Working Paper Proceedings

Engineering Project Organization Conference
Devil's Thumb Ranch, Colorado
July 29-31, 2014

Targeted Adaptation Strategy: Reducing Climate Change Impacts by Integrating Social Vulnerability Analyses and Climate- Resilient Infrastructure Adaptation

Amy Schweikert, University of Colorado Boulder, USA
Paul Chinowsky, University of Colorado Boulder, USA
Xavier Espinet, University of Colorado Boulder, USA

Proceedings Editors
Paul Chan, The University of Manchester and Robert Leicht, The Pennsylvania State University

TARGETED ADAPTATION STRATEGY: REDUCING CLIMATE CHANGE IMPACTS BY INTEGRATING SOCIAL VULNERABILITY ANALYSES AND CLIMATE-RESILIENT INFRASTRUCTURE ADAPTATION

Amy Schweikert[1], Paul Chinowsky[2], Xavier Espinet[3]

KEYWORDS: roads, climate change, adaptation, social vulnerability, integrated assessment, investment prioritization

ABSTRACT: This research effort introduces an integrated assessment model which combines quantitative data sets of socio-economic vulnerability to climate change and physical infrastructure (road) vulnerability to climate change. An analysis comparing an adaptation strategy and a business as usual strategy are compared using life-cycle costs through 2050.

The contribution of this research is to move beyond the identification of vulnerabilities to a quantitative assessment of specific adaptation options that reduce a community or regions vulnerability to climate change. Due to constraints of reality, investments must be prioritized. Sociological literature highlights the impact of the built environment (including roads) on the welfare of the surrounding populations. A proactive investment in roads reduces future vulnerabilities to climate impacts. Incorporating a social perspective also provides immediate co-benefits including increased resiliency to extreme events and higher quality of life through better quality and quantity of transportation corridors and reduced costs. This reduces the institutional risk of investment by providing immediate tangible benefits.

Road adaptation investments are prioritized based upon life-cycle costs and social vulnerability to climate change. Analysis is completed using a social vulnerability index (based on the SoVI), a physical vulnerability assessment using the Infrastructure Planning Support System (IPSS) tool, and geographic information systems (GIS).

[1] Graduate Research Fellow, Mortensen Center in Engineering for Developing Communities, University of Colorado Boulder. *amy.schweikert@colorado.edu*
[2] Professor, Department of Civil, Environmental and Architectural Engineering. University of Colorado Boulder. *paul.chinowksy@colorado.edu*
[3] Research Assistant, Department of Civil, Environmental and Architectural Engineering. University of Colorado Boulder. *xavier.espinet@colorado.edu*

1.0 - INTRODUCTION

The built environment - including roads, bridges, buildings, electricity, water systems and more – represents a significant portion of public and private investment portfolios. It is continually being expanded to facilitate economic and social welfare of populations (Erath et al 2009). Accordingly, ongoing investments and research focus on improving efficiency and resiliency. Unfortunately, due to many factors including modelling capabilities, many of these investments are made from an economic and technical perspective that fails to integrate a range of critical factors, including the effects of climate change (Tyler and Moench 2012; Kwiatkowski et al 2013). Additionally, many of these projects designed and built for the betterment of societal welfare rarely consider the existing and future vulnerabilities of the populations (Robinson 2006; Lucas 2011).

From an organizational perspective, governments and public agencies that are responsible for the built environment including road infrastructure (the focus of this paper), have an imperative to create safe, efficient, and sustainable infrastructure. Therefore, decision-making cannot be made without consideration of the long-term provision of public services and must consider up front the considerations which can reduce unnecessary costs and maintenance and increase the quality of life (Feng et al 2013; Chi et al 2013). This broader perspective is integrated into many projects through an Environmental Impact Assessment (EIA) which is a required assessment of the broader environmental concerns of a project (Chi et al 2013).

