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A SUSTAINABILITY FRAMEWORK TO PRIORITIZE PROACTIVE CLIMATE CHANGE ADAPTATION INVESTMENTS FOR IMPACTS ON ROAD INFRASTRUCTURE USING A DATA-DRIVEN APPROACH

by

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B.A., Boston University, 2009

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This thesis entitled:

A Sustainability Framework To Prioritize Proactive Climate Change Adaptation Investments For Impacts On Road Infrastructure Using A Data-Driven Approach

written by Amy Elizabeth Schweikert

has been approved for the Department of Civil, Environmental, and Architectural Engineering

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Paul Chinowsky

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Bernard Amadei

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Date__________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

ABSTRACT

Schweikert, Amy Elizabeth (Ph.D., Civil, Environmental, and Architectural Engineering)

A Sustainability Framework To Prioritize Proactive Climate Change Adaptation Investments For Impacts On Road Infrastructure Using A Data-Driven Approach

Thesis directed by Professor Paul S. Chinowsky

As questions of climate change impacts, adaptation, and policy gain prominence in discussions at the local, national, and international levels, there is opportunity to address many of these challenges in meaningful ways.

The goal of the research presented here is to provide data-driven support to policy makers and practitioners about how, when, and where to prioritize investments in road infrastructure to reduce vulnerability to climate change. The research question that guided this dissertation is, "How can planners and decision-makers incorporate a holistic perspective on future road infrastructure transportation planning with the uncertainties posed by a changing climate?"

A data-driven methodology, including engineering-based stressor response functions to assess climate change impacts were developed. Applying climate change models, these functions were then used to estimate financial and technical costs and benefits of proactive and reactive adaptation investment scenarios for road infrastructure. Finally, the triple bottom line framework for sustainability is used to apply this information alongside environmental and social climate change impact metrics to identify areas for infrastructure investments that should be prioritized based upon a three-pillar approach. GIS is used to synthesize the triple bottom line data and visually display critical geographic areas.

Together, this work presents advances in the knowledge and methods used to address questions of sustainability and climate change in terms of road infrastructure. More broadly, these methods contribute to the discussion about how sustainability can be incorporated into routine decisions by policy makers as well as how climate change impacts can be quantified into information that can be utilized today in decision-making. While there are many sources of uncertainty in future planning, it is imperative that investments being made today account for potential impacts of climate change, both on the infrastructure elements themselves and the communities which they are designed to serve.

CONTENTS

ACKNOWLEDGEMENTS

As I finish the final touches on this dissertation research, it is a bit surreal to realize all of the research, hours of editing and analyzing, of creating and collaborating have come to an end (at least for this). This process is something I was never quite convinced I would actually finish – and there are a lot of people and organizations that have contributed in different ways to the final product below.

Firstly, an appreciation for the organizations that are interested in understanding more about climate change, including the proactive measures we can take to address some of the issues. From project ideas to flexibility and funding, it has been a valuable experience to be part of several research teams. Notably, project funding from the following organizations has been critical to my academic career so far: The World Bank, The United Nations University World Institute for Development Economics (UNU-WIDER), The United States Agency for International Development (USAID), The Asian Development Bank, and the United States Environmental Protection Agency (US EPA).

Secondly, a huge thank you to my colleagues, advisors, professors, and fellow students throughout my career at University of Colorado Boulder. This notably includes my committee members: Dr. Bernard Amadei, Dr. Ross Corotis, Dr. Seth Spielman, and Dr. Sherman Robinson. Each of you has provided guidance, feedback, and encouragement to bring in a social science perspective to the engineering research, and I am very grateful for that. For my colleagues and peers - from challenging but useful and inspiring coursework, interesting team projects, and mostly just the informal conversations that happen when passionate people are put together to pursue a goal, this experience has been incredibly formative. The Mortenson Center for Engineering in Development Communities (MCEDC) has also played a role, including funding as a Mortenson Fellow, but more broadly in bringing me to engineering in the first place. Without the vision that engineering can be meaningful, collaborative, and useful in some of the world's poorest regions, I wouldn't have been drawn to the Civil Systems program in the first place.

On a personal note, there are several individuals without whom I without a doubt would not be finishing this work. Most notably, my advisor, Dr. Paul Chinowsky. It is rare that someone would offer an opportunity to a student without the right resume – I didn't have an engineering background coming into the program here at University of Colorado Boulder, and it took a lot of encouragement, vision, and support to enter, succeed, and ultimately finish this Ph.D. work. Along with Dr. Chinowsky, my lab mates and cohort throughout the past five years have been essential. They have made what is a challenging and sometimes lonely experience a lot of fun.

Finally, the support of my parents, my sisters, my friends, and my church has given me a new appreciation for the power of community operating in the best ways. So, it is with extreme joy and gratitude that I finish the final words of this culminating document and step into whatever adventure is coming next!

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LIST OF ACRONYMS AND TERMS USED

AASHTO	American Association of State and Highway Transportation Officials
AR4	Fourth Assessment Report (of the IPCC)
AR5	Fifth Assessment Report (of the IPCC)
CalTrans	California Department of Transportation
CCAP	Climate Change Action Plan
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CO2	Carbon Dioxide (related to GHG emissions)
FHWA	Federal Highway Administration
GHG	Greenhouse gas (refers to emissions)
GIS	Geographic Information Systems (mapping software)
IPCC	Intergovernmental Panel on Climate Change
IPSSTM	Infrastructure Planning Support System
RCP	Representative Concentration Pathways (AR5 Scenarios)
SACOG	Sacramento Area Council of Governments (municipal planning group)
SDGs	Sustainable Development Goals (UN)
SoVI	Social Vulnerability Index (specific to model developed by Cutter et al. 1996)
TBL	Triple Bottom Line
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNU-WIDER	United Nations University World Institute for Development Economics Research

CHAPTER 1

INTRODUCTION

Motivation

The complex nature of development poses many challenges. As populations increase, natural hazards damage cities and threaten lives, and questions of poverty, justice, and equity are more readily incorporated into political discussions, the need for broader and more multi-faceted approaches to development decisions is more evident. The rise in 'sustainability' as a method and mindset for approaching complex humanitarian and environmental issues adds layers of consideration about future generations and broadens the traditional decisions frameworks focused on profit and economic growth. There are many existing issues around social equity, economic development, and sustainability that will require thoughtful consideration and a large number of resources to tackle. In most cases, each of these challenges will be further exacerbated by a changing climate and warming world.

While the international community as well as local governments are (in varying stages) actively studying and beginning to address many of the potential vulnerabilities and impacts of climate change, there remains a considerable paucity of information related to quantitative measurements and the cross-disciplinary methods needed to address the systemic shifts climate change may bring. In particular, far fewer resources are being expended to integrate adaptation and mitigation measures into current practices than recent research calls for (Revi and Sattherwaite 2013). The significant problem with this approach is that resources are being spent to grow, develop, construct and expand the built environment with little to no consideration of the future environment in which these infrastructures will exist. Increasing damages from natural hazard events including Hurricane Sandy and Hurricane Katrina in the United States indicate that the past is increasingly limited as a reliable metric for future trends. These disasters, along with notable increases in the severity of impacts from events such as wildfires, droughts and floods, call for a sharp rise in the urgency of understanding the nexus of the built environment, populations, and the changing climate.

This dissertation focuses on one aspect of the built environment - road infrastructure - and presents a methodological approach for analyzing the impacts associated with a changing future climate; the benefits and costs for proactively incorporating many of the concerns posed by climate change; and finally introduces a broader framework for explicitly incorporating the environmental and social impacts of investment decisions. While uncertainties with climate change exist, current information and modeling tools (part of the development of which is covered in this dissertation) allow for the incorporation of climate considerations into current processes.

In addition to the imperative to seek answers to understand climate change impacts, the need to augment traditional decision frameworks affords an opportunity to policy makers: In many ways, social science literature focused on population vulnerability and natural hazards have recognized the importance of the built environment to withstanding and recovering from a disaster, while their counterparts in infrastructure planning often focus heavily on financial and technical considerations. The necessity of augmenting the existing decision frameworks to incorporate climate change also presents the opportunity to broaden the quantitative consideration of environmental and social impacts in transportation planning. From this perspective, this dissertation explores the concepts of sustainability, road infrastructure, social vulnerability, and climate change planning from a data-driven modeling approach.

Context: Climate Change & Urban Resilience

Increasing community resilience, particularly in the context of a changing climate and increasingly costly impacts from weather events, is becoming a top agenda for planners at all levels of government and society. This is evidenced in the reports of the Intergovernmental Panel on Climate Change (IPCC) (Revi and Sattherwaite 2013; Field et al. 2014) the European Commission Climate Programme (European Commission 2014; Nemry and Demirel 2012), the United States Climate Action Plan (Executive Office of the President 2013), the Rockefeller Resilient Cities Program (Tyler and Moench 2012; The Rockefeller Foundation 2015), the Bloomberg Commission's Risky Business Report (Bloomberg, Paulson, Jr., and Steyer 2014), and a number of state and municipal climate action plans (see: (Boulder County 2007; "State of Vermont - Tropical Storm Irene After Action Report/Improvement Plan" 2012; Center for Science in the Earth System (The Climate Impacts Group) et al. 2007). The result of this greater attention to impacts is an emerging shift in focus from mitigating climate change to adapting to the likely impacts that are and will continue to happen from climate change (Füssel and Klein 2006). Because of the recent nature of this shift in research focus, there is a resulting paucity of specific, targeted, and actionable research tools available to policy makers looking to actively reduce community vulnerability to climate change impacts (see: (Transportation Research Board 2008; Tyler and Moench 2012; Schweikert et al. 2014).

There are several significant barriers to addressing these challenges, including: the complex and interdisciplinary nature of 'community vulnerability' (see: Füssel 2007; Tyler and Moench 2012; Cutter, Boruff, and Shirley 2003; Lynn, Kathy; MacKendrick, Katharine; Donoghue, Ellen M. 2011), disagreement between models about the specific changes climate change will bring (Revi and Sattherwaite 2013; Nemry and Demirel 2012), and the underlying nature that climate change presents a potential situation that has no comparable historical precedent (see: (Koko, Van der Geest, Kees, and Kreft, Sonke 2013; Koetse and Rietveld 2009; Larsen et al. 2008). One suggestion for addressing these challenges is by doing interdisciplinary analyses that integrate impacts and adaptation recommendations with other policy concerns. Specifically, by specifying adaptation measures that meet current stakeholder needs and are "robust against uncertain future developments" (Füssel and Klein 2006).

A focus of research from multiple disciplines has highlighted the important role that the built environment will play in the measure of community resilience to climate change (S. L. Cutter, Boruff, and Shirley 2003; Flanagan et al. 2011; Tierney and Bruneau 2007). Infrastructure that maintains function under stress, whether longer-term climate stress or acute events, can affect the ability of communities to withstand, respond and recover from events. The impacts of climate change are adding potentially compounding issues to existing challenges by adding unplanned stresses to networks which are already degrading; even without climate change considerations, the issue of infrastructure quality, quantity, planning, funding, operations, and maintenance is an ongoing challenge to local, state and national planners (Nicholson and Du 1997; American Society of Civil Engineers 2015).

Therefore, despite a growing call for incorporating a more holistic and long-term perspective in infrastructure planning (Transportation Research Board 2008), due to limitations in modeling, information, and data availability, most projects fail to integrate a range of critical life-cycle factors including the effects of climate change (Tyler and Moench 2012; Kwiatkowski et al. 2013; Erath et al. 2009). This increases the vulnerability of existing and future infrastructure and the communities that rely on them, particularly in terms of 'lifeline infrastructure', including water supply, energy supply, sewage management, communication systems and more (Dalziell and Nicholson 2001; Revi and Sattherwaite 2013).

Defining the Discussion

In terms of discussing issues like vulnerability, resilience, and sustainability, the terms are important to define. Many domains use these words to indicate specific ideas or actions within their fields. Conversely, many of the terms are used interchangeably: recent literature on sustainability research and integrated assessment models notes that terms like 'vulnerability', 'resilience', 'holistic' and 'sustainable' are often used interchangeably without specific definitions that can be used within cross-disciplinary discussions (Bocchini et al. 2014; O'Brien et al. 2006; Turner, B.L. 2003; Sachs 2012; Martens 2006; Kajikawa 2008; Hacking and Guthrie 2008).

"Vulnerability" is a key term used broadly. While it generally has a similar definition related to the compounding effects of risk and exposure, each body of literature has specific concerns, techniques, and areas of focus. The social science and hazards literature (see:

Tierney and Bruneau 2007; Cutter et al. 2008; Barnett and Adger 2007) has recognized the impact of climate change on society, both in terms of specific hazard events and long-term changes that may alter the structure, economy, and society of a community (see: Flanagan et al. 2011; Tierney and Bruneau 2007; Cutter et al. 2008; Barnett and Adger 2007). There is a strong recognition of the important role that the built environment and lifeline infrastructure play in vulnerability of communities. However, the oft-siloed approach of different expert domains means that usually the planning, prioritization, and implementation of projects does not take specific factors of social vulnerability or disparity into account (Robinson 2006; Lucas 2011; Tierney and Bruneau 2007). As defined more fully in each domain in Chapter 2, the definition of vulnerability used in this dissertation is in line with the general definitions from social vulnerability and infrastructure literature: vulnerability is the set of existing conditions that make something (such as a community, or infrastructure) less able to withstand, adapt to, cope with, and recover from a stress or strain (Füssel 2007; S. Cutter et al. 2009; Tyler and Moench 2012; Berdica 2002; Kajikawa 2008)

"Resilience" is a term that has recently emerged in many studies surrounding climate change and work on community development. Turner (2003) states that it enters the discussion from roots in ecology literature and has evolved to convey a meaning of a system's (or community's) "ability to bounce back to a reference state after a disturbance" and "the capacity of a system to maintain certain structure and functions despite disturbance". This is closely linked with the ideas of adaptation and 'adaptive capacity' where a system is evaluated in terms of flexibility to withstand and adjust to stress, or for social systems to evolve in response to disturbances (Turner, B.L. 2003; Timmerman 1981;

Rose 2004). This definition agrees with work by Bocchini et al. (2014), who goes further into a civil infrastructure-specific definition: “resilience is usually associated with the ability to deliver a certain service level even after the occurrence of a [stressful]…event.” Additionally, ideas of not only withstanding a disturbance but being able to effectively and quickly recover from an event is often discussed (O’Brien et al. 2006).

Similar to resilience is the idea of “sustainability”, which tends to be used in situations where the idea of resilience today is coupled with a longer-term view of performance and impacts (specifically, those that consider the future) (Bocchini et al. 2014; Kajikawa 2008). In describing a proposed outline for the development of the Sustainable Development Goals (SDGs), Sachs (2012) proposes the outline of the goals into the three categories that make up the triple bottom line framework: economic, environmental, and social. “Sustainability” therefore, is an oft-used word to describe a set of ideas, ideals, and goals which center on multi-dimensional awareness of spatial and temporal aspects – in many uses it means something which is *not* vulnerable (Kajikawa 2008; O’Brien et al. 2006; S. L. Cutter et al. 2008; Bocchini et al. 2014; Martens 2006; Kemp and Martens 2007).

Coupled with these definitions (and often used interchangeably in the discussion, especially in older literature) is the idea of “holistic” analysis or modeling. In many studies relating to vulnerability, resilience and/or sustainability, the idea of a ‘holistic’ approach is used to indicate that any study or work related to increasing sustainability or resilience of a project (or reducing vulnerabilities) takes a holistic approach. As the idea of the Triple Bottom Line (TBL) has evolved, it and other variations (sometimes a ‘fourth’ pillar focused on policy or governance is included, see: (Martens 2006; Hacking and Guthrie 2008) have been used as a framework for addressing resilience analyses in a ‘holistic’ way. The explicit incorporation of 'economic', 'environmental' and 'social' considerations in an equally-weighted (at least in principle) manner is largely a defining framework for discussions surrounding sustainable development practices.

RESEARCH QUESTION

Therefore, the following research question defines the work in this dissertation: How can planners and decision-makers incorporate a holistic perspective on future road infrastructure transportation planning with the uncertainties posed by a changing climate?

CONTRIBUTION

The contribution of this dissertation is twofold: Firstly, to present a method for quantitatively analyzing the financial costs and benefits of proactive investment in road infrastructure under changing future climate conditions. Second, this dissertation introduces the Triple Bottom Line as an applicable framework for discussing the broader benefits to proactive investments in road infrastructure under the uncertainties of climate change.

OVERVIEW OF DISSERTATION

The foundational concept for this dissertation is analyzing, quantifying, and utilizing data to determine the impact of projected climate changes on road infrastructure. The second contribution is to apply this information in the triple bottom line framework, incorporating the economic and technical impacts of climate change with relevant social and environmental concerns.

Both of these contributions are exhibited in Chapter 5, which uses an illustrative case study for how this approach can be used in decision making to inform investment policy for proactive adaptation to climate change. Specifically, the concept of the Triple Bottom Line (TBL) as a framework for sustainable and holistic infrastructure planning is utilized as a novel approach to the infrastructure and climate change planning process.

Chapter 2 provides a background overview of the relevant literature to the foundational concepts of this dissertation and clarifies the point of departure for this research. Specifically, a literature review on road infrastructure, sustainability, and social vulnerability are each explored. A brief history and overview of current knowledge regarding climate change is provided, particularly focusing on international efforts headed by the United Nations Intergovernmental Panel on Climate Change (IPCC). This provides a context for the development of a climate change impact analysis tool and the broader analysis utilized in the final research chapter of this dissertation.

Chapters 3 and 4 focus on the application and maturing of a stressor-response methodology for evaluating the impacts of climate change on road infrastructure. Both studies use CMIP3 climate change models and look at the potential costs of proactive adaptation (See Appendix I for climate change model information). This is compared to reactive adaptation; both are based on a no-climate change historical baseline scenario.

For all three research chapters, climate change models are used. All available models were used for the analysis: for CMIP3 models (Chapters 3 and 4), all available scenarios were used as well, including the available A1B, A2 and B1. For Chapter 5, which uses the CMIP5 models, only the 4.5RCP was utilized for the analysis. The choice to restrict the number of scenarios run for Chapter 5 is based partially on available data, but also on a desire to present the results of climate change impact framework modeling using the triple bottom line. Therefore, a conservative estimate of future climate impacts was used. If a similar study is repeated using RCP6 or RCP8.5, it is likely the results from climate change impacts would be much higher.

Chapter 5 uses this information, but updates the methodology with CMIP5 climate change models as well as specific information about the local inventory of roads provided by GIS. It also presents these results in the TBL framework. Quantitative assessment of the impacts of climate change from a social vulnerability perspective are included using a social vulnerability index developed by the Pacific Institute (Cooley, Heather; Moore, Eli; Heberger, Matthew; Allen, Lucy 2012). Assessment of potentially avoided greenhouse gas (GHG) emissions are also analyzed based upon a methodology developed for this study that quantifies the embodied CO_2 emissions from repair materials (asphalt) that could be avoided from a proactive adaptation investment choice. These three are combined using the TBL framework to illustrate how TBL can enhance sustainable investment prioritization to climate change impacts on road infrastructure.

Chapter 6 presents a discussion on limitations to the research presented as well as further explanation for the scope of the studies presented in Chapters 3-5. Finally, Chapter 7 is a concluding chapter where guidance for future work is presented, including a discussion pertaining to the Sustainable Development Goals (SDGs) as well as a brief discussion on the broader implications of bringing the TBL framework to infrastructure planning and policy under climate change.

CHAPTER 2

BACKGROUND & LITERATURE OVERVIEW

Road Infrastructure

Criticality & Vulnerability

Road transportation networks are the foundation of most trade, commerce, and community functions including commuting to work and school (Dalziell and Nicholson 2001; Erath et al. 2009). Transportation networks are one of only two assets mentioned in every Executive Order and/or government document since 1983 addressing "critical infrastructure" (the other is water supply and wastewater systems) (Moteff and Parfomak 2004). Additionally, it is an important capital asset to any nation and constitutes a large amount of investment spending annually as well as contributing to economic growth (Fernald 1999; Neumann et al. 2014). A 2005 report by the American Society of Civil Engineers (ASCE) estimates that degradation of the transport networks leads to an estimated $94 billion need for repairs, and additional costs to motorists of $54 billion in repairs and operating costs, while freight costs are increased by $8 billion due to delays alone (Nagurney, Qiang, and Nagurney 2010). This critical role makes the question of road network vulnerability a top concern for public and private entities as well as planners at all levels (Jenelius, Petersen, and Mattsson 2006).

Despite these high costs, the definition and treatment of road network 'vulnerability' in the literature is a fairly new concept and does not have a homogenous definition in the literature (Jenelius, Petersen, and Mattsson 2006; Berdica 2002; Taylor and D'Este 2007). Generally, there is disagreement about whether a definition is context-specific (Taylor and D'Este 2007; Jenelius, Petersen, and Mattsson 2006), only applies to rare, 'big' risk events (Jenelius, Petersen, and Mattsson 2006), and whether vulnerability refers to 'total failure' or 'safe-fail' events (Berdica 2002).

There is agreement that vulnerability is a function of risk and resiliency and/or robustness (Berdica 2002; Nicholson and Du 1997). Risk refers to potentially negative outcome resulting from an event and the resulting consequences. *Resiliency* and *robustness* are used in different studies and can both be used to mean 'the ability to withstand strain' and the 'ability to recover from a strain'. Often, vulnerability is closely discussed alongside 'risk', 'redundancy', and/or 'reliability' and recognized to have negative outcomes on economic, environmental and/or societal conditions (Taylor and D'Este 2007; Berdica 2002).

A recommendation of many of these studies is the incorporation of 'sustainable' planning, most often referring to incorporating a more holistic, life-cycle maintenance and cost projection method, particularly in terms of hazard or climate change vulnerability analyses (see: Feng et al. 2013; Chi, Ruuska, and Guangbin 2013; Berdica 2002; Koetse and Rietveld 2009) . Chi, Ruuska, and Guangbin (2013) discuss the increasingly mandatory inclusion of an *Environmental Impact Assessment (EIA)*, stating that this shows a growing recognition that infrastructure projects have direct and indirect impacts on the surrounding environment. The EIA is designed to integrate these concerns into project decision making, creating a precedent for a broader holistic analysis of projects during the planning phases. Considering this 'end-of-life' thinking into the front-end of the project is crucial to create sustainable projects and avoid displacing the responsibility for negative externalities (termed *displaced agency)* (Levitt et al. 2010; Chi, Ruuska, and Guangbin

2013). Identifying vulnerabilities at the earliest possible level is a key focus, "since most proactive measures are…preferable to reactive ones from an economic point of view" (Berdica 2002).

Additionally, many of these studies mention the compounding cost impacts that climate change will have (see: Nagurney, Qiang, and Nagurney 2010; Neumann et al. 2014; Koetse and Rietveld 2009; Dalziell and Nicholson 2001) and the negative impacts degradation has on communities (see: Erath et al. 2009; Chi, Ruuska, and Guangbin 2013; Feng et al. 2013). The climate change impact (defined as the incremental changes in precipitation and temperature weather elements and changes in the frequency and severity of extreme events resulting from climate change) could be characterized as 'abnormal' strains on the system (Berdica 2002; Erath et al. 2009). Therefore, as described above, climate change impacts should be considered in all phases of road planning and design, thus re-defining climate change from an 'abnormal' strain to a 'normal' strain that is readily incorporated in current and future planning processes. This would serve the dual purpose of reducing the risk associated with projected changes and acknowledging the holistic impacts of infrastructure on society. The up-front approach to planning, including life-cycle costing and planning considerations can substantially reduce lifetime costs of operations and maintenance and maximize the asset performance (Feng et al. 2013; Berdica 2002). As a note, for this dissertation, the research is focused only on the impacts of precipitation and temperature as daily changes and does not address extreme events such as flooding. The incorporation of extreme events will increase costs and damages exponentially in many cases and represents an important next-step consideration for this research.

Climate Change

There is a large breadth of existing literature related to climate change, focused on a wide range of topics from the atmospheric science components to the impacts on ecosystems and everything in between. A growing field of research is the impact potential climate changes will have on the transportation network. These studies focus on assessing impacts ('vulnerability studies') and suggested adaptations. This section focuses on the specific literature related to transportation, seeking to provide a robust overview of key reports, action plans, and vulnerability studies relevant to this research.

Climate change has been at the forefront of discussions globally since the founding of the United Nations Intergovernmental Panel on Climate Change (IPCC) in 1988. While the early work of the IPCC focused on creating and understanding the science of global climate change and mitigation options, more recently a prominent shift has been made to include vulnerability assessments, adaptation options, and the financing of climate-resilient projects (Arent et al. 2014). The IPCC's Fifth Assessment Report (AR5), concludes that "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased" (Revi and Sattherwaite 2013). Increased CO_2 emissions, among other causes of climate change, have triggered real consequences such as hotter summers and changing extreme weather patterns. One element that is recognized as particularly susceptible to the effects of climate change is transportation infrastructure (Bollinger et al. 2013; Koetse and Rietveld 2009; Meyer, Amekudzi, and O'Har 2010). Both new and old infrastructure must consider how climate change will increase costs for adaptation, maintenance, and its potential negative impacts on transit (Farrag-Thibault 2014; Keener et al. 2013; Hambly et al. 2013; Sattherthwaite 2009).

On a global and regional scale, there are three recent seminal pieces of literature related to climate change vulnerability, adaptation, and planning: The IPCC AR5 Report (Field et al. 2014; Revi and Sattherwaite 2013), the European Commission's Climate Programme (Nemry and Demirel 2012; European Commission 2014), and the Rockefeller Resilient Cities Program (Tyler and Moench 2012; The Rockefeller Foundation 2015).

The IPCC AR5 Report states that there is "high agreement" (although "limited evidence") that climate change will negatively affect transport infrastructure. This includes changes in freeze-thaw cycles, temperature extremes, and precipitation. Additionally, road infrastructure is included in guidance sections related to vulnerability reduction, disaster risk management, and urban resilience (Field et al. 2014, Revi and Sattherwaite 2013). The Working Group II Report Section 8 on Urban Resilience has several observations and recommendations regarding transport infrastructure including that climate change may increase the costs to maintain and repair road networks, requiring transport planners to reassess maintenance costs, traditional design materials, and take a 'whole-of-life' approach (Revi and Sattherwaite 2013 Section 8.3.3.6). This inclusion of "climate risk management at the planning or design phase" can lower costs and help identify "vulnerable populations and locations at risk" (Revi and Sattherwaite 2013 Section 8.4.1.5).

The European Commission's Climate Action Programme was established in 2010 and focuses mainly on climate policy related to emissions and carbon (European Commission 2014). Several key reports have emerged from the European Commission, including Nemry and Demirel (2012), which is focused on identifying climate change trends, the vulnerabilities posed to rail and road infrastructure, and selected adaptation options. Despite high uncertainty, this study marked a first attempt at quantifying climate change impact and producing a technical report available to policy makers in transport planning. The methodology used to estimate paved road degradation due to temperature change is one application of the methodology developed by Dr. Paul Chinowsky's research group and part of the methodology of this proposal. Conservative estimates mark the cost of climate change to transport infrastructure in the millions of dollars for the EU Study (Nemry and Demirel, 2012).

The Rockefeller Resilient Cities Project is a network of 100 cities (chosen through application to the program) designed to incorporate different aspects of 'resilience' into the context of the city. These lessons are then designed to scale up to a global learning database that can influence a future urban environment more resilient to shocks and incremental stress. A notable paper in this project is Tyler and Moench (2012), which focuses on the Asian Cities Climate Change Research Network as a starting point to build resilience in ten major urban centers in Asia. The key approach to this effort is the recognition that cities are complex, interrelated, and operate on several critical systems. The paper outlines a conceptual framework for identifying key drivers of vulnerability, investments to increase resiliency through adaptation, and a systemic analysis approach to holistically evaluate the climate change issue within the urban context.

In addition to these three groups, a number of climate adaptation assessment plans exist for the United States (see: Meyer, Amekudzi, and O'Har 2010; Kafalenos et al. 2008; U.S. Department of Transportation 2011; Executive Office of the President 2013; Meyer, Amekudzi, and O'Har 2010; Bloomberg, Paulson, Jr., and Steyer 2014), for specific cities and states (see: California Transportation Commission 2011; Cambridge Systematics, Inc. 2013; Johnson 2012; Biging, Radke, and Hak Lee 2012), and research groups focused on global considerations of climate change (see: Environmental Change Initiative; Koko, Van der Geest, Kees, and Kreft, Sonke 2013; Field et al. 2014). Many of these plans share common assessment of vulnerable assets, challenges faced, and suggestions for continued research.

The Climate Change Action Plan (CCAP) was first presented by President Obama in 2013. It states that the Federal government will "work with state and local governments to prepare for the unavoidable impacts of climate change" (Executive Office of the President 2013). Much of the responsibility relays upon the state and local governments to implement climate change policies and practices and begin to counteract the effects of climate change.

According to the National Climate Assessment (Melillo, Richmond, and Yohe 2014), public and private sector reactions to climate change have been to plan for future adaptations projects. However, many of these plans have yet to see large scale implementation, leaving the U.S. behind in climate change adaptation. As a first step, the Federal Highway Administration (FHWA) has developed a report outlining steps for agencies to begin incorporating climate change concerns into infrastructure planning (Transportation Research Board 2008). In this FHWA report, a six-step process was outlined on how new infrastructure plans can incorporate the effects of climate changes. This outline includes steps to recognize the role of climate change in infrastructure management, coordinate with other organizations on methods to deal with climate change, and integrate land use and funding challenges. The report, while giving guidelines on how to plan, fails to specify specific quantitative measures to help recognize when climate change will have an effect or how much potential changes in climate will cost the infrastructure improvements (ICF International 2008; Agarwal, Maze, and Souleyrette 2005).

In response to these commitments and explicit regional concerns, the State of California has recognized the condition of their current transportation infrastructure and potential effects climate change will play in current and future infrastructure developments. California's Department of Transportation ("CalTrans") acknowledges the cost to fix the transportation system keeps surmounting, while increased traffic incessantly wears down their existing roadways (California Transportation Commission 2011). Not only is the infrastructure in need of improvement, California is particularly susceptible to the effects of climate change due to their expansive coastline and temperate climate. With rising sea levels and increasing CO_2 admissions from vehicles, "climate variability and extreme events, such as storms and precipitation of increased intensity, will require changing operational responses from transportation providers" (Cambridge Systematics, Inc. 2013). Multiple agencies, including the California Environmental Protection Agency, provide information about the current and future impacts of climate change. This data is passed on to law makers; however, many reports neglect the specific impacts and actions that decision makers can take to mitigate the impact climate change will have on California's infrastructure. California's transportation system has already felt the effects of climate change with the increase of extreme weather events (duVair, Wickizer, and Burer 2003). While California has been on the forefront of much advancement in climate change policy and programs, the incorporation of climate change as a concern for transportation planning still receives little attention in terms of influencing the implementation of infrastructure projects (van den Berg 2013).

In an effort to help policy makers and planners incorporate climate change impacts into transportation and wider decision making, some tools have been developed for use. Notably, the Climate Change Adaptation Tool for Transportation (CCATT) is designed to help assess climate change and transportation. However, as a barrier to routine use, CCATT requires detailed input from local administrators, making its ease of use and implementation difficult for common use (Oswald and McNeil 2013). Additionally, the MAGICC/SCENGEN 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 (University Corporation for Atmospheric Research (UCAR) 2007).

As mentioned above, there are many reports that broadly outline ways to incorporate climate change into transportation infrastructure planning, but there is a paucity of detailed, quantitative information that can aid the decision process. Many other climate change analysis tools are designed for use by scientists and researchers, but the academic focus makes the translation to policy and integration into routine decision-making difficult (Tribbia and Moser 2008).

SOCIAL VULNERABILITY

Why Social Vulnerability?

Despite the clear fact that transport networks exist only because of the populations which use them, traffic planning and network literature gives little explicit recognition of the interactions and impacts between the two systems, particularly in relation to climate change investment and planning. However, in disaster and social impact literature, there is a strong recognition of the importance of the built environment and need for quantitative assessments and interventions to address the identified social vulnerabilities. Chakraborty, Tobin, and Montz (2005) note in a study of extreme event evacuation in Florida that populations can “be more or less vulnerable depending on their proximity to transportation routes or facilities”. Cutter, Boruff, and Shirley (2003) use a statistical analysis to determine the top factors contributing to social vulnerability: two of the top 11 factors are related to quality, quantity, and impact of infrastructure on the surrounding communities. Several pieces of literature recognize the importance of the physical environment’s ability to withstand disaster as a key component in identifying the vulnerability of a population (Downing 1991; Timmerman 1981; S. L. Cutter 1996; Bohle, Downing, and Watts 1994; Füssel 2007; Tierney 2012).

Therefore, the motivation to include a meaningful social vulnerability analysis in the process of enhancing decision making capability under the uncertainty of climate change is twofold. First, it is recognized by Lynn, MacKendrick, and Donoghue (2011) that climate change decision making processes must consider climate vulnerability, equity, and justice if the goal is to adequately provide services, information, education, and support to society.

Secondly, Cutter, Boruff, and Shirley (2003) state that the incorporation of physical infrastructure is critical to reducing social vulnerability of populations:

> "Using [the Social Vulnerability Index] in conjunction with biophysical risk data means that mitigation efforts can be targeted at the most vulnerable groups or counties. The development and integration of social, built environment, and natural hazard indicators will improve our hazard assessments and justify the selective targeting of communities for mitigation based on good social science, not just political whim."

What is Social Vulnerability?

A fundamental component of social vulnerability is the recognition that within communities, there are different (geographically defined) areas where sub-populations have different levels of vulnerability and resilience to events that can affect their ability to withstand and recover from hazard events (Cutter et al. 2008). The recognition of this principle, and identification of these areas, helps planners and emergency managers effectively allocate resources and plans to ensure the poorest and most vulnerable populations have their needs met in a hazard situation (Morrow 1999).

However, similar to transport network literature, social and hazard literature has no agreed-upon definition for 'vulnerability'. Many papers make a distinction between social, economic, and physical factors (Bohle, Downing, and Watts 1994; Dow and Downing 1995; S. Cutter et al. 2009; Füssel 2007; UNFCCC) and several define the term using the product from differentiated values for 'risk' and 'exposure' (Tyler and Moench 2012; S. L. Cutter et al. 2008). Many of the latter works define geographic location as a critical factor in risk and/or exposure (S. L. Cutter et al. 2008; Füssel and Klein 2006; Füssel 2007). Most papers focused on defining social vulnerability seek to identify specific variables or a combination of underlying factors, the "unique social and political patterns" within populations and communities, that "result in accentuated risk for some categories of people" (Morrow 1999).

There are a number of vulnerability studies, assessments and frameworks that identify key contributors to community vulnerability. These factors include: poverty level, age (elderly and young), education level, language, existence and access to public services, and more (see: Finch, Emrich, and Cutter 2010; Flanagan et al. 2011; Morrow 1999; S. L. Cutter et al. 2008; S. L. Cutter, Boruff, and Shirley 2003; Tierney and Bruneau 2007). These underlying characteristics make some areas of a community more vulnerable than others. Most vulnerability studies reviewed for this proposal focus exclusively on the identification of vulnerabilities and recovery patterns; none suggested tangible investment strategies to address the existing and future issues identified.

For this proposal, the definition of vulnerability falls in line with most common definitions found in sociological and disaster literature: vulnerability is the inherent and existing conditions and characteristics of a group of people which negatively affect the ability to absorb, cope, respond, and recover from strains on the system. This builds on work from Cutter et al. (2009), Füssel (2007), and Tyler and Moench (2012).

Social Vulnerability and Climate Change

The incorporation of an explicit social vulnerability metric in the context of discussing holistic planning and prioritization of road infrastructure is an integral part of the broader climate change conversation. While much road infrastructure literature (as discussed above) focuses on questions of economy and efficiency, literature on climate change often begins with the premise of environmental or 'climate' justice. Environmental justice is the concept that it is those populations most impacted by changing climate conditions that are least able to respond and recover (Koko, Van der Geest, Kees, and Kreft, Sonke 2013). The literature states that while this is partially attributable to geographic location, it is also highly impacted by the social factors which allow particular groups to be more susceptible to harm and less able to respond.

Nearly every study reviewed related to climate change and social vulnerability noted two key recommendations: first, that decision-making and policy must specifically incorporate social vulnerability concerns and second, that climate change rarely poses entirely new risks, but exacerbates existing vulnerabilities, thus providing a starting point for addressing future vulnerabilities (Lynn, Kathy; MacKendrick, Katharine; Donoghue, Ellen M. 2011; Koko, Van der Geest, Kees, and Kreft, Sonke 2013; Leichenko 2011; Barnett and Adger 2007).

In terms of planning recommendations, there were few differences noted between planning specifically for negative climate change impacts and the existing disaster risk reduction frameworks: both express a desire for analytical tools and methodologies to assess risk and vulnerability and identify opportunities for action, and both show a growing recognition of enhancing the underlying characteristics of a community that make it more resilient (Parks and Roberts 2006). Most studies reviewed on climate change and social vulnerability note the importance of the built environment, key infrastructure, hazard planning and adaptation, and addressing social disparities within communities (Chakraborty, Tobin, and Montz 2005; S. L. Cutter, Boruff, and Shirley 2003).

Addressing the challenges posed by environmental justice is “a considerable challenge” because climate change affects sociological, ecological and other systems (Parks and Roberts 2006). While many reports focus on identifying vulnerabilities as a way to then develop better adaptation and response strategies, an alternative view is that impacts of climate change could be significantly reduced if we could cope better with current climate risks (Parks and Roberts 2006). However, none of the reports offer specific adaptation measures and state that it is not clear how the information can be specifically used to reduce vulnerability (Leichenko 2011; S. Cutter et al. 2009; Lynn, Kathy; MacKendrick, Katharine; Donoghue, Ellen M. 2011). It is from this perspective that the Triple Bottom Line Framework is introduced as a method for incorporating many of these concerns in the context of decision-making.

A HOLISTIC APPROACH: THE TRIPLE BOTTOM LINE

The contribution of this dissertation is to introduce a method for quantitative and holistic methods to measure the costs and benefits of proactive investment in road infrastructure given the uncertainties of future climate change. The method and results are designed to provide a basis for discussion, iteration, and improvement as the available knowledge, modeling tools, and understanding of needs for policy decisions become more defined. This is a critical step forward in terms of climate change, where, “the production of climate science has steadily grown….but its usability remains relatively limited in terms of decision support and policy design” (Dilling and Lemos 2011).

