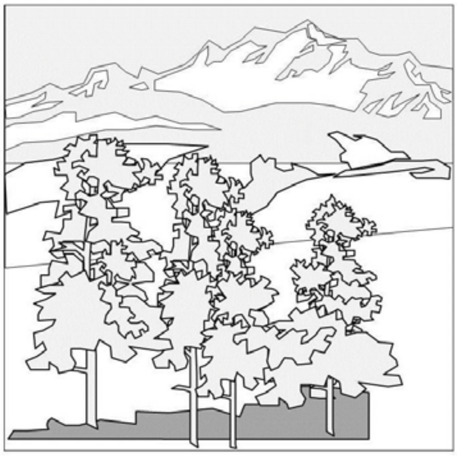

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CLIMATE CHANGE ADAPTATION AND ROADS: DUTCH CASE STUDY OF COST IMPACTS AT THE ORGANIZATION LEVEL

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ABSTRACT

This paper presents a cost analysis and adaptation evaluation of the climate change impacts on the highway network of the Netherlands. Impact analysis is a growing trend in climate change adaptation research but there is a lack of detailed quantitative modeling. Results are often provided at the national or international scale for economic and policy support. Our work modifies an existing cost modeling methodology, the Infrastructure Planning Support System, and is intended to produce results that are more detailed and pertinent at the organizational level. The two main objectives are: 1) refining the stressor-response relationships and cost of adaptation calculation between climate change and porous asphalt and 2) increase the spatial granularity of analysis through use of Regional Climate Models (RCMs). As a case study, climate change impacts are investigated for the Dutch highway network through collaboration with Rijkswaterstaat (the Dutch national highway organization). Costs are then calculated for alternate adaptation strategies through 2100. Potential vulnerabilities and increased operational costs for porous asphalt are of particular concern in the Netherlands, as the large majority of Dutch roads are paved with porous asphalt. Initial results reveal regional variability but highlight the overall trend that proactive adaptation is financially advantageous, in some cases producing savings of up to €90 million annually. Also, the results reveal a trend in which regional climate models predict costs that are typically higher than those calculated using global models.

KEYWORDS: Climate change adaptation, roads, transportation organizations, infrastructure planning

INTRODUCTION

Climate change adaptation research has been a quickly growing field as scientists and practitioners now acknowledge that even with mitigation the planet will experience certain unavoidable levels of climate change (IPCC 2007). While the questions of how much and when are still debated, there has been an increasing search for improved understanding of the potential impacts on transport infrastructure from future climate change. There are also several detailed research works that have analyzed specific material responses to climate change, such as pavement implications (Mills et al 2009). As a larger quantity of data is produced, it is important to examine the scientific robustness, but also the relevance and usability of that information for the infrastructure designers and operators.

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Organizations, often public organizations, already are and will continue to be responsible for planning and implementing climate change adaptation measures in the future. This is especially true for the transportation infrastructure sector, which is primarily managed by public agencies and requires long-term planning of both design and maintenance. In order 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 in depth 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 organizational perspective. The work intends to advance the science of climate change adaptation research through improvements to the modeling methodology, while also producing results that are more relevant and implementable at the organizational level.

Within the transportation sector 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 and Demirel 2012). Roads are designed to operate with minor variability in weather but long-term changes in climate are 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 temperatures (Peterson et al. 2008).

It is important for transportation (highway) agencies to understand and adapt to these impacts for the end-users safety, for their own organizational benefit (e.g. cost and resource efficiency) and also 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, highlighted in the U.S. by Chinowsky et al (n.d.). 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 analyzing climate change impacts to the Dutch road network using data, technical design requirements, and organizational characteristics specific to Rijkswaterstaat (RWS), the highway agency of the Netherlands. Motorways are analyzed, in part because that is the only type of road that RWS directly manages, but also because motorway costs are ten times higher than other road types in Europe (Doll and Van Essen 2008). Higher costs of construction and maintenance equate to higher risk and potentially higher costs of inaction. The highway network is also a high priority in the Netherlands, as it connects the country's economically valuable ports with all of Europe.