The contribution of this research is to move beyond the identification of vulnerabilities to a quantitative assessment of specific adaptation options that reduce a community or regions vulnerability to climate change. Additionally, metrics of social vulnerability are utilized, providing two benefits. First, due to constraints of reality, investments must be prioritized. Social vulnerability and sociological literature highlights the impact of the built environment (including roads) on the welfare of the surrounding populations. Second, a proactive investment in road infrastructure reduces future vulnerabilities to climate impacts. However, with a social impact perspective, it also provides immediate co-benefits including increased resiliency to extreme events and higher quality of life through better quality and quantity of transportation corridors and reduced costs. This reduces the political risk of investment that may only see future benefits by providing immediate tangible benefits.

A case study for the State of California is used to illustrate how these domains of knowledge can be combined to guide decision making and investment policy. Two data sets are utilized: one measuring road infrastructure (“physical”) vulnerability to climate change and one measuring the vulnerability of society (“social”) to climate change. They are combined to create a prioritized investment strategy based on combined vulnerability to climate change.

2.0 – RESEARCH FOUNDATIONS AND PROBLEM DEFINITION

The concepts of climate change, transportation network vulnerability and social vulnerability have substantial literature bases in their respective fields of study. In many studies, two of the three topics overlap. Most studies, specifically those addressing vulnerability in any of the three categories, focus on identifying vulnerabilities but do not suggest tangible, actionable items to reduce vulnerability, particularly those related to climate change. Most studies are done from the perspective of a single discipline, noting the merit of cross-discipline study but rarely integrating the concepts. This section provides a brief foundation for each concept and then explains the integrated approach used for this research effort.

2.1 – Project Governance Impact

The engineering project organizations field recognizes the need for *sustainable infrastructure* to consider whole project life-cycle up front, a holistic recognition of wider impacts, and the importance of creating value for stakeholders (Chi et al 2013; Feng et al 2013; Fellows 2014). The up-front approach to planning, including life-cycle costing and planning considerations can substantially reduce lifetime costs of operations and maintenance and maximize the asset performance (Feng et al 2013). Additionally, the mandatory inclusion of appraisals including an *Environmental Impact Assessment (EIA)* shows a growing recognition that infrastructure projects have direct and indirect impacts on the surrounding environment. The EIA is designed to integrate these concerns into project decision making, creating a precedent for a broader holistic analysis of projects during the planning phases. Considering this 'end-of-life' thinking into the front-end of the project is crucial to create sustainable projects and avoid displacing the responsibility for negative externalities, termed *displaced agency* (Levitt et al 2010, Chi et al 2013).

Feng et al (2013) states that,

> "The impacts of large engineering projects are far-reaching from many perspectives: On the one hand, LEPs not only substantially improve the quality of human life, but are strongly connected to the productivity and competitiveness of a country and "constitute one of the most important business sectors in the world"… On the other hand, LEPs also bring potential externalities (i.e., overuse of natural resources, environmental pollution, etc.) as well as unintended consequences".

Therefore, there is a clear mandate for planning and implementation of projects which consider a life-cycle analysis. In areas where the climate is expected to vary from historic records, understanding and incorporating the potential changes is imperative for sustainable design and responsible decision making.

2.2 - Climate Change

Climate change has been at the forefront of discussions globally since the founding of the United Nations Intergovernmental Panel on Climate Change (IPCC) in 1988. While the early work of the IPCC focused on creating and understanding the science of global climate change and mitigation options, more recently a prominent shift has been made to include vulnerability assessments, adaptation options, and the financing of climate-resilient projects (IPCC 2014). In recent years there have been several large-scale efforts aimed at identifying critical components of infrastructure and the potential for adaptation to increase resiliency to climate change, particularly at the city and regional level.

A notable effort in expanding climate analysis to adaptation options at a systematic level is the Rockefeller Foundation's *Asian Cities Climate Change Resiliency Network* (ACCCRN) (Tyler and Moench 2012). The research is ongoing, with the goal of creating a framework that can guide specific climate adaptation investments. The in-progress publication identifies, as part of a larger framework consideration, the need to consider specific investments in infrastructure that increase redundancy and robustness. A key finding is the need for institutions (including public policy makers) to invest in updated engineering codes, proactive investment, and a policy specifically highlighting the needs of the most vulnerable groups.

