MODELING CLIMATE CHANGE ADAPTATION IN TRANSPORTATION INFRASTRUCTURE ORGANIZATIONS

by

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A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Doctor of Philosophy

Department of Civil, Environmental, and Architectural Engineering
2017

This thesis entitled:
Modeling Climate Change Adaptation in Transportation Infrastructure Organizations
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has been approved for the Department of Civil, Environmental, and Architectural Engineering

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IRB protocol #16-0352

ABSTRACT

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Modeling Climate Change Adaptation in Transportation Infrastructure Organizations

Dissertation directed by Dr. Paul Chinowsky

Climate change and extreme weather threaten to reduce the effectiveness and increase the cost of transportation infrastructure in the immediate and long-term future. Despite research that describes the imminent impacts of climate change and policy recommendations to adapt to those impacts, adaptation remains limited in practice. Therefore, this dissertation research is guided by two broad questions: 1) what are the long-term impacts of climate change on transportation infrastructure? and 2) why are transportation organizations not adapting to climate change? Climate change adaptation research has focused primarily on more obvious and sudden impacts from extreme events and more predictable changes in sea-level rise and storm surge. Research has also primarily produced results at a macro economy scale or detailed engineering design scale. While a large portion of research also includes the impacts of temperature and precipitation changes, it is often qualitative or quasi-quantitative and tends to focus on events like flooding or heat waves. Less attention has been paid to quantifying the more uncertain, gradual, and chronic impacts from long-term changes in climate, even though those changes pose a similar, if not greater, risk to infrastructure. Through quantifying the impacts on road networks of gradual changes in temperature, precipitation, and freeze-thaw, a goal of this research is to create and improve the tools, and more importantly the knowledge, that transportation managers need to successfully plan, design, build, and manage infrastructure for long-term effectiveness and resilience. Chapter 3 of this dissertation quantifies the long-term changes in temperature and precipitation on a road network using a stressor-response adaptation model. The model is based on two adaptation strategies, a proactive "climate-proofing" approach which modifies design and construction of roads prior to predicted climate change, and a reactive approach which repairs the increased damage caused by climate change to maintain the original lifespan of the road. The cost of each strategy is

calculated and compared annually through 2100. The data collection and modeling are performed at the organization and network level, to increase the relevance to and implementation by transportation organizations. The Netherlands is used as a case study and the costs of adapting to changes in temperature and precipitation are predicted to range from €0-150 million annually. Proactive adaptation is typically predicted to cost less than a reactive approach. Chapter 4 investigates an even less understood climate stressor, freeze-thaw. A new methodology is developed and incorporated into the adaptation model to quantify the long-term impacts of changes in freeze-thaw cycles. This modeling is also performed using the Dutch road network as a case study. Adaptation costs for freeze-thaw are forecast to range from €0-5 million annually. Unlike temperature and precipitation, freeze-thaw changes will reach a time, approximately 2055, when reactive maintenance is anticipated to cost less than proactively climate-proofing roads.

The work in Chapters 3 and 4 contributes practically to the Dutch transportation agency and fills a knowledge gap by providing a method for other agencies. The work also quantitatively shows that climate change adaptation is a long-term and persistent problem that requires ongoing attention from transportation organizations. This leads into the work in Chapter 5, which investigates the question of why transportation organizations are not implementing climate change adaptation, despite being aware and, in some cases, well-informed of it. This research theorizes that implementation is limited because climate change adaptation is not a singular process or outcome, as much of the current research suggests, but it is a holistic system of many ongoing organizational processes and elements. Chapter 5 uses a systematic literature review to identify these processes and elements, which are suggested in research as technical and organizational strategies for climate change adaptation. The 20 factors are then used in a Delphi survey of industry and academic experts to validate their selection from literature and provide additional insight into their relative importance and urgency. The factor results establish the theory of adaptation as an organization system and provide a useful avenue for future research.

ACKNOWLEDGEMENTS

I would not be where I am personally, professionally, and with this dissertation, without the support of many wonderful people. No matter how much I question my abilities throughout my life, I always feel confident in my ability to surround myself with amazing people.

I thought I would “save the best for last” but I could not wait to thank the most important person in my life. Kate, thank you for everything you have done and continue to do for me and for our little furry family. I would not be finishing this dissertation and continuing on with my career in academia if not for you. Your support has been a constant and positive force, and you have continually put me ahead of yourself, even while confronting your own challenges and achieving your own successes. I hope that you can understand the depth of my gratitude, admiration, and love for you.

Thank you to my parents for their love and support throughout my entire life. You have always made me feel confident in myself and I have been able to try new and difficult things in my life because I’ve always known that you are there to support me in success and failure.

Thank you, Paul, for your support throughout my time at CU Boulder. You have been an incredibly flexible and positive advisor. I would not be researching what I am without the support you gave me starting here at CU. Thank you to my dissertation committee as well. Amy, thank you for your keen insights, for helping me earn the NSF GRFP, and for allowing me to be an honorary member of your research group. Keith, thank you for your insight and honorary research group membership as well – and thank you for supporting my career through your advice and willingness to help at any time. Mike, thank you for sharing your extensive experience with me and helping me think through some of the big picture ideas of my research. And Irina, thank you not only for your research and academic mentorship, but also for being an inspiring and supportive friend.

One of my main motivations for getting a PhD degree was to be able to teach and mentor students. This desire was created and strengthened because of the wonderful mentors I have had throughout my life. One mentor in particular, Samuel P. Clemence, had a deep and long-lasting impact on my desire to be a professor and a mentor. Thank you, Sam, for being such a unique and genuine person – I hope someday to be half as positive and impactful to my students as you have been to yours.

At CU I was fortunate to have a smart, supportive, and fun group of peers that to look up to, learn from, and share experiences with. You all had a positive impact on my time here, so thank you (in no particular order): A-A-ron Opdyke, Xavi Espinet, Erick Oechler, Eric Antillon, Tim McGuire, Laura Kohler, Sarah Welsh-Huggins, Amy Schweikert, Jessica Kaminksy, Liz Jordan, John Wanberg, Wesam Beitelmal, and Keith's and Amy's research groups. And I am especially grateful to have shared the same smelly office and climbing rope with Jeffrey Walters, who is a kind, smart, and hilarious friend. I was also fortunate to be taught by or have worked with some very smart and equally friendly people, including Rita Klees, Robyn Sandekian, Abel Chavez, Matthew Morris, and many more.

During my time in the Netherlands, I received great support and friendship from Hendrik Cramer, Frederick van Amstel, Andreas Hartmann, Alexander Vasenev, Frank Bijleveld, Carissa Champlin, Julietta Matoscastano, and Vedran Zerjav. I am especially grateful to Timo and Natalya Hartmann (and Janik and Sophia) for being such amazing hosts and friends from the minute I arrived.

I would not be completing this PhD if not for the generous financial support from several organizations. Thank you to the CEAE department, the Dutch Organisation for Scientific Research, the University of Twente, and Paul for various forms of financial support. And thank you to the National Science Foundation Graduate Research Fellowship program. Portions of this work are supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1144083. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Chapter 1 INTRODUCTION

PROBLEM

Climate change poses a threat to transportation infrastructure worldwide. Direct costs to infrastructure, including users, and indirect costs to country economies are forecast to be on the scale of hundreds of millions of dollars annually by the middle of the century. (Chinowsky et al. 2013c; a; Pryzluski et al. 2011; Schwartz and Meyer 2014) It is a uniquely long-term (Morgan et al. 1999) and uncertain issue, with a range of future scenarios that vary based on natural and human-induced variability (Moss et al. 2010; van Vuuren et al. 2011). Regardless which scenario is realized, there are unavoidable changes, such as sea-level rise and higher temperatures, that will impact transport infrastructure in the near and long-term future, some of which are already being observed. (IPCC 2015)

Climate change will impact a variety of transportation modes, will result from a variety of stressors, and will manifest in a multitude of ways. Impacts are predicted on air, rail, road, water, and other types of (cycling, for example) transportation infrastructure and their respective users. (Eisenack et al. 2012) Climate change is expected to impact transportation through sea level rise, extreme weather events, storm surge, higher daily temperature, longer and more severe heat waves, melting permafrost, increased precipitation and flooding, more frequent rock and mud slides, and longer and more severe droughts. The impacts are predicted to manifest in physical damage – such as pavement rutting, raveling, heaving, coastal flooding, increased bridge scour, and rail buckling – as well as social and service disruption – including user delays, freight disruption and delays, emergency response, and evacuation route blockage. (Eisenack et al. 2012; Humphrey et al. 2008; Koetse and Rietveld 2009; Meyer et al. 2010b; Schwartz and Meyer 2014)

To avoid or lessen the severity of impacts, transportation infrastructure can be adapted to withstand predicted changes in climate. Adaptation is defined differently depending on the organization or researcher, but can generally be described as a process or outcome that leads to a reduction in harm, or risk of harm, or realization of benefits associated with climate variability and climate change. (VCCCAR 2017) Examples of adaptation include oversizing culverts for increased stream flow, raising floodwalls for rising sea level, relocating coastal roads and facilities, modifying freight load restrictions, and increasing pavement drainage. (Bierbaum et al. 2013; de Bruin et al. 2009b; Colin et al. 2016; Oswald Beiler et al. 2016) Road infrastructure is particularly vulnerable to climate change in terms of cost (Nemry et al. 2012) and the effect on design and management (Asam et al. 2015; Colin et al. 2016; Espinet et al. 2016).

Research Gaps

Gradual impacts from long-term change in climate and organizational-level analysis

Research shows that individuals are more likely to be more aware of climate change and increase their support for adaptation policies when they experience a climate event, like flooding. (Demski et al. 2017) However, the gradual impacts from temperature and precipitation on transportation infrastructure do not share the same immediacy and conspicuousness as flooding, storms, and sea-level rise. While there is a large collection of research describing impacts and adaptation options for road infrastructure, there is a lack of research quantifying these impacts and costs of adaptation for gradual impacts.

For example, Lounis and McAllister (2016) discuss resilience and sustainability for risk-based decision making, analyzing the relationship between these two concepts and how risk-informed design can reduce negative impacts and decrease recovery time after an extreme event. However, this literature focuses mostly on extreme events and does not consider long-term gradual changes in climate stressors. Past research in this domain also uses the community as the unit of analysis, not transportation or infrastructure management organizations. Koetse & Rietveld (2009) detail evidence of climate change impacts, for example slowdown of traffic due to increased precipitation, but do not quantify the impacts to physical infrastructure for the purposes of improving infrastructure management and financial optimization. Kameshwar & Padgett present a method for fragility risk analysis of portfolio of highway bridges subjected to extreme events (earthquake and hurricanes). This is an example of a study performed at an engineering design level but not an organizational decision making and planning level. Bowering et al (2014) studied the flooding impacts of precipitation, however this work only investigated flooding and not the long-term impacts of precipitation. It also uses municipalities as the unit of analysis (London, Ontario, Canada), not state and national infrastructure organizations.

When climate research on transportation infrastructure is quantitative, it is often overly general or overly technical. (Eisenack et al. 2012) There is a lack of detailed research at the network and organizational level. Additionally, research often focuses on specific climate stressors that are more certain to occur, like sea level rise, or are predicted to have very large consequences, like storm surge. This research attempts to fill this gap by investigating the impacts of climate change from the long-term impact of temperature and precipitation, which have more uncertain likelihood or consequence because of their more gradual and potentially less obvious consequences. Additionally, there is a need for research that quantifies the impacts to road infrastructure from long-term changes in freeze-thaw cycle patterns. While there are several studies that investigate permafrost and seasonal freeze-thaw patterns (Alfaro et al. 2009; Daniel et al. 2017; Doré et al. 2016; Melvin et al. 2017; Nelson and Brigham 2003) there is a lack of understanding about how future changes in air temperature will affect pavement through localized freeze-thaw cycles.

This research also attempts to fill the gap of organizational-level analysis by combining detailed technical adaptation and high-level policy considerations to analyze the impacts of climate change at an organizational decision-making level. This research further investigates the outcome of using high-level climate input Global Circulation Models (GCMs) compared to more detailed Regional Climate Models (RCMs), to show the dependence of adaptation outcomes on climate input.

Adaptation implementation

Despite a substantial increase in climate change impact research in the last fifteen years, attention to adaptation is still relatively low in Europe (EEA 2014) and the United States (FHWA

2014a). Research has expanded beyond the identification and measurement of impact into areas including vulnerability assessment (FHWA 2012a), the economics of adaptation (de Bruin et al. 2009a; Schweikert et al. 2014), risk management (Liso 2006; O'Har 2013), asset management (Armstrong et al. 2014; FHWA 2013a), and robust decision making (Daron 2015; Espinet et al. 2015). While these are important steps in the larger research trajectory of climate change adaptation, little research has been completed to understand how these frameworks and tools are implemented by organizations for which they are intended.

Research, and particularly industry action, have been limited to large-scale regional projects and one-time pilot studies. Research is still needed on actual implementation of adaptation, including institutional and organizational elements that fill gaps between policy recommendations and site-specific technical adaptation. (Eisenack et al. 2012) This theoretical knowledge gap manifests itself in industry in a lack of action and difficulty implementing climate change adaptation.

In the United States, state Departments of Transportation (DOTs) are one of the main transportation organizations for which climate change adaptation frameworks, tools, and research are intended. At the national level, DOTs are given policy recommendations to "implement" and "incorporate" climate change adaptation in their organizations. (FHWA 2014b; USDOT 2014) However, there is little understanding of whether adaptation is happening, to what extent it is happening, and how it is happening. All state DOTs have access to the same national policy guidance, research, and funding sources (Baxter 2012), but there is a wide range of implementation across the United States. (FHWA 2012b)

While there are studies that examine climate change adaptation in organizations, including DOTs, they have typically been high-level reviews (Meyer et al. 2010b; Stark 2012), singular pilot studies (FHWA 2011), project-based (FHWA 2013b; Rasmussen et al. 2011), or internationally focused (EEA 2014). Without understanding how organizations are implementing climate change adaptation, the work being completed at the individual process level will be limited in its effectiveness. Agencies need to understand not just specific climate change adaptation strategies; they also need to understand what a holistic climate change program is and how to implement it.

RESEARCH OVERVIEW

The research gaps, questions, methods, and proposed contributions addressed in this dissertation are summarized below. There are two broad questions that guide the research within this work: 1) What are the impacts of climate change on transportation infrastructure? and 2) Why are transportation infrastructure organizations not implementing climate change adaptation?

The gaps in existing literature are:

- Impact analysis in transportation is often too high-level (industry/economy scale) or too detailed (material level);
- Quantitative impact analysis focuses most often on sea-level rise and extreme events, and does not adequately capture the long-term impacts of gradual changes in precipitation and temperature;
- There is little understanding of if and how transportation infrastructure organizations are implementing climate change adaptation; and
- Adaptation frameworks typically focus on singular processes and there is little research on the systemic organizational implications of implementing climate change adaptation.

Figure 1.1 is a conceptualization of the climate change adaptation research field and where this dissertation fits in relation to existing literature. The organizations and institutions referenced are not restricted to transportation and include research on other types of infrastructure, organizations, and institutions.

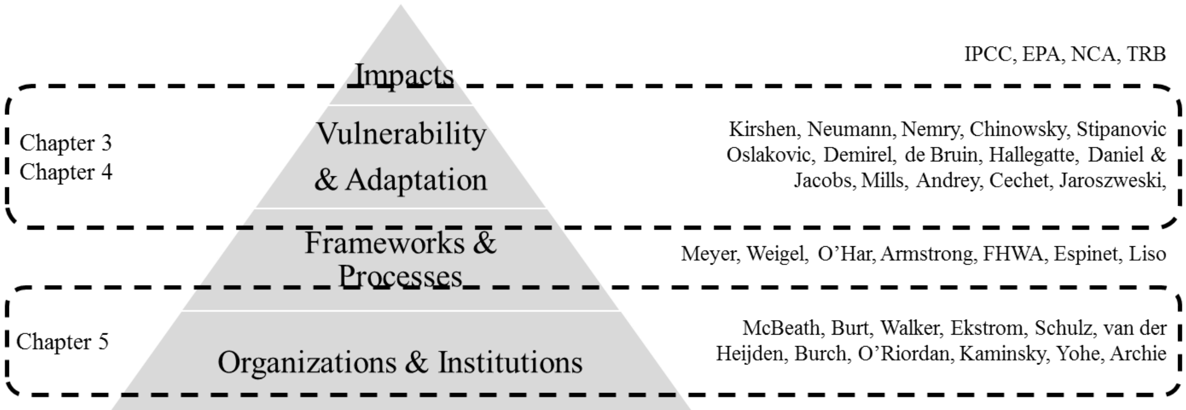

Figure 1.1: Existing Literature and Dissertation Research Conceptualization

The research questions to address the gaps in literature are summarized below in Table 1.1, based on the chapters of this dissertation. Chapter 2 provides more background information on climate change, adaptation, and infrastructure organizations.

Table 1.1: Research Question Overview

Chapter 3	**RQ1** What are the impacts of long-term changes in temperature and precipitation on road infrastructure? What are the adaptation costs?
	RQ1.1 What is the process for modeling impacts and costs at the organizational planning level?
	RQ1.2 How do these impact forecasts differ when using GCMs versus RCMs?
Chapter 4	**RQ2** What are the impacts of long-term changes in freeze-thaw cycles on a road network? What are the adaptation costs?
	RQ 2.1 What is the relationship between changes in air temperature and pavement freeze-thaw cycles?
	RQ2.2 What are the impacts specific to porous asphalt?
Chapter 5	**RQ3**: How do transportation infrastructure organizations implement climate change adaptation?
	RQ 3.1 How are transportation infrastructure organizations currently incorporating climate change? (Appendix)
	RQ3.2 What is a holistic climate change adaptation program? What are the organizational and institutional elements of a climate change adaptation program?

Research Context

The data for Chapters 3 and 4 was collected in the Netherlands, in cooperation with the University of Twente and the Dutch Ministry of Infrastructure and Environment, Rijkswaterstaat. The focus on the Netherlands was practical because the work was funded by the Dutch Organization for Scientific Research (NWO), and the necessary data existed and was available. Beyond these practical motivations, the Netherlands provided a relevant and useful theoretical perspective for the research. The Netherlands is known as a worldwide leader in long-term planning, sustainability, and consideration of climate change. They have made policy decisions to both optimize the efficiency of their road network and to incorporate social and environmental considerations. The balance between cost efficiency, surface water runoff, and noise reduction provides an interesting context, where potentially competing interests are further complicated by climate change. These competing interests are common in transportation infrastructure organizations around the world.

The Netherlands also shares many characteristics with countries throughout the developed world, particularly in Europe and North America. The Netherlands is a transportation hub for Europe, connecting seaports to inland countries with intra- and inter-country highways similar to state and interstate highways in the United States. These highways carry individual users and freight traffic and contribute substantially to the country's and region's economic success. Additionally, the climate of the Netherlands is analogous to other countries in Europe and states in the United States. While the specific changes in temperature, precipitation, and freeze-thaw cycles will vary by region, these stressors will impact other regions in similar ways. The data collection, fundamental engineering basis, and process outcomes of this research will be applicable to similar countries and states.

Chapter 5 focuses on transportation infrastructure organizations in the United States and data was collected from industry and academic experts in the U.S. In this case, the unit of analysis is state DOTs, metropolitan planning organizations (MPOs), and large municipalities (New York

City, for example). While the results from Chapters 3 and 4 were not used in Chapter 5, the fundamentals of climate change adaptation knowledge were assumed to be applicable in both contexts. The unit of analysis is different in name, the Netherlands as a country and state DOTs as states, but are similar in function and size.

METHODS

This research was conducted using a mixed methods approach. Chapters 3 and 4 use a basic stressor-response methodology to model adaptation (response) of infrastructure to climate change impacts (stressor). The model is built with a series of stressor-response equations, which are detailed in Chapters 3 and 4. The equations and other parameters were programmed using MATLAB. These chapters also used statistical correlation to relate air temperature and pavement temperature at specific locations in the Netherlands.

The research in Chapter 5 is completed using a systematic literature review and an expert Delphi panel. The literature review included an initial review of 1,671 non-unique articles. In the end, 507 unique documents were reviewed in detail to create a list of factors used to develop a survey for use in an expert Delphi panel. The Delphi survey was completed by 13 experts, pre-qualified based on education, experience, industry qualifications, and previously completed publications. Additional details of all methods are included in subsequent chapters.

Figure 1.2 provides an overview of the dissertation research.

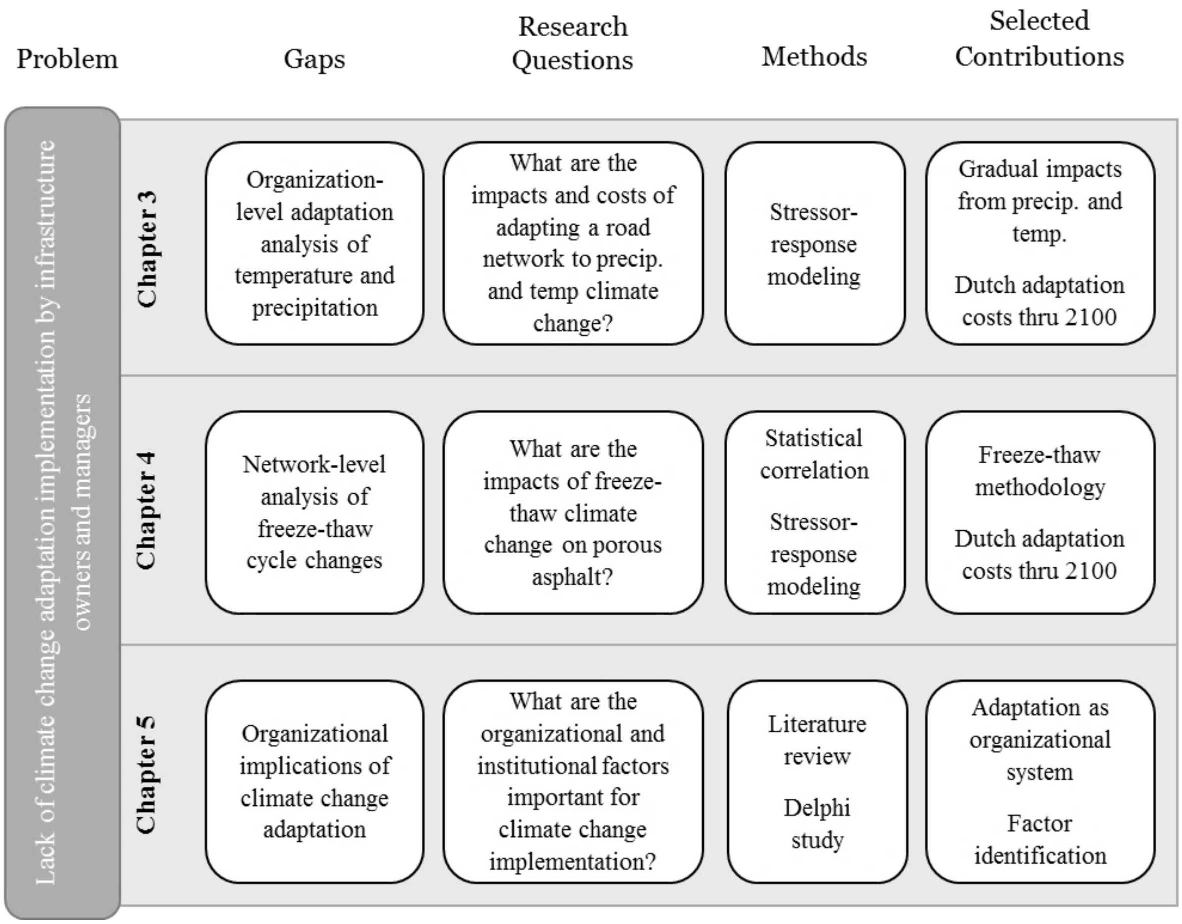

Figure 1.2: Research Overview

CONTRIBUTIONS

The adaptation analysis in chapters three and four contribute to the growing literature on the impacts of climate change on transportation infrastructure. Practically, it provides cost data and adaptation strategies to Dutch infrastructure managers and describes the benefits and limitations of increasing the granularity of impact analysis. Theoretically, Chapters 3 and 4 create two new methodologies for infrastructure managers to 1) incorporate local empirical data into climate change adaptation modeling and 2) analyze freeze-thaw as a climate stressor.

The purpose of Chapter 5 is to create the basis for a theoretical link between existing transportation management processes in an organization (a state DOT, for example) to the development of a climate change adaptation program. The main contribution of this work is to develop a theoretical organizational model for climate change adaptation, which provides a systems/holistic approach to understanding climate change adaptation. This dissertation establishes the organizational and institutional elements needed in transportation agencies to implement climate change adaptation.

There are many links in research and practice between climate change adaptation and existing DOT processes but there is not yet a systemic/holistic understanding of what is needed to develop and implement a program. Understanding the systemic organizational and institutional underpinnings of climate change adaptation processes will help agencies achieve ongoing adaptation implementation.

The work in Chapter 5 also began with a desktop survey of current climate change adaptation activities in United States DOTs, which is included in Appendix X. The findings from this survey were that DOTs are generally not implementing climate change adaptation, despite policy recommendations to do so. Those states that are performing adaptation activities have typically been involved in one-off pilot projects, not programmatic development. The survey identifies existing areas of practice, such as enterprise risk management (ERM) and long-term planning that, based on the results from the Delphi study, are important for climate change adaptation implementation.

DISSERTATION FORMAT

This dissertation follows a journal article format, where Chapters 3, 4 and 5 are stand-alone articles. Chapter 2 provides additional background. Chapters 3, 4, and 5 were submitted as articles and are currently under review with separate peer-reviewed journals. Chapter 3 was submitted to the Mitigation and Adaptation Strategies for Global Change. Chapter 4 was submitted to the American Society of Civil Engineers (ASCE) Journal of Infrastructure Systems. Chapter 5 was submitted to Transport Policy. The author respectfully requests that any citations to the work presented in Chapters 3, 4, and 5 refer to the eventual published versions, rather than this dissertation. Chapter 6 provides a summary of theoretical and practical contributions of this dissertation and suggests directions for future research. Appendices are included at the end of this dissertation to report details of the literature review performed for the Delphi study, IRB approval, and additional research that would not fit within the journal articles due to space limitations.

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Chapter 2 BACKGROUND

Climate has always been a part of transportation infrastructure design and management; it is a fundamental principle that civil infrastructure cannot be separated from the environment in which it is built. (Meyer 2006) There has been rapid growth over the past two decades in the amount of climate-related research, however, as scientists and practitioners have acknowledged that the climate on which they have based their design and management practices is changing. (IPCC 2007a)

Initially, research focused on the transportation industry's contributions to global warming through greenhouse gas (GHG) emissions. The transportation industry is estimated to be responsible for 27% of the United States' GHG emissions. (EPA 2015) This is primarily through fossil fuel use and carbon dioxide (CO_2) emissions, which accounts for approximately 5% of GHG emission globally. (FHWA 2015a) This naturally led to research on how this impact could be mitigated, through a primary focus on vehicles with strategies such as more fuel-efficient vehicles, alternative fuels, and reducing vehicle miles traveled (VMT). (IPCC 2007a) The design, construction, operation, and overall management of transportation infrastructure contributes less to GHG emissions, and research therefore remained primarily focused on vehicle impact mitigation.

However, in the past decade climate change research has expanded from studying the impact of transportation on the environment to the impact of a changing environment on transportation. While the research and debate over mitigation continues, there is general consensus that some amount of climate change is now unavoidable and that some form of adaptation will be required in almost every global industry, including transportation. (IPCC 2015)

Impact research began with high-level, policy and economic analysis to understand the macro effects that climate change would have on a variety of industries, including both natural and human systems. (IPCC 2015) This included books studying the global economic impacts (Stern 2007a), work focusing on the disparate impacts to developing countries, the ethics of climate change (Broome 2008), and publications focused broadly on infrastructure (Hallegatte 2009), in which transportation is either not included or treated as one element of a larger system. The conclusions of much of this research are that climate change has potentially positive and negative impacts, although primarily negative, resulting in financial, physical, natural resource, and human costs over the coming decades. (IPCC 2014)

As research became more detailed and industry specific, top-down economic analysis and policy recommendations (Kirshen et al. 2008; Neumann 2009) were supplemented with bottom-up impact and engineering analysis (Cechet 2005; Mills et al. 2009). This impact literature was the first step in understanding the vulnerability of transportation infrastructure and is still a growing body of literature, as new methods, tools, and techniques are developed to understand the wide-ranging impact of climate change on transportation infrastructure.