This paper uses the previously developed Infrastructure Planning Support System (Chinowsky et al 2011) to analyze the Dutch case study. Inputs are modified to appropriately reflect RWS's pavement characteristics and costs. The model produces initial results with global climate input that has been used for previous case studies. Regional climate models, which are capable of a higher resolution, are then used to produce additional results. These two outcomes are compared and the costs of alternate adaptation options are presented nationally and regionally through 2100.

BACKGROUND

The research setting for climate change adaptation and the current state of road impact studies are first described. This includes motivations for selecting the Netherlands as a case study. Then the research method is described, primarily through explanation of the assumptions and process of the IPSS model. This also includes the current selection of the Dutch data source for both climate and roads. Initial data (modeling results) are presented, followed by discussion of future research and overall implications of the current and expected results.

Climate change adaptation and road infrastructure

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 general consensus that some form of adaptation will be required to address the amount of climate change that is now unavoidable (IPCC 2007). Economic modeling of the impact and adaptation costs has been completed in many industry sectors, especially in agriculture and water resources (Tol 2002). This broad quantification of the potential impacts is an important tool for economists and policy-makers. But as Jotzo states in his report on the limitations of economic modeling for climate change adaptation, more detailed sector-specific modeling is required to enable local adaptation action (Jotzo 2010).

This is true within the transportation sector and there are an increasing number of studies, (Jaroszweski et al. 2010, Peterson et al. 2008, TRB 2008) that examine the risks of climate change to transportation infrastructure. Specifically, higher temperatures and increased precipitation will result in the acceleration of road degradation, primarily through rutting and raveling. The quantification and modeling of cost impacts is being researched (Chinowsky et al. n.d., Nemry and Demirel 2012), however there are still few detailed studies, such as Mote 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” (Nemry and Demirel 2012).

Some of the sector-specific modeling that has previously been completed for road transportation was executed using the Infrastructure Planning Support System (IPSS). This support system was developed by the Institute for Climate and Civil Systems at the University of Colorado Boulder to model the cost impact of adaptation options for climate change and road infrastructure. In addition to the social benefits of roads in developing countries, this work also detailed the importance of roads to the overall economic success of a country (P. Chinowsky et al. 2011). This is especially true for the highway system of the Netherlands.

The Netherlands

With the busiest seaport in Europe (AAPA 2013) and the 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 14 percent of all international road travel in the European Union (“Logistics gateway to Europe and beyond” 2013). As stated on their government’s 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). This includes 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. This includes their road network, highlighted by Snelder et al (2005) and by Rijkswaterstaat, the Dutch highway agency, which has begun investigating the climate change risks to their road network. It is a main topic in their annual report (RWS 2012) and they 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, 2012). These characteristics, along with a large collection of available data, make the Netherlands an effective case study for this project.

Porous Asphalt Pavement

As described previously, the Dutch include environmental concerns in their road network planning. This includes the impact to surrounding environment, as well as quality of life for nearby citizens. 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 and land use planning. As the population grows and the use of automobiles increases, RWS has made noise reduction a priority (Van der Valk 2002, Huurman et al. 2010). As a result, as well as for additional reasons such as drainage, the Dutch road network is now constructed with approximately 90% 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 2009). 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 2009), 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 with age and clogging of pores (Bendsten et al. 2005). These will be important for RWS to consider when evaluating the long-term effectiveness of PA pavement in a changing future climate.

RESEARCH METHOD

The research is conducted through a combination of climate modeling, empirical data analysis, and adaptation of the existing climate change adaptation modeling system, IPSS. The model has been used for several case studies, including countries in Europe (P. Chinowsky et al. 2011), but until now the model has been used primarily for developing countries. The adaptation analysis was performed at an economy-wide scale for planning, policy, and investment implications. Using the Netherlands as a case study, the IPSS model is expanded to include country-specific road characteristics and increased granularity of analysis. The methodology for incorporating country-specific road design and maintenance data is important for strengthening the relationships between climate stressors (temperature, precipitation) and physical road response (damage). The increased granularity provides a more focused, regional analysis that will assist in planning and investment decisions, particularly if a country experiences a wide range of climate.