The terms 'vulnerability' and 'resilience' are seen in virtually any publication relating to climate change, their meanings can vary widely based on the topic and there is no agreed-upon definition. For this research effort, they are defined separately for physical infrastructure (in this case, roads) and social considerations. In broad terms, vulnerability and resilience are related in that *high vulnerability* means *low resilience*. The goal of the research is to prioritize investments to reduce vulnerability, thus increasing resilience to climate change. For both physical and social considerations, *vulnerability to climate change* is defined as: "exposure to increased climate hazards, particularly for low-capacity elements" (Tyler and Moench 2012; Cutter 1996; Bohle et al 1994; Fussel 2007; Cutter et al 2008; Cooley et al 2012; Flanagan et al 2011).

2.3 - Transportation Network Vulnerability and IPSS

2.3.1 - Transport Network Vulnerability

Physical infrastructure vulnerability, particularly related to road transportation networks, does not have a homogenous definition in the literature (Jenelius et al 2006; Berdica 2002). Generally, there is disagreement about whether a definition is context-specific (Taylor and D'Este 2007; Jenelius et al 2006), only applies to rare, 'big' risk events (Jenelius et al 2006), and whether vulnerability refers to 'total failure' or 'safe-fail' events (Berdica 2002).

There is agreement that vulnerability is a function of both risk and resiliency and/or robustness (Berdica 2002; Nicholson and Du 1994). Risk refers to potentially negative outcome resulting from an event and the resulting consequences. *Resiliency* and *robustness* are used in different studies and can both be used to mean 'the ability to withstand strain' and the 'ability to recover from a strain'.

Given these definitions, both the incremental changes in weather (precipitation and temperature elements) and changes in the frequency and severity of extreme events resulting from climate change could be characterized as 'abnormal' strains on the system (Berdica 2002; Erath et al 2009). The goal of this research, then, is to introduce an organizational and management change to consider climate change impacts in all phases of road planning and design, thus re-defining climate change from an 'abnormal' strain to a 'normal' strain. This serves the dual purpose of reducing the risk associated with projected changes and acknowledging the holistic impacts of infrastructure on society.

Most studies cite that a broader, more holistic perspective of road planning, design and management would benefit the functionality of the system as a whole and result in less vulnerability (Berdica 2002). Identifying vulnerabilities at the earliest possible level is a key focus, "since most proactive measures are…preferable to reactive ones from an economic point of view." The modeling of 'degradable transportation systems (DTS)' presented by Nicholson and Du (1997) likewise posit the benefit of proactive intervention to reduce degradation from a wide variety of events including weather.

2.3.2 - IPSS

Building upon the definitions and imperative for integrations of forward-looking, holistic approaches to infrastructure management, the IPSS system is designed to address many of these questions by presenting a range of future climate models and presenting results in terms of fiscal cost on an annual and life-cycle basis and a risk assessment based on model projections (IPSS 2014).

Evaluating the impacts of climate change on infrastructure, including roads, is an area of much recent study, including large studies by the World Bank (Foster 2008), the Federal Highway Administration (2014), the Rockefeller Foundation (Tyler and Moench 2012; 100 Resilient Cities 2014) and the European Union (Nemry and Demirel 2012). One consistent finding in the literature is that climate change poses a threat to existing and future infrastructure, including high costs for adaptation, maintenance, and potential negative impacts on transit [Hambly et al 2013; Keener et al 2013; Sattherwaite 2007]. While the basis for considering climate change impacts on road infrastructure is well established, the quantification of these results in monetary terms or on a time-scale receives less attention [Burkett 2002; duVair et al 2002; Oswald and McNeil 2012], and no studies quantitatively review adaptation policy options.

The IPSS software is built on specific engineering data to evaluate the impact changes in climate will have on existing and future road infrastructure performance. Evaluation of cost is based on two distinct strategies, or policy approaches: reactive and proactive. The proactive strategy, *adapt*, is based on incorporating measures to make the road infrastructure resilient to climate impacts by changing specific elements during the design and construction. The adapt strategy performs upgrades on the design standards of the roads to increase resilience to stressor impacts. The reactive strategy, *no adapt* approach, does not consider the future climate change impacts. Instead, any impact of climate change will be addressed by increasing the maintenance, often leading to a higher frequency of maintenance and repair works. The increase in frequency of maintenance works can be a cause of vulnerability in the transport network, as defined by Berdica (2002). Frequent maintenance also causes wider issues which address stakeholder (dis)satisfaction, including impacts such as increased noise and environmental pollution and increased traffic interruptions (Moselhi 2005).

