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Planning resilient roads for the future environment and climate change: Quantifying the vulnerability of the primary transport infrastructure system in Mexico

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ABSTRACT

Climate projections predict an increase in future climate variability. To ensure economically, socially and environmentally responsible transportation planning, it is necessary to consider future weather variations driven by climate change. Despite growing evidence that considering climatic changes is an imperative for resilient future infrastructure, management agencies rarely incorporate climate change into decision-making processes. One reason is the lack of tangible information and tools to help predict and plan for future conditions.

This paper presents the impacts and cost of climate change on the road infrastructure of Mexico. Climate change is projected to require an extra national expenditure on road maintenance that ranges from $1.5 to 5 billion USD by 2050. The *Infrastructure Planning Support System (IPSS)*, a tool developed by the authors, is used to quantify impacts of climate change for this study. The results reinforce the need to incorporate forward-looking planning to reduce vulnerability by increase road infrastructure resilience to the future weather changes and provide quantified information for decision makers to consider.

1. Introduction

Transportation infrastructure is crucial for trade, commerce, and community functions including commuting to work and school (Ochia, 1990; Erath et al., 2009). This is especially evident in economically developing communities, where road infrastructure quality and quantity is positively related to economic and social growth (Esfahani and Ramírez, 2003; Calderón and Servén 2004). Additionally, roads are one of the main capital assets of any country, and therefore one of the largest portions of national and regional budgets and investments (Fernald, 1999; Neumann et al., 2014). This critical role makes the question of transportation infrastructure vulnerability and degradation a top concern for public and private entities as well as planners at all levels (Jenelius et al., 2006).

Road vulnerability, understood as the potential of a road to lose serviceability or accessibility due to a hazard event, can be defined as a function of both risk and resiliency (Nicholson and Du, 1997; Berdica, 2002). Risk normally refers to the probability that an event with negative consequence will occur. Resiliency is used similarly in different studies and tends to describe the potential to efficiently recover from an external strain. The concept of resilience could be transferable to roads as, for example, the potential to recover serviceability after a strain to the transportation system. In particular, road vulnerability is recognized to have direct negative outcomes on economic, environmental and/or societal conditions (Berdica, 2002; Taylor and D'Este, 2007).

Many previous studies, including Berdica (2002) and Taylor and D'Este (2007), recommend incorporating "sustainable" infrastructure planning in order to reduce potential vulnerabilities. In particular, a highlight from most of these studies is a recommendation that to incorporate sustainability, it is crucial to identify vulnerabilities in the early stages of the planning process (Berdica, 2002). Sustainable infrastructure planning is most often referred as a holistic planning process that incorporates life-cycle assessments with the inclusion of projected future cost from maintenance and repairs due to hazard and weather related events (Dasgupta and Tam, 2005; Frangopol and Liu, 2007; Koetse and Rietveld, 2009).

At the same time, many recent studies are indicating that climate change can exacerbate vulnerabilities on road infrastructure, causing increased degradation rates (Koetse and Rietveld, 2009; Neumann et al., 2014; Taylor and Philp, 2015). Climate change impacts can lead to an increase in the variability of weather patterns and changes in the frequency and severity of extreme events. These impacts have been characterized as an additional strain in

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the transportation system, based on the definition of 'risk' presented above (Berdica, 2002; Erath et al., 2009).

However, despite this increased recognition of the potential severity of climate change impacts on transportation infrastructure, only small steps are being taken to address these issues. The World Bank is starting to advocate for proactive planning, particularly in Latin America (McAndrews et al., 2012). Recent literature has addressed the issue in location-specific case studies (Savonis et al., 2015; Suarez et al., 2005) and in broader frameworks (Meyer and Weigel, 2011), as well as in quantitative modelling (Schweikert et al., 2014).

These previous works form a solid base for the necessity of incorporating climate change impacts into all phases of transportation planning with the purpose of reducing risks to future projected climate changes. An additional benefit is that the inclusion of these projected impacts onto the life-cycle costing and planning of road systems can substantially reduce financial costs from increased vulnerabilities, rehabilitation and additional maintenance (NRC, 2008). It is recognized that decision-makers seek to address climate change in order to reduce risk, life-cycle cost (including unplanned maintenance and repair), and degradation rates of roads, which are increasing beyond historical precedent (Füssel and Klein, 2006; Rattanachot et al., 2015). Incorporating potential future climate conditions into current decision-making will support a more holistic, forward-looking approach and ultimately more climate-resilient road infrastructure designs (Meyer et al., 2010; Meyer and Weigel, 2011; EEA, 2014).