Infrastructure Planning Support System (IPSS)

Cost modeling is completed using IPSS, the climate adaptation modeling system 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 primarily for developing countries. This research expands on the paved road portion of the model by increasing the capacity to analyze in greater detail and include the porous asphalt road type.

The climate data is initially analyzed on a 0.5^{o} by 0.5^{o} (longitude/latitude) grid for temperature and precipitation. Using higher resolution regional climate models, additional analysis is performed at the 0.25^{o} by 0.25^{o} scale. The forecasted climate change within each grid cell is applied to the length of road located in that same grid to analyze the impact on road performance and design life.

The model uses thresholds and stressor-response functions to predict the impact that changes in climate stressors, in this case temperature and precipitation, will have on a road. The functions relate incremental changes in temperature and precipitation, i.e. changes that cross a predetermined threshold, to changes in design or maintenance that will “climate-proof” the road against the future climate. In the Chinowsky and Arndt (2012) paper, more detailed explanation of the functions, stressor-response methodology, and thresholds can be found. Chinowsky et al (2013) also provides background on the impact functions and underlying assumptions of the model. For this case study, the basic assumptions and process of the 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, this modifies the system to produce results that are organization-specific and on a finer spatial scale than previously attained.

The IPSS results are presented based on two alternate adaptation strategies. The “no adapt” strategy calculates costs based on increased maintenance that is required to maintain the design life of the road, without altering the initial design of that road. The “adapt” strategy calculates costs for altering the initial design of a road to be more climate resilient during its lifespan, rather than preserving the initial design life exclusively through maintenance. The adaptation evaluation is performed at the beginning of each road’s design life. If the climate model forecasts that a threshold will be crossed during a road’s design life, the cost for adapting and not adapting are then calculated. The costs are calculated each year as a percentage of the total road network is renewed. Using data from RWS in the Netherlands produces quantitative results that are based on actual costs, policy, and procedure, making them more actionable for the infrastructure planners.

Climate

In addition to the global climate models that IPSS typically utilizes, this case study includes downscaled climate data that is specific for the Netherlands’ region of Europe.

Climate description of the Netherlands

The Netherlands has a temperate maritime climate, with cool summers and moderate winters. The country is small and, as a result, there is little variation inland, 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. Precipitation is distributed equally throughout the year.

Regional Climate Model Simulations

Regional Climate Models (RCMs) are a complementary research method to the coarser resolution Global Climate Models (GCMs). 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 a RCM simulation, with a spatial resolution of 25-50 km, is dependent by the RCM itself and by the driving GCM.

The ENSEMBLES project was a large research program founded by the European Commission in 2004. The main aim, and core, of the ENSEMBLES project was running multiple climate models ('ensembles') with the aim to produce a range of future predictions assessed to decide which of the outcomes are more likely (probable) 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 SRES emission scenario. In this study it was decided to use one model per institute and only those models that extended their simulation until 2100. This leads to Table 1 that lists the eight models that are used in this study. [ENSEMBLES 2009]

Table 1: List of RCMs used in this study with their driving GCMs

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)

Road network

The Netherlands has one of the densest road networks in the world with approximately 137,000km (IRF 2012). As described previously, the road network selected for this study was limited to motorways. Rijkswaterstaat directly manages the motorways and they are of critical economic importance to the country. Thus, the total length of the road network was determined to be 4,472 km (RWS 2012). Currently, the national total is distributed regionally based on population and land area weighting. The amount of roads allocated to each province is based on the following Equation (**1**. The resulting distribution is shown in Figure 1.