In both strategies, the cost presented it based on the actions needed to maintain the original designed life span of the roads. IPSS looks ahead and identifies the predicted impact of climate change during the life span of the road, analyzing based on ‘perfect foresight’ for each climate scenario analyzed. The climate analysis performed in IPSS has three main steps.

First, the climate change in the region of study is determined. IPSS has a flexible input for different climate models; this study uses 54 different AR4 GCMs (general circulation models) to obtain the predicted future values of several climate stressors including precipitation and temperature. These values are compared to the historical climate data to obtain the increment of change of these stressors due to climate change. Analysis is completed at the CRU (climate research unit) resolution, a worldwide grid of 0.5 degrees of latitude and longitude (which represents approximately 250 km^2) [UEA 2013; Schlosser et al 2012].

The second step predicts the impact of the climate change stressor on the road inventory. These equations reflect the response of the road materials to the climate impact stressors, and have been developed using a combination of previous research on materials science, case studies and historical data. IPSS works with three different types of road inventory: paved, gravel and dirt. Impacts are determined per kilometer of road. All the specific road type response equations, thresholds and methodologies are detailed in previous work [Schweikert et al 2014; Arndt et al 2013; Chinowsky and Arndt 2012; Chinowsky et al 2013; CHinowsky et al 2011]. They have also been used in international climate studies including a study for the European Union [Nemry and Demirel 2012] and Canada [Industrial Economics 2010].

Once the impact of climate change is calculated, IPSS will compute the cost of these impacts, as a result of maintenance increases and/or construction costs. The results will differ depending on the strategy selected: adapt (proactive) or no adapt (reactive). The cost of the no adapt strategy will be computed as the increase of maintenance and rehabilitation of the existing road inventory as result of the increase of degradation due to the impact of climate change in order to maintain the original lifespan. The cost of the adapt strategy will be computed as the additional cost to upgrade the road inventory to resist the future climate impact combined with the road inventory which has not yet been adapted (This is due to constraints of reality: it is unrealistic to assume that an entire road inventory can be adapted through technical upgrades in a short period of time.

Assumptions for this study include an annual adaptation rate of: 5% for paved roads, 2% for gravel and 1% for dirt roads).

2.4 - Social Vulnerability

Social vulnerability to climate change is based on socio-economic and health factors relating to vulnerability to weather events. The specific index used for this study was developed by the Pacific Institute for the State of California (Cooley et al 2012). The social vulnerability data is an aggregate ranking based upon 19 distinct factors of social vulnerability indicators. The analysis is based upon the Social Vulnerability Index (SoVI) introduced by Dr. Susan Cutter (Cutter et al 2003). While the SoVI is a fairly recent introduction into social vulnerability literature, it builds on a long history of literature from the fields of sociology and disaster research which highlight that individual factors can compound one another to create increased vulnerability of certain populations groups.

Similar to transport network literature, social literature has no agreed-upon definition for 'vulnerability'. Many papers make a distinction between social, economic, and physical factors (Liverman 1990; Bohle et al 1994; Dow and Downing 1995; Cutter 2009; Fussel 2007; United Nations 2004; Moss et al 2001) and several define the term using the product from differentiated values for 'risk' and 'exposure' (Tyler and Moench 2012; Cutter et al 2006). Many of the latter works define geographic location as a critical factor in risk and/or exposure (Cutter et al 2006; Fussel and Klein 2006; Fussel 2007). The term 'resilience' is important as well: "resilience is the ability of a social system to respond and recover" (Cutter 2009).

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

All social vulnerability studies, including disaster literature, focus on identifying vulnerabilities. None reviewed to date provide tangible investment strategies to address the existing and future issues identified. While mapping the vulnerabilities is an important step in understanding the issues, it does not provide targeted action.

