future climate change impacts. Instead, any impact of climate change will be addressed by increasing the maintenance, often leading to a higher frequency of maintenance and repair works.

In both strategies, the cost of climate change is based on the actions needed to maintain the original designed life span of the roads. IPSS looks ahead and identifies the predicted impact of climate change during the life span of the road, analyzing based on ‘perfect foresight’ for each climate scenario analyzed. The climate analysis performed in IPSS has three main steps.

Table 1: Summary of selected characteristics of countries analysed in study

Country	World Bank defined income level	Total Land Area (Sq. km, thousands)	GDP (PPP) ($Billion)	Road Expenditures ($million)	Total KM Road (thousands)	% Paved Roads
Bolivia	Lower-middle	1,083	45.1	161	62.5	7%
Cameroon	Lower-middle	473	42.8	148	50.0	10%
Croatia	Upper-middle	56	79.2	1,912	29.0	89%
Ethiopia	Lower	1,000	76.6	127	36.5	19%
Italy	High	294	1,756.0	130,600	487.8	81%
Japan	High	364	4,141.0	179,400	1,196.9	79%
New Zealand	High	268	116.5	2,022	93.7	65%
Sweden	High	410	333.2	3,718	427.0	32%
The Philippines	Lower-middle	298	324.8	757	204.9	10%
Venezuela	Upper-middle	882	355.2	1,052	96.1	34%

First, the climate change in the region of study is determined. IPSS has a flexible input for different climate models; this study uses 54 different AR4 GCMs (general circulation models) to obtain the predicted future values of several climate stressors including precipitation and temperature. These values are compared to the historical climate data to obtain the increment of change of these stressors due to climate change. Analysis is completed at the CRU (climate research unit) resolution, a worldwide grid of 0.5 degrees of latitude and longitude (which represents approximately 250 km^2) [31, 34].

The second step predicts the impact of the climate change stressor on the road inventory. These equations reflect the response of the road materials to the climate impact stressors, and have been developed using a combination of previous research on materials science, case studies and historical data. IPSS works with three different types of road inventory: paved, gravel and dirt. Impacts are determined per kilometer of road. All the specific road type response equations, thresholds and methodologies are detailed in previous work [1, 32, 6, 7, 8, 9, 10]. They have also been used in international climate studies including a study for the European Union [27] and Canada [18].

Once the impact of climate change is calculated, IPSS will compute the cost of these impacts, as a result of maintenance increases and/or construction costs. The results will differ depending on the strategy selected: reactive or proactive. The cost of the reactive strategy will be computed as the increase of maintenance and rehabilitation of the existing road inventory as result of the increase of degradation due to the impact of climate change in order to maintain the original lifespan. The cost of the proactive strategy will be computed as the additional cost to upgrade the road inventory to resist the future climate impact combined with the road inventory which has not yet been adapted (This is due to constraints of reality: it is unrealistic to assume that an entire road inventory can be adapted through technical upgrades in a short period of time. Assumptions for this study include an annual adaptation rate of:

5% for paved roads, 2% for gravel and 1% for dirt roads).

Finally, the impact is reported in different metrics. For both the reactive and proactive approach, IPSS provides fiscal costs, the opportunity cost, and a "regret" metric. The opportunity cost represents the amount of future infrastructure development that will not occur because of money that is now being directed to climate change related costs. Specifically, it is the kilometers of secondary, paved road inventory that could be built if funds were not diverted to climate impact adaptation (see: [10]). Opportunity cost is particularly useful for this study because allows for comparison between countries with varying roadstock and climate impacts which produce a wide range of fiscal costs.

The regret values identify the risk and vulnerability of road infrastructure to climate change. The regret metric evaluates the risk of climate change in absolute value of money that could be lost. There are two components: "adapt regret" and "no adapt regret". The adapt regret value is the amount of money lost if a proactive adaptation policy is followed, but no climate change occurs. The no adapt regret metric evaluates a scenario where a reactive policy was taken, yet climate change occurred as predicted in the model. Each of these output metrics is described in greater detail with the results in sections 4 and 5.

4. Results

4.1 Climate impact results

The first step of IPSS impact analysis is determining the changes in future climate. For this study, we ran 54 unique future climate scenarios to predict future changes in precipitation and temperature. There are several variables calculated; among these are change in maximum monthly precipitation and maximum seven-day temperature. Figure 4.1 shows these results for one GCM scenario for Ethiopia in the year 2050. These results indicate a significant change in climate compared to the historical baseline, including up to 100 mm+ increase in maximum monthly precipitation and increases in temperatures over 4 degrees C in nearly half the country. These results are used by IPSS to then determine the impact of each stressor on the existing road network. This process is replicated for every country in the study.

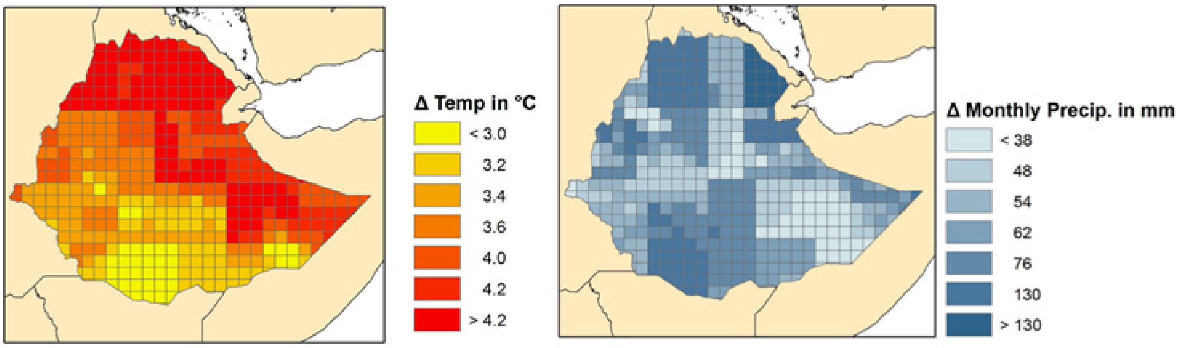

Fig. 1. Projected changes in climate in 2050 at CRU level for maximum GCM scenario for Ethiopia.

4.2 Selected impact data for ten countries

In this study, 54 distinct models are utilized to assess future potential impacts, including detailed excel results, summary costs by decade, risk tables which compares GCM projections against each other, histograms which show distribution of GCM projections, maps to visualize results at administrative units within countries, and tables representing opportunity cost and regret calculations. There are two challenges this 10-country comparison study presents: firstly, a plethora of data results. For this study, there are over 500,000 data points. The multiple tool outputs of IPSS are designed to help sort through this information and make it useful for a range of users. The second challenge of this particular study is the issue of comparing results across countries with vastly different roadstock networks, climate impacts and income distributions and spending. Therefore, the results presented in Tables 1 and 2 were selected to provide a comparative impact across these countries. Mainly due to length limitations, the authors present only a selection of comparative results. Examples of these other outputs can be seen in other studies completed by the authors including [7, 8, 9, 25, 32].

Table 2 details some findings of this study including average annual costs, opportunity cost, and the regret metric for 2050 and 2100 decades for the maximum and median GCM scenarios and for both the adapt (proactive) and no adapt (reactive) policy approaches. Figure 2 details opportunity cost for the 2100 maximum GCM scenario for both the adapt and no adapt policy approaches.

Table 2: Summary of selected results for ten countries analyzed in study

Country	Decade	Avg. Annual Cost (Adapt) USD$million		Avg. Annual Cost (No Adapt) USD$million		Opportunity Cost (Adapt) %		Opportunity Cost (No Adapt) %		Adapt Regret USD$million		No Adapt Regret USD$million	
		Median	Maximum	Median	Maximum	Median	Maximu	Median	Maximum	Median	Maximum	Median	Maximum
Bolivia	2050	$ 6.6	$ 8.4	$ 16.1	$ 56.4	38%	96%	45%	165%	$ 115.7	$ 449.0	$ 298.4	$ 1,083.5
	2100	$ 10.4	$ 13.0	$ 44.1	$ 62.9	110%	196%	281%	604%	$ 400.9	$ 882.6	$ 1,846.1	$ 3,964.9
Cameroon	2050	$ 3.0	$ 5.7	$ 5.6	$ 15.7	21%	31%	23%	51%	$ 50.6	$ 116.2	$ 168.8	$ 378.8
	2100	$ 3.5	$ 4.5	$ 13.3	$ 23.9	46%	66%	88%	187%	$ 81.8	$ 208.0	$ 660.8	$ 1,402.4
Croatia	2050	$ 2.3	$ 12.2	$ 2.2	$ 27.3	2%	12%	1%	12%	$ 12.7	$ 78.2	$ 48.1	$ 450.2
	2100	$ 12.9	$ 16.1	$ 63.0	$ 143.5	18%	32%	40%	124%	$ 16.3	$ 81.6	$ 1,543.6	$ 4,800.4
Ethiopia	2050	$ 5.0	$ 6.6	$ 16.3	$ 50.9	27%	40%	39%	117%	$ 85.9	$ 222.7	$ 409.2	$ 1,220.3
	2100	$ 5.4	$ 6.6	$ 26.5	$ 101.8	51%	70%	145%	475%	$ 103.8	$ 282.8	$ 1,507.4	$ 4,944.9
Italy	2050	$ 106.1	$ 153.4	$ 175.4	$ 534.2	8%	11%	9%	16%	$ 1,016.6	$ 1,524.6	$ 5,100.0	$ 9,648.1
	2100	$ 129.5	$ 157.9	$ 451.9	$ 1,348.4	18%	25%	34%	98%	$ 1,087.6	$ 1,592.5	$ 20,032.2	$ 58,226.8
Japan	2050	$ 122.5	$ 435.6	$ 276.4	$ 1,062.6	4%	12%	5%	15%	$ 1,168.4	$ 3,530.9	$ 6,418.5	$ 21,020.4
	2100	$ 221.2	$ 453.1	$ 821.4	$ 1,711.8	11%	26%	24%	62%	$ 1,471.1	$ 3,886.8	$ 34,300.1	$ 88,245.1
New Zealand	2050	$ 5.8	$ 10.1	$ 8.9	$ 17.2	3%	4%	3%	4%	$ 105.2	$ 193.1	$ 268.9	$ 400.9
	2100	$ 5.9	$ 12.8	$ 8.6	$ 17.3	6%	9%	7%	15%	$ 180.8	$ 446.7	$ 662.1	$ 1,335.6
The Philippines	2050	$ 29.1	$ 32.1	$ 33.9	$ 128.5	44%	48%	56%	88%	$ 340.0	$ 390.8	$ 1,715.9	$ 2,718.1
	2100	$ 31.3	$ 32.5	$ 88.9	$ 166.8	85%	91%	171%	340%	$ 422.5	$ 424.8	$ 5,269.3	$ 10,448.7
Sweden	2050	$ 31.3	$ 103.8	$ 34.5	$ 121.1	6%	13%	6%	14%	$ 1,170.6	$ 2,603.6	$ 1,299.7	$ 2,897.0
	2100	$ 47.5	$ 106.9	$ 58.7	$ 155.3	15%	38%	17%	47%	$ 2,952.9	$ 7,529.3	$ 3,582.1	$ 9,583.3
Venezuela	2050	$ 17.0	$ 20.3	$ 59.4	$ 78.2	16%	19%	25%	33%	$ 192.6	$ 255.9	$ 1,219.6	$ 1,633.8
	2100	$ 17.5	$ 18.3	$ 143.5	$ 148.9	31%	37%	132%	152%	$ 195.8	$ 259.4	$ 6,481.9	$ 7,469.8

While developing countries such as Bolivia, Cameroon and Ethiopia see relatively low annual average costs in the 2050 decades for the proactive adapt scenario, even for the maximum GCM ($8.4, $5.7 and $6.6 million, respectively), those same costs translate into very high opportunity costs (96%, 31%, and 40%, respectively). These indicate that even with adaptation, Bolivia could nearly double its existing paved road infrastructure if climate change does not occur, while Cameroon and Ethiopia could improve their networks by approximately a third. However, the proactive adaptation approach matters greatly; for these same countries, the 2050 maximum GCM costs increase to $56, $15 and $50 million respectively if a reactive approach is taken. This increases the opportunity costs to 165% for Bolivia, 51% for Cameroon and 117% for Ethiopia. If the 2100 decade is examined, this opportunity cost increases to 604%, 187%, and 475%, respectively, for the no adapt reactive approach.

Developed countries including Italy, Japan and Sweden see much higher relative annual average costs than the developing countries, but markedly lower opportunity costs. This reflects the large existing paved road networks in these countries, but in all countries, the policy approach matters greatly. For the 2050 decade, the maximum GCM average annual cost for the adapt approach is $154 million for Italy, $436 million annually for Japan and $104 million for Sweden. The reactive no adapt approach increases these costs to $534 million, $1.1 billion, and $121 million respectively. By the end of the century, these costs for reactive adaptation increase to $1.3 billion annually for Italy, $1.7 billion annually for Japan, and $155 million annually for Sweden. For each country in both decades and scenarios presented, proactive adaptation is less expensive than a reactive no adapt approach.

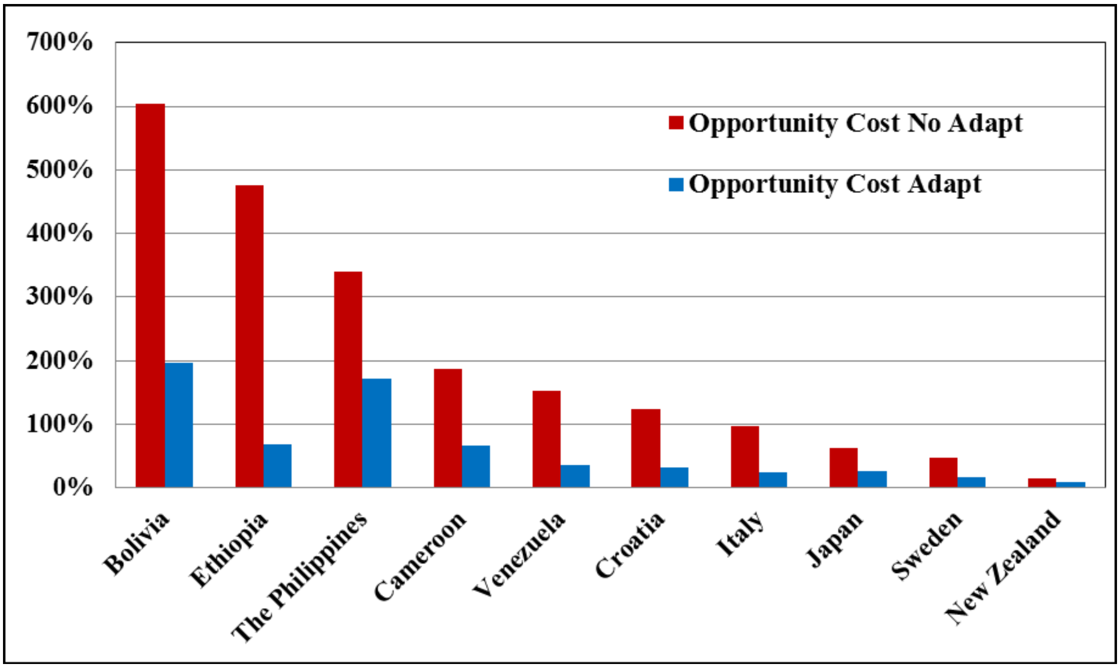

Fig. 2. Opportunity cost for maximum GCM scenario for 2100

An initial goal of this study was to compare developing and developed countries to determine if there is a higher burden on developing countries in terms of negative climate impacts on road infrastructure. While the annual fiscal costs are relatively higher for the developed countries, the opportunity costs show a much higher impact on developing countries: Bolivia has an opportunity adapt cost of 96% (2050) and 196% (2100), while Japan, with the highest annual fiscal costs, sees an opportunity adapt cost of 12% (2050) and 26% (2100). This is a fairly consistent finding between all countries.

The last metric displayed in this paper is the regret metric. In Table 2, the regret metric for adapt and no adapt scenarios is given. The regret metric explains two different future realities: the “adapt regret” is the cost a country would have over-spent if climate change did not occur. Essentially, this metric captures the amount of money spent with a proactive adaptation to climate change, but the future reality is that no climate change occurs. The “no adapt regret” metric shows the cost to a country if climate change does occur, but no adaptation has taken place. While these findings are fiscal amounts and thus hard to compare directly across countries, the policy implication is clear: in both the median and maximum scenario and in 2050 and 2100 cumulative points, in all countries, a proactive adaptation policy is less costly than a reactive approach. For some countries, these metrics are not widely spread: in Sweden, the adapt regret for 2050 is $2.6 billion while the no adapt regret is $2.9 billion. However, in many countries it is much wider: In Italy the adapt regret for 2050 and 2100 is $1.5 billion while the no adapt regret is $9.6 billion and $58.2 billion for 2050 and 2100, respectively. This is consistent with developing countries: Cameroon sees a seven-fold cost increase between adapt and no adapt regret: $81 million to $660 million in the median scenario and $208 million to $1.4 billion in the maximum scenario.

4.3 Criticality and connectivity

In all countries, one critical function of road infrastructure is connectivity, reliability and access. In rural areas, particularly in developing countries, access and reliability of roads is an essential function for social welfare and economic growth [41, 42, 43, 44, 45, 46, 47]. These impacts are seen in isolated areas of developed countries as well. Whether it is a primary paved road or a network of dirt or gravel roads, ensuring the year-round drivability of these roads is a base consideration for policy makers concerned with economic and social welfare. Climate change poses a threat in two main ways. Firstly, climate change poses a threat through increased severity and frequency of extreme events which may wash out or severely damage roads. This is evident in many recent events throughout the world, from the recent flooding in Colorado to wet-season access in sub-Saharan Africa [39, 40, 47, 50, 51]. Additionally, climate change poses a long-term threat to the viability and durability of these roads through incremental changes in surface condition and use. The funds required to maintain existing roads under impacts is a major component of the opportunity cost for countries, but may not always be accurately reflected; indeed, those areas with low fiscal costs may have high climate impact but a very low roadstock infrastructure, reflecting an enhanced criticality level for areas with a paucity of roads. In this aspect, the mapping tool of IPSS may be the most important analysis tool to allow for the identification of these key roads. By mapping road networks on climate impact maps, critical roads located in high-impact CRU grids should be prioritized for investment. For planning purposes, where investment decisions are being made, the consideration of climate change is a key component of the planning process: as shown in the results above, a proactive approach to adapting to climate impacts can significantly reduce life-cycle costs. This applies to constructing and designing future road infrastructure, and to this end IPSS can be a helpful first step in planning and adaptation to climate impacts [1, 7, 8, 9, 49, 48].

5. Discussion and Conclusion

The current study showed consistent findings with the 2011 study conducted by the authors [10]. Developing countries will incur a higher relative cost of climate change impact to the road infrastructure networks through 2100, but starting as early as the 2020 decade. For all countries analysed, proactive adaptation measures can significantly reduce impacts and costs when compared with the reactive no adapt scenario. Developed countries face significant fiscal costs to adapt or react to climate impacts. One major update for the current study was using 54 GCM climate models compared to 6 in the original study. The increase in models analysed showed consistent findings, but from a risk perspective can offer valuable insight to policy and decision makers about the trends in climate models and the aggregate differences in adapt and no adapt policies. These findings are not directly discussed in this paper but are valuable in terms of understanding climate variability and risk in current and future investment and decision making.

For future research efforts, the expansion of this approach to other infrastructure assets including buildings, energy, communication and water infrastructure could provide insight on whether the disproportionate relative impact falls on developing countries. Additionally, it is an ongoing effort to integrate academic research findings with relevant policy decision-making.

References

[1] Arndt, C., Chinowsky, P., Strzepek, K., and Thurlow, J. (2013) 'Climate Change and Infrastructure Investment in Developing Countries: The Case of Mozambique', *Climatic Change*.

[2] Austroads (2004) 'Impact of Climate Change on Road Infrastructure', Austroads Publication No. AP–R243/04, Sydney, Australia.

[3] Bohle, Hans G., Thomas E. Downing, and Michael J. Watts. "Climate change and social vulnerability: toward a sociology and geography of food insecurity."*Global Environmental Change* 4.1 (1994): 37-48.

[4] Bollinger, L. A., Bogmans, C. W. J., Chappin, E. J. L., Dijkema, G. P. J., Huibregtse, J. N., Maas, N., Schenk, T. et al. (2013) 'Climate adaptation of interconnected infrastructures: a framework for supporting governance', *Regional Environmental Change*, 1-13.

[5] Burkett, V.R. (2002) ‘Potential Impacts of Climate Change and Variability of Transportation in Gulf Coast/Mississippi Delta Region’, *The Potential Impacts of Climate Change on Transportation Research Workshop.* US Department of Transportation Center for Climate Change and Environmental Forecasting.

[6] Chinowsky, P. and Arndt, C. (2012) ‘Climate Change and Roads: A Dynamic Stressor–Response Model’, *Review of Development Economics*, 16(3), pp. 448-462

[7] Chinowsky, Paul S., et al. (2012) ‘Infrastructure and Climate Change: Impacts and Adaptations for South Africa’, UNU-WIDER Research Paper WP2012/105.

[8] Chinowsky, Paul S., et al. (2013) ‘Infrastructure and climate change: Impacts and adaptations for the Zambezi River Valley’, UNU-WIDER Research Paper WP2013/041.

[9] Chinowsky, P., Schweikert, A., Manahan, K., Strzepek, K., and Schlosser, C.A. (2013) ‘Climate change adaptation advantage for African road infrastructure’, Climatic Change, 117.1-2, pp. 345-361.

[10] Chinowsky, Paul S., Hayles, Carolyn, Schweikert, Amy and, Strzepek, Niko (2011). ‘Climate Change As Organizational Challenge: Comparative Impact On Developing And Developed Countries,’ Engineering Project Organization Journal, 1(1).

[11] Cutter, Susan L., Bryan J. Boruff, and W. Lynn Shirley. "Social vulnerability to environmental hazards*." *Social science quarterly* 84.2 (2003): 242-261.

[12] duVair, P., Douglas W., and Burer, M.J. (2002) ‘Climate Change and the Potential Implications for California’s Transportation System’, *The Potential Impacts of Climate Change on Transportation Research Workshop.* US Department of Transportation Center for Climate Change and Environmental Forecasting.

[13] Galbraith, R.M., Price, D.J., and Shackman, L. (2005) ‘Scottish Road Network Climate Change Study’, Scottish Executive.

[14] Gwilliam, K., Foster, V., Archondo-Callao, R., Briceno-Garmendia, C., Nogales, A. and Sethi, K. (2008) ‘The Burden of Maintenance: Roads in Sub-Saharan Africa’, Background Paper 14, Africa Infrastructure Country Diagnostic, The World Bank.

[15] Hambly, D., Andrey, J., Mills, B., and Fletcher, C. (2013) ‘Projected implications of climate change for road safety in Greater Vancouver, Canada’, *Climatic Change*, 116(3-4), pp. 613-629.

[16] HDM-4 (2008) ‘Highway Development and Management Model (HDM-4) Dissemination Tools’, The World Bank Group. Updated 2008-12-15. http://go.worldbank.org/JGIHXVL460

[17] Hughes, G. and Chinowsky, P. ‘Adapting to Climate Change for Infrastructure in North-East Asia’, The Economics of Climate Change and Low Carbon Growth Strategies in North-East Asia. Asian Development Bank. *Draft.* 29 February 2012.

[18] Industrial Economics (2010). ‘Costing Climate Impacts and Adaptation: A Canadian Study on Public Infrastructure’, Report to the National Round Table on the Environment and the Economy, Canada.

[19] IPCC (2007) ‘Climate Change 2007: Synthesis Report’, Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland.

[20] IPSS: The Infrastructure Planning Support System. Institute of Climate and Civil Systems. Updated 2013. http://clicslab.org

[21] IRF (2012). *World Road Statistics 2012*, International Road Federation, Geneva, Switzerland.

[22] Karl, T.R., Melillo, J.M., and Peterson, T.C. eds. (2009) *Global climate change impacts in the United States*. Cambridge University Press.

[23] Keener, V.W., Marra, J.J., Finucane, M.L., Spooner, D., and Smith, M.H. (2013) *Climate Change and Pacific Islands: Indicators and Impacts: Report for the 2012 Pacific Islands Regional Climate Assessment*. Island Press.

[24] Koetse, M.J., and Rietveld, P. (2009) ‘The impact of climate change and weather on transport: An overview of empirical findings’, *Transportation Research Part D: Transport and Environment*, 14(3), pp. 205-221.

[25] Kwiatkowski, K.P., Stipanovic Oslakovic, I., ter Maat, H.W., Hartmann, A., Chinowsky, P., and Dewulf, G.P.M.R. (2013) ‘Climate Change Adaptation and Roads: Dutch Case Study of Cost Impacts at the Organization Level’, Working Paper Series, Proceedings of the Engineering Project Organization Conference, Winter Park, CO, July 9-11, 2013.

[26] Mills, B., Tighe, S., Andrey, J., Smith, J., and Huen, K. (2009) ‘Climate Change Implications for Flexible Pavement Design and Performance in Southern Canada’, Journal of Transportation Engineering, 135(10), pp. 773–782.

[27] Nemry, F. and Demirel, H. (2012) ‘Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures’, European Commission, Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS).

[28] Oswald, M.R., and McNeil, S. (2012) ‘Climate Change Adaptation Tool for Transportation: Mid-Atlantic Region Case Study’, *Journal of Transportation Engineering*, 139(4), pp. 407-415.