$$(1) \qquad \mathrm{R_P} = \mathrm{R_N} * 0.5\left(\left(\frac{\mathrm{Pop_P}}{\mathrm{Pop_N}}\right) + \left(\frac{\mathrm{A_P}}{\mathrm{A_N}}\right)\right)$$

Where:
R = Roadstock (km)
Pop = Population

A = Land area (km)
Subscript P = Province
Subscript N = National

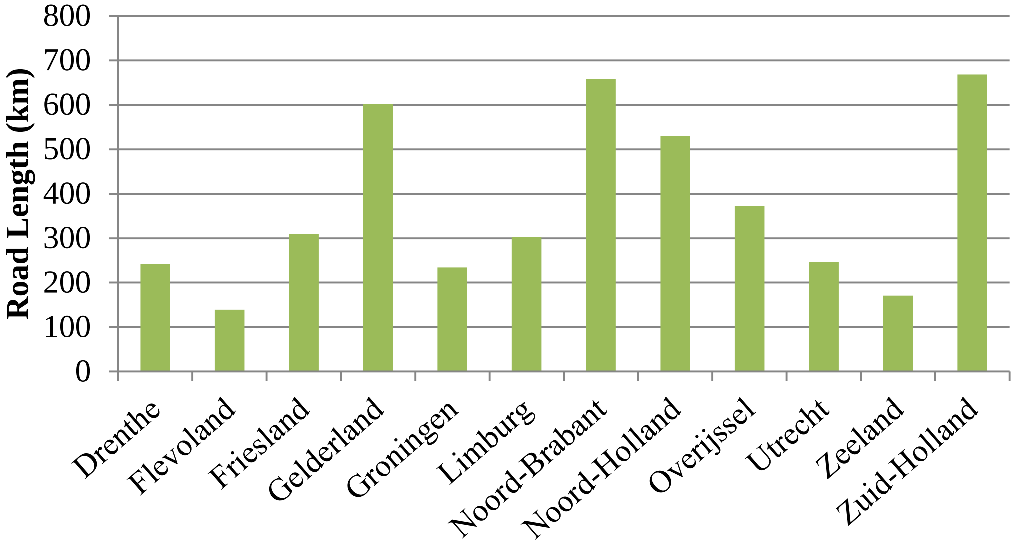

Figure 1: Road Network Distribution by Province

In addition to the total length, the road (pavement) type needed to be defined for the network. As previously described, a large majority, approximately 90%, of roads in the Netherlands (Huurman et al. 2010) are porous asphalt (PA). The majority of those roads are paved with ZOAB – *Zeer Open Asfalt Beton* – the PA design that is specific to Rijkswaterstaat. For modeling purposes, the assumption was therefore made to define all roads as ZOAB. Future work will include exploration of the possibility to include additional pavement types. There is existing research on PA pavement features (see background above for references) that defines general design life and cost, but in order to be as organizationally applicable as possible, these were defined for ZOAB specifically.

The lifespan of porous asphalt, ZOAB included, can be highly variable. In a Dutch report on road management modeling, historic life cycle and maintenance characteristics of ZOAB are provided in detail. ZOAB design life has been observed to be as short as 5 years and as long as 20 or more. Based on the data, the average lifespan is approximately 11 years, which we 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 (2005) and input into IPSS.

RESULTS AND DISCUSSION

The research is currently ongoing. In this paper, we focus on two analyzes for comparison. For both scenarios, the pavement characteristics and costs were updated from the default values to the Dutch case. First, the model was run with the suite of 56 Global Climate Models used in previous IPSS case studies. Second, the model was run with the collection of eight Regional Climate Models. The results are reviewed for the cost implications to the Netherlands. They are also compared with each other in the context of what effect climate downscaling has on the cost output.