2.5 - Integrating social and physical network vulnerability

The overwhelming focus of nearly all transport network literature, including those focused on climate change, is on technical adaptation and mitigation measures and the economic costs projected by vulnerability assessments. Despite the clear fact that transport networks exist only because of the populations which use them, traffic planning and network literature gives little to no recognition of the interactions and impacts between the two systems. However, in disaster and social impact literature, there is a strong recognition of the importance of the built environment and need for quantitative assessments and interventions to address the identified social vulnerabilities. Chakraborty et al (2005) notes in a study of extreme event evacuation in Florida that [vulnerable] populations can "be more or less vulnerable depending on their proximity to transportation routes or facilities". Cutter et al (2003) uses a statistical analysis to determine the top factors contributing to social vulnerability: two of the top 11 factors are related to quality, quantity, and impact of infrastructure on the surrounding communities. Several pieces of literature recognize the importance of the physical environment's ability to withstand disaster as a key component in identifying vulnerability of the population (Liverman 1990; Downing 1991; Timmerman 1981; Cutter 1996; Bohle et al 1994; Fussel 2007; Tierney 2012).

This paper represents a step in integrating the quantitative assessment data of the built environment (road infrastructure) and social vulnerability of the analyzed communities, meeting one need described by Cutter et al (2003) which should be of top concern to investment decision makers, particularly in the public realm:

> "The relationship between the level of social vulnerability and biophysical risk is the obvious next step…in adding a physical component, vulnerability can be examined not just as a social or a biophysical phenomenon, but as a complex interaction of the two. This integrative step will help advance our understanding of vulnerability science at the local, regional and national scales. The SoVI can assist local decision makers in pinpointing those factors which threaten the sustainability and stability of the [geographic area]. Using this index in conjunction with biophysical risk data means that mitigation efforts can be targeted at the most vulnerable groups or counties. The development and integration of social, built environment, and natural hazard indicators will improve our hazard assessments and justify the selective targeting of communities for mitigation based on good social science, not just political whim."

3.0 - METHODOLOGY

3.1 – Integrated Assessment Modeling

This research effort is built upon the individual foundations of the IPSS road analysis and the SoVI adaptation to climate change methods. Both are described in Section 2 and provide two strong quantitative data sets for analysis of vulnerability to climate change in a given geographic location.

The social vulnerability data is taken from an open-source data set provided by the Pacific Institute ("Map: Social Vulnerability Index Data", 2014). It is built on the SoVI model developed by Cutter (1996) which defines 32 distinct variables that contribute to social vulnerability to environmental hazards at a county level throughout the United States. An updated (2000) map of the data highlights California (particularly Southern California) as highly vulnerable to environmental hazards ("Social Vulnerability Index for the United States (42 Variable Technique)" 2013). Building upon this technique, the Pacific Institute used 19 of the variables determined to be directly related to climate change. These variables are independently assessed for vulnerability at the Census Tract level. California has 7,049 Census tract levels, each representing approximately 4,000-5,000 persons (US Census 2014). Each variable is then combined to create a relative "vulnerability score" based upon terciles; the least vulnerable third of Census areas are deemed "low", the highest vulnerability tercile is deemed "high", while those in the middle tercile are deemed "medium". The vulnerability assessment is treated as static based upon the most recently available data (in most cases, the 2010 Census). While this is a definite limitation of the study, it is impossible to project trends accurately for the future decades, and a static snapshot used for assessment purposes is consistent with methodologies for assessing integrated stakeholder analysis for large infrastructure projects (Feng et al 2013). It provides a baseline assessment of vulnerability for this model.