CLIMATE CHANGE IMPACTS ON TRANSPORTATION

Climate change will be varied around the world and within the United States. Temperatures will rise, precipitation will become more intense in some cases and may decrease in others, and sea-levels will rise. (IPCC 2014) Detailed forecasts are uncertain and dependent on a variety GHG emission scenarios. (van Vuuren et al. 2011) There are low-emissions scenarios, in which GHG emissions are aggressively curbed, which forecast conservative changes in climate. There are also high-emissions scenarios, in which GHG emissions are either not stabilized or increased, which predict much more dramatic and potentially damaging changes in temperature and precipitation.

Transportation infrastructure is designed and constructed using engineering standards that are based on historic climate patterns. That infrastructure is typically designed to operate within a range of expected climate variation. As future climate is expected to change, in many cases it will extend beyond, either above or below, that anticipated range. This is a particularly challenging problem for transportation, as the design life of different types of infrastructure ranges from ten to 100 years (Humphrey et al. 2008), which means that infrastructure being built today may be operating in climate substantially different from the climate for which it was designed.

Regardless of which emissions scenario or climate model is used, transportation will be impacted by both extreme weather events and gradual changes in climate. The primary risks to transportation are:

- Increases in very hot days and heat waves;
- Increases in arctic temperatures;
- Rising sea levels;
- Increases in intense precipitation events; and
- Increases in hurricane intensity.

Additional risks include changes in freeze-thaw cycles, increase in drought conditions for some areas, changes in flooding patterns, increased wind velocity, and increases in storm intensity. (Humphrey et al. 2008; International and ICF International 2010; WRA et al. 2012) Understanding and quantifying the impact of climate change on specific types of transportation infrastructure is difficult, in part because of the high levels of uncertainty. Changes in temperature and precipitation may result in positive outcomes, in the form of warmer winters for example, but also potentially severe negative outcomes from increased rainfall and higher temperatures (Peterson et al. 2008).

There are studies that examine the risks of climate change to different transportation infrastructures. They describe more specific impacts, for example higher temperatures and increased precipitation will result in the acceleration of road degradation, primarily through rutting and raveling. (Jaroszweski et al. 2010; Peterson et al. 2008) And there are even more detailed studies that have analyzed specific material responses to climate change, such as the implications of climate change on pavement design. (Cechet 2005; Mills et al. 2009)

All types of infrastructure, including roads, airports, seaports, rails, tunnels, and bridges are at risk from extreme weather events and coastal flooding, and most are also at risk from gradual changes in temperature and precipitation. (Humphrey et al. 2008; IPCC 2014) These climate stressors have the potential to accelerate infrastructure deterioration, increase severe damage and failures, decrease safety, and increase traffic, all of which will have an impact economic in addition to the direct impact on infrastructure and its users. (Nemry et al. 2012) o

The National Climate Assessment (USGCRP 2014) describes risk as a combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur. Figure 2.1 is an illustrative list of the types of impacts to various infrastructure types, including the predicted likelihood and magnitude of consequences.

Illustrative Risks of Climate-related Impacts

Magnitude of Consequences	Likelihood of Occurrence: Low	Medium	High	Virtually Certain
High	Subway and tunnel flooding	Increased widespread flooding of transportation facilities	Major localized flooding disrupts transportation systems	Inundation of coastal assets due to storm surge
Medium	Increased rock/mud slides blocking road and rail facilities	Train derailment due to rail buckling	Increased disruption of barge traffic due to flooding	Short-term road flooding and blocked culverts due to extreme events
Low	Lower visibility from wildfires due to drought conditions	Northward shift of agricultural production places more demand and stress on roads and systems not prepared for higher volumes	Pavement heaving and reduced pavement life due to high temperatures	Inundation of local roads due to sea level rise
Positive (beneficial)	Reduced flight cancellations due to fewer blizzards	Reduced maintenance costs for highways and airports due to warmer winters	Reduced Great Lakes freezing, leading to longer shipping season	Longer seasonal opening of Northwest Passage

Figure 2.1: Climate Impacts on Transportation (Schwartz and Meyer 2014)

The uncertainty and variation inherent to climate change can limit the applicability of impact research, as it is often focused on a specific region, a specific stressor, a specific type of infrastructure or a combination of all three. (FHWA 2011). For example, an impact assessment of the flooding risks to Danish roads (Grauert and Axelsen 2014) may not be applicable to other countries or types of infrastructure. That is partly why there has been an increase in research being completed on the techniques and frameworks to understand vulnerability, rather than specific impacts. (Bollinger et al. 2014; FHWA 2012a; IPCC 2014)

Understanding how to determine vulnerability to climate change allows infrastructure managers to determine risks and impacts that are specific to their region and assets. There are many definitions of vulnerability and proposed frameworks that vary from industry to industry. According to the Intergovernmental Panel on Climate Change (IPCC), vulnerability is the propensity or predisposition to be adversely affected, which encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. (IPCC 2014) The National Climate Assessment (NCA) describes vulnerability as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. (USGCRP 2014). In the transportation industry, research has largely been led by the Federal Highway Administration (FHWA), which used multiple case studies to develop the framework shown in Figure 2.2. (FHWA 2012a) There are many challenges involved in each stage of this process, including difficulties with data collection and analysis, available technology, and high levels of uncertainty. (ICF International et al. 2014)

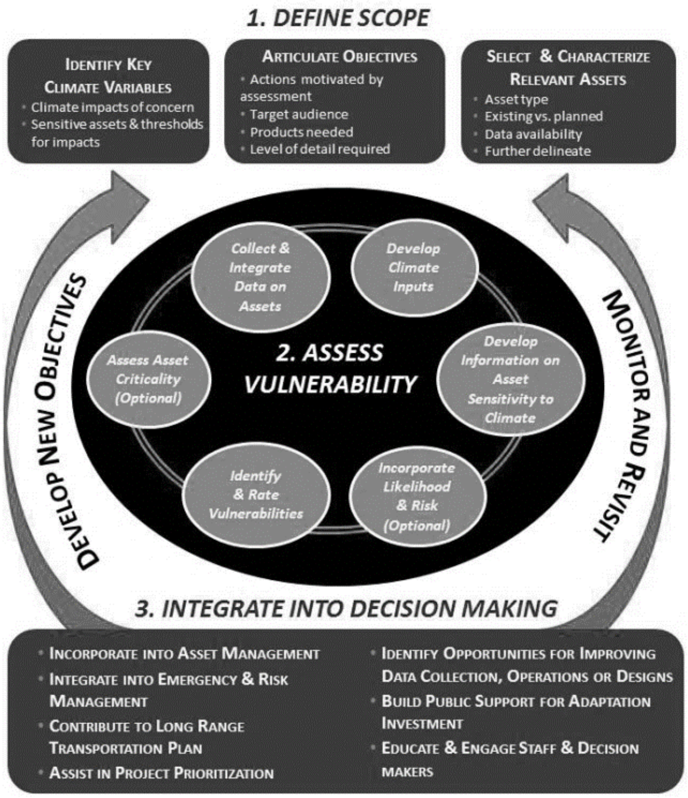

Figure 2.2: Vulnerability Assessment Framework (FHWA 2012a)

As reflected in the three-step process in the framework, research and industry focus on climate change has evolved from mitigation to identification of impacts, to assessment of risk and vulnerability, and finally to adaptation. To illustrate this, the United States Department of Transportation (USDOT), recommends that state DOTs consider adaptation an equal priority to mitigation. (USDOT 2014) It is important for transportation agencies to understand and adapt to climate change impacts for the end-user's safety, for their own organizational benefit, and also because of the role that roads play in national commerce and international trade. (Melillo et al. 2014; Nemry et al. 2012; USDOT 2014) Despite this, attention to adaptation is still relatively low. (EEA 2014)

CLIMATE CHANGE ADAPTATION

There are many different definitions, frameworks, and approaches to climate change adaptation but the main principle guiding all of them is the idea that adaptation can reduce the impacts of climate change. An illustrative list of definitions is provided in Table 2.1.

Table 2.1 Definitions of Climate Change Adaptation

UNFCCC (United Nationals Framework Convention on Climate Change)	Actions taken to help communities and ecosystems cope with changing climate condition
IPCC (Intergovernmental Panel on Climate Change)	Process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities
UNDP (United Nations Development Program)	Process by which strategies to moderate, cope with and take advantage of the consequences of climatic events are enhanced, developed, and implemented
UKCIP (United Kingdom Climate Impacts Programme)	Process or outcome of a process that leads to a reduction in harm or risk of harm, or realization of benefits associated with climate variability and climate change
NCCARF (National Climate Change Adaptation Research Facility, Australia)	Actions undertaken to reduce the adverse consequences of climate change, as well as to harness any beneficial opportunities
NCA (National Climate Assessment, United States)	Action to prepare for and adjust to new conditions, thereby reducing harm or taking advantage of new opportunities. Also: adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects

(USGCRP 2014; VCCCAR 2017)

Much of the work on adaptation focuses on policy making and either local action (Burch 2010) or the national policy level (Jotzo 2010) and is not specific to transportation infrastructure (Berkhout et al. 2006; Bollinger et al. 2014; Liso 2006). There is a large segment of general adaptation research that takes a “top-down” approach, providing prescriptive policy guidance. (Burton et al. 2002) Economic modeling of the impact and adaptation costs has also been completed in many industry sectors, especially in agriculture and water resources (Tol 2002). This broad quantification is an important tool for economists and policy-makers, but more detailed sector-specific modeling is required to enable local adaptation action (Jotzo 2010). This also leads to a pattern where organizations include adaptation into planning and policy documents but do not take any action as a result. (Ford et al. 2011)

The modeling of adaptation strategies and costs is also being researched in transportation infrastructure (de Bruin et al. 2009a; Schweikert et al. 2014) however there is still a need for detailed studies, such as MacArthur et al. (2012) in the United States, which analyze climate and road characteristics that are unique to a specific organization. As stated in a report on climate change impact to European Union rails and roads, both vulnerability and adaptation costs would need to be assessed under a much higher spatial resolution in order to take adaptation action. (Nemry et al. 2012)

More detailed adaptation research often takes a “bottom-up” approach, investigating the options for specific climate stressors and infrastructure types. For example, adapting to temperature impacts on road infrastructure may include rejuvenation spray, modifying seals, or adopting base bitumen binders with higher softening points (FHWA 2014a; WRA et al. 2012). Or for precipitation, adaptation actions include resealing the surface more frequently, improving surface drainage by expanding the road surface, and increasing the strength of underlayment. (FHWA 2015b; WRA et al. 2012)

Some research includes both quantitative and qualitative methods, like the case of de Bruin et al. (2009b), that focuses on ranking and prioritization of adaptation options. While these methodologies are important, as they expand set of tools available to infrastructure managers, they often isolate adaption within one project, within one process, or create an entirely new process outside of what organizations already perform.

Similar to climate change impacts, research on specific regions (Kirshen et al. 2008), stressors (Neumann et al. 2011), or infrastructure types is important to advance the academic literature and tools available to practitioners, but the broader context of climate change adaptation must also be investigated. That is the gap that many proposed frameworks and approaches fill by focusing on integrating climate change adaptation with theory and practice that is not beholden to a specific region, stressor, or infrastructure type.

Rowan et al. (2013) utilize a sensitivity matrix to incorporate a wide range of climate stressors. Meyer and Weigel (2011) suggest an adaptive systems management approach that, among other steps, includes vulnerability assessment, risk appraisal, and cost analysis and can be applied to a wide range of infrastructure assets. Meyer et al. (2009) details how asset management can be used to address climate change adaptation. (O'Har 2013) expands on the asset management approach by specifically suggesting a risk-based asset management approach. The Moving Ahead for Progress in the 21st Century Act (MAP-21) is the funding and authorization bill that governs federal surface transportation spending in the United States. Per this legislation, "each State is required to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system." (23 U.S.C. 119(e)(1), MAP-21 § 1106). (FHWA 2013c) This presents an opportunity for climate change adaptation to be an integrated component of the risk-based asset management programs from their initiation, or infancy for states that have already started a program.

Additionally, Wall and Meyer (2013) discussed the benefits and limitations of a collection of risk-based frameworks. Armstrong et al. (2014) discuss the integration of climate change adaptation into decision-making and planning. And a review of international practices revealed that other countries are using a variety of approaches, most of which focus on risk, asset management, and planning. While each approach and framework is different, one thing they have in common is that they all focus on a process. Typically, this is a process that already exists within transportation agencies or is planned to be implemented.

CLIMATE CHANGE ADAPTATION AND ORGANIZATIONS

"Business as usual" has changed in many ways for transportation managers. (Campbell et al. 2005) The nature of transportation in the 21st century has already forced organizations to move beyond project-level considerations into cross-cutting systemic issues (USDOT 2014) and they will need to continue adapting by learning how to operate in an uncertain future. (Berkhout et al. 2006)

The development of adaptation frameworks is often guided by global or national strategies, such as the Intergovernmental Panel on Climate Change report, the European Union's Climate and Energy Policy, and the United States Climate Action Plan. For example, in the transportation industry, the USDOT has used the National Climate Assessment (USGCRP 2014) and executive orders from the President (House and The White House 2013) to develop a policy statement and plan for all state Departments of Transportation (DOTs).

The former Secretary of Transportation, Ray LaHood, issued a statement that "climate change adaptation should be integrated into core policies, planning, practices, and programs" (LaHood 2011) and the USDOT "strongly encourages consideration of potential climate change impacts in the transportation planning process" (USDOT 2014). USDOT further states that "mainstreaming consideration of climate in all activities related to planning, constructing, operating and maintaining transportation infrastructure and providing transportation services can ensure that resources are invested wisely and that services and operations remain effective."(USDOT 2014)

As evidenced by the frameworks and policies, research and industry both suggest that climate change adaptation should be incorporated into existing transportation processes. This is consistent with literature suggesting that the implementation of adaptation is more likely if it is consistent with existing programs that are already designed for non-climatic stresses and integrated into policy strategies. (Burch 2010; O'Riordan et al. 1999; Yohe 2001) There is also evidence that when incorporating uncertainty, as with climate change adaptation, organizations should not look for the best strategy, but rather the best strategy process. (Burt and van der Heijden 2003)

Further, research states that as the priority moves from policy to producing measurable results and action, the focus should also move from the national to local level (Bulkeley and Betsill, 2005; Burstrom and Korhonen, 2001). In Europe, this means focusing on the organizations responsible for infrastructure management, such as national ministries of transportation. In the case of transportation in the United States, this means a shift to focusing on state Departments of Transportation. However, similar to other local contexts, the implementation and barriers of climate change adaptation are less understood at this level. (Burch 2010)

Research on processes, institutions, and barriers to climate change implementation is primarily non-transportation specific. Research in other public infrastructure industries, such as water resources or land management, can help pre-identify certain elements as potential barriers. (Archie et al. 2014) There is also existing research that highlights the importance of institutions when examining the processes involved in climate change adaptation. (Ekstrom and Moser 2013) Additionally, Burch (2010) suggested that it was not a lack of capacity but a facilitation of resources and institutional barriers that kept organizations from climate change action.

While USDOT states that implementing climate change adaptation into organizations and processes is integral to successful adaptation, there is only one state that has published information on incorporating climate change adaptation into its organization. (Major et al. 2011) FHWA has completed a regional project on this topic but it focused on land use and scenario planning, not specifically on climate change adaptation in DOTs. (FHWA 2014a) USDOT anticipates a publication in 2015 on the integration of climate change adaptation but it focuses only on coastal highways. (USDOT 2014) While there are many proposed frameworks and tools, there has not yet been a study on the organizational and institutional aspects of climate change adaptation in Departments of Transportation.

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Chapter 3 CLIMATE CHANGE ADAPTATION MODELING OF A NATIONAL ROAD NETWORK: COMBINING GLOBAL, REGIONAL, AND LOCAL INPUTS

Keywords: climate change, adaptation, roads, transportation, organizations, modeling

ABSTRACT

This paper presents a cost analysis of adaptation options for impacts of climate change on a national highway system. Impact analysis is an integral part of climate change adaptation research, but there is a lack of quantitative modeling to support decision-making in transportation organizations. This project addresses this need by expanding an existing cost modeling methodology, the Infrastructure Planning Support System (IPSS), to produce adaptation cost forecasting that balances the need for empirical engineering input with the complexity and scale of climate change modeling. The adaptation modeling is based on a stressor-response methodology that was originally developed to use General Circulation Models (GCMs) and generalized road data in developing countries. The two main objectives of this research are to 1) refine the input data and stressor-response equations of the IPSS model and 2) compare results from analysis using GCMs and Regional Climate Models (RCMs). The researchers use the case of long-term temperature and precipitation changes in the Netherlands to accomplish these objectives. Data from meteorological stations were correlated with data from in situ pavement monitoring to obtain an empirical relationship between global/regional climate change and direct pavement impacts. RCM results forecast higher overall costs of adaptation than GCMs, as well as higher levels of regional variability. By incorporating RCMs, the researchers have achieved better accuracy and established the need for data collection and analysis on the regional level, to calibrate and update impact prediction models.

INTRODUCTION

Climate change adaptation research has been a quickly growing and changing field as scientists and practitioners now acknowledge that even with mitigation, the planet will experience certain unavoidable levels of climate change (IPCC 2015). While the questions of how much and when are still debated, research has sought to identify and understand the potential impacts on transport infrastructure from future climate change. There are studies on specific material responses to climate change, such as pavement implications (Mills et al. 2009) and there are studies that analyze broad economic sectors (Stern 2007b; Tol 2002a). As a larger quantity of data is produced, it is important to examine not only the scientific robustness but also the relevance and usability of the data for infrastructure owners and managers.

Climate change adaptation is a multi-scale issue, affecting societies, organizations, and individuals that have differing motivations and decision-making abilities. (Adger et al. 2005) Organizations, often public organizations, are responsible for planning and implementing climate change adaptation for public infrastructure. This is especially true for transportation infrastructure, which is primarily managed by public agencies and requires long-term planning of both design and maintenance. To anticipate and plan for changes that may be required in the uncertain future, these agencies require information that is more detailed than sector-wide analysis but less specialized than material property studies. The research project described in this paper builds on those efforts by combining economic modeling and material science while also maintaining an organization decision-making perspective. The work intends to advance the science of climate change adaptation research through improvements to impact and adaptation modeling methodology, while also producing results that are more relevant and implementable at the organizational level.

Highway organizations face a difficult challenge, as roads are a particularly vulnerable part of infrastructure. For example, as much as half of road maintenance costs are attributable to weather stresses. (Nemry et al. 2012) Roads are designed to operate with minor variability in weather, but long-term changes in climate are often not accounted for in current planning and design standards. Changes in temperature and precipitation may result in positive outcomes, in the form of warmer winters for example, but also potentially severe negative outcomes from increased rainfall and higher maximum temperatures. (Peterson et al. 2008; Schwartz and Meyer 2014)

It is useful for transportation (highway) agencies to understand and adapt to these impacts for the end-users' safety, for their organizational benefit (e.g., cost and resource efficiency) and because of the role that roads play in national commerce and international trade. Consequently, as the need for evaluation of adaptation options and costs has been established, research on climate change and roads has become increasingly quantitative. However, these economic modeling results are not intended to be organization-specific but instead are more useful at the national policy level. (Jotzo 2010)

This work addresses that gap by modeling the impacts of long-term changes in temperature and precipitation on road infrastructure for a specific organization. The Netherlands is used an as example case for this analysis. The Netherlands is a useful case because of their attention to climate change, dense road network, and their temperate climate. Motorways are analyzed, in part because that is the type of road that national road agencies directly manage, but also because motorway costs are ten times higher than other road types in Europe. (Doll et al. 2008), which increases the financial risk of future climate change adaptation impacts. The highway network is also a major factor for the economy, especially in a densely populated and highly developed country like the Netherlands.

This research builds on an existing climate change adaptation model, the Infrastructure Planning Support System (Chinowsky et al. 2011). The IPSS modeling process applies to a wide range of countries and regions in the world. For this reason, the methods are described in detail, and the Netherlands is used as an example case study. For this project, the IPSS model is run using its original inputs, which are based on previously published engineering research. The inputs are then reviewed and modified to reflect agency pavement characteristics and costs. Results are produced first using a suite of General Circulation Models (GCMs) that have been utilized in previous studies. Regional climate models (RCMs) are then used to produce downscaled results. The results are presented as costs of alternate adaptation options, nationally and provincially, through 2100. The results based on GCMs are compared with results based on RCMs, to review the effect that downscaled results can have on adaptation modeling.

BACKGROUND

Climate change research has evolved from focusing primarily on mitigation to include the exploration and evaluation of adaptation options. While there continues to be debate over the merits and means of mitigation, there is a consensus that some form of adaptation will be required to address the amount of climate change that is now unavoidable (IPCC 2014). Economic modeling of the impact and adaptation costs has been completed in many industry sectors, especially in agriculture and water resources. (Tol 2002b) This broad quantification of the potential impacts is an important tool for economists and policy-makers. However, when considering the limitations of economic modeling for climate change adaptation, more detailed sector-specific modeling is required to enable local adaptation action. (Jotzo 2010)

COST IMPLICATIONS OF CLIMATE CHANGE IMPACTS

This is true within the transportation sector as well, and there are an increasing number of studies that examine the risks of climate change to transportation infrastructure. (Jaroszweski et al. 2010; Peterson et al. 2008) Specifically, higher temperatures and increased precipitation will result in the acceleration of road degradation through a variety of mechanisms, in large part through rutting and raveling. (Dawson and Carrera 2010) The quantification and modeling of network cost impacts are being researched. (Chinowsky et al. 2013a; Nemry et al. 2012) However, there are still few detailed studies, such as (MacArthur et al. 2012) in the United States, which analyze climate and road characteristics that are unique to a specific organization. As stated in a report on climate change impact to European Union rails and roads, to encourage changes in decision-making, “Both vulnerability and adaptation costs would need to be assessed under a much higher spatial resolution”. (Nemry et al. 2012)

The economics of climate change adaptation are important because of potential direct costs to infrastructure organizations and the role that transport infrastructure plays in the economic productivity of a country and region. (Canning and Pedroni 1999; Kessides 1993) For example, the Extreme Weather Impacts on European Networks of Transport (EWENT) project forecast that for all of Europe the future direct costs to road infrastructure from extreme weather, considering climate change, are estimated to be €1.2 billion annually. (Nokkala et al. 2012) The larger societal costs for accidents, time loss, and freight and logistics disruptions are estimated to be €7-17.6 billion annually. (Nokkala et al. 2012)

The economic costs of climate change have the potential to affect countries disproportionately as some countries, particularly developing countries, face less robust networks. (Chinowsky et al. 2011) Developed countries, like the Netherlands, also face risk because they depend more on the reliability of their network, have a much higher concentration of roads (Queiroz and Gautam 1992), and have higher cost roads. This connection between road networks and economic activity is relevant for the highway system of the Netherlands, particularly because of its importance in regional commerce.

THE NETHERLANDS

With the busiest seaport in Europe (AAPA 2012) and a reputation as a major worldwide transportation hub, the Netherlands relies heavily on the success of their road network. It is the largest inland shipper of goods in Europe, transporting them from the Port of Rotterdam to all parts of Europe using the country's motorway system. The Netherlands also constitutes approximately fourteen percent of all international road travel in the European Union ("Logistics gateway to Europe and beyond" 2013). As stated on their government website, it is a priority for the Netherlands to increase their economic competitiveness worldwide by continually improving their road infrastructure ("Freight transport by road" 2013), including safety, environmental, and efficiency concerns.

The Dutch place significant emphasis on long-term planning, sustainability, and optimization. (Van Der Valk 2002) They frequently reevaluate their existing systems to ensure current solutions are still the most effective, including the road network (Snelder et al. 2007) as the Ministry of Infrastructure and the Environment, Rijkswaterstaat, has made climate change risks a central topic in their annual report (RWS 2012). They have also participated in a World Road Association study, in which road infrastructure owners/operators expressed a need for "methodologies for mapping of critical/vulnerable infrastructure and estimating the costs of adapting to climate change." (WRA et al. 2012) These characteristics, along with a collection of available data, make the Netherlands an effective case study for this project.

The Netherlands has a temperate maritime climate, with cool summers and moderate winters. The country is small, covering 41,526 square kilometers, 33,883 of which are land. ("Netherlands facts, information, pictures" 2017) There is little inland climate variation although the influence of the sea is noticeable in the western part of the country. Daytime temperatures vary from 2-6 °C in wintertime and 17-20 °C in summertime. The entire country is classified as a Cfb Köppen-Geiger climate zone, which is a warm temperate humid climate with the average warmest month lower than 22°C and four or more months with an average above 10°C. As seen in Figure 3.1, precipitation is distributed evenly through the year. (The World Bank 2016)

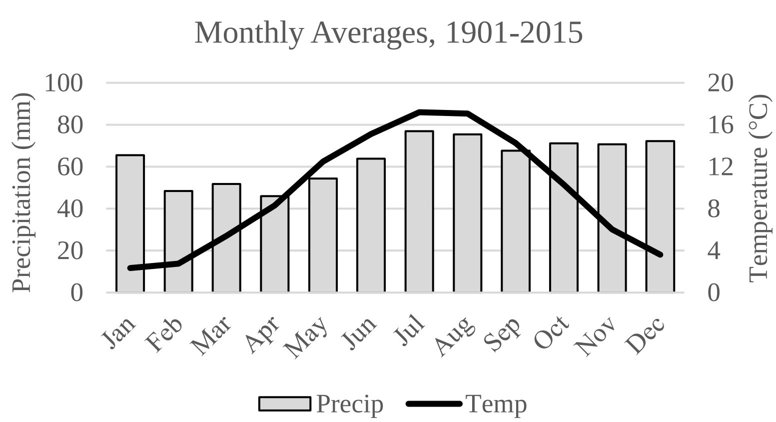


Figure 3.1: Monthly Average, Temperature and Precipitation in the Netherlands (1901-2015)

POROUS ASPHALT PAVEMENT

Porous asphalt (PA) pavement is characterized by a high percentage of interconnected voids in the top friction layer of the pavement. This creates high permeability and is also capable of reducing tire noise. A major motivation for its use in the Netherlands is that it is more cost and space efficient than sound barriers. (Alvarez et al. 2006) PA pavements also have high resistance to rutting. (Miradi 2009a) Despite these benefits of using porous asphalt, there are drawbacks which are important to consider in the context of climate change. Porous asphalt has a limited lifespan that is shorter than most alternative pavement types (Miradi 2009b); it is susceptible to increased raveling and accelerated aging from rainwater and de-icing salt (Su 2013); and it has been shown that noise reduction effectiveness can be significantly reduced by age and clogging of pores (Bendsten et al. 2005). These are relevant characteristics for any transportation infrastructure organization when considering the long-term effectiveness of PA pavement in a changing future climate.

The Dutch include environmental concerns in their road network planning, not only considering the impact to the surrounding environment but also the quality of life for citizens living nearby. With a small land area and dense road network, people in the Netherlands often live near highways, and noise reduction is, therefore, an environmental consideration for road design and planning. As the population grows and the use of automobiles increases, RWS has made noise reduction a priority. (Huurman et al. 2010b; Van Der Valk 2002) The focus on noise reduction, combined with PA pavement's stormwater drainage benefits, has led the Dutch road network to be constructed with approximately 90% porous asphalt pavement.

RESEARCH METHOD

The research is completed using a stressor-response cost modeling method. The specific model, the Infrastructure Planning Support System (IPSS) has been used for several case studies. While it has been used to analyze several countries in Europe, (Chinowsky et al. 2011) the IPSS model has been used primarily for analyzing infrastructure developing countries. The adaptation analysis in developing countries was performed at an economy-wide or international scale for large-scale planning, policy, and investment decision support. The methodology for incorporating country-specific road design and maintenance data is important for strengthening the understanding of the relationships between climate stressors (temperature, precipitation) and physical road response (damage).

Using the Netherlands as a case study, this project investigates the following questions. What are the long-term impacts and adaptation costs of gradual changes in temperature and precipitation? What information is needed to conduct this analysis at the organizational level? What are the differences in forecast costs when using GCMs versus RCMs?