Total Costs

Figure 2 below shows the total cost of climate change to the Netherlands through 2100 in quartiles. It is clear from these results that at a national level, adaptation will cost less by the end of the century than no adaptation. For example, in the 75th percentile model results using Dutch RCMs, the savings from adaptation are approximately €10 billion. The chart also highlights the difference between results using global versus regional models. At the lower quartiles, results for GCMs are similar and in once instance higher than the costs from regional models. However, the general trend is that regional models, which are a higher-resolution input, produce cost outputs that are higher than with GCMs. If it is assumed that RCMs are more accurate than GCMs, then these results show that the more accurate cost values are higher than the original model output. This is particularly true for the higher quartiles, or the so-called "worst case scenarios."

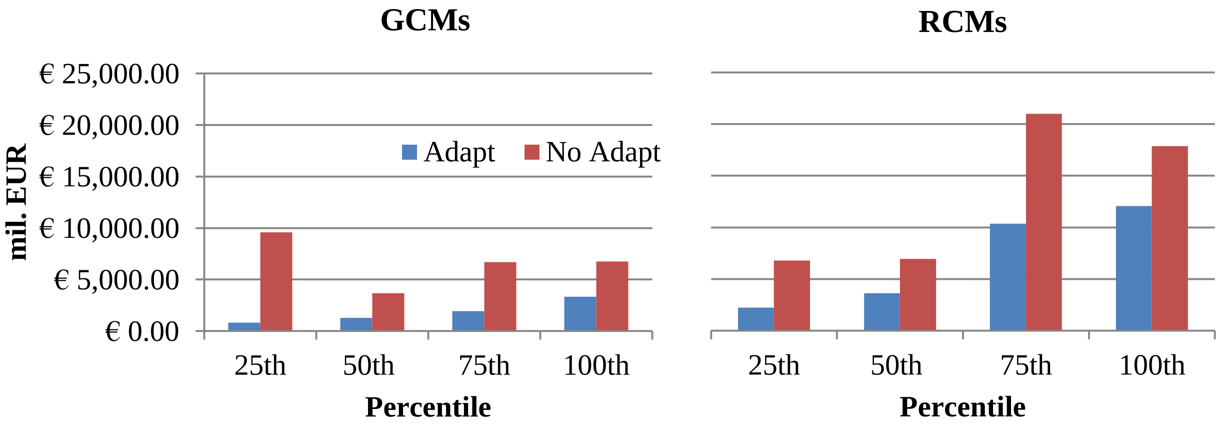

Figure 2: Total Cost of Climate Change Through 2100

Annual Costs

Table 2 and Figure 3 below provide greater detail for the median and maximum results. The average annual cost is presented at three points between the beginning of the simulation (2011) and the end (2100). As seen above, there are general trends that adaptation will typically cost less than no adaptation, and that the RCMs predict higher cost of both strategies than the GCMs. While reviewing the timeline results it is helpful to refer back to a previous point made in the introduction that it is less a question of if adaptation is appropriate, but when. Some of the results, particularly in the maximum RCM scenario, show costs that are very similar between adapting and not adapting, 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 adaptation saves money from the beginning, as seen in the 75th percentile RCM scenario.

Table 2: Average Annual Cost of Climate Change

GCMs

Average annual cost (million Euros)				
	Median		Maximum	
	adapt	no adapt	adapt	no adapt
2030	€ 17.38	€ 30.23	€ 42.52	€ 58.10
2050	€ 15.01	€ 48.14	€ 44.55	€ 94.17
2090	€ 19.49	€ 53.71	€ 42.05	€ 100.62

RCMs

Average annual cost (million Euros)				
	Median		Maximum	
	adapt	no adapt	adapt	no adapt
2030	€ 36.05	€ 43.43	€ 170.06	€ 172.23
2050	€ 40.47	€ 45.92	€ 187.24	€ 191.54
2090	€ 39.09	€ 106.53	€ 134.94	€ 224.46