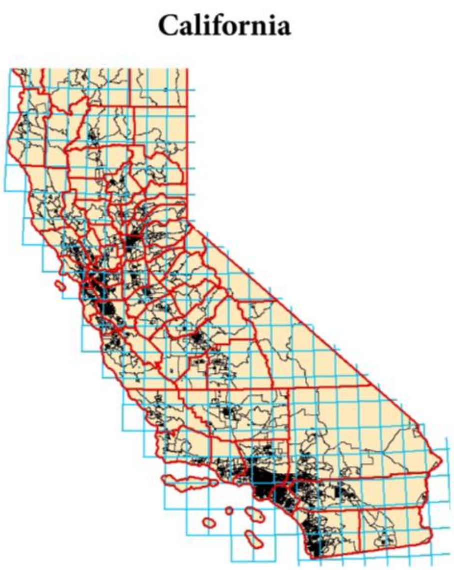
The data from IPSS provides two specific metrics: an "Adapt" cost and a "No Adapt" cost (Chinowsky et al 2013). The *adapt* cost represents a proactive approach to building roads that can withstand projected climate change impacts throughout their lifetime by adjusting design standards at the time of reconstruction. *No adapt* represents the cost to road infrastructure if damages from climate change impacts are repaired after they occur. For the illustration presented in Section 4, only costs from long-term climate impacts are presented (changes in precipitation and temperature). For this project, no extreme events are incorporated into the costs, although improving the baseline level of infrastructure by adaptation will provide current benefits to withstand extreme weather events (FHWA 2014). The data presented is for the median (50^{th} percentile, based upon adaptation cost) GCM data. For this illustrative example, the concept utilized by the Pacific Institute of tercile definitions of vulnerability was utilized, based upon the Adapt total costs in the 2050 decade. Thus, in comparing the Adapt and No Adapt maps, the same definition of cost impacts is utilized: 'Low' indicates a cost equivalent less than $19.6 million dollars (2014 equivalent USD, no discounting) annually; 'Medium' indicates a cost equivalent between $19.6 and $32.1 million annually; and 'High' indicates an annual cost of greater than $32.1 million.

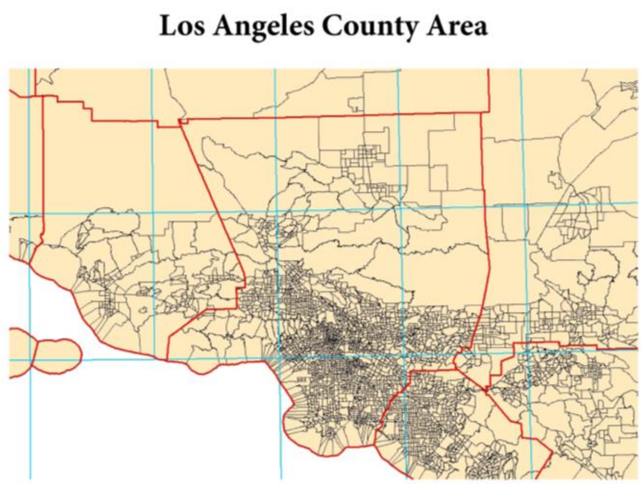
Combining these two methods to produce a multi-faceted definition of vulnerability most closely resembles an *integrated assessment model (IAM)* which is a commonly used analysis method in the social sciences and environmental policy (Revi and Sattherwaite 2013; Fussel and Klein 2006). It is defined as a model which "reaches beyond the bounds of a single discipline and considers more than one sector or one aspect of the problem" (Rothman and Robinson 1997). Additionally, the aim of the research is to provide guidance to policy makers about how to prioritize their climate adaptation investments for maximum financial and social benefit, not simply advance the state of academic engineering analysis knowledge (Rothman and Robinson 1997).

3.2 – Geographic Information Systems (GIS) Mapping

To combine the data sets of social vulnerability and costs of infrastructure adaptation (and no adaptation), GIS queries were used to build definitions of terms based on attribute data including the vulnerability rankings for each separate type of infrastructure. Social vulnerability data is provided at a census tract level while the physical infrastructure vulnerability data is provided at the CRU level. GIS was used to join these data sets. Where multiple CRUs overlaid with one census tract, an average cost was taken based upon the total area of the census tract in each CRU. Graphic 1 and 2 show this mapping level overlay for county, CRU, and census tract levels for the State of California and the Los Angeles County Area. County boundaries are provided in red to illustrate the diverse set of data within the purview of one decision making body and the need for prioritization of investments.

Graphic 1 and 2: GIS overlay of spatial data analysis units for the State of California and the Los Angeles County Area. Data shown includes CRU in blue (climate change impact analysis unit, for precipitation and temperature), County boundaries (administrative decision-making level unit) in red, and Census Tract level (social vulnerability analysis unit) in black. The Census tracts reflect the density of populations throughout the state, visualized at a smaller scale in Los Angeles County.