The Triple Bottom Line is a fundamental component of the concept of sustainability and is presented as a useful framework for holistically analyzing the benefits of proactive investment in road infrastructure relative to climate change.

Sustainability & the Triple Bottom Line

"Sustainability" as a concept is often traced back to the 1987 publication of the World Commission on Environment and Development's *Brundtland Commission* report, which defined sustainable development as "that [which] meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). This concept has been the basis for a number of international efforts to move towards a better understanding of the components of, and actions which will enhance, sustainable development. Specifically, since the World Conference on Sustainable Development in Rio de Janeiro in 1992, the UN has served as a forum for international agreements on sustainable development. Most recently, the 17 "Sustainable Development Goals" ("SDGs") were ratified in September 2015 based upon the proposal: "Transforming Our World: The 2030 Agenda for Sustainable Development" (Sustainable Development Knowledge Platform 2015).

The SDGs include seven goals explicitly mentioning 'sustainability' with Goals 9, 11 and 13 specifically focusing on principles relevant to this dissertation. Goal 9 focuses on infrastructure, stating: "[The goal is to] build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation". This statement has eight sub-goals that further elucidate the focus of this statement, with 9.1 focusing on 'quality, reliable, sustainable and resilient infrastructure…with a focus on…equitable access for all". Goal 11 is focused on environmental and social aspects of planning and development in urban areas: "Make cities and human settlements inclusive, safe, resilient and sustainable". The ten sub-goals include one that states, "Support positive economic, social and environmental links…by strengthening national and regional development planning." Finally, Goal 13 is specific to climate change: "Take urgent action to combat climate change and its impacts (acknowledging the role of leadership provided by the UNFCCC". The sub-goals are focused on resilience and adaptive capacity, integration of adaptation into national strategies, policies and planning, and an effort to improve education and awareness of the importance of adaptation. The specific targets and metrics used to measure these goals have not been finalized as of the finalization of this dissertation, but will likely be important for considering these specific goals in the broader context of infrastructure development and sustainability.

But broader than the specific goals, the preamble to the proposal document as well as other documents from the United Nations Sustainable Development group mention 'people, profit, and planet' as well as other references to define how sustainability should be framed in the political context. These agreements and others have paralleled (with an expanded goal of encompassing current processes) the efforts of the IPCC to understand, quantify, measure, and set best practices for current and future development.

In the academic realm, the domain of sustainability science has evolved over the last forty years, recently gaining greater prominence (the journal *Sustainability Science* was first published in 2006). Broadly, sustainability science is focused on studying the trans-disciplinary science and practice of 'sustainability' (Kajikawa 2008). However, this leaves ample room for ongoing discussion surrounding the purpose and focus of the sustainability science realm: The concepts of sustainability and multi-disciplinary thinking first gained prominence through "Limits to Growth" by Donella Meadows et al., published in 1972. The concept of sustainability and 'systems' thinking was highlighted as a top priority for science and technology (Donella Meadows et al. 1972). Ostrom, Janssen, and Anderies (2007) posit that sustainability science is an applied science focused on scientific knowledge obtained from existing disciplines to build capabilities specific to sustainability science. Several publications define sustainability science as an 'area' that brings together different researchers and multidisciplinary perspectives, but not yet a unique and distinct field of research (Palmer 2007; National Research Council, Policy Division. Board on Sustainable Development 1999).

Most recently, and reaching the conclusion after a comprehensive review of sustainability science literature, sustainability science is defined as a distinct discipline that 'arches' over existing disciplines (Kajikawa 2008). In this view, it provides a framework to address issues related to sustainability without severing ties to existing disciplines. Martens (2006) outlines four aspects of sustainable development including intergenerational considerations (analysis considering a time period of at least 25-50 years), multiple levels of scale of analysis (relevant to specific issues being studied), multiple domains (three-pillar concept of integrating multiple perspectives for consideration), and multiple interpretations (each domain has a different view of what sustainable development is and how to achieve it).

Within these definitions, sustainability science necessarily covers a wide range of topics. Climate change is one of the most-written about topics, but most work focuses on environmental impacts, mitigation of emissions, and a small amount of work focused on impacts on the built and human environments (Kajikawa 2008). In terms of the construction management industry, Ugwu and Haupt (2007) recognize that the construction industry must consider 'strategic sustainability objectives' not only as concepts but actively begin to incorporate specific actions at the project level. However, the difficulty comes in competing priorities, lack of quantified metrics for assessing sustainability, and the short-term focus of decision-making. Several articles focused on sustainability in construction processes note the importance of considering environmental issues (specifically, greenhouse gas emissions) and social concerns, although these are usually driven by the need to meet customer demands, price restrictions, and other considerations. Generally, environmental life-cycle analyses dominate any 'sustainable' processes while broader social considerations are omitted (see: Bocchini et al. 2014; Kucukvar and Tatari 2013; Huang, Bird, and Bell 2009; Fellows 2014; Gallivan et al. 2010; Padgett and Tapia 2013; Ding 2008).

This work focused on sustainability science provides a useful context for enhancing the construction management perspective by broadening the objectives at the policy level. By evaluating and addressing many cross-disciplinary, complex issues, sustainability frameworks can enhance the ability to consider multiple objectives in one process. Particularly, the use of a *triple bottom line* ("TBL") (also referred to as *P3* or *three-pillar model*) explicitly focuses on three areas which, while interconnected in reality, are often treated separately in academic literature and practice: "*social*, *environmental*, *and economic*" or "*people, profit, and planet*" (Kajikawa 2008; Zimmerman 2005). Each of these sectors has traditional disciplines which are focused on addressing both historical and climate-change related issues to sustainability. It is in the combination, however, where actionable solutions are likely to be found, particularly when there are competing interests and needs at the policy level.

In terms of infrastructure planning under climate change uncertainty, the multiple-domain TBL approach can align with identified needs in literature to reduce social vulnerability, account for environmental impacts of projects, and provide transparent methods for prioritizing road investments. The American Association of State Highway and Transportation Officials (AASHTO) published a working document in 2009 focused on 'Best Practices' in sustainability and transportation, which had an explicit focus on TBL. This document defines 'sustainable transportation' as a system which is efficient and effective in supporting the economy, allows equal access to individuals and societies, and limits emissions. It specifically mentions using the TBL framework to "guide planning, policy decisions, and implementation" (CH2M Hill, Good Company for the Center for Environmental Excellence, and AASHTO 2009).

Along these lines, Leichenko (2011) recognizes the benefits of a holistic perspective to planning in the face of climate change:

> "Long-term urban sustainability [to climate change] includes both adaptation and mitigation strategies [and] needs to be bundled with broader development policies and plans…in many cases, existing policies that are aimed at addressing other urban problems, such as [infrastructure] in risk prone areas, can be adapted to promote climate change resilience at little or no cost."

LITERATURE AND BACKGROUND SUMMARY

Each of the sections above details the existing knowledge surrounding the foundational concepts used in this dissertation. Table 1 summarizes key literature pieces broadly into the categories covered in this dissertation.

Table 2.1: Key Literature Topics and Papers

Literature	Subject	Key Papers
Transportation	Social and Economic Impact	Koetse and Rietveld 2009; Dalziell and Nicholson 2001; Tyler and Moench 2012; Taylor and D'Este 2007; Nagurney, Qiang, and Nagurney 2010
	Need for Risk Assessment	"Potential Impacts of Climate Change on US Transportation" 2008, 290; Jaroszweski, Chapman, and Petts 2010; Taylor and D'Este 2007; Berdica 2002; Füssel 2007
	Specific Social Vulnerability Considerations	Chi, Ruuska, and Guangbin 2013; Preston and Rajé 2007; Erath et al. 2009; Field et al. 2014; Füssel 2007
Climate Change	State of the science	Revi and Sattherwaite 2013; Field et al. 2014
	Importance of Proactive Adaptation	Kamal-Chaoui and Roberts 2009; Tyler and Moench 2012; Archer et al. 2014; Jaroszweski, Chapman, and Petts 2010
	Impacts on society and built environment	Martinich et al. 2012; U.S. Environmental Protection Agency 2015; Tyler and Moench 2012; Koko, Van der Geest, Kees, and Kreft, Sonke 2013; USAID 2013; Barnett and Adger 2007
Triple Bottom Line (Sustainability)	Definitions and Applications	Meadows et al. 1972; Kajikawa 2008; Martens 2006; World Commission on Environment and Development 1987; Hacking and Guthrie 2008; Sustainable Development Knowledge Platform 2015
	Climate Change Application	Thomalla et al. 2006; Turner, B.L. 2003; Leichenko 2011; Sachs 2012
	Related to Infrastructure and/or Planning	Bocchini et al. 2014; Tribbia and Moser 2008; Ugwu and Haupt 2007; Kucukvar and Tatari 2013

POINT OF DEPARTURE

The background information above provides context for understanding the breadth, depth, and diversity of work related to the complex issues of climate change, infrastructure planning, social considerations, and sustainability. While each of these areas individually is vast in its domain, it is in the quantification and combination of useful and relevant knowledge that move this dissertation beyond existing work. Specifically, this dissertation aims to support more informed decisions and the application of the holistic framework of the TBL.

There are two distinct points of departure for this research. In the context of a demand for better understanding of climate change impacts, this dissertation is built upon the development of a modeling approach that provides the first comprehensive and quantitative system built upon detailed engineering stressor-response equations. While there are many broad frameworks and site-specific, detailed engineering models developed to estimate vulnerabilities to climate change, the methodology used in this research moves beyond existing information in four distinct ways. First, it utilizes a full range of CMIP3 and CMIP5 climate change models provided by the IPCC. Most other work focused on climate change modeling impacts use a limited, or single, set of models. Secondly, this research uses engineering-based stressor-response methodologies to estimate the impacts of specific climate stressors on specific infrastructure elements. This assessment using verified materials studies and specific design and maintenance criteria is unique to this research. Third, this research moves beyond vulnerability assessments to suggest specific adaptation options based upon the climate projections. While there are some localized and detailed assessments of potential adaptation options in specific studies, there are no other modeling tools that allow for comparison of reactive and proactive adaptation considerations for all infrastructure elements with a life-cycle approach. Fourth, the impacts of climate change for both vulnerability and adaptation impacts are quantified fiscally. This financial component is unique to this research. The use of each of these four contributions is evident in the studies completed in Chapters 3-5.

The second point of departure for this research is the application of a sustainability framework, the Triple Bottom Line, to the context of infrastructure planning and climate change. While TBL is used in sustainability literature to frame policy discussions related to sustainability, and increasingly in the non-profit business sector, the application of TBL in a quantified assessment of benefits to climate change adaptation investment is unique. This is introduced in Chapter 5 and provides an illustrative example for further iteration, discussion, and refinement through application to real-world decision contexts. This information is displayed using geographic information systems (GIS), a mapping tool that allows for the visual display of information. While GIS is often used in planning contexts, the use of GIS to integrate the TBL pillars into a holistic prioritization metric is unique to this research presented in Chapter 5.

CHAPTER 3

SUMMARY OVERVIEW

This chapter marks the first research step in this dissertation, focusing on the development of the IPSS™ methodology to analyse the quantitative impacts of climate change on road infrastructure. The study is focused on South Africa based upon a research project focused on climate adaptation as part of an effort under the United Nations University World Institute for Development Economics (WIDER). The section below provides a brief overview of the paper and outlines the contribution of this paper to the larger dissertation effort. The full journal article, published in *American Society of Civil Engineering (ASCE) Journal of Infrastructure Systems,* can be found in Appendix III. No additional information or text is included in the Appendix III.

Clarifying note: The early work using IPSS™ referred to two analysis strategies: 'adapt' and 'no adapt'. These correspond directly to the terminology used elsewhere throughout this dissertation as 'proactive adaptation' and 'reactive adaptation', respectively. The reason for the change in terminology was the recognition that the analysis process for 'no adapt/reactive adaptation' was not a true 'no adaptation' scenario (ie: "do nothing"). The analysis process focuses on repairing damages as they occur; not ignoring them. A second terminology matter is the use of "Maximum" climate scenario impacts. In Chapter 3, this refers to the highest impact scenario; in Chapters 4 and 5, this is replaced with the 95th percentile scenario. This change was made to eliminate potential high outlier scenarios.

Overview & Contribution

While climate change is an increasing concern of governments and planning agencies around the world, the development of a quantitative methodology to analyze impacts from a changing climate in a meaningful way has not yet been developed. This paper presents a stressor-response methodology that focuses on quantifying how specific exogenous climate factors ('stressors') effect components of road infrastructure construction and maintenance ('response'). This paper is scoped to focus on the impacts from daily precipitation and temperature changes; it does not include extreme events that would likely greatly increase the impacts of climate change.

The study is focused in South Africa because of the recognized to need to understand, adapt to, and mitigate the negative effects of climate change on the largest road infrastructure network in Africa. As a leader in economic development, South Africa also aims to provide leadership in identifying and reducing the impacts of climate change on development processes. A specific concern of this work is to quantify the financial ramifications of proactive versus reactive decision-making: what will it cost to invest proactively to adapt to climate change, and what is the cost of business as usual and repairing damages as they occur?

This paper uses CMIP3 climate models from the IPCC. The work was funded by the United Nations University World Institute for Development Economics (UNU-WIDER) and was commissioned to create a methodology that could be applied to other geographic contexts. The results represent an early contribution to the IPSS™ methodology that is used throughout this dissertation.

Publication

This paper is published in the *American Society of Civil Engineering (ASCE) Journal of Infrastructure Systems*. This journal is focused on cross-disciplinary papers focused on methodologies for sustaining civil infrastructure. A full version of the published paper is included in Appendix III.

Citation

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"ROAD INFRASTRUCTURE AND CLIMATE CHANGE: IMPACTS AND ADAPTATIONS FOR SOUTH AFRICA"

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Abstract

This paper presents the results of the impact of climate change on the road infrastructure within South Africa. The approach builds upon previous work associated with the UNU-WIDER Development under Climate Change effort emphasizing the impact of climate change on roads. The paper illustrates how climate change effects on road infrastructure can be evaluated at a national and provincial level to produce quantitative estimates of climate change from multiple future climate scenarios.

The results of the study indicate that the national level climate change cost impact in South Africa will vary between USD$116.8 million and USD$228.7 million annually in the 2050 decade for the median and maximum climate scenarios if a no adaptation policy action is taken; conversely, if a proactive adaptation approach is taken, these costs can be reduced to USD $55.7 million. The savings in cost due to climate change impacts based upon the policy approach is equivalent to building more than 10,000 kilometers of new, secondary paved road by 2050. By 2090, the proactive adaptation savings could equal the construction of more than 20,000 kilometers of new, secondary paved roads,

approximately 30% of the existing paved road network in South Africa (IRF 2012). The analysis focuses on the advantage from a pro-active policy approach: upgrading road infrastructure where climate impacts will exceed current design and maintenance standards.

The paper presents these costs at a provincial impact level through the potential impacts of 54 distinct potential climate scenarios. Decadal and average annual costs are detailed through 2100.

Introduction

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

In terms of future climate change impacts, road infrastructure is one component susceptible to the projected changes. A consistent finding is that high costs for adaptation, maintenance and potential negative impacts on transit are projected to be necessary to maintain existing road infrastructure quality (Keener et al.. 2013; Hambly et al. 2007; Satterthwaite 2007). While there is a strong basis both on a local level and through international studies for evaluating the impact of climate change on road infrastructure and the importance of accounting for these impacts, there are few studies that quantify these costs in monetary terms and over a time-scale for planning (Burkett 2002, duVair et al. 2002, Oswald et al.. 2012, TRB 2008; Galbraith et al. 2005). This study recognizes the importance of understanding climate impacts and quantifies the costs of existing road infrastructure in South Africa as a case study for the application of modelling results.

Paved, gravel, and dirt road inventories were selected as the infrastructure types evaluated in this study both because of their economic, social, and development importance and the planning and life-cycle these infrastructure elements normally have. The study examines the extent to which climate change from 54 IPCC-approved general circulation models (GCMs) climate scenarios will divert resources from the further development of infrastructure to the maintenance and adaptation of the existing road infrastructure.

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

Background

There is a large body of existing literature establishing the imperative to evaluate potential climate change impacts on infrastructure, including work by the World Bank, for the European Union, and in Canada (EACC 2010, Nemry et al. 20120, Hambly et al. 2013). 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 and the greater impacts on economics and social welfare. 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 et al. 2012).

Research completed by the Transportation Research Board in the United States, the Scottish Executives, and Austroads in Australia are notable efforts in bridging this research gap (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. 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.

One focus of many studies is sea level rise and flooding in coastal areas (Burkett 2002, duVair et al. 2002, Savonis et al. 2008 Oswald 2012). This study does not address sea level rise or coastal flooding in South Africa.

The assessment for this study was completed using an analysis tool created by the authors, the *Infrastructure Planning Support System* (IPSS™). An overview of methodology is explained briefly below and more details can be found on IPSS™ in Schweikert and Chinowsky (2012). Other existing impact assessment tools the *Climate Change Adaptation Tool for Transportation* (CCATT), which detailed input of actual road stock obtained from local administrators (Oswald 2012). Another tool is the *Model for the Assessment of Greenhouse-gas Induced Climate Change A Regional Climate SCENario GENerator* (MAGICC/SCENGEN) (University Corporation for Atmospheric Research 2007), a software that analyzes future scenarios of climate change at global-mean and regional levels. The 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 impact studies on infrastructure is that they either focus on a narrow potential impact of climate change, or the studies fail to provide specific estimates of cost or damages that may result from potential climate change scenarios. In response to this gap in the climate change literature, the authors have been actively engaged in developing specific estimates of climate change impacts on infrastructure elements. Chinowsky et al. (2011) document the potential cost impacts of climate change on road infrastructure in ten countries that are geographically and economically diverse. The study illustrates both the potential real costs that countries may incur due to climate change scenarios as well as the potential opportunity costs of diverting infrastructure resources to climate change adaptation. Chinowsky and Arndt (2012) refine these results in the context of Southern Africa and the potential use of multiple climate scenarios in a probabilistic economic approach. Additionally, the analysis presented in this paper provides a policy component designed to inform infrastructure planners of the risks, costs, and adaptation and mitigation options in response to climate change. The response methodology introduced in these efforts has been extended by additional researchers to analyze impacts from climate change on bridges (Stratus Consulting 2010) and roads in northern climates (Industrial Economics 2010) as well as broader studies including Nemry and Demirel (2012) focusing on infrastructure vulnerabilities in the European Union.

Methodology

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

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

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

Decision Approach: "Adapt" and "No Adapt" Scenarios

Analysis is performed from two perspectives: a Proactive Adaptation ("Adapt") and a No Adaptation ("No Adapt"). Both are examined from engineering and design-focused perspectives. The "Adapt" analysis assumes perfect foresight with respect to climate change impacts and a policy that applies these forward-looking climate projections to upgrade new roads as they are re-built and maintained. The "adapt" approach focuses on adjusting road design to improve resilience to climatic impacts. This is the chosen method of analysis for two reasons: it is feasible to assume that the large existing stock of road infrastructure will remain in place in the coming decades and will therefore incur damages that require mitigation; secondly, while many adaptation options are suggested for particularly vulnerable roads lying in flooding plains, coastal areas, and other vulnerable areas, these options require very specific, localized data and decision making that is outside the scope of a regional and country-level analysis. The Adapt Policy scenario incurs up-front costs to adapt an existing road to mitigate future damages that are projected from increases in precipitation or temperature. For dirt road infrastructure, roads are upgraded to an adapted gravel road and therefore are less susceptible to increased precipitation impacts. The "No Adapt" analysis assumes no adaptation changes are put in place. Roads are rebuilt according to previous baseline standards. The costs incurred are from increased maintenance necessary to retain the design life of the original road as degradation of the road infrastructure occurs from climate change stressors.

In addition to these overall policy approaches, the maintenance savings from adaptation is considered to emphasize the quantifiable costs and benefits associated with Adaptation. This metric is applied to unpaved (dirt and gravel) roads. Many of the costs related to an unpaved road network are related to precipitation damage combined with traffic levels. Upgrading these roads can reduce the overall maintenance requirements.

General Circulation Models

The climate change projections utilized in this study were analyzed using data from General Circulation Models (GCMs). GCMs provide climatological data for future climate change scenarios through 2100. The data used in this analysis include the available A2, A1B and B1 scenarios, which represent different scenarios of future development based on technological advancement, population change, and emissions. These are based on the accepted definitions of the Intergovernmental Panels Fourth Assessment Report (IPCC 2007). To provide a robust analysis of possible climate change projections, all GCM data sets approved by the IPCC containing complete data projections for climate data for South Africa were used in the analysis on the South African roadstock. In total, 54 GCMs were used for analysis. This is represented in the results section utilizing several display metrics.

The current analysis has been carried out using climate change projections analyzed by GCMs at the resolution of 0.5° grid squares, which were then aggregated to the level of admin01 (first sub-national unit). The GCMs selected are the models that have complete datasets appropriate for making temperature and precipitation projections through 2100 (Schlosser et al.. 2012). For each model, historical monthly climate data is used from the Climate Research Unit (CRU) for 1951–2000 to produce a baseline scenario for each geographic region analyzed. The baseline scenario assumes that future weather patterns will retain the characteristics of historical climate variability. Taking the baseline scenario, a 10-year moving average of the monthly deviations in temperature and precipitation are used to establish average deltas that are applied to the new projected baselines in each GCM. The application of these deltas to the baselines in each of the future decades provides the climate scenarios that are used as the basis for the specific impact analyses.

Division of Road Inventory

A primary output of the current study is to provide cost information. Key to this analysis is data on the existing roadstock in each geographic area analyzed. Where possible, existing roadstock information is extracted from geographic information systems (GIS) information to provide direct roadstock. However, the GIS database is limited in representing all road types available. Therefore, GIS data is augmented by data from the Africa Infrastructure Country Diagnostic (AICD) and International Road Federation (IRF). The available data is then allocated at an admin01 level based on GIS information, population density, and area, and adjusted for additional factors where necessary (IRF 2009, Chinowsky et al. 2011, Gwilliam et al. 2008, AICD 2013). For analysis purposes, it is assumed that once the roadstock is allocated to a province, the roadstock is evenly distributed throughout the province. This is both a restriction of data availability and an assumption based upon the granularity of data available in the GCM climate outputs.

Secondly, to ensure that the allocation of road inventory correctly correlates to the GCM data provided, the CRU grid cells of 0.5 degree latitude by 0.5 degree longitudinal (an approximately 250 km^2 area) are the basis of this data translation. This means that where exact GIS representation of roadstock was not available, the admin01 estimates were allocated to CRU scale uniformly, with adjustments for population where necessary. The information used in this analysis is CRU TS 2.1 (Climate Research Unit Time Series Version 2.1). Several data parameters are included; this analysis focuses on the reported precipitation and maximum temperature (Mitchell et al. 2004; Strzepek and Fant 2011).

Impact functions

In this analysis, climate change impacts are quantified in terms of total kilometers of road degraded prior to lifecycle design and total cost of repairing or mitigating future damages. The impacts are determined by a "stressor-response" methodology, in which exogenous factors (i.e. stressors) have a direct effect on and subsequent response by, focal elements. In the context of climate change and infrastructure, these elements include: changes in precipitation levels, temperatures, storm frequency and intensity, and wind speeds (Chinowsky and Arndt 2012, Chinowsky et al. 2011). For road infrastructure, the two focal elements analyzed in this study are precipitation and temperature changes.

This process utilizes multiple baseline data inputs. A combination of material science reports, usage studies, case studies, and historic data were used for each infrastructure category. Where possible, data from material manufacturers was combined with historical data to obtain an objective response function. When these data were not available, response functions were extrapolated based on performance data and case studies from sources such as departments of transportation, road agencies, and international transportation and construction research (Chinowsky and Arndt 2012).

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

Approach to Calculating New Construction Costs

In the case of new construction, cost impacts are only considered for the Adapt scenario. New construction costs are only modified if climate change is anticipated using climate models. Since the No Adapt approach is limited to repairing damages after they occur, no changes in existing building practices are put in place for the No Adapt analysis. Rather, the No Adapt scenario is focused entirely on Maintenance costs that are incurred due to climate change impact.

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

The materials methodology is based on the premise that roads should be constructed to a level that anticipates the future changes in climate conditions and the accompanying changes in material requirements. Following this concept, this methodology determines if new structures such as paved roads will be subject to material changes if it is anticipated that a significant climate change stressor will occur during their projected lifespan.

Similarly, the second option for adaptation for new construction is to alter the type of infrastructure being constructed to one that has the capacity to handle the anticipated climate change. For example, if climate change is anticipated for dirt roads, then a consideration has to be made for either increasing maintenance costs as described below or altering these roads to be gravel roads. For the gravel road option, the cost of adaptation is based on the need to strengthen the road with a crushed gravel mix. The benefit with this approach is that basic maintenance as well as climate induced maintenance is eliminated on the dirt road (because it has been adapted) during the design life span of the road.

For unpaved roads, a direct approach is used for estimating the cost impact of changes in climate stressors. The stressor-response relationship associates the change in construction costs with changes in maximum monthly precipitation. Available data suggests that there is no relationship between temperature and the cost of building unpaved roads. Ramos-Scharron and MacDonald (2007) attribute about 80 percent of unpaved road degradation to precipitation, while the remaining 20 percent is attributed to factors such as the tonnage of traffic and traffic rates. Given this attribution to precipitation and the focus on retaining design lifespan, we assume that base construction costs for unpaved roads increase based upon thresholds of precipitation increase relative to the baseline. Our approach is summarized as follows:

$$CC_U = 0.8 \cdot MIP \cdot BC_{\mathrm{U}} \quad \text{(Eq.1)}$$

where CC_{U} is the change in construction costs for unpaved roads associated with a unit change in climate stress or design requirements, MIP is the increase in maximum monthly precipitation, and BC_{U} is base construction costs for unpaved roads. A full explanation of the precipitation stressor-response impacts is detailed in Chinowsky and Arndt (2012).

For paved roads, temperature is an additional key factor. Where temperatures are expected to increase, this can affect road surface, degradation, and reduce the lifespan of the road. For example, hotter temperatures could imply changing asphalt properties. The selected approach for estimating the adaptation measures for paved roads in areas where a rise in temperature is predicted is by upgrading the asphalt type and asphalt binder to withstand a higher pavement temperature. Table 1 shows the corresponding pavement temperatures (converted by using Equation 2) and the estimated cost per lane-km.

Based on available maximum daily temperature, the average value for 7-day maximum ambient temperature is calculated for each CRU grid for each climate change scenario. This then allows deriving the corresponding gridded 7-day pavement temperature values by CRU grid and is applied to the road inventory.

The relation between pavement temperature and ambient temperature is assumed as (Lavin 2003):

$$Tp = 0.9545\ (Ta - 0.00618\ L2 + 0.2289\ L + 42.2) - 17.78 \qquad \text{(Eq.2)}$$

Where:
Tp is the pavement temperature (°C)
Ta is the ambient temperature (°C)
L is the latitude (arc degrees)

Cost associated with asphalt binder is calculated by multiplying the upper cost figures (Table 3.1) with the road length information (paved primary, secondary, and tertiary). Assuming an average number of lanes for each type of road, the costs are calculated, aggregated at country level and combined with maintenance, precipitation and other cost-impact information to determine the estimated cost of climate change under a given climate scenario.

TABLE 3.1: Asphalt binder grade, corresponding maximum pavement temperature, and estimated cost per lane kilometer (USD)

Asphalt Binder Grade	Tmax_7day (˚C)	Cost (USD/lane km)
PG-46	46	$ 317,040
PG-52	52	$ 337,961
PG-58	58	$ 362,102
PG-64	64	$ 387,851
PG-70	70	$ 415,210
PG-76	76	$ 444,178
PG-82	82	$ 474,755

Approach to Calculating Maintenance Costs

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

For gravel and dirt roads, maintenance impacts are induced by changes in maximum monthly precipitation rates. The result of increased precipitation is increased erosion, creating a need to increase maintenance to retain the original design life. To estimate the changes in road maintenance costs, the amount of erosion is used as a basis for determining the percent of maintenance increase required. The calculation of the erosion rates for dirt and gravel roads is based on three factors: (1) precipitation amount, (2) traffic levels, and (3) slope of the road. In terms of precipitation, studies indicate that increases in terms of precipitation have a direct impact on the design life of a dirt road with minimal slope and low traffic levels (Dube et al. 2004). This base case is augmented as traffic rates and slope percentages increase, resulting in significantly greater erosion rates. For example, a dirt road with medium slope and medium traffic volume (as defined by the studies and adjusted by the authors) would have an erosion factor 10 times greater than flat slope with low traffic levels (Sheridan and Noske 2005).

The maintenance costs associated with climate change occur for both the Adapt and No Adapt scenarios. In terms of the Adapt scenario, roads that currently exist and therefore have not had the opportunity to be upgraded (a limitation of the reality of cost and time to upgrade roads), will require maintenance during the remaining part of their lifespan as climate change stressors are encountered. At the time in which these roads require rehabilitation at the end of their useful lifespan, they will then be modified according to the New Construction option. Additionally, when climate impacts exceed the design specifications but do not pass a threshold, there are incurred maintenance costs for adapted roads.

In terms of the No Adapt scenario, maintenance costs are the only costs associated with road infrastructure. In this case, maintenance costs are incurred at every point that climate change impacts occur above the baseline (no climate change) scenario. The goal is instituted to retain the original lifespan through repairs where possible.

Additional Metrics Used

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 regions being studied. The difficulty in this determination is the variation in the regions in terms of amount of current road inventory and the projected cost of climate change for each region. Given these variances, a metric is required that reflects the relative impact in the region while not overly weighting the total cost of climate change on the area. The current solution to this issue is the adoption of the opportunity cost metric established by the authors in previous studies (Chinowsky et al. 2011).

The opportunity cost for a region 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. This is defined by the total cost of climate change (for either adapt or no adapt scenario) and the kilometers of new, secondary paved road that could have been built. The percentage is relative to the existing paved road network (constant, pre-analysis inventory). In this study, 'adaptive advantage' is used to define the fiscal savings between the no adapt and net adapt costs.

Net Adaptation Cost: Roads

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

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

Study Results

The analysis detailed in this study provides an estimated cost of the potential climate change cost to South Africa's road infrastructure. Table 3.2 shows the costs by selected decades for the median and maximum GCM scenarios. The impacts range from an adapt cost of USD$1.1 million (2030) to a no adapt cost of USD$389.1 million annually (2090). These costs are equivalent to 3,700 and nearly 26,000 kilometers, respectively, of new, secondary paved road. Figure 3.1 details these decadal findings and shows a clear adaptive advantage between the estimated costs for no adapt and net adaptation policy approaches (USD$115 – 171 million, respectively for the median and maximum scenarios for the 2050 decade). The costs provided in these results do not include a discount factor. Although time-value of money will play a distinct role in future cost obligations for these impacts, the results presented here are intended to provide a relative comparison of impacts as well as an indication of incurred costs in today's terms. Discount rates should be applied to understand the final economic impact of climate change and the potential impact in future cost perspectives.

FIGURE 3.1: Selected National Level Results. Annual Average Costs by Decade for Median (50th percentile) and Maximum (100th percentile) GCMs

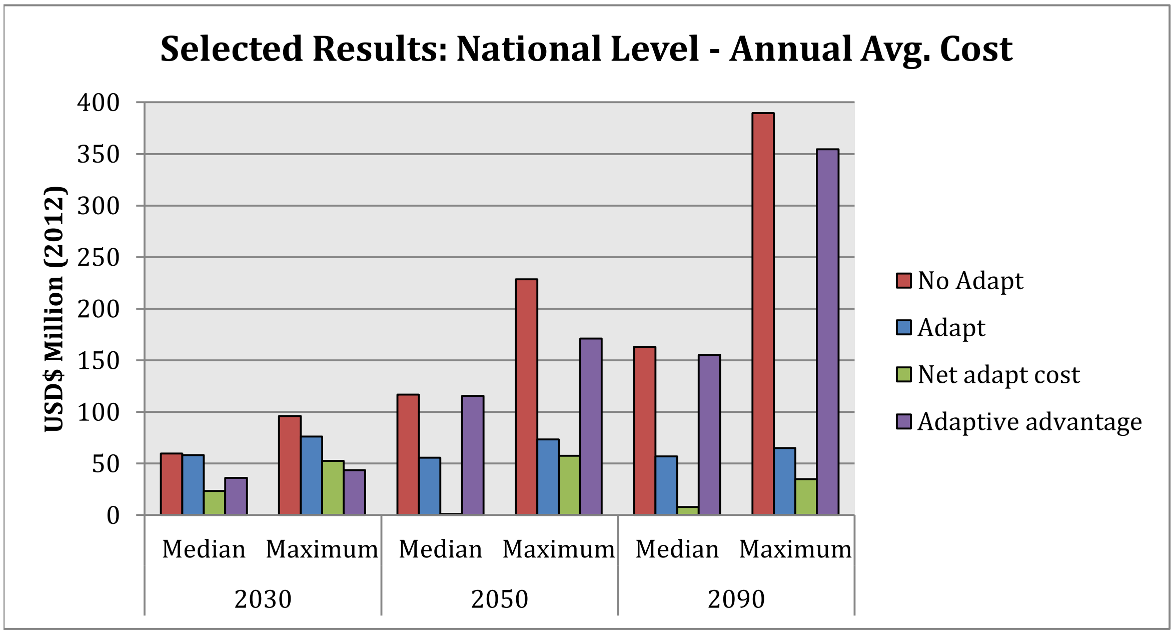


TABLE 3.2: Decadal average annual road costs, national level. Selected GCM scenarios

Decade	Scenario	Annual avg. cost USD$ million No Adapt	Annual avg. cost USD$ million Adapt	Net adapt cost USD$ million Adapt	Adaptive advantage USD$ million	Opp. cost % Adapt	Opp. cost % No Adapt	Equiv. KM Adapt	Equiv. KM No Adapt
2030	Median	59.6	58.2	23.5	36.2	6.1	6.3	3,880	3,997
	Maximum	96.0	76.3	52.5	43.4	8.1	10.1	5,086	6,397
2050	Median	116.8	55.7	1.1	115.7	5.9	12.3	3,710	7,789
	Maximum	228.7	73.3	57.5	171.2	7.7	24.1	4,889	15,245
2090	Median	163.2	56.8	7.8	155.4	6.0	17.2	3,789	10,878
	Maximum	389.6	65.0	35.0	354.6	6.9	41.1	4,335	25,974

The maximum and median scenario results are shown in Figures 3.2 and 3.3. While the costs are higher in the maximum scenario, the trends are the same: the no adapt scenario progressively increases while adapt and net adapt costs are much lower over time.