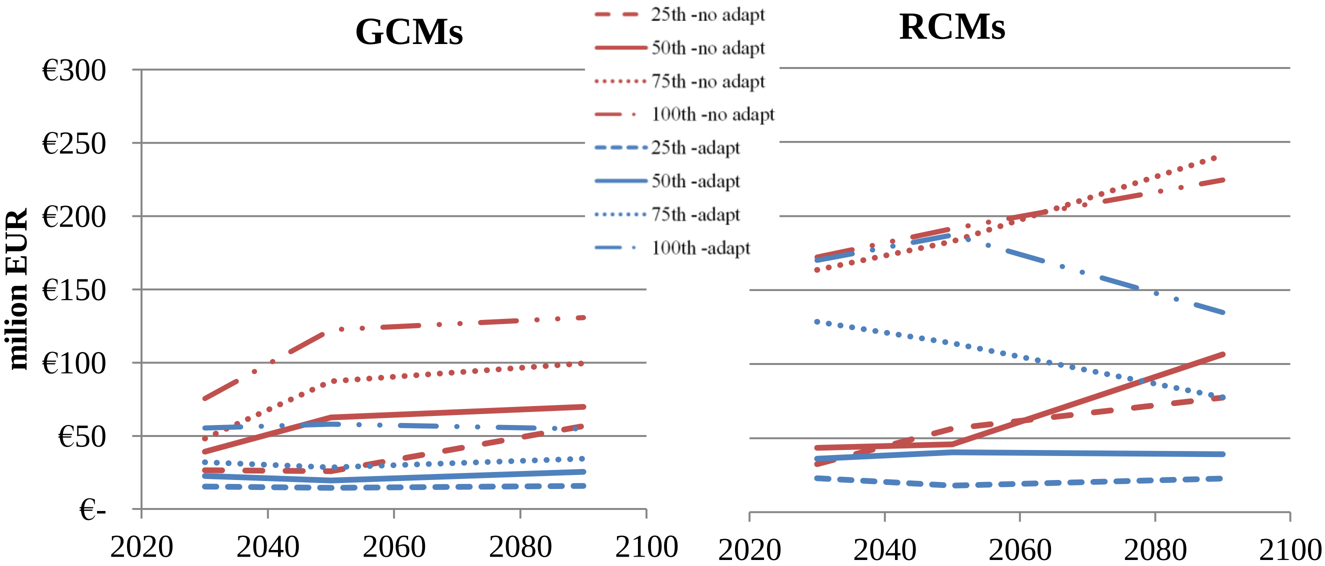

Figure 3: Average Annual Cost of Climate Change

Regional Costs

Costs are also calculated regionally, by province. The average cost for each strategy is shown below in Figure 4. These regional variations are important to examine because Rijkswaterstaat’s organization and planning is performed at the regional level and not all national trends will be applicable to each province. Both the GCM and RCM results show similar distribution by province. Noord-Brabandt, Gelderland, and Noord-Holland have the three highest annual costs, when the GCM input is used. Noord-Brabandt, Gelderland, and Zuid-Holland are the three highest with RCM input. 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 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 a greater level of variation (€110 million) between provinces than the GCMs (€60 million).