The data was overlaid to determine a 3 by 3 matrix of vulnerability. The lowest ranking is *low infrastructure vulnerability*, *low social vulnerability*, while the highest ranking is *high infrastructure vulnerability*, *high social vulnerability* (Table 1).

Table 1: Investment Priorities based on Quantitative Assessment Modeling

	Low Social Vulnerability	Medium Social Vulnerability	High Social Vulnerability
Low Infrastructure Vulnerability	9	8	7
Medium Infrastructure	6	4	2

Vulnerability			
High Infrastructure Vulnerability	5	3	1

Geographic areas where the risk of cost from climate change to infrastructure is 'low' are given the least priority. Even where social vulnerability is high, the data from road vulnerability indicates that an investment in this area may be better served in other sectors related to social vulnerability. The second highest priority for investment is "Medium Infrastructure, High Social Vulnerability". Areas with high social vulnerability (Ranking #2) are given higher priority in this analysis than an area with "High Infrastructure, Medium Social Vulnerability" (Ranking #3) because the impact of a "medium" road infrastructure vulnerability reduction may contribute highly to reducing the social vulnerability of an area. This is also true for Ranking #5, where "High Infrastructure" vulnerability is not prioritized above Ranking #4 because it occurs in an area with low social vulnerability, indicating that this area may be more socially resilient to climate impacts. This scale could be adjusted according to local priorities and desired economic returns on infrastructure adaptation investment.

4.0 - RESULTS

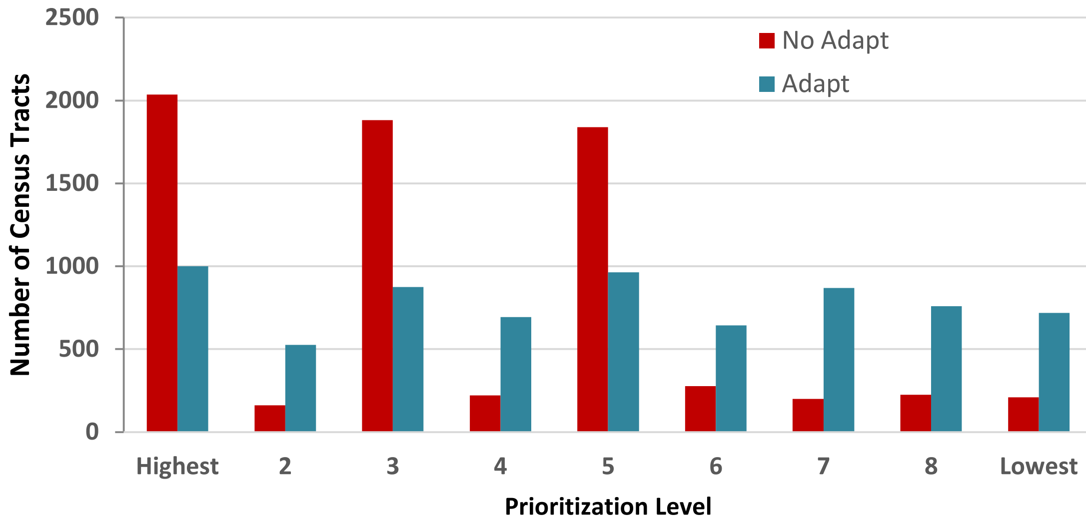
The results for this study are based on an integrated data model using county level road infrastructure costs (an indicator for physical vulnerability to climate change) and social vulnerability scoring based upon 19 factors (an indicator for social vulnerability to climate change). The results are presented for the State of California followed by a discussion on the Los Angeles County (LAC) area. LAC is a highly populated urban area that sees impacts from climate change and with approximately 40% of the population ranked 'high' in social vulnerability to climate change (Cooley et al 2012; "Social Vulnerability Index for the United States (42 Variable Technique)" 2013).

4.1 - State of California

The state of California sees varying impacts in terms of climate change vulnerability based on geography and adaptation strategy. For the *adapt* approach, the vulnerability state-wide is much lower, with approximately 4,000 census tracts with vulnerability ratings of 5 or lower. For the *no adapt* approach, only approximately 2,700 census tracts have a vulnerability rating of 5 or lower. For the highest vulnerability rankings (#1-3), the *adapt* approach has 2,402 census tracts in this category while the *no adapt* approach has over 4,000. This is shown in graph 1 and Figures 1 and 2.