Infrastructure Planning Support System (IPSS)

The Infrastructure Planning Support System was designed by the Institute for Climate and Civil Systems (iCliCS) at the University of Colorado Boulder. Previous versions of the IPSS model analyzed paved, gravel, and dirt roads in developing countries. Due to a regional/international perspective and data limitations in developing countries, the IPSS model included generalized parameters and used climate data inputs from GCMs. This research expands on the paved road portion of the IPSS model by adding the capability to analyze porous asphalt, incorporating empirical data-drive parameters, and utilizing Regional Climate Models.

IPSS uses a stressor-response methodology to predict the response (damage) of an asset (road) from a stressor (temperature and precipitation). Examples of stressor-response equations are provided below. A more detailed explanation of the functions, stressor-response methodology and thresholds can be found in Chinowsky and Arndt (2012) and Chinowsky et al. (2013).

Equation 3.1 $\mathrm{CostProactive}_{T} = N_{Thresh} * C_{Thresh} * C_{base}$

Where:
$\mathrm{CostProactive}_{T}$ = change in road construction costs associated with temperature
N_{Thresh} = number of precipitation or temperature thresholds exceeded

C_{Thresh} = cost per threshold increase
C_{base} = base construction costs for paved or gravel roads

Equation 3.2 $$\text{CostReactive}_T = L_T * C_{Maint}$$

Where:
CostReactive_T = change in road maintenance costs associated with a unit change in temperature
L_T = percent change in road lifespan associated with a unit change in temperature
C_{Maint} = cost of preventing a given road lifespan decrement

To estimate the reduction in lifespan that could result from an incremental change in climate stress (L_T) it is assumed that such a reduction is equal to the percent change in climate stress, scaled for the stressor's effect on maintenance costs, as shown in Equation 3.3.

Equation 3.3 $$L_T = \frac{\Delta T}{T_{base}} * C_{MaintBase} * Road_{Degrade}$$

Where:
L_T = percent change road lifespan associated with a unit change in temperature
ΔT = change in temperature
T_{base} = base level of temperature with no climate change
$C_{MaintBase}$ = standard maintenance costs for the road type
$Road_{Degrade}$ = standard road degradation rate

These functions relate incremental changes in temperature and precipitation to changes in design or maintenance that will "climate-proof" the road against damage from future climate change impacts. For this case study, the basic assumptions and process of the IPSS model remain the same. However, Dutch road design parameters – including cost, lifespan, and pavement type – replace the original IPSS road inputs. Combined with the downscaled climate modeling, these changes modify the system to produce results that are organization-specific and on a finer spatial scale than previously attained.

The cost results are presented based on two alternate adaptation strategies; both strategies assume that the goal is to maintain the original design life of the road. The "reactive" strategy is based on a “wait-and-see” approach, where the original design life is upheld through additional maintenance performed after the damage occurs. The “proactive” strategy upholds the original design life through changes in the initial design of a road. These changes climate-proof the road by changing the design to withstand the changes in temperature and precipitation that are forecast to occur during the road’s lifespan. Examples of proactive adaptation are modifying the asphalt mix design or increasing the pavement thickness.

The IPSS model evaluates the future changes in temperature and precipitation at the beginning of each road’s design life. If the climate model forecasts that changes in temperature and precipitation will exceed a predetermined threshold during that road’s design life, the adaptation model calculates the costs for both proactive and reactive adaptation. Aggregating to the network level, the adaptation costs are calculated for based on what percentage of the entire road network is reconstructed or resurfaced per year. The climate variables used for this research are the maximum monthly precipitation and a 7-day moving average of maximum daily temperature. The thresholds are determined using previous pavement research that studies the effects of climate stress on roads, regardless of climate change. For example, the default threshold for precipitation is 10 cm, derived from a combination of previous research. (Miradi 2004; N.D. Lea International Ltd. 1995) The thresholds can be modified, and the precipitation threshold was updated to 5 cm using pavement characteristics and planning preferences from the Netherlands.

Climate Data

In addition to the GCM data that IPSS typically utilizes, this case study includes downscaled climate data that is specific for the Netherlands’ region of Europe. The climate data is initially analyzed on a 0.5° longitude by 0.5° latitude grid for temperature and precipitation. Using higher resolution RCMs, analysis is then performed at the 0.25° by 0.25° scale.

Regional Climate Models are a complementary research method to the coarser resolution General Circulation Models. High resolution is one key advantage of RCMs (spatial resolution of

25-50 km) compared with GCMs (spatial resolution at best around 100-200 km), especially in regions with variable land forms or characteristics. The quality of an RCM simulation, with a spatial resolution of 25-50 km, is dependent upon the RCM itself and upon the driving GCM.

The ENSEMBLES project was a large research program founded by the European Commission in 2004. The main aim of the ENSEMBLES project was to run multiple climate models ('ensembles') with the goal of producing a range of future predictions equipped to decide which of the outcomes are more likely than the others.

In the ENSEMBLES project, fifteen institutes ran their RCMs at 25 km spatial resolution, with boundary conditions from five different GCMs, all using the same Special Report on Emissions Scenarios (SRES) emission scenario. In this study, it was decided to use one RCM per institute and only those that extended their simulation until 2100. Table 3.1 sets forth the eight RCMs that are used in this study. (van der Linden and Mitchell 2009) Multiple RCMs were selected because, as the ENSEMBLES researchers describe, there is inherent uncertainty and variation in climate modeling and using at least two or more RCMs driven by two or more GCMs helps reduce under sampling of that uncertainty.

Table 3.1: List of RCMs used for this study with their driving GCMs

RCM	**Driving GCM**	**Reference**
CNRM ALADIN	ARPEGE	(Radu et al. 2008)
DMI HIRHAM	ECHAM5	(Christensen et al. 2007)
ICTP REGCM	ECHAM5	(Pal et al. 2007)
KNMI RACMO	ECHAM5	(van Meijgaard et al. 2008)
MPI REMO	ECHAM5	(Jacob 2001)
SMHI RCA	BCM	(Kjellström et al. 2005)
METOFFICE HadRM	HadCM3	(Pope et al. 2007)
ETH CLM	HadCM3	(Böhm et al. 2006)

The specific climate output is difficult to compare in detail, as temperature and precipitation forecasts vary within GCMs, within RCMs, and between GCMs and RCMs. Therefore, impact modeling results are presented in percentiles or averages. However, some general conclusions were drawn from the ENSEMBLES project that are important to consider when reviewing the impact modeling in this research. When the RCMs were taken to a higher resolution, almost all models simulated higher levels of precipitation than GCMs. This could be in part because downscaling reinforces bias already present in the GCMs, but also in part because RCMs are better equipped to include seasonal effects and regional weather patterns. While the average of temperature results remained similar across RCMs driven by various GCMs, this project was not able to utilize all RCMs to forecast through 2100. The RCMs selected tended to simulate higher temperatures than the suite of GCMs, particularly for maximum temperatures and extremes.

ROAD NETWORK

The Netherlands has one of the densest road networks in the world with approximately 137,000 km (IRF 2012) in 33,883 square km of land area, or 4 km of road per square km. The road network selected for this study was limited to motorways because these roads are directly managed at the national level, and they are of critical economic importance to the country. The total length of the motorway road network is 4,470 km (RWS 2012), separated into primary and secondary roads. The primary difference between primary and secondary is the cost of construction, which is reflected in the IPSS input parameters. For adaptation modeling, the national total is distributed regionally based on population and land area weighting, as seen in Equation 3.4. The resulting distribution is shown in Table 3.2 and Figure 3.2.

Equation 3.4 $$R_P = R_N * 0.5\left(\left(\frac{Pop_P}{Pop_N}\right) + \left(\frac{A_P}{A_N}\right)\right)$$

Where:
R = Roadstock (km)
Pop = Population
A = Land area (km)
Subscript P = Province
Subscript N = National

Table 3.2: Road Network Distribution by Province

Province	Primary	Secondary	Total (km)
Drenthe	164.4	77.1	241.4
Flevoland	94.7	44.4	139.1
Friesland	210.8	98.9	309.7
Gelderland	409.3	191.9	601.3
Groningen	159.3	74.7	233.9
Limburg	206.2	96.7	302.9
Noord-Brabant	448.1	210.1	658.2
Noord-Holland	361.0	169.2	530.2
Overijssel	253.4	118.8	372.2
Utrecht	167.7	78.6	246.3
Zeeland	116.2	54.5	170.7
Zuid-Holland	455.0	213.3	668.3
Total	3046.0	1428.0	4474.0

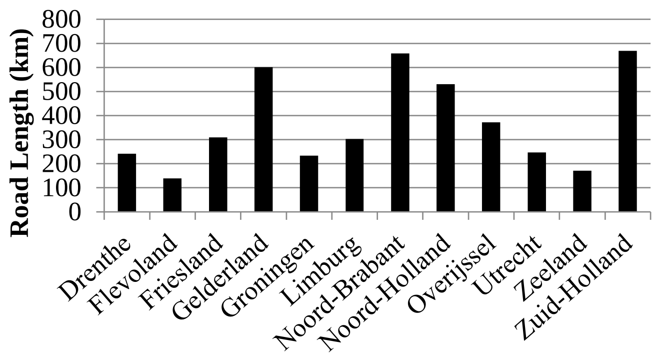


Figure 3.2: Road Network Distribution by Province

Beyond length, the road pavement type also needs to be defined for the network in order calculate adaptation costs. As previously described, approximately 90% of roads in the Netherlands (Huurman et al. 2010b) are porous asphalt (PA). Most those roads are paved with ZOAB – Zeer Open Asfalt Beton – the PA design specific to Rijkswaterstaat. Given the ongoing policy requirement to pave using porous asphalt, the assumption is made to define all roads as ZOAB.

While there is existing research on general PA pavement design life and cost, the adaptation costs are being modeled specifically for the Netherlands and for their ZOAB pavement. The lifespan of porous asphalt, ZOAB included, can be highly variable. In a Dutch report on road management modeling, historical life cycle and maintenance characteristics of ZOAB are provided in detail. ZOAB design life has been observed to be as short as five years and as long as twenty years or more. Based on the data, the average lifespan is approximately eleven years, which the researchers selected for this case study. (CROW 2002)

The end of a road's lifespan in the Netherlands is determined by the next instance when it requires resurfacing. Therefore, the construction cost for ZOAB roads in the Netherlands was selected as the average cost of resurfacing per kilometer (€615,000), rather than the cost to completely construct a new road, including excavation, sub-base, etc. Similarly, routine maintenance on ZOAB roads in the Netherlands is typically considered to be winter maintenance, small patching, and crack repair. That cost per kilometer (€130,000) was also selected from van der Wal and de Bondt (2005) and input into IPSS.

RESULTS

TEMPERATURE CORRELATION

The Netherlands Road Weather Information System (RWIS) is a continuous monitoring system for early warning of slipperiness on highway pavement surfaces. The RWIS system consists of 285 Road Weather Stations (RWS) combined with small local meteorological measuring stations. These stations are used to produce warnings of potentially upcoming slippery situations based on road surface temperature, resistance (dry, wet, or salt), dew point, and precipitation. The road surface temperatures were analyzed at three locations on highway A10 for this project via embedded temperature sensors, as shown in Figure 3.3 Road temperatures were measured in the surface layer, and air temperatures were measured next to the road.

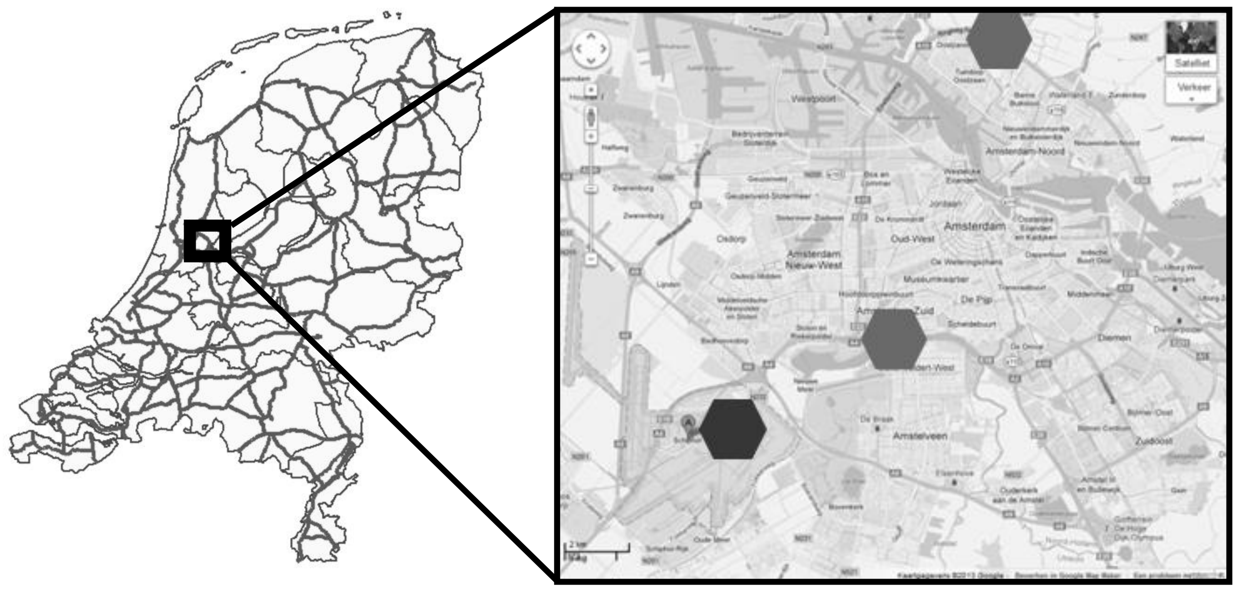


Figure 3.3: Map, location of road sensors and KNMI weather stations on highway A10

To establish correlations between official meteorological stations, road temperatures were initially correlated to the air temperature immediately adjacent to the road. This was then correlated to temperatures measured at the nearest meteorological weather station, in this case, KNMI Schiphol weather station. Temperature measurements were correlated for the period of 3 years. Results are presented in Figure 3.4. The goal of this part of the research is to establish numerical correlations that can be used for translating air temperatures into pavement temperatures, where no direct measurement of the road surface temperatures exists. Previous IPSS modeling used a relationship between pavement and air temperature based on latitude.

Equation 3.5 $$T_P = 0.9545(T_A - 0.00618\ L2 + 0.2289\ L + 42.2) - 17.8$$

Where:
T_A = air temperature (^oC)
T_P = pavement temperature (^oC)
L = latitude (arc degrees)

While this latitude-based equation is useful in many different countries, it is particularly useful when data is limited. The Netherlands has the necessary empirical data to create improved correlations, so these will replace the previous equation. The relationship between air and road temperature is used in predicting damage that is dependent on road temperature. As seen below, the temperature conversion equations have very high correlation factors and are appropriate for adaptation modeling purposes.

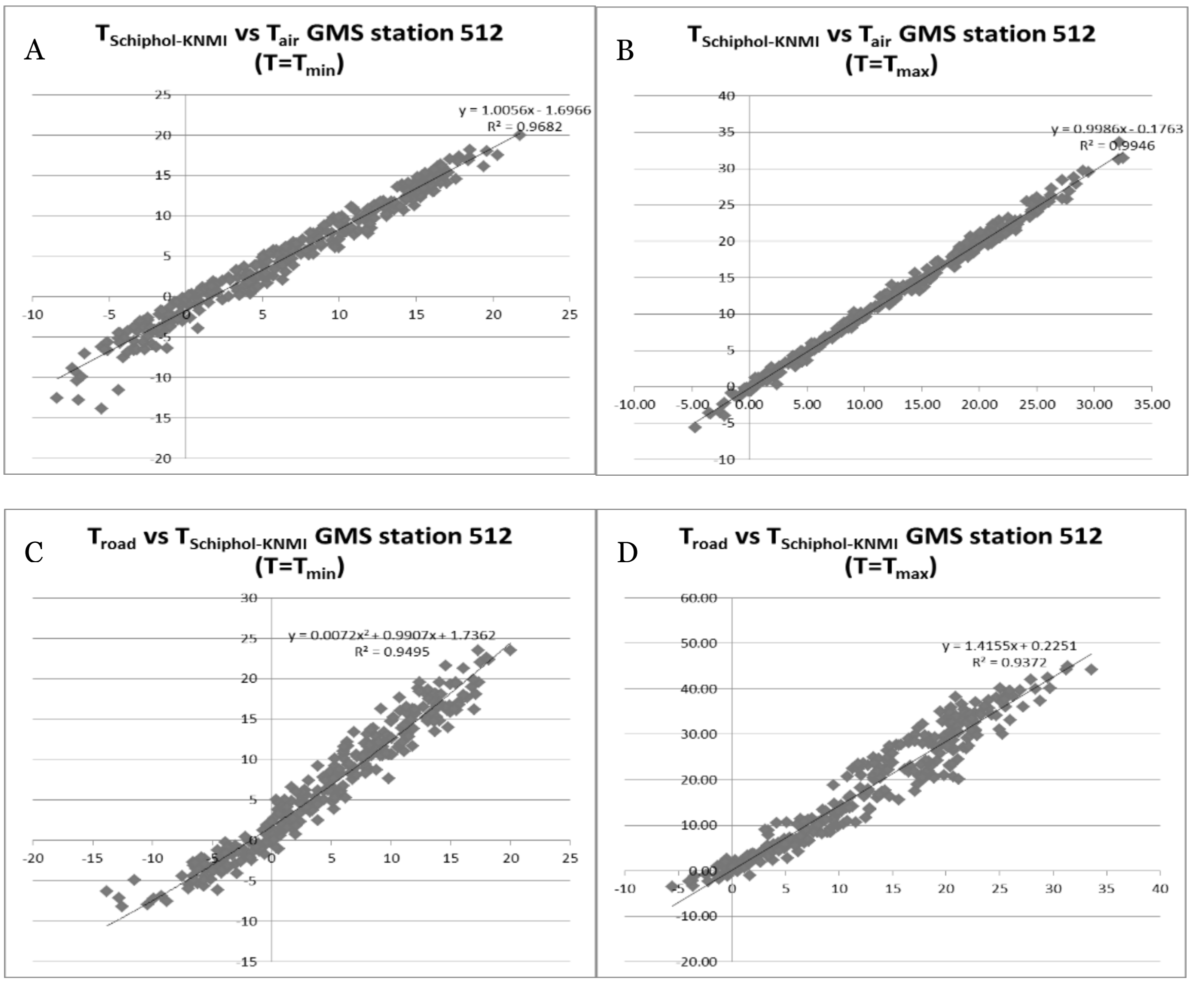


Figure 3.4: Results of correlation between air and pavement temperature

Note: Chart A, correlation between minimum air temperatures measured beside the road and with official KNMI station; Chart B, correlation between maximum air temperature measured beside road and with official KNMI station; Chart C, correlation between minimum road temperature and air temperature measured at the KNMI station; Chart D, correlation between maximum road temperature and air temperature measured at the KNMI station

ADAPTATION ANALYSIS

Two broad analyses, one for GCMs and one for RCMs, are completed for comparison. For both options, the pavement characteristics and costs were updated from the default IPSS values to the Dutch case. First, IPSS was run with the suite of fifty-six GCMs used in previous case studies. Second, IPSS was run with the collection of eight RCMs from the ENSEMBLES project. Both model runs calculated annual costs for each adaptation strategy, proactive and reactive, for each year through 2100. Because the results are primarily intended for long-term planning and decision-making, the costs are presented in this paper in total costs and average annual costs. The results are reviewed primarily for comparison with each other in the context of what effect climate downscaling has on the cost output, and secondarily for the potential cost implications to the Netherlands.

Figure 3.5 below shows the total cost of climate change to the Netherlands through 2100 in quartiles. The results are sorted based on proactive costs, and because the two strategies are linked to the same climate model, the reactive approach does not necessarily follow an increasing pattern.

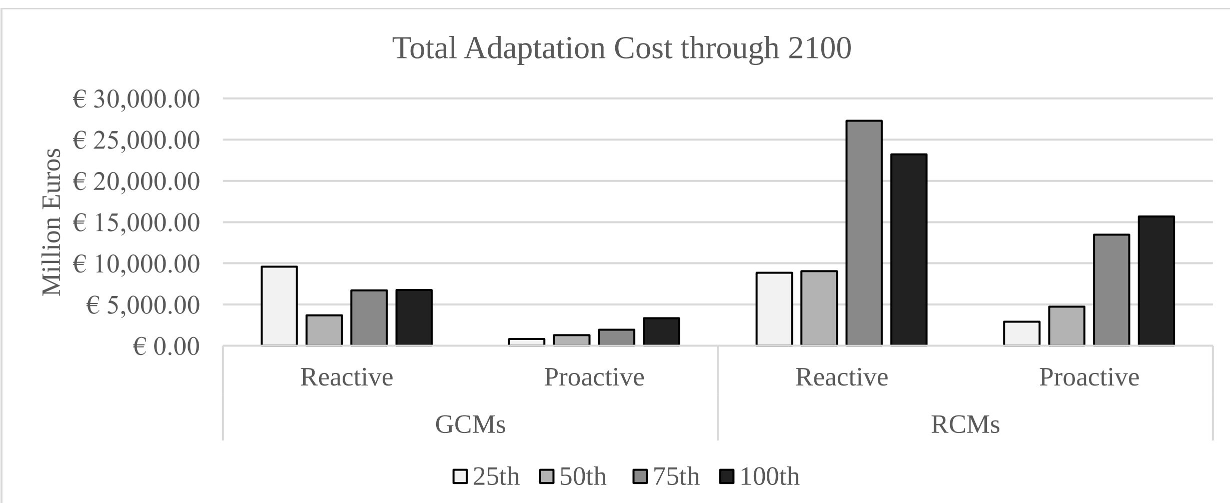


Figure 3.5: Total Cost of Climate Change Through 2100

The costs calculated using RCMs are higher, except in one case of the lowest reactive quartile, than the costs calculated using GCMs. This shows that using downscaled climate data, particularly climate models that have been pre-selected and run for a specific region, can have a substantial effect on the forecast of adaptation costs. The higher adaptation costs forecast using RCMs corresponds with the fact that the RCMs selected for this study generally predict larger increases in temperature and precipitation than the GCMs. In the more extreme cases, the 75th and 100th percentiles, the costs from RCMs were 3.4-4.1 times higher than from GCMs for reactive adaptation and 4.7-7 times higher for proactive adaptation.

The results also show that at a national level, the total cost of adaptation through the century will be less for a proactive approach than reactive. For example, in the 75th percentile results using Dutch RCMs, reactive adaptation costs are approximately €10 billion more than proactive.

ANNUAL COSTS

Table 3.3 and Figure 3.6 below provide greater detail for the median and maximum results at various time windows through 2100. These results show similar general trends that proactive adaptation will typically cost less than reactive adaptation, and that RCMs predict higher cost of both strategies than GCMs. While reviewing the timeline results, it is helpful to refer to a previous point made in the introduction that, in most cases, adaptation is less a question of whether it is necessary, but when. Some of the results, particularly in the maximum RCM scenario, show costs that are very similar to proactive and reactive adaptation until 2050. At that point, the climate changes more drastically than in the previous 40 years, and the adaptation advantage becomes more pronounced. There are, however, cases where proactive adaptation could cost less from now until the end of the century, as seen in the 75th percentile RCM scenario.

Table 3.3: Average Annual Cost of Climate Change (million Euros)

	2030				2050				2090			
	RCM		GCM		RCM		GCM		RCM		GCM	
Percentile	Proactive	Reactive	Proactive	Reactive	Proactive	Reactive	Proactive	Reactive	Proactive	Reactive	Proactive	Reactive
25th	€30	€42	€15	€27	€23	€74	€14	€26	€30	€101	€16	€57
50th	€47	€57	€22	€39	€53	€60	€20	€63	€51	€139	€25	€70
75th	€167	€213	€32	€48	€149	€238	€28	€87	€101	€313	€34	€100
100th	€221	€224	€55	€76	€243	€249	€58	€122	€175	€292	€55	€131

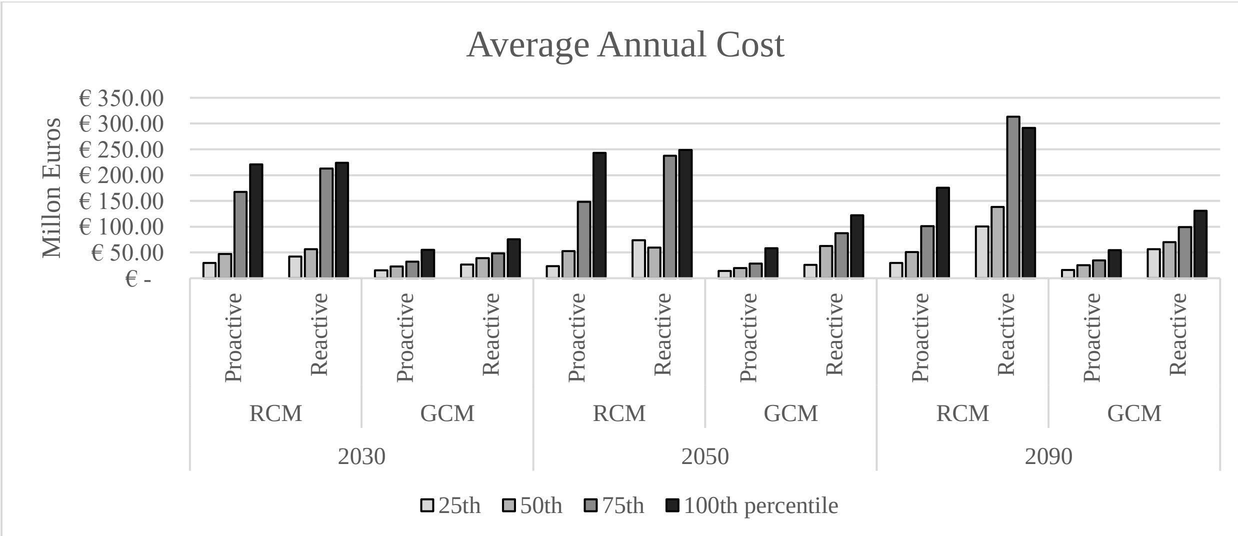
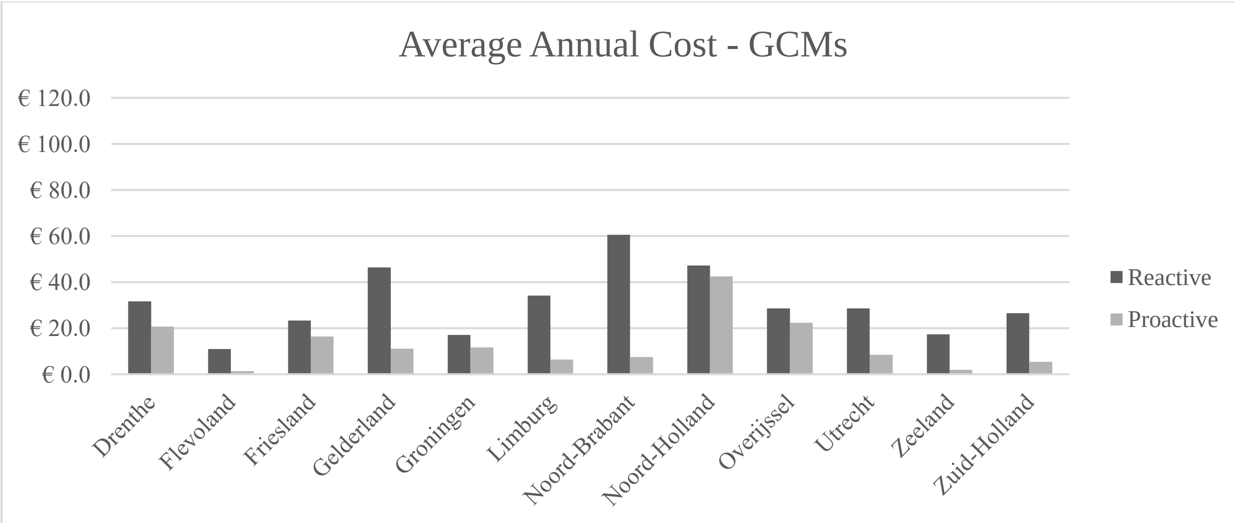


Figure 3.6: Average Annual Cost of Climate Change

REGIONAL COSTS

Costs are also calculated regionally by province. The average cost for each strategy is shown below in Figure 3.7. These regional variations are important to examine because transportation agency planning and management is often performed at a regional level and not all national trends will apply to each province. Both the GCM and RCM results show similar distribution by province. When the GCM input is used Noord-Brabandt, Gelderland, and Noord-Holland have the three highest annual costs. With RCM input Noord-Brabandt, Gelderland, and Zuid-Holland have the three highest annual costs. Regional costs vary greatly, as seen in the €110 million difference between Noord-Brabant and Flevoland in the RCM projections. These variations are influenced by the roadstock input and the climate data. As future work refines the input for road length per province, the accuracy of the regional results will increase. Variation caused by the climate modeling will likely not change, as the modification from GCM to RCM has already been made. As expected, the RCM results show generally higher costs across the country and a greater level of variation (€110 million) between provinces than the GCMs (€60 million).