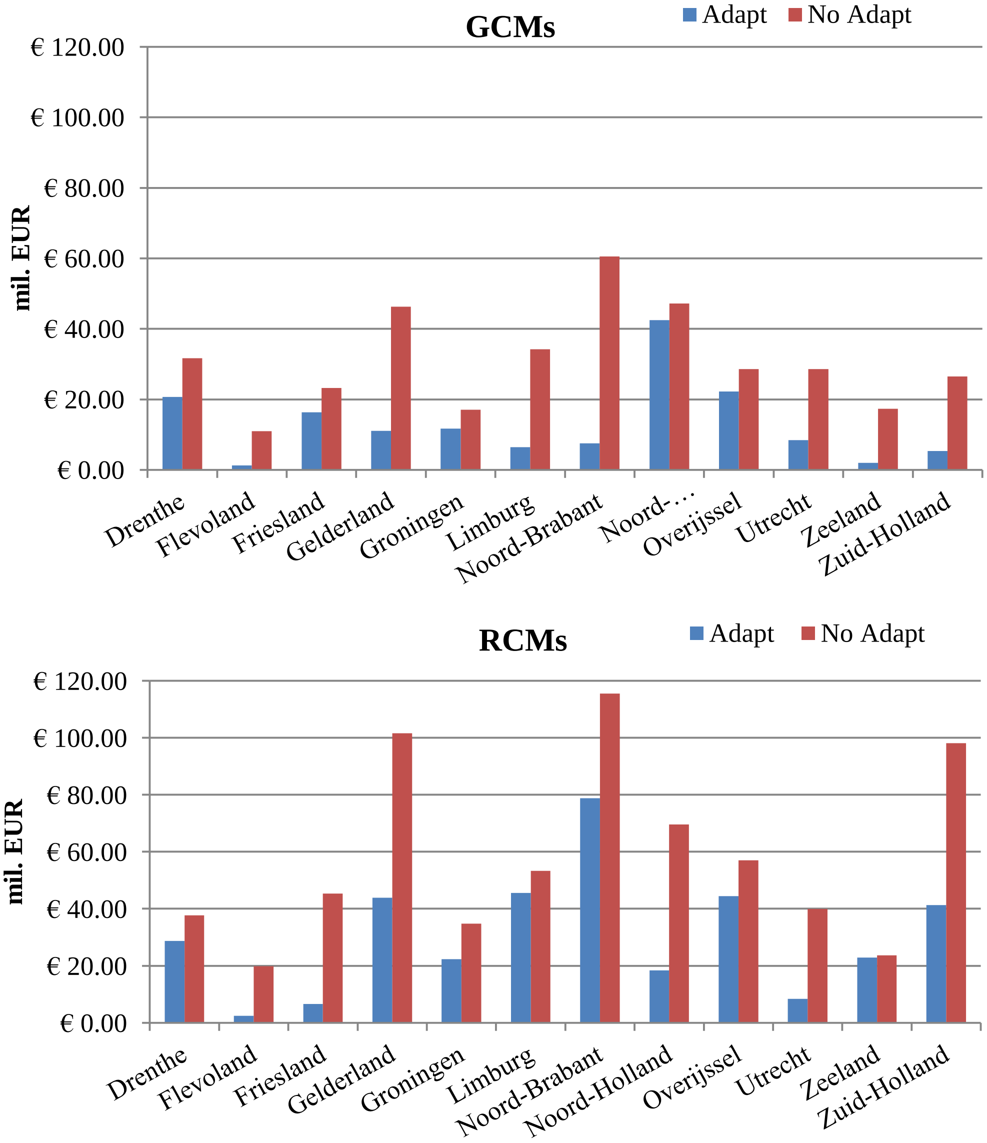

Figure 4: Average Annual Cost of Climate Change, per Province

LIMITATIONS/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 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. While the Dutch climate collection includes fewer models, the regional modeling provides higher resolution data. The project currently uses 8 RCMs compared to the 56 GCMs. The 8 regional models were selected due to data requirements (temperature and precipitation data through 2100) but additional models may be used in the future to provide a larger set of results.

In addition to climate data, the quality and specificity of other input data influences the output of the 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. This equation and other inputs will continue to be updated as additional information is received from Rijkswaterstaat.

CONCLUSION

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 detailed climate, pavement, and cost data advance the adaptation modeling and also produce more accurate and actionable results. This improves support for decision-making, long-term planning, design, and maintenance within the organization.

The initial results from IPSS support the thesis that in most regions it is not a question of if, but when, is the appropriate time to adapt. The challenge that climate change presents for road infrastructure is a short and long-term concern. The cost through 2100 in the Netherlands is as high as €21 billion. If a proactive adaptation approach is properly managed, however, it could save as much as €10 billion during that time. 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.

It is particularly useful for the Netherlands to review the impacts of climate change in respect to analogous climate. They rely almost entirely on porous asphalt and it is imperative for the long-term sustainability of the road infrastructure that PA roads will still be resilient and effective under future climate conditions. The results presented in this paper are intended to provide insight into that future and also support the ability for an effective organizational response.

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