Several existing studies demonstrate how proactive investment in transportation infrastructure is equivalent to or lower than life-cycle cost estimates, and also improves the performance of the infrastructure under climate stress throughout its lifetime (Schweikert et al. 2014; Chinowsky et al., 2014). These cost savings are usually due to retrofit or repair needs for infrastructure unable to withstand future damages, because they were built to historical climate standards. While uncertainty in climate modelling limits the ability of planners to invest with perfect foresight, the recognition of changing future weather variability and incorporation of flexible design and adaptation options today should be a consideration for transportation decision makers (NRC, 2008). One method for doing so, the modelling system IPSS (*Infrastructure Planning Support System*), is explained and explored throughout the remainder of this paper.

The first section of this paper reviews the current state of literature and work done regarding climate change mitigation and adaptation in Mexico. Specifically, this first section focuses on efforts in Mexico to prepare the country against future impacts of climate change through adaptation strategies. The second section explains the methodology used in this study to calculate road vulnerabilities and the engineering approach based on incorporating life-cycle engineering onto transportation planning. In the third section, the regional impacts of the transportation system are analyzed, including a discussion of risk and uncertainty during road planning. The paper concludes by discussing the importance of incorporating long-term transportation planning to increase resilience and reduce vulnerabilities of regions and communities who rely on road transportation.

2. Climate change action plans in Mexico – background

The future projected changes in climate for Mexico include increased average temperatures, increased extreme low temperatures and both severe flooding and drought (IPCC, 2014). These predicted climate change impacts could result in severe and widespread changes, including: the replacement of tropical forests with savannahs, an increase in arid vegetation, potential species extinction, loss of costal vegetated wetlands, diminished agricultural production, increased disparity between social classes, a drier environment across portions of the country, increased droughts and simultaneous increases in the intensity of rain and tropical cyclones (Ibarrarán et al., 2009; NCCS, 2013; IPCC, 2014).

Driven by the country's awareness of climate impacts, the Mexican Government has demonstrated commitment, a long-term vision, and political will to addressing climate change by implementing national policies and by taking a leading role in several rounds of global negotiations to address climate change (Schafer, 2013). Notably, in 1994, Mexico joined the United Nations' Framework Convention on Climate Change (UNFCCC) and in 2005 signed the Kyoto Protocol. Based on these commitments, the country preceded to create several laws and guiding documents to help direct efforts in mitigating and adapting to climate change.

A key effort was the 2005 creation of the *Interministerial Commission on Climate Change*. The group is responsible for establishing and creating strategies to address climate change. Out of this commission came the creation of the *National Strategy on Climate Change* (ENACC) in 2007 and the *Special Climate Change Program* (PECC) in 2009 (Sosa-Rodriguez, 2013). Other programs were created to support these bodies, including the *Energy Saving and Efficient Use Program* and the *Renewable Energy Development Program*, both established in 2009 (Sosa-Rodriguez, 2013).

All the aforementioned efforts were focused on reducing carbon emission, through national efforts to mitigate the anthropogenic causes of climate change. In 2014, the Ministry of the Environment and Natural Resources (SEMARNAT) released the *Special Climate Change Program 2014–2018,* an important step towards policy-level acknowledgement of potential adaptation needs and strategies (PECC, 2014).

The PECC is one of the policy planning instruments developed after the General Climate Change Law (LGCC, 2012) was passed in 2012. The PECC complements the previous existing mitigation policies and develops a set of adaptation strategies and guidelines to address the impact of climate change, reducing vulnerabilities of population, ecosystems and productive sector and increasing resiliency of strategic infrastructure.

The *Adaptation Plan* created by the PECC is divided into three stages. The first stage 2008–2012) assesses the country's vulnerability to climate change and conducts an economic evaluation of priority measures. The second stage 2013–2030) focuses on strengthening adaptation capacities, and the third stage 2030–2050) is designed to consolidate the capacities already established in stages one and two. The aim of the *Adaptation Plan* has specific reference to infrastructure:

> "[Focus on how to] Reduce vulnerability of population and productive sectors and increase its resilience and the resistance of strategic infrastructure. The objective seeks to consolidate and modernize actions and instruments to reduce social vulnerability, favouring prevention and risk management over disaster reconstruction." *PECC, 2014-2018pg.33*

The *National Climate Change Strategy* launched in 2013 by the Mexican Federal Government (NCCS, 2013), also includes the importance of adapting infrastructure to future impacts of climate change. The document reinforces the need to incorporate climate change criteria into the planning and building of new strategic infrastructure (such as communications, transportation, and energy). Adaptation is highlighted as best being achieved at the local level; the design of measures to be developed will depend on the region and context of implementation. The document encourages local and regional governments to follow a preventative approach, where adaptation is prioritized based on investments that reduce vulnerability, in contrast to measures that merely address damages