FIGURE 3.2: National Level Results, Annual Avg. Cost by Decade for Median (50th percentile) GCM results. Adapt, Net Adapt (including maintenance savings calculations) and no adapt scenarios

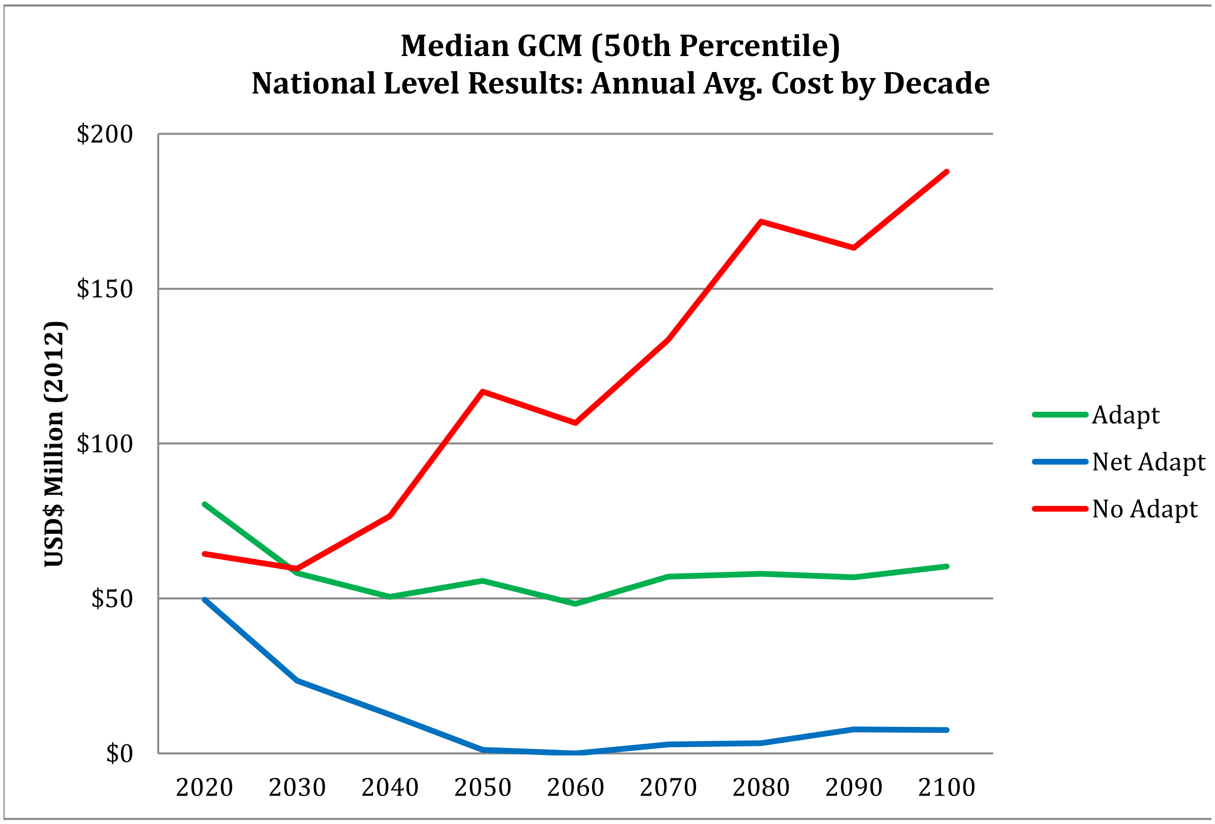
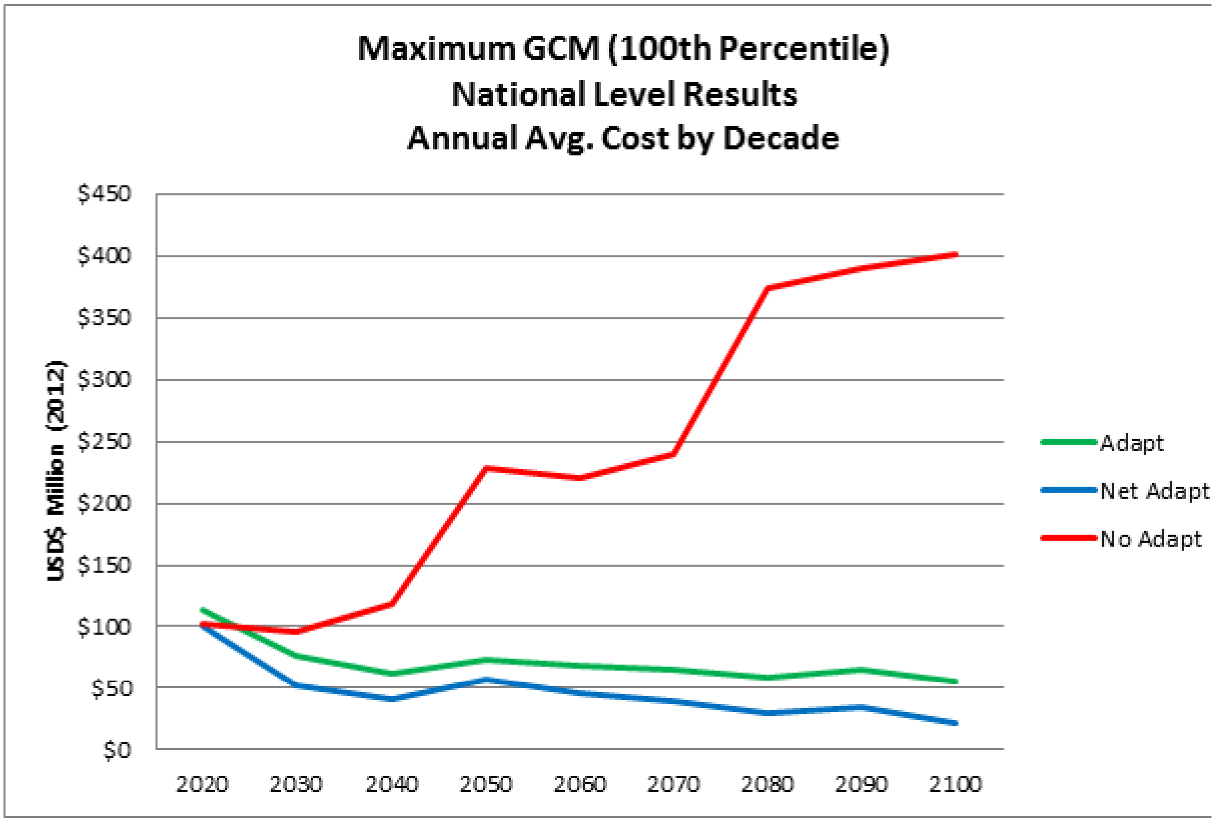
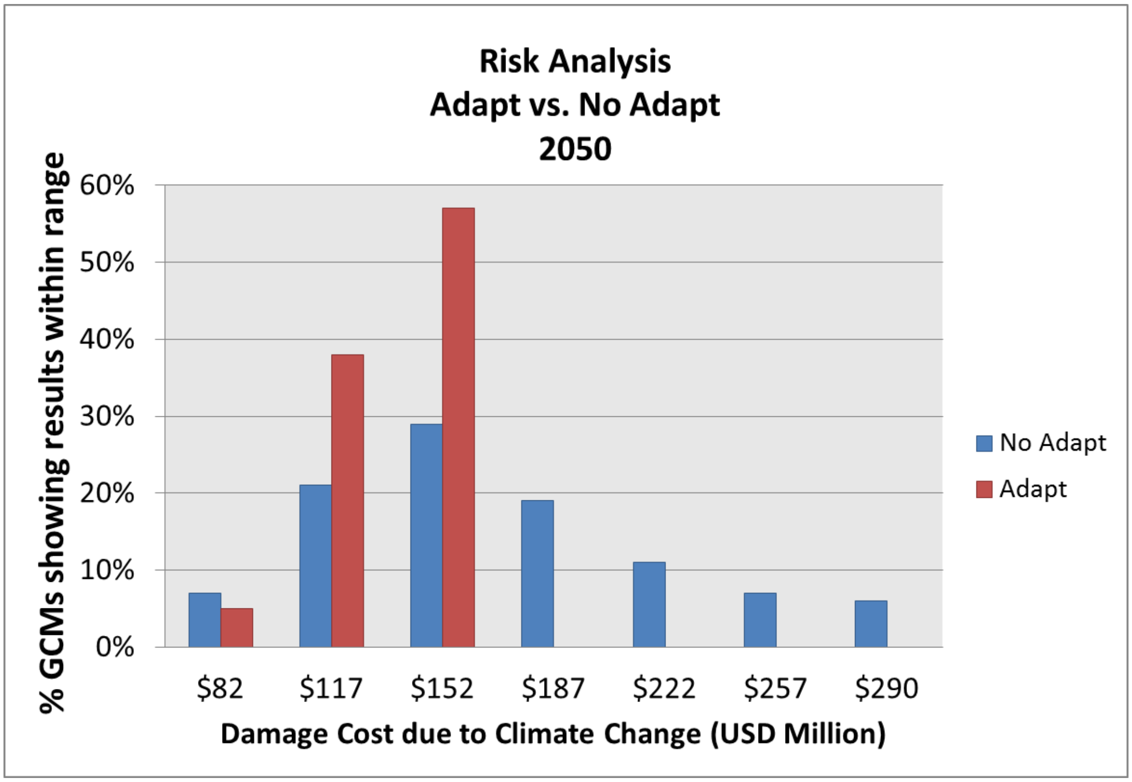


FIGURE 3.3: National Level Results, Annual Avg. Cost by Decade for Maximum (100th percentile) GCM results. Adapt, Net Adapt (including maintenance savings calculations) and no adapt scenarios



54 GCMs were used in this analysis. Each produces a different cost based upon projected changes in future climate impacts. Figure 3.4 is a histogram analysis showing the relative risk of investment based upon all scenarios. For example, an investment of $152 million annually (results shown for 2050 decade) with an adapt approach would ensure that all GCM projections are covered. This means that all road infrastructures would be 'climate resilient'. However, if this same investment were made with a no adapt approach, there is a 45% chance that the climate impacts would require greater investment to mitigate the damages. These results show that adaptation to climate change is important to consider at current and future stages of road infrastructure management policy.

FIGURE 3.4: Histogram chart displaying the results of annual avg. costs in 2050 decade for each of the 54 GCMs used in analysis. The "risk analysis" highlights the percentage of GCMs which estimate a cost in a given range for this decade.



National Level Results

The potential impact of climate change on South Africa's national road network could be as high as US$96 US$229, and US$390 million annually in 2030, 2050, and 2090 respectively if no adaptation measures are taken (Table 3.2). This cost is reduced if a pro-active adaptation strategy is taken (Figure 3.2). The benefits from adapting road infrastructure pro-actively including savings from decreased maintenance on unpaved road infrastructure, decreased vulnerability to climate change impacts, and a more robust and reliable road infrastructure system.

In the 2090 decade, there is a net savings of over US$354 million if the adaptation approach is taken for the maximum GCM impact scenario. This is largely because the adapted road infrastructure is more resilient to climate impacts, including upgrading dirt road infrastructure to gravel and paved roads, reducing the annual maintenance requirements. Even in earlier decades, such as 2030, there is an adaptive advantage of USD$36-43 million dollars annually between the median and maximum climate scenarios, respectively.

The opportunity cost of climate change on South African road infrastructure is between 6-41 per cent depending on the GCM scenario and decade analyzed (see table 3.2). South Africa has a large existing road network of over 360,000 km; However, only 17 per cent of this roadstock is paved (IRF 2012). By adapting unpaved road infrastructure by enhancing the drainage capacities of dirt and gravel roads and, where traffic and precipitation impacts indicate upgrading to a paved surface, there are fiscal savings as well as additional benefits including less maintenance from extreme events, increased connectivity of roads, and higher traffic and freight volumes. This is especially evident in the provincial (regional) results.

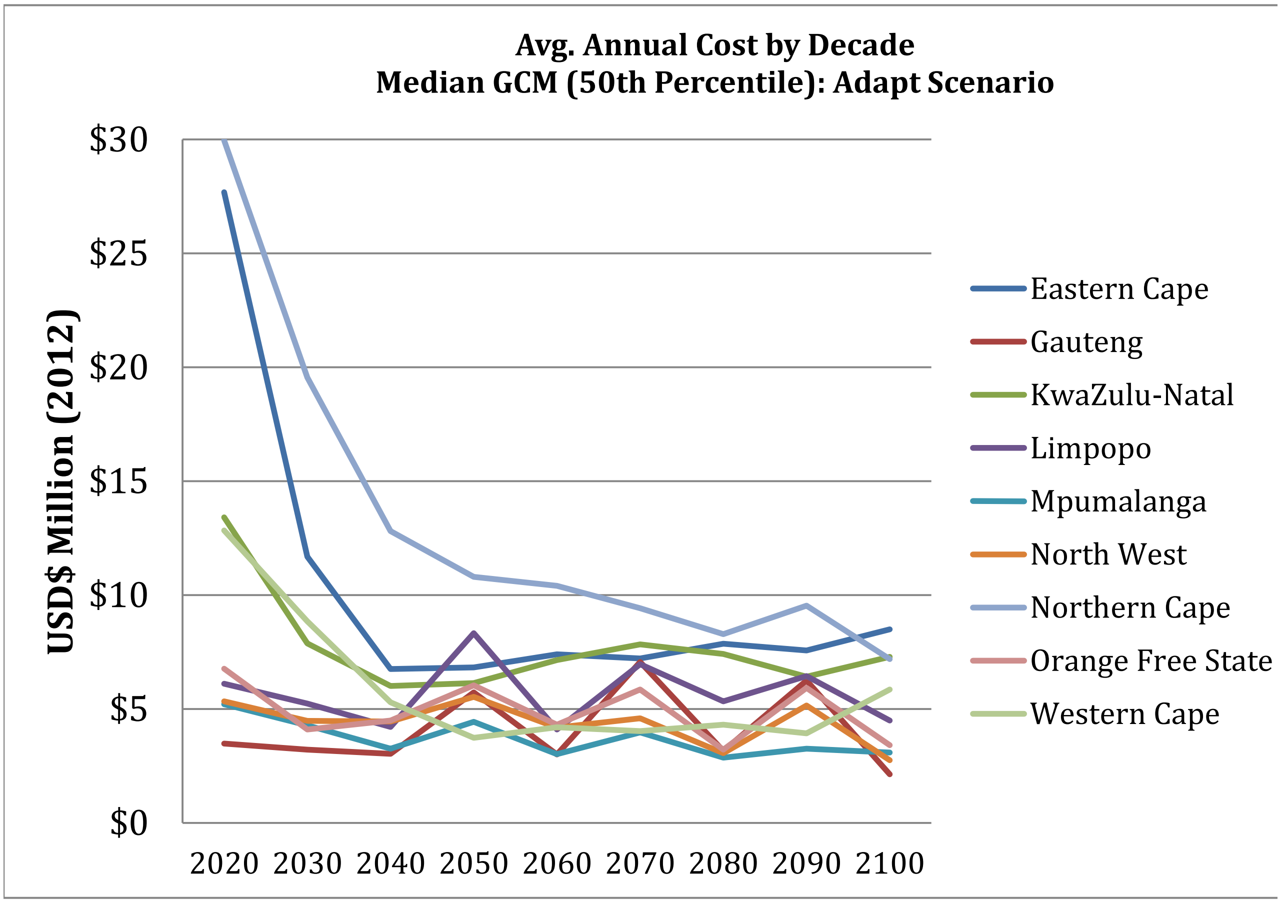
Provincial Level Results

At the provincial level, there is an adaptive advantage for nearly all of the provinces in each decade. In 2050 with the median GCM results (50th percentile), the adaptive advantage ranges from USD$2.2 to $15.6 million annually (Table 3.3). Northern Cape and Eastern Cape see high initial adaptation costs (Figure 3.5) but by the mid-2030 time frame, all adaptation costs are below USD$10 million annually. This indicates that with an upfront investment in climate change adaptation, the large unpaved network that is vulnerable to climate change can be mitigated and improved.

TABLE 3.3: Provincial Level Annual Avg. Cost, 2050 decade. Median GCM Scenario (50th Percentile)

	Annual avg. cost US$ million No Adapt	Annual avg. cost US$ million Adapt	Adaptive advantage US$ million
Eastern Cape	$ 11.8	$ 6.8	$ 4.9
Gauteng	$ 8.0	$ 5.7	$ 2.2
KwaZulu-Natal	$ 13.2	$ 6.1	$ 7.1
Limpopo	$ 13.6	$ 8.3	$ 5.3
Mpumalanga	$ 8.9	$ 4.4	$ 4.5
North West	$ 13.2	$ 5.5	$ 7.7
Northern Cape	$ 26.4	$10.8	$ 15.6
Orange Free State	$ 13.5	$ 6.0	$ 7.4
Western Cape	$ 7.6	$ 3.7	$ 3.9

FIGURE 3.5: Average Annual Cost by Decade for Median GCM Scenario, Adaptation. Provincial Level Results



Additionally, these results indicate that of the two stressors examined, precipitation and temperature, temperature will have a higher impact. This is seen in provinces such as Gauteng, where the network is mostly paved roads. Because of higher adaptation costs, the adaptive advantage is relatively small (Table 3.3). However, total cost is not the only metric that should be considered when deciding between an Adapt and No adapt policy approach.

Pro-active adaptation strategy minimizes vulnerability of road infrastructure to climate impacts and reduces the need for extra maintenance costs, increased disruption of traffic, and other impacts associated with damages to road infrastructure.

Limitations

The current study is based on several key components which introduce uncertainty into the quantitative analysis within the study. The climate data used for this analysis comes from a collection of 54 different GCMs with acknowledged variability and uncertainty. These projections are also performed at a global scale, which necessitates down-scaling for application to country and region-specific analysis.

Additionally, the study relies on existing material studies to derive the impact stressors. Although the study bases its findings on recognized authorities and studies, the quantitative cost estimates are dependent on the findings from these and similar studies. Issues such as specific, localized pavement types, local conditions, construction, and maintenance techniques can all combine to affect specific cost impacts. Therefore, the quantitative cost results may differ based on alternative studies.

A noted limitation is the lack of discounting used to present final impacts. In this study, it was determined that using constant costs would provide a relative indicator of climate change impacts. From this perspective, the time series are provided to give a representative picture of future climate impacts and costs as they are expected to be incurred. Discount rates provide a realistic economic perspective, but detract from the relative impacts that are being emphasized in the current paper.

Because of data limitations in terms of future climate scenario projections, localized data specific to South Africa, and the scale of the analysis, there are some components not included in the costs analysis of this study. For example, with unpaved road erosion rates, impacts including storm surge, flooding, and specific drainage measures that have been taken beyond the standards used for analysis are not considered. Additionally, flooding is an important factor in understanding damages of climate change, but is not considered in this analysis because of specificity of data required in terms of micro-scale hydrologic modelling and detailed road infrastructure placement data. It is likely that a more detailed and micro-scale analysis including these elements will increase the costs presented in this study.

Discussion and Conclusion

In conclusion, the current study examines the potential effects of climate change on the road infrastructure of South Africa. The study focused on using an engineering approach to determining the specific effects of climate stressors on road surfaces. Based on a combination of actual and estimated totals for each province within South Africa, the study illustrates the variance in provincial effects and focuses on the national level adaptive advantage if a pro-active adapt strategy is taken.

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

The analysis approach utilized in this study is highly replicable for similar studies in other countries. The GCMs used provide climate data on nearly every nation in the world. Because the study is performed at a national and provincial level, the results can highlight areas of vulnerability in need of further study, but not limited by requiring detailed local data such as hydrologic modelling and specific road specifications and locations. The estimates provide an analysis on the climate change impact on road infrastructure and provide a method for a study which produces quantitative results. A similar method has been applied to a four-country study of Asia (Hughes and Chinowsky 2012), and a similar method with more localized data inputs has been used to complete a study on Mozambique (Arndt et al. 2013), Vietnam, and Southern Africa (Chinwosky and Arndt 2012).

CHAPTER 4

SUMMARY OVERVIEW

This chapter represents an updated methodology from Chapter 3 and lays the groundwork for the broader holistic analysis introduced in Chapter 5. This paper won 'Best Paper' in the category of *Climate Change* at the Transportation Research Board Annual Meeting in 2015 and was published in the Transportation Research Record (see below for publication information). The full published article can be found in Appendix IV. No additional text or information is included in the Appendix IV version.

Clarifying note: The early work using IPSS™ referred to two analysis strategies: 'adapt' and 'no adapt'. These correspond directly to the terminology used elsewhere throughout this dissertation as 'proactive adaptation' and 'reactive adaptation', respectively. The reason for the change in terminology was the recognition that the analysis process for 'no adapt/reactive adaptation' was not a true 'no adaptation' scenario (ie: "do nothing"). The analysis process focuses on repairing damages as they occur; not ignoring them.

Overview & Contribution

This paper bridges the gap between the development of a quantitative stressor-response analysis of climate change impacts on road infrastructure (Chapter 3) and the application of a sustainability framework to decision making (Chapter 5). It matures the methodology developed for use in South Africa by using GIS-based input information for more accurate inventory assessment, uses costs specific to the location being studied, and introduces new methods for understanding the results, including box-plot results that show the range of CMIP3 predictions on the network and the mapping of 95th% results for visual information communication. This paper introduces a metric only used in this Chapter; the "Adapt, no climate change" metric. This value is the cost that would be spent on adaptation investments made based on the impacts predicted from the climate models, but then under the reality that no climate change occurs. This represents a 'wasted' money spent value and is included in the analysis to show the potential regret from both a proactive and reactive view.

A focus of this study is to identify specific vulnerabilities of the road network to climate change impacts temporally as well as spatially. It then provides a parallel analysis of adaptation decisions that can reduce the financial costs of climate change throughout the life-cycle of the roads. While this comparison of proactive and reactive adaptation approaches is used in the first paper, the granularity of analysis and results is of a finer resolution in this study, allowing for more localized context. Finally, it introduces the need for broader environmental and social considerations, though they are not assessed in this study.

PUBLICATION

This paper won "Best Paper" in the category of *Climate Change* at the 2015 Transportation Research Board's Annual Meeting (January 2015) and is published in the *Transportation Research Record: Journal of the Transportation Research Board, No. 2532.*

The Transportation Research Record (TRR) is the official publication of the Transportation Research Board (TRB), which is part of the National Academies. All publications in TRR are submitted to the TRB Annual Meeting and then selected for publication in TRR according to procedures approved by the Governing Board of the National Research Council. Usually, less than 20% of submitted papers are accepted for publication each year. TRR is considered one of the most widely distributed and read transportation journals in the world, ranked first in the number of cities distributed, second in Eigenfactor Score, and first in the number of articles. The TRB Annual Meeting occurs each year in Washington, D.C., and covers all transportation modes and inquiries of research. Annual attendance is around 12,000 professionals each year, including policy makers, administrators, practitioners, researchers, government, and industry.

CITATION

Schweikert, A., Espinet, X., Goldstein, S., & Chinowsky, P. (2015). “Resilience versus Risk: Assessing the Cost of Climate Change Adaptation to California’s Transportation System and the City of Sacramento”. *Transportation Research Record: Journal of the Transportation Research Board, No. 2532*: pgs. 13-20. DOI: 10.3141/2532-02

"RESILIENCE VERSUS RISK: ASSESSING THE COST OF CLIMATE CHANGE ADAPTATION TO CALIFORNIA'S TRANSPORTATION SYSTEM AND THE CITY OF SACRAMENTO"

Amy Schweikert, Xavier Espinet, Sara Goldstein, Paul Chinowsky

Submitted 2014, Published 2015

Abstract

Quantitative assessment of the vulnerability, adaptation options, and economic impacts of climate change on road infrastructure is essential to building a more robust and resilient transportation network. To date, most research has focused on qualitative statements and broad findings or on location-specific case studies. This paper details a quantitative, engineering-based analysis of the impacts of specific climate stressors on different types of road infrastructure. The results are designed to be utilized by transportation planners to understand the vulnerability, risk, and adaptation options for creating a climate-resilient road network by providing specific design changes and fiscal cost analysis.

This study aims to build on previous work and address several gaps, including: using all IPCC-approved climate models to provide guidance despite uncertainty; providing results similar to existing risk and vulnerability analyses to allow for implementation in existing planning processes; and introducing a methodology requiring only routinely available road network information to allow for replicability across the US.

The State of California is used as an illustrative case study that helps identify the existing vulnerabilities of the road network to climate change and the fiscal savings possible through proactive adaptation strategies. Findings show that for the higher impact model (95th percentile), California could save $1.9 billion between 2015-2050 by proactive adaptation.

The contribution of this research is to move beyond the identification of vulnerabilities to a quantitative assessment of specific adaptation options that reduce a community or regions vulnerability to climate change.

Introduction

Climate change has been at the forefront of discussions globally since the founding of the United Nations Intergovernmental Panel on Climate Change (IPCC) in 1988. While the early work of the IPCC focused on creating and understanding the science of global climate change and mitigation options, more recently a prominent shift has been made to include vulnerability assessments, adaptation options, and the financing of climate-resilient projects (Arent et al. 2014). The IPCC's Fifth Assessment Report (AR5), concludes that "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased" (IPCC 2013). Increased CO_2 emissions, among other causes of climate change, have triggered real consequences such as hotter summers and changing extreme weather patterns. One element that is particularly susceptible to the effects of climate change is transportation infrastructure (Bollinger et al. 2013; Koetse and Rietveld 2009; Meyer, Amekudzi, and O'Har 2010). Roads serve as a connection for most of the United States' economic and social activity; the risks of climate change to roads threaten the associated economic growth, development, and social welfare benefits of infrastructure expansion (Farrag-Thibault 2014).

The impacts of climate change have exacerbated the existing vulnerabilities of aging US infrastructure. In 2013, America's infrastructure was rated at a D+ by the American Society of Civil Engineers (ASCE) *Report Card for America's Infrastructure* (American Society of Civil Engineers 2015). This projection neglects the effects that climate change poses to existing infrastructure and the unprecedented challenges to future infrastructure viability. Both new and old infrastructure must consider how climate change will increase costs for adaptation, maintenance, and its potential negative impacts on transport networks; accounting for the largest state and national fixed assets (Farrag-Thibault 2014; Keener et al. 2013; Hambly et al. 2013; Sattherthwaite 2009).

Research to date shows that there is a high risk posed from climate change to America's transportation infrastructure (Mallick et al. 2014; Meagher et al. 2012). The challenge facing policy makers is to incorporate scientific information, a range of climate models, and risk assessments into routine decision making. As recognized by the State of Vermont, the best way to address and mitigate climate change risk is to plan and prepare for it (Johnson 2012). For the context of this paper, there are several cities in California who have completed initial assessments to determine potential risks from climate change (Griggs and Russell 2012; Biging, Radke, and Hak Lee 2012). Findings show that planners find value in vulnerability assessments and data for informing decision making, yet there is still a disconnect between science and information accessible with current resources. Tribbia and Moser (2008) present a case study on the State of California and show that political will, better resources, and more accessible information relevant to policy makers' current processes are necessary to fully implement climate change into routine decision making.

This study presents results designed to illustrate the available information for decision making. Results are presented from a tool designed for addressing many of these needs. Developed by the authors, the Infrastructure Planning Support System (IPSS™) is an engineering-based tool which uses a stressor-response methodology to determine the impacts of specific climate stressors on infrastructure. This study focuses on the impacts of incremental impacts (daily precipitation and temperature) on existing road infrastructure. Results are shown for the 2015-2050 time period. A proactive adaptation strategy is compared with a no-adapt reactive approach. Analysis is done for 54 available climate models approved by the IPCC. Both approaches are compared to a baseline no climate change scenario. Results are given for three specific climate scenarios representing approximately the 5th, 50th, and 95th percentiles of impact. Results are presented in terms of annual fiscal costs for the State of California and the City of Sacramento. Additionally, for the City of Sacramento, results are presented alongside additional key infrastructure including schools, libraries, hospitals, and rail infrastructure. This is designed to help contextualize the results from road infrastructure to integrate into the larger urban planning process and prioritize investment decisions. California was chosen because of existing work identifying climate change vulnerability, the extensive transportation network, open-source data availability, and diverse geography allowing for more readily applicable results to other contexts.

Background

The US is beginning to realize the potentially severe and detrimental impacts climate change may have on current and future transportation infrastructure. The challenge lies in identifying the risk and implementing specific actions to adapt. In an effort to begin countering the effects of climate change, the US has adopted a *Commitment to Act* policy as part of the outcome of the Climate Change Action Plan (CCAP). According to CCAP as presented in 2013, the Federal government will "work with state and local governments to prepare for the unavoidable impacts of climate change" (US Department of State 2014). Much of the responsibility relays upon the state and local governments to implement climate change policies and practices and begin to counteract the effects of climate change.

According to the National Climate Assessment, public and private sector reactions to climate change have been to plan for future adaptations projects. However, many of these plans have yet to see large scale implementation, leaving the US behind in climate change adaptation (Melillo, Richmond, and Yohe 2014). As a first step, the Federal Highway Administration (FHWA) has developed a report outlining steps for agencies to begin incorporating climate change concerns into infrastructure planning. In this FHWA report, a seven-step process was outlined on how new infrastructure plans can incorporate the effects of climate changes. This outline includes steps to recognize the role of climate change in infrastructure management, coordinate with other organizations on methods to deal with climate change, and integrating land and funding challenges. The report, while giving guidelines on how to plan, stops short of specifying specific quantitative measures to help recognize when climate change will have an effect or how much potential changes in climate will cost the infrastructure improvements (ICF International 2008; Agarwal, Maze, and Souleyrette 2005). Additional research finds specific vulnerability to climate change for four sites in New England, but acknowledges a need for greater geographic scalability, increased number of climate models, and a need to continue to quantify the uncertainty to increase decision-makers' capability to incorporate climate concerns (Meagher et al. 2012).

The State of California has recognized the condition of their current transportation infrastructure and potential effects climate change will play in future infrastructure developments. California's Department of Transportation acknowledges the cost to fix the transportation system keeps increasing, while increased traffic incessantly wears down their existing roadways (California Transportation Commission 2011). Multiple agencies, including the California Environmental Protection Agency, provide information about the current and future impacts of climate change. This data is passed on to law makers; but many reports neglect the specific impacts and actions that decision makers can take to mitigate the impact climate change will have on California's infrastructure. California's transportation system has already felt the effects of climate change with the increase of extreme weather events (duVair, Wickizer, and Burer 2003). While California has been on the forefront of many advancements in climate change policy and programs, the incorporation of climate change as a concern for transportation planning still receives little attention in terms of influencing the implementation of infrastructure projects (van den Berg 2013).

In an effort to help policy makers and planners incorporate climate change impacts into transportation and wider decision making, some tools have been developed for use. Notably, the Climate Change Adaptation Tool for Transportation (CCATT) is designed to help assess climate change and transportation. However, as a barrier to routine use, CCATT requires detailed input from local administrators, making its ease of use and implementation difficult for common use (Oswald and McNeil 2013). Additionally, the MAGICC/SCENGEN 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 (University Corporation for Atmospheric Research (UCAR) 2007). A few previous studies estimate the potential impact of climate change on specific case studies, but acknowledge that more climate change models are needed to more fully understand the potential impacts and uncertainties (Meagher et al. 2012; Mallick et al. 2014). Lu and Peng (2011) focus on identification of critical sections of the transport network, and note that proactive measures in transportation planning and engineering should be taken, including vulnerability analysis of the network, but fail to suggest actionable adaptation options.

Methodology

This study utilizes a methodology with three phases for California and a fourth phase of analysis for the City of Sacramento. The first phase is to collect the input data used in the analysis. The second phase is analyzing the impact of climate change on the road infrastructure network obtained in phase one. This second phase is done using an analysis tool developed by the authors, the Infrastructure Planning Support System (IPSS™). The third phase is analyzing the results produced by IPSS™ for the State of California and for the City of Sacramento. This phase utilizes data from a range of climate models from 2015-2050 and compares a proactive adaptation strategy with a reactive 'no adapt' policy. Results are presented in terms of economic cost based on construction and maintenance needs. A fourth phase, a criticality analysis and specific application to policy makers, is applied only to the City of Sacramento because of the detailed information utilized to do the analysis.

The first phase requires obtaining road inventory for the State of California and the City of Sacramento. An open-source database of the existing road network was processed using geographic information systems (GIS) (2013 TIGER/Line Shapefiles: Roads, U.S. Census Bureau, Geography Division 2014; "Hospital; Light Rail; Schools" 2014). Further, this information was sorted for analysis based upon common definitions of road surface and attributes. Nine types of roads were used in this study: paved, gravel and unpaved road surface types and attributes common to primary, secondary, and tertiary networks. No freeways were analyzed in this study. The total network analyzed in this study includes 36,255 miles of total roads, including approximately 24,600 paved roads. This data was analyzed at the county level for California and the City boundaries for Sacramento.

Second, the IPSS™ system was used to analyze the impact of climate change on the road network. The IPSS™ software provides annual cost estimates of the impact of climate change on road and building infrastructure on an annual basis through 2100. A range of climate models are combined with infrastructure inventory and engineering-based stressor-response equations to determine the impact of both extreme events (ex: flooding) and incremental climate changes (ex: precipitation and temperature) on specific infrastructure elements. The system identifies the financial cost on a yearly basis and allows users to compare proactive adaptation measures with reactive non-adaptation measures; both of which are compared to a baseline 'no climate change' scenario.

To model future changes in climate, IPSS™ uses 54 different AR4 GCMs (general circulation models) to obtain the predicted future values of 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) (UEA 2013; Schlosser, A. et al. 2011).

IPSS™ analysis is done in terms of a proactive adaptation strategy and a reactive 'no adapt' policy. Both are analyzed with the baseline goal of retaining the original design life of the infrastructure despite changes in climate stress. This approach follows previous work that finds climate change causes a significant change in deterioration of roads and "work is needed to improve…design and construction…to make pavements more resistant to the effects of climate change." (Mallick et al. 2014). For the reactive 'no adapt' approach, costs are based upon increased frequency and severity of maintenance required to fix climate-related damages. For the proactive adaptation strategy ("Adapt"), costs are based upon the increased cost of construction to account for climate-related damages over the lifespan of the infrastructure as well as the maintenance costs from road inventory which has not yet been adapted. For this study, adaptation rates are set at 5% of the roadstock inventory annually to reflect a distribution of the age of the roadstock. Additionally, an adaptation strategy where no climate change occurs ("Adapt no CC") is presented. These costs are based upon an adaptation strategy projected by the GCM model, where then no climate change occurs. This shows the 'wasted' cost of adaptation spent and is provided as a comparison model to understand the potential financial regret if the historical climate occurs despite projections by the climate models.

Adaptation is defined for the IPSS™-based analysis as a road where design changes have been made to withstand projected changes in temperature and precipitation throughout the life-cycle of the road. For example, where heat is expected to increase, the asphalt binder properties are adjusted according to existing standards. For this study, this applies the *Superpave* increments of pavement temperature, traffic, and cost, among other variables (Transportation Research Board 2005). When pavement temperature is predicted to increase above a threshold, the mix is adjusted to withstand increased heat and avoid degradation costs. In this example, the reactive calculation is the increased maintenance costs required to repair the degradation and performance failure due to increased heat stress.

IPSS™ predicts the impact of the climate change stressor on the road inventory by using engineering based stressor-response equations. 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. Impacts are determined for each type of road (paved, gravel, earth and primary, secondary, tertiary) and assessed per kilometer of road. The change in asphalt binder described above is one example of the stressor-response approach. All the specific road type response equations, thresholds and methodologies are detailed in previous work (Schweikert et al. 2014; P. Chinowsky and Arndt 2012; P. S. Chinowsky, Price, and Neumann 2013; P. Chinowsky et al. 2013; P. Chinowsky et al. 2011). They have also been used in international climate studies including a study for the Asian Development Bank (Westphal, Hughes, and Brommelhorster 2013), the European Union (Nemry and Demirel 2012) and Canada (Industrial Economics 2012).

The third phase of this study is focused on analyzing the results produced by IPSS™. The large amount of data produced must be filtered to help create 'usable science' - information about climate change that can be incorporated into existing decision strategies. Therefore, this phase is critical to the usefulness of the IPSS™ tool and study results. For this study, results from three specific climate models are presented for California and Sacramento: a low-end projection (5^{th} percentile) the median (50^{th} percentile) and a high end model (the 95^{th} percentile), based on the total cost through 2050 predicted by each of the models. The *reactive*, *adapt*, and *adapt without climate change* results are presented for each.

For the City of Sacramento, a fourth analysis phase is utilized to provide a more detailed example of how this information can be used to inform decision-making and risk management. A criticality analysis is done to identify key routes and costs associated with road infrastructure that is determined to be highest priority. These results are shown in terms of mapping key assets, costs of adapting portions of the road network, and risks associated with not adapting in terms of total costs. For this analysis, additional infrastructure is incorporated including public schools, bridges which cross waterways, libraries, hospitals, and airports ("Hospital; Light Rail; Schools" 2014). These assets were selected because they play key roles in community activity and resilience, both on a daily basis and in times of weather-related emergencies (Cutter et al. 2009; Thomalla et al. 2006). GIS is utilized to display the information alongside climate change cost estimates to highlight the large amount of data that can be visually displayed and utilized in the decision process (Wu et al. 2013).

Results

State of California

Vulnerability Assessment & Adaptation Options

The current road inventory for California was used to analyze the risk of climate change impacts through 2050. These costs are modeled using the IPSS™ system to determine the impacts of changing future climate on existing inventory. Figure 4.1 shows the projected changes in precipitation and temperature compared to the historic baseline.

FIGURE 4.1: Projected changes in precipitation (left, in millimeters) and temperature (right, in Celsius) based on 95th percentile GCM in the year 2050 as compared to historical baseline averages. Results presented at CRU level.

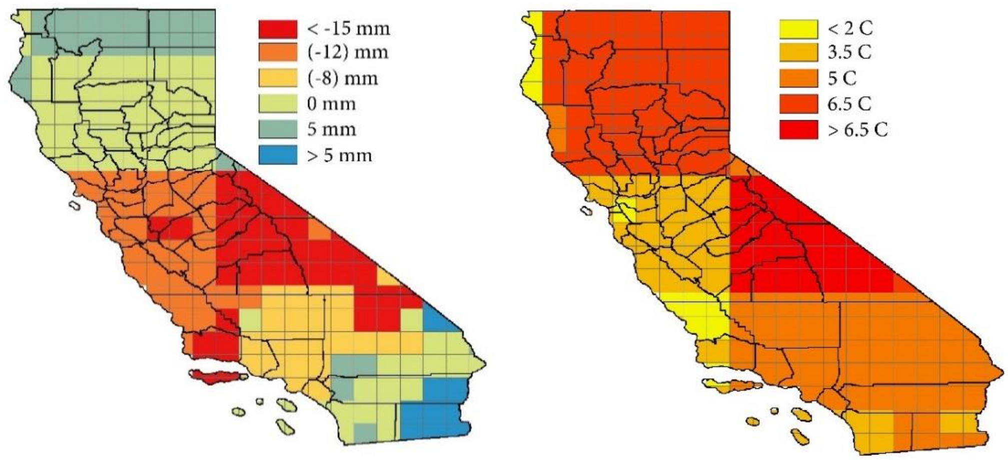
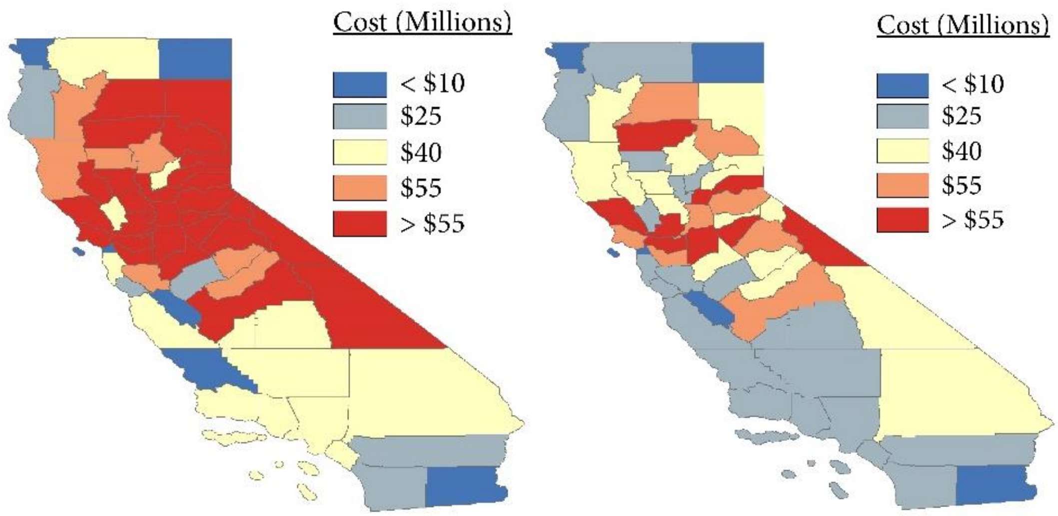


Table 4.1 presents the total costs for California based upon the GCM model utilized. Since all models are equally unlikely to occur, three models were selected to provide policy makers with a concise overview of possible risk information. The range of costs for California is large, with the minimal risk (5th percentile) reactive cost at $593 million dollars and the higher end (95th) at over $3.6 billion. However, across all models, the Adapt scenario presents significantly lower costs for the time period with a range of $405 million to $1.7 billion. The risk of adaptation is relatively low, for even if climate change does not occur, the costs are between $326 and $430 million ('adapt no climate change').

While there is a small fiscal benefit from adaptation, there are additional benefits including less maintenance, less traffic interruptions, and an overall more reliable and robust road infrastructure system.

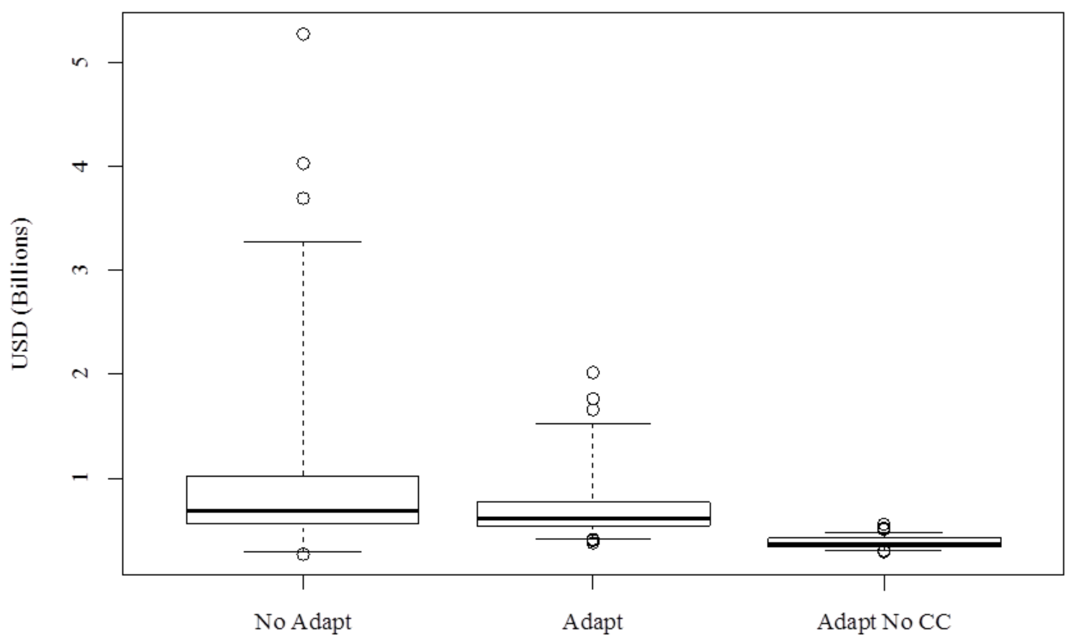
FIGURE 4.2: County level vulnerability to climate change in 2050, based on average annual cost 2015-2050 for 95th percentile GCM results. Left graphic shows cost based on Reactive Policy; Right graphic shows costs for proactive “adapt” policy. Costs overall are reduced by approximately $1.7 billion with proactive adaptation policy.



Risk Assessment

Another way to assess the risk posed by future climate change is to understand the potential damages projected by the entire range of models. Figure 4.3 shows a box plot graphic with results from the full range of 54 climate models run for California. The graph shows the range of cost projections based upon three policy scenarios: proactive adaptation, reactive no adaptation, and adaptation where no climate change occurs. The whisker edges show the costs for the 95th and 5th percentile boundaries, the box edges show the costs for the 75th and 25th percentiles, and the black line in the middle of the box represents the median GCM cost. The graphic clearly shows that while the medians for the three policy approaches are not vastly different, the risk is severely enhanced with a reactive approach, with whiskers and outliers spanning a range greater than $4 billion USD. The risk is much lower with an adapt approach, where the maximum cost is just over $2 billion with the 75th percentile falling around $700 million. Additionally, if a proactive adaptation approach is taken and climate change does not occur, the range of costs is much lower with a maximum cost under $600 million total.

FIGURE 4.3: Box and whisker plot detailing the total range of costs from 54 IPCC-approved GCM models. Results represent three policy choices: reactive, proactive adaptation, and adaptation where no climate change occurs. Costs are total cumulative costs for 2015-2050 based on existing road infrastructure for the State of California.



City of Sacramento

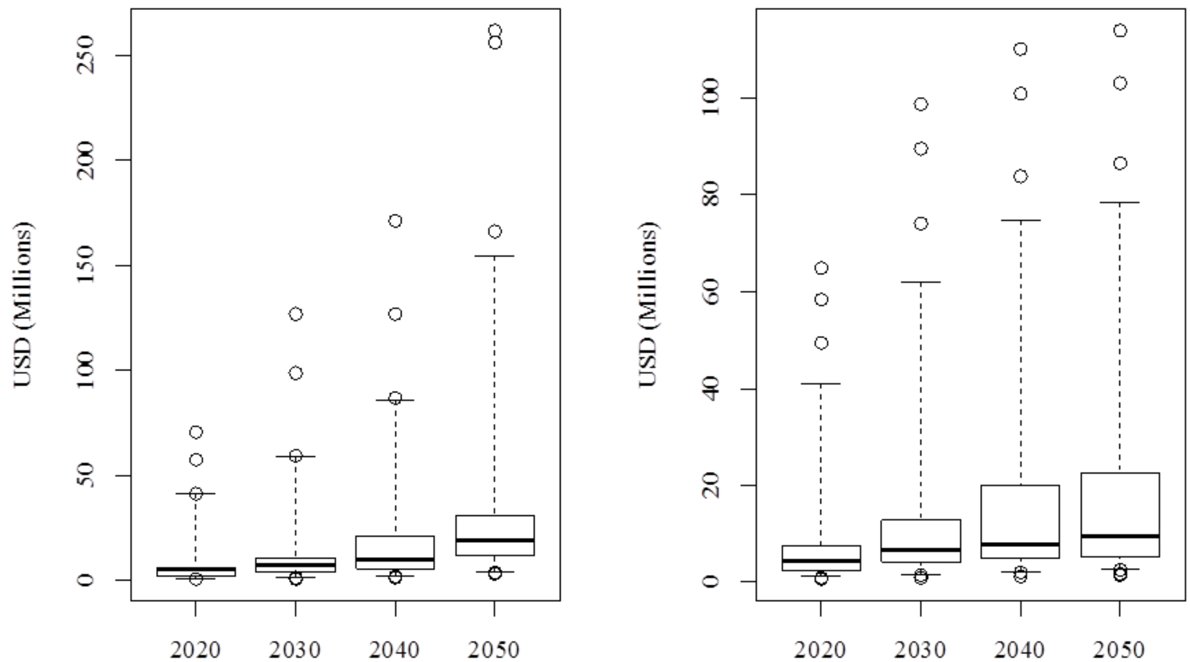
An analysis for the City of Sacramento included applying the specific impacts of climate change models for the geographic region of the city. Therefore, different climate models respective to the costs associated with the City of Sacramento were utilized. The median GCM projected approximately a 2 degree Celsius increase in temperature by 2050, while the 95th percentile projects an increase of over 4 degrees Celsius. Because of the urban nature of Sacramento, most roads are paved. The major impact on paved roads is temperature, therefore this accounts for the majority of costs. In all scenarios, adaptation to climate change is highly beneficial, with margins of economic benefit much higher than the results for the State of California: For the 95th percentile, a savings of over $152 million is possible by adapting, while if adaptation is done and climate change does not occur, the total extra cost is $12 million for the same time period and model (Table 4.1). Because adaptation takes place over time as roads are rehabilitated, the difference in cost is due to increased climate stress before adaptation of a road is completed.

TABLE 4.1: Costs of climate change impact on road infrastructure. 2015-2050 cumulative costs. Based on existing infrastructure. Results in USD Million.

	California				**Sacramento**		
	95th	**50th**	**5th**		**95th**	**50th**	**5th**
Reactive	$ 3,693	$ 627	$ 593		$ 262	$ 19	$ 5
Adapt	$ 1,758	$ 584	$ 405		$ 103	$ 9	$ 3
Adapt No CC	$ 430	$ 338	$ 326		$ 12	$ 2	$ 1

The range of costs is reflected in Figure 4.4: A box and whisker diagram shows the range of costs by decade for all 54 GCMs. The whiskers incorporate the 95th to 5th percentiles, the box edges represent 75th and 25th model cost projections and the black line represents the median GCM. The variability increases over time. It is highly notable that the Adapt policy sees a logarithmic increase in cost over time while the reactive policy sees an exponential increase in costs over time. This shows an increase in risk margin over time for a reactive policy.

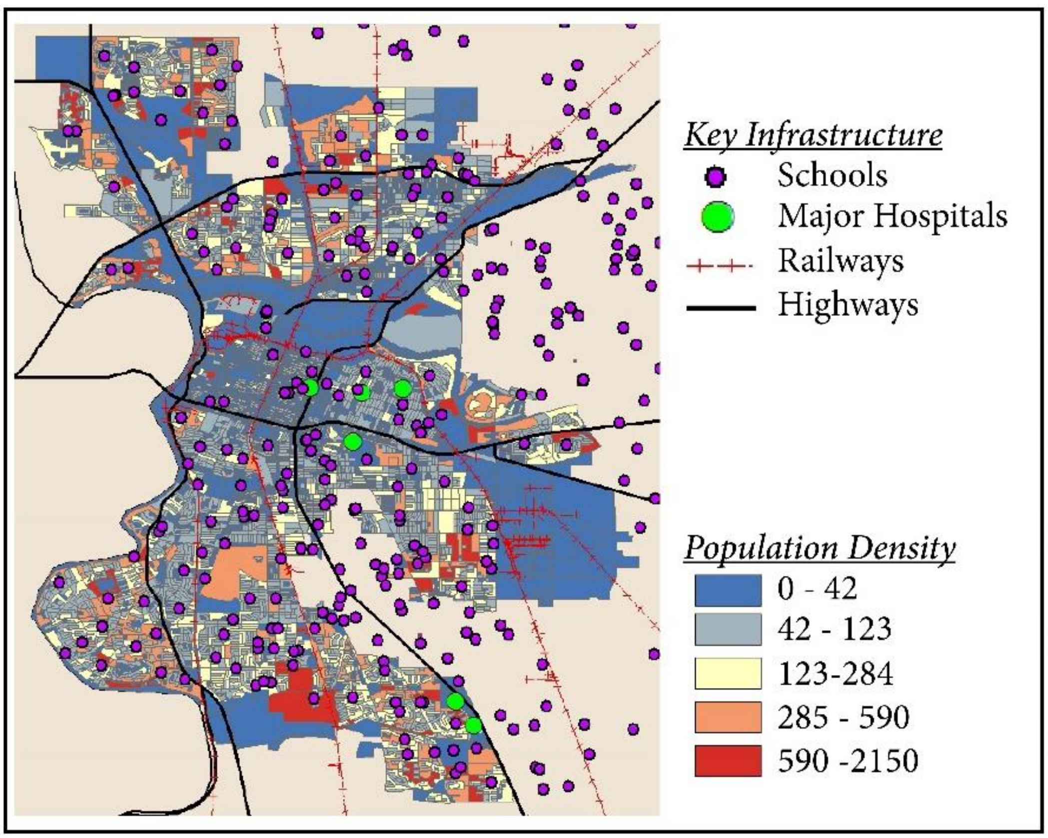
FIGURE 4.4: A box and whisker plot detailing total costs for City of Sacramento. The impacts of climate change are based on 54 IPCC-approved GCM models. Results presented as average annual cost per decade for two policy approaches: Proactive adaptation (Right) and reactive no adapt (Left). Note differences in scale (All costs in USD Million, present dollars)



Criticality of Roads and Other Infrastructure

Roads exist for community use, economic and social activity and are vital in emergency situations. For an urban setting, the maintenance and expansion of roads is one of many competing priorities for growth and resilience. For the City of Sacramento, climate change poses potentially high costs if not addressed proactively. However, where budget and time constraints limit the investment potential, prioritizing investments based on community use, criticality, and other factors is important (Hunt, and Watkiss 2010; Johnson 2012). As a segue to an important discussion, Figure 5 is presented as an example of the types of infrastructure that can be considered alongside roads to determine criticality of investment for climate resilience. Key highways are marked in black, with hospitals in green and schools in purple. Additionally, a population density map is provided to give an idea of the number of persons dependent on different neighborhood roads based on their home locations. For example, near the center of this graphic there is a small area with four major hospitals, the intersection of two major highways and a rail line. This area may be a key priority for investment based on traffic patterns and criticality. Assessing their resilience to climate related incidents is an important next step.

FIGURE 4.5: Map of the City of Sacramento including key infrastructure, roadways, and population density.



Limitations

This study is designed as a state-wide assessment of the vulnerability, adaptation options, and cost-benefit analysis of the existing road network of California to the impacts of climate change through 2050. There are several limitations to the current approach. A main source of uncertainty comes from the data used for analysis. Inherently, future climate modeling is uncertain (Arent et al. 2014; IPCC 2013). However, the authors seek to reduce this risk as much as possible by utilizing all available models that are approved by the IPCC to provide a range of analysis for future climate changes.

Additionally, a limitation of the modeling approach used is the assumption of 'perfect foresight' for adaptation. The approach used in this study posits that adaptation is done at the time of re-construction to account for all climate-related damages throughout the lifetime of the infrastructure. It is highly unlikely that the projected changes will occur exactly as modeled.

A final key limitation of this study is that analysis was limited to looking at incremental changes in climate (precipitation and temperature) on existing road infrastructure. It therefore does not account for sea level rise, flooding, other extreme events, and growth of infrastructure. While all of these are within the capabilities of the IPSS™ tool to analyze, the scope of this study as well as the available input data limited the study.

Discussion and Conclusion

Climate change has the potential to severely damage existing road infrastructure and place constraints on the resources available to address future projects. Policy makers and planners are aware of this situation, yet face limited tools and knowledge that are readily available to assist in allocating resources and planning for a changing climate that are needed today. This paper presents a quantitative example of the costs of climate change to the State of California's road network through 2050 using all available IPCC-approved AR4 climate models. Instead of selecting only a narrow range of models or prescribing general guidelines, the IPSS™ tool utilized presents a range of all available climate models and specific impact guidance based on yearly economic costs.

This study has several implications for the wider US transportation system. Particularly, the IPSS™ tool and methodology used are applicable to any geographic region. There are several similarities between the California road network analyzed and infrastructure in other US States; for example, the *Superpave* asphalt standard is widely used throughout the US. Information from these design standards are included in the impact analysis. Additionally, while specific impacts of climate change are calculated using available information about the construction of California's road network (including historical climate data), these inputs are flexible and can be adjusted to meet the specific requirements of planners in any geographic area. Finally, this study illustrates that even with (or perhaps, particularly with) a large transportation network recognized as vulnerable to climate change impacts, a proactive approach to planning and addressing climate change is a fiscally responsible undertaking. Costs are expected to increase significantly and non-linearly in the future; highlighting the need for proactive planning (Mallick et al. 2014).

Additionally, this study addresses existing gaps in literature including: a methodology applicable to a wide geographic area; input data readily available for most US States, allowing for potential replicability; a move away from 'static' and 'stationary' engineering planning that relies only on historical performance data; and quantifying impacts and uncertainty to provide a foundation to move forward. The methodology additionally incorporates vulnerability, adaptation, and risk assessment, which are commonly used in transportation decisions, making it readily available for incorporation into existing decision processes (Hunt, and Watkiss 2010).

The need to incorporate future climate changes is important. It is critical to understand the cost-benefit of adaptation when compared with a reactive strategy. In all models used in this paper, California and the City of Sacramento can save significant amounts of money, as well as side benefits such as increased resilience to extreme events and more resilient infrastructure, by adapting proactively. For the higher end scenarios (95^{th} percentile), California can save nearly $1.7 billion between 2015-2050 by adaptation; a median scenario provides a savings of $43 million and the 5^{th} percentile has a savings of approximately $188 million.

This paper also seeks to comment on a major uncertainty of climate change: what if an adaptation scenario is chosen, yet climate change does not occur as expected? While this question remains impossible to fully answer, this paper provides a beginning approach to addressing the issue by providing quantitative information to assess the potential risk. The "adaptation with no climate change" value provides the amount of money that would be 'wasted' if proactive adaptation strategy is followed, yet no climate change occurs.

The IPSS™ system used to analyze climate provides a step forward in understanding risk, adaptation options, and assessing the vulnerabilities of infrastructure to climate change. By continuing to include the latest models and partner with decision-making institutions, the tool can continually enhance the ability of planners to incorporate accessible, quantitative information in their decision processes. This is an important step in creating a more robust and resilient transportation system for the United States and the world.

CHAPTER 5

OVERVIEW & CONTRIBUTION

Sustainability as a concept is growing in popularity. This provides an opportunity to enhance the decision making process with a broader, explicit incorporation of sustainability concerns, including social vulnerability and environmental impacts. The paper is designed to provide a case study as a proof-of-concept for the applicability of existing knowledge to augment the capacity of decision makers. Building on previous work presented in Chapters 2 and 3, this Chapter takes the unique technical analysis of proactive and reactive investment in road infrastructure under climate change as one of three pillars used in the decision process. It adds a method for analyzing social vulnerability to climate change as well as the quantification of greenhouse gas emissions from the proactive decision perspective.

Specifically, this study analyzes the impacts of climate change from a recognized sustainability framework, the triple bottom line (TBL). This means that climate change impacts are analyzed individually for economic, social, and environmental perspectives. The framework is applied to the Sacramento, California region and focuses on the SACOG transportation planning area. Using GIS, this paper illustrates how a quantitative approach to sustainable planning under climate change can be incorporated to prioritize road infrastructure investments. It is designed to provide a basis for effective, focused discussion on the improvement and availability of techniques to inform climate change planning. There are many areas where increased data availability, local knowledge and prioritization, and incorporation with broader policy considerations can improve this approach. This model is designed to be iterative, with feedback and discussion informing the future work of sustainable infrastructure planning under climate change.

Publication (Submitted)

This paper was submitted to the Transportation Research Board's 2016 Annual Meeting in the category of Society under a call for The Triple Bottom Line.

The Transportation Research Record (TRR) is the official publication of the Transportation Research Board (TRB), which is part of the National Academies. All publications in TRR are submitted to the TRB Annual Meeting and then selected for publication in TRR according to procedures approved by the Governing Board of the National Research Council. Usually, fewer than 20% of submitted papers are accepted for publication each year. TRR is considered one of the most widely distributed and read transportation journals in the world, ranked first in the number of cities distributed, second in Eigenfactor Score, and first in the number of articles. The TRB Annual Meeting occurs each year in Washington, D.C., and covers all transportation modes and inquiries of research. Annual attendance is around 12,000 professionals each year, including policy makers, administrators, practitioners, researchers, government, and industry.

Citation

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"THE TRIPLE BOTTOM LINE: BRINGING A SUSTAINABILITY FRAMEWORK TO PRIORITIZE CLIMATE CHANGE INVESTMENTS FOR INFRASTRUCTURE PLANNING"

Amy Schweikert, Paul Chinowsky, Xavier Espinet

Submitted: 7/30/2015

Abstract

Climate change is an increasing concern of agencies, governments, and societies around the world. It poses potential adverse impacts to civil infrastructure, with consequences that include increased financial resources, economic impacts, social impacts, and planning issues. This paper aims to enhance and broaden the discussion on sustainability and the importance of the consideration of social, environmental, and technical aspects in relation to infrastructure planning. Particularly under climate change, these considerations allow for more holistic, effective, and long-term benefits to communities and economies. This paper introduces the Triple Bottom Line (TBL) approach to sustainability as a framework for holistic infrastructure planning under the uncertainty of climate change. The Technical Pillar will focus on the impacts of climate change on road infrastructure and the cost-benefit of potential adaptation options; Environmental considerations include quantifying the potential increase in GHG emissions from increased roadworks required by climate change damages; and social information

will be quantified using an index based upon the SoVI method. Each of these 'pillars' of sustainability will be analyzed individually and mapped using Geographic Information Systems (GIS). Finally, a 'holistic' approach will be discussed where these individual layers are combined using GIS to display the information. A case study focused on the Sacramento Region of California is used as a proof-of-concept for how the triple bottom line framework introduced here can be utilized to provide actionable, more equitable decision-making for investment in critical infrastructure adaptation policy.

Introduction

The growing awareness of the impacts of climate change, particularly on the built environment and the consequential implications for society, calls for more robust and quantitative means of measuring impacts and planning for the future. However, without even considering future changes in climate, policy makers, researchers, and citizens alike recognize that there are gaps in society's ability to fully address issues of social inequality, degrading infrastructure, and increased greenhouse gas emissions, among many other issues. While climate change does not pose many wholly new problems, it does compound existing issues with new questions of temporal elements, higher levels of uncertainty, and an increased urgency to address vulnerabilities that will be further exploited by a changing future climate.

Work focused on sustainability science provides a useful context for evaluating and addressing many cross-disciplinary, complex issues. Particularly, the use of a *triple bottom line* ("TBL") (also referred to as *P3* or *three-pillar model*) explicitly focuses on three areas which, while interconnected in reality, are often treated separately in academic literature and practice: "*social*, *environmental*, *and economic*" or "*people, profit, and planet*" (Kajikawa 2008; Zimmerman 2005). Each of these sectors has traditional disciplines which are focused on addressing both historical and climate-change related issues to sustainability. It is in the combination, however, where actionable solutions are likely to be found, particularly when there are competing interests and needs at the policy level.

Specifically in response to the awareness of the need for better information about what climate change may mean for planners, several states, cities, and agencies have created documents calling for better information about climate change specific to their interest areas. The U.S. Environmental Protection Agency (EPA) has recently released a report: "Climate Change in the United States: Benefits of Global Action" (also referred to as the "CIRA" Report), which highlights many of the domain-specific and broader impacts of climate change on infrastructure and society (U.S. Environmental Protection Agency 2015). Related to infrastructure and social vulnerability, this report specifically uses work focused on how the impacts of sea level rise impacts on coastal areas in the United States and how the impacts are distributed among different levels of equity and vulnerable populations (Martinich et al. 2012). The study determined that it is critical for policy regarding climate change to explicitly incorporate environmental justice concerns that target investments towards vulnerable populations. Another study focuses on the importance of converging the concepts of resilience and sustainability within infrastructure planning because of the relevance of infrastructure to hazard and risk planning, impacts on populations, and the multiple facets of infrastructure planning (Bocchini et al. 2014).

In another example, Tribbia and Moser (2008) review information for coastal managers in California and how climate change is affecting their daily decision-making capacity and focus. Using case study and interview data, they conclude that planners need and will use specific information about social, economic, and environmental concerns of climate to make better development decisions. In the context of urban resilience, Leichenko (2011) states that urban resilience must "focus on enhancing the capacity of cities, infrastructure systems and urban populations and communities to quickly and effectively recover from both natural and human-made hazards….climate change is regarded as one of many threats for urban areas which must build resilience". Additionally, he states that the next generation of urban resilience research must incorporate equity concerns into any resilience strategy.

These papers, among much other recent work, provide a clear call for broader assessment of the nature of sustainability and resilience. In relation to infrastructure planning, this relates directly to the current focus on creating more sustainable and resilient 'critical infrastructure'; of which road transportation networks play a substantial role (US DHS, n.d.; Berdica 2002; Moteff and Parfomak 2004; Taylor and D'Este 2007; Tyler and Moench 2012). The triple bottom line and sustainability framework provide a useful method for combining many aspects related to infrastructure planning.

Therefore, this paper aims to enhance and broaden the discussion on sustainability and the importance of the consideration of social, environmental, and technical aspects in relation to infrastructure planning. Particularly under climate change, these considerations allow for more holistic, effective, and long-term benefits to communities and economies.

Specifically, the triple bottom line framework will be used: technical information will focus on the impacts of climate change on road infrastructure and the cost-benefit of potential adaptation options; environmental information will quantify the potential increase in GHG emissions from increased roadworks required by climate change damages; and social information will be quantified using an index based upon the SoVI method. Each of these 'pillars' of sustainability will be analyzed individually and mapped using Geographic Information Systems (GIS). Finally, a 'holistic' approach will be discussed where these individual layers are combined using GIS to display the information. A case study is used as a proof-of-concept for how the triple bottom line framework introduced here can be utilized to provide actionable, more equitable decision-making for investment in critical infrastructure adaptation policy.

Background

The domain of sustainability science is focused on studying the trans-disciplinary science and practice of 'sustainability' (Kajikawa 2008; Donella Meadows et al. 1972). The concepts of sustainability and multi-disciplinary thinking first gained notoriety through "Limits to Growth" by Donella Meadows, published in 1972. The concept of sustainability and 'systems' thinking was highlighted as a top priority for science and technology (Meadows et al. 1972).

While the domain has evolved over the last forty years, it has recently gained greater prominence (the journal *Sustainability Science* was first published in 2006). In academia, there are still differing definitions on the characteristics and nature of sustainability science. The Brundtland Report is often referred to as one of the first accepted definitions of sustainability, stating that, "sustainable development … meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). Ostrom et al. (2007) posit that sustainability science is an applied science focused on scientific knowledge obtained from existing disciplines to build capabilities specific to sustainability science. Several publications define sustainability science as an 'area' that brings together different researchers and multidisciplinary perspectives, but not yet a unique and distinct field of research (National Research Council, Policy Division. Board on Sustainable Development 1999; Palmer 2007). Most recently, and following a comprehensive review of sustainability science literature, sustainability science is defined as a distinct discipline that 'arches' over existing disciplines (Kajikawa 2008). In this view, it provides a framework to address issues related to sustainability without severing ties to existing disciplines. Martens (2006) outlines four aspects of sustainable development including intergenerational considerations (analysis considering a time period of at least 25-50 years), multiple levels of scale of analysis (relevant to specific issues being studied), multiple domains (three-pillar concept of integrating multiple perspectives for consideration), and multiple interpretations (each domain has a different view of what sustainable development is and how to achieve it).

Within this definition, sustainability science necessarily covers a wide range of topics. Climate change is one of the most-written about topics, but most work focuses on environmental impacts, mitigation of emissions, and a small amount of work on impacts on the built and human environments (Kajikawa 2008). In relation to climate change, there is a growing recognition that some impacts of climate change are unavoidable, and therefore mitigation measures need to be coupled with vulnerability assessments and adaptation investments to address the changes (Revi and Sattherwaite 2013; Füssel and Klein 2006; Tyler and Moench 2012; Turner, B.L. 2003). In terms of critical infrastructure, this vulnerability has been widely recognized at the policy level, including: within the United States, *The White House Climate Action Plan*(Executive Office of the President 2013), the *Transportation Research Board Special Report 290* (Transportation Research Board 2008), and the *Department of Homeland Security Climate Action Plan* (Department of Homeland Security 2013; US DHS); globally this has been a concern even longer, within development agencies, country governments, and non- and inter-governmental groups all investing to understand vulnerability to climate change and potential investment strategies (Center for Science in the Earth System (The Climate Impacts Group) et al. 2007; Tyler and Moench 2012; Nemry and Demirel 2012; Revi and Sattherwaite 2013).

Especially at the policy level, understanding, planning, and implementing strategies to deal with climate change impacts on critical infrastructure is imperative. From a direct financial impact perspective, unforeseen and/or unbudgeted costs can cripple an economy, particularly at the local level (Department of Homeland Security 2013; Larsen et al. 2008; Bloomberg, Paulson, Jr., and Steyer 2014). These unaddressed impacts can also result in much higher costs of repair and maintenance than are necessary if a proactive, planned adaptation approach is taken: a recent EPA report highlights cost at approximately $4 billion USD annually by 2050 for the US (U.S. Environmental Protection Agency 2015; Neumann et al. 2014). While the direct financial impacts are substantial, the most detrimental costs are incurred indirectly in terms of economic loss due to increased travel time, travel difficulties, and social impacts (Berdica 2002; Dalziell and Nicholson 2001; Füssel and Klein 2006). Loss of critical infrastructure can adversely impact livelihoods, increase cost of transportation of goods, and have ripple effects throughout the economy and society. This is particularly acute if multiple links are lost or are damaged for an extended period of time (Dalziell and Nicholson 2001; Berdica 2002; Füssel and Klein 2006). Climate change directly exacerbates existing vulnerabilities to weather and other events by incrementally degrading the quality of infrastructure. This incremental damage accelerates degradation, making infrastructure more vulnerable to hazardous events than can be modeled based on historic weather and degradation data (Dalziell and Nicholson 2001; Meyer, Amekudzi, and O'Har 2010).

These additional and indirect impacts motivate the consideration of critical infrastructure adaptation within the triple bottom line framework. The three-pillar approach is important because it maintains deep domain expertise within each pillar, but then combines the three for assessment and recommendations based upon results considered in the holistic framework. This is helpful for guiding investments in critical infrastructure in two main ways: first, a sustainability approach inherently introduces a spatial and a temporal aspect for consideration. Road infrastructure is a spatial consideration and exists throughout the world as a means for development, economy, safety, and society. Climate change impacts are temporal, with varying impacts throughout time requiring different reactions and investments throughout the life-cycle. Secondly, climate change planning increases the uncertainty of decision-making, particularly in a technical field where precise historical data which informs design is no longer reliable (Meyer, Amekudzi, and O'Har 2010; Larsen et al. 2008; Koetse and Rietveld 2009;

Department of Homeland Security 2013; Executive Office of the President 2013). Incorporating a more holistic view of vulnerability allows for an expanded set of goals, including an explicit human component (Martens 2006). Additionally, a sustainability approach more definitively considers the necessary components of tradeoffs; between robustness and vulnerability and between costs and benefits (Ostrom, Janssen, and Anderies 2007; Tyler and Moench 2012). With transportation, this is particularly acute: from a criticality perspective, more roads means that there is more robustness if a road fails, but from an environmental perspective, more roads means more pollution and greater greenhouse gas emissions. Acknowledging and addressing these tradeoffs and uncertainties within a more holistic societal framework may create more usable results for decision makers to consider.

The case study utilized in this paper is focused on the Sacramento Area Council of Governments (SACOG), a six-county metropolitan planning group encompassing El Dorado, Placer, Sacramento, Sutter, Yuba and Yolo Counties in Northern California in the United States ("Sacramento Area Council of Governments"). SACOG was selected as a proof-of-concept case study for several reasons, including open-source availability of GIS data of infrastructure in the region and an ongoing 2035 transportation plan that includes the reduction of emissions 16% from vehicles by 2035, consideration of lower-income populations, and broader concerns associated with holistic infrastructure planning (Sacramento Area Council of Governments; "Sacramento Area Council of Governments"; Sacramento Area Council of Governments). There are also currently a number of laws and funding mechanisms in SACOG and California that focus on climate change adaptation, mitigation, and education (Association of Bay Area Governments, Metropolitan

Transportation Commission, Bay Area Air Quality Management District, Bay Conservation and Development Commission 2014; Sacramento Area Council of Governments). Results from this study will be discussed, where relevant, in the context of stated SACOG goals and existing infrastructure.

Methodology

This analysis is based upon a three-pillar analysis with a fourth step of integration. Each pillar is evaluated individually and results are provided in GIS based upon quantitative results. A first step critical to the technical and environmental pillars is climate change information that can be used to determine financial impact of climate change and the environmental impact of increased road repair works.

Climate Change Information

The first phase of this study required obtaining usable climate modeling information for the case study region. The current ensemble of models used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) is known as CMIP5 models ("Coupled Model Intercomparison Project Phase 5") and future climate change is modeled based upon a set of scenarios known as RCPs ("Representative Concentration Pathways"). RCPs are specific scenarios of future climate based upon the approximate total radiative forcing in year 2100 relative to 1750. RCP 4.5 represents a stabilization scenario, where the global mean surface temperature change in the 2050 decade is projected to range from 0.9-2.0˚C compared to 1985-2000 baseline (Stocker et al. 2013). For this analysis, 19 climate models from the RCP4.5 scenario were used based on data provided by the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) 5th phase, accessed from the "*Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections*" archive. The information for this analysis was downscaled using daily bias-correction and constructed analogs (BCCA) techniques (See Appendix I for detailed information on accessing the information and the list of models used) (World Climate Research Programme; U.S. Department of the Interior, Bureau of Reclamation 2013).

The data obtained provides daily precipitation and temperature minimums and maximum values for 1/8° grids for 2016-2050 for the case study area. These data sets were then processed using the IPSS™ software system to provide information specific to the technical and environmental pillar analyses below.

First Pillar: Economic/Technical

The first pillar of analysis for this paper is focused on road infrastructure. This is the most familiar component for transportation planners in terms of quantifying costs of infrastructure construction and maintenance based upon specific climate parameters, engineering materials and design guidebooks, and field tests. However, this pillar is focused specifically on quantifying the potential impacts and adaptation options for road infrastructure from changes in the future climate. For this analysis, this paper builds directly upon previous published work, including Schweikert et al. (2015) published in 94th Annual Transportation Research Record (presented at TRB 94th Annual Meeting in January

2015) (Schweikert et al. 2015). The analysis for quantifying climate changes on road infrastructure is completed using the IPSS™ software tool.

The IPSS™ software is developed by Resilient Analytics and designed to provide annual cost estimates of the impact of climate change on road and building infrastructure on an annual basis through 2100. The climate models described above and the road infrastructure inventory for the SACOG region (Sacramento Area Council of Governments) are used as input information to the IPSS™ system. They are analyzed using engineering-based stressor-response equations to determine the impact of and climate changes (ex: precipitation and temperature) on specific infrastructure elements. The system identifies the financial cost on a yearly basis and allows users to compare proactive adaptation measures with reactive non-adaptation measures; both of which are compared to a baseline 'no climate change' scenario.

The IPSS™ System provides costs on a year basis based upon the modeled impacts from daily climate model data. The 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. Impacts are determined for each type of road (paved, gravel, earth and primary, secondary, tertiary) and assessed per kilometer of road. All the specific road type response equations, thresholds and methodologies are detailed in previous work (Schweikert et al. 2015; Schweikert et al. 2014; Neumann et al. 2014; P. S. Chinowsky, Price, and Neumann 2013; P. Chinowsky et al. 2014; P. Chinowsky and Arndt 2012; P. Chinowsky et al. 2013). They have also been used in international climate studies including a study for the Asian Development Bank

(Westphal, Hughes, and Brommelhorster 2013), the European Union (Nemry and Demirel 2012), and Canada (Industrial Economics 2010).

For this study, the costs are based on comparing two distinct strategies, or policy approaches of proactive and reactive investment for adaptation. The baseline goal is to retain the original design life of the infrastructure despite changes in climate stress. The costs are based upon the increased cost of construction to account for climate-related damages over the lifespan of the infrastructure as well as the maintenance costs from road inventory which has not yet been adapted. Upgrades on the design standards of the roads increase resilience to stressor impacts projected by the climate models to occur in the life-cycle of the road. This proactive adaptation strategy is compared with a reactive strategy where increased climate change stress results in damages to the road requiring an increase in unplanned maintenance and repair works. The resulting value is called the 'adaptive advantage' and reflects the cumulative financial savings from a proactive approach compared to a reactive approach for each model. While no extreme events are considered in this analysis, by proactively investing to improve the baseline level of infrastructure will provide current benefits to withstand extreme weather events (Meyer, Amekudzi, and O'Har 2010).

Second Pillar: Environmental

The environmental pillar of this analysis focuses on the increased greenhouse gas (GHG) emissions necessitated by the increased road maintenance from the impacts of climate change. Estimating GHG emissions associated with road construction, operation and maintenance can be done using a number of techniques. Existing tools include the *Road Construction Model* produced by the Sacramento Air Quality Management District and the *GreenDOT* tool. Both have robust ways of accounting emissions based on various factors associated with road infrastructure. However, it is difficult to isolate emissions related specifically to climate change with these tools. Therefore, the environmental pillar for this analysis is narrowly scoped, focusing specifically on the emissions related to increased material required by increased maintenance and repairs from climate change damages from increased temperature.

A broader accounting of climate change impacts on emissions in future work should include a life-cycle analysis accounting for emissions from equipment used in climate-related repairs, emissions from vehicles caused from increased congestion, and other damages related to climate-induced damages besides cracking due to heat (Walker, Entine, and Kummer 2002; Federal Highway Administration 1999). Additionally, repairs specific to gravel and unpaved roads should be accounted for, particularly in terms of precipitation impacts. Because precipitation changes are negligible in damage calculations in the region being studied and temperature does not have a significant effect on unpaved roads, it was not included in this analysis. The numbers provided by this analysis approach are only a fraction of the total emissions caused by climate change in relation to road infrastructure.

The focus of the environmental pillar is the avoided GHG emissions (measured as tonnes of CO_2) by taking a proactive adaptation approach (conversely, these numbers are also the increased emissions from climate change damages on road infrastructure). While the technical pillar focuses on the adaptation options that can be implemented to increase road resiliency to climate change impacts, the environmental pillar focuses on quantifying the emissions that can be avoided by taking this proactive approach. The potentially-avoided GHG emissions are calculated based upon the increase in required materials to repair roads damaged by increased heat.

The increased necessity for maintenance is calculated using the IPSS™ system. Where damages are projected to occur on the road network due to changes in climate beyond specific thresholds, damages are incurred. For this analysis, the main driver of increased maintenance is from heat increases which cause cracking. The analysis from IPSS™ highlights on a yearly basis where thresholds have been exceeded due to climate change and damage has occurred. Damages are calculated on the 1/8° grid scale and applied to the road infrastructure within that grid.

Cracking is calculated when a threshold for heat is exceeded due to historical baseline comparison. Cracking of asphalt pavement is a common phenomenon and is considered the primary mode of deterioration in pavements (Federal Highway Administration 1999). Because of the growing recognition of the importance of addressing cracks as a preventative maintenance technique, the analysis focuses on repairing cracks on an annual basis when heat impacts occur. The incidence of cracking is estimated based upon the IPSS analysis. The frequency of cracks per kilometer and size of crack is estimated using the PASER and FHWA specifications, particularly focused on transverse cracking caused by heat (US Department of Transportation, Federal Highway Administration 1999; Federal Highway Administration 1999; Walker, Entine, and Kummer 2002). Because specific prediction of exact cracking occurrence is difficult, the cracking estimated to occur from an increase in temperature is approximated to the PASER *level 7* surface rating, where cracking occurs and is addressed through increased frequency of routine sealing procedures (Walker, Entine, and Kummer 2002).