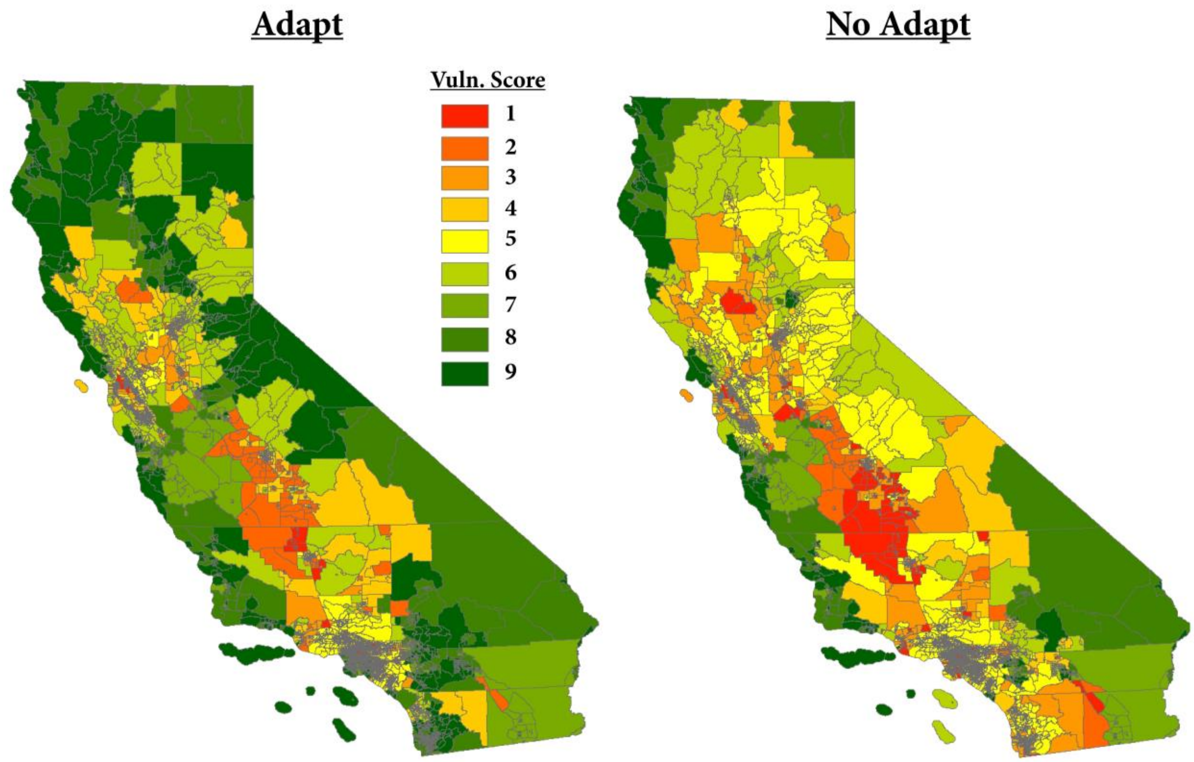
Approximately 17% of all geographic analysis areas for infrastructure vulnerability showed that adaptation to climate change is more expensive than no adaptation. However, in all cases, the difference was not enough to earn a different ranking in terms of "low", "medium", or "high". There are no census tracts where the difference in increased adaptation cost increases the level of vulnerability.

Graph 1: "***Investment Prioritization: Census Track Vulnerability to Climate Change, Adapt vs. No Adapt Comparison".*** This shows the number of census tracts with each priority rating for the *adapt* and *no adapt* strategies for investing in climate change resilient road infrastructure. Numbers are based on a static 2012 social vulnerability to climate change rating paired with a physical infrastructure vulnerability metric based on the 2050 cumulative cost of climate change. See Table 1 for ranking definitions.



There are 1,698 high or medium socially vulnerable census tracts (about 25%) that see a benefit from adaptation significant enