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The infrastructure planning support system: Analyzing the impact of climate change on road infrastructure and development

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ABSTRACT

This paper details the Infrastructure Planning Support System (IPSS), a software tool that incorporates five areas of analysis, including climate change, environment, and social impact, to provide a holistic, longer-term approach to the management and planning of road infrastructure. The system combines quantitative and qualitative analysis methods to develop an estimated fiscal cost, in addition to estimates of GHG emissions, transportation time and cost savings, and a prioritization metric focusing on social impact of road construction.

The IPSS system has been applied in several case studies, including South Africa, Mozambique, Vietnam, a pan-African analysis, and several Asian countries including China, South Korea, Mongolia, and Japan. This paper serves as the first comprehensive explanation of the IPSS system, including the literature review, background, and methodology. The results section focuses on the costs of climate change in an illustrative case study of the State of Colorado in the United States, due to specific data and outputs required for the other analysis components. This paper focuses on the need for a holistic systems approach, its relevance to transportation planning and investment, and one example of how climate change considerations can be quantified and applied at the policy level.

1. Introduction

Road infrastructure is a key asset of governments and economies throughout the world. Managing this asset requires efficient decision-making that prioritizes economic cost-benefit analysis, often to the exclusion of exogenous factors including social benefits, environmental costs and climate change impacts. In the context of developing countries, this can present a challenge, but also an opportunity. By expanding their planning considerations, governments have the opportunity to substantially influence development in terms of increased resiliency, positive impacts on household income, reduced poverty levels, as well as increased access to healthcare, education, and market knowledge. Additionally, climate change is an emerging factor that is expected to disproportionately impact less developed communities (World Bank, 2010) and is a crucial consideration for protection of current and future infrastructure.

While these broader impacts should be included in the decision-making process they are frequently downplayed because of the difficulty in creating a cost-benefit justification within short to medium-term planning and budgets. This can exacerbate existing challenges regarding infrastructure investments in developing countries (Gwilliam et al., 2008; UNFCCC 2009, 2010; Keener et al., 2013; Hambly et al., 2013; Satterthwaite, 2007).

This paper outlines an approach to broadening this perspective through the Infrastructure Planning Support System (IPSS). IPSS is a decision support tool designed for use by infrastructure planners and policy-makers to broaden the criterion and methods of analysis in road transportation investment. It was developed by the Climate and Civil Systems Research Group (see: IPSS, 2014). Output from a recent study on Colorado in the United States is provided as an illustrative example of the tool's capability, particularly the calculation of projected climate change impacts on existing road infrastructure from a range of climate models.

However, the IPSS system has been utilized in a number of studies for a diverse range of countries including: The Netherlands, South Africa, Ghana, Vietnam, Mongolia, China, the United States and a pan-African analysis. These studies have been commissioned by the World Bank, Asian Development Bank, Canadian Government, United States Environmental Protection Agency, United Nations University, and others (Chinowsky and Arndt, 2012; Chinowsky et al., 2011, Chinowsky et al., 2012, Chinowsky et al., 2013a, Chinowsky et al.,

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2013b; Industrial Economics, 2010; Hughes and Chinowsky, 2012; Kwiatkowski et al., 2013; Stratus Consulting, 2010; Westphal et al., 2013; World Bank, 2010).

In terms of climate change analysis, IPSS steps beyond current available tools by providing the capacity to analyze the impact of any number of climate models on all road infrastructure in any geographic location in the world. IPSS incorporates technical, engineering-based research to determine the fiscal costs of incremental and extreme event impacts on road infrastructure. Beyond climate change, IPSS supports a holistic approach to decision making by including modules that address flooding, transport costs, social impacts, and financial modeling.

The enhanced decision support capability of IPSS is designed to improve decision-making by incorporating a greater range of holistic costs, benefits, and risks. By improving the road planning and decision-making process, IPSS subsequently aims to increase the social welfare and long-term resiliency of communities and countries. In developing countries, improved road planning, maintenance and investment will manifest itself in improved access to social services and a more robust infrastructure, which both serve to increase community resilience to general development challenges and emerging issues such as climate change. For countries with robust existing infrastructures, IPSS will assist decision makers in protecting critical assets while supporting investment decisions and long-term resiliency.

This paper outlines the components utilized in the IPSS tool for decision-making, the background for each component, a brief methodology, and concludes with an illustrative case study of the State of Colorado to provide examples of the climate change impact decision-making outputs. A discussion of results, limitations and conclusion is then provided.

2. Background

The construction and expansion of road infrastructure is linked to economic growth, development, and social welfare (Kessides, 1993). Because of their exposure to environmental conditions transport infrastructure systems, including roads, are particularly vulnerable to climate change (Bollinger et al., 2013; Koetse and Rietveld, 2009). Therefore, the risks of climate change to roads threaten the associated economic growth, development, and social welfare benefits of infrastructure expansion.

Recent case studies in the Netherlands examined the level of climate change adaptation implementation in government agencies. Within these organizations there was a general goal to link climate change to a more integrated approach to sustainable development. However, it was found that the agencies gave only minor consideration to long-term planning in this regard (van den Berg, 2013). Similarly in many transportation planning agencies, climate change recommendations remain focused on overall effects of safety, degradation, and demand alterations. Despite the increasing recognition of climate change as a concern for transportation planning, it receives little attention in terms of influencing the implementation of infrastructure projects. As highlighted in the following section, the omission of climate change is a major shortcoming in the set of existing road development tools.

2.1. Road infrastructure and climate change decision processes and tools

Road investment decisions often place an emphasis on increasing the quantity and quality of infrastructure through a focus on construction and basic cost-benefit analysis approaches. In developing countries this focus is often hindered due to the lack of technical capacity and institutional structure in place to support successful ventures. Issues such as deficient maintenance, lack of enforcement for material and construction codes, and political interference each contribute to the lower likelihood of long-term investment success in these countries (Dabla-Norris et al., 2010).

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 is that climate change poses a threat to existing and future infrastructure, including high costs for adaptation, maintenance, and potential negative impacts on transit (Keener et al., 2013; Hambly et al., 2013; Satterthwaite, 2007). 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 (Burkett, 2002, duVair et al., 2002, Oswald and McNeil, 2012).

Research completed by the Transportation Research Board in the United States and the Scottish Executives are notable efforts in bridging this research gap (TRB, 2008; Galbraith et al., 2005). 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 (Karl et al., 2009). 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 (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.

Another focus in climate change impacts is sea level rise and flooding in coastal areas. Burkett (2002), duVair et al. (2002), Savonis et al. (2008), and Oswald and McNeil (2012) present multiple studies and tools investigating the effects of sea level rise and flooding from climate change on transportation infrastructure. Burkett (2002) and Savonis et al. (2008) identify that sea level rise poses a threat to low-lying infrastructure and has high costs due to a high concentration of infrastructure, specifically designed for trade and movement of goods. Similarly, Savonis et al. (2008) extensively examines risks to existing transportation infrastructure due to climate change along the Gulf Coast region of the United States in phase I of an ongoing study.

3. Tool overview

3.1. Points of departure

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 (HDM-4, 2008). 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 analyze climate change including the Climate Change Adaptation Tool for Transportation (CCATT) (Oswald and McNeil, 2012). CCATT requires detailed input from local administrators.

The MAGICC/SCENGEN (UCAR, 2007) 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 difficult.

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

The following sections highlight the core emphasis of this paper: a tool which addresses the need for policy makers to incorporate a broader perspective on investment decisions in road infrastructure.

3.2. IPSS tool overview and components

3.2.1. Software and user experience

IPSS is designed for use by a range of transport and policy practitioners. The model requires minimal inputs, with the standard analysis including road inventory and the location of analysis (ex: country). IPSS input and analysis can be at either the CRU (climate research unit, approximately $50 \times 50\,\text{km}^2$ units), Admin02 (county equivalent), Admin01 (state equivalent), or national levels. Any number of climate change models can be run. The standard analysis includes an Admin01 level analysis with results from 54 AR4 GCM models approved by the IPCC (including models from A2, A1B, and B1 scenarios) (IPCC, 2007). These climate models provide specific weather information on a daily basis through 2100 for stressor elements including precipitation and temperature. Nine road types are analyzed, including a primary, secondary, and tertiary classification for paved, gravel, and earth roads.

Depending on the desired output, a number of modifications can be made to the base IPSS analysis. If specific cost and impact equations are available for roads in a specific area, these can be defined by the user. The default is defined through a robust set of research reflecting international standards for each road type and climate-stressor impact (see: Arndt et al., 2012; Chinowsky et al., 2011; 'IPSS'; Chinowsky and Arndt, 2012).

The input interface allows a user to select analysis options such as the discount rate, types of road to adapt, growth rates for infrastructure, which climate models to analyze, and the types of output information that are desired. Flexible inputs, if desired by the user, is managed and uploaded through a set of Microsoft Excel worksheets including adaptation costs and impacts, weather stressors and timing of adaptations and/or new growth or project construction. The program runs in Matlab, with Excel interface for users.

IPSS output is focused on the climate change analysis and is provided in five separate ways: Excel cost information on a yearly or decadal level, histogram analysis of the range of climate model costs, specific model time-series graphs, maps, and a regret analysis. Each provides a specific perspective of analysis. These are illustrated in Section 4 below for a representative study of the State of Colorado, USA.

3.2.2. 5 Components of analysis

There are 5 main components of IPSS designed to inform investment decisions. The focus of the tool is to inform on climate change impact and decision policy ("Climate" and "Flooding" below), but three additional elements are included to capture some of the indirect costs and benefits roads provide: "Financial", "Transport", and "Social".

In addition to the five IPSS components, the system provides three distinct decision analyses based on climate adaptation policies. These are discussed in greater detail in Section 4, but critical to the climate and flooding descriptions below.

Climate: Construction, maintenance, and adaptation costs are provided for each road type at CRU level for every year analyzed for each distinct climate model. The three perspectives of adaptation, reaction, and no climate change are given. The climate analysis focuses on incremental changes in long-term climate relative to the historic baseline, including precipitation and temperature.

Flooding: Construction, maintenance, and adaptation costs are provided for each road type at CRU level for every year analyzed for each distinct climate model. The flooding analysis focuses on extreme events occurring relative to the historic flooding record.

Financial: Several tools are provided including an optional, user-defined discount rate, a bond or loan financing comparison, and decadal averages of costing to compare models and long-term considerations. Output is incorporated in the climate and flooding costs if a discount rate is used and for comparison of long-term considerations.

Transport: New roads and/or improving the surface type of roads will reduce travel time, maintenance and repair costs of vehicles, and fuel consumption cost. However, the greater traffic levels can also increase vehicle CO2 emissions. (Schrank et al., 2012). IPSS provides graphs and tables with the estimated changes in transportation costs for each adaptation measure considered. If future transportation demand analysis is desired, a road inventory growth model can be included.

Social: Most applicable in the developing country context, the social component of IPSS provides a ranking comparison of road options which will most benefit the surrounding communities. These are estimated through quantification of several variables including local employment opportunities, school and healthcare access, road density and others. Output is given in Excel and in map form to highlight areas where road infrastructure may be most beneficial compared to others (Schweikert, 2013).

4. Application

4.1. Climate change and development: theory and practice

Recently, studies have been conducted to analyze the impact of climate change on transport infrastructure in order to develop possible adaptation strategies (e.g. World Bank, 2010, Nemry and Demirel, 2012). Similarly, there have been several detailed studies that examine material property impacts from climate change, such as pavement deterioration (Mills et al., 2009). These works provide greater understanding of specific physical damage to assets from climate change. However, in order to plan for changes that may be required in the uncertain future, road planners require information that is both more specific than sector-wide analysis and less detailed than material property studies (Kwiatkowski et al., 2013). As described in the following section, this is the analysis gap that IPSS aims to fill.

According to Berkhout et al. (2006), climate change adaptation will be implemented primarily by organizations, both public and private. Within those organizations, decision-making is essential to determining whether and how climate change adaptation will occur. Therefore, implementation of a planning tool that expands the set of criteria and analyses must be adaptable to existing organization capabilities. This may be particularly true and highly relevant for developing countries, who are not only at higher risk to climate change impacts but are also often in the process of improving institutional functions and governance (Gwilliam et al., 2008; Burkett, 2002; Robinson, 1999, 2006; Cutter et al., 2009; Kumar and Barrett, 2008; African Union, 2005; Van de Walle, 2002).

4.2. Policy and decision-making application

As mentioned in Section 3, IPSS is designed for use by policy and decision practitioners in the road infrastructure and development sector. The system is designed to answer three specific questions about climate change:

1. What is the cost to increase road infrastructure resilience to climate change (the cost of adaptation)?
2. What is the cost to react to climate change impacts on road infrastructure (the cost of not adapting)?
3. What happens if roads are adapted to climate change and it doesn't occur?

The cost of resilience to climate change is calculated through the flooding and climate analyses as defined above. IPSS analyzes the impact of a distinct number of climate models on road infrastructure and provides a forward-looking adaptation policy. For example, if temperature is projected to increase, paved road infrastructure is analyzed to see if the road temperature will exceed a certain threshold. The thresholds are determined based on historic climate conditions. If the threshold is exceeded, the adaptation option is to change the asphalt binder being utilized to enable it to withstand the increase in temperatures. The adaptation options are incorporated at the time of construction or reconstruction of roads. For precipitation and flooding impacts, they include elements such as upgrading the drainage infrastructure and increasing the sub-base to minimize washout and rutting.

The cost of reacting to climate change is calculated through an increase in required maintenance that repairs damages incurred by climate impacts. For example, if precipitation is projected to increase incrementally, the climate impact would be increased degradation of road infrastructure, particularly in the case of gravel and earth roads.

The final analysis question IPSS answers is the 'regret' factor: what happens if either of the above policy approaches are selected and climate change does not happen? This question is answered by comparing the cost of both a resilient and reactive approach to the historic, no climate change baseline. This is best illustrated in Section 4.3 below. It is designed to help policy makers analyze the risk of climate change by understanding the potential money lost if the decision chosen does not match future reality.

4.3. Illustrative example: the state of Colorado, USA

Colorado is one of 50 states in the United States of America. It has a population of approximately 5.2 million, is approximately 270,000 square kilometers in area and has a paved road infrastructure of approximately 67% of the total roads (Colorado Department of Transportation, 2013).

As part of a state-wide vulnerability assessment, IPSS was utilized to run a state-wide analysis of the vulnerability of road infrastructure through 2100 at the county level for 54 GCMs (IPCC, 2007). The results are displayed for climate change impacts below.

Table 1
Annual average cost from climate change impact to Colorado State, USA in USD$ millions.
(Source: Author's calculations).

		Adapt – resilient approach			No adapt – reactive approach		
		Paved	Gravel	Unpaved	Paved	Gravel	Unpaved
2030	25th	$4.3	$4.9	$0.5	$2.5	$3.4	$0.2
	50th	$3.2	$7.1	$0.6	$1.6	$9.1	$0.4
	75th	$4.2	$8.3	$0.7	$1.5	$12.3	$0.5
	100th	$8.5	$10.0	$0.8	$8.8	$14.5	$0.8
2050	25th	$4.7	$1.8	$0.5	$9.3	$2.4	$0.2
	50th	$5.3	$2.2	$0.5	$6.0	$3.7	$0.2
	75th	$6.6	$2.3	$0.5	$17.9	$15.3	$0.4
	100th	$8.5	$3.8	$0.7	$31.9	$5.8	$0.7
2090	25th	$4.2	$2.2	$0.6	$11.9	$7.3	$0.4
	50th	$5.4	$2.7	$0.7	$14.2	$15.3	$0.5
	75th	$6.4	$3.4	$0.8	$22.5	$11.8	$1.1
	100th	$8.8	$5.3	$0.8	$28.9	$24.2	$1.4

Table 1 depicts a simplified summary for the Excel results. The average annual cost for the 2030, 2050, and 2090 decades are shown for the GCMs representing the quartile climate model results. The 'adapt' results represent the proactive, resilient approach and the 'no adapt' results represent the reactive approach. Both are costs above the baseline, historic approach which represents no climate change.

The maximum cost (100th%) for the 2050 decade shows an advantage in a resilient approach, with a potential cost savings of over USD$22 million annually for the paved road inventory. The median climate scenario (50th%) shows more balanced results, with adaptation actually being more costly in this decade than a reactive approach. These similar cost results illustrate why (particularly in developing countries) the additional analysis components of social and transportation analysis may prove useful. For example, if costs are similar for adaptation compared with a reactive approach, the road may result in important benefits in social components such as access and mobility and therefore present an overall beneficial investment.

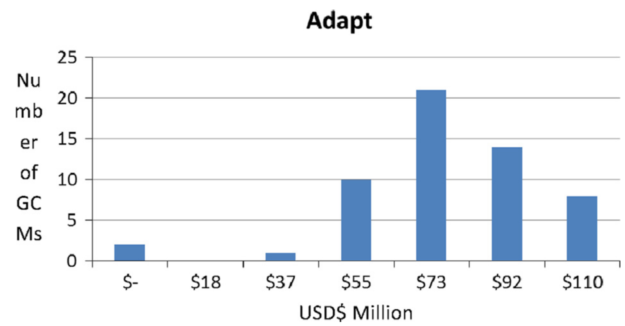
Chart 1 depicts graphically the average annual cost per decade for one climate model, the median (50th%) GCM. The adaptation approach ('resilient') is shown with an average cost ranging from USD$11-USD$15 million annually. The no adapt ('reactive') approach shows costs ranging from USD$6–USD$29 million throughout the century. The adapt no climate change approach shows the cost of adaptation if climate change does not occur and ranges from USD$6–USD$11 million annually. This graphic highlights the importance of understanding the timing of climate change impacts.

Graphics 1 and 2 are histograms representing the reactive and resilient approaches to climate change, no adapt and adapt respectively. The histograms are the total cost projected by each of the 54 GCMs. For example, these show that all 54 GCMs predict a total annual cost for, using the adapt approach, of less than USD $110 million. Comparing to the no adapt approach, only approximately half, or 28 GCMs, project costs less than USD$110 million. Two GCMs project costs above USD$500 million. As each GCM is equally unlikely to occur, these help graphically depict the risk being taken by either approach and identify trends among GCMs (Schlosser et al. 2011).

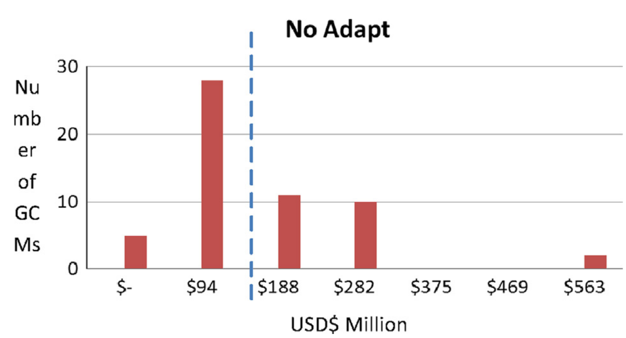
Graphics 3 and 4 depict maps of the 2050 decadal annual average cost for the maximum (100th%) GCM scenario for Colorado at the County (Admin01) level. These results highlight certain counties as being most vulnerable to climate change based upon the climate model projection and the existing road infrastructure. El Paso, Weld, Broomfield, Adams and Pueblo counties show the highest costs for the no adapt scenario. Based on this graphic, adaptation is fairly equal or lower cost than a no adapt approach.

Graphic 5 shows the climate change regret for adaptation and no adaptation policies. This means that for a projected climate future, the regret is calculated based upon two scenarios: For the 'adapt regret', this calculates the 'wasted cost' if adaptation is done based upon a projected climate, but then the climate change does not actually occur. The 'no adapt regret' shows the cost of not adapting to climate change, but the specific scenario projected does actually occur. This represents the cost of reacting to climate change.

For the median climate scenario, the graphic shows that if adaptation is done based upon a projected climate future, and if climate change does not occur, there is a 'wasted' cost of approximately USD$8 million annually. If climate change does occur as projected in the GCM, but no adaptation is done, the cost is approximately USD$51 million per year. If the maximum (most extreme) climate GCM projection is adapted for but does not happen, the adapt regret is approximately USD$15 million per year. However, if this most extreme projection does occur and no adaptation is done, the cost to road infrastructure will be nearly USD$182 million per year.



Graphic 1. Distribution of results (costs in USD$ Millions) of 54 unique GCM results for Colorado, USA. 2011–2100. (Source: Author's calculations)



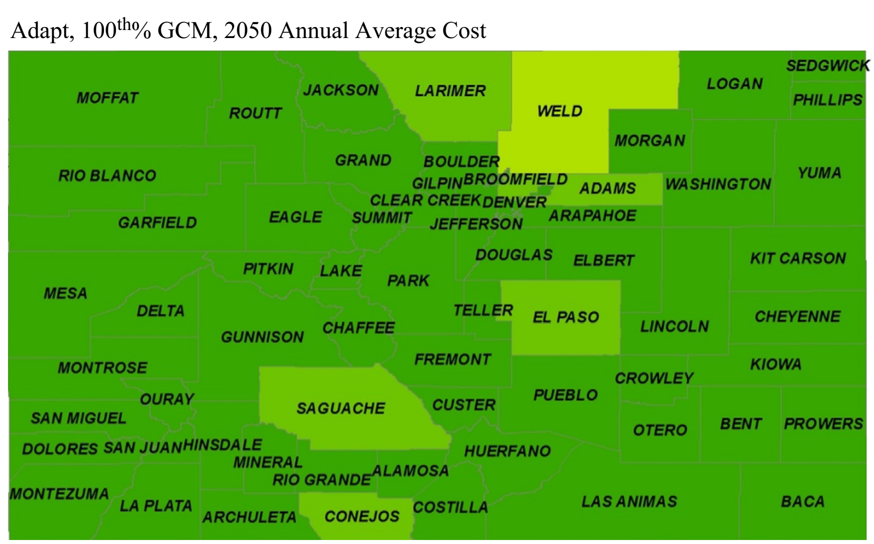
Graphic 2. Distribution of results (costs in USD$ Millions) of 54 unique GCM results for Colorado, USA. 2011–2100. (Source: Author's calculations).

4.4. Discussion and limitations

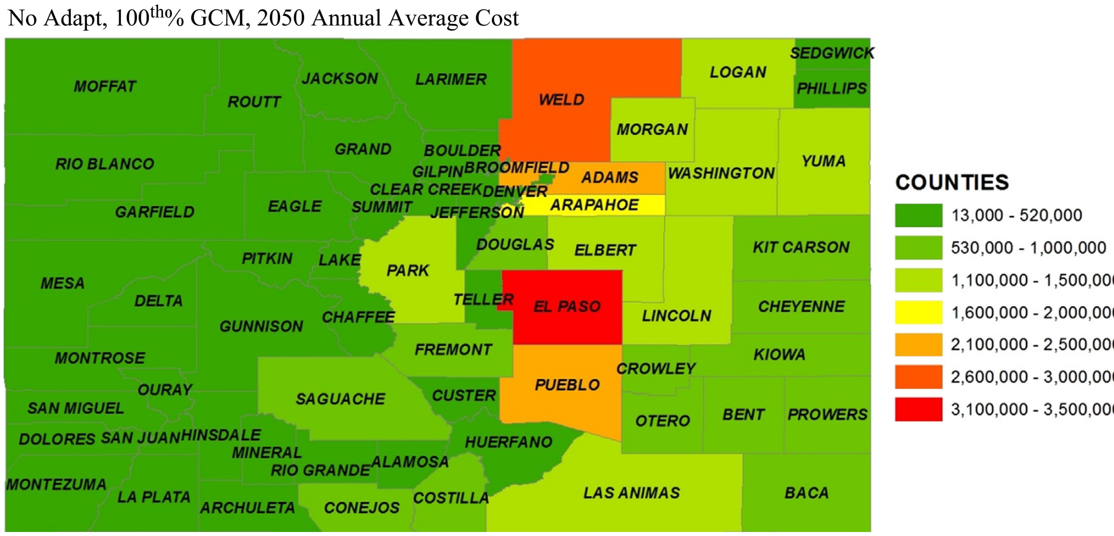
The results from the illustrative case study of Colorado show that in the longer-term, adaptation is beneficial in terms of the cost of climate change. However, there are several factors that should be considered when incorporating these results into a decision-making process.

Firstly, in all cases, the time frame matters: in most cases, the benefits of resilient adaptation are not seen until the 2030, 2040, or 2050 decades. This result, however, is not as simplistic as it seems. For the adaptation approach, no roads are adapted until the projected climate dictates it. Then, because of realistic constraints of resources, only a small percentage of roads are adapted each year. The default calculation is 5%. This means that while adaptation may not provide a distinct fiscal benefit for the first 25 years of analysis, you cannot simply decide not to adapt until that benefit starts. In some cases, the actual cost-benefit from adaptation is seen because you reach a point where the majority of the roads are now adapted to withstand climate impacts. This will take a minimum of 20 years, and probably much longer.

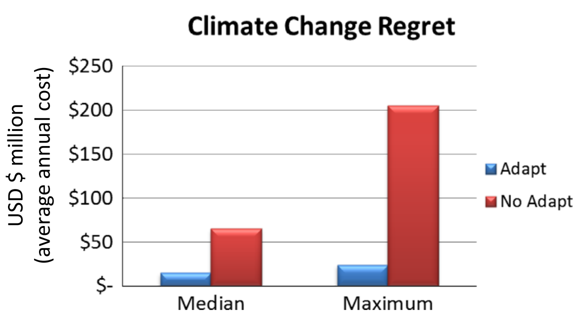
Secondly, there are several variables involved in the projection of costs. Each climate model utilized, whether a GCM or other, is uncertain and the future unknown. There is therefore a measure of uncertainty inherent in the practice of climate change adaptation and analysis. Additionally, costs may vary based upon detailed local conditions that cannot be captured in the analysis. For example, detailed hydrologic modeling may reveal that certain kilometers of road are especially vulnerable to washout based upon a small amount of precipitation; unless specific data is entered by the user in the flexible input option, this cannot be fully captured. Another uncertainty is the reality of projected and proscripted maintenance versus that which is actually conducted. In proper road maintenance, there are standards for maintenance



Graphic 3. Admin01 level mapping of results for Colorado, USA. 2050 average decadal cost (USD$ Millions) for maximum (100th%) GCM scenario for adapt and no adapt scenarios (Source: Author's calculations)



Graphic 4. Admin01 level mapping of results for Colorado, USA. 2050 average decadal cost (USD$ Millions) for maximum (100th%) GCM scenario for adapt and no adapt scenarios (Source: Author's calculations)



Graphic 5. Graphic 5 shows the difference between two policy approaches with two different future realities: if climate change does or does not occur. The median and maximum GCM scenario results are displayed for climate change future projections. Blue "Adapt" regret shows the fiscal cost difference between adaptation to climate change if it does and does not occur. Red "No Adapt" regret shows the fiscal cost difference between no climate change occurring and climate change occurring but no adaptation taking place. Costs are USD$Million annual average for Colorado. USA. (Source: Author's calculations)

quality and the recurrence of certain activities which may not always be completed as per technical guidelines.

4.5. Other projects

Table 2 summarizes results from other studies conducted using the IPSS tool for climate analysis of road infrastructure. In most studies, the overall cost of resilient adaptation is far less than the cost of reactive repairing ("no adapt"). It is important to note, however, that several factors can affect this summary result as stated in Section 4.4.

Nearly every study presented here shows that adaptation is beneficial for the 100th% scenario. Savings can be as high as USD $500 million for Japan annually, USD$2.4 billion for China annually, and $65 billion for the African continent annually. The median climate model results are more varied, though with the exception of Mongolia, China and Japan, adaptation is more cost-effective. These results show the international application of IPSS. These trends in climate impact analysis of high amounts of savings with an adaptation approach show a greater impetus for planners to consider climate change in their medium and longer-term planning decisions.

5. Conclusion and future work

Climate change represents both a near-term and long-term challenge for infrastructure policy makers. Addressing this challenge through informed and balanced considerations is a key to successful adaptation policies. A large network of road assets can represent high fiscal costs for developed nations, while developing countries often face very high fiscal savings by proactive adaptation, particularly of the unpaved road networks.

However, an overemphasis on traditional economic considerations for road projects often limits the full realization of development potential for road infrastructure, particularly in developing countries and areas where social welfare and overall economic development is a primary concern. Additionally, the omission of climate change in long-term planning increases vulnerability and risk of future damage and costs, which will further attenuate the infrastructure's potential benefits. Altering this perspective will manifest itself in improved access to social services and a more robust infrastructure, which both serve to increase community resilience to general development challenges and emerging issues such as climate change. For countries with robust existing infrastructures, it will be crucial to protect assets from climate change risks, in order to maximize investments and increase their own resilience to future impacts.

In this paper, the IPSS system is presented as a tool to assist policy makers in making these balanced decisions. IPSS increases the level of complexity that can be incorporated into road analysis and planning by adding quantitative analysis of non-economic and non-technical criteria to the existing focus on cost-benefit analysis. As detailed in multiple studies conducted with IPSS on a global basis, the ability to incorporate climate change concerns at an early stage can result in multiple millions of dollars in savings on an annual basis. Conversely, adopting a wait-and-see approach can significantly reduce the opportunity to add roadstock to inventories in many climate contexts.

In summary, IPSS bridges the planning-climate change analysis gap through its usability at both a policy and planning level, its scalability of inputs and results, and its ability to incorporate and reduce complexity. It has been used for the analysis of more than 50 countries in studies commissioned by a range of organizations. However, IPSS is not intended to provide policy makers with the answer on whether climate change will occur. Rather, IPSS is intended to bring the multiple perspectives on climate change

Table 2
Summary of results from previous studies performed using IPSS[a]. All costs are average annual decadal for 2050 decade, unless noted otherwise.

Country	Scenario	Adapt (USD$Mil)	No adapt (USD$Mil)	Project reference
Japan	Med. (50th%)	1190	802	Westphal et al. (2013)
	Max. (100th%)	1519	2037	
China	Med. (50th%)	4585	4205	Westphal et al. (2013)
	Max. (100th%)	5202	7595	
South Korea	Med. (50th%)	159	195	Westphal et al. (2013)
	Max. (100th%)	219	572	
Mongolia	Med. (50th%)	64	37	Westphal et al. (2013)
	Max. (100th%)	123	182	
South Africa	Med. (50th%)	5	144	Chinowsky et al. (2012a)
	Max. (100th%)	159	308	
Malawi	Med. (50th%)	10	34	Chinowsky et al. (2013c)
Mozambique	Med. (50th%)	17	30	Chinowsky et al. (2013c) World Bank (2010)
Zambia	Med. (50th%)	41	80	Chinowsky et al. (2013c)
Thailand	Med. (50th%)	260	324	Author's calculations
Vietnam	Med. (Hot)	88	180	Chinowsky and Arndt (2012), Chinowsky et al. (2012b)
	Max. (Hot)	47	230	
Pan-Africa (49 countries) Average Annual Decadal (2010–2100)	Med (Avg.)	5635	44835	Chinowsky et al. (2011)
	Max. (Avg.)	20727	86338	Chinowsky et al. (2013c)

[a] Sources: Chinowsky, Paul, Schweikert, Amy, Strzepek, Niko, Strzepek, Kenneth, and Kwiatkowski, Kyle (2012a). Climate change impacts and adaptation for South Africa, Working Paper 105, UNU-WIDER.
Chinowsky, Paul, Schweikert, Amy, Strzepek, Niko, Manahan, Kyle, and Strzepek, Kenneth, (2012b). Road infrastructure and climate change in Vietnam, Working Paper 80, UNU-WIDER.
World Bank (2010). Economics of Adaptation to Climate Change (EACC) Study. See web site at http://documents.worldbank.org/curated/en/2010/01/16436675/economics-adaptation-climate-change-synthesis-report for correct reference.

impacts to bear on specific infrastructure investment options in order to enhance the long-term success of these investments.

References

Arndt, C., Chinowsky, P., Strzepek, K., Thurlow, J., 2012. Climate change, growth and infrastructure investment: the case of Mozambique. Rev. Dev. Econ. 16 (3), 463–475.
Berkhout, F., Hertin, J., Gann, D.M., 2006. Learning to adapt: organisational adaptation to climate change impacts. Clim. Change 78 (1), 135–156.
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. Reg. Environ. Change 1–13.
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.
Chinowsky, P., Arndt, C., 2012. Climate change and roads: a dynamic stressor-response model. Rev. Dev. Econ. 16 (3), 448–462.
Chinowsky, Paul S., et al., 2012. Infrastructure and Climate Change: Impacts and Adaptations for South Africa. UNU-WIDER Research Paper WP2012/105.
Chinowsky, Paul S., et al., 2013a. Infrastructure and climate change: Impacts and adaptations for the Zambezi River Valley. UNU-WIDER Research Paper WP2013/041.
Chinowsky, P., Schweikert, A., Manahan, K., Strzepek, K., Schlosser, C.A., 2013b. Climate change adaptation advantage for African road infrastructure. Clim. Change 117 (1–2), 345–361.
Chinowsky, Paul, S., Price, Jason, C., Neumann, James, E., 2013c. Assessment of Climate Change Adaptation Costs for the U.S. Road Network. Global Environ. Change 23 (4): 764–73, http://dx.doi.org/10.1016/j.gloenvcha.2013.03.004.
Chinowsky, P., Hayles, C., Schweikert, A., Strzepek, N., Strzepek, K., Schlosser, C.A., 2011. Climate change: comparative impact on developing and developed countries. Eng. Project Organ. J. 1 (1), 67–80.
Colorado Department of Transportation, 2013. ⟨http://coloradodot.info⟩.
Cutter, Susan, Christopher Emrich, Jennifer Webb, Daniel Morath, 2009. Social Vulnerability to Environmental Hazards: A Review of the Literature. Oxfam America. ⟨http://adapt.oxfamamerica.org/resources/Literature_Review.pdf⟩.
Dabla-Norris, E., et al., 2010. Investing in public investment: an index of public investment efficiency. J. Econ. Growth 17 (3), 235–266.
duVair, P., Douglas W., 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.
Galbraith, R.M., Price, D.J., Shackman, L., 2005. Scottish Road Network Climate Change Study, Scottish Executive.
Gwilliam, K., Foster, V., Archondo-Callao, R., Briceno-Garmendia, C., Nogales, A., Sethi, K., 2008. The Burden of Maintenance: Roads in Sub-Saharan Africa, Background. Africa Infrastructure Country Diagnostic, 14. The World Bank, Washington D.C.
Hambly, D., Andrey, J., Mills, B., Fletcher, C., 2013. Projected implications of climate change for road safety in Greater Vancouver, Canada. Clim. Change 116 (3–4), 613–629.
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⟩.
Hughes, G., Chinowsky, P., 2012. 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.
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.
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.
IPSS. The Infrastructure Planning Support System. Institute of Climate and Civil Systems. Updated 2014. ⟨http://clicslab.org⟩.
Karl, T.R., Melillo, J.M., Peterson, T.C. (Eds.), 2009. Global Climate Change Impacts in the United States. Cambridge University Press.
Keener, V.W., Marra, J.J., Finucane, M.L., Spooner, D., Smith, M.H., 2013. Climate Change and Pacific Islands: Indicators and Impacts: Report for the 2012 Pacific Islands Regional Climate Assessment. Island Press.
Kessides, C., 1993. The Contributions of Infrastructure to Economic Development a Review of Experience and Policy Implications. The World Bank, Washington, D.C.
Koetse, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: an overview of empirical findings. Transp. Res. Part D: Transp. Environ. 14 (3), 205–221.
Kwiatkowski, K.P., Stipanovic Oslakovic, I., ter Maat, H.W., Hartmann, A., Chinowsky, P., 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.
Kumar, Ajay, Barrett Fanny, January 2008. Stuck in Traffic: Urban Transport in Africa. Africa Infrastructure Country Diagnostic. The World Bank Group.
Mills, B., Andrey, J., 2002. Climate change and transportation: potential interactions and impacts. In: proceedings of The Potential Impacts of Climate Change on Transportation: Workshop Summary, US Department of Transportation, Workshop, 1–2 October, ⟨http://climate.volpe.dot.gov/workshop1002/⟩.
Mills, B., Tighe, S., Andrey, J., Smith, J., Huen, K., 2009. Climate change implications for flexible pavement design and performance in Southern Canada. J. Transp. Eng. 135 (10), 773–782.
Nemry, F., 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).
Oswald, M.R., McNeil, S., 2012. Climate change adaptation tool for transportation: mid-Atlantic region case study. J. Transp. Eng. 139 (4), 407–415.

Robinson, Dr Richard., 1999. A new approach to quantifying economic and social benefits for low-volume roads in developing countries. Impact Assess. Proj. Appraisal 17.2, 147–155.

Robinson, R., 2006. A perspective on road sector restructuring in developing and transitional countries. Public Adm. Dev. 26, 265–278, http://dx.doi.org/10.1002/pad.408.

Satterthwaite, D., 2007. Adaptation Options for Infrastructure in Developing Countries. A Report to the UNFCCC Financial and Technical Support Division. UNFCCC, Bonn, Germany.

Savonis, M.J., Burkett, V.R., 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.

Schlosser, A., Gao, X., Strzepek, K., Sokolov, A., Forest, C., Awadalla, S., 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.

Schrank, D., Eisele, B., Lomax, T., 2012. "2012 Urban Mobility Report". Transportation Institute Texas A&M University.

Schweikert, A., 2013. The Social Impact Score: A Framework for Including Social Benefits in Rural Road Prioritization Investments and Decision Making (Master thesis). University of Colorado, Paul Chinowsky, Advisor.

Stratus Consulting, 2010. Climate Change Impacts on Transportation Infrastructure. Report Prepared for U.S. Environmental Protection Agency.

TRB, 2008. Potential Impacts of Climate Change on U.S. Transportation. Special Report. Transportation Research Board, National Research Council, United States p. 298.

Union, 2005. Africa. Transport and the Millennium Development Goals in Africa.

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.

United Nations Framework Convention on Climate Change, 2009. COP15. 7–19 December 2009. Copenhagen, Denmark. Published 30 March 2010 at: 〈http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600005734〉.

United Nations Framework Convention on Climate Change, 2010. COP16 November 2010. Cancun, Mexico. Published 15 March 2011 at: 〈http://unfccc.int/meetings/cancun_nov_2010/meeting/6266/php/view/reports.php〉.

Van de Walle, Dominique, 2002. Choosing rural road investments to help reduce poverty. World Dev. 30.4, 575–589.

van den Berg, M.M., 2013. Policy Making on an Uncertain Climate: Adaptation to Climate Change By Local Governments (Ph.D. thesis). University of Twente, The Netherlands.

Westphal, M.I., Hughes, G.A., Brömmelhörster, J., 2013. Economics of Climate Change in East Asia.

World Bank, 2010. Economics of Adpatation to Climate Change. Synthesis Report. The World Bank.