Equations 1 and 2 detail the calculation for required material per kilometer of damage and the GHG emissions from the material. Equations 1 and 2 are performed separately for paved primary roads, paved secondary roads, and paved tertiary road inventory. GHG emissions are based on estimated CO_2 emissions from embodied materials emissions (Gallivan et al. 2010) . The estimated volume of asphalt per volume of repair is estimated using information from the Nebraska Department of Roads specifications for a wearing course of standard construction (Nebraska Department of Roads 2012).

$$M = S * N_l * (C_d * C_w * C_l)$$

(Eq.1)

Where:
M = material required for maintenance
S = severity of surface damage (cracks per mile)
N_l = number of lanes
C_d = crack depth
C_w = crack width
C_l = crack length (based on width of lanes)

$$E_1 = F * (M * N_{d1} * Y)$$

(Eq.2)

Where:
E_1 = total emissions in tons of CO_2
F = tons of CO_2 emissions per m^3 of asphalt repair material
M = required material
N_{d1} = number of damaged kilometers of primary road
Y = number of years damage occurs

These calculations lead to estimated embodied CO_2 from increased repairs due to climate change heat damages on the roads. Table 5.1 lists the estimated tons of CO_2 emissions per kilometer of repair needed.

TABLE 5.1: Est. CO_2 emissions per km repair from material use	
Road Type	Est. Tons of CO_2 per km
Paved Primary	3.46
Paved Secondary	1.76
Paved Tertiary	1.76

Third Pillar: Social

The third pillar for the triple bottom line analysis is the “Social” pillar, or “People” pillar focused specifically on the population within the study area. A fundamental component of social vulnerability is the recognition that within communities, there are different geographically defined areas where sub-populations have different levels of vulnerability that can result in disparity of impact and recovery from hazard events (Cutter et al. 2008). The recognition and identification of these areas is designed to help planners and emergency managers effectively allocate resources and plans to ensure the poorest and most vulnerable populations have their needs met in a hazard situation (Morrow 1999).

The impacts of climate change on issues of social equity, development, and vulnerability are an integral part of climate change literature. Particularly relevant to this proposal is the concept of climate justice, defined as the concept that often those populations being most impacted by climate-change related events are least able to respond and recover (Koko, Van der Geest, Kees, and Kreft, Sonke 2013). The literature states that while this is partially attributable to geographic location, it is also highly impacted by the social factors which allow particular groups to be more susceptible to harm and less able to respond. These factors are often difficult to quantify, but as defined in the section above, this vulnerability includes a lack of access to resources (knowledge, information, and technology); limited access to political power and representation; infrastructure stock, age, density and type; and physical limitations of individuals (including elderly, infirm, disabled, and children) (Cutter, Boruff, and Shirley 2003; Edmonds, Geoff 1998). The recent CIRA Report released by the EPA utilizes many of these concepts in their assessment of coastal populations at risk from sea level rise (U.S. Environmental Protection Agency 2015; Martinich et al. 2012).

For this pillar, the analysis uses a social vulnerability index from an open-source data set provided by the Pacific Institute (Cooley, Heather; Moore, Eli; Heberger, Matthew; Allen, Lucy 2012). It is built on the SoVI model developed by Cutter (1996) which defines 32 distinct variables that contribute to social vulnerability to environmental hazards at a county level throughout the United States (Cutter 1996). Building upon this technique, the Pacific Institute used 19 of the variables determined to be directly related to climate change (specifically focused on heat). These variables are independently assessed for vulnerability at the Census Tract level (United States Census Bureau). Each of the 19 individual variables is scored based upon the most recent available data (most variables use 2010 U.S. Census data), then standardized and ranked using the Z-Score technique to create a vulnerability score (Cooley, Heather; Moore, Eli; Heberger, Matthew; Allen, Lucy 2012).

The vulnerability assessment is treated as static based upon the most recently available data (in most cases, the 2010 Census). While this is a limitation of the study, it is impossible to project trends accurately for the future decades, and a static snapshot used for assessment purposes is consistent with methodologies for assessing integrated stakeholder analysis for large infrastructure projects (Feng et al. 2013). It provides a baseline assessment of vulnerability for this model.

Synthesizing the Triple Bottom Line Approach

The final step in this analysis is to utilize the information from each pillar and synthesize into a single decision making strategy. This illustrative analysis takes a multi-criteria decision approach where each pillar is ranked equally and an additive process is utilized to provide a composite ranking, which is a common process in transportation planning and allows for flexible use by decision makers (Macharis, de Witte, and Ampe 2009; Triantaphyllou and Baig 2005; Macharis, Cathy, and Jeroen Ampe 2007). In reality, this step requires knowledge about local preference and goals and the weighting of the criteria, and these can be incorporated into the final decision process. This process is illustrated below in the Results Section with specific spatial examples for this analysis.

Results

Quantitative results from the three analyses are detailed using GIS. The maps in Figure 5.1 show the priority level for each pillar based upon the quantitative results, with darker colors indicating greater priority. Figure 5.2 details an example of how a multi-criteria approach to decision making using the triple bottom line framework can be spatially expressed to reflect high priority investment areas.

While a total of 19 models were run, the results reflect the outcome from the 95th percentile model to show the higher end impacts from one potential future. These results are based on the IPSS™ analysis for the CNRM_CM5 RCP4.5 model.

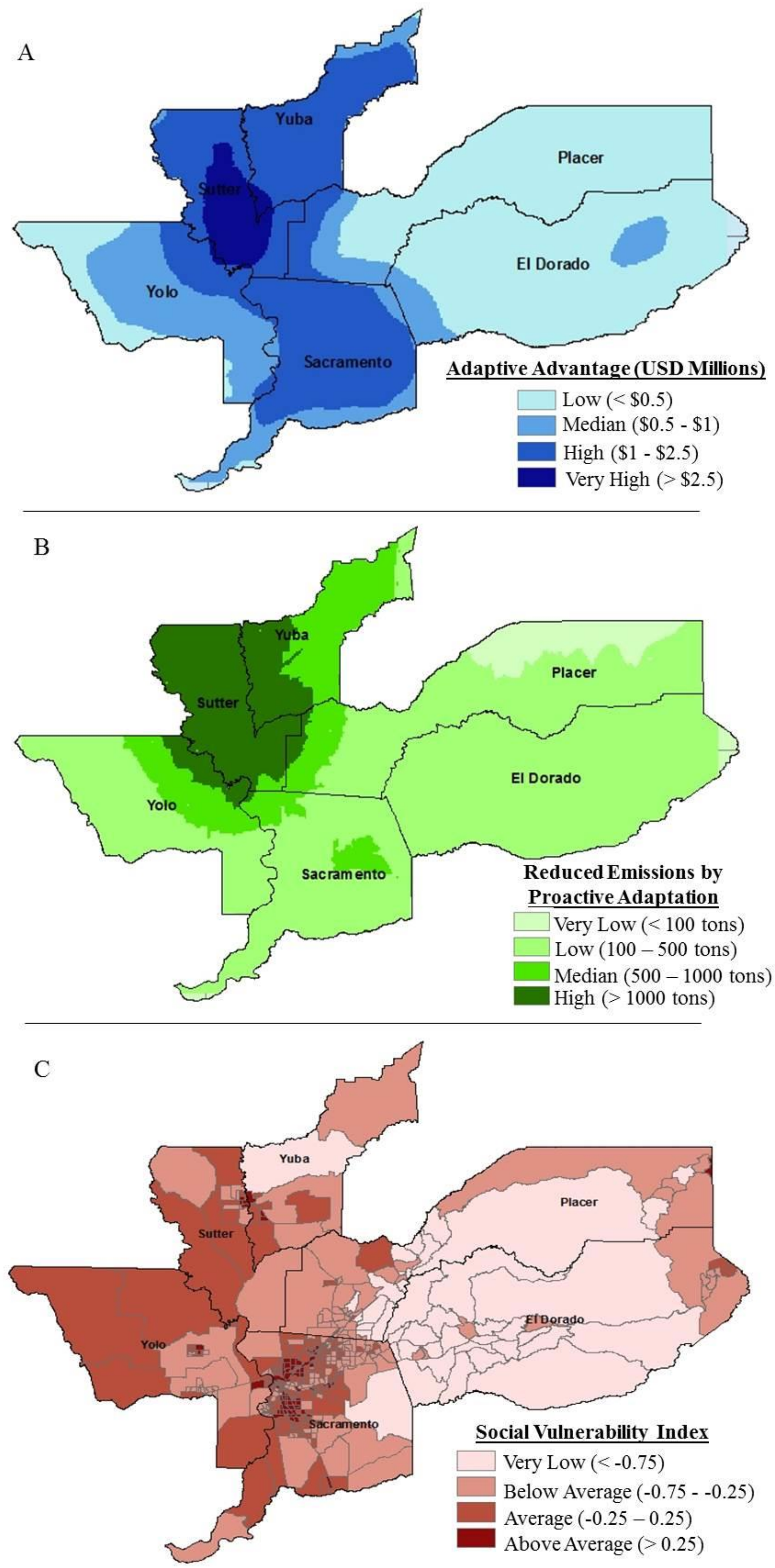
Individual Pillar Results

An individual analysis was performed for each pillar. For the technical and environmental pillars, the annual impacts generated by IPSS™ for the 95th percentile model from the 4.5RCP Scenarios were used. Figure 5.1 reflects the spatial distribution of results in the SACOG Region: 5.1A is the Technical pillar; 5.1B is the Environmental pillar; 5.1C is the Social pillar.

The “adaptive advantage” mapped in Figure 5.1A reflects the cumulative financial savings (2015-2050) from taking a proactive adaptation policy when compared to the cumulative costs of a reactive approach. The “emissions saved” mapped in Figure 5.1B reflects the emissions avoided by taking a proactive approach, based on reduced maintenance requirements from climate change damages required by a reactive approach.

The social vulnerability map in Figure 5.1C reflects 2010 data for vulnerability of populations based on Census tracts.

FIGURE 5.1: Individual Pillar Results for SACOG Region. Maps A and B reflect results from the 95th% GCM scenario for RCP4.5 based on cumulative impacts 2015-2050. Figure 1A is the Technical Pillar, Figure 1B reflects the Environmental Pillar, and Figure 1C is the Social Vulnerability Results

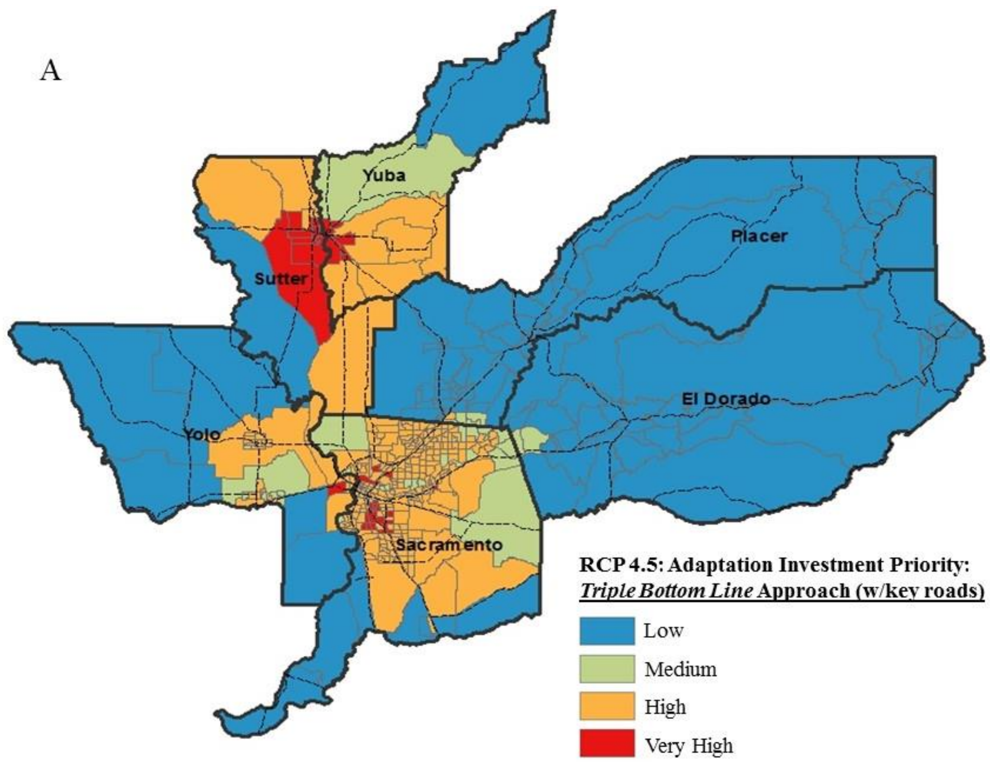


Triple Bottom Line Results: Prioritization

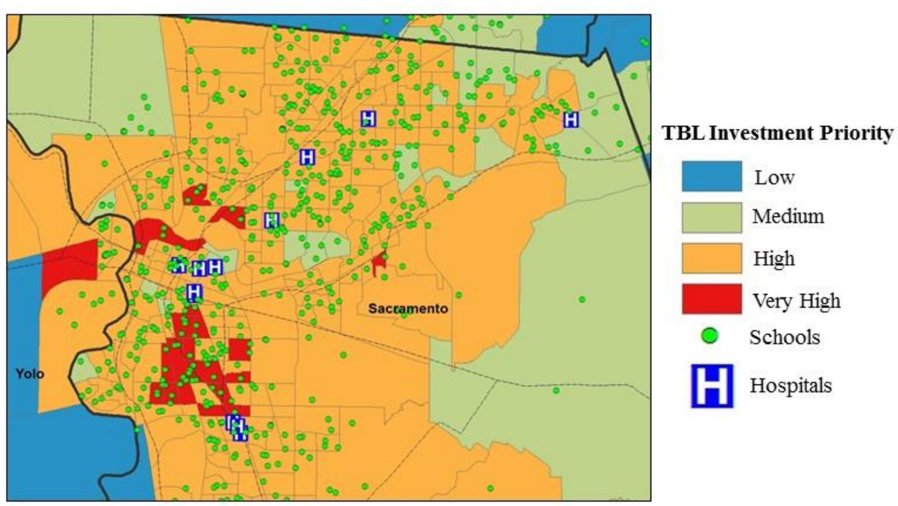
Combining the quantitative results from each pillar above and ranking the census tracts (as the lowest level of analysis) for investment priority is based on a multi-criteria approach and equally-weighted ranking of the three factors (Figure 5.1A). A 'Very High' ranking means that at least two of the three pillars have 'high' rankings for prioritization for proactive adaptation investment: indicating that at least 500 tonnes CO_2 are saved; greater than $2.5 million USD are saved; and investments occur in geographic areas where population vulnerability is above 0.5. For 'low' rankings, at least two pillars have 'low' prioritization rankings: less than 100 tonnes of CO_2 emissions avoided; less than $0.5 million USD saved; with investments occurring in areas with a less vulnerable population below -0.5.

FIGURE 5.2: "Triple Bottom Line Prioritization" – Investment priority for SACOG Region based on three-pillar TBL analysis. Cumulative climate change impacts at 2050 for 95th% model, RCP 4.5. Results displayed at Census Tracts, the lowest geographic unit of analysis

A



B



The areas around Yuba City indicate highest priority investment based on TBL prioritization. This is due to very high impacts of climate change in this region, indicating high levels of financial savings and emissions reduction if proactive adaptation is taken. Sacramento has varied prioritization levels within the city (see: Figure 5.2B). Combined with GIS information for hospitals and schools (Sacramento Area Council of Governments) this illustrates how multiple priorities can be used to inform priority investment areas. For example, the Southern part of Sacramento sees a concentration of Hospitals with several Census Tracts with "Very High" rankings. These areas contain highly vulnerable populations (above 0.5), see very high savings from proactive adaptation (>$1 million), and have medium savings from emissions (between 500-1,000 tonnes CO_2). These roads may see a higher benefit from proactive investment than other areas in the County.

Limitations and Future Work

This analysis has several limitations based on scope of the study and data availability. A key source of uncertainty is the climate change models. This is reduced by analyzing all available CMIP5 RCP4.5 models and can be updated as future models evolve. Another limitation is the static nature of the analysis, which does not account for improved construction or maintenance technologies that may change costs and/or reduce emissions. This analysis also utilizes a static measure of social vulnerability to climate change. Finally, the environmental pillar is narrowly scoped to estimate emissions based on only embodied CO_2 from maintenance materials.

Many of these limitations can be addressed using local knowledge and existing sector-specific tools. This could include utilizing forecasted demographic change data based on local assessments, or data from the American Association of State Highway and Transportation Officials (AASHTO) *Census Transportation Planning Products (CTPP)* data (Federal Highway Administration 2015). This would help forecast potential social vulnerability changes and other information that could be useful where more detailed planning analyses are required. For emissions, a broader accounting of GHG including equipment, construction, congestion, and other factors should be included for a more accurate assessment.

Conclusion

The application of the TBL methodology to the Sacramento region provides an insight that is unique to the planning lexicon. Rather than separating climate impacts, environmental concerns, and social vulnerability, the TBL provides a consolidated perspective that highlights the combined vulnerability of specific geographic regions. This analysis graphically demonstrates how prioritization of climate change road investments in the Sacramento region could be considered from a combined perspective. The benefits to the community, environment, and infrastructure are individually important, but the combined perspective provides an investment plan that provides the greatest opportunity for long-term benefits.

By utilizing specific individual data for each pillar, the TBL holistic perspective can enhance the effectiveness of climate change planning as part of larger community goals while maintaining rigorous analysis of infrastructure, emissions, and social considerations.

The approach utilized in this paper is designed to be a starting point for effective, focused discussion on the improvement and availability of techniques to inform climate change planning. There are many areas where increased data availability, local knowledge and prioritization, and incorporation with broader policy considerations can improve this approach. This model is designed to be iterative, with feedback and discussion informing the actual value to today's policy makers.

Climate change will in many cases exacerbate existing issues associated with infrastructure planning, maintenance, design and integrity. It is affected by processes which increase our GHG emissions. Finally, it is often the most vulnerable persons that are most greatly affected by adverse weather conditions and their impacts. By framing the discussion in a holistic but technically rigorous manner, the TBL can provide a framework for effective and holistic infrastructure policy.

CHAPTER 6

DISCUSSION

This discussion chapter focuses on synthesizing the research presented in Chapters 3-5 and discussing the limitations and scope decisions that are relevant to the conclusions and findings. The purpose of this dissertation is to provide a data-driven approach to understanding the implications of climate change impacts on infrastructure and providing decision support for investments. The studies presented in Chapter 3 and 4 were research papers contributing to the development of the IPSS™ system. The focus of the IPSS™ analysis process as utilized in this dissertation is to provide an engineering-based method for quantifying the potential impacts of climate change on road infrastructure. Chapter 5 represents a culminating study where the IPSS™ system is utilized alongside social and environmental analyses to provide a holistic decision support perspective using the TBL framework.

Research Synthesis

The stressor-response methodology used to estimate potential impacts of climate change on road infrastructure was developed through several studies, with many early ones focused in developing countries, including Mozambique, Southeast Asia, Vietnam, and sub-Saharan Africa (Westphal, Hughes, and Brommelhorster 2013; Chinowsky et al. 2014; Chinowsky and Arndt 2012; Chinowsky et al. 2013; Chinowsky et al. 2015). Many of these studies were funded by development agencies including the World Bank, the Asian

Development Bank (ADB), the U.S. Environmental Protection Agency (EPA) and the United Nations University World Institute for Development Economics Research (UNU-WIDER). These studies acknowledged the recognition that climate change poses economic and social challenges to development initiatives, especially in the medium and longer-term horizons. A finding of all of the studies is that there are potentially high (in some cases, extremely high) costs to reactive approaches to managing climate change damages to infrastructure.

A study originally published in 2011 (Chinowsky et al. 2011) compared the impacts of climate change across ten economically and geographically diverse countries globally. It showed that while more economically developed countries (those with World Bank Income Classification as "High Income" or "Upper-Middle Income") face higher financial costs of climate change impacts under certain IPCC CMIP3 scenarios, less economically developed countries (those with World Bank Income Classification "Lower-Middle Income" or "Low-Income" economies) face much higher opportunity costs. The *Opportunity Cost* metric was defined by the authors to indicate the amount of new paved road inventory that could be built with the money required to adapt to climate change impacts and damages. This original paper won "Best Paper" at the *Engineering Project Organization Conference* in 2011. The study was updated in 2014 to reflect the new CMIP5 climate models and refined IPSS™ stressor-response methodologies. The updated paper won "Best Paper" at the 2014 *Humanitarian Technology: Science, Systems, and Global Impacts Conference* in Boston, Massachusetts (Schweikert et al. 2014). Both of these studies and awards show a strong interest in the engineering approach used to analyze climate change impacts as well as the broader policy implications to development and equity.

In line with this early work, Chapter 3 focuses on the impacts of climate change to the South African road network. The findings are consistent with overall results from many of the other studies: with exceptions, it is cost-effective over time to proactively invest in road infrastructure to enable it to withstand projected climate change impacts. Findings suggest that for the more severe climate scenarios, South Africa's paved road network could be expanded by around 15% (near 10,000 km) by 2050. The analysis in Chapter 3 presents an early version of the stressor-response methodology. This paper provides a basic overview to the IPSS™ methodology used for analysis, including stressor-response equations for how calculations for costs of new construction due to precipitation and temperature factors.

Chapter 4 builds upon the methodology used in Chapter 3. It uses the IPSS™ stressor-response methodology and CMIP3 climate models to estimate the impacts of climate change on road infrastructure in California. GIS-based road information was used for input information, including location and surface type. Additionally, the IPSS™ system was updated to include location-specific analysis metrics, including the SUPERPAVE binder system that is used on paved roads by CalTrans (Transportation Research Board 2005; Dwight 2011). These modifications helped localize and customize the analysis on the existing road infrastructure in California. The results showed that heat increases are a major vulnerability of the paved road system in California, with higher-end models showing costs in the $3-4 billion range for a reactive approach by 2050. The analysis showed that a proactive adaptation investment strategy could reduce these costs; as much as $1.7 billion could be saved over the analysis period.

Chapter 4 also introduced the "adapt, with no climate change" metric, which showed the amount of money that would be spent on proactive adaptation measures if the prediction from the climate model was followed, yet did not occur. This provides a 'waste' metric to show the potential wasted dollars if climate change does not occur and historical climate occurs in the future. Another interesting finding from this study is the comparison of the results predicted by all the CMIP3 climate scenarios used. Boxplot graphics were used to illustrate the range of results predicted by IPSS™: These showed that while the medians for the three potential approaches are not vastly different, the risk from higher end scenarios is severely enhanced with a reactive approach, with whiskers and outliers spanning a range higher than $4 billion USD. The risk is much lower with an adapt approach, where the maximum cost is just over $2 billion with the 75th percentile falling around $700 million. Additionally, if a proactive adaptation approach is taken and yet climate change does not occur, the range of costs is much lower with a maximum cost under $600 million total. This Chapter advanced the methodology for estimating the impacts of precipitation and temperature on a large road network over time. It also noted the need for broader context for the incorporation of results into policy and prioritization discussions, which were addressed in Chapter 5.

Chapter 5 built on the technical and financial information about the impacts of climate change on road infrastructure by making the analysis at a local transportation policy decision-making level. The application of the IPSS™ System to the SACOG region presents an example of how this information can be used within a decision-making unit. Additionally, the Triple Bottom Line was used to illustrate how a broader perspective on sustainability could help inform, prioritize, and improve proactive adaptation strategies to increase resilience to climate change.

The findings in Chapter 5 provide a new perspective on climate change investments: the TBL results prioritize proactive adaptation investments in areas where the avoided costs (financial savings) from climate damages are high, the potential to reduce GHG emissions from materials used in repairs is high, and the local population is more socially vulnerable to climate change heat impacts. The prioritization process is categorized in four levels: "Low", "Medium", "High", and "Very High". These prioritizations are based on an additive process combining the individual pillar results, each of which was ranked using four categories based on the specific results from that pillar. For example, a "High" environmental pillar ranking meant that more than 1,000 tons of embodied CO_2 emissions could be reduced if proactive adaptation investments were made. For the social pillar, an "Average" ranking meant that the population in a Census Tract had a social vulnerability index Z-Score of -0.25 to +0.25, indicating that the combined 19 indicators of the index show a composite score that reflects average levels compared to all other tracts in the study area. Similarly, a "Median" ranking for the technical/financial pillar indicates that proactive adaptation could result in savings between $0.5-1 million USD when compared to the reactive approach.

In combining the pillars, the four category rankings for each pillar were synthesized. A "Very High" prioritization ranking meant that at least two of the three individual pillars had the highest ranking for their pillar, while the third had a second-to-highest ranking in their pillar. A "Low" ranking in prioritization indicates that at least two of the three pillars had the lowest possible category rankings, while the third was at or below the second-lowest ranking. While this is a simple approach to ranking priority, it aligns with the established TBL literature of equally-weighted ranking methods. It also represents a straightforward approach to how multiple quantitative results can be used to inform investment policy relating to climate change impacts on infrastructure.

Implications

This work represents three important contributions to the domain of planning and decision-making around infrastructure and climate change. Moving beyond qualitative assessments of potential vulnerabilities to climate change into results based on engineering stressors and a range of climate information is imperative (see: Transportation Research Board 2015). By providing quantifiable vulnerability and adaptation assessments, the financial and technical analysis provided through IPSS™ can highlight important aspects of infrastructure that should be further considered for specific investments and action. The application of the TBL framework to specific infrastructure investment decisions shows that 'sustainability' can be more than a stated goal. By using local priorities, available data, and GIS, the TBL pillars can each have a thorough analysis, yet also individually contribute to the final decision process through a holistic perspective. This data-driven approach can improve the quality, availability, and accessibility of information for decision makers, a key component of information being utilized in the planning process (Tribbia and Moser 2008; Dilling and Lemos 2011).

Limitations and Scope

An important component of the research presented in this dissertation is the limitations and scoping of each approach. In some cases, data availability was limited and affected the modeling choices available. In others, scope decisions were made because of specific objectives of the research; for example, discounting was not used in the financial costs of results when they are presented. Discounting is discussed in more detail below. This section details the main limitations and scoping decisions made throughout this research.

A major limitation of modeling climate change impacts is the models used to forecast the future weather changes. Chapters 3 and 4 present results obtained from using the CMIP3 models. Chapter 5 uses the recently released CMIP5 models, but only results from the first runs of 4.5 RCP scenarios (see Appendix I). A limitation with choosing only the 4.5 RCP scenarios is that it is considered a highly conservative model in terms of projecting the potential magnitudes of future climate change. Utilizing additional RCP scenarios, including RCP 8.5, would likely greatly increase the cost of climate change to the road infrastructure analysis. A limitation of climate change models is the inherent uncertainty associated with modeling future weather, which climate change compounds beyond historical precedent (Dessai and Hulme 2004; Hallegatte 2009). While uncertainty is common in decision-making and techniques such as cost-benefit analysis are used to minimize the potential risks associated, climate change modeling and impact assessment can be described as having 'deep' uncertainty (Fankhauser et al. 1999; Jones 2000; Lempert et al. 2004; Yohe and Neumann 1997). This issue is currently being addressed in literature, including Lempert and Collins (2007) and Espinet, Schweikert, and Chinowsky (2015). A prevailing technique is the use of 'robust' decision-making, which selects an optimal decision based on the lowest regret in the modeled outcomes. This area of research may greatly inform future work with selecting specific scenarios and their impact projections to model climate change adaptation decisions.

Chapter 3 presents early IPSS™ work and the analysis is based on several key limitations (many of which were improved upon in later research endeavors) including: not customizing analysis specific to South African road construction techniques, assuming current traffic use and road standards, assuming perfect foresight for modeling and investment in climate adaptation scenarios, presenting costs in current dollars (no discounting metric is used), and the limitations inherent in using the CMIP3 climate models.

Many of the limitations specific to Chapter 3 persist through later work, including the analyses presented in Chapters 4 and 5. Some are specific to the scope and focus of the work. For example, the assumption of current technology and construction practices as well as not accounting for future traffic patterns in the analysis is based on two main factors. The first is that without specific information about forecasted planning for a specific geographic region, assumptions about future traffic patterns, growth and/or technologies introduce more uncertainty into the modeling. At the local level where this information is available and used for other planning purposes, using forward-looking information in these categories could greatly benefit the analysis and make it more consistent with other studies being performed to inform decisions and investments. However, for the scope of these studies, that information was not readily available. A second reason for not incorporating these factors is that there is a large amount of inherent uncertainty in climate change forecasting and modeling. Where possible, these studies were designed to remove the uncertainty associated with future growth and technology, as well as other factors, in both the modeling and the interpretation of results. The focus of this research is to create a methodological framework to improve decision-making capacity related to infrastructure planning under climate change. Therefore, the operationalization of the studies focuses on making transparent and focused analyses specifically related to climate change.

In each of the research chapters, discounting costs was not done for the cost impacts of climate change on road infrastructure. For the costs presented in Chapters 3 and 4, a sensitivity analysis to analyze the impact of different discount rates (for example, comparing a no-discount analysis with 1%, 3%, and 5% rates) could provide insight into the changing values. It is likely that any discount rate will reduce the attractiveness of investing in proactive adaptation works as the net present value of proactive adaptation investments will likely decrease when compared to a reactive approach, because the reactive approach typically incurs costs in later years. There are two main justifications for not discounting in the study done in Chapter 5 specifically: first, discounting is often used to provide a net present value for future benefits, whereas in the instance of climate change costs, it is a dollar cost incurred based on damages. Secondly, because the pillars are combined for the triple bottom line approach, the technical pillar costs were not discounted to align more closely with the metric used for the environmental pillar: it is not possible (or, at least, straightforward) to discount CO_2 emissions incurred over time. Therefore, both pillars' results were presented in actual values with no discounting applied.

Chapter 5 represents a culminating paper that builds on the technical analysis approach used in Chapters 3 and 4. The IPSS™ system was utilized to analyze the financial and technical impacts of climate change on the road system in the SACOG region from a proactive and reactive investment perspective. In Chapter 4, specific modifications were made to IPSS™ to represent local conditions of roads in California, such as the use of the *SUPERPAVE* system (see Chapter 4; Dwight 2011; Transportation Research Board 2005). The major change in this technical approach for Chapter 5 was the use of CMIP5 climate change models. These represent an updated modeling perspective on the potential changes in future weather (see Appendix I). However, the major contribution of Chapter 5 was the use of the TBL framework.

With the incorporation of the additional metrics of environmental and social impacts of climate change, several additional limitations are introduced. Specific choices about the scope of each pillar, as well as the combination of the pillars for a single analysis metric both required specific scoping decisions. These scoping choices and limitations stem both from availability of data and a broader intention that the purpose of the paper was to create a baseline quantitative analysis from which iterative discussion could enhance the techniques used in means that are effective, efficient and applicable to policy makers.

For the environmental pillar, the analysis was scoped extremely narrowly for this study. This was done to address two issues. The first is that a key tenant of the TBL approach is to avoid, whenever possible, overlaps between pillars to eliminate double-accounting for certain metrics. To some degree, there is overlap between the environmental and economic pillar because the environmental analysis is based on embodied emissions from repair roadworks. These repair roadworks are necessitated by the damages from climate change and coincide temporally with financial costs from the reactive adaptation analysis in the economic pillar. However, beyond this, the pillar is scoped to focus on the materials used as the only source of emissions. For example, a broader accounting of GHG emissions from repair roadworks would likely include estimated increased traffic, because idling traffic contributes to emissions. This was not included due to potential overlap with the social pillar as well as a lack of data on potential traffic impacts. A second reason for the narrow scope of the environmental pillar lies in the desire not to imply a 'best' system of accounting emissions. Many municipalities, especially those already focused on addressing climate change and sustainability issues, have detailed systems for accounting emissions related to road infrastructure and traffic (such as "Road Construction Model" produced by the SAQMD, the "GreenDOT", and many others). It is suggested that this is an area where local information and knowledge can be readily used to improve and expand the scope of analysis for the environmental pillar. However, despite these limitations, accounting for emissions embodied in the increased materials required to repair road damages from climate change does present a quantitative, focused assessment of one impact that could be avoided from proactive adaptation investments.

For the economic pillar, the data-driven approach taken in this dissertation limits the scope of economic impacts to the direct financial implications of taking a proactive investment perspective versus a reactive investment approach. This results in specific financial savings over time. This approach provides an economic metric of 'costs avoided', which can be useful in planning budgeting measures and analyzing direct budget impacts based upon policy choice. However, there is a lot of work in the economics literature that classifies and addresses many of the larger issues that are likely to be caused by road damages, repairs, and broader implications. Rose (2004) addresses the quantification of economic losses from natural and manmade hazards in the context of community vulnerability. Distinctions between losses that are *direct* (for example, production in businesses that is reduced due to damage from a hazard) are compared with losses that are *indirect* and *induced* (all other economic impacts, including the 'intangibles'). Some of the key challenges also include the scale of analysis (regional compared with national or international) and the more complicated models captured in methods such as general equilibrium modeling ("CGE"). Abler et al. (2000) address these challenges in the context of climate change and sustainability. The proposed method involves four categories of economic impacts: two are *direct* impact categories including market goods and services production and nonmarket goods and services production; two are *indirect*: the impacts on other sectors within the region and impacts which are larger in scale including other regions and countries. This study also notes the importance of smaller regional analyses because decisions are made at the sub-national levels.

These and other works demonstrate the importance of framing the economic discussion carefully and with substantial data: for longer-term analyses at a regional level, the incorporation (and distinction) of direct, indirect, induced and broader costs are critical to creating a robust economic pillar. For the study presented in Chapter 5, this level of economic modeling was not readily accessible, necessitating a direct-cost model focused on the costs of road infrastructure damages from climate change and adaptation investments specific to climate change.

The social pillar presented in Chapter 5 is an important contribution to the literature on the method for incorporating a robust, quantitative metric that is tied to a specific hazard threatening a population. Grimm et al. (2008) specifically identify heat as a well-documented impact of climate change on persons living in urban areas. Wood et al. (2015) state that the recognition of vulnerability is important, but tying specific hazards to a population's ability to respond and recover from the hazard is critical for informed policies and actions.

In much literature in the construction industry – particularly those focused on 'sustainability' – there is a significant lack of addressing social factors in a robust manner (or at all). The main component of a 'sustainable' discussion is focused on environmental factors, with little or no incorporation of social metrics that address the populations using and/or affected by the infrastructure: Chen, Okudan, and Riley (2010) state that the construction industry increasingly sees the importance of social awareness, but studies reveal that time and budget constraints remain the driving criteria behind decisions. Other studies recognize the importance of social and environmental aspects, but vary widely on what is considered for incorporation in the analysis scope (Wu and Pagell 2011; Ugwu and Haupt 2007; Kimmet and Boyd 2004).

While the social vulnerability index used in Chapter 5 has significant limitations, it is an important example of how the incorporation of a quantitative, holistic, and widely-accepted method (based on the SoVI index) for understanding the vulnerability of populations to heat impacts can be included. However, it is a limited approach to assessing social vulnerability to climate change considerations and can benefit greatly as an area for future research. Three key limitations exist within this analysis: the static nature of the assessment, the level of analysis and data gathering, and the Z-Score process for ranking Census Tracts. The first two are limitations because of data availability, the Z-Score approach for methodology is used because it has precedence (see: S. L. Cutter, Boruff, and Shirley 2003; S. Cutter et al. 2009; Finch, Emrich, and Cutter 2010; S. L. Cutter et al. 2008) but other alternative methods may also be useful (see: Wood et al. 2015). The index used for analysis comes from the Pacific Institute and full information can be found in their report as well as in Appendix II (Cooley, Heather; Moore, Eli; Heberger, Matthew; Allen, Lucy 2012). As a direction for next steps, there are three areas that could be directly applicable: a social vulnerability analysis that incorporates some sort of quantitative measure of adaptation (not just vulnerability); a metric that is temporal and covers the same time distance as the technical and economic pillars; and a metric which corresponds more directly to infrastructure, specifically road access. A logical expansion would be to draw on locally available transportation planning data which considers population growth, movement and development as well as alternative transportation considerations. More work is needed to quantitatively asses what kind of adaptations may be available for populations facing climatic change impacts.

A final scope of this study that is important to the results presented in Chapter 5 is the equal weighting of the three pillars in the TBL framework. Each pillar was evaluated individually and results were ranked in four categories. Each was based on absolute values in the results, with groupings occurring roughly in quartiles. Then, these groupings were combined in an additive method to create a 'prioritization' ranking. If any of the pillars were weighted more heavily than the others, this could significantly alter the areas highlighted for prioritization in the final metric. There are challenges to combining the pillars; Hacking and Guthrie (2008) point out the importance of not simply "drawing objectives into a single list" but recognizing the linkages and interdependencies that are critical to systems. The pillars in TBL are designed to be analyzed separately and combined only at the end to minimize overlap of counting metrics and maintain depth of expertise in each pillar. However, there always remains a choice at the policy level to emphasize areas to align with broader decisions about what should be sustainable, what is not being accounted for, and other important aspects of decision making (Kajikawa 2008; Kemp and Martens 2007; Hacking and Guthrie 2008).

Several authors cite the need for TBL to be incorporated into broader decision frameworks, and call on work in multi-criteria decision analysis to support processes that recognize the complexity of bringing together diverse sets of information into a single metric (Kimmet and Boyd 2004; Hacking and Guthrie 2008). However, while these decisions are important and normal at the policy level, there is broad support both in multi-criteria decision analysis (MCDA) literature (Montibeller and Franco 2001; Sterman 2001; Steele et al. 2008; Wang et al. 2009) and sustainability literature (Sachs 2012; Ugwu and Haupt 2007; Wu and Pagell 2011; O'Brien et al. 2006; Martens 2006; Kimmet and Boyd 2004) for the equal consideration of the pillars. Wang et al. (2009) review multiple methods of MCDA used in decision-making around sustainability, covering 12 subjective weighting methods, 9 objective weighting methods and 2 combination weighting methods; the conclusion states that it is critical to remember that criteria weights "influence directly the decision-making results of…projects' alternatives" and that equally weighted criteria are still the most popular.

Additionally, the consideration of improving resilience-focused decision capability inherently requires a broader, systems perspective (Turner, B.L. 2003; Bocchini et al. 2014). An area for future work, especially for detailed, location-specific analyses, could be a different method of combining the pillars to reflect local priorities. And while it is normative values that ultimately decide where emphasis is placed, it is important that the weighting of criteria is transparent, replicable, and the sensitivity of weights is understood relative to the final outcome (Kimmet and Boyd 2004; Steele et al. 2008; Kajikawa 2008).

CHAPTER SUMMARY

This Discussion chapter focused on expanding the decisions and limitations of the research presented in Chapter 3-5. Chapter 5 ultimately combines the climate change impacts research into a broader perspective for data-driven guidance about sustainability in investment decisions related to climate change. The scoping of the pillars and application of the framework to road investments is an important contribution to the current calls for more resilient and sustainable infrastructure. Future work focused in this area should expand the scope of the environmental pillar to encompass local data on emissions and perhaps other environmental impacts important to road transportation. The economic pillar also represents an area for future work, where costs of climate change adaptation are placed in a larger framework of economy, indirect and induced benefits, and broader consideration of investment impacts. Overall, this work provides a baseline for discussion about future work in this area and how it can be tailored to specific decision-making contexts.

CHAPTER 7

CONCLUSION

As questions of climate change impacts, adaptation, and policy gain prominence in discussions at the local, national, and international levels, there is opportunity to address many of these challenges in meaningful ways. The purpose of the research presented in this dissertation is to identify and build on existing research strategies that quantitatively analyze vulnerabilities to climate change. By understanding vulnerabilities, potential actions for adaptation can be identified. Comparing the costs and benefits of proactive adaptation investments allows decision makers a better and more relevant understanding of what a changing future climate could mean to their areas of concern.

The goal of the research presented here is to provide data-driven support to policy makers and practitioners about how, when, and where to prioritize investments in road infrastructure to reduce vulnerability to climate change. The research question that guided this dissertation is, "How can planners and decision-makers incorporate a holistic perspective on future road infrastructure transportation planning with the uncertainties posed by a changing climate?"

This was first addressed in Chapters 3 and 4 by contributing case studies covering the methodological development of the IPSS™ system. IPSS™ is designed to use engineering-based stressor response equations to compare the costs of climate change from two perspectives: a proactive adaptation investment and the costs from a reactive strategy. Chapter 5 then built on these studies to expand the methodology to include a sustainability perspective. Beyond considering simply the financial and technical concerns associated with climate change impacts, it incorporated an environmental component looking at embodied GHG emissions differences between the two strategies. It also considered a social vulnerability component where geographic regions with higher relative vulnerability to climate change heat impacts were identified. This approach used GIS mapping and concluded with an investment prioritization ranking based on each of these three pillars, formally framed in the Triple Bottom Line framework.

Together, these three chapters present advances in the knowledge and methods used to address questions of sustainability and climate change in terms of road infrastructure. More broadly, these methods contribute to the discussion about how sustainability can be incorporated into routine decisions by policy makers as well as how climate change impacts can be quantified into information that can be utilized today in decision-making. While there are many sources of uncertainty in future planning, it is imperative that investments being made today account for potential impacts of climate change, both on the infrastructure elements themselves and the communities which they are designed to serve.

These research chapters were framed in the context of broader questions of climate change impacts and adaptation concerns, road infrastructure vulnerability, social impacts, and sustainability and planning. While each of these is a broad domain with specific research, the goal of applying the TBL framework alongside the IPSS™ results is to highlight the importance of seeking systemic approaches to address systemic issues. The three focus areas of this dissertation were: analyzing climate change impacts on roads quantitatively; providing cost assessment metrics to address quantification of costs and benefits of proactive adaptation investments in road infrastructure; and applying the TBL framework to ascertain a holistic perspective on sustainable development and planning under climate change. These focus areas address both of the contributions of the research that are introduced in Chapter 1: "Firstly, to present a method for quantitatively analyzing the financial costs and benefits of proactive investment in road infrastructure under changing future climate conditions. Second, this dissertation introduces the Triple Bottom Line as an applicable framework for discussing the broader benefits to proactive investments in road infrastructure under the uncertainties of climate change."

Additionally, Chapter 6 discusses many of the limitations of the work presented in Chapter 3-5. Some of the limitations are due simply to a lack of available information; others are based on specific scoping decisions that pertain to the overarching goals of the research. Areas for further work are also discussed. Future work can especially benefit in three areas: continuing to expand the scope of the engineering-based stressor response cost-benefit approach used in the IPSS™ system, improving the quantitative measurement of social impact considerations, and by continued pursuit of systemic approaches to aid in sustainable and informed decision-making.

The expansion of the IPSS™ system to other infrastructure is ongoing. Areas of research include building façade damages, freeze-thaw impacts on roads and buildings, energy analyses of building use and climate change impacts, urban flooding impacts, and other modules (see: Westphal, Hughes, and Brommelhorster 2013; Resilient Analytics 2015; Chinowsky, Price, and Neumann 2013; Neumann et al. 2014). As questions of resilience, adaptation, and vulnerabilities to climate change become more urgent, research that quantifies and addresses these challenges becomes more applicable to routine processes and decisions. Ideally, the output of the IPSS™ system can continue to expand to address many of these challenges.

In terms of sustainability planning and actions, future work in this area pertains directly to the 2030 Agenda being carried out by the United Nations Sustainable Development Group (see: Sustainable Development Knowledge Platform 2015). The Sustainable Development Goals (SDGs) outline initiatives and priorities focused on what 'sustainable' development should look like in the coming years. Several of the goals (#9, 11, and 13) focus on specific aspects of infrastructure, urban resilience and/or climate change. Jeffrey Sachs states that the SDGs need to incorporate the TBL perspective with "new urgency…[arising] from a new realization bought to global awareness by earth science and the yearly changes around us." He also states that the TBL perspective may vary in specific definition, but should be used as the outline for the SDGs because it addresses the principles of sustainable development from a perspective focused on the ultimate goal of 'human well-being' (Sachs 2012).

In line with the SDGs and broader literature focused on sustainability and resilience, this dissertation falls readily into line with the existing calls for more resilience analyses and practices surrounding infrastructure management and climate change. It is clear that there are significant existing complexities around issues of development, equity, vulnerability, and sustainability. Realities of degrading infrastructure quality and challenges of social welfare face planners and policy makers on a daily basis. Add to these layers of complexity and uncertainties about future conditions due to climate change and the problems are exacerbated beyond historical precedent. While the exact pattern of future climate change is unknown, new research and science focused on the potential changes, the likely impacts of those changes, and broader objectives around sustainability and resilience in planning create a clear call for a mindset focused on proactive adaptation investments and actions. Where possible, reducing the baseline vulnerability of communities can overall increase the resiliency to potential future hazards. In terms of infrastructure, ensuring that roads are in good condition and prepared for likely life-cycle changes can enhance their functionality and reduce costs over time. As science and research continues to advance, the need for iterative, quantitative and specific processes to address known gaps in both knowledge and practice is imperative.

By building upon domain expertise in areas of social vulnerability, road infrastructure vulnerability and adaptation research, climate change impacts modeling, and sustainability thinking, the TBL framework as applied to adaptation investment prioritization in this dissertation is an actionable tool to move beyond qualitative statements to quantitative action. Climate change poses increased uncertainty for the future, but decisions made about infrastructure today must incorporate considerations of climate impacts of the coming decades. The resilience of communities is affected by infrastructure, and the adaptation investments we make today can undermine future resilience, or vastly improve the sustainability of communities, of policy, and of infrastructure in ways that not only combat the impacts of climate change but allow for the advancement of resilient and sustainable thinking, planning and action.

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APPENDIX I: CLIMATE CHANGE MODELS AND INFORMATION

For the CMIP5 models used in Chapter 5, the information was obtained from the CMIP5 multi-model ensemble archive (Brekke et al. 2013). A full list of the models used from the 4.5 RCP scenario are provided in Table A1 below. The authors acknowledge the World Climate Research Programme's Working Group on Coupled modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table A1 below) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. (see: World Climate Research Programme; Brekke et al. 2013; U.S. Department of the Interior, Bureau of Reclamation 2013)

TABLE A1: CMIP5 Daily Models for California Downloaded:		
Model Name	**Institute Name**	**Institute ID**
access1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	BCC
canesm2	Canadian Centre for Climate Modelling and Analysis	CCCMA
ccsm4	National Center for Atmospheric Research	NCAR
cesm1-bgc	Community Earth System Model Contributors	NSF-DOE-NCAR
cnrm-cm5	Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS
csiro-mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
gfdl-cm3	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
gfdl-esm2g	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL

gfdl-esm2m	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
inmcm4	Institute for Numerical Mathematics	INM
ipsl-cm5a-lr	Institut Pierre-Simon Laplace	IPSL
ipsl-cm5a-mr	Institut Pierre-Simon Laplace	IPSL
miroc-esm	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC
miroc-esm-chem	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC
miroc5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC
mpi-esm-lr	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M
mpi-esm-mr	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M
mri-cgcm3	Meteorological Research Institute	MRI
noresm1-m	Norwegian Climate Centre	NCC

APPENDIX II: SOCIAL VULNERABILITY INDEX: FACTORS AND INFORMATION

The social vulnerability index used in Chapter 5 to assess the social pillar of the Triple Bottom Line analysis is created by the Pacific Institute (see: Cooley, Heather; Moore, Eli; Heberger, Matthew; Allen, Lucy 2012). The stated purpose of the index is:

> "To compare social vulnerability to climate change among areas within the state, we created an index that combines a number of individual vulnerability factors into a single, composite indicator. Our Social Vulnerability Index is useful for assessing overall vulnerability and comparing areas within the state. It should help policymakers to identify areas where efforts are especially needed to build community resilience to climate-related impacts." (The Pacific Institute 2015)

The information is based on the SoVI Index work of Cutter, Boruff, and Shirley (2003) and uses Z-Scores to normalize data across Census Tracts.

The Z-Score technique is used to normalize data that exists in different units. There are limitations to this method, including a smoothing of data represented within any specific tract, and that in combination, some 'vulnerability factors' may be under-represented.

The index used in Chapter 5 uses 19 specific variables related to heat. A full list is in Table A2 below.

TABLE A2: Social Vulnerability Index: Vulnerability to Climate Change (Pacific Institute; Cooley et al. 2012)	
Description	**Source**
Households by type; Total households; Nonfamily households; Householder living alone; 65 years and over; Percent	American Community Survey, 2005-9, Table DP5YR-2
Percentage of population under age 18	American Community Survey, 2005-9, Table B09001
Percentage of households renter-occupied	American Community Survey, 2005-9, Table B25003
Language spoken at home; Population 5 years and over; Language other than English; Speak English less than "very well"; Percent	American Community Survey, 2005-9, Table DP5YR-2
Percent people of color	American Community Survey, 2005-9, Table B03002
Percent earning <200% poverty level	American Community Survey, 2005-9, Table C17002
Educational attainment; Population 25 years and over; Percent high school graduate or higher; Estimate	American Community Survey, 2005-9, Table DP5YR-2
Percent of population in Group Quarters	American Community Survey, 2005-9, Table B26001
Employment status; Population 16 years and over; In labor force; Civilian labor force; Unemployed; Percent	American Community Survey, 2005-9, Table DP5YR-3
Fertility; Number of women 15 to 50 years old who had a birth in the past 12 months; Percent	American Community Survey, 2005-9, Table DP5YR-2
Percent of civilian employed population 16 and over working in Ag/Forestry/Mining or Construction	American Community Survey, 2005-9, Table DP5YR-3
Place of birth; Total population; Foreign born; Percent	American Community Survey, 2005-9, Table DP5YR-2
Percentage of total population that is low-income and has low access to a supermarket or large grocery store	The Reinvestment Fund (2010). TRF Supermarket Study of Low Access Areas

Average percent of youth that were overweight or obese, 2003-2007. fraction of children that are overweight or obese in tract (i.e. fraction over 85th percentile for age and gender based on the CDC growth curves	Ortega Hinojosa, Digital data files sent to authors by email.
Percent impervious surface	Calculated by Jessdale et al using data from Nat'l Land Cover Dataset, 2001
percent tree canopy (area-averaged at block group level, population weighted up to tract)	Calculated by Jessdale et al using data from Nat'l Land Cover Dataset, 2001
proportion of households with no vehicle available	Calculated by Jessdale et al using data from ACS 2005-9
Pre-term birth rate	Preterm birth rates by Census Tract for CA for 2006 from EHIB at CDPH. Eric Roberts.
Percent of households with air conditioning	Data from CEC aggregated by EHIB?

APPENDIX III

Published version of: "Road Infrastructure and Climate Change: Impacts and Adaptations for South Africa"

By: Amy Schweikert; Paul Chinowsky; Kyle Kwiatkowski; Akash Johnson; Elizabeth Shilling; Kenneth Strzepek; and Niko Strzepek

Road Infrastructure and Climate Change: Impacts and Adaptations for South Africa

Amy Schweikert[1]; Paul Chinowsky[2]; Kyle Kwiatkowski[3]; Akash Johnson[4]; Elizabeth Shilling[5]; Kenneth Strzepek[6]; and Niko Strzepek[7]

Abstract: This paper presents the results of a study on the impact of climate change on road infrastructure in South Africa. The approach used built on previous work associated with the UNU-WIDER Development under Climate Change (DUCC) effort, emphasizing understanding of the impact of climate change on roads. This paper illustrates how climate change effects on road infrastructure can be evaluated at a national and provincial level to produce quantitative estimates of climate change from multiple future scenarios. The results of the study indicate that the national-level climate change cost impact in South Africa will vary between US$116.8 million and US$228.7 million annually in the 2050 decade for the median and maximum climate scenarios if a no-adaptation policy action is taken. Conversely, if a proactive adaptation action is taken, these costs can be reduced to US$55.7 million. The savings in costs arising from climate change impacts based on this policy approach is equivalent to building more than 10,000 km of new, secondary paved road by 2050. The analysis focused on the advantage of a proactive policy approach: the upgrade of road infrastructure where climate impacts will exceed current design and maintenance standards. A stressor-response methodology created by the writers is briefly explained, including the application of 54 potential climate futures using general circulation models (GCMs) approved by the Intergovernmental Panel on Climate Change (IPCC). This paper focuses on provincial-level impacts of both a proactive and a reactive approach. Decadal and average annual costs are detailed through 2100.

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Author keywords: Climate change; Infrastructure; Adaptation; Global.

Introduction

South Africa is the largest economy in Sub-Saharan Africa and is a member of several regional and international development organizations, including the African Union, the UN Security Council, the G20, and others [Department for International Development (DfID) 2011]. As one of the highest-ranking regional emitters of carbon dioxide (11th globally), South Africa is taking a leading role in reducing and mitigating climate change impacts (DfID 2011). When compared to other Sub-Saharan African nations, it has a highly developed infrastructure representing a large network of assets that may result in high costs from impacts of potential changes in the future climate. Still facing many challenges common to developing nations, including further reduction of poverty, development of rural services, and continued economic growth, the country has limited funds available to adequately address the threat that climate change poses to the existing infrastructure. The limitations on these available funds challenge developing countries to identify the threats posed by climate change, to develop adaptation approaches to the predicted changes, to incorporate changes into mid-range and long-term development plans, and to secure funding for the proposed and necessary adaptations [United Nations Framework Convention on Climate Change (UNFCCC) 2009].

In terms of future climate change impacts, road infrastructure is one asset susceptible to projected changes. A consistent finding is that the high costs of adaptation and maintenance and the potential negative impacts on surface transportation are projected to be necessary to maintain existing road infrastructure quality (Keener et al. 2013; Hambly et al. 2013; Satterthwaite 2007). Although there is a strong basis both on a local level and through international studies for evaluating the impact of climate change on road infrastructure and the importance of accounting for these impacts, there are few studies that quantify these costs in monetary terms and over a timescale for planning [Burkett 2002; duVair et al. 2002; Oswald et al. 2012; Transportation Research Board (TRB) 2008; Galbraith et al. 2005]. This study recognized the importance of understanding climate impacts and quantified the costs of existing road

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infrastructure in South Africa as a case study for the application of modeling results.

Paved, gravel, and dirt roads were selected as the infrastructure types to be evaluated in this study because of both their economic, social, and development importance and their associated long planning and life cycles. The study examined the extent to which climate change from 54 IPCC-approved general circulation model (GCM) climate scenarios will divert resources from further development of infrastructure to the maintenance and adaptation of existing infrastructure.

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

Background

There is a large body of existing literature establishing the imperative to evaluate potential climate change impacts on infrastructure, including work performed by the World Bank for the European Union and projects in Canada (EACC 2010; Nemry et al. 2012; Hambly et al. 2013). One consistent finding is that climate change poses a threat to existing and future infrastructure, including high costs of adaptation and maintenance, potential negative impacts on transportation, and potential negative impacts on economic and social welfare. Although the basis for considering climate change impacts on road infrastructure is well established, the quantification of these results in monetary terms or on a timescale receives less attention (Burkett 2002; duVair et al. 2002; Oswald and McNeil 2012).

Research completed by the Transportation Research Board in the United States, the Scottish Executives in Scotland, and AUSTROADS in Australia is notable for bridging this research gap (TRB 2008; Galbraith et al. 2005; Austroads 2004). However, the emphasis of these studies is primarily awareness and the informing of public officials regarding policy implications for the infrastructure sector. A comprehensive study in this regard, carried out by Mills and Andrey (2002), presented a general framework for the consideration of climate impacts on transportation. First, it enumerated baseline weather conditions and episodic weatherinfluenced hazards that make up the environment in which infrastructure is built, maintained, and used. Second, it noted that the weather-related context will change with climate change, affecting the frequency, duration, and severity of the hazards. These hazards have the potential to affect the transportation infrastructure itself, its operation, and the demand for transportation.

An increasing focus of climate impact studies is sea-level rise and flooding in coastal areas (Burkett 2002; duVair et al. 2002; Savonis et al. 2008; Oswald and McNeil 2012). Although this is an important topic of study, it is outside the scope of this project and is not addressed in this paper.

The assessment for this study was completed using an analysis tool created by the writers, the Infrastructure Planning Support System (IPSS). An overview of methodology is briefly explained in the next section, and more details on IPSS can be found in Schweikert et al. (2014). Other existing impact assessment tools include the Climate Change Adaptation Tool for Transportation (CCATT), which details input of actual roadstock obtained from local administrators (Oswald and McNeil 2012), and the Model for the Assessment of Greenhouse-Gas Induced Climate Change: A Regional Climate Scenario Generator (MAGICC/SCENGEN) (University Corporation for Atmospheric Research 2007), which analyzes future scenarios of climate change at global-mean and regional levels. MAGICC/SCENGEN 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 existing impact studies on infrastructure is that they either focus on a narrow potential impact of climate change or 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 writers 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. Their study illustrates both the potential real costs that countries may incur because of climate change scenarios and the potential opportunity costs of diverting infrastructure resources to climate change adaptation. Chinowsky and Arndt (2012) refine these results in the context of Southern Africa and the potential use of multiple climate scenarios in a probabilistic economic approach. Additionally, the analysis presented in this paper provides a policy component designed to inform infrastructure planners of the risks, costs, and adaptation and mitigation options in response to climate change. The response methodology introduced in these efforts has been extended by other researchers to analysis of impacts from climate change on bridges (Stratus Consulting 2010) and roads in northern climates (Industrial Economics 2010). Broader studies, including Nemry et al. (2012), focus on infrastructure vulnerabilities in the European Union.

Methodology

The methodology adopted to determine specific climate impacts was based on a stressor-response approach (Chinowsky and Arndt 2012). In this methodology, it is assumed that exogenous factors, or stressors, have a direct effect on focal elements. In the context of climate change and infrastructure, these factors are specific weather elements impacted by climate change, including changes in precipitation levels, temperatures, storm frequency, and wind speeds, which are predicted by each GCM model. Therefore, a stressorresponse value is the quantitative impact that a specific stressor has on a specific infrastructure element. In this study, different elements of paved, gravel, and dirt roads were analyzed. A two-phase approach was used based on the stressor-response methodology that first determined the appropriate climate effects on the given infrastructure inventory in the selected locations and,

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second, determined the cost impacts on this infrastructure based on a set of stressor-response functions.

For roadstock, the stressors were examined in the context of paved, gravel, and dirt road infrastructure components to illustrate the impact of each stressor on the individual components based on the intensity of the stressor. The stressors of interest for roads are precipitation and temperature. For example, the potential increase in precipitation levels was examined as a specific quantitative impact on unpaved roads in terms of the impact of life span based on the degree of increase in the precipitation that leads to erosion. In this manner, the research diverged from a focus on qualitative summaries to an emphasis on quantitative estimates.

In the roads applications, the overall approach to determining potential impacts involved three steps of analysis: (1) climate model projections, (2) existing infrastructure stock estimation, and (3) analysis of climate change impact on infrastructure components.

Decision Approach: "Adapt" and "No-Adapt" Scenarios

Analysis was performed from two perspectives: proactive adaptation ("adapt") and no adaptation ("no-adapt"). Both were examined from engineering and design-focused perspectives. The adapt analysis assumed perfect foresight with respect to climate change impacts and a policy that applies these forward-looking climate projections to the upgrading of new roads as they are rebuilt and maintained. The adapt approach focused on adjusting road design to improve resilience to climatic impacts. This was the chosen method of analysis for two reasons: (1) it is feasible to assume that the large existing stock of road infrastructure will remain in place in the coming decades and will therefore incur damages that require mitigation; (2) although many adaptation options are suggested for particularly vulnerable roads lying in floodplains, coastal areas, and other vulnerable locations, they require very specific, localized data and decision making that is outside the scope of a regional and country-level analysis. The adapt policy scenario incurs upfront costs to adapt an existing road to mitigate future damages that are projected from increases in precipitation or temperature. For dirt road infrastructure, roads are upgraded to an adapted gravel road and therefore are less susceptible to increased precipitation impacts. The no-Adapt analysis assumed that no adaptation changes are put in place; rather, roads are rebuilt according to existing baseline standards. The costs incurred are from the increased maintenance necessary to retain the design life of the original road because degradation occurs from climate change stressors.

In addition to these overall policy approaches, the maintenance savings from adaptation were considered to emphasize the quantifiable costs and benefits associated with adaptation. This metric was applied to unpaved (dirt and gravel) roads. Many of the costs related to an unpaved road network are those of precipitation damage combined with traffic levels. Upgrading these roads can reduce overall maintenance requirements.

General Circulation Models

The climate change projections in this study used data from general circulation models (GCMs), which provide climatological data for future climate change scenarios through 2100. The data used in this analysis included the available A2, A1B, and B1 scenarios, which describe future development based on technological advancement, population change, and emissions. These scenarios are based on the accepted definitions of the IPCC's fourth assessment report (IPCC 2007). To provide a robust analysis of possible climate change projections, all GCM data sets approved by the IPCC containing complete data projections for the South African climate were used in the analysis of South African roadstock. In total, 54 GCMs were used. The section "Study Results" presents them utilizing several display metrics.

The analysis was carried out using climate change projections analyzed by the GCMs at a resolution of 0.5° grid squares, which were then aggregated to the level of admin01 (first subnational unit). The GCMs selected had complete data sets appropriate for making temperature and precipitation projections through 2100 (Schlosser et al. 2011). For each model, historical monthly climate data from the climate research unit (CRU) for 1951–2000 were used to produce a baseline scenario for each geographic region analyzed. The baseline scenario assumed that future weather patterns will retain the characteristics of historical climate variability. Taking the baseline scenario, a 10-year moving average of monthly deviations in temperature and precipitation was used to establish average deltas that were applied to the new projected baselines in each GCM. The application of these deltas to the baselines in each of the future decades provided the climate scenarios that formed the basis for the specific impact analyses.

Division of Road Inventory

A primary output of the study was cost information. The key to this analysis was data on the existing roadstock in each geographic area analyzed. Where possible, existing roadstock information was extracted from geographic information systems (GIS) information to provide direct roadstock estimates. However, the GIS database is limited in its representation of all road types available. Therefore, in this study GIS data were augmented by data from the Africa Infrastructure Country Diagnostic (AICD) and the International Road Federation (IRF). The available data were then allocated at an admin01 level based on GIS information, population density, and area, and were adjusted for additional factors where necessary (IRF 2012; Chinowsky et al. 2011; Gwilliam et al. 2008; AICD 2011). For analysis purposes, it was assumed that once the roadstock was allocated to a province, it was evenly distributed throughout it. This was both a restriction of data availability and an assumption based on the granularity of data available in the GCM climate outputs.

Second, to ensure that the allocation of road inventory correctly correlated with the GCM data provided, the CRU grid cells of 0.5° latitude by 0.5° longitudinal (approximately 250 km²) were the basis of this data translation. This means that where exact GIS representation of roadstock was not available, the admin01 estimates were allocated to the CRU scale uniformly, with adjustments for population where necessary. The information used in this analysis was Climate Research Unit Time Series Version 2.1

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(CRU TS 2.1). Several data parameters were included; the analysis focused on the reported precipitation and maximum temperature (Mitchell et al. 2004).

Impact Functions

Climate change impacts were quantified in terms of total kilometers of road degraded prior to life-cycle design and the total cost of repairing or mitigating future damages. The impacts were determined by a "stressor-response" methodology, in which exogenous factors (i.e., stressors) have a direct effect on, and elicit a response from focal elements. In the context of climate change and infrastructure, these elements include changes in precipitation levels, temperatures, storm frequency and intensity, and wind speeds (Chinowsky and Arndt 2012; Chinowsky et al. 2011). For road infrastructure, the two focal elements analyzed in this study were precipitation and temperature changes.

The determination of stressor-response effects used multiple baseline data inputs. A combination of material science reports, usage studies, case studies, and historic data was employed for each infrastructure category. Where possible, data from material manufacturers were combined with historical data to obtain an objective response function. When these data were not available, response functions were extrapolated based on performance data and case studies from sources such as departments of transportation, road agencies, and international transportation and construction research organizations (Chinowsky and Arndt 2012).

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

Approach to Calculating New Construction Costs

In the case of new construction, cost impacts were considered only for the adapt scenario. New construction costs were modified only if climate change was anticipated during the projected life span of the asset as predicted by specific climate models. Because the noadapt approach was limited to repairing damages after they occur, no changes in existing building practices were put in place for the no-adapt analysis. Rather, this scenario focused entirely on maintenance costs incurred because of climate change impact.

The derivation of the stressor-response values for new construction costs followed two general approaches, each of which retained the focus of building a new infrastructure component to a standard that enables it to withstand projected climate changes over its design life span. The first approach estimated stressor-response values based on the cost associated with the change in material requirements; the second emphasized adaptation to an alternate infrastructure type. The materials approach was used to generate stressor-response values for paved and gravel roads.

The materials methodology was based on the premise that roads should be constructed to a level that anticipates future changes in climate conditions and accompanying changes in material requirements. Following this concept, this methodology determined if new structures, such as paved roads, will be subject to material changes when it is anticipated that a significant climate change stressor will occur during their life span.

Similarly, the second option for adaptation for new construction was to alter the type of infrastructure being constructed to one that has the capacity to handle the anticipated climate change. For example, if climate change is anticipated in an area with dirt roads, a consideration has to be made for either increasing maintenance costs, as described later, 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 of this approach is that basic and climate-induced maintenance is eliminated on the dirt road (because it has been adapted).

For unpaved roads, a direct approach was used for estimating the cost impact of changes in climate stressors. The stressorresponse relationship associates the change in construction costs with changes in maximum monthly precipitation. Available data suggest that there is no relationship between temperature and the cost of building unpaved roads. Ramos-Scharron and MacDonald (2007) attribute approximately 80% of unpaved road degradation to precipitation and 20% to factors such as tonnage and frequency of traffic. Given this emphasis on precipitation and the focus on retaining design life span, we assumed that base construction costs for unpaved roads increase based on thresholds of precipitation increase relative to the baseline. Our approach is summarized as follows:

$$CC_U = 0.8 \cdot MIP \cdot BC_U \quad (1)$$

where CC_U = change in construction costs for unpaved roads associated with a unit change in climate stress or design requirements; MIP = increase in maximum monthly precipitation; and BC_U = base construction costs for unpaved roads. A full explanation of the precipitation stressor-response impacts is detailed in Chinowsky and Arndt (2012).

For paved roads, temperature is an additional key factor. Where temperatures are expected to increase, this can affect road surface and degradation and can reduce the life span of the road. For example, hotter temperatures can mean changing asphalt properties. The cost of adaptation of paved roads in areas where a rise in temperature is predicted was calculated by upgrading the asphalt binder to withstand a higher pavement temperature. Table 1 shows the corresponding pavement temperatures [converted using Eq. 2] and the estimated cost per lane-km.

Table 1. Asphalt Binder Grade, Corresponding Maximum Pavement Temperature, and Estimated Cost per Lane-Kilometer

Asphalt binder grade	Maximum pavement temperature (°C)	Cost (US$)/
PG-46	46	317,040
PG-52	52	337,961
PG-58	58	362,102

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PG-64	64	387,851
PG-70	70	415,210
PG-76	76	444,178
PG-82	82	474,755

Based on available maximum daily temperature, the average value for a seven-day maximum ambient temperature was calculated for each CRU grid for each climate change scenario. This calculation allowed derivation of the corresponding gridded seven-day pavement temperature values by CRU grid and was applied to the road inventory.

The relation between pavement temperature and ambient temperature was assumed as (Lavin 2003)

$$T_p = 0.9545(T_a - 0.00618L^2 + 0.2289L + 42.2) - 17.78 \quad (2)$$

where T_p = pavement temperature (°C); T_a = ambient temperature (°C); and L = latitude (arc degrees).

The cost associated with asphalt binder was calculated by multiplying the upper cost figures (Table 1) with the road length information (paved primary, secondary, and tertiary). Based on assumptions for the number of lanes for each type of road, the costs were calculated, aggregated at the country level, and combined with maintenance, precipitation, and other cost-impact information to determine the estimated cost of climate change under a given climate scenario.

Approach to Calculating Maintenance Costs

Similar to the stressor-response functions for new construction, the functions for estimating maintenance differs for paved, gravel, and dirt roads. For paved roads, an approach was adopted that bases the cost of maintenance on the cost of preventing a reduction in life span. The implementation of this approach involved two basic steps: (1) estimating the life span decrement resulting from a unit change in climate stress and (2) estimating the costs of avoiding this decrement. To estimate the reduction in life span that could result from an incremental change in climate stress, it was assumed that such a reduction is equal to the percentage change in climate stress, scaled for the stressor's effect on maintenance costs.

For gravel and dirt roads, maintenance impacts are induced by changes in maximum monthly precipitation rates. The result of increased precipitation is increased erosion, which creates a need to increase maintenance to retain the original design life. To estimate the changes in road maintenance costs, the amount of erosion was used as a basis for determining the percentage of maintenance increase required. The calculation of erosion rates for dirt and gravel roads was based on three factors: (1) precipitation amount, (2) traffic levels, and (3) road slope. In terms of precipitation, studies indicate that increases in precipitation have a direct impact on the design life of a dirt road with minimal slope and low traffic levels (Dubé et al. 2004). This base case is augmented as traffic rates and slope percentages increase, resulting in significantly greater erosion rates (Sheridan and Noske 2005).

The maintenance costs associated with climate change occur for both the adapt and the no-adapt scenario. According to the adapt scenario, a road that currently exist and therefore has not had the opportunity to be upgraded (a limitation of the reality of cost and the time to upgrade roads) requires maintenance during the remainder of its life span as climate change stressors are encountered. When such roads require rehabilitation at the end of their useful life span, they are modified according to the new construction option. Additionally, when climate impacts exceed the design specifications but do not pass a threshold, there are incurred maintenance costs for adapted roads.

In terms of the no-adapt scenario, maintenance costs are incurred at every point that climate change impacts occur above the baseline (no climate change) scenario. The goal is to retain the original life span through repairs where possible.

Additional Metrics Used

Opportunity Cost

The final element required for the study was to establish a common evaluation metric that could be used for each of the regions being studied. The difficulty in such a determination is the regional variation in current road inventory and the projected cost of climate change for each region. Given these variances, a metric is required that reflects the relative impact on the region while not overly weighting the total cost of climate change on it. The solution was the adoption of the opportunity cost metric established by the writers in previous studies (Chinowsky et al. 2011)

The opportunity cost for a region is equal to the total percentage increase in the paved road network that could be achieved if the money were not being diverted to climate change adaptation. This was defined by the total cost of climate change (for either the adapt or the no-adapt scenario) and the kilometers of new, secondary paved road that could be built with this amount of funding. The percentage is relative to the existing paved road network (the constant, preanalysis inventory). "Adaptive advantage" was used to define the fiscal savings between the no-adapt and net adapt costs.

Net Adaptation Cost: Roads

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

In many cases, adaptation costs are high because of higher construction costs for paved or gravel road infrastructure when compared with gravel or dirt road infrastructure. The savings in routine maintenance costs often offset these costs—completely in some cases.

Study Results

The analysis detailed in this study provided an estimate of the potential climate change cost to South Africa's road infrastructure. Table 2 shows the costs by selected decades for the median and maximum GCM scenarios. The impacts range from an adapt cost of US$1.1 million annually (2030) to a no-adapt cost of US$389.1 million annually (2090). These costs are equivalent, respectively, to 3,700 km and nearly 26,000 km of new, secondary paved road. Fig. 1 details these decadal findings and shows a clear adaptive

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advantage between the estimated costs for the no-adapt and net adaptation approaches (US$115–171 million, respectively, for the median and maximum scenarios for the 2050 decade). The costs provided in these results do not include a discount factor. Although the time-value of money plays a distinct role in future cost obligations for these impacts, the results presented here are intended to provide a relative comparison of impacts and an indication of incurred costs in today's terms. Discount rates should be applied in order to understand the final economic impact of climate change and the potential impact of future cost perspectives.

The maximum and median scenario results are shown in Figs. 2 and 3. Although the costs are higher in the maximum scenario, the trends are the same: the no-adapt scenario progressively increases whereas the adapt and net adapt costs consistently decrease over time.

Fifty-four GCMs were used in this analysis. Each produced a different cost based on projected changes in future climate impacts. Fig. 4 is a histogram analysis showing the relative risk of investment based on all scenarios. For example, an investment of US$152 million annually (results shown for the 2050 decade) with the adapt approach would ensure that all GCM projections are covered. This means that all road infrastructures will be "climate resilient." However, if this same investment were made with a noadapt approach, there would be a 45% chance that the climate impacts would require greater investment to mitigate the damages. These results show that adaptation to climate change is important to consider at current and future stages of road infrastructure management policy.

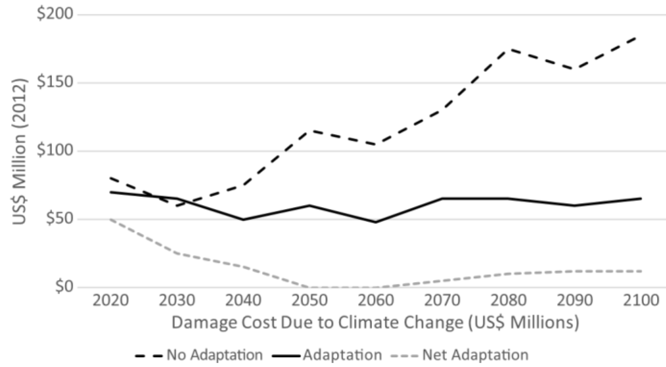

Fig. 2. Median GCM (50th percentile) national-level results: annual average cost by decade

National-Level Results

The potential impact of climate change on South Africa's national road network may be as high as US$96, US$229, and US$390 million annually in 2030, 2050, and 2090 if no adaptation measures are taken (Table 2). This cost is reduced if a proactive adaptation strategy is taken (Fig. 2). The benefits from adapting road infrastructure proactively include savings from decreased maintenance on unpaved road infrastructure, decreased vulnerability to climate change impacts, and a more robust and reliable road infrastructure.

Table 2. National-Level Decadal Average Annual Road Costs for Selected GCM Scenarios

		Annual average Annual average Net adaptation Adaptive Oppurtunity Oppurtunity Equivalent Equivalent cost cost cost advantage cost (%) cost (%) km km							
Decade	Scenario	No-adapt	Adapt	Adapt	No-adapt	Adapt	No-adapt	Adapt	No-adapt
2030	Median	59.6	58.2	23.5	36.2	6.1	6.3	3,880	3,997
	Maximum	96.0	76.3	52.5	43.4	8.1	10.1	5,086	6,397
2050	Median	116.8	55.7	1.1	115.7	5.9	12.3	3,710	7,789
	Maximum	228.7	73.3	57.5	171.2	7.7	24.1	4,889	15,245
2090	Median	163.2	56.8	7.8	155.4	6.0	17.2	3,789	10,878
	Maximum	389.6	65.0	35.0	354.6	6.9	41.1	4,335	25,974

Note: All costs are in US$ millions.

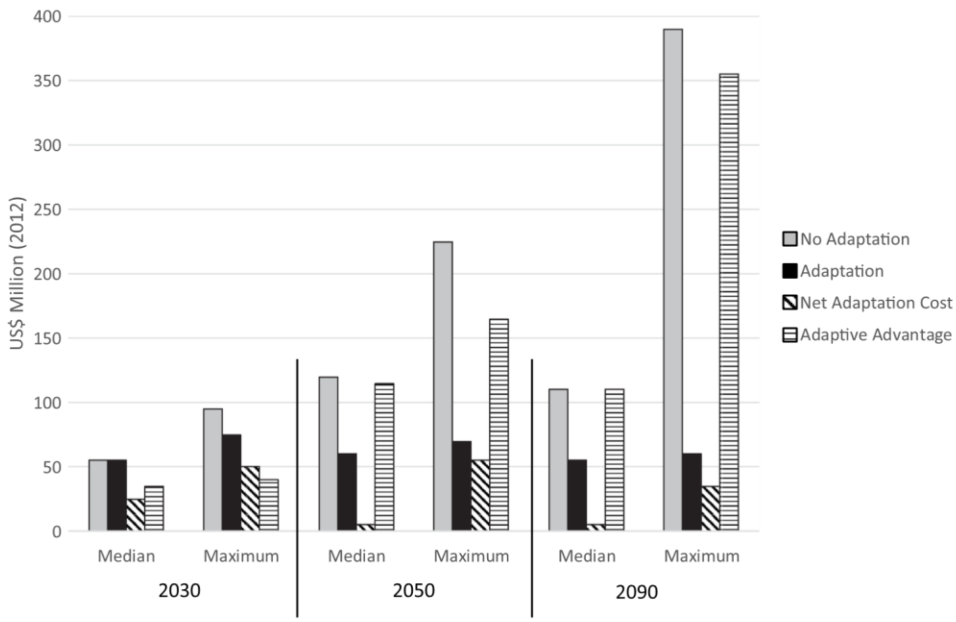

Fig. 1. Selected national-level results: average annual cost

In the 2090 decade, there is a net savings of over US$354 million if the adaptation approach is taken for the maximum GCM impact scenario. This is largely because the adapted road infrastructure is more resilient to climate impacts. Adaptation includes upgrading dirt road infrastructure to gravel and paved roads to reduce annual maintenance requirements. Even in earlier decades, such as 2030, there is an adaptive advantage of US$36–43 million annually between the median and maximum climate scenarios.