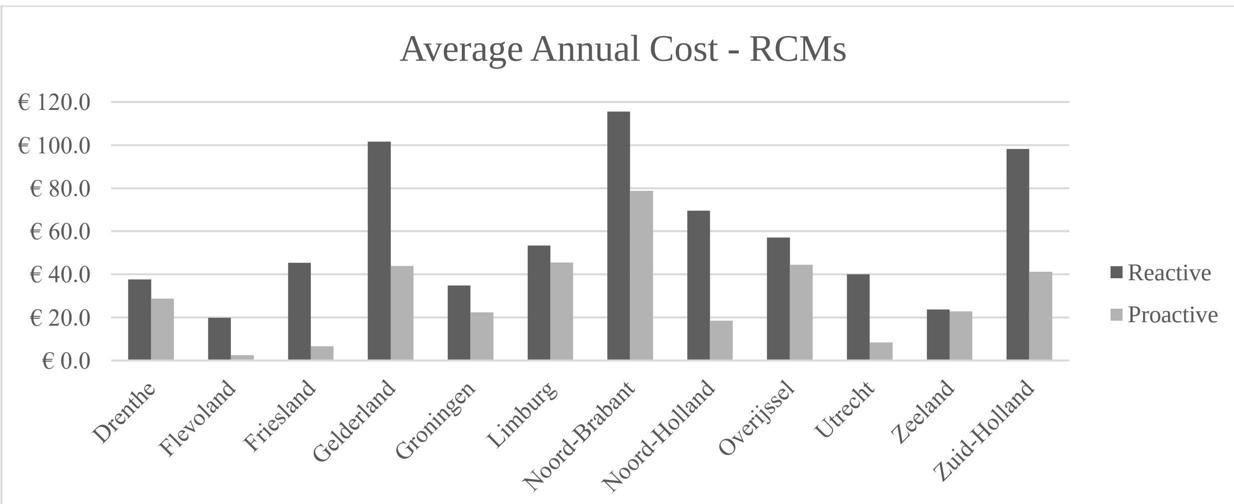


Figure 3.7: Average Annual Cost of Climate Change, per Province

DISCUSSION AND CONCLUSION

The detailed climate, pavement, and cost data advance adaptation modeling methodology and produce more accurate and actionable results for transportation organizations. This improves support for decision-making, long-term planning, design, and maintenance within the organization. The combination of Rijkswaterstaat's reputation for long-term planning, strict maintenance procedures, and recent budget constraints (RWS 2012) further highlights the need for adaptation analysis that addresses their organization and regional priorities, not just sector-wide concerns.

The initial results from IPSS support that thesis that in most regions it is not a question of if there is an appropriate time to adapt to climate change, but when. The challenge that climate change presents for road infrastructure is both a short- and long-term concern. Given the current policy, cost, and engineering conditions used for this adaptation modeling, the cost of climate change through 2100 could be as high as €21 billion in the Netherlands. This is not an outcome but a forecast and varies up to €10 billion depending on which adaptation strategy is taken. There are also potential opportunities from a changing climate in the Netherlands. In some regions, drier climate will require less robust drainage design, and as future research will investigate, warmer winters could reduce damage and subsequent maintenance on highways. Relying almost entirely on porous asphalt has its benefits and costs, and understanding the future costs of changes in temperature and precipitation will help with overall network effectiveness and resilience.

LIMITATIONS AND FUTURE RESEARCH

Economic modeling of climate change adaptation is limited by uncertainties in climate modeling. (Jotzo 2010) One method to combat this is to include a large range of climate models in the analysis so that a distribution of potential outcomes is obtained. In this case, the range of GCMs provides a larger data set than RCMs. While the Dutch climate collection includes fewer climate models, the regional modeling provides higher resolution data. The project currently uses eight RCMs compared to 56 GCMs. The eight regional models were selected due to data requirements (temperature and precipitation data through 2100), but additional RCMs may be used in the future.

In addition to climate data, the quality and specificity of other input data influences the output of the adaptation model. While the Dutch cost data and pavement characteristics are an improvement over the original inputs, there is still an unavoidable level of simplification. A main goal of this research is to produce results on a finer scale that are also organization-specific.

Therefore, future research will attempt to expand the inputs to include several types of asphalt pavement rather than assuming one type for the entire road network. Similarly, construction costs, maintenance costs, and lifespan will be updated based on these additional road types.

For cost, damage, maintenance, and climate interactions, empirical relationships from historic data will be used, when possible. For example, the equation converting air temperature to pavement temperature has been updated for the Dutch climate. Dutch government meteorological data is combined with pavement temperature measurements to create a relationship that is specific to the regional climate and the road properties. The researchers will continue to update this equation and other inputs when possible. The process of identifying what data to use and collecting it provides useful information for any transportation agency attempting to model their climate change adaptation costs.

ACKNOWLEDGEMENTS

The project team would like to thank the Netherlands Organisation for Scientific Research (NWO) for funding through the Sustainable Accessibility of the Randstaad Project and Rijkswaterstaat, for their generous collaboration. Portions of this material is also based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1144083. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Chapter 4 MODELING IMPACTS AND ADAPTATION COSTS OF FREEZE-THAW CLIMATE CHANGE ON A POROUS ASPHALT ROAD NETWORK

Keywords: climate change, adaptation, porous asphalt, freeze-thaw, roads, planning

ABSTRACT

Changes in weather patterns pose a threat to the serviceability and long-term performance of roads and porous asphalt (PA) roads are particularly sensitive to the freezing-thawing (FT) phenomenon. The main objective of this research is to assess the impact of climate change, particularly freezing and thawing cycles, on porous asphalt. Climate models predict changes in air temperature, not pavement temperature. In order to predict the climate change impact on pavements performance, this requires first establishing a relationship between air and road temperature and a correlation between pavement performance and FT cycles. This project focuses on the Netherlands, where PA pavement use has become mandatory and recent severe winters have increased the discussion about cold weather performance of porous asphalt and the potential challenges of changing winter weather patterns. When considering long-term changes in climate, the cost impacts of freeze-thaw on PA pavement are predicted to vary regionally and, in most areas, reach a point in the middle of the century when a reactive "wait-and-see" approach is more advantageous than proactive adaptation. Further research is suggested to refine the relationship between observed damage and freeze-thaw impacts on PA pavement.

INTRODUCTION

In recent winters, ravelling and pothole damage have increased discussion in the Netherlands about cold weather performance of porous asphalt (PA) and the potential challenges of changing winter weather patterns. (RWS 2010; Voskuilen et al. 2012) PA pavement use has become mandatory in the Netherlands, primarily for environmental reasons. This includes the impact of road construction to the surrounding environment, as well as quality of life for nearby citizens. With a small land area and dense highway network, residents in the Netherlands often live near highways and noise reduction is a critical issue for road and land use planning. As the population grows and the use of automobiles increases, the Dutch highways and waterways agency has made noise reduction a priority (Van Der Valk 2002). As a result, the Dutch highway network is now constructed with approximately 90% PA pavement. (Huurman et al. 2010b) This reliance on PA pavement increases the importance of incorporating climate change into long-term planning of the Netherlands highway network (Bles et al. 2012).

This research analyses the extent to which winter damage can be expected to change because of long-term climate change and what impacts that will have on the entire road network. Current climate change impact research often produces results on a systemic, macro scale, and less is known about the regional impact to specific road types. To address this gap, this paper investigates the impact of winter conditions, more specifically the impact of freeze-thaw cycles, on PA roads in the Netherlands.

The paper first introduces the background of porous asphalt pavement, winter impacts on PA pavement, and climate change impact research on this topic. The methods are then described for 1) air and temperature pavement correlation 2) freeze-thaw cycle estimation and 3) climate change adaptation modelling. The results of the first two analyses are presented and used as inputs into the climate change adaptation model.

The research is conducted using a combination of empirical data analysis, climate projections, and cost modelling. Historic winter maintenance data was recorded by Rijkswaterstaat (RWS), the ministerial road authority of the Netherlands, and winter weather data was provided by the Royal Netherlands Meteorological Institute (KNMI), the Dutch meteorological institute. By analysing these databases for correlations between weather and road damage, a stressor-response function is developed that relates the frequency of freeze-thaw cycles to the frequency of pavement damage. The stressor-response function is incorporated into a previously developed model, the Infrastructure Planning Support System (IPSS), which analyses the impacts of climate change on infrastructure and approximates costs of different adaptation options for those impacts. Using Dutch regional climate models, the researchers analyzed the potential impacts of adapting PA pavement to future climate changes in freeze-thaw cycling, which have implications on maintenance, design, and long-term planning of the Netherlands' road network.

The changes in winter climate and ensuing impact on road damage vary regionally within the Netherlands. Given the pavement characteristics, future climate change will impact the long-term viability and maintenance considerations of PA pavement. The IPSS results highlight regions where proactive adaptation may result in lower cost impacts than a reactive approach and vice versa. These results have practical implications for the Netherlands and other countries using porous asphalt for highways, both for short and long-term planning and policy decision-making. Adaptation strategies, pavement characteristics, and cost data used for the adaptation modelling are based on actual maintenance and design practices in the Netherlands, which result in output and recommendations that are both relevant and actionable for the Netherlands Ministry of Transportation.

BACKGROUND

Porous Asphalt Pavement

Porous asphalt (PA) pavement is characterized by a high percentage course aggregate and a high percentage of interconnected voids in the top friction layer of the pavement. (Mohan 2010). The maximum aggregate size used in single layer PA pavements is 16 mm with a layer thickness of 50 mm and a built-in air void of 20%. Standard bitumen without modification is used for single layer PA pavements. In 2007, Rijkswaterstaat increased the bitumen percentage from 4.2 to 5.2% and this is considered to increase the lifetime of the pavements by around 10-15%. For two-layer PA the maximum aggregate size in the top layer is normally 8 mm (Vejdirektoratet (Danish Road Directorate) 2012), as presented in Figure 4.1.

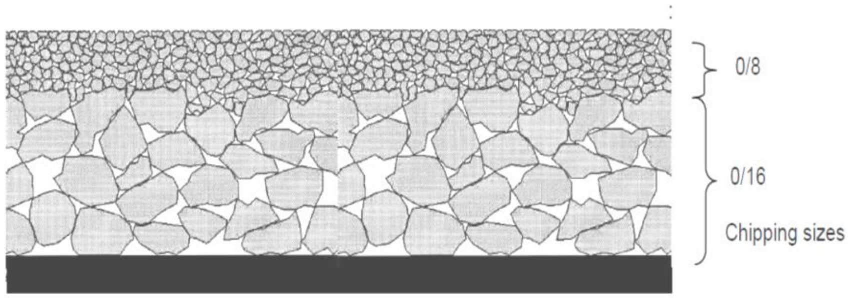

Figure 4.1: Two-layer porous asphalt (Hagos 2008)

This Two Layer Porous Asphalt (TLPA) is shown with 0/16 and 0/8 aggregate matrix in the bottom and top layer, respectively. The TLPA with 0/8 chipping size and 30 mm thickness as a top layer has the advantage of reducing traffic noise to 4-6 dB(A) compared to 2-3 dB(A) reduction by Single Layer Porous Asphalt (SLPA) (thickness 50 mm). An additional advantage of TLPA includes reduced clogging problems of the PA surfacing layer (Hagos 2008).

The high permeability of PA has several benefits, including: increased road user safety as a result of few accidents from standing water and poor visibility from splashing water (Takahashi 2013), high resistance to rutting (Miradi 2009a), less groundwater pollution from a reduction of suspended solids and pollutants in stormwater runoff compared to impervious pavement (Berbee et al. 1999), and less noise pollution to the surrounding environment from a reduction of tire noise (Huurman et al. 2010a). A major motivation for the use of PA in the Netherlands is that its cost and space efficiency in reducing noise is higher than sound barriers (Alvarez et al. 2006).

There are drawbacks to PA, particularly in the context of weather impacts. Porous has a shorter lifespan than most alternative pavement types (Hagos 2008; Miradi 2009a), it is susceptible to increased raveling and accelerated aging from rainwater and de-icing salt (Su 2013), and it has been shown that the effectiveness of noise reduction can be significantly reduced with age and clogging of pores (Bendsten et al. 2005). Additionally, lower temperatures exacerbate these drawbacks by increasing stress in PA pavement and the rate of damage increases with more frequent temperature fluctuations. (Mohan 2010). These last points are important when evaluating the long-term effectiveness of PA pavement as climate patterns change in the future.

POROUS ASPHALT PAVEMENT AND FREEZE-THAW

Low temperatures, moisture, and resulting freeze-thaw cycles damage PA pavement. During the winter season, moisture in PA may freeze and thaw in cycles. This cycle of freezing and thawing can cause a volume change within the material, create stress on the pavement, and result in a loosening of the bond between aggregate and binder. This may be exacerbated by vehicles displacing or disturbing surfacing materials, which in turn allows more moisture to ingress. (Galbraith et al. 2005) Small cracks develop in pavements with aged and hardened bitumen. Water penetrates these cracks and in periods of frost the water freezes and accelerates the loosening of aggregate from the pavement surface. (Mohan 2010)

This loosening of aggregate, or ravelling, is the most common failure of PA pavement and primarily occurs in the winter season. The Permanent International Association of Road Congresses (PIARC) states that rutting or cracking failure modes rarely appear in PA, except for reflection cracks, and that loss of material through ravelling is one of the major reasons for road maintenance. (PIARC 1993)

The expected lifetime of single layer PA is one to two years less than for dense asphalt concrete. In the Netherlands, experience has shown that the approximate service life for PA wearing courses is 10 years versus 12 years for dense asphalt concrete (Van der Zwan et al. 1990). Additionally, PA pavement damage increases at the end of its expected lifetime. Old PA pavement is more sensitive to freeze-thaw cycles and older PA is also shown to be less effective at noise reduction. (Huurman et al. 2010a)

The 2009/10 and 2010/11 winters were severe in the Netherlands, characterized by heavy snowfall, frost, and more frequent freeze-thaw cycles. At the same time, an increase in damage (ravelling and potholes) was observed throughout the network. As 90% of the highway network is constructed of PA pavement, this corresponds with the research on failure modes of PA in cold temperatures. The damages observed consisted mostly of ravelling, potholes and material loss at longitudinal joints between porous asphalt sections, as seen in Figure 4.2.

Figure 4.2: Frost damage on porous pavement (RWS 2012)

CLIMATE CHANGE

A severe winter is statistically seen only once in every ten years in the Netherlands. As seasonal climate patterns change, so will the frequency of severe winters. Rijkswaterstaat has recognized the need for more fundamental research into the causes of frost damage and started in 2009 to monitor specific damage during the winter period, based on regular weekly visual inspections.

In Europe, the large Extreme Weather Impacts to European Networks of Transport (EWENT) and WEATHER research projects showed, using global and downscaled regional climate models, that patterns of freeze-thaw cycles will change from now until 2100. The general trend is that the frequency of freeze-thaw cycles may increase in the next several decades, but that is expected to decline in the second half of the century. (Leviäkangas et al. 2011; Pryzluski et al. 2011) As temperatures rise, winters will become warmer and there will fewer days with minimum temperatures below freezing.

There are many research studies that investigate the detailed mechanical and physical impacts of climate on porous asphalt pavement (Watson and Rajapakse 2000; Zuo et al. 2007), including moisture (Kiggundu and Roberts 1988; Kringos et al. 2008), low temperature (Voskuilen et al. 2012), and freeze-thaw (Van Deusen et al. 1998). These studies are useful to understand the detailed impacts of climate stressors on different pavement types, particularly PA, but typically do not include consideration of future climate change. There is research that incorporates climate change, some of which are industry reports that study a wide range of stressors and regions (Carrera and Dawson 2010; Lamb et al. 2012) and some academic research focusing on more detailed analysis of impacts on pavement design (Meagher et al. 2012), including consideration of freeze-thaw (Daniel et al. 2017).

However, there is yet to be research that focuses specifically on the long-term climate change implications of freeze-thaw on porous asphalt pavement, particularly with a network-wide cost perspective. This research fills that gap through climate change adaptation modelling, by combining an analysis of freeze-thaw cycles and road damage with regional climate change predictions.

METHODOLOGY AND DATA

The overall research question for this project is: what are the impacts and adaptation costs of long-term changes in freeze-thaw cycles on a porous asphalt road network? The Dutch motorway network is used as a case for investigation, because the road network is primarily porous asphalt, the Netherlands recently observed an increase in winter damage, and a previous adaptation analysis was performed on the same road network for long-term changes in temperature and precipitation (Kwiatkowski et al. n.d.). The climate adaptation modeling is completed using a stressor-response methodology, in which equations are used to relate changes in a climate stressor (freeze-thaw) to physical impacts (increased degradation) on an infrastructure asset (porous asphalt roads). The degradation is then equated to a financial cost using two response strategies, proactive and reactive adaptation. The specific tool used for this analysis is the Infrastructure Planning Support System (IPSS). Research using IPSS has already been published and contains more in-depth explanation of the methodology. (Chinowsky and Arndt 2012; Kwiatkowski et al. n.d.; Schweikert et al. 2014)

The most relevant aspect of the IPSS model for the freeze-thaw investigation is the development of adaptation thresholds. The adaptation evaluation is performed at the beginning of a road's design life. Results from climate models are used to determine if a climate stressor is predicted to change during the road lifespan. If that stressor changes it is reviewed against a predetermined threshold to determine if it exceeds the threshold value. If the threshold is crossed, the climate change is predicted to cause addition damage to the road, at which point the adaptation cost is calculated. The adaptation cost is calculated based on two broad strategies. Proactive adaptation is the cost to alter design and construction to "climate-proof" a road prior to the anticipated stressor change. Reactive adaptation is the cost to "wait-and-see" by using additional maintenance to repair damage to a road after the anticipated climate change has occurred.

To complete the adaptation modeling, two sub-questions first need to be investigated. To relate future changes in climate to freeze-thaw cycling, the research first investigates: what is relationship between air temperature and pavement temperature? Second, the research analyzes: using air temperature, how are freeze-thaw cycles calculated and how does this relate to observed damage in the Netherlands? Finally, the research uses the analysis from the first two questions as inputs to the larger question of what cost impacts to the porous asphalt road network will result from future changes in freeze-thaw cycles? An overview of this research process is provided in Figure 4.3. Data was collected from a variety of sources and is discussed in greater detail in the individual sections.

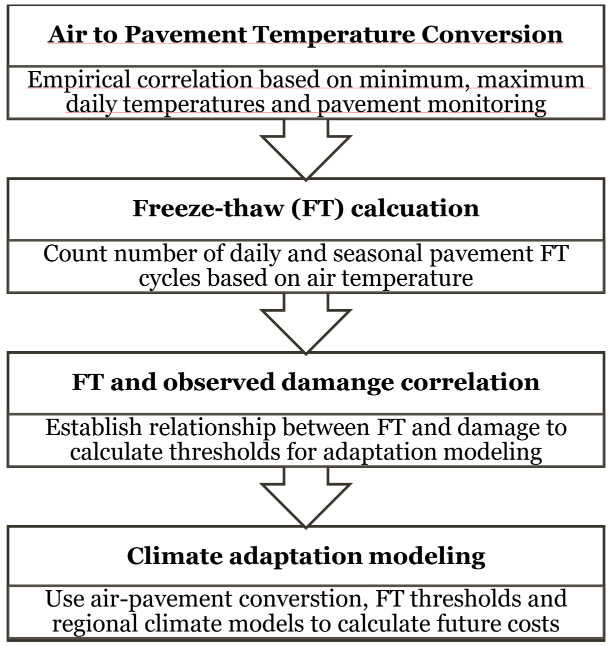

Figure 4.3: Research Flow Chart

TEMPERATURE ANALYSIS

Climate change impact studies for road infrastructure require information on future road temperature. While that information is not directly provided, climate models typically predict air temperature. (IPCC 2014; Mills et al. 2009; Peterson et al. 2008; TRB 2007) For this reason, a mathematical relationship is needed to convert air temperature to road temperature. This relationship can then be used to estimate future pavement temperatures from future air temperature, provided from Global Circulation Models (GCMs) or Regional Climate Models (RCMs). This relationship can also be used to estimate pavement temperature at locations where no direct observations are available, for example due to technical problems or areas between other stations.

For this project, temperature data was provided by the Royal Netherlands Meteorological Institute (KNMI) synoptic weather stations (KNMI 2017) and Rijkswaterstaat's Dutch Road Weather Information System (RWIS). RWIS is a continuous information monitoring system used for early warning of slipperiness on highway pavement surfaces. The system consists of a network of 285 road weather stations, where road surface temperatures are measured along with air temperature and other variables like humidity of the air and conductivity in the road. This research uses only the pavement and air temperature data.

Road temperature is measured at 2 mm below the road surface, in two or more road lanes, depending on the width of the road and the location. Data from the system are stored on a central server, along with meta information like the location and the lane that was monitored. Temperature readings are available with a resolution of five minutes. For this study, we analysed road surface temperatures measured at 27 locations in the Netherlands, mainly in the western part of the country. The locations are shown in Figure 4.4.

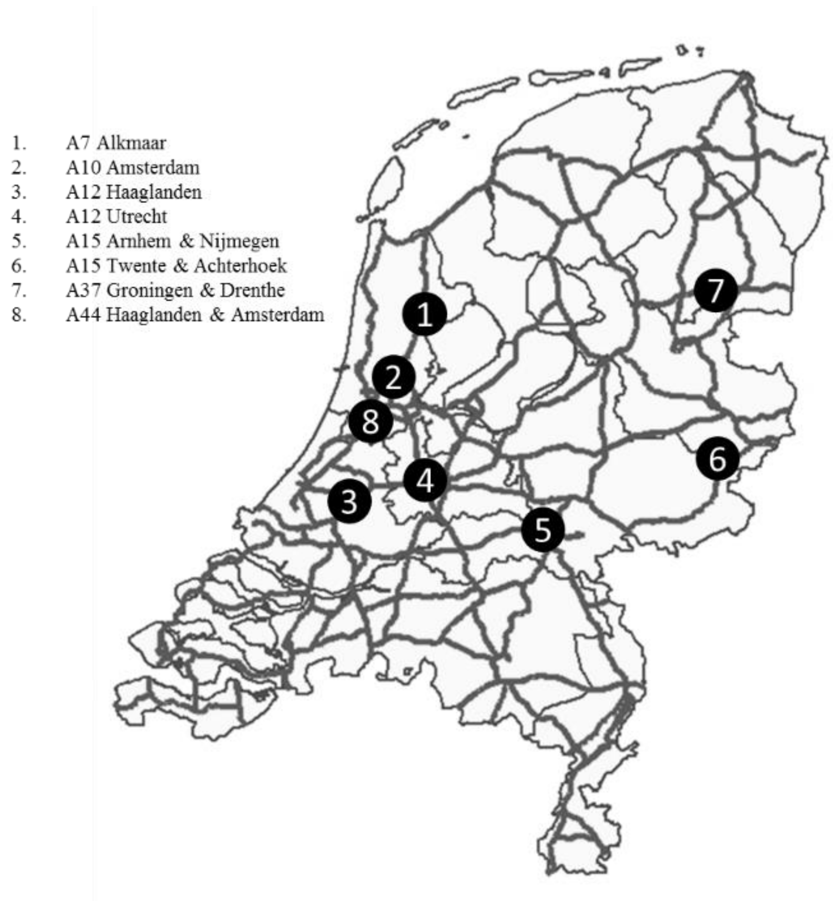

Figure 4.4: Location of road sensors on selected highway sections

The analyzed data was collected from the 2010/2011, 2011/2012 and 2012/2013 winters. For each location, the researcher team checked the quality of the readings by comparing data points from the primary sensor with nearby sensors. Individual sensors at a specific location typically agreed, in which case data was selected from the first sensor. If the data contained obvious outliers or gaps in the data exceeded several days, the next sensor was selected, using the same criteria, until a complete record was formed.

An example of the correlation analysis on highway A10 is shown in Figure 4.5. Road temperatures were first correlated to the air temperature immediately adjacent to the road. The air temperature at that location was then correlated to temperatures measured at the nearest meteorological station, the KNMI Schiphol station in this case. The goal of this part of the research was to establish numerical correlations that can be used for translating air temperatures into pavement temperatures, where no direct measurement of the road surface temperatures exists. The established correlations will be then used in predicting frost damage that is dependent on road temperature. As seen in Figure 4.5 below, the temperature conversion equations have very high correlation factors and are appropriate for the modelling purposes.

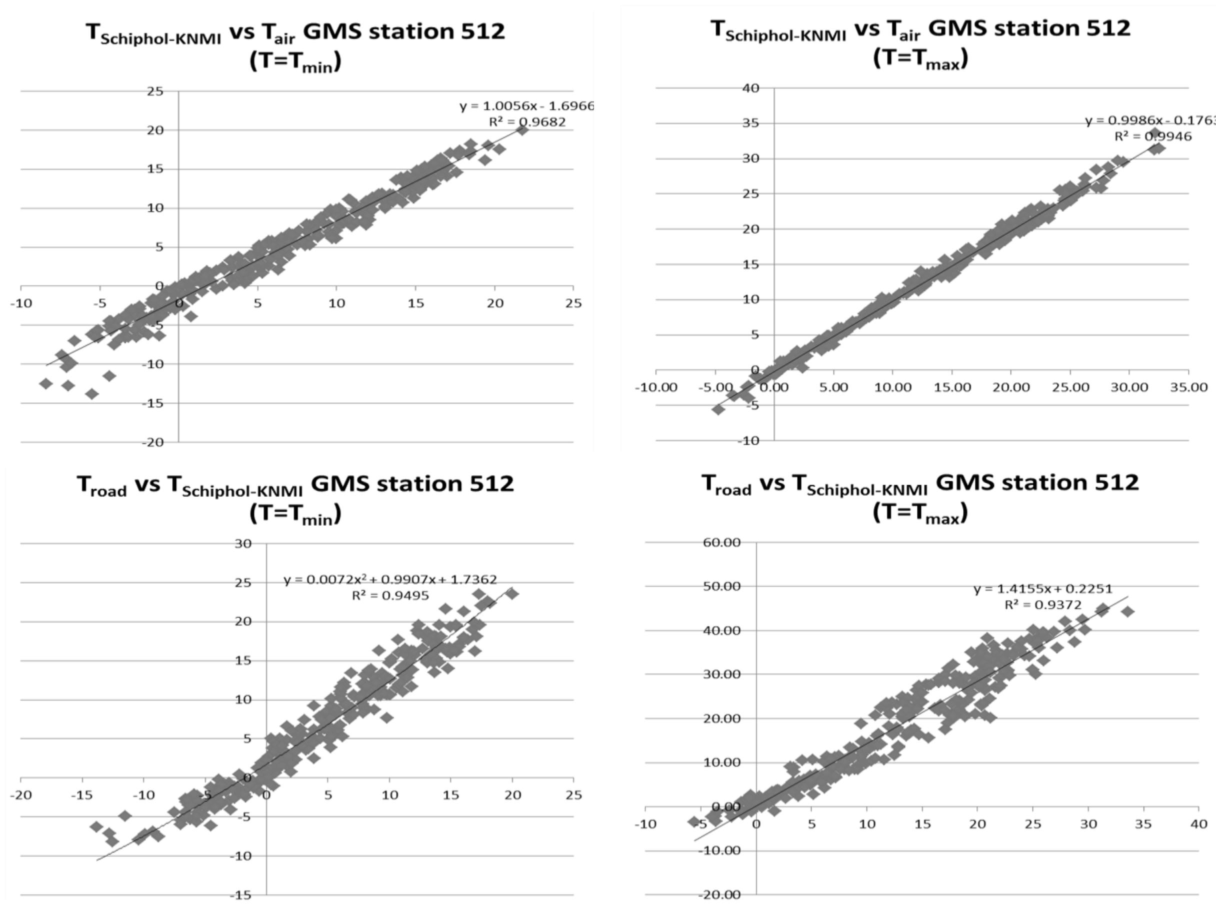

Figure 4.5: Results of air-pavement temperature analysis

a) correlation between minimum air temperature measured beside the road and with official KNMI station; b) correlation between maximum air temperature measured beside the road and with official KNMI station; c) correlation between minimum road temperature and air temperature measured at the KNMI station; d) correlation between maximum road temperature and air temperature measured at the KNMI station.

FREEZE-THAW ANALYSIS

The number of freeze-thaw (FT) cycles is anticipated to be an important indicator of winter road damage (Hagos 2008; Kestler et al. 2011). Eight representative road sections in different regions were selected for analyzing FT-related damages. The selection was based on different traffic intensities and winter conditions, creating a matrix from low traffic intensity and less harsh winter to high traffic intensity and harsher winter. Most definitions of an FT cycle involve the daily maximum and minimum temperature. Therefore, the correlations were determined for these temperatures only.

Several methods to determine the occurrence of a FT cycle have been published in the literature; Table 4.1 provides an overview of these methods and the following paragraphs highlight the differences between these methods. Most definitions of a FT cycle involve the daily maximum and minimum temperature. Therefore, the correlations were determined for these temperatures only. Figure 4.6 depicts the number of FT events detected from the air temperature measurements at Schiphol Airport from the years 1981-2012. Method 2 is not shown because results from that method are virtually the same as the ones from Method 1.

Table 4.1: Definitions of a freeze-thaw cycle

Method	Description of calculation methods to obtain # FT cycles and source
0	Max. temp. ≥ 0°C, minimum temperature <= -1 (Ho and Gough 2006)
1	Max. temp. ≥ 0°C and min. temp. ≤ -2.2°C in observation day (Schmidlin 1987)
2	Max. temp. ≥ 0°C occurring after a min. temp. ≤-2.2°C in observation day (Russell 1943)
3	A day with max. temp. ≥ 0°C and min. temp. ≤ 0°C (VISHER 1945)
4	Max. temp. > 0°C and min. temp. < 0°C in the observation day (Hershfield 1974)
5	Max. temp. > 0°C and min. temp. ≤ 0°C (Hayhoe et al. 1992)
6	Max. temp. ≥ 1.2°C following min. temp. of ≤ -2.2°C (Fraser 1959)

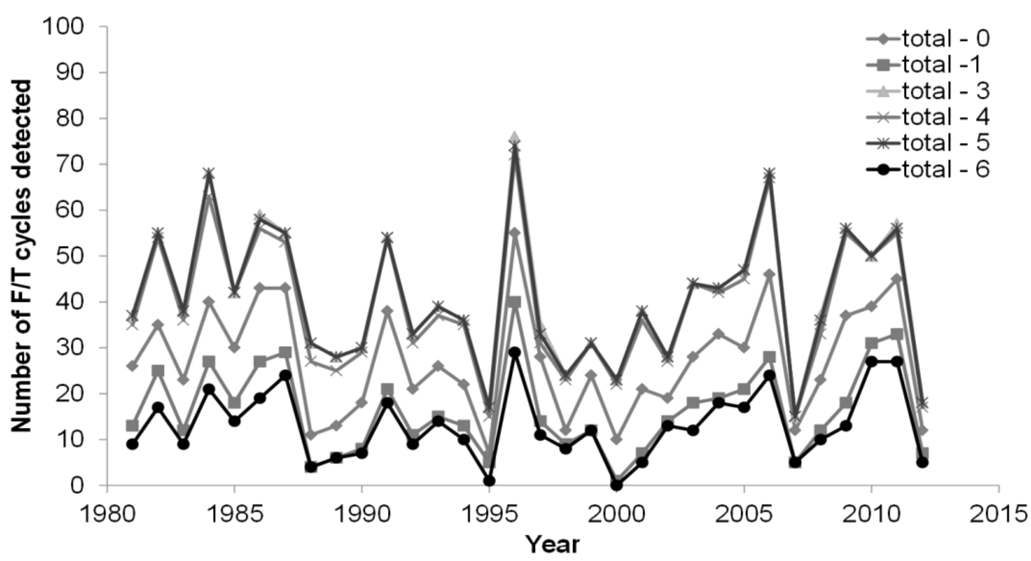

Figure 4.6: Freeze-Thaw Cycles from 1981-2012

The methods are generally separated into lower and higher tiers, with Method 0 (Ho and Gough 2006) between the two. Table 4.2 shows example results of applying Method 1, an example of the lower tier, and Method 4, and example of the higher tier, to the representative road sections.

Table 4.2: Number of Freeze-Thaw Cycles, 2010-2012 Winters

	Method 1		**Method 4**	
Representative Road Section	**2010/2011**	**2011/2012**	**2010/2011**	**2011/2012**
1. A7 – Alkmaar	20	8	50	19
2. A10 – Amsterdam	23	9	44	14
3. A12 – Haaglanden	13	8	39	14
4. A12 – Utrecht	24	11	53	22
5. A15 – Arnhem & Nijmegen	23	9	46	14
6. A15 – Twente & Achterhoek	23	12	46	25
7. A37 – Groningen & Drenthe	20	9	46	26
8. A44 – Haaglanden & Amsterdam	13	6	41	10

With the freeze-thaw cycles calculated, the next step was to quantify the amount of damage from freeze-thaw cycles. Rijkswaterstaat began collecting winter damage in 2009. Damage identified in the surface layer of PA pavements during winter season (beginning of October to end of March) were considered FT-related damages. These damages were divided in three groups – raveling, potholes and open crack – with notations of the location and length of damage. The damage was quantified as the length of the affected road and then expressed as a percentage of the total length of road section.

Figure 4.7 and Figure 4.8 show the amount of damage recorded in two different winters, compared with the number of freeze-thaw cycles. Method 1 and 4 are used as illustrative examples of the lower and higher tier, respectively.

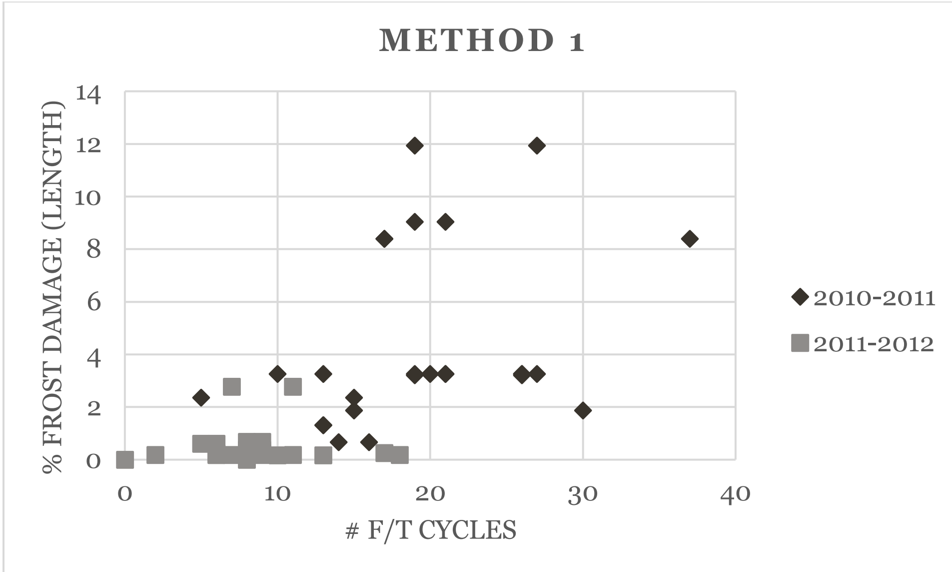

Figure 4.7: Winter damage in relation to freeze-thaw cycles, Method 1

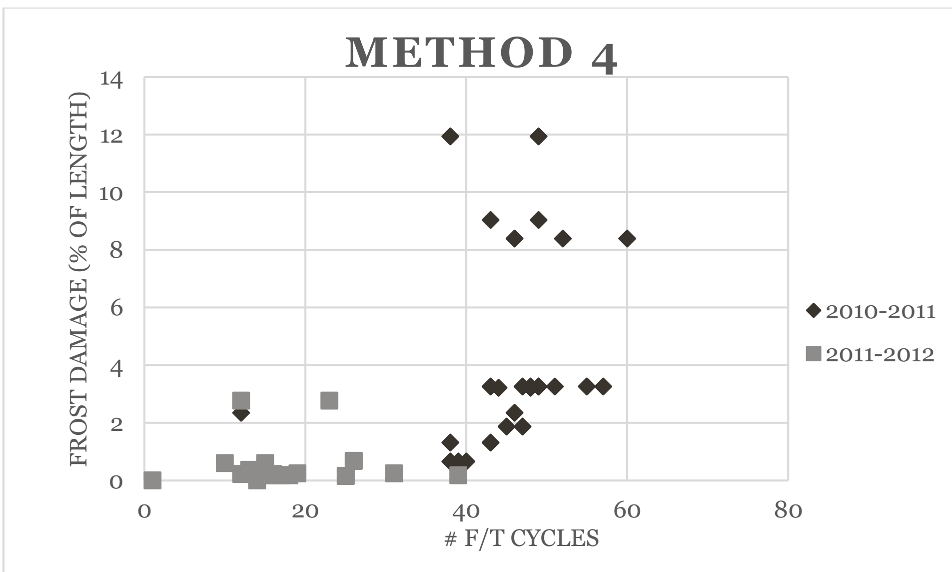

Figure 4.8: Winter damage in relation to freeze-thaw cycles, Method 4

The linear and polynomial correlations were weak, as there is a dramatic increase in damage after the number of FT cycles reaches a certain level, approximately 15 for Method 1 and 40 for Method 4. Ultimately, Method 0 was used to establish the thresholds for the climate change adaptation analysis. It is a more recently developed methodology and was expected to balance over and under calculation. The results using this method also fell between the lower and high tiers of FT cycle calculations. Figure 4.9 graphs the correlation between damage and FT cycles calculated using Method 0.

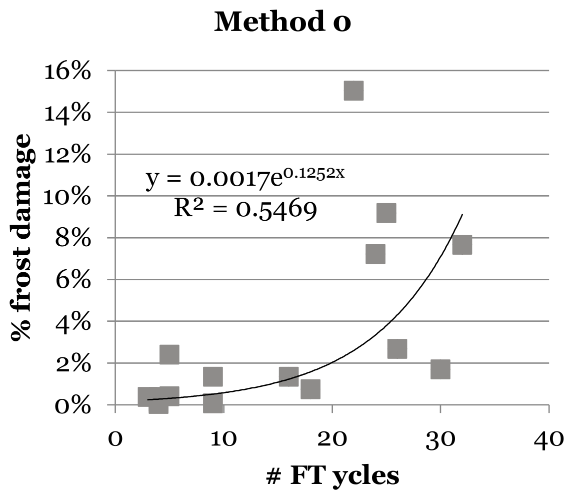

Figure 4.9: Winter Damage - FT Cycle Correlation (2011/12 - 12/13 Winters)

CLIMATE CHANGE ADAPTATION ANALYSIS

The final step of the research is to combine the results of the air-pavement temperature analysis and the FT-winter damage analysis with additional inputs to model the impact and adaptation costs from future changes in freeze-thaw cycles. This modeling was completed using the Infrastructure Planning Support System (IPSS), as described in the methodology section.

ADDITIONAL INPUTS

A list of one the main inputs, Regional Climate Models (RCMs), is provided in Table 4.3. These RCMs were produced from the ENEMBLES project and were selected for their applicability to the Netherlands and for the availability of data through the year 2100. Additional explanation can be found in Kwiatkowski et al. (n.d.) The air temperature data from these models was used as input for the air-pavement conversion equation to obtain pavement temperatures, that were used to calculate the predicted number of freeze-thaw cycles in a given year.

Table 4.3: Regional Climate Models and driving General Circulation Models

RCM	Driving GCM	Reference
CNRM ALADIN	ARPEGE	(Radu, et al. 2008)
DMI HIRHAM	ECHAM5	(Christensen, et al. 2006)
ICTP REGCM	ECHAM5	(Pal, et al. 2007)
KNMI RACMO	ECHAM5	(Van Meijgaard, et al. 2008)
MPI REMO	ECHAM5	(Jacob 2001)
SMHI RCA	BCM	(Kjellström, et al. 2005)
METOFFICE HadRM	HadCM3	(Pope et al. 2007)
ETH CLM	HadCM3	(Böhm et al. 2006)

The other main input used in the IPSS model is the length and type of road. The Dutch motorway network consists of three main types of pavement, DAB, ZOAB, and ZOAB TW. Dicht Asphalt Beton (DAB) is traditional asphalt concrete. Zeer Open Asphalt Beton (ZOAB), is their main type of porous asphalt pavement and constitutes the majority of motorways in the Netherlands. ZOAB Twe Laags (ZOAB TW) is a two-layer version of their porous asphalt pavement. The costs of construction (i.e. resurfacing), maintenance, and lifespan for each type is provided in Table 4.4.

Table 4.4: Dutch road type costs and lifespans

	DAB	ZOAB	ZOAB-TW
Resurfacing	€560,000	€590,000	€990,000
Maintenance	€106,000	€112,000	€188,000
Lifespan*	18/12	17/11	13/9

Note: *Lifespan = (left lane) / (right lane)

ADAPTATION RESULTS

A summary of results is presented below in Figures 4.10, 4.11, 4.12, and 4.13. The costs of both proactive and reactive adaptation strategies are calculated annually through 2100. For the purposes of this research, proactive adaptation is a change in the road pavement type. For example, a proactive adaptation would be to construct a road with double-layer PA instead of single-layer PA in advance of predicted changes in climate. The results are summarized into average annual costs and presented nationally and by province.

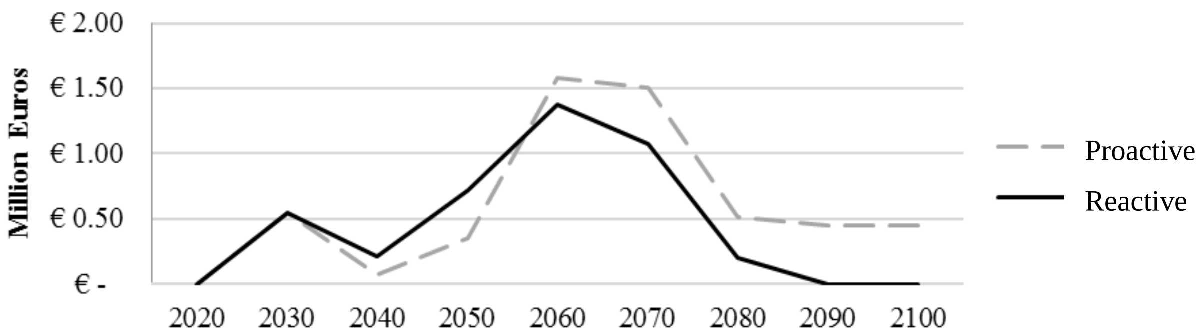

Figure 4.10: Median average annual cost from freeze-thaw climate change (national)

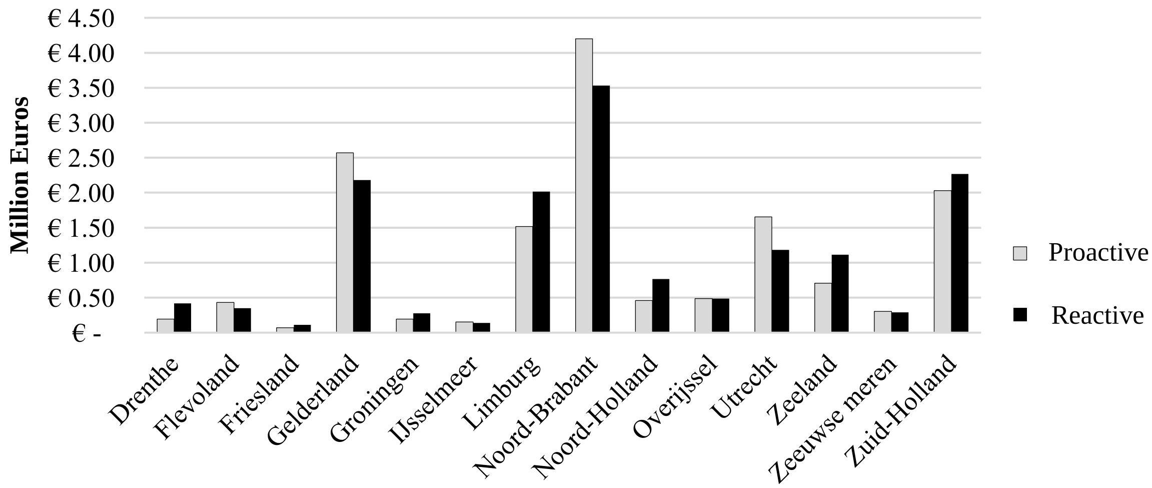

Figure 4.11: Median average annual cost from freeze-thaw in 2050 (by province)

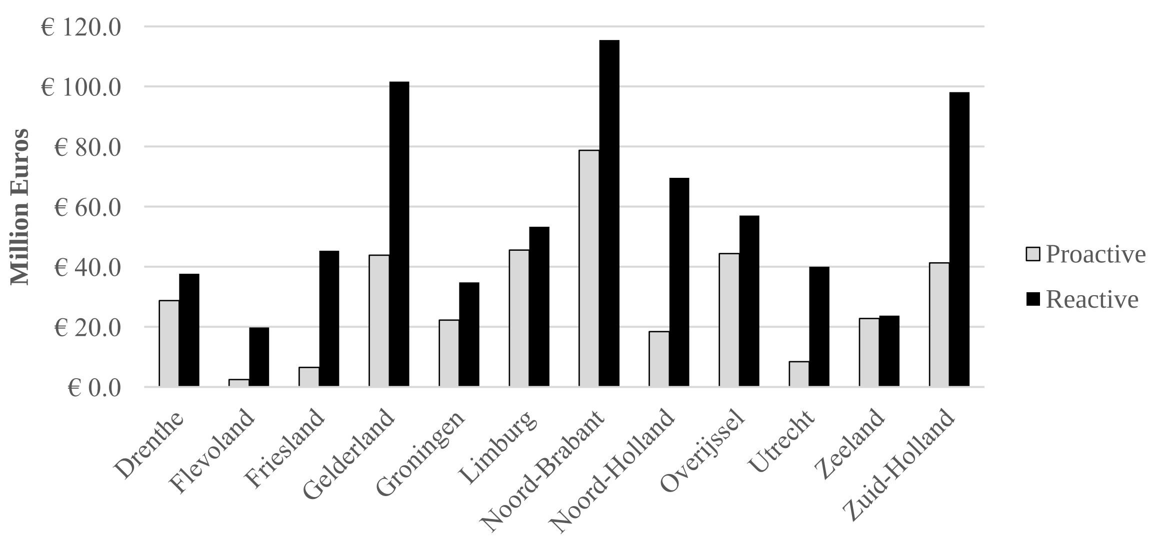

Figure 4.12: Average annual cost from temperature and precipitation (by province)

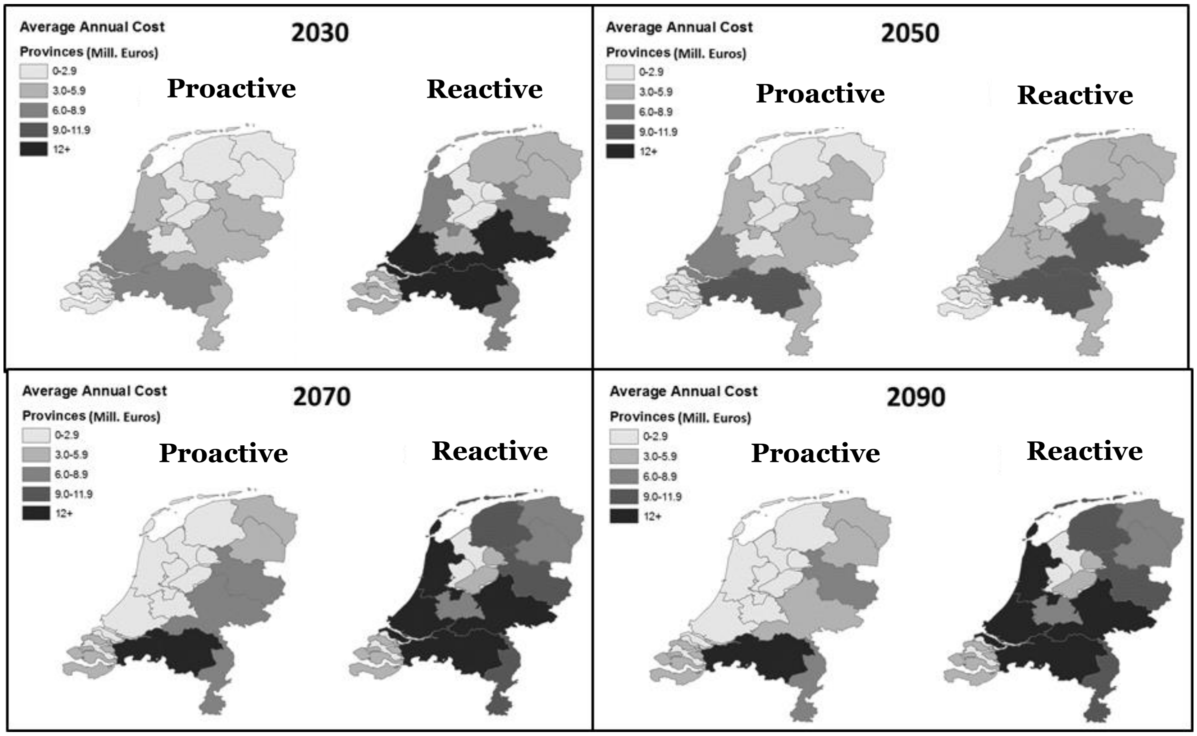

Figure 4.13: Average annual cost from freeze-thaw in 2030, 2050, 2070, 2090

DISCUSSION

Climate change research often describes the future as a series of unavoidable impacts. For example, coastal water levels in the Netherlands will rise and continue to rise throughout the foreseeable future. (de Bruin et al. 2009b) In that case, the recommendation is typically that infrastructure owners and operators should focus on how to adapt to the risk and how to do it as efficiently and effectively as possible. The research in this paper, however, describes the future of freeze-thaw cycles as both a risk and an opportunity.

Figure 4.10 shows the predicted average annual cost of both adaptation strategies from 2020 through 2100. From 2020-2057, proactive adaptation is forecast to cost less than reactive maintenance. However, from 2057-2100 the trend reverses and reactive maintenance is predicted to cost less than proactive design and construction adaptations. This aligns with simulated trends in RCMs from the ENSEMBLES program, which predicted a similar decrease in frequency of FT cycles in the latter half of the century. While long-term increases in temperature will most likely result in increased damage and cost, higher daily temperatures in the winter could reduce the total number of freeze-thaw cycles and reduce overall winter damage.

When comparing provincial impacts, there are places the in Netherlands where changes in freeze-thaw cycles will cause more damage than others. In this case, that would be changing road types to ZOAB-TW. In these areas, taking proactive actions to adapt could cost less than reactively increasing maintenance. This is the case for Limburg province in 2050, as shown in Figure 4.11. However, there are also areas where changes in freeze-thaw cycles will be advantageous, resulting in less damage. For example, Gelderland is predicted to experience lower costs in 2050 using a reactive maintenance approach.

These provincial-level results are intended to provide a greater level of detail for decision-making and policy in Ministry of Infrastructure, because the freeze-thaw impacts vary as much as €12 million or more between regions of the country. Figure 4.13 shows both the regional and temporal variability of freeze-thaw impact in the Netherlands. There are some provinces, particularly in the south of the country, which are more vulnerable relative to other areas. However, the results show that even provinces that are less vulnerable will experience variability from decade to decade.

As described in the methodology section, the climate adaptation modeling was previously performed to analyze the Netherlands' vulnerability to changes in temperature and precipitation. (Kwiatkowski et al. n.d.) Figure 4.12 shows a portion of the results from that analysis to provide context for the FT adaptation costs. Nationally, the cost of adapting to changes in FT cycles ranges from €0 to over €12 million annually, while the cost of adapting to changes in temperature and precipitation ranges from €0 to over €100 million. That scale, combined with the predicted decrease in cost from FT in the latter half of the century, forecasts changes in FT cycles to be a secondary risk to temperature and precipitation.

LIMITATIONS AND FURTHER RESEARCH

As is the case with any climate change research, this work is based on projections of future climate, which include an inherent level of uncertainty. This project attempted to mitigate that uncertainty by including a suite of climate models that are regionally specific to northern Europe, rather than one model or one set of models provided by one organization. Additionally, the analysis depends on the amount and quality of data on pavement temperature and winter damage/maintenance. The research team is working continuously with relevant Dutch agencies to maintain accurate databases and update the analysis as additional data is collected. Further research is planned include updated analysis with more complete datasets.

CONCLUSION

The combination of Rijkswaterstaat's reputation for long-term planning, strict maintenance procedures, and recent budget constraints (RWS 2012) further highlight the need for adaptation analysis that addresses their organizational and regional priorities, not only sector-wide concerns. To achieve this, the research incorporates organizational and regional-specific information, such as weather station and pavement sensor data. The robust correlation between air and pavement temperatures allows for the calculation of freeze-thaw impacts on pavement into the future. The correlation analysis between FT cycles and winter damage was not as definitive and was used to create adaptation thresholds based on a range of risk levels. Additional research is suggested to refine this relationship, including a more detailed accounting of potentially confounding factors, such as traffic and incomplete data collection. However, combined with regional climate models, pavement material properties, and organizational cost data, the IPSS freeze-thaw modelling produces more accurate and actionable results than what is currently incorporated into decision-making processes. This improves support for design, maintenance, and long-term planning within the organization.

Taking the cost results into consideration, the new design and maintenance strategies can be adjusted in advance to maximize the opportunity or minimize the impact. Unique to the Netherlands is their heavy reliance on porous asphalt. It is imperative for the long-term sustainability of their road infrastructure that PA roads will still be effective under future climate conditions.

A major takeaway from this research is that road operators, planners, and policy-makers need to prepare themselves for increased variability in the future, as it relates to freeze-thaw cycles and pavement. The adaptation modelling results support the thesis that in most regions it is not a question of if, but when adaptation will be required. In some regions, however, drier climate will require less robust drainage design and warmer winters could reduce freeze-thaw damage and subsequent costs.

ACKNOWLEDGEMENTS

The project team would like to thank the Netherlands Organisation for Scientific Research (NWO) for funding through the Sustainable Accessibility of the Randstaad Project and Rijkswaterstaat, for their generous collaboration. Portions of this material is also based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1144083. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Chapter 5 CLIMATE CHANGE ADAPTATION AS AN ORGANIZATIONAL SYSTEM IN TRANSPORTATION INFRASTRUCTURE ORGANIZATIONS: IDENTIFYING PROCESSES AND INSTITUTIONAL ELEMENTS

Keywords: climate change adaptation, transportation, organization, institution, process, Delphi

ABSTRACT

Incremental climate change and extreme weather events threaten to reduce the effectiveness and increase the cost of transportation infrastructure in the immediate and long-term future. Research and industry have produced frameworks, methods, and tools to adapt infrastructure to climate change but implementation has remained limited. This research theorizes that this is because climate change adaptation is an organizational system, not solely a technical solution. This paper identifies the individual factors of the organizational system through literature review and ranks the importance and urgency of these factors using a Delphi study. The results of the Delphi confirm the results of the literature review and provide a list of twenty factors that are important to the implementation of climate change adaptation in a transportation agency. Leadership and executive support, long-term planning, and operations and maintenance were identified as the most important factors. Leadership and executive support, risk management, internal communication, and financial support were identified as the most urgent factors; all factors were considered urgent enough to address in the next one to two years. By identifying the most important and urgent factors, this research will assist transportation managers in prioritizing investments and defining the steps that need to be taken to incorporate climate change adaptation into transportation agencies.

INTRODUCTION

Climate change resiliency and adaptation have become a larger focus of the transportation industry and research efforts over the past decade. As increasing numbers of scientists and practitioners acknowledge that even with mitigation the planet will experience certain unavoidable levels of climate change, discussions have begun to transition from mitigation to resilience. (IPCC 2015) While the questions of how much and when are still debated, the transportation field has progressed from the study of mitigating greenhouse gas (GHG) emissions to estimating climate change impacts, vulnerability to impacts, and the current emphasis on adaptation. According to the United States Department of Transportation (DOT), adaptation should now be an equal consideration to mitigation. (USDOT 2014)

Many transportation infrastructure agencies, particularly state DOTs, cities, and Metropolitan Planning Organizations (MPOs), have therefore created or are in the process of creating climate change adaptation strategies and plans. However, despite the policy recommendations and an increase in research, attention to and implementation of adaptation is still relatively low. (EEA 2014)

Concurrently, research frameworks are emerging that focus on incorporating climate change into existing processes within an agency. (FHWA 2008; Meyer et al. 2010b; Schmidt and Meyer 2009) USDOT policy guidance is for state DOTs to incorporate climate change adaptation into nearly all of their existing processes, including risk and asset management, long-term planning, and operations and maintenance. (USDOT 2014) However, even with this emerging focus, there is a lack of understanding and guidance about how DOTs implement climate change within and across organizational processes.

In 2009, the barriers to climate change adaptation were found to be the need for tools to assess vulnerability, uncertainty about asset criticality, and limited funding. (Plumeau and Lawe 2010) Since then, many tools have been developed and new methods proposed, eliminating or reducing some of those barriers. While the tools, methods, and frameworks cover a wide range of solutions, there is a lack of understanding of the organizational implications of climate change adaptation and only a moderate understanding of executing adaptation action (Dowds and Aultman-hall 2015). This research moves beyond a focus on tools to study the organizational barriers to adaptation by examining climate change adaptation as an organizational management issue for agencies such as local/city government, state DOTs, and MPOs.

This research takes the first step in developing an organizational framework for climate change adaptation that links existing transportation management processes to the development of a climate change adaptation program. This project determines the most important and urgent factors that agencies implementing climate change adaptation should address. These factors, to be later incorporated into an organizational model, are identified through a literature review. They are validated and ranked by industry and academic experts in a Delphi survey.

BACKGROUND

CLIMATE CHANGE ADAPTATION AND TRANSPORTATION

Climate science shows our climate has already changed, certain levels of additional change are unavoidable, and those changes may be even greater depending on our mitigation efforts in the future. (IPCC 2015; USGCRP 2014) Research also shows that all types of infrastructure, including roads, airports, seaports, rails, tunnels, and bridges are vulnerable to extreme weather events and coastal flooding, as well as gradual changes in temperature and precipitation. (Humphrey et al. 2008; IPCC 2015; Meagher et al. 2012; Meyer et al. 2010b) These climate stressors have the potential to accelerate infrastructure deterioration, increase severe damage and failures, decrease safety, and increase traffic, all of which will have an economic impact in addition to the direct impact on infrastructure and its users. (Melillo et al. 2014; Nemry et al. 2012)

As knowledge about vulnerability increases, transportation agencies need to transition from assessing vulnerabilities to addressing them. (Savonis et al. 2014) Much of the initial work on adaptation has focused on either very local action (Burch 2010) or national policy-making (Jotzo 2010) and is not specific to transportation infrastructure. (Berkhout et al. 2006; Bollinger et al. 2014; Liso 2006)

Many industry sectors, including transportation, have completed economic modeling of the impact and adaptation costs. (Chinowsky et al. 2013a) This quantification is an important tool for economists and policy-makers, but there are limitations to economic modeling for climate change adaptation, and more detailed sector-specific research is required to enable local adaptation action (Jotzo 2010). Not providing the appropriate scale and type of research can lead to a pattern where organizations include adaptation into planning and policy documents but do not take any action as a result. (Berrang-Ford et al. 2011)

As priorities move from policy to producing measurable results and action, the focus should also move from the national to local level. (Bulkeley and Betsill 2010; Burström and Korhonen 2001) Therefore, there is a need for studies that are unique to specific organizations (MacArthur et al. 2012). In the case of transportation in the United States, this means shifting focus to specific agencies, such as city transportation departments, state DOTs and MPOs.

While implementation and barriers of climate change adaptation are less understood at this level (Burch 2010), the amount of research on particular frameworks and methods for climate change adaptation has increased. Rowan et al utilize a sensitivity matrix to incorporate a wide range of climate stressors. (Rowan et al. 2013a) Meyer and Weigel (Meyer and Weigel 2011) and Wall (Wall et al. 2015) suggest an adaptive management approach that, among other steps, includes vulnerability assessment, risk appraisal, and cost analysis and can be applied to a wide range of infrastructure assets. (Meyer and Weigel 2011) Meyer et al detail how asset management can be used to address climate change adaptation. (Meyer et al. 2010a) Other recommendations expand on the asset management approach by specifically suggesting a risk-based asset management approach (O'Har 2013), which aligns well with the Fixing America's Surface Transportation (FAST) Act requirement for risk-based asset management (114th Congress and Congress 2015).

While each approach and framework are different, one thing they have in common is that they all focus on a process. In some cases, it is a process that already exists within transportation agencies, in others the framework develops an entirely new process specific to climate change adaptation. These studies add to the body of knowledge and expand the set of tools available to infrastructure managers. However, they often isolate adaptation within one project or process or create an entirely new process outside of what organizations already perform.

Climate Change Adaptation and Organizations

The former Secretary of Transportation, Ray LaHood, stated that "climate change adaptation should be integrated into core policies, planning, practices, and programs" (LaHood 2011) and the USDOT "strongly encourages consideration of potential climate change impacts in the transportation planning process." (USDOT 2014) USDOT further states that "mainstreaming consideration of climate in all activities related to planning, constructing, operating and maintaining transportation infrastructure and providing transportation services can ensure that resources are invested wisely and that services and operations remain effective."(USDOT 2014)

Incorporating climate change adaptation into existing transportation processes is consistent with literature suggesting that the implementation of adaptation is more likely if it is consistent with existing programs that are already designed for non-climatic stresses and integrated into policy strategies. (Burch 2010; O'Riordan et al. 1999; Yohe 2001)

Much of the research on processes, institutions, and barriers to climate change implementation is non-transportation specific. Research in other public infrastructure industries, such as water resources or land management, can help pre-identify certain elements as potential barriers. (Archie et al. 2014) However, these approaches typically take an industry-wide stakeholder perspective, rather than examining a single organizational actor. When examining organizations, it has been shown that it is not a lack of capacity but a facilitation of resources and institutional barriers that keep organizations from climate change action. (Burch 2010)

Despite the USDOT policy recommendations, there are relatively few cases examining the incorporation of climate change adaptation into organizations, including one detailed study in

New York (Major et al. 2011). Many of the case studies and publications are project-based, often focusing on singular pilot projects and not ongoing project development. FHWA has completed a regional project on this topic, but it focused on land use and scenario planning, not specifically on climate change adaptation in DOTs. (FHWA 2014a) USDOT anticipates a publication on the integration of climate change adaptation, but it focuses only on coastal highways. (USDOT 2015) There is a need for more rigorous and in-depth study of the organizational implications of climate change adaptation, particularly on the organizational change necessary to implement adaptation processes in transportation agencies.

Organizational Modeling

The literature review and Delphi study conducted for this paper are part of a larger research goal to model the organizational aspects of climate change adaptation in transportation agencies. This requires combining organizational change and process development into a single framework. Based on their flexibility and focus on general process and institutional environments, organizational maturity modeling is an effective framework for this goal. On a broad level, "maturity models describe the development of an entity over time. This entity can be anything of interest: a human being, an organizational function, etc." (Klimko 2001) A maturity model is a structure that describes the elements of a process at different stages of development. It provides separation between stages of development, and describes means for advancing from one stage to the next. (Pullen 2007) Many of the first maturity models were based on quality process improvement (Crosby 1983) and the Capability Maturity Model (CMM) (Paulk et al. 1993). While many maturity models are based on these models and their principles, the method has expanded into a wide range of industries. (Wendler 2012)

Maturity models and the concept of maturity are not new to the transportation, construction, and engineering industries. For example, a maturity model was used to examine the level of asset management formalization in infrastructure management (Zeb et al. 2013). The approach was also used to study institutional architecture for Transportation Systems Operation and Maintenance (TSOM). (TRB 2011)

The organizational maturity framework is used in this research as it examines processes of the organization that will support an overall climate change adaptation program. Formalizing these processes of climate change adaptation allows agencies to quantify and compare management practices to a benchmark, determine existing capabilities, strengths, and weakness, and identify best practices. (Zeb et al. 2013; Zephir et al. 2011)

During the early stages of a topic's research and implementation, a maturity model can also provide a roadmap for organizations to guide decision-making and investment. It formalizes roles and responsibilities without focusing on particular individuals in an organization (Bate 1998) and identifies elements needed to change or create a new organizational culture (Chinowsky et al. 2007). Climate change adaptation includes inherent uncertainty, and a maturity model limits process uncertainty and variability by controlling outputs, tasks, or behaviors. (McBride 2010) These characteristics apply to the case of climate change adaptation in transportation agencies, which makes the maturity model a useful approach to understanding adaptation challenges as well as future stages of mature adaptation.

METHODOLOGY

RESEARCH QUESTIONS

To increase reliability and theoretical grounding, the research follows a rigorous process to develop the organizational model. The first step of developing a maturity model is to determine scope. (De Bruin et al. 2005) In this case, the scope has been pre-determined as climate change adaptation in transportation organizations. The next steps are to design and populate the model, which are the topic of this paper. Therefore, this research project investigates the following research questions: What are the most important factors of a climate change adaptation program for transportation infrastructure organizations? What are the most urgent factors to develop in a climate change adaptation program?

FACTORS

A literature review is a useful and important method in populating the factors of an organizational maturity model. (De Bruin et al. 2005) This method has also been used for the pre-identification and sorting of factors that will be used in a Delphi study, including studies focusing on complex infrastructure systems (Kaminsky and Javernick-Will 2013) To identify the factors for this Delphi study on climate change adaptation and transportation, a literature review was conducted of scholarly and non-scholarly publications. The review was limited to English language articles and used keyword searches in the ASCE library, Web of Science, and Engineering Village databases for scholarly articles. Non-scholarly publications were found through referral in article bibliographies and through review of major industry reports from Transportation Research Board (TRB), American Association of State Highway Transportation Officials (AASHTO) and Federal Highway Administration (FHWA).

The keywords used for the search were "climate change," "adapt*," "transport*," and "infrastructure." The asterisk is a standard Boolean method to search for all words containing the root term, for example using "adapt*" to search for adapt, adapting, and adaptation. The search was purposefully kept broad during this initial step to reduce unintended pre-exclusion of publications, given the broad and interdisciplinary nature of the field. After eliminating duplicates the second step required reading abstracts to determine relevance to transportation infrastructure organizations. At this point the articles were searched and coded for factors being proposed as a strategy for adapting transport infrastructure to climate change. For example, an article that proposes creating a new job role dedicated to climate change adaptation would be coded as "organizational structure/staffing." As another example, if an article proposed a "top-down" climate change adaptation strategy, this would be coded as "leadership and executive support." If multiple factors were proposed in the same publication, the article would be coded simultaneously for each factor. After theoretical saturation was reached and no additional factors were identified in the articles, factors were categorized into the broader framework of two categories: technical/business process and organizational/institutional elements. These categories are based on previous maturity model research (TRB 2011) and modified for this project. The list of all factors identified through literature review is:

- Technical and business processes:
    - Operations and maintenance;
    - Strategic management;
    - Planning (long-term);
    - Planning (short-term);
    - Environmental;
    - Asset management;
    - Engineering/design;
    - Sustainability;
    - Risk management (project);
    - Risk management (enterprise);
    - Research;
    - Finance/budgeting.
- Organizational and institutional elements:
    - Leadership and executive support;
    - Internal communication;
    - External communication;
    - Cross-sector collaboration;
    - External partnerships;
    - Financial support;
    - Organizational structure/staffing;
    - Formal knowledge sharing/organizational learning.

DELPHI METHOD

Subjective research techniques are used when objective methods cannot be effectively used. Objective techniques cannot be used to study the implementation of climate change adaptation in the transportation industry, primarily because there is not enough activity to observe, the resources required to carry out that type of research are restrictive, and the conditions are too difficult to control. Topics related to this research, such as program planning

(Delbecq et al. 1975), factor ranking (Linstone and Turoff 2002; Walters and Javernick-Will 2015), setting priorities (Geisser et al. 2011; Pawlowski Okoli, C. 2004), and risk (Hallowell and Gambatese 2010), often require the use of subjective research, because there is not enough observable empirical evidence to collect. This is also the case for climate change adaptation because there is a limited amount of implementation to observe, but also because this research aims to not only understand current adaptation practices, it is also forward-looking and seeks to understand what adaptation will be beyond the present.

Given the objectives and constraints of this portion of the research, a Delphi study is the most appropriate method to answer the research questions. Delphi studies, both within engineering and throughout other fields, vary in design and implementation but are defined by an overall set of shared characteristics. A Delphi study is a systematic, anonymous survey of prequalified individual experts. A Delphi consists of multiple rounds of a survey, in which each round is identical to the next, except that each survey includes feedback from the previous round. The group results of the survey are summarized and presented as feedback to the participants alongside the original survey questions. The experts are instructed to review the group feedback and consider modifying their response. The goal of a Delphi study is to achieve stability, which shows that group and individual responses are no longer changing from round to round. After stability is reached, the results can be tested for consensus, which is generally defined as agreement between the experts (von der Gracht and Gracht 2012; Hallowell and Gambatese 2010; Linstone and Turoff 2002)

Selecting Experts

The Delphi methodology differs from simple survey methods because the population being surveyed is purposefully homogenous. Delphi studies have been criticized for non-uniformity between panelist expertise (Hsu and Sandford 2007); the reliability of results is therefore increased by following a set of thoughtful, objective, and pre-defined criteria for selecting experts. Following recommendations and standard guidelines for Delphi techniques to increase methodological rigor (Hallowell and Gambatese 2010) and adapting it to this project, the project used a flexible point system for selecting experts, shown in Table 5.1.

Table 5.1:Delphi panel exerpt selection criteria

Criterion	Points
works or has worked for transportation infrastructure management organization (state DOT, MPO, or similar)	2
is or was senior management for a transportation infrastructure management organization	1
works or has worked for other transportation organization (Federal Highway Administration, Transportation Research Board, or similar)	2
member or chair of nationally recognized committee focused on transportation and climate change adaptation	1
works or has worked for city/municipal transportation department	2
works or has worked directly on a climate change adaptation project	3
primary or secondary author of climate change plan (author of transportation section only is acceptable)	2
member of climate change adaptation professional network	1
professional licensure/accreditation (Professional Engineer, Certified Transportation Planner, etc.)	1
at least 5 years of professional experience with climate change adaptation	2
advanced degree in the field of transportation engineering, management, or similar	2
primary or secondary author of scholarly journal article on transportation and climate change adaptation	1 per, up to 3
primary or secondary author of non-scholarly journal article/report on transportation and climate change adaptation	1 per, up to 2
author or editor of book on transportation and climate change adaptation	2
presented at conference or workshop on transportation and climate change adaptation	1 per, up to 2
note: 6 points required for inclusion, and at least 2 points must be related to climate change	

As a survey of experts, particularly in emerging fields, the survey population for Delphi studies is often small. Other studies have included panels ranging from 3 to 80 members. While there is not a significant correlation between the size of the group and effectiveness (Boje and Murnighan 1982; Brockhoff 2002), it is typically recommended that the group be a minimum of 8-13 (Hallowell and Gambatese 2010; Ludwig 1997). Because Delphi studies can suffer from low response rates (Hsu and Sandford 2007), particularly in the first round (Geisser et al. 2011), the survey for this project oversampled to ensure enough panelists would remain throughout the study.

Forty experts met the requirements of the criteria and were contacted to participate. 16 responded in round one, 13 of which went on to complete all three rounds of the study. Of those 13 panelists, 3 were academics, 1 was a municipal employee, 4 were consultants, and 5 were professionals working for infrastructure organizations. Only experts based in the United States were considered, because the political and organizational environments of other countries introduced too much variability.

Stability and Consensus

Stability is a measure of the change in answers between rounds and is the most appropriate criterion for deciding whether or not a Delphi should be terminated. (von der Gracht and Gracht 2012) Consensus is generally defined as agreement amongst the experts, but the specific definition and calculation varies between studies (von der Gracht and Gracht 2012) A Delphi panel can reach stability, meaning that the panel's answers are not changing from round to round, but not reach consensus. Both stability and consensus were used in this study, with stability used as the primary criterion for terminating the Delphi, at which point consensus was measured to determine what conclusions could be drawn from the data.

Measures of central tendency are typically used to report Delphi results and the most common are the mean and median. The stability of the responses is measured by the change in variation between rounds, defined as the standard deviation divided by the mean. The coefficient of variation (CV) was used to measure consensus in lieu of standard deviation, because it is facilitated comparison between the survey questions. Past research has also compared various measures of stability and found that change in CV was sufficient and in some cases the most accurate. (Kasim et al. 2012; Shah and Kalaian 2009)

The threshold value for stability in this project is 0.10, which was found to be sufficient in previous studies (Shah and Kalaian 2009), including a systematic literature review of Delphi methodology (von der Gracht, 2012). After the group response to a question crosses below the threshold, it will be considered complete. Stability will only be considered after three rounds of the Delphi, because that is considered a best practice minimum number of rounds.

Consensus is measured as the CV at the time a question meets the stability threshold. Therefore, after each question is considered stable, the CV is compared to the threshold value. The consensus criterion is based on variation from the mean or median, such as variance or deviation. (von der Gracht and Gracht 2012) The mean was used in this Delphi study because it provided more nuance than the median and few instances of outliers were expected. In the end, there was only one instance of an outlier among the 40 individual ratings that each expert made in the survey. Following practices from previous research, the consensus threshold was set at 0.20 (von der Gracht and Gracht 2012)

Limitations

Collecting enough empirical data on climate change adaptation programs is not possible, making expert survey the most effective method. However, there are limitations to this, including the number and quality of experts surveyed. The size of the expert panel was acceptable based on previous research but there are limitations associated with the selection process. Experts without publicly available identifying information may have been missed and there were pre-identified experts that did not complete the survey.

There are also biases associated with this type of research, including myside, contrast, primacy, and collective unconscious biases. Attempts were made to limit the impact of certain biases, such as the group feedback to mitigate myside bias and random ordering of factors to mitigate contrast and primacy bias, but bias is difficult to eliminate entirely. The next steps of the larger research project aim to further limit these biases by collecting additional qualitative data, providing a fuller description of factor judgments, and the triangulation of data through document collection and observations.

DATA COLLECTION

Delphi studies typically use one of two main approaches to the first round. The traditional approach uses an open-ended first round that asks panelists to create a list of factors, which are then typically used to form questions for round 2. The alternative approach uses closed-ended questions in the first round. This study used a closed opening round based on the use of literature review to pre-identify factors.

There are four main questions in the survey. The questions were first asked in regard to technical and business processes and were then repeated for organizational and institutional elements. Panelists were provided with the list of factors from the literature review but were not provided specific definitions. The definitions were not provided because the experts that met the qualification criteria were expected to be knowledgeable about each topic. Additionally, the research questions were focused on transportation agencies in general, including DOTs, MPOs, and cities. Specific factor definitions may differ between agency types, and even between agencies of the same type, but general factors as understood by the experts are applicable across agencies.

First, the experts were asked about the relative importance of each factor based on a Likert scale, as seen below. Importance Likert scales have been used in previous Delphi studies (Geisser et al. 2011; Hallowell and Gambatese 2010) and were considered appropriate to determine a relative ranking of factors that provides more information than a simple rank order. Importance and urgency were separated in this project, like the method of separating probability and severity ratings to reduce bias when studying risk factors (Hallowell and Gambatese, 2010).

<u>Question 1</u>: "How important is it that each individual process be a component of a climate change adaptation program in a transportation infrastructure organization?

1. Not at all important
2. Slightly important
3. Moderately important
4. Very important
5. Extremely important"

Second, the experts were asked about the urgency of each process. The scale of urgency, shown in the list below, is based on standard organizational and transportation planning horizons. For example, a one-year timespan is associated with annual planning and reporting, 2-5 years is associated with short-term planning and construction project schedules, and a 10 to 20-year timeframe associated with long-term planning horizons.

Question 2: "How urgent is it that each individual process become a component of a climate change adaptation program in a transportation infrastructure organization?

1. Not at all
2. In the next 10-20 years
3. In the next 5-10 years
4. In the next 2-5 years
5. In the next 1-2 years
6. Immediately"

In the second and third round, participants were requested to use a blank box to provide an explanation for their responses, particularly if their response was different from the group mean. Requiring justification is one method to reduce myside bias, a bias when individuals generate arguments on only one side of an issue. The Delphi study concluded after the third round, when the stability of the panel's responses met the criteria.

RESULTS

The results of the study are shown in Table 5.2. The results of the Delphi study are the descriptive statistics of the final round of the Delphi, in this case the mean, coefficient of variation (CV) to measure consensus, and change in CV between rounds to measure stability. These are the values recorded when stability and consensus thresholds were met, which was the third round of this study. The table of results shows the mean separately for each question, sorted from maximum to minimum.

Table 5.2: Statistics after third and final round of Delphi study

Question	Process/Element	Mean	Coefficient of Variation (CV)	Change in CV*
Technical and business process importance	Planning (long-term)	4.5	0.14	0.00
	Operations and maint	4.5	0.14	0.03
	Strategic mgmt	4.4	0.17	0.03
1 = not at all important	Asset mgmt	4.4	0.11	0.00
2 = slightly important	Risk mgmt (project)	4.4	0.17	0.03
3 = moderately important	Risk mgmt (enterprise)	4.4	0.19	0.00
4 = very important	Finance/budgeting	4.4	0.14	0.02
5 = extremely important	Engineering/design	4.2	0.16	0.07
	Research	4.0	0.17	0.03
	Sustainability	3.9	0.14	0.02
	Environmental	3.8	0.15	0.01
	Planning (short-term)	3.4	0.22	0.00
		Mean	**CV**	**Change in CV**
Technical and business process urgency	Risk mgmt (enterprise)	5.5	0.11	0.00
	Risk mgmt (project)	5.5	0.17	0.02
	Asset mgmt	5.4	0.12	0.02
1 = not at all	Strategic mgmt	5.4	0.16	0.00
2 = in the next 10-20 years	Engineering/design	5.3	0.11	0.02
3 = in the next 5-10 years	Finance/budgeting	5.3	0.15	0.01
4 = in the next 2-5 years	Environmental	5.2	0.11	0.00
5 = in the next 1-2 years	Operations and maint	5.2	0.13	0.01
6 = immediately	Planning (short-term)	5.2	0.11	0.03
	Research	5.2	0.11	0.01
	Planning (long-term)	5.1	0.17	0.12
	Sustainability	5.0	0.26	0.01
		Mean	**CV**	**Change in CV**
Organizational and institutional element importance	Leadership/exec support	4.8	0.09	0.01
	Financial support	4.3	0.17	0.02
	Collaboration	4.2	0.14	0.01
	Internal communication	4.2	0.13	0.01
1 = not at all important	External partnerships	4.2	0.16	0.01
2 = slightly important	Knowledge/org. learning	3.8	0.21	0.01
3 = moderately important	External communication	3.7	0.16	0.02
4 = very important	Org structure/staffing	3.2	0.25	0.00
5 = extremely important				
		Mean	**CV**	**Change in CV**
Organizational and institutional element urgency	Leadership/exec support	5.9	0.06	0.00
	Financial support	5.5	0.11	0.00
	Internal communication	5.5	0.09	0.04
	External partnerships	5.2	0.11	0.02
1 = not at all	Org structure/staffing	5.2	0.11	0.02
2 = in the next 10-20 years	Collaboration	5.2	0.17	0.00
3 = in the next 5-10 years	Knowledge/org. learning	5.1	0.09	0.02
4 = in the next 2-5 years	External communication	4.9	0.16	0.01
5 = in the next 1-2 years				
6 = immediately				

*change in coefficient of variation between round 2 and round 3

Per the criteria, only one factor, sustainability, does not meet the threshold for stability. After the third round, the change in CV for sustainability is 0.12, only 0.02 higher than the 0.10 threshold. Combined with the fact that all other factors had passed the threshold, the research team concluded the entire study because an additional round would not contribute any additional information.

At the conclusion of the study, all but three factors met the threshold to be considered a consensus answer. The three factors that did not meet consensus requirements are short-term planning (0.22 CV regarding importance), sustainability (0.26 CV regarding urgency), and organizational structure/staffing (0.25 CV regarding importance). These factors are within 6% of the threshold and will not be considered separately from the other factors when discussing the results.

Regarding importance, the factor rankings range from 3.2, or "moderately important," to 4.8, "extremely important." All but two factors (short-term planning and organizational structure/staffing) are at least "very important." For urgency, the factors range from 4.8, or "in the next 1-2 years," to 5.9, or "immediately." Because the factors reached both stability and consensus, broader conclusions can be drawn.

DISCUSSION

First, the fact that all factors were ranked "moderately important" or above, and all factors were ranked urgent "in the next 1-2 years" or "immediately" validates their selection as factors from the literature review. Some of the expert comments also validate the consideration of climate change adaptation as an organization-wide system, rather than a stand-alone process. For example, one expert stated that "educating everyone in an organization about climate change will help communicate the importance of the issue to the organization and spur innovative thinking in all sectors. Climate change won't affect just one part of an organization; everyone should consider how it might affect their work and division."

Second, these factors were all considered important and urgent enough for further inclusion in the organizational maturity model. The expert feedback supports the need to integrate adaptation into existing processes and capabilities, which a maturity model accomplishes. For example, one expert said "we are truly trying to make it (climate change adaptation) more programmatic." Another expert highlighted the fact that their organization can build on an existing capability, external partnerships, by saying "this really requires working with local governments and emergency management both of which are key external partners that we have worked with extensively in the past."

Third, the minimum timeframe for a factor was judged to be 4.9, just below the "1-2 years" answer. This means the experts agree that organizations should begin to consider all climate change adaptation factors in the next 1 to 2 years. There are obvious practical limitations to this, including resource limitations and competing priorities beyond climate change. However, while adaptation has certainly received increased attention in the past 3-5 years, these results show a level of urgency not yet demonstrated by most transportation agencies.

The urgency to incorporate climate change adaptation was supported by expert comments that discussed the need for action now so that change can happen over time. For example, when asked to explain their rankings for asset management and sustainability, one expert said that change needs to happen "sooner because it takes a while to turn the aircraft carrier and it needs to start now." Another expert expanded on this, saying "it is critical to include Operations and Maintenance immediately in climate change adaptation planning because there are changes to operations and maintenance that can be made today that might affect the performance of transportation infrastructure long into the future." Providing additional detail, another expert highlighted the fact that urgency is affected by the interconnectivity of factors when saying "I have increased the urgency of internal communication to better reflect the need for broad internal institutional agreement in the need to address climate change, which moves up the timeline for securing external funding."

As seen in Table 5.2, there is a top-ranked factor for each question. Long-term planning was judged to be the most important technical/business process, and enterprise risk management was judged to be the most urgent. Leadership/executive support was judged to be both the most important and most urgent organizational and institutional factor. This was supported by qualitative responses from the experts, such as "these are inherently interdisciplinary problems and it takes enlightened leadership to foster such collaboration."

The importance and urgency of these top factors align with their inherent goals and timelines. For example, long-term planning in transportation sets agency goals and priorities, often looking forward 10-20 years. Long-term plans also cover a wide range of organizational departments. Climate change is anticipated to impact a wide range of organizational units and be a critical challenge now and in the following decades, so it is effective to use long-term planning as a priority to incorporate climate change adaptation. Long-range planning is also closely related to future budgeting, which was also identified as an important and urgent factor by the experts.

Enterprise risk management is an interesting factor because it is not a universally practiced process in transportation agencies. Like climate change adaptation, enterprise risk is an expanding research field and emerging practice implemented by a few agencies. It shares other similarities with adaptation that explain its urgency and potential benefit to organizations. Enterprise risk management examines risks that span beyond specific projects, both in scope and timeframe, allowing managers to identify and respond to risks that threaten the entire organization. Enterprise risk management will provide agencies with an effective way to identify the broader risks and consequences of climate change adaptation, which may not always be captured in traditional project risk management. Additionally, the urgency of considering risk management aligns well with DOT requirements to develop risk-based asset management programs. If investments are already needed to develop risk management processes, incorporating climate change during that development will create a more robust process while maximizing the impact of those investments.

Leadership and executive support was also the clear top factor for both importance and urgency. This institutional support was even considered more important and urgent than funding. This reveals a couple of key characteristics of climate change adaptation in transportation agencies. First, it shows that while bottom-up approaches can be useful to develop tools or spark interest for adaptation, top-down support and direction is necessary for program development. Second, this also shows where the current state of practice is in the industry. Agencies are not far enough along in the program development process to be prioritizing other organizational and institutional capabilities. Leadership and executive support is needed to create momentum and sustainable change before focus can be placed on developing other capabilities.

CONCLUSION

A literature review identified 20 factors as organizational strategies to implement climate change adaptation in transportation infrastructure organizations. These 20 factors were separated into to two groups: technical/business processes and organizational/institutional elements. Using a Delphi study, all factors were confirmed to be both important (very and extremely important) and urgent (in the next 1-2 years and immediately) by a group of qualified experts. While many of the factors were ranked similarly to each other, leadership and executive support was ranked as both the most important and most urgent organizational/institutional element. Long-term planning is ranked as the most important technical/business process and enterprise risk management as the most urgent. These factors will play a particularly important role during the early stages of program development.

As transportation agencies begin to incorporate climate change adaptation into their organizations, they should consider the holistic development of an adaptation program. The literature review and Delphi study produced useful results and are also rigorous steps toward developing an organizational model for climate change adaptation. An organizational maturity model will provide a roadmap and benchmark for program development, as well as detailed framework to assess their current climate change adaptation capability and steps to increase their capability through process and institutional improvement.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 1144083. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Chapter 6 DISCUSSION AND CONCLUSION

All of the research in this dissertation works to increase understanding of climate change adaptation in transportation organizations. The trajectory of the research in this dissertation mirrors the trajectory of many parts of the field of climate change adaptation research. The research begins by treating adaptation as a technical problem, identifying specific climate stressors and quantifying the future impact of climate change on specific assets. The work on temperature and precipitation also helped identify a gap in research used for the subsequent research on freeze-thaw cycles, just as the general field of adaptation research continues to identify areas of missing information on specific stressors and assets. It is necessary to continue filling in the gaps of technical knowledge about specific impacts of climate change on infrastructure, but it is not sufficient.

The quantitative modeling research, particularly the consideration of implementation, helped identify the gap in research on which the remainder of the dissertation work focused. At the end of a workshop in which the results of the temperature, precipitation, and freeze-thaw research were presented to infrastructure managers, one manager said: "This is very interesting, but what do we do with it now?" This group of managers had reached a place where they identified and understood many of the technical problems, and in some cases the solutions as well, of climate change adaptation for their infrastructure. The problem was no longer just the technical solving a problem, it was the organizational implementation of the solutions and strategies, the "what do we do with this now." While the field of climate change adaptation has worked understand the implementation gap, there have been many different singular strategies proposed, but no holistic, systemic understanding of the organizational challenges to climate change adaptation. Therefore, the dissertation research moved from increasing technical knowledge about climate change adaptation by quantifying specific impacts to infrastructure towards increasing socio-technical knowledge about the organizational and institutional challenges of adaptation in transportation infrastructure organizations.

Chapter 3 quantified the impacts to road infrastructure from long-term changes in precipitation and temperature using a stressor-response methodology. This work led to identification of the research gap and practical need for similar analysis of freeze-thaw changes in Chapter 4. The work in Chapter 4 required additional data collection and development of a new modeling methodology. The adaptation analysis work focused on the Netherlands, where the research and interactions with Dutch practitioners led to the questions and work in Chapter 5. Turning the focus to the United States, the research in Chapter 5 used a literature review and an expert panel to identify and rank the organizational and institutional factors needed for climate change adaptation implementation. Figure 6.1 summarizes the contributions of this research.

This dissertation describes a process of theory building for an organizational perspective of climate change adaptation, while answering the overarching research questions "what are the impacts of climate change on road infrastructure?" and "why are organizations not implementing climate change adaptation?" These are important questions considering the potential negative financial, safety, quality of life, and economic impacts. These are also urgent questions, considering the intended lifespan of most transportation infrastructure. The brief answer is that long-term changes in precipitation, temperature, and freeze-thaw in the Netherlands are predicted to cause additional damage and cost infrastructure managers more money in the future (in the range of zero to greater than €100 million annually, depending on location, stressor, and adaptation strategy). Additionally, infrastructure organizations are not yet implementing climate change adaptation because they are not considering the organizational and institutional implications of doing so. The solution is to understand climate change adaptation as an organizational system.

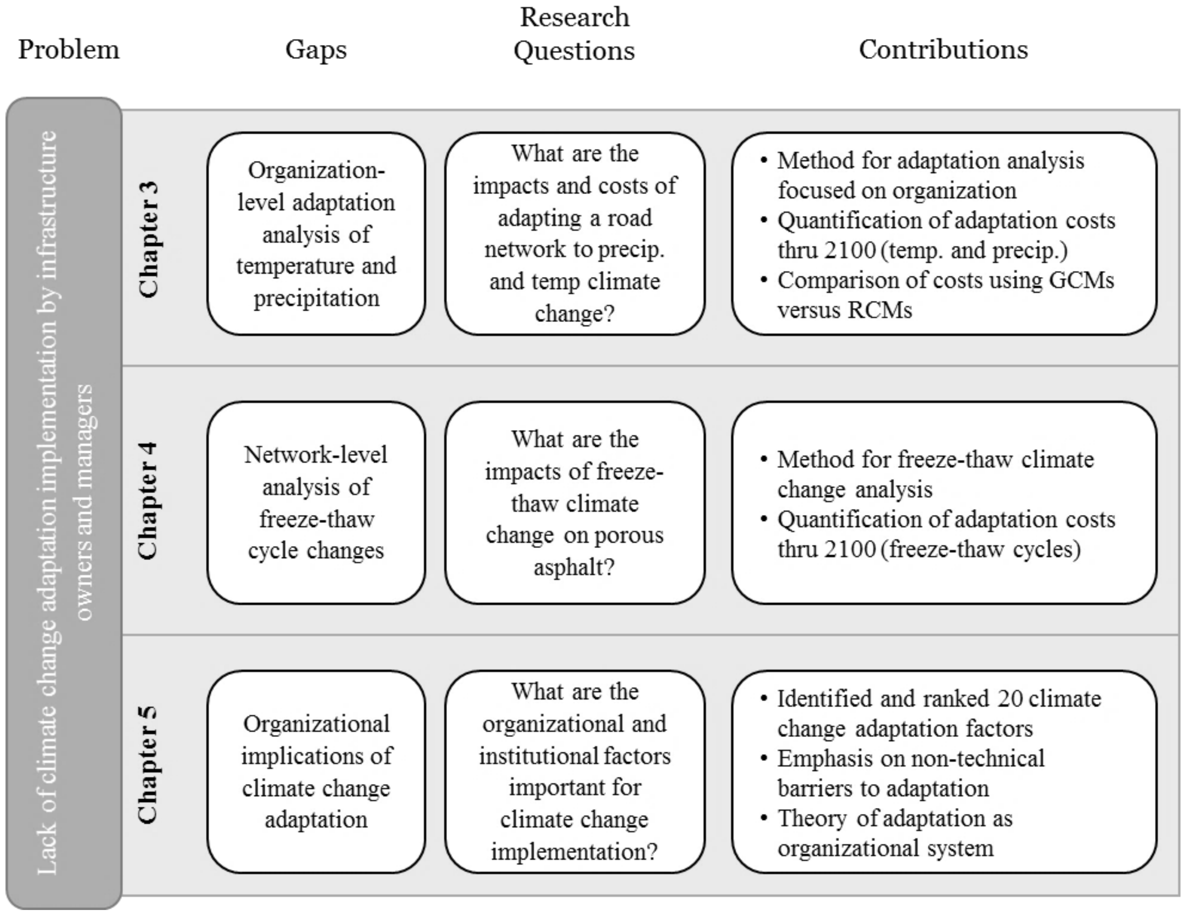

Figure 6.1: Research Contribution Summary

CONTRIBUTIONS

The quantitative modeling in Chapters 3 and 4 contributes to the growing literature on impacts of climate change on transportation infrastructure. First, the modeling provides cost data and adaptation strategies to Dutch infrastructure managers. These results are intended to be used in short and long-term planning, to minimize the future costs of climate change. Second, the research in Chapter 4 creates a methodology for infrastructure managers to incorporate freeze-thaw as a climate stressor into impact analysis. The majority of attention in academia and practice is focused on sea-level rise, temperature increase, and precipitation changes. There are very few methodologies that specifically and separately address the impacts of changes in freeze-thaw cycles and those methodologies that do exist are more often focused on long-term seasonal changes. This new methodology can be used by infrastructure planners to estimate the future impact of changes in the number of daily freeze-thaw cycles, whether that be an increase or decrease in damage and cost. Third, Chapters 3 and 4 discuss the benefits and limitations of increasing the granularity of adaptation analysis. There is extensive research focusing on increasing the granularity of climate modeling and much of that research includes comparisons between broader global models, regional models, and locally-downscaled models. There is less research that compares the adaptation modeling results using the various scales of climate models. Chapters 3 and 4 compare adaptation cost results using global and regional climate models to highlight the substantial influence that these inputs have on the results and reinforce the need for consensus on the most appropriate and robust models. Finally, Chapter 5 identifies organizational and institutional elements necessary for the implementation of climate change adaptation in transportation agencies and establishes the basis for development of an organizational model. The work adds to the theoretical basis of the general maturity model approach, by beginning to incorporate organizational and institutional theory, while also expanding the breadth of application. The identification and rating of organizational and institutional elements is the first step of this organizational modeling and can also be used by transportation infrastructure managers to prioritize investments as they begin to consider climate change adaptation.

THEORY

A main contribution of the research is the development of a new methodology for conducting climate change adaptation analysis on the impacts of freeze-thaw cycles, as well as the advancement of an existing methodology for temperature and precipitation. The new and modified methodologies fill the gap in research of empirical and engineering-based quantification of climate change impacts at the network level. In particular, these methodologies fill the gap in research by quantifying the gradual impacts of long-term changes in climate stressors (temperature, precipitation, and freeze-thaw) while incorporating local infrastructure and management characteristics. This is an important niche to fill for organizational planning and decision-making, since a large portion of the research on adaptation has a detailed design or large-scale international focus. Combining empirical data (i.e. observed winter damage and locally recorded temperature data) is a contribution of these methodologies as well, and an area for further research. Incorporating local data is important to improve the relevance, and potentially the accuracy, of impact estimates but the accuracy and reliability of data and correlations can and should be improved.

Another main contribution from this dissertation is theorizing climate change adaptation as an organizational system, which will lead to the development of an organizational model for adaptation implementation. Theorizing beyond the technical aspects of the problem and focusing on the organizational and institutional implications provides a new way to examine adaptation and related fields, like resilience. Organizational and institutional theory are well established fields, but neither has been combined with a systems approach to analyze climate change adaptation. This area of research is an excellent source of future work and will continue to be developed in more depth through continuations of this dissertation research and new projects. The work in Chapter 5 also identified 20 factors that were determined to be important for the implantation of climate change adaptation in transportation organizations. These factors form the basis for the organizational model and provide ideas for future research on adaptation and organizational theory. These contributions work toward answering one of the main questions of the research – "why are transportation organizations not implementing climate change adaptation?" – and fill the general gap in research about organizational implications and barriers of adaptation.

The literature review and Delphi show that the problem of implementing climate change adaptation shares similarities with other challenges and broader themes in organizational and institutional change. Many of the elements – leadership and executive support, internal communication, organizational structure/staffing, for example – are identified in literature and practice as important for any type of organizational change. However, there are portions of the Chapter 6 results that reveal some unique aspects of the climate change adaptation challenge.

Transportation infrastructure organizations are often known for changing slowly over time and in response to external forces. Combined with the fact that attention to and implementation of climate change adaptation is still in its relative infancy, the organizational and institutional elements may be new to infrastructure managers whether or not they are well established in the general organizational change field. Additionally, as with many engineering organizations, transportation infrastructure organizations often have silos of individual disciplines or business operations. Breaking down or crossing silos to accomplish new tasks and organizational change is not a novel idea. But the field of climate change adaptation has, until recently, focused primarily on singular processes as solutions to the problem. Because this research uses a systems approach and incorporates multiple processes that traditionally exist in silos, it is novel in transportation infrastructure management to identify and evaluate the relative importance of all organizational, institutional, and technical elements as part of the same adaptation system.

There are also several elements in this research that other organizational change literature might not expect to be as important or urgent as they were here. For example, partnerships and cross-sector collaboration were both identified as elements of climate change adaptation in literature. They were also scored as two of the most important and urgent factors by the expert panel. External partnerships and cross-sector collaboration may not typically be seen to be as important in other fields or general organizational change. While every organization relies in some way on partners and collaboration, it is particularly important in the field of climate change adaptation. Many transportation agencies do not have the knowledge, expertise, or even the resources to develop that expertise for much of the work required for climate change adaptation.

For example, a state DOT does not and most likely will never have a climatologist that can create and or manage the climate change modeling data. Instead, it is important to consider and include an external partner in the organizational change process, so that the agency can identify what they need and how to make it an integrated part of their adaptation system. Cross-sector collaboration is also unique to infrastructure and climate change. Given the nature of public infrastructure and the reliance of other sectors – emergency response, energy, freight commerce, for example – on those roads, any changes to future infrastructure and the way it is managed could substantially effect other individuals, businesses, and sectors. Without collaboration, transportation infrastructure organizations may make changes that have negative effects on certain sectors or may make sub-optimal changes because they are not incorporating valuable information from those sectors.

Practice

The findings from this dissertation can also be used to improve climate change adaptation in practice. The adaptation analysis contributes to answering both main research questions. When asking "what are the impacts of climate change on transport infrastructure?" this research provides the impacts, adaptation strategies, and costs for temperature, precipitation, and freeze-thaw impacts on porous asphalt road networks. The results are useful for Dutch infrastructure planners and can be incorporated into cost-benefit analysis, decision-making, and long-term planning. The main recommendation is to proactively adapt (i.e. modify pavement design by switching pavement types) most of the country's road infrastructure. While the freeze-thaw analysis showed that reactive adaptation would save money in the latter half of the century, the scale of freeze-thaw-related costs is much lower than temperature and precipitation, which show that proactive adaptation is particularly advantageous in the latter half of the century. These results can also be used to determine if there will be a time in the next century when the cost of continuing to use porous asphalt will be higher than the alternative strategy of using a different pavement type (dense asphalt, which is less vulnerable to precipitation impacts) and additional noise-reduction measures, such as sound barriers.

One of the most interesting results of the adaptation cost modeling is the comparison between adaptation costs using GCM versus RCM input data. Given the exact same conditions of location, time, stressor, and adaptation strategy, costs predicted using RCMs were as much as seven times higher than when using GCMs. Regardless of climate input, however, the comparison of the timeline of costs through 2100 shows that when considering temperature and precipitation, the costs of a reactive strategy will increase over time while the costs of a proactive strategy will decrease. As infrastructure is adapted for its lifespan, it is frequently also adapted for the longer-term climate change beyond its lifespan. When only using a reactive approach, those same roads are not adapted and any increase in stress will result in additional damage and cost.

The results of the literature review and Delphi study can also be used to improve adaptation implementation. While there is still further research to be done, the factors and rankings can educate infrastructure managers, particularly organizational leadership, about the most important individual factors and the organization-wide implications of adaptation. As seen in the Delphi study results, leadership is important to implementing climate change adaptation. The development of an adaptation program can include some bottom-up elements but needs top-down leadership and support to be successful. The results can also be used to inform organizations about the importance of specific departments to climate change adaptation. This will be especially useful for risk and asset management groups. They are currently required by the federal government to develop risk-based asset management programs, which presents a unique opportunity to include climate change adaptation in the formation of these programs.

LIMITATIONS

Chapters 3, 4, and 5 each include brief discussion of the limitations of the research. Some are repeated here and other broader limitations of the dissertation are discussed as well.

The research includes an inherent level of uncertainty. The uncertainty within climate models is a unique research stream within the larger climate change field. Some researchers claim that it is naïve to claim increased confidence and reduced uncertainty as models progress, for example from IPCC's AR4 to AR5 ensemble. (Knutti and Sedláček 2012) This dissertation research does not directly concern climate modeling and uncertainty but is affected by it. The analysis performed in this dissertation relies on the output of climate change modeling and any uncertainty in modeling results is therefore present in the adaptation modeling. One way this research mitigates this limitation is to, whenever possible, use a range of climate models. Using a range of models is widely recognized as a way to mitigate the biases and variability of individual models. (IPCC 2007b; Knutti and Sedláček 2012) In the case of global models, 54 GCMs were used from the IPCC AR4 CMIP3 climate ensemble (details in Appendix D). Eight RCMs were used for downscaled results from the ENSEMBLES project. Uncertainty may also be exacerbated by the uncertainties or inaccuracies in adaptation model inputs and parameters. This is particularly true for data like winter damage reports, which are used because they are the best (or only) data currently available but still lack accuracy. This is an important area for future research, as discussed in the Future Research section below.

Forecasting also includes inherent limitations with validation. Models can be validated by using a range of perspective and an even wider range of techniques. Forecasting models, like the adaptation model used in this research, can use structural validation, in which the processes of the model are validated to work as intended, and data validation, in which the input data is tested for reliability and goodness of fit. These models can also undergo a face validity test, in which independent experts validate the reasonableness of a model's fit to the real-world system. However, forecasting models cannot be validated based on the actual results or input-output transformations. Because these models predict results of a future scenario, they cannot be directly compared to actualities of the real-world system that the model represents. While input data was validated and the model was validated structurally during development, it cannot be validated based on output.

The Delphi study also had limitations. Any human research has the potential for bias and due to the nature of the group response portion, the Delphi study is at risk from several biases. Attempts were made to limit the impact of certain biases, such as the group feedback to mitigate myside bias and random ordering of factors to mitigate contrast and primacy bias. Further, while careful steps were taken to select a qualified group of experts, the answers to the questions are inherently subjective; there it is not objective measure of importance. Also, the responses were clustered within a relatively small range of scores. While this is helpful for confirming the results of the literature review, it means that fewer detailed conclusions can be drawn from the direct comparison between factor rankings. In other words, comparing a 4.3 score (very important) for "Financial Support" to a 3.8 (very important) score for "Knowledge/Organizational Learning" has limited meaning on its own. However, there were factors, such as 4.8 (extremely important) for Leadership/Executive Support," that were substantially higher than others, such as 3.2 for "Organization Structure/Staffing," from which more meaningful conclusions can be drawn.

Finally, using only one country as an example case, the Netherlands for the adaptation analysis and the United States for the Delphi study, limits the generalizability of the results. For example, the actual costs calculated for the Dutch road network are not applicable to other countries. However, the research is still useful for other countries, for both the results and the methodology. For example, there are other countries and regions of the world that use porous asphalt and share similar climate stressors, economic contexts, and management challenges. The scale and timeframe of the climate change impacts, as well as the adaptation strategies, are immediately relevant to these countries. Future work can also investigate additional cases to produce adaptation cost results for specific countries or states, but also to create a collection of cases for cross-comparison. Given the Netherlands' dense road network, high cost of construction and maintenance, and the economic importance of their transport infrastructure, they are an example of a high-risk country from which other regions can learn. The Delphi study shares similar generalizability limits, because the focus was placed exclusively on the United States. This was done to limit the impact of confounding factors, such as cultural and political differences, on the study results but it also limits the generalizability to other countries. However, the underlying theory of adaptation as an organizational system is still applicable to other contexts and will continue to be explored within and outside of the United States in future research.

FUTURE RESEARCH

The primary area of future research that will be pursued beyond this dissertation is the further investigation and eventual completion of the organizational model of climate change adaptation. The literature review and Delphi study were the first two steps toward developing an organizational model for climate change adaptation and in-depth case studies are the next step. Interviews, document review, and observations in transportation agencies will provide a deeper and clearer picture of the organizational and institutional barriers to adaptation implementation. Case studies will include a variety of state Departments of Transportation that range from the least to most advanced in their consideration and implementation of climate change adaptation. An organizational maturity model will provide a roadmap and benchmark for program development, as well as detailed framework to assess their current climate change adaptation capability and steps to increase their capability through process and institutional improvement. The cases will be analyzed using qualitative coding and comparative analysis to uncover pathways to implementation and build the stages of maturity in the organizational model.

Other suggestions for future research build directly from the limitations of this current research. First, further work is needed in the field of adaptation research to define and quantify measures and metrics of climate change impact. This type of work is similar to the recent push in the field for measures of resilience and other concepts that are difficult to both define and measure. For climate change, it is important to limit uncertainty and confounding factors by using measures that isolate climate as effectively as possible. For example, in this research, winter damage data was collected by Rijkswaterstaat and used as an empirical basis for the adaptation analysis. While this data was collected specifically to quantify the effect of changing winter weather patterns, it was not detailed enough to identify the exact source of the damage and there was no historic baseline for this data to determine any increases that were specifically correlated with changing climate. In general, current measures are most often qualitative or quasi-quantitative (for example, risk categories) and do not isolate the exclusive impacts of climate change from confounding factors, such as traffic, weight, and baselines levels of climate degradation. More accurate measurement and data collection, or at least more accurately defined proxies, need to be developed to increase the reliability and validity of adaptation modeling.

To increase the generalizability of impact results, future work for both adaptation and organizational modeling should include additional cases and international components. For example, an additional literature review and survey is suggested that focuses specifically on non-U.S. research and experts. Further analysis of climate change adaptation factors is also planned to be completed using an in-depth multiple case study methodology. This will provide more evidence to validate the previously identified factors but will most importantly provide knowledge about the interrelation of factors and the stages of change and maturity that organizations progress through when implementing adaptation. This work is anticipated to result in the completion of an organizational maturity model for climate change adaptation in transportation organizations.

Another area of future research is the incorporation of climate change adaptation into a larger theory of resilience and organizations. The IPCC defines resilience as: the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation. (IPCC 2007c) Adaptation is specifically included in this and other definitions of resilience, but there is a lack of understanding about how adaptation and resilience interrelate, particularly when using an organizational perspective. Adaptation and resilience do not exist in isolation either. More research is needed in the broader field that addresses the political, regulatory, and cultural barriers to implementing resilience and adaptation.

CLOSING THOUGHTS

As research, including portions of this dissertation, continues to fill technical gaps in quantifying the impacts and adaptation costs for climate change and infrastructure, I believe the next problem to solve is a socio-technical one. The research in Chapter 5 works to establish a socio-technical theory of adaptation within organizations and I think it will be crucial for that research, and most other adaptation and resilience research, to incorporate systems perspectives and methods. The plethora of information being produced in the climate change research field will not lead to knowledge without understanding the non-technical challenges and it will not lead to action without a combined understanding of both the social and technical challenges. To increase action and implementation of climate change adaptation, it is crucial to understand adaptation's interrelationship with other factors, particularly the current capabilities and "ways of doing business" within transportation organizations. In other words, adaptation needs to be incorporated into the processes and tasks that agencies already perform.

During my research, I completed some additional work that could not be included in this dissertation, including observations and interviews with several different DOT practitioners. This work was completed at several workshops, individual interviews, and team meetings for a resilience pilot project. During these workshops and interviews, I observed that many state DOTs began incorporating climate change through their sustainability departments. This was a de facto decision because climate change is often conceptually linked with environmental issues and sustainability is often built within environmental departments. While some consideration of climate change is better than none, placing climate change, and particularly adaptation, within environmental departments limits the potential for implementation. Because most states have not incorporated climate change adaptation into their organizations, this is a beneficial time to research adaptation and provide practical recommendations for systemic organizational-wide implementation. I look forward to continuing this research personally and hope to encourage future research in these important areas.

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Appendix A IRB APPROVAL

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APPROVAL

18-May-2016

Dear Kyle Kwiatkowski,
On **18-May-2016** the IRB reviewed the following protocol:

Type of Submission:	Initial Application
Review Category:	Exempt - Category 2
Title:	Developing a Maturity Model for Climate Change Adaptation in Transportation Infrastructure Organizations
Investigator:	Kwiatkowski,Kyle
Protocol #:	16-0352
Funding:	Federal
Documents Approved:	DelphiQuestions and Consent (18May16); 15-0709 Protocol (18May16);
Documents Reviewed:	Protocol; HRP-211: FORM - Initial Application v5;

The IRB approved the protocol on **18-May-2016**.

Click the link to find the approved documents for this protocol: Approved Documents. Use copies of these documents to conduct your research.

In conducting this protocol you must follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,
Douglas Grafel
IRB Admin Review Coordinator
Institutional Review Board

Appendix B DESKTOP SURVEY OF STATE CLIMATE CHANGE ACTIVITY

One of the research questions of this dissertation research is: "How are transportation infrastructure organizations currently incorporating climate change?" This question was answered using a desktop survey of publicly available information on state DOTs. This information will also be used as the basis for the selection of cases for future work using in-depth case studies to further analyze the organizational and institutional barriers to implementing climate change adaptation.

All 52 state Departments of Transportation were analyzed using several variables, described in Table B.1. Adaptation implementation by transportation agencies was defined using three main categories, research/pilot projects, long-term planning, and other. I measured the external environment by describing the level of state climate change activity happening outside of the agency. Specific non-climate processes, enterprise risk management and asset management were also identified, as they are proposed by research as strategies to implement climate change adaptation and are readily identifiable. Risk-based asset management is also a recently mandated program that DOTs are required to develop and implement. An agencies willingness and ability to implement risk and asset management programs is also a proxy indicator for their willingness and ability to create organizational change for other new programs, such as climate change adaptation. The climate zones of each state are also included so that additional theoretical variance can be included in the eventual case studies.

Results of the desktop survey are summarized in Table B.2 and

Figure B.1. Detailed results are included in Figure B.4. The figure includes six maps highlighting the individual criteria that were used for initial screening and two maps showing the general and detailed climate zones in the contiguous United States. The color shading represents the degree of implementation for each criterion, with lighter colors representing less implementation and darker colors representing more implementation.

Table B.1: Desktop Survey Criteria Development

Category	Variable	Measure	References
Climate change implementation	Research/Pilot studies	What is the current/recent level of participation in research/pilot studies, particularly in partnership with national agencies (FHWA, AASHTO, FTA, etc.)?	(AASHTO 2011, 2015; FHWA/FTA 2015; FHWA 2008, 2012b; c, 2013b, 2014a; Stark 2012; USDOT 2015)
	Other activities	What other climate change activities (excluding research/pilot studies) have been identified at the DOT?	
	Long-term planning	Does the DOT's current long-range transportation plan (LRTP) include climate change?	
Statewide implementation	Non-DOT state climate change activity	What climate change planning is already happening in the state government?	(C2ES 2015; Georgetown Climate Center and Center 2015)
Other processes anticipated for use in model	Non-climate change DOT activity	Does the DOT have an enterprise risk management program?	(Cambridge Systematics et al. 2007; FHWA 2007, 2015c; Lindquist 2012; Rose et al. 2015; Schmidt and Meyer 2009)
		Does the DOT have an established asset management program?	
State characteristics	General climate	Which general U.S. climate zone is the state in?	(CoCoRaHS 2011; Karl and Koss 1984; Kottek et al. 2006; NOAA 2015)
	Specific climate	Which specific Köppen-Geiger zones are in the state?	
	Major weather events	Have there been any recent extreme weather events?	

Desktop survey notes

- Existing Non-Climate Processes, Enterprise Risk Management:
  - 0 = no identified ERM occurring in DOT
  - 4 = identified ERM occurring in DOT
- Existing Non-Climate Processes, Asset Management:
  - 0 = no identified AM occurring in DOT
  - 4 = identified AM occurring in DOT
- Existing Non-Climate Processes, Long-term Planning:
  - 0 = no identified long-term planning occurring in DOT
  - 1 = some type of long-term plan published by DOT
  - 2 = long-term plan mentions statewide climate change planning
  - 3 = long-term planning includes climate change mitigation
  - 4 = long-term planning includes climate change adaptation
- Non-DOT State-wide CC:
  - 0 = no state climate change planning
  - 1 = state climate change plan published with no adaptation
  - 2 = state climate change plan published with mention of adaptation
  - 3 = state climate change adaptation plan in progress
  - 4 = state climate change adaptation plan published
- DOT CC Activity FHWA:
  - +1 for FHWA peer exchange participation
  - +1 for FHWA knowledge gap meeting participation
  - + 2 for FHWA pilot study participation
- DOT CC Activity Other:
  - +1 for activity identified by USDOT
  - +1 for activity identified by AASHTO
  - +1 for activity identified by FHWA
  - Note: 0.5 point if activity exclusively related to mitigation
- Color shading follows the standard Microsoft Word 3-color conditional formatting rule. Yellow represents midpoint values, green represents lowest values, and red represents highest values. This has been applied to aid in visual sorting only and does not affect the end results.
- Köppen-Geiger Climate Classifications:

Main Climates	Precipitation	Temperature
A: equitorial	W:desert	h: hot arid
B: arid	S: steppe	k: cold arid
C: warm temperate	f: fully humid	a: hot summer
D: continental	s: summer dry	b: warm summer
E: polar	w: winter dry	c: cool summer
	m: monoonal	d: extremely continental
		F: polar
		T: polar

All 52 state DOTs are categorized below according to their current level of climate change adaptation consideration

Table B.2: State DOTs Categorized by Climate Change Adaptation Consideration

No consideration	Little consideration	Moderate consideration	More/most consideration
Alabama	Colorado	Alaska	California
Arkansas	District of Columbia	Arizona	Oregon
Delaware	Georgia	Connecticut	New York
Idaho	Hawaii	Florida	Washington
Indiana	Illinois	Maine	
Kansas	Iowa	Maryland	
Kentucky	Louisiana	Massachusetts	
Mississippi	Minnesota	Michigan	
Missouri	Nevada	New Mexico	
Montana	New Jersey	Vermont	
Nebraska	Rhode Island	Virginia	
North Carolina	Tennessee		
North Dakota	Utah		
Ohio	Wisconsin		
Oklahoma			
Pennsylvania			
Puerto Rico			
South Carolina			
South Dakota			
Texas			
West Virginia			

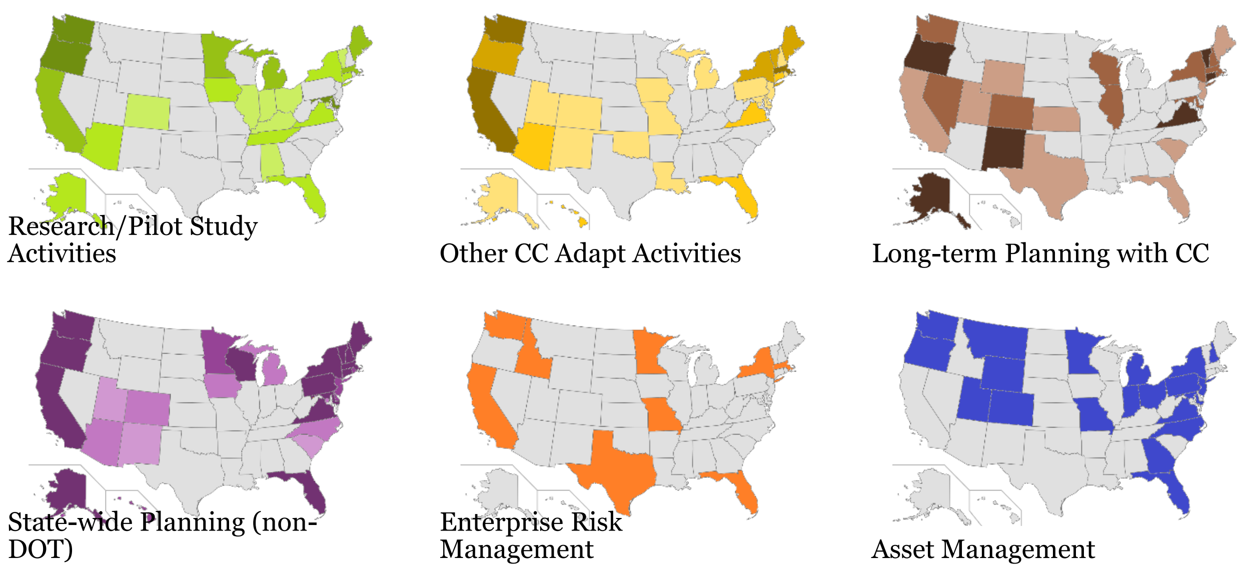

Figure B.1: Desktop Survey Summary Results

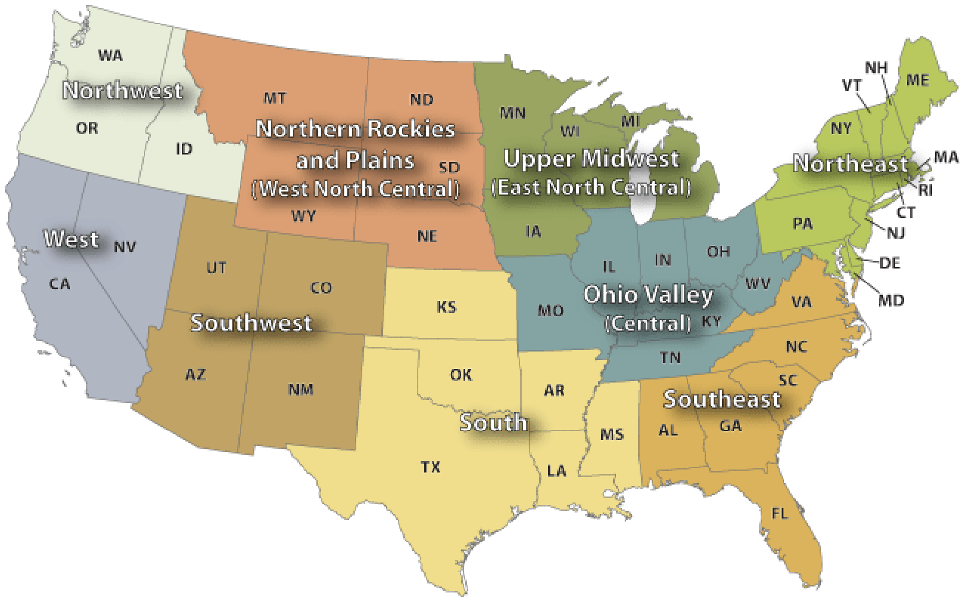

Figure B.2: Regional Climate Zones in the United States (Karl and Koss 1984)

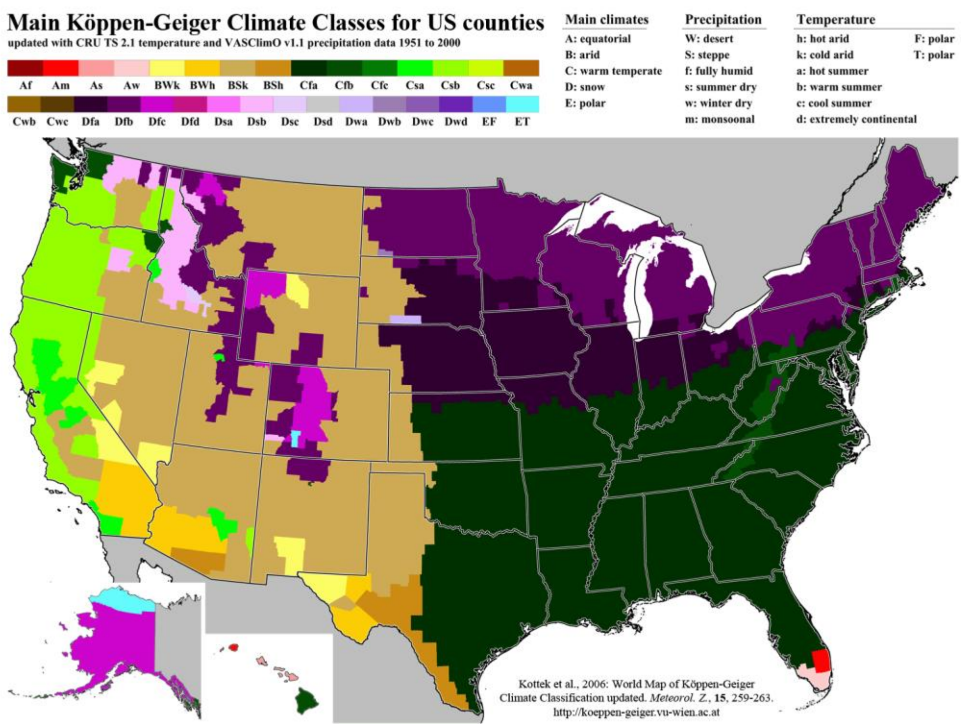

Figure B.3: Detailed Climate Zones (by county) in the United States (Kottek et al. 2006)

DOT Information		Existing Non-CC		Non-DOT CC		DOT CC Activity				Activities	Climate/Geography/Extreme Events		
State	DOT Abbreviation	Enterprise Risk Mgmt	Asset Mgmt	State-wide CC Plan	Sub-total	Long-term Planning	FHWA	Other	Sub-total	Total	General Climate Zone	Koppen-Geiger Zones	Recent Extreme Events
Alabama	ALDOT	0	0	0	0	1	1	0	2	2	Southeast	Cfa	Hurrican Katirna
Alaska	ADOT	0	0	4	4	4	2	1	7	11	Alaska	Dfc, Cfc, ET, Dsc, Cfb, Dfb, Dwc	
Arizona	ADOT	0	0	2	2	1	2	2	5	7	Southwest	BSk, Cfb, Csb, Csa, BSh, BWh	Drought; Wildfires
Arkansas	AHTD	0	0	0	0	1	0	0	1	1	South	Cfa	Flooding; Tornadoes
California	Caltrans	4	0	4	8	2	3	4	9	17	West	Csb, Csa, Dsc, BSk, BSh, BWh, BWk	Wildfires
Colorado	CDOT	0	4	2	6	3	1	0.5	4.5	10.5	Southwest	BSk, Dfa, Dfb, Dfc	Flooding
Connecticut	ConnDOT	0	0	4	4	4	2	2	8	12	Northeast	Dfb, Cfa, Dfa, Cfb	Superstorm Sandy
Delaware	DelDOT	0	0	3	3	1	0	1	2	5	Northeast	Cfa	Superstorm Sandy
District of Columbia	DDOT	0	0	2	2	1	1	1	3	5	Northeast/Southeast	Cfa	Superstorm Sandy
Florida	FDOT	4	4	4	12	2	1	2	5	17	Southeast	Cfa, Am, Aw	Hurricane Katrina
Georgia	GDOT	0	4	0	4	1	0	2	3	7	Southeast	Cfa	Hurricane Katrina
Hawaii	HDOT	0	0	3	3	1	0	2	3	6	Hawaii	Af, Cfb, As, Af, Am	
Idaho	ITD	4	0	0	4	1	0	0	1	5	Northwest	Csb, Dsb, BSk, Csa, Dfb, Dsc, Dfc, Cfb	Drougtt/Wildfire
Illinois	IDOT	0	0	0	0	3	1	0	4	4	Midwest	Cfa, Dfa	Flooding; Tornadoes
Indiana	INDOT	0	4	0	4	1	1	0	2	6	Midwest	Cfa, Dfa, Dfb	Flooding; Tornadoes
Iowa	DOT	0	0	2	2	1	2	1	4	6	Upper Midwest (East North Central)	Dfa	Drought;Tornadoes; Flooding
Kansas	KDOT	0	0	0	0	2	0	0	2	2	South	Cfa, Dfa, BSk	Drought; Tornadoes
Kentucky	KYTC	0	0	0	0	1	1	0	2	2	Ohio Valley (central)	Cfa	Tornadoes
Louisiana	DOTD	0	0	0	0	1	0	2	3	3	South	Cfa	Hurricane Katrina
Maine	MDOT	0	0	4	4	2	3	2.5	7.5	11.5	Northeast	Dfb	Superstorm Sandy
Maryland	MDOT	0	4	4	8	3	4	1	8	16	Northeast	Cfa, Cfb	Superstorm Sandy
Massachussetts	Mass Highway	4	0	4	8	3	3	4	10	18	Northeast	Cfa, Dfb, Dfa	Superstorm Sandy
Michigan	MDOT	0	4	2	6	1	3	1	5	11	Uppder Midwest (East North Central)	Dfb, Dfa	Flooding (2013)
Minnesota	Mn/DOT	4	4	3	11	1	3	0	4	15	Uppder Midwest (East North Central)	Dfb, Dfa	Drought; Tornadoes
Mississippi	MDOT	0	0	0	0	1	0	0	1	1	South	Cfa	Hurricane Katrina
Missouri	MoDOT	4	4	0	8	1	0	1	2	10	Ohio Valley (central)	Dfa, Cfa	Flooding
Montana	MDT	0	4	0	4	1	0	0	1	5	Northern Rockies and Plains (West North Central)	Dfb, BSk, Dfc, Dsb	Drought; Wildfires; Flooding
Nebraska	NDOR	0	0	0	0	1	0	0	1	1	Northern Rockies and Plains (West North Central)	Dfa, BSk	Tornadoes
Nevada	NDOT	0	0	0	0	3	0	0	3	3	West	Csb, BWk, BSk, Dfb, Csa	Drougt/Wildfires
New Hampshire	NHDOT	0	4	4	8	3	0	1	4	12	Northeast	Dfb	Superstorm Sandy
New Jersey	NJDOT	0	4	3	7	2	0	1	3	10	Northeast	Cfa, Dfa, Dfb	Superstorm Sandy
New Mexico	NMDOT	0	0	1	1	4	0	1	5	6	Southwest	BSk, Cfb, Csb, Dfb, BWk	Drought; Wildfires
New York	NYSDOT	4	4	4	12	3	2	3	8	20	Northeast	Dfb, Dfa, Cfa	Superstorm Sandy
North Carolina	NCDOT	0	4	2	6	1	0	0	1	7	Southeast	Cfa, Cfb	Superstorm Sandy; Flooding
North Dakota	NDDOT	0	0	0	0	1	0	0	1	1	Northern Rockies and Plains (West North Central)	Dfb, BSk, Dfa	Flooding
Ohio	ODOT	0	4	0	4	1	1	0	2	6	Ohio Valley (central)	Cfa, Dfa, Dfb	Superstorm Sandy
Oklahoma	ODOT	0	0	0	0	1	0	0.5	1.5	1.5	South	Cfa, BSk	Flooding; Tornadoes
Oregon	ODOT	0	4	4	8	4	4	3	11	19	Northwest	BSk, Csb, Dsb	
Pennsylvania	PENNDOT	0	4	4	8	1	0	1	2	10	Northeast	Dfb, Cfa, Cfb, Dfa	Superstorm Sandy
Puerto Rico?	DTOP	0	0	0	0	1	0	0	1	1	Puerto Rico	Am	Superstorm Sandy
Rhode Island	RIDOT	0	0	3	3	3	0	1	4	7	Northeast	Cfa, Cfb	Superstorm Sandy
South Carolina	SCDOT	0	0	1	1	1	0	0	1	2	Southeast	Cfa	Flooding
South Dakota	SDDOT	0	0	0	0	2	0	0	2	2	Northern Rockies and Plains (West North Central)	Dfa, BSk, Dwa, Dfb	Drought; Flooding
Tennessee	TDOT	0	0	0	0	1	2	0	3	3	Ohio Valley (Central)	Cfa	Flooding; Tornadoes
Texas	TxDOT	4	0	0	4	2	0	0	2	6	South	BSk, Cfa, BSh, BWh	Flooding; Tornadoes
Utah	UDOT	0	4	1	5	2	0	1	3	8	Southwest	BSk, Cfb, Dfb, Cfa, Csa, Dfa, Dfc, BWk, Csb	
Vermont	Vtrans	0	0	4	4	4	1	3	8	12	Northeast	Dfb	Hurrican Irene
Virginia	VDOT	0	4	4	8	4	2	2	8	16	Southeast	Cfa, Cfb	Superstorm Sandy
Washington	WSDOT	4	4	4	12	3	4	4	11	23	Northwest	Csb, BSk, Csa, Dsc, Dfc, Cfb, Dsb	Mudlides; Wildfires
West Virginia	WVDOT	0	0	0	0	1	0	0	1	1	Ohio Valley (Central)	Cfa, Cfb, Dfb	Superstorm Sandy
Wisconsin	WisDOT	0	0	4	4	3	0	0	3	7	Upper Midwest (East North Central)	Dfb, Dfa	
Wyoming	WYDOT	0	4	0	4	2	0	0	2	6	Northern Rockies and Plains (West North Central)	Dfb, BSk, Dfc, BWk	Drought

Figure B.4: Desktop Survey Detailed Results

The following 2 spreadsheets are magnified portions of the main spreadsheet presented above.

DOT Information		Existing Non-CC		Non-DOT CC		DOT CC Activity				Activities
State	DOT Abbreviation	Enterprise Risk Mgmt	Asset Mgmt	State-wide CC Plan	Sub-total	Long-term Planning	FHWA	Other	Sub-total	Total
Alabama	ALDOT	0	0	0	0	1	1	0	2	2
Alaska	ADOT	0	0	4	4	4	2	1	7	11
Arizona	ADOT	0	0	2	2	1	2	2	5	7
Arkansas	AHTD	0	0	0	0	1	0	0	1	1
California	Caltrans	4	0	4	8	2	3	4	9	17
Colorado	CDOT	0	4	2	6	3	1	0.5	4.5	10.5
Connecticut	ConnDOT	0	0	4	4	4	2	2	8	12
Delaware	DelDOT	0	0	3	3	1	0	1	2	5
District of Columbia	DDOT	0	0	2	2	1	1	1	3	5
Florida	FDOT	4	4	4	12	2	1	2	5	17
Georgia	GDOT	0	4	0	4	1	0	2	3	7
Hawaii	HDOT	0	0	3	3	1	0	2	3	6
Idaho	ITD	4	0	0	4	1	0	0	1	5
Illinois	IDOT	0	0	0	0	3	1	0	4	4
Indiana	INDOT	0	4	0	4	1	1	0	2	6
Iowa	DOT	0	0	2	2	1	2	1	4	6
Kansas	KDOT	0	0	0	0	2	0	0	2	2
Kentucky	KYTC	0	0	0	0	1	1	0	2	2
Louisiana	DOTD	0	0	0	0	1	0	2	3	3
Maine	MDOT	0	0	4	4	2	3	2.5	7.5	11.5
Maryland	MDOT	0	4	4	8	3	4	1	8	16
Massachussetts	Mass Highway	4	0	4	8	3	3	4	10	18
Michigan	MDOT	0	4	2	6	1	3	1	5	11
Minnesota	Mn/DOT	4	4	3	11	1	3	0	4	15
Mississippi	MDOT	0	0	0	0	1	0	0	1	1
Missouri	MoDOT	4	4	0	8	1	0	1	2	10
Montana	MDT	0	4	0	4	1	0	0	1	5
Nebraska	NDOR	0	0	0	0	1	0	0	1	1
Nevada	NDOT	0	0	0	0	3	0	0	3	3
New Hampshire	NHDOT	0	4	4	8	3	0	1	4	12
New Jersey	NJDOT	0	4	3	7	2	0	1	3	10
New Mexico	NMDOT	0	0	1	1	4	0	1	5	6
New York	NYSDOT	4	4	4	12	3	2	3	8	20
North Carolina	NCDOT	0	4	2	6	1	0	0	1	7
North Dakota	NDDOT	0	0	0	0	1	0	0	1	1
Ohio	ODOT	0	4	0	4	1	1	0	2	6
Oklahoma	ODOT	0	0	0	0	1	0	0.5	1.5	1.5
Oregon	ODOT	0	4	4	8	4	4	3	11	19
Pennsylvania	PENNDOT	0	4	4	8	1	0	1	2	10
Puerto Rico?	DTOP	0	0	0	0	1	0	0	1	1
Rhode Island	RIDOT	0	0	3	3	3	0	1	4	7
South Carolina	SCDOT	0	0	1	1	1	0	0	1	2
South Dakota	SDDOT	0	0	0	0	2	0	0	2	2
Tennessee	TDOT	0	0	0	0	1	2	0	3	3
Texas	TxDOT	4	0	0	4	2	0	0	2	6
Utah	UDOT	0	4	1	5	2	0	1	3	8
Vermont	Vtrans	0	0	4	4	4	1	3	8	12
Virginia	VDOT	0	4	4	8	4	2	2	8	16
Washington	WSDOT	4	4	4	12	3	4	4	11	23
West Virginia	WVDOT	0	0	0	0	1	0	0	1	1
Wisconsin	WisDOT	0	0	4	4	3	0	0	3	7
Wyoming	WYDOT	0	4	0	4	2	0	0	2	6

DOT Information		Climate/Geography/Extreme Events		
State	DOT Abbreviation	General Climate Zone	Koppen-Geiger Zones	Recent Extreme Events
Alabama	ALDOT	Southeast	Cfa	Hurrican Katirna
Alaska	ADOT	Alaska	Dfc, Cfc, ET, Dsc, Cfb, Dfb, Dwc	
Arizona	ADOT	Southwest	BSk, Cfb, Csb, Csa, BSh, BWh	Drought; Wildfires
Arkansas	AHTD	South	Cfa	Flooding; Tornadoes
California	Caltrans	West	Csb, Csa, Dsc, BSk, BSh, BWh, BWk	Wildfires
Colorado	CDOT	Southwest	BSk, Dfa, Dfb, Dfc	Flooding
Connecticut	ConnDOT	Northeast	Dfb, Cfa, Dfa, Cfb	Superstorm Sandy
Delaware	DelDOT	Northeast	Cfa	Superstorm Sandy
District of Columbia	DDOT	Northeast/Southeast	Cfa	Superstorm Sandy
Florida	FDOT	Southeast	Cfa, Am, Aw	Hurricane Katrina
Georgia	GDOT	Southeast	Cfa	Hurricane Katrina
Hawaii	HDOT	Hawaii	Af, Cfb, As, Af, Am	
Idaho	ITD	Northwest	Csb, Dsb, BSk, Csa, Dfb, Dsc, Dfc, Cfb	Drougtt/Wildfire
Illinois	IDOT	Midwest	Cfa, Dfa	Flooding; Tornadoes
Indiana	INDOT	Midwest	Cfa, Dfa, Dfb	Flooding; Tornadoes
Iowa	DOT	Upper Midwest (East North Central)	Dfa	Drought;Tornoadoes; Flooding
Kansas	KDOT	South	Cfa, Dfa, BSk	Drought; Tornadoes
Kentucky	KYTC	Ohio Valley (central)	Cfa	Tornadoes
Louisiana	DOTD	South	Cfa	Hurricane Katrina
Maine	MDOT	Northeast	Dfb	Superstorm Sandy
Maryland	MDOT	Northeast	Cfa, Cfb	Superstorm Sandy
Massachussetts	Mass Highway	Northeast	Cfa, Dfb, Dfa	Superstorm Sandy
Michigan	MDOT	Uppder Midwest (East North Central)	Dfb, Dfa	Flooding (2013)
Minnesota	Mn/DOT	Uppder Midwest (East North Central)	Dfb, Dfa	Drought; Tornadoes
Mississippi	MDOT	South	Cfa	Hurricane Katrina
Missouri	MoDOT	Ohio Valley (central)	Dfa, Cfa	Flooding
Montana	MDT	Northern Rockies and Plains (West North Central)	Dfb, BSk, Dfc, Dsb	Drought; Wildfires; Flooding
Nebraska	NDOR	Northern Rockies and Plains (West North Central)	Dfa, BSk	Tornadoes
Nevada	NDOT	West	Csb, BWk, BSk, Dfb, Csa	Drought/Wildfires
New Hampshire	NHDOT	Northeast	Dfb	Superstorm Sandy
New Jersey	NJDOT	Northeast	Cfa, Dfa, Dfb	Superstorm Sandy
New Mexico	NMDOT	Southwest	BSk, Cfb, Csb, Dfb, BWk	Drought; Wildfires
New York	NYSDOT	Northeast	Dfb, Dfa, Cfa	Superstorm Sandy
North Carolina	NCDOT	Southeast	Cfa, Cfb	Superstorm Sandy; Flooding
North Dakota	NDDOT	Northern Rockies and Plains (West North Central)	Dfb, BSk, Dfa	Flooding
Ohio	ODOT	Ohio Valley (central)	Cfa, Dfa, Dfb	Superstorm Sandy
Oklahoma	ODOT	South	Cfa, BSk	Flooding; Tornadoes
Oregon	ODOT	Northwest	BSk, Csb, Dsb	
Pennsylvania	PENNDOT	Northeast	Dfb, Cfa, Cfb, Dfa	Superstorm Sandy
Puerto Rico?	DTOP	Puerto Rico	Am	Superstorm Sandy
Rhode Island	RIDOT	Northeast	Cfa, Cfb	Superstorm Sandy
South Carolina	SCDOT	Southeast	Cfa	Flooding
South Dakota	SDDOT	Northern Rockies and Plains (West North Central)	Dfa, BSk, Dwa, Dfb	Drought; Flooding
Tennessee	TDOT	Ohio Valley (Central)	Cfa	Flooding; Tornadoes
Texas	TxDOT	South	BSk, Cfa, BSh, BWh	Flooding; Tornadoes
Utah	UDOT	Southwest	BSk, Cfb, Dfb, Cfa, Csa, Dfa, Dfc, BWk, Csb	
Vermont	Vtrans	Northeast	Dfb	Hurrican Irene
Virginia	VDOT	Southeast	Cfa, Cfb	Superstorm Sandy
Washington	WSDOT	Northwest	Csb, BSk, Csa, Dsc, Dfc, Cfb, Dsb	Mudlides; Wildfires
West Virginia	WVDOT	Ohio Valley (Central)	Cfa, Cfb, Dfb	Superstorm Sandy
Wisconsin	WisDOT	Upper Midwest (East North Central)	Dfb, Dfa	
Wyoming	WYDOT	Northern Rockies and Plains (West North Central)	Dfb, BSk, Dfc, BWk	Drought

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Appendix D Global Climate Models Used in Research

Table D.3: Global Climate Models Used in Research

bccr_bcm2_0_sresa1b	Bjerknes Centre for Climate Research, Norway
bccr_bcm2_0_sresa2	
bccr_bcm2_0_sresb1	
cccma_cgcm3_1_sresa1b	Canadian Center for Climate Modelling and Analysis, Canada
cccma_cgcm3_1_sresa2	
cccma_cgcm3_1_sresb1	
cccma_cgcm3_1_t63_sresa1b	
cccma_cgcm3_1_t63_sresb1	
cnrm_cm3_sresa1b	Centre National de Recherches Meteorologiques, France
cnrm_cm3_sresa2	
cnrm_cm3_sresb1	
csiro_mk3_0_sresa1b	Australia's Commonwealth Scientific and Industrial Research Organisation, Australia
csiro_mk3_0_sresa2	
csiro_mk3_0_sresb1	
csiro_mk3_5_sresa1b	
csiro_mk3_5_sresa2	
csiro_mk3_5_sresb1	
gfdl_cm2_0_sresa1b	Geophysical Fluid Dynamics Laboratory, United States of America
gfdl_cm2_0_sresa2	
gfdl_cm2_1_sresa1b	
gfdl_cm2_1_sresa2	
gfdl_cm2_1_sresb1	
giss_aom_sresa1b	Goddard Institute for Space Studies, United States of America
giss_aom_sresb1	
giss_model_e_h_sresa1b	
giss_model_e_r_sresa1b	
giss_model_e_r_sresa2	
giss_model_e_r_sresb1	
iap_fgoals1_0_g_sresa1b	Institute of Atmospheric Physics, China
iap_fgoals1_0_g_sresb1	
inmcm3_0_sresa1b	Institute for Numerical Mathematics, Russia
inmcm3_0_sresa2	
inmcm3_0_sresb1	
ipsl_cm4_sresa1b	Institut Pierre Simon Laplace, France
ipsl_cm4_sresa2	
ipsl_cm4_sresb1	
miroc3_2_hires_sresa1b	Atmosphere and Ocean Research Institute, the University of Tokyo
miroc3_2_hires_sresb1	
miroc3_2_medres_sresa1b	
miroc3_2_medres_sresa2	

miroc3_2_medres_sresb1	National Institute for Environmental Studies, Japan Agency for Marine-Earth Science and Technology, Japan
mpi_echam5_sresa2	Max-Planck-Institut for Meteorology, Germany
mpi_echam5_sresb1	
mri_cgcm2_3_2a_sresa2	Meteorological Research Institute, Japan
mri_cgcm2_3_2a_sresb1	
ncar_ccsm3_0_sresa1b	National Center for Atmospheric Research, United States of America
ncar_ccsm3_0_sresa2	
ncar_ccsm3_0_sresb1	
ncar_pcm1_sresa1b	
ncar_pcm1_sresa2	
ukmo_hadcm3_sresa1b	K Met. Office, United Kingdom
ukmo_hadcm3_sresa2	
ukmo_hadgem1_sresa1b	
ukmo_hadgem1_sresa2'	

Models provided in CMIP3, the model ensemble for IPCC's Fourth Assessment Report (AR4) (IPCC 2007b, 2016)