[29] Satterthwaite, D. (2007) ‘Adaptation Options for Infrastructure in Developing Countries’, A Report to the UNFCCC Financial and Technical Support Division, UNFCCC, Bonn, Germany.

[30] Savonis, M.J., Burkett, V.R., and Potter, J.R. (2008) ‘Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I’, US Climate Change Science Program.

[31] Schlosser, A., Gao, X., Strzepek, K., Sokolov, A., Forest, C., Awadalla, S., and Farmer, W. (2011) ‘Quantifying the Likelihood of Regional Climate Change: A Hybridized Approach’, Report 205, MIT Joint Program on the Science and Policy of Global Change, October 2011.

[32] Schweikert, A., Kwiatkowski, K., Chinowsky, P., and Espinet, X. (In Review) “The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development.” *Transport Policy*, In Review.

[33] TRB (2008) ‘Potential Impacts of Climate Change on U.S. Transportation’, Special Report 298, Transportation Research Board, National Research Council, United States.

[34] UEA, 2013. “Data.” Climate Research Unit. University of East Anglia (UEA). <http://www.cru.uea.ac.uk/data> Accessed January 31, 2014.

[35] University Corporation for Atmospheric Research (UCAR) (2007) ‘Model for the Assessment of Greenhouse-gas Induced Climate Change A Regional Climate SCENario GENerator (MAGICC/SCENGEN)’, University Corporation for Atmospheric Research.

[36] Westphal, M.I., Hughes, G.A., and Brömmelhörster, J. (2013) ‘Economics of Climate Change in East Asia.’

[37] World Bank (2010) ‘Economics of Adpatation to Climate Change’, Synthesis Report, The World Bank.

[38] World Bank (2009) ‘The Costs to Developing Countries of Adapting to Climate Change New Methods and Estimates’, Consultation Draft, World Bank.

[39] Coffman, Keith. “Property losses from Colorado flood projected at about $2 billion” Thomson Reuters News. 19 September 2013. http://www.reuters.com/article/2013/09/19/us-usa-colorado-flooding-idUSBRE98H1BA20130919

[40] Boulder Office of Emergency Management (OEM). http://boulderoem.com/emergency-status/458-9-15-2013-general-updates

[41] “National Infrastructure Protection Plan”. Critical infrastructure Resource Center. Department of Homeland Security.http://training.fema.gov/EMIWeb/IS/is860a/CIRC/NIPPinfo.htm

[42] “Presidential Proclamation - - Critical Infrastructure Security and Resilience Month, 2013” 31 October 2013. http://www.whitehouse.gov/the-press-office/2013/10/31/presidential-proclamation-critical-infrastructure-security-and-resilienc

[43] Bradbury, A. S. C. "Transport, mobility and social capital in developing countries." PROCEEDINGS-INSTITUTION OF CIVIL ENGINEERS ENGINEERING SUSTAINABILITY. Vol. 159. No. 2. INSTITUTION OF CIVIL ENGINEERS, 2006.

[44] Bryceson, D., et al. "Roads to Poverty Reduction? Dissecting rural roads’ impact on mobility in Africa and Asia." Reducing Poverty and Inequality: How can Africa be included (2006).

[45] Africa Union, UN Economic Commission for Africa. “Transport and the Millennium Development Goals in Africa”. February 2005.

[46] World Bank. 2000. “World Development Report 2000/2001: Attacking Poverty”. World Bank and Oxford University Press. http://wdronline.worldbank.org/worldbank/a/c.html/world_development_report_2000_2001/abstract/WB.0-1952-1129-4.abstract.

[47] Van de Walle, Dominique. "Choosing rural road investments to help reduce poverty." World Development 30.4 (2002): 575-589.

[48] Sofreco. “Study on Programme for Infrastructure Development in Africa (PIDA): Africa’s Infrastructure Outlooks 2040” PIDA Phase I Study Summary. 2011.

[49] Raballand, Gaël, et al. "Revising the roads investment strategy in rural areas: an application for Uganda." World Bank Policy Research Working Paper Series, Vol (2009).

[50] Lebo, Jerry, and Dieter Schelling. Design and appraisal of rural transport infrastructure: Ensuring basic access for rural communities. No. 496. World Bank Publications, 2001.

[51] Lombard, P., and L. Coetzer. "The Estimation of the Impact of Rural Road Investments on Socio-economic Development." (2006).