The opportunity cost of climate change on South African road infrastructure is between 6–41% depending on the GCM scenario and the decade analyzed (Table 2). South Africa has a large existing road network of over 360,000 km; However, only 17% of this roadstock is paved (IRF 2012). Through adaptation of the unpaved road network by enhancing the drainage capacities of dirt and gravel roads and, where traffic and precipitation impacts indicate, by

Table 3. Decade 2050 Provincial-Level Annual Average Cost, Median GCM Scenario (50th Percentile)

Province	Annual average advantage No adapt	Annual average Adapt	Adaptive cost cost No adapt
Eastern Cape	11.8	6.8	$ 4.9
Gauteng	8.0	5.7	2.2
KwaZulu-Natal	13.2	6.1	7.1
Limpopo	13.6	8.3	5.3
Mpumalanga	8.9	4.4	4.5
North West	13.2	5.5	7.7
Northern Cape	26.4	10.8	15.6
Orange Free State	13.5	6.0	7.4
Western Cape	7.6	3.7	3.9

Note: All costs are in US$ millions.

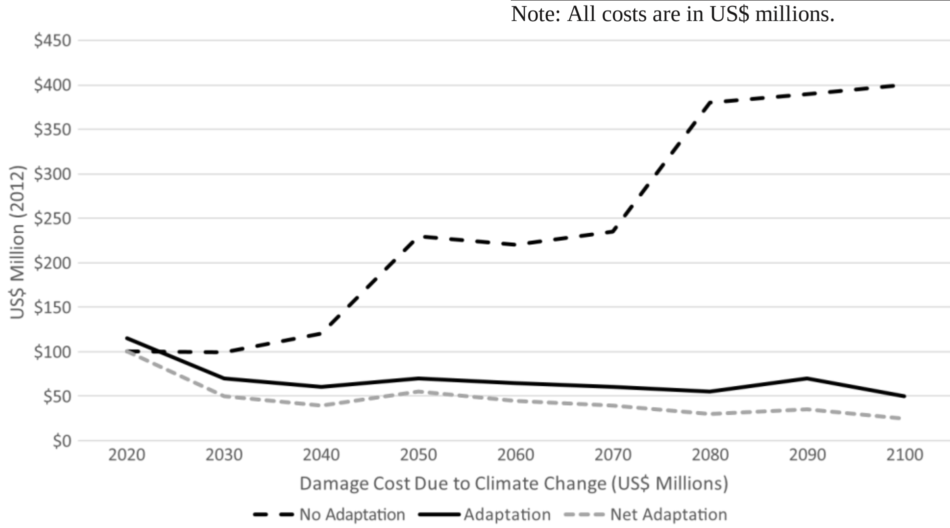

Fig. 3. Maximum GCM (100th percentile) national-level results: annual average cost by decade

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upgrading to a paved surface, there are fiscal savings as well as additional benefits, including less maintenance from extreme events, increased road connectivity , and higher traffic and freight volume tolerances. The benefits from these findings are especially evident in the provincial (regional) results.

network is mostly paved roads. Because of higher adaptation costs, the adaptive advantage is relatively small (Table 3). However, total cost is not the only metric that should be considered when deciding between an adapt and no-adapt policy approach. A proactive adaptation strategy minimizes the vulnerability of road infrastructure to climate impacts and reduces the need for extra maintenance costs, increased disruption of traffic, and other impacts associated with repair of damages to road infrastructure.

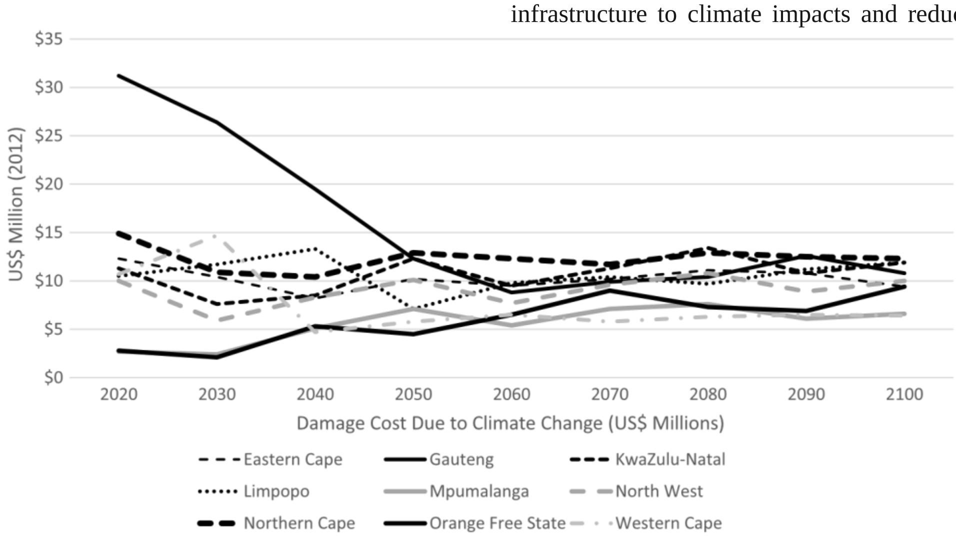

Fig. 5. Median GCM (50th percentile) annual cost by decade: adapt scenario

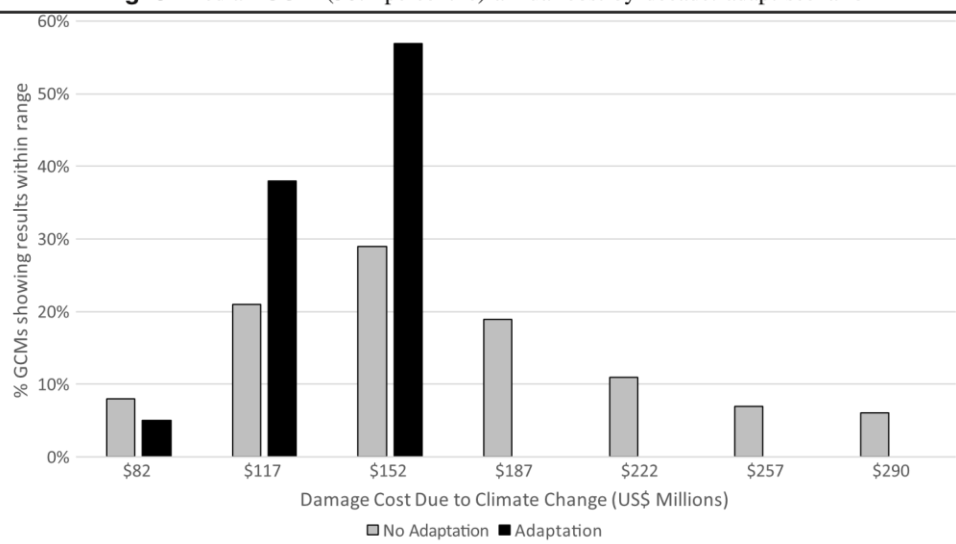

Fig. 4. Risk analysis: adapt versus no-adapt, 2050

Provincial-Level Results

At the provincial level, there is an adaptive advantage for nearly all of the provinces in each decade. In 2050, with the median GCM results (50th percentile), the adaptive advantage is US$2.2–15.6 million annually (Table 3). The Northern Cape and the Eastern Cape see high initial adaptation costs (Fig. 5), but by the mid-2030s all adaptation costs are below US$10 million annually. This indicates that, with an upfront investment in climate change adaptation, the large unpaved network that is vulnerable to climate change can be mitigated and improved.

Additionally, these results indicate that of the two stressors examined, precipitation and temperature, temperature has a higher impact. This is seen in provinces such as Gauteng, where the

Limitations

The current study was based on several key data sets that introduced uncertainty into the quantitative analysis. The climate data used for this analysis came from a collection of 54 GCMs with acknowledged variability and uncertainty. These projections were also performed at a global scale, which necessitated downscaling for application to country and region-specific analysis.

The adapt and no-adapt analyses were simplifications of reality. Although a "perfect foresight" model was assumed for the adapt analysis, limitations existed based on current climateforecasting

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capabilities. The accuracy of the adapt policy was restricted by the uncertainty of the forecasting methods available. However, given the limited alternatives, this approach was utilized with the limitations remaining as a caution about specifics in the results.

Additionally, the study relied on existing material studies to derive the impact stressors. Although it based its findings on recognized authorities and studies, the quantitative cost estimates were dependent on findings from these and similar studies. Issues such as specific, localized pavement types, local conditions, construction, and maintenance techniques can all combine to affect specific cost impacts. Therefore, the quantitative cost results may differ based on alternative studies.

A noted limitation was the lack of discounting used to present final impacts. In this study, it was determined that using constant costs would provide a relative indicator of climate change impacts. From this perspective, the time series wereprovided to give a representative picture of future climate impacts and costs as they are expected to be incurred. Discount rates provided a realistic economic perspective, but detracted from the relative impacts emphasized in this study.

Because of data limitations in terms of future climate scenario projections, localized data specific to South Africa, and the scale of the analysis, some components were not included in the costs analysis. For example, with unpaved road erosion rates, certain impacts were not considered, including storm surge, flooding, and specific drainage measures that were taken beyond the standards used for analysis. Additionally, flooding was an important factor in understanding the damages from climate change, but was not considered in this analysis because of the specificity of data required in terms of microscale hydrologic modeling and detailed road infrastructure placement data. It is likely that a more detailed and more microscale analysis that includes these elements will increase the costs presented in this study.

Discussion and Conclusions

This study examined the potential effects of climate change on the road infrastructure of South Africa. It focused on an engineering approach to determining the specific effects of climate stressors on road surfaces. On the basis of a combination of actual and estimated totals for each South African province, the study illustrated the variance in provincial effects and focused on the national-level adaptive advantage of a proactive adapt strategy.

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

The analysis approach utilized in this study is highly replicable for similar studies in other countries. The GCMs used provide climate data on nearly every nation in the world. Because the study was carried out at a national and a provincial level, its results can highlight areas of vulnerability in need of further study that will not be limited by the requirement for detailed local data such as hydrologic modeling and discrete road specifications and locations. The estimates provide both an analysis of climate change impacts on road infrastructure and a study methodology that produces quantitative results. A similar method has been applied to a four-country study of Asia (Hughes and Chinowsky 2012), and similar studies with more localized data inputs have been carried out on Mozambique (Arndt et al. 2012), Vietnam (Westphal et al. 2013), and Southern Africa (Chinowsky and Arndt 2012).

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APPENDIX IV

Published version of: “Resilience Versus Risk: Assessing Cost of Climate Change Adaptation to California’s Transportation System and the City of Sacramento, California”

By: Amy Schweikert, Xavier Espinet, Sara Goldstein, and Paul Chinowsky

Resilience Versus Risk

Assessing Cost of Climate Change Adaptation to California's Transportation System and the City of Sacramento, California

Amy Schweikert, Xavier Espinet, Sara Goldstein, and Paul Chinowsky

Quantitative assessment of the vulnerability and adaptation options of road infrastructure and economic impacts of climate change is essential to building a more robust and resilient transportation network. To date, most research has focused on qualitative statements and broad findings or on location-specific case studies. This study details a quantitative, engineering-based analysis of the impacts of specific climate stressors on types of road infrastructure. The results are designed to be utilized by transportation planners to understand the vulnerability, risk, and adaptation options for creating a climate-resilient road network by providing specific design changes and fiscal cost analysis. The current study aims to build on previous work and addresses several gaps: use of all climate models approved by the Intergovernmental Panel on Climate Change to provide guidance despite uncertainty, provision of results similar to existing risk and vulnerability analyses to allow for implementation in existing planning processes, and introduction of a methodology requiring only routinely available road network information to allow for replicability across the United States. California is used as an illustrative case study that helps identify the existing vulnerabilities of the road network to climate change and the fiscal savings possible through proactive adaptation strategies. Findings show that for the higher-impact model (95th percentile), California could save $1.9 billion between 2015 and 2050 by proactive adaptation. The contribution of this research is to move beyond the identification of vulnerabilities to a quantitative assessment of specific adaptation options that reduce a community's or region's vulnerability to climate change.

Climate change has been at the forefront of discussions globally since the founding of the United Nations Intergovernmental Panel on Climate Change (IPCC) in 1988. Although the early work of the IPCC focused on creating and understanding the science of global climate change and mitigation options, more recently a prominent shift has been made to include vulnerability assessments, adaptation options, and the financing of climate-resilient projects (*1*). The IPCC's *Fifth Assessment Report* (AR5) concludes that "warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of

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greenhouse gases have increased" (*2*). Increased carbon dioxide emissions, among other causes of climate change, have triggered real consequences such as hotter summers and changing extreme weather patterns. One element that is particularly susceptible to the effects of climate change is transportation infrastructure (*3–5*). Roads serve as a connection for most of the United States' economic and social activity; the risks of climate change for roads threaten the associated economic growth, development, and social welfare benefits of infrastructure expansion (*6*).

The impacts of climate change have exacerbated the existing vulnerabilities of aging U.S. infrastructure. In 2013, America's infrastructure was rated a D+ by ASCE in *2013 Report Card for America's Infrastructure* (*7*). This projection neglects the effects that climate change poses to existing infrastructure and the unprecedented challenges to future infrastructure viability. How climate change will increase costs for adaptation and maintenance and its potential negative impacts on transport networks must be considered for both new and old infrastructure; the largest state and national fixed assets must be accounted for (*6, 8–10*).

Research to date shows that climate change poses a high risk to America's transportation infrastructure (*11, 12*). The challenge facing policy makers is to incorporate scientific information, a range of climate models, and risk assessments into routine decision making. As recognized by the state of Vermont, the best way to address and mitigate climate change risk is to plan and prepare for it (*13*). For the context of this study, there are several cities in California that have completed initial assessments to determine potential risks from climate change (*14, 15*). Findings show that planners find value in vulnerability assessments and data for informed decision making, yet there is still a disconnect between science and information accessible with current resources. Tribbia and Moser present a case study on the state of California and show that political will, better resources, and more accessible information relevant to policy makers' current processes are necessary to fully integrate climate change into routine decision making (*16*).

This study presents results designed to illustrate the available information for decision making. Results from a tool designed to address many of these needs are discussed. Developed by the authors, the Infrastructure Planning Support System (IPSS) is an engineeringbased tool that uses a stressor–response methodology to determine the impacts of specific climate stressors on infrastructure. This study focuses on the effects of incremental impacts (daily precipitation and temperature) on existing road infrastructure. Results are shown for the 2015–2050 time period. A proactive adaptation strategy is compared with a nonadaptation, reactive approach. Analysis is done for 54 available climate models approved by the IPCC. Both approaches are compared with a baseline scenario of no climate change. Results are given for three specific climate scenarios representing approximately the 5th, 50th, and 95th percentiles of impact. Findings are presented in terms of annual fiscal costs for the state of California and the city of Sacramento, California. In addition, for Sacramento, results are presented alongside additional key infrastructure costs for schools, libraries, hospitals, and rail infrastructure. This scheme is designed to help contextualize the results from road infrastructure and to integrate them into the larger urban planning process and prioritize investment decisions. California was chosen because of existing work identifying climate change vulnerability, the extensive transportation network, open-source data availability, and diverse geography; this existing work allows for results more readily applicable to other contexts.

BACkground

The United States is beginning to realize the potentially severe and detrimental impacts that climate change may have on current and future transportation infrastructure. The challenge lies in identifying the risk and implementing specific actions to adapt. In an effort to begin countering the effects of climate change, the United States has adopted a Commitment to Act policy as part of the outcome of the Climate Change Action Plan. According to this action plan as presented in 2013, the federal government will "work with state and local governments to prepare for the unavoidable impacts of climate change" (*17*). Much of the responsibility lies on state and local governments to implement climate change policies and practices and begin to counteract the effects of climate change.

According to the U.S. National Climate Assessment, public- and private-sector reactions to climate change have been to plan for future adaptation projects. However, many of these plans have yet to see large-scale implementation; this lack of action leaves the United States behind in climate change adaptation (*18*). As a first step, FHWA developed a report outlining steps for agencies to begin incorporating climate change concerns into infrastructure planning. In this FHWA report (*19*), a seven-step process was outlined on how new infrastructure plans can incorporate a response to the effects of climate change. This outline includes steps to recognize the role of climate change in infrastructure management, coordinate with other organizations on methods to deal with climate change, and integrate land and funding challenges. The report, although giving guidelines on how to plan, stops short of specifying quantitative measures to help recognize when climate change will have an effect or how much potential changes in climate will cost in infrastructure improvements (*19, 20*). Additional research finds specific vulnerability to climate change for four sites in New England but acknowledges a need for greater geographic scalability, an increased number of climate models, and a continued quantification of the uncertainty to increase decision makers' capability to incorporate climate concerns (*12*).

The state of California has recognized the condition of its current transportation infrastructure and the potential effects of climate change on future infrastructure development. The California Department of Transportation acknowledges that the cost to fix the transportation system keeps increasing, whereas increased traffic incessantly wears down the existing roadways (*21*). Multiple agencies, including the California Environmental Protection Agency, provide information about the current and future impacts of climate change. These data are passed on to lawmakers, but many reports neglect the specific impacts and actions that decision makers can take to mitigate the impact of climate change on California's infrastructure. California's transportation system has already felt the effects of climate change with the increase of extreme weather events (*22*). Although California has been on the forefront of much advancement in climate change policy and programs, the incorporation of climate change as a concern for transportation planning still receives little attention in terms of influencing the implementation of infrastructure projects (*23*).

In an effort to help policy makers and planners incorporate climate change impacts into transportation and wider decision making, some tools have been developed. Notably, the Climate Change Adaptation Tool for Transportation is designed to help assess the status of climate change and transportation. However, as a barrier to routine use, this tool requires detailed input from local administrators; this requirement makes its ease of use and implementation difficult (*24*). In addition, the MAGICC/SCENGEN 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 (*25*). A few previous studies estimate the potential impact of climate change with specific case studies but acknowledge that more climate change models are needed to more fully understand the potential impacts and uncertainties (*11, 12*). Lu and Peng focus on identification of critical sections of the transport network and note that proactive measures in transportation planning and engineering should be taken, including a vulnerability analysis of the network, but they fail to suggest actionable adaptation options (*26*).

MeThodology

This study utilizes a methodology with three phases for California and a fourth phase of analysis for the city of Sacramento. The first phase is to collect the input data used in the analysis. The second phase is analyzing the impact of climate change on the road infrastructure network obtained in Phase 1. This second phase uses an analysis tool developed by the authors, the IPSS. The third phase is to analyze the results produced by the IPSS for the state of California and for the city of Sacramento. This phase utilizes data from a range of climate models from 2015 to 2050 and compares a proactive adaptation strategy with a reactive, nonadaptation policy. Results are presented in terms of economic cost based on construction and maintenance needs. The fourth phase, a criticality analysis and specific application to policy makers, is applied only to the city of Sacramento because of the detailed information needed for the analysis.

The first phase requires obtaining a road inventory for the state of California and the city of Sacramento. An open-source database of the existing road network was processed with geographic information systems (*27, 28*). Further, this information was sorted for analysis based on common definitions of the road surface and attributes. Nine types of roads were used in this study: a combination of paved, gravel, and unpaved road surface types and attributes common to primary, secondary, and tertiary networks. No freeways were analyzed in this study. The total network analyzed includes 36,255 mi of roads, including approximately 24,600 paved roads. These data were analyzed at the county level for California and within the city boundaries for Sacramento.

Second, the IPSS was used to analyze the impact of climate change on the road network. The IPSS software provides annual cost estimates of the impact of climate change on road and building infrastructure on an annual basis through 2100. A range of climate models is combined with infrastructure inventory and engineeringbased stressor–response equations to determine the impact of both extreme events (e.g., flooding) and incremental climate changes (e.g., precipitation and temperature) on specific infrastructure elements. The system identifies the financial cost on a yearly basis and allows users to compare proactive adaptation measures with reactive nonadaptation measures, both of which are compared with a baseline no-climate-change scenario.

To model future changes in climate, IPSS uses 54 different AR4 general circulation models (GCMs) to obtain the predicted future values of climate stressors including precipitation and temperature. These values are compared with historical climate data to obtain the increment of change of these stressors due to climate change. Analysis is completed at the climate research unit resolution, a worldwide grid of 0.5 degrees of latitude and longitude (which represents approximately 250 km^2) (*29*, *30*).

IPSS analysis is done in terms of a proactive adaptation strategy and a reactive nonadaptation policy. Both are analyzed with the baseline goal of retaining the original design life of the infrastructure despite changes in climate stress. This approach follows previous work finding that climate change causes a significant change in deterioration of roads and "work is needed to improve . . . design and construction . . . to make pavements more resistant to the effects of climate change" (*11*). For the reactive nonadaptation approach, costs are based on increased frequency and severity of maintenance required to fix climate-related damages. For the proactive adaptation strategy ("adapt," Table 1), costs are based on the increased cost of construction to account for climate-related damages over the life span of the infrastructure as well as the maintenance costs from road inventory that has not yet been adapted. For this study, adaptation rates are set at 5% of the road stock inventory annually to reflect a distribution of the age of the road stock. In addition, an adaptation strategy in which no climate change occurs ("adapt, no climate change," Table 1) is presented. These costs are based on an adaptation strategy projected by the GCM, in which no climate change occurs. This model shows the wasted cost of adaptation spent and is provided as a comparison model to understand the potential financial regret if the historical climate occurs despite projections by the climate models.

Adaptation is defined for the IPSS-based analysis as making design changes to withstand projected changes in temperature and precipitation throughout the life cycle of the road. For example, where heat is expected to increase, the asphalt binder properties are adjusted according to existing standards. For this study, this design change applies Superpave® increments of pavement temperature, traffic, and cost, among other variables (*31*). When pavement temperature is predicted to increase above a threshold, the mix is adjusted to withstand increased heat and avoid degradation costs. In this example, the reactive calculation is the increased maintenance costs required to repair the degradation and performance failure due to increased heat stress.

IPSS predicts the impact of the climate change stressor on the road inventory by using engineering-based stressor–response equations. These equations reflect the response of the road materials to the climate impact stressors and were developed with a combination of previous research on materials science, case studies, and historical data. Impacts are determined for each type of road (paved, gravel, earth, and primary, secondary, tertiary) and assessed per kilometer of road. The change in asphalt binder just described is one example of the stressor–response approach. All the specific road-type response equations, thresholds, and methodologies are detailed in previous work (*32*–*36*). They have also been used in international climate studies including those for the Asian Development Bank (*37*), the European Union (*38*), and Canada (*39*).

The third phase of this study is focused on analyzing the results produced by the IPSS. The large amount of data produced must be filtered to help create usable science: information about climate change that can be incorporated into existing decision strategies. Therefore, this phase is critical to the usefulness of the IPSS tool and study results. For this study, results from three specific climate models are presented for California and Sacramento—low-end projection (5th percentile), the median (50th percentile), and a highend model (95th percentile)—that are based on the total cost through 2050 predicted by each of the models. The reactive, adapt, and adapt without climate change results are presented for each.

For Sacramento, a fourth analysis phase is utilized to provide a more detailed example of how this information can be used to inform decision making and risk management. A criticality analysis is done to identify key routes and costs associated with road infrastructure that is determined to be of the highest priority. These results are shown in terms of mapping key assets, costs of adapting portions of the road network, and risks associated with not adapting in terms of total costs. For this analysis, additional infrastructure is incorporated including public schools, bridges that cross waterways, libraries, hospitals, and airports (*28*). These assets were selected because they play key roles in community activity and resilience, both on a daily basis and in times of weather-related emergencies (*40*, *41*). A geographic information system is utilized to display the information alongside climate change cost estimates to highlight the large amount of data that can be visually displayed and utilized in the decision process (*42*).

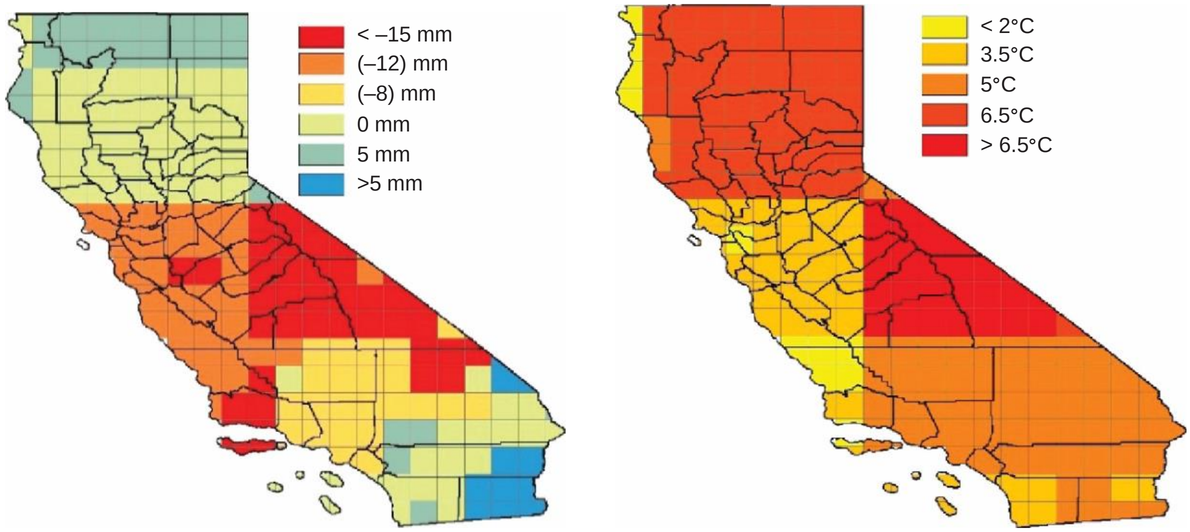
reSulTS State of California

Vulnerability Assessment and Adaptation Options

The current road inventory for California was used to analyze the risk of climate change impacts through 2050. These costs are modeled by using IPSS to determine the impacts of changing future climate on existing inventory. Figure 1 shows the projected changes in precipitation and temperature compared with the historic baseline.

Table 1 presents the total costs for California on the basis of the GCM model utilized. Since all models are equally unlikely to occur, three models were selected to provide policy makers with a concise overview of information on possible risk. The range of costs for California is large, with the minimal risk (5th percentile) reactive cost of $593 million and the higher end (95th percentile) of over $3.6 billion. However, across all models, the adapt scenario presents significantly lower costs for the time period with a range of $405 million to $1.7 billion. The risk of adaptation is relatively low, for even if climate change does not occur, the costs are between $326 million and $430 million (adapt, no climate change). Although there is a small fiscal benefit from adaptation, there are additional benefits including less maintenance, fewer traffic interruptions, and an overall more reliable and robust road infrastructure system.

Figure 2 shows the comparative costs based on the reactive and adapt strategies at the county level for California. For most counties, adaptation is less costly than the reactive policy. However, this finding is not true in every county for this GCM. The northern and central parts of the state incur much higher costs from a reactive strategy. For adaptation, most counties are below $40 million annually to adapt to climate change. For the reactive scenario, approximately two-thirds of the counties have costs greater than $55 million annually.



(a) (b)

FIGURE 1 Projected changes on basis of 95th percentile GCM in 2050 as compared with historical baseline averages in (*a*) precipitation (mm) and (*b*) temperature (°C). Results are presented at climate research unit level.

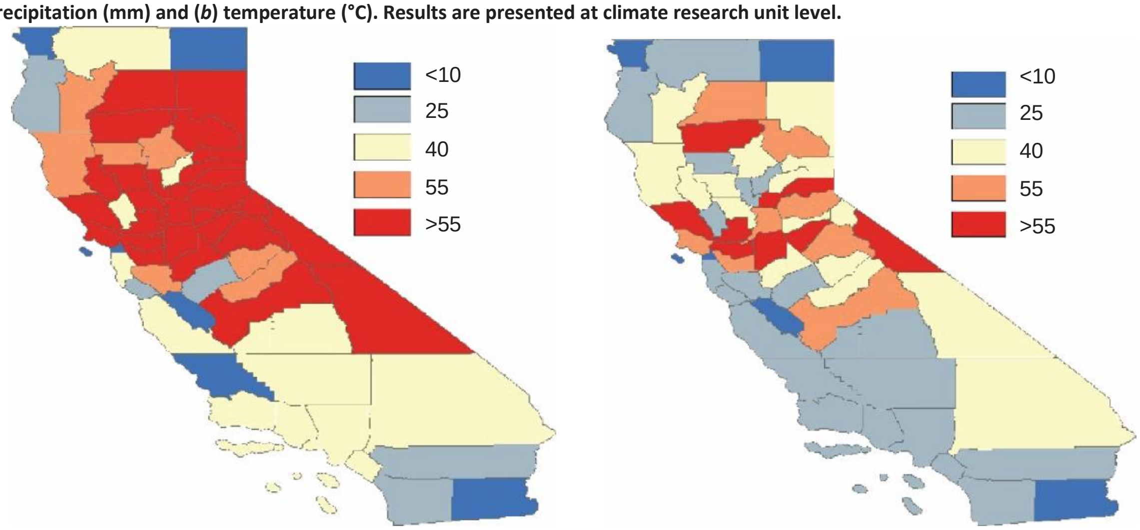


TABLE 1 Cumulative Costs of Climate Change Impact on Road Infrastructure, 2015–2050

Scenario	Cost ($ millions) by California Percentiles			Cost ($ millions) by Sacramento Percentiles		
	95th	50th	5th	95th	50th	5th
Reactive	3,693	627	593	262	19	5
Adapt	1,758	584	405	103	9	3
Adapt, no climate change	430	338	326	12	2	1

Risk Assessment

Another way to assess the risk posed by future climate change is to understand the potential damages projected by the entire range of models. Figure 3 shows a box plot with results from the full range of 54 climate models run for California. The graph shows the range of cost projections based on three policy scenarios: proactive adaptation, reactive with no adaptation, and adaptation in which no climate change occurs. The whisker edges show the costs for the 95th and 5th percentile boundaries, the box edges show the costs for the 75th and 25th percentiles, and the black line in the middle of the box represents the median GCM cost. Figure 3 clearly shows that

Cost ($ millions)

Cost ($ millions)

(a) (b)

FIGURE 2 County-level vulnerability to climate change in 2050 based on average annual cost for 2015 to 2050 for 95th percentile GCM results: (*a*) costs based on reactive policy and (*b*) costs for proactive adapt policy. Costs overall are reduced by approximately $1.7 billion with proactive adaptation policy.

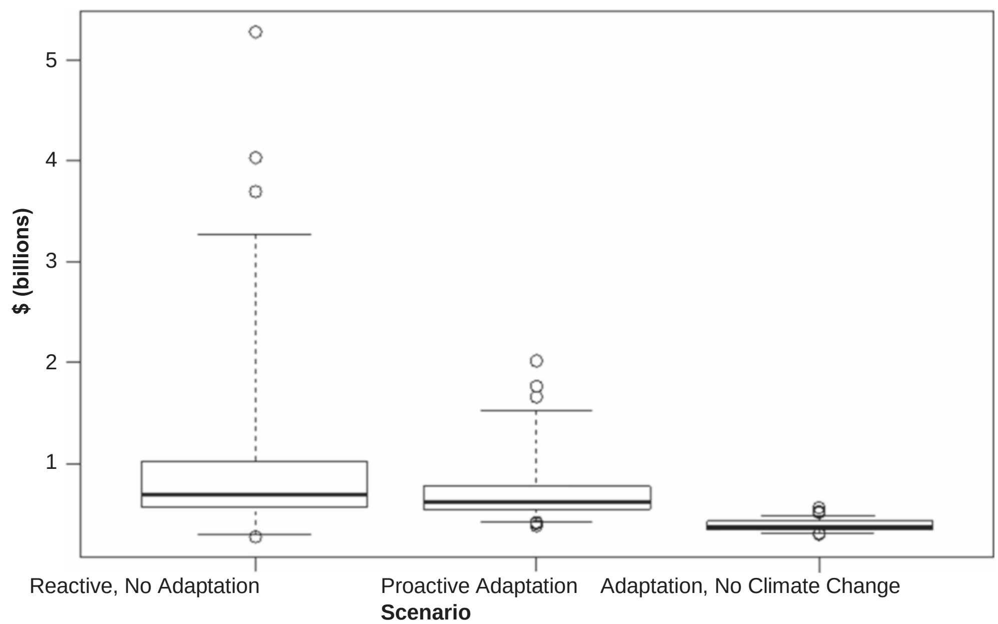


FIGURE 3 Box-and-whisker plot detailing the total range of costs from 54 IPCC-approved GCMs and representing three policy choices: reactive, proactive adaptation, and adaptation where no climate change occurs. Costs are total cumulative costs for 2015–2050 and are based on existing road infrastructure for the state of California.

although the medians for the three policy approaches are not vastly different, the risk is severely enhanced with a reactive approach, with whiskers and outliers spanning a range greater than $4 billion. The risk is much lower with an adapt approach, for which the maximum cost is just over $2 billion with the 75th percentile falling around $700 million. Also, if a proactive adaptation approach is taken and climate change does not occur, the range of costs is much lower with a maximum cost under $600 million total.

City of Sacramento

An analysis for the city of Sacramento included applying the specific impacts of climate change models for the geographic region of the city. Therefore, different climate models with respect to the costs associated with Sacramento were utilized. The median GCM projected approximately a 2°C increase in temperature by 2050, whereas the 95th percentile projects an increase of over 4°C. Because of the urban nature of Sacramento, most roads are paved. The major impact on paved roads is temperature; therefore this element accounts for the majority of costs. In all scenarios, adaptation to climate change is highly beneficial, with margins of economic benefit much higher than the results for the state of California: for the 95th percentile, a savings of over $152 million is possible by adapting, whereas if adaptation is done and climate change does not occur, the total extra cost is $12 million for the same time period and model (Table 1). Because adaptation takes place over time as roads are rehabilitated, the difference in cost is a result of increased climate stress before adaptation of a road is completed.

The range of costs is reflected in Figure 4. A box-and-whisker diagram shows the range of costs by decade for all 54 GCMs. The whiskers incorporate the 95th to 5th percentiles, the box edges of the 75th and 25th percentiles of model cost projections, and the black line represents the median GCM. The variability increases over time. The adapt policy sees a logarithmic increase in cost over time, whereas the reactive policy sees an exponential increase in costs over time. This finding shows an increase in the risk margin over time for a reactive policy.

Roads exist for community use and economic and social activity and are vital in emergency situations. For an urban setting, the maintenance and expansion of roads form one of many competing priorities for growth and resilience. For Sacramento, climate change poses potentially high costs if not addressed proactively. However, where budget and time constraints limit the investment potential, prioritizing investments based on community use, criticality, and other factors is important (*16, 43*). As a segue to an important discussion, Figure 5 is presented as an example of the types of infrastructure that can be considered alongside roads to determine the criticality of investment for climate resilience. Key highways are marked in black, with hospitals in green and schools in purple. In addition, a population density map is provided to give an idea of the number of persons dependent on different neighborhood roads based on their home locations. For example, near the center of this graphic there is a small area with four major hospitals, the intersection of two major highways, and a rail line. This area may be a key priority for investment based on traffic patterns and criticality. Assessing the area's resilience to climate-related incidents is an important next step.

liMiTATionS

This study is designed as a statewide assessment of the vulnerability to the impacts of climate change, adaptation options, and cost–benefit analysis of the existing road network of California through 2050. There are several limitations to the current approach. A main source

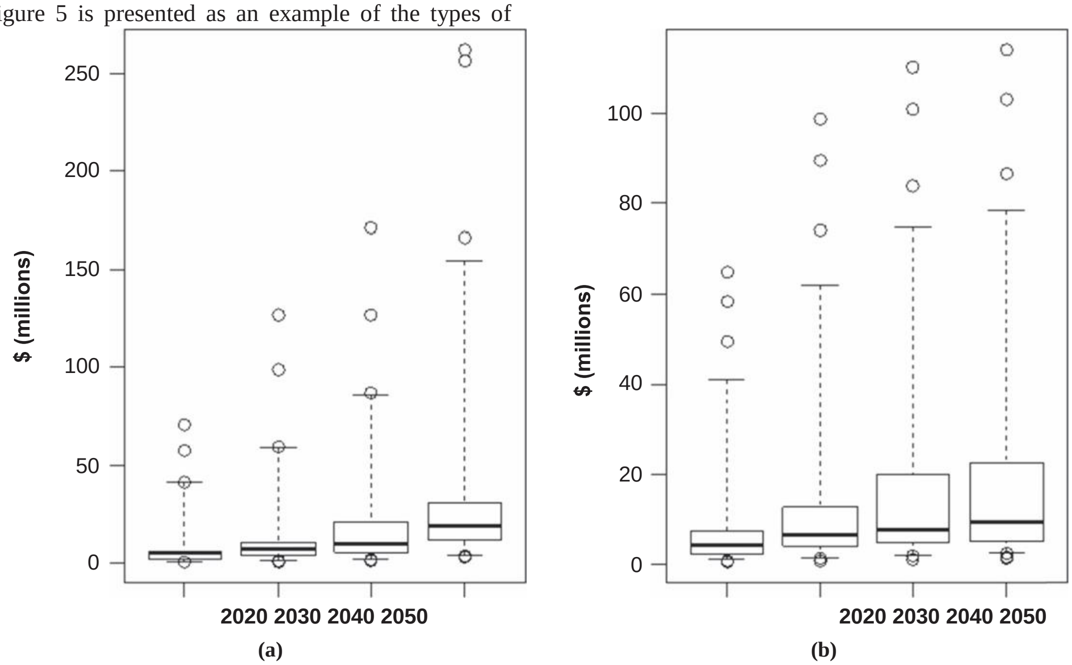


FIGURE 4 Box-and-whisker plot detailing total costs for the City of Sacramento from impacts of climate change based on 54 IPCC-approved GCMs, with results presented as average annual cost per decade for two policy approaches: (*a*) proactive adaptation and (*b*) reactive, no adaptation [differences in scale (all costs in $ millions, 2015)].

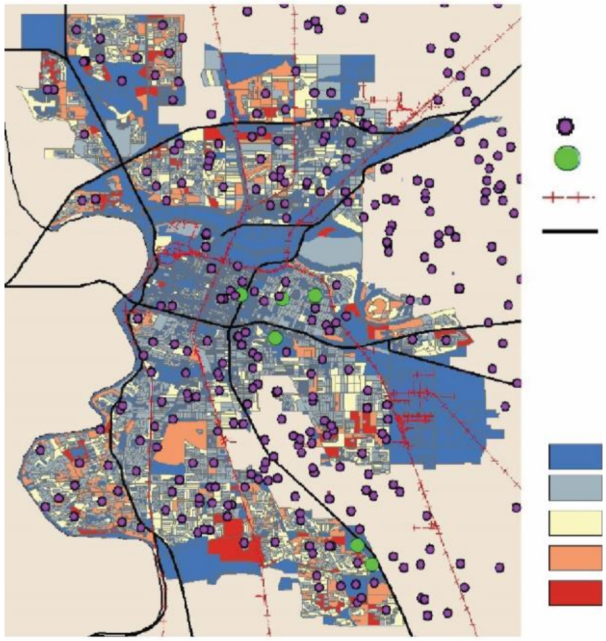


FIGURE 5 Map of the City of Sacramento, including key infrastructure, roadways, and population by block.

of uncertainty comes from the data used for analysis. Inherently, future climate modeling is uncertain (*1*, *2*). However, the authors sought to reduce this risk as much as possible by using all available models that are approved by the IPCC to provide a range of analysis for future climate change.

In addition, a limitation of the modeling approach used is the assumption of perfect foresight for adaptation. The approach used in this study posits that adaptation is done at the time of reconstruction to account for all climate-related damage throughout the lifetime of the infrastructure. It is highly unlikely that the projected changes will occur exactly as modeled.

A final key limitation of this study is that the analysis was limited to considering incremental changes in climate (precipitation and temperature) on existing road infrastructure. It therefore does not account for sea level rise, flooding, other extreme events, and growth of infrastructure. Although all of these events are within the capabilities of the IPSS tool to analyze, the scope of this study as well as the available input data limited the study.

diSCuSSion And ConCluSionS

Climate change has the potential to severely damage existing road infrastructure and place constraints on the resources available to address future projects. Policy makers and planners are aware of this situation yet have limited tools and knowledge that are readily available to assist in allocating resources and planning for a changing climate. A quantitative example is presented of the costs of climate change to the state of California's road network through 2050 by using all available IPCC-approved AR4 climate models. Instead of selecting only a narrow range of models or prescribing general guidelines, the IPSS tool utilized presents a range of all available climate models and specific impact guidance based on yearly economic costs.

This study has several implications for the wider U.S. transportation system. In particular, the IPSS tool and methodology used are applicable to any geographic region. There are several similarities between the California road network analyzed and infrastructure in other U.S. states; for example, the Superpave asphalt standard is widely used throughout the United States. Information from these design standards is included in the impact analysis. Also, although specific impacts of climate change are calculated with available information about the construction of California's road network (including historical climate data), these inputs are flexible and can be adjusted to meet the specific requirements of planners in any geographic area. Finally, this study illustrates that even with (or perhaps particularly with) a large transportation network recognized as vulnerable to climate change impacts, a proactive approach to planning and addressing climate change is a fiscally responsible undertaking. Costs are expected to increase significantly and nonlinearly in the future, highlighting the need for proactive planning (*11*).

This study addresses existing gaps in the literature including a methodology applicable to a wide geographic area; input data readily available for most U.S. states, allowing for potential replicability; a move away from static and stationary engineering planning that relies only on historical performance data; and quantification of impacts and uncertainty to provide a foundation on which to build. The methodology also incorporates vulnerability, adaptation, and risk assessment, which are commonly used in transportation decisions; this inclusion makes the method readily available for incorporation into existing decision processes (*42*).

The need to incorporate future climate change is important. It is critical to understand the cost and benefit of adaptation when compared with a reactive strategy. In all models used in this study, the governments of California and Sacramento can save significant amounts of money as well as receive side benefits such as increased resilience to extreme events and more resilient infrastructure by adapting proactively. For the higher-end scenarios (95th percentile), California can save nearly $1.7 billion between 2015 and 2050 by adaptation; a median scenario provides a savings of $43 million and the 5th percentile has a savings of approximately $188 million.

This study also seeks to comment on a major uncertainty of climate change: What if an adaptation scenario is chosen, yet climate change does not occur as expected? Although this question remains impossible to answer fully, this study provides a beginning approach to addressing the issue by providing quantitative information to assess the potential risk. The adapt, no climate change value provides the amount of money that would be wasted if a proactive adaptation strategy is followed but no climate change occurs.

The IPSS tool used to analyze climate provides a step forward in understanding risk, adaptation options, and the vulnerabilities of infrastructure to climate change. By continuing to include the latest models and partner with decision-making institutions, planners can use the tool to continually enhance their ability to incorporate accessible, quantitative information in their decision processes. This is an important step in creating a more robust and resilient transportation system for the United States and the world.

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APPENDIX V

Submitted version of: "The Triple Bottom Line: Bringing A Sustainability Framework to Prioritize Climate Change Investments for Infrastructure Planning"

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The Triple Bottom Line: Bringing A Sustainability Framework to Prioritize Climate Change Investments for Infrastructure Planning

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ABSTRACT

Climate change is an increasing concern of agencies, governments, and societies around the world. It poses potential adverse impacts to civil infrastructure, with consequences that include increased financial resources, economic impacts, social impacts, and planning issues. This paper aims to enhance and broaden the discussion on sustainability and the importance of the consideration of social, environmental, and technical aspects in relation to infrastructure planning. Particularly under climate change, these considerations allow for more holistic, effective, and long-term benefits to communities and economies. This paper introduces the Triple Bottom Line (TBL) approach to sustainability as a framework for holistic infrastructure planning under the uncertainty of climate change. The Technical Pillar will focus on the impacts of climate change on road infrastructure and the cost-benefit of potential adaptation options; Environmental considerations include quantifying the potential increase in GHG emissions from increased roadworks required by climate change damages; and social information will be quantified using an index based upon the SoVI method. Each of these 'pillars' of sustainability will be analyzed individually and mapped using Geographic Information Systems (GIS). Finally, a 'holistic' approach will be discussed where these individual layers are combined using GIS to display the information. A case study focused on the Sacramento Region of California is used as a proof-of-concept for how the triple bottom line framework introduced here can be utilized to provide actionable, more equitable decision-making for investment in critical infrastructure adaptation policy.

INTRODUCTION

The growing awareness of the impacts of climate change, particularly on the built environment and the consequential implications for society, calls for more robust and quantitative means of measuring impacts and planning for the future. However, without even considering future changes in climate, policy makers, researchers, and citizens alike recognize that there are gaps in society's ability to fully address issues of social inequality, degrading infrastructure, and increased greenhouse gas emissions, among many other issues. While climate change does not pose many wholly new problems, it does compound existing issues with new questions of temporal elements, higher levels of uncertainty, and an increased urgency to address vulnerabilities that will be further exploited by a changing future climate.

Work focused on sustainability science provides a useful context for evaluating and addressing many cross-disciplinary, complex issues. Particularly, the use of a *triple bottom line* ("TBL") (also referred to as *P3* or *three-pillar model*) explicitly focuses on three areas which, while interconnected in reality, are often treated separately in academic literature and practice: "*social*, *environmental*, *and economic"* or "*people, profit, and planet" (1, 2)*. Each of these sectors has traditional disciplines which are focused on addressing both historical and climate-change related issues to sustainability. It is in the combination, however, where actionable solutions are likely to be found, particularly when there are competing interests and needs at the policy level.

Specifically in response to the awareness of the need for better information about what climate change may mean for planners, several states, cities, and agencies have created documents calling for better information about climate change specific to their interest areas. The U.S. Environmental Protection Agency (EPA) has recently released a report: "Climate Change in the United States: Benefits of Global Action" (also referred to as the "CIRA" Report), which highlights many of the domain-specific and broader impacts of climate change on infrastructure and society *(3)*. Related to infrastructure and social vulnerability, this report specifically uses work focused on how the impacts of sea level rise impacts on coastal areas in the United States and how the impacts are distributed among different levels of equity and vulnerable populations *(4)*. The study determined that it is critical for policy regarding climate change to explicitly incorporate environmental justice concerns that target investments towards vulnerable populations. Another study focuses on the importance of converging the concepts of resilience and sustainability within infrastructure planning because of the relevance of infrastructure to hazard and risk planning, impacts on populations, and the multiple facets of infrastructure planning *(5)*.

In another example, Tribbia and Moser *(6)* review information for coastal managers in California and how climate change is affecting their daily decision-making capacity and focus. Using case study and interview data, they conclude that planners need and will use specific information about social, economic, and environmental concerns of climate to make better development decisions. In the context of urban resilience, Leichenko *(7)* states that urban resilience must "focus on enhancing the capacity of cities, infrastructure systems and urban populations and communities to quickly and effectively recover from both natural and human-made hazards….climate change is regarded as one of many threats for urban areas which must build resilience". Additionally, he states that the next generation of urban resilience research must incorporate equity concerns into any resilience strategy.

These papers, among much other recent work, provide a clear call for broader assessment of the nature of sustainability and resilience. In relation to infrastructure planning, this relates directly to the current focus on creating more sustainable and resilient 'critical infrastructure'; of which road transportation networks play a substantial role *(8–12)*. The triple bottom line and sustainability framework provide a useful method for combining many aspects related to infrastructure planning.

Therefore, this paper aims to enhance and broaden the discussion on sustainability and the importance of the consideration of social, environmental, and technical aspects in relation to infrastructure planning. Particularly under climate change, these considerations allow for more holistic, effective, and long-term benefits to communities and economies. Specifically, the triple bottom line framework will be used: technical information will focus on the impacts of climate change on road infrastructure and the cost-benefit of potential adaptation options; environmental information will quantify the potential increase in GHG emissions from increased roadworks required by climate change damages; and social information will be quantified using an index based upon the SoVI method. Each of these 'pillars' of sustainability will be analyzed individually and mapped using Geographic Information Systems (GIS). Finally, a 'holistic' approach will be discussed where these individual layers are combined using GIS to display the information. A case study is used as a proof-of-concept for how the triple bottom line framework introduced here can be utilized to provide actionable, more equitable decision-making for investment in critical infrastructure adaptation policy.

BACKGROUND

The domain of sustainability science is focused on studying the trans-disciplinary science and practice of 'sustainability' *(1, 13)*. The concepts of sustainability and multi-disciplinary thinking first gained notoriety through "Limits to Growth" by Donella Meadows, published in 1972. The concept of sustainability and 'systems' thinking was highlighted as a top priority for science and technology *(13)*.

While the domain has evolved over the last forty years, it has recently gained greater prominence (the journal *Sustainability Science* was first published in 2006). In academia, there are still differing definitions on the characteristics and nature of sustainability science. The Brundtland Report is often referred to as one of the first accepted definitions of sustainability, stating that, "sustainable development … meets the needs of the present without compromising the ability of future generations to meet their own needs" *(14)*. Ostrom et al. *(15)* posit that sustainability science is an applied science focused on scientific knowledge obtained from existing disciplines to build capabilities specific to sustainability science. Several publications define sustainability science as an 'area' that brings together different researchers and multidisciplinary perspectives, but not yet a unique and distinct field of research *(1*6, *17)*. Most recently, and following a comprehensive review of sustainability science literature, sustainability science is defined as a distinct discipline that 'arches' over existing disciplines *(1)*. In this view, it provides a framework to address issues related to sustainability without severing ties to existing disciplines. Martens *(18)* outlines four aspects of sustainable development including intergenerational considerations (analysis considering a time period of at least 25-50 years), multiple levels of scale of analysis (relevant to specific issues being studied), multiple domains (three-pillar concept of integrating multiple perspectives for consideration), and multiple interpretations (each domain has a different view of what sustainable development is and how to achieve it).

Within this definition, sustainability science necessarily covers a wide range of topics. Climate change is one of the most-written about topics, but most work focuses on environmental impacts, mitigation of emissions, and a small amount of work on impacts on the built and human environments *(1)*. In relation to climate change, there is a growing recognition that some impacts of climate change are unavoidable, and therefore mitigation measures need to be coupled with vulnerability assessments and adaptation investments to address the changes *(12, 19–21)*. In terms of critical infrastructure, this vulnerability has been widely recognized at the policy level, including: within the United States, *The White House Climate Action Plan(22)*, the *Transportation Research Board Special Report 290 (23)*, and the *Department of Homeland Security Climate Action Plan (8, 24)*; globally this has been a concern even longer, within development agencies, country governments, and non- and inter-governmental groups all investing to understand vulnerability to climate change and potential investment strategies *(12, 19, 25, 26)*.

Especially at the policy level, understanding, planning, and implementing strategies to deal with climate change impacts on critical infrastructure is imperative. From a direct financial impact perspective, unforeseen and/or unbudgeted costs can cripple an economy, particularly at the local level *(24, 27, 28)*. These unaddressed impacts can also result in much higher costs of repair and maintenance than are necessary if a proactive, planned adaptation approach is taken: a recent EPA report highlights cost at approximately $4 billion USD annually by 2050 for the US *(3, 29)*. While the direct financial impacts are substantial, the most detrimental costs are incurred indirectly in terms of economic loss due to increased travel time, travel difficulties, and social impacts *(9, 20, 30)*. Loss of critical infrastructure can adversely impact livelihoods, increase cost of transportation of goods, and have ripple effects throughout the economy and society. This is particularly acute if multiple links are lost or are damaged for an extended period of time *(9, 20, 30)*. Climate change directly exacerbates existing vulnerabilities to weather and other events by incrementally degrading the quality of infrastructure. This incremental damage accelerates degradation, making infrastructure more vulnerable to hazardous events than can be modeled based on historic weather and degradation data *(30, 31)*.

These additional and indirect impacts motivate the consideration of critical infrastructure adaptation within the triple bottom line framework. The three-pillar approach is important because it maintains deep domain expertise within each pillar, but then combines the three for assessment and recommendations based upon results considered in the holistic framework. This is helpful for guiding investments in critical infrastructure in two main ways: first, a sustainability approach inherently introduces a spatial and a temporal aspect for consideration. Road infrastructure is a spatial consideration and exists throughout the world as a means for development, economy, safety, and society. Climate change impacts are temporal, with varying impacts throughout time requiring different reactions and investments throughout the life-cycle. Secondly, climate change planning increases the uncertainty of decision-making, particularly in a technical field where precise historical data which informs design is no longer reliable *(22, 24, 27, 31, 32)*. Incorporating a more holistic view of vulnerability allows for an expanded set of goals, including an explicit human component *(18)*. Additionally, a sustainability approach more definitively considers the necessary components of tradeoffs; between robustness and vulnerability and between costs and benefits *(12, 15)*. With transportation, this is particularly acute: from a criticality perspective, more roads means that there is more robustness if a road fails, but from an environmental perspective, more roads means more pollution and greater greenhouse gas emissions. Acknowledging and addressing these tradeoffs and uncertainties within a more holistic societal framework may create more usable results for decision makers to consider.

The case study utilized in this paper is focused on the Sacramento Area Council of Governments (SACOG), a six-county metropolitan planning group encompassing El Dorado, Placer, Sacramento, Sutter, Yuba and Yolo Counties in Northern California in the United States *(33)*. SACOG was selected as a proof-of-concept case study for several reasons, including open-source availability of GIS data of infrastructure in the region and an ongoing 2035 transportation plan that includes the reduction of emissions 16% from vehicles by 2035, consideration of lower-income populations, and broader concerns associated with holistic infrastructure planning *(33–35)*. There are also currently a number of laws and funding mechanisms in SACOG and California that focus on climate change adaptation, mitigation, and education *(34, 36)*. Results from this study will be discussed, where relevant, in the context of stated SACOG goals and existing infrastructure.

METHODOLOGY

This analysis is based upon a three-pillar analysis with a fourth step of integration. Each pillar is evaluated individually and results are provided in GIS based upon quantitative results. A first step critical to the technical and environmental pillars is climate change information that can be used to determine financial impact of climate change and the environmental impact of increased road repair works.

Climate Change Information

The first phase of this study required obtaining usable climate modeling information for the case study region. The current ensemble of models used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) is known as CMIP5 models ("Coupled Model Intercomparison Project Phase 5") and future climate change is modeled based upon a set of scenarios known as RCPs ("Representative Concentration Pathways"). RCPs are specific scenarios of future climate based upon the approximate total radiative forcing in year 2100 relative to 1750. RCP 4.5 represents a stabilization scenario, where the global mean surface temperature change in the 2050 decade is projected to range from 0.9-2.0˚C compared to 1985-2000 baseline *(37)*. For this analysis, 19 climate models from the RCP4.5 scenario were used based on data provided by the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) 5th phase, accessed from the "*Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections*" archive. The information for this analysis was downscaled using daily bias-correction and constructed analogs (BCCA) techniques *(38, 39)*.

The data obtained provides daily precipitation and temperature minimums and maximum values for 1/8° grids for 2016-2050 for the case study area. These data sets were then processed using the IPSS™ software system to provide information specific to the technical and environmental pillar analyses below.

First Pillar: Economic/Technical

The first pillar of analysis for this paper is focused on road infrastructure. This is the most familiar component for transportation planners in terms of quantifying costs of infrastructure construction and maintenance based upon specific climate parameters, engineering materials and design guidebooks, and field tests. However, this pillar is focused specifically on quantifying the potential impacts and adaptation options for road infrastructure from changes in the future climate. For this analysis, this paper builds directly upon previous published work, including Schweikert et al. (2015) published in 94th Annual Transportation Research Record (presented at TRB 94th Annual Meeting in January 2015) *(40)*. The analysis for quantifying climate changes on road infrastructure is completed using the IPSS™ software tool.

The IPSS™ software is developed by Resilient Analytics and designed to provide annual cost estimates of the impact of climate change on road and building infrastructure on an annual basis through 2100. The climate models described above and the road infrastructure inventory for the SACOG region *(41)* are used as input information to the IPSS™ system. They are analyzed using engineering-based stressor-response equations to determine the impact of and climate changes (ex: precipitation and temperature) on specific infrastructure elements. The system identifies the financial cost on a yearly basis and allows users to compare proactive adaptation measures with reactive non-adaptation measures; both of which are compared to a baseline 'no climate change' scenario.

The IPSS™ System provides costs on a year basis based upon the modeled impacts from daily climate model data. The 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. Impacts are determined for each type of road (paved, gravel, earth and primary, secondary, tertiary) and assessed per kilometer of road. All the specific road type response equations, thresholds and methodologies are detailed in previous work *(29, 40, 42–46)*. They have also been used in international climate studies including a study for the Asian Development Bank *(47)*, the European Union *(26)*, and Canada *(48)*.

For this study, the costs are based on comparing two distinct strategies, or policy approaches of proactive and reactive investment for adaptation. The baseline goal is to retain the original design life of the infrastructure despite changes in climate stress. The costs are based upon the increased cost of construction to account for climate-related damages over the lifespan of the infrastructure as well as the maintenance costs from road inventory which has not yet been adapted. Upgrades on the design standards of the roads increase resilience to stressor impacts projected by the climate models to occur in the life-cycle of the road. This proactive adaptation strategy is compared with a reactive strategy where increased climate change stress results in damages to the road requiring an increase in unplanned maintenance and repair works. The resulting value is called the 'adaptive advantage' and reflects the cumulative financial savings from a proactive approach compared to a reactive approach for each model. While no extreme events are considered in this analysis, by proactively investing to improve the baseline level of infrastructure will provide current benefits to withstand extreme weather events *(31)*.

Second Pillar: Environmental

The environmental pillar of this analysis focuses on the increased greenhouse gas (GHG) emissions necessitated by the increased road maintenance from the impacts of climate change. Estimating GHG emissions associated with road construction, operation and maintenance can be done using a number of techniques. Existing tools include the *Road Construction Model* produced by the Sacramento Air Quality Management District and the *GreenDOT* tool. Both have robust ways of accounting emissions based on various factors associated with road infrastructure. However, it is difficult to isolate emissions related specifically to climate change with these tools. Therefore, the environmental pillar for this analysis is narrowly scoped, focusing specifically on the emissions related to increased material required by increased maintenance and repairs from climate change damages from increased temperature. The numbers provided by this analysis approach are only a fraction of the total emissions caused by climate change in relation to road infrastructure.

The focus of the environmental pillar is the avoided GHG emissions (measured as tonnes of CO_2) by taking a proactive adaptation approach (conversely, these numbers are also the increased emissions from climate change damages on road infrastructure). While the technical pillar focuses on the adaptation options that can be implemented to increase road resiliency to climate change impacts, the environmental pillar focuses on quantifying the emissions that can be avoided by taking this proactive approach. The potentially-avoided GHG emissions are calculated based upon the increase in required materials to repair roads damaged by increased heat and precipitation.

The increased necessity for maintenance is calculated using the IPSS™ system. Where damages are projected to occur on the road network due to changes in climate beyond specific thresholds, damages are incurred. For this analysis, the main driver of increased maintenance is from heat increases which cause cracking. The analysis from IPSS™ highlights on a yearly basis where thresholds have been exceeded due to climate change and damage has occurred. Damages are calculated on the 1/8˚ grid scale and applied to the road infrastructure within that grid.

Cracking is calculated when a threshold for heat is exceeded due to historical baseline comparison. Cracking of asphalt pavement is a common phenomenon and is considered the primary mode of deterioration in pavements *(49)*. Because of the growing recognition of the importance of addressing cracks as a preventative maintenance technique, the analysis focuses on repairing cracks on an annual basis when heat impacts occur. The incidence of cracking is estimated based upon the IPSS™ analysis. The frequency of cracks per kilometer and size of crack is estimated using the PASER and FHWA specifications, particularly focused on transverse cracking caused by heat *(49–51)*. Because specific prediction of exact cracking occurrence is difficult, the cracking estimated to occur from an increase in temperature is approximated to the PASER *level 7* surface rating, where cracking occurs and is addressed through increased frequency of routine sealing procedures *(51)*.

Emissions are calculated based on the material required for maintenance (filling of cracks resulting from climatic damages). This calculation is based on severity of surface damage (including the crack depth, width, and length) based upon the PASER guide. Calculations vary for primary roads when compared with secondary and tertiary asphalt roads. GHG emissions are based on estimated CO_2 emissions from embodied materials emissions *(52)* . The estimated volume of asphalt per volume of repair is estimated using information from the Nebraska Department of Roads specifications for a wearing course of standard construction *(53)*.

The estimated tons of CO_2 emissions per kilometer of repair needed for primary roads are: 3.46 tonnes. For secondary and tertiary roads, the estimated increase in emissions per kilometer is 1.76 tonnes of CO_2.

Third Pillar: Social

The third pillar for the triple bottom line analysis is the “Social” pillar, or “People” pillar focused specifically on the population within the study area. A fundamental component of social vulnerability is the recognition that within communities, there are different geographically defined areas where sub-populations have different levels of vulnerability that can result in disparity of impact and recovery from hazard events *(54)*. The recognition and identification of these areas is designed to help planners and emergency managers effectively allocate resources and plans to ensure the poorest and most vulnerable populations have their needs met in a hazard situation *(55)*.

The impacts of climate change on issues of social equity, development, and vulnerability are an integral part of climate change literature. Particularly relevant to this proposal is the concept of climate justice, defined as the concept that often those populations being most impacted by climate-change related events are least able to respond and recover *(56)*. The literature states that while this is partially attributable to geographic location, it is also highly impacted by the social factors which allow particular groups to be more susceptible to harm and less able to respond. These factors are often difficult to quantify, but as defined in the section above, this vulnerability includes a lack of access to resources (knowledge, information, and technology); limited access to political power and representation; infrastructure stock, age, density and type; and physical limitations of individuals (including elderly, infirm, disabled, and children) *(57, 58)*. The recent CIRA Report released by the EPA utilizes many of these concepts in their assessment of coastal populations at risk from sea level rise *(3, 4)*.

For this pillar, the analysis uses a social vulnerability index from an open-source data set provided by the Pacific Institute *(59)*. It is built on the SoVI model developed by Cutter (1996) which defines 32 distinct variables that contribute to social vulnerability to environmental hazards at a county level throughout the United States *(60)*. Building upon this technique, the Pacific Institute used 19 of the variables determined to be directly related to climate change (specifically focused on heat). These variables are independently assessed for vulnerability at the Census Tract level *(61)*. Each of the 19 individual variables is scored based upon the most recent available data (most variables use 2010 U.S. Census data), then standardized and ranked using the Z-Score technique to create a vulnerability score *(59)*.

The vulnerability assessment is treated as static based upon the most recently available data (in most cases, the 2010 Census). While this is a limitation of the study, it is impossible to project trends accurately for the future decades, and a static snapshot used for assessment purposes is consistent with methodologies for assessing integrated stakeholder analysis for large infrastructure projects *(62)*. It provides a baseline assessment of vulnerability for this model.

Synthesizing the Triple Bottom Line Approach

The final step in this analysis is to utilize the information from each pillar and synthesize into a single decision making strategy. This illustrative analysis takes a multi-criteria decision approach where each pillar is ranked equally and an additive process is utilized to provide a composite ranking, which is a common process in transportation planning and allows for flexible use by decision makers *(63–65)*. In reality, this step requires knowledge about local preference and goals and the weighting of the criteria, and these can be incorporated into the final decision process. This process is illustrated below in the Results Section with specific spatial examples for this analysis.

RESULTS

Quantitative results from the three analyses are detailed using GIS. The maps in Figure 1 show the priority level for each pillar based upon the quantitative results, with darker colors indicating greater priority. Figure 2 details an example of how a multi-criteria approach to decision making using the triple bottom line framework can be spatially expressed to reflect high priority investment areas.

While a total of 19 models were run, the results reflect the outcome from the 95th percentile model to show the higher end impacts from one potential future. These results are based on the IPSS^{TM} analysis for the CNRM_CM5 RCP4.5 model.

Individual Pillar Results

An individual analysis was performed for each pillar. For the technical and environmental pillars, the annual impacts generated by IPSS^{TM} for the 95th percentile model from the 4.5RCP Scenarios were used. Figure 1 reflects the spatial distribution of results in the SACOG Region: 1A is the Technical pillar; 1B is the Environmental pillar; 1C is the Social pillar.

The “adaptive advantage” mapped in Figure 1A reflects the cumulative financial savings (2015-2050) from taking a proactive adaptation policy when compared to the cumulative costs of a reactive approach. The “emissions saved” mapped in Figure 1B reflects the emissions avoided by taking a proactive approach, based on reduced maintenance requirements from climate change damages required by a reactive approach. The social vulnerability map in Figure 1C reflects 2010 data for vulnerability of populations based on Census tracts.

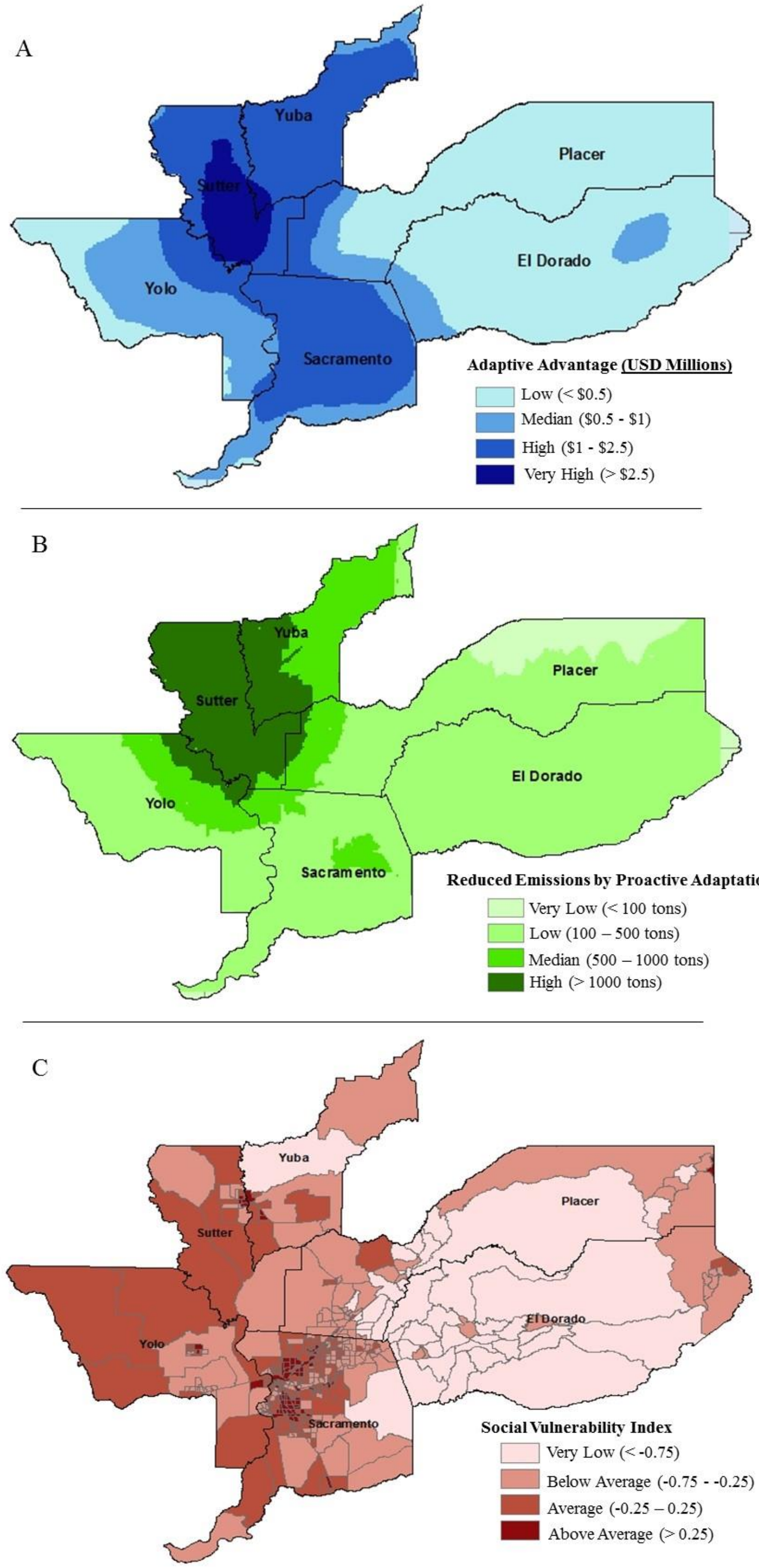

FIGURE 1: Individual Pillar Results for SACOG Region. Maps A and B reflect results from the 95th% GCM scenario for RCP4.5 based on cumulative impacts 2015-2050. Figure 1A is the Technical Pillar, Figure 1B reflects the Environmental Pillar, and Figure 1C is the Social Vulnerability Results

Triple Bottom Line Results: Prioritization

Combining the quantitative results from each pillar above and ranking the census tracts (as the lowest level of analysis) for investment priority is based on a multi-criteria approach and equally-weighted ranking of the three factors (Figure 1A). A ‘Very High’ ranking means that at least two of the three pillars have ‘high’ rankings for prioritization for proactive adaptation investment: indicating that at least 500 tonnes CO_2 are saved; greater than \$2.5 million USD are saved; and investments occur in geographic areas where population vulnerability is above 0.5. For ‘low’ rankings, at least two pillars have ‘low’ prioritization rankings: less than 100 tonnes of CO_2 emissions avoided; less than \$0.5 million USD saved; with investments occurring in areas with a less vulnerable population below -0.5.

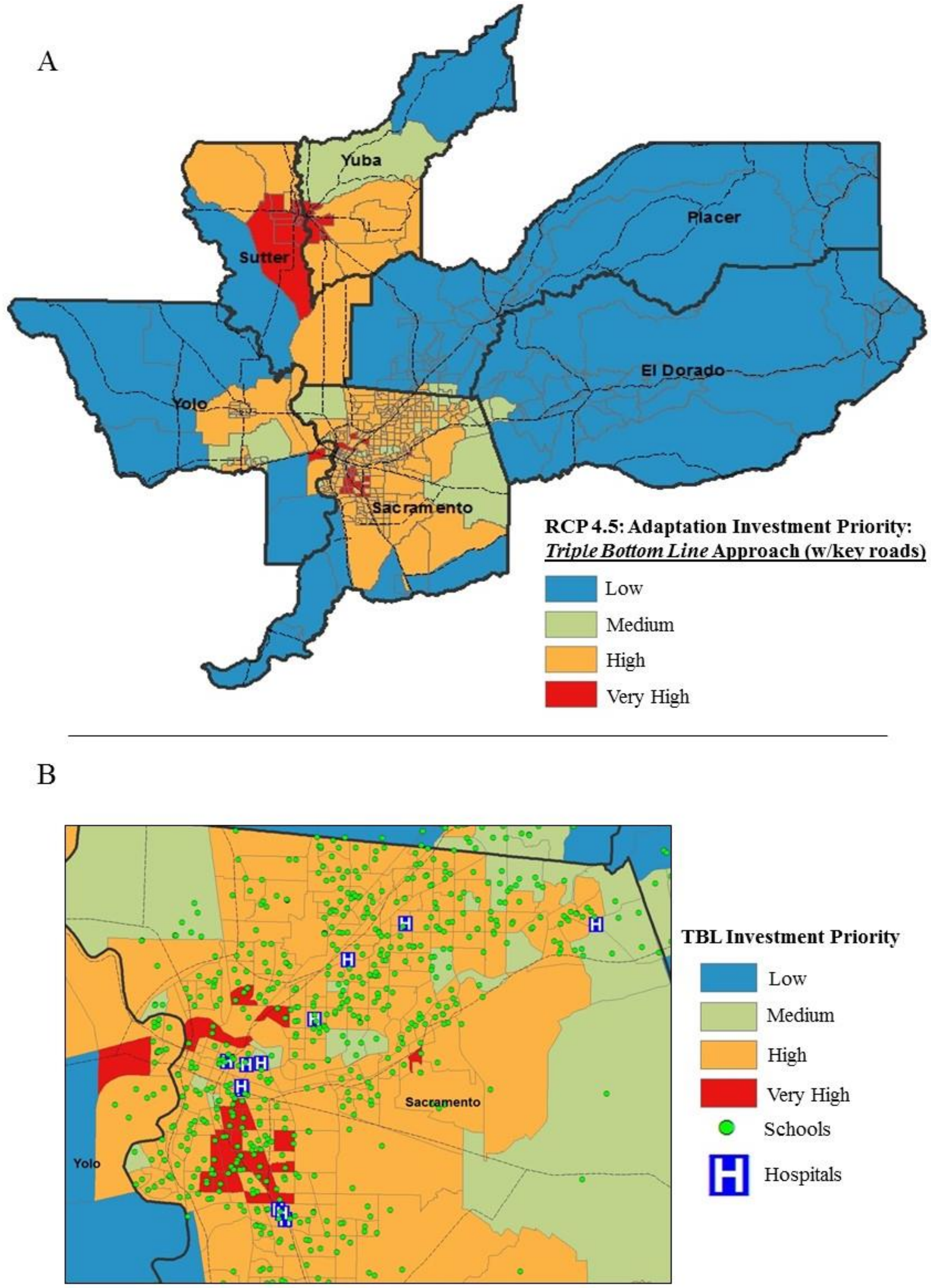

FIGURE 2: "Triple Bottom Line Prioritization" – Investment priority for SACOG Region based on three-pillar TBL analysis. Cumulative climate change impacts at 2050 for 95th% model, RCP 4.5. Results displayed at Census Tracts, the lowest geographic unit of analysis

The areas around Yuba City indicate highest priority investment based on TBL prioritization. This is due to very high impacts of climate change in this region, indicating high levels of financial savings and emissions reduction if proactive adaptation is taken. Sacramento has varied prioritization levels within the city (see: Figure 2B). Combined with GIS information for hospitals and schools *(41)* this illustrates how multiple priorities can be used to inform priority investment areas. For example, the Southern part of Sacramento sees a concentration of Hospitals with several Census Tracts with "Very High" rankings. These areas contain highly vulnerable populations (above 0.5), see very high savings from proactive adaptation (>$1 million), and have medium savings from emissions (between 500-1,000 tonnes CO_2). These roads may see a higher benefit from proactive investment than other areas in the County.

LIMITATIONS AND FUTURE WORK

This analysis has several limitations based on scope of the study and data availability. A key source of uncertainty is the climate change models. This is reduced by analyzing all available CMIP5 RCP4.5 models and can be updated as future models evolve. Another limitation is the static nature of the analysis, which does not account for improved construction or maintenance technologies that may change costs and/or reduce emissions. This analysis also utilizes a static measure of social vulnerability to climate change. Finally, the environmental pillar is narrowly scoped to estimate emissions based on only embodied CO_2 from maintenance materials.

Many of these limitations can be addressed using local knowledge and existing sector-specific tools. This could include utilizing forecasted demographic change data based on local assessments, or data from the American Association of State Highway and Transportation Officials (AASHTO) *Census Transportation Planning Products (CTPP)* data *(66)*. This would help forecast potential social vulnerability changes and other information that could be useful where more detailed planning analyses are required. For emissions, a broader accounting of GHG including equipment, construction, congestion, and other factors should be included for a more accurate assessment.

CONCLUSION

The application of the TBL methodology to the Sacramento region provides an insight that is unique to the planning lexicon. Rather than separating climate impacts, environmental concerns, and social vulnerability, the TBL provides a consolidated perspective that highlights the combined vulnerability of specific geographic regions. This analysis graphically demonstrates how prioritization of climate change road investments in the Sacramento region could be prioritized from a combined perspective. The benefits to the community, environment, and infrastructure are individually important, but the combined perspective provides an investment plan that provides the greatest opportunity for long-term benefits.

By utilizing specific individual data for each pillar, the TBL holistic perspective can enhance the effectiveness of climate change planning as part of larger community goals while maintaining rigorous analysis of infrastructure, emissions, and social considerations.

The approach utilized in this paper is designed to be a starting point for effective, focused discussion on the improvement and availability of techniques to inform climate change planning. There are many areas where increased data availability, local knowledge and prioritization, and incorporation with broader policy considerations can improve this approach. This model is designed to be iterative, with feedback and discussion informing the actual value to today's policy makers.

Climate change will in many cases exacerbate existing issues associated with infrastructure planning, maintenance, design and integrity. It is affected by processes which increase our GHG emissions. Finally, it is often the most vulnerable persons that are most greatly affected by adverse weather conditions and their impacts. By framing the discussion in a holistic but technically rigorous manner, the TBL can provide a framework for effective and holistic infrastructure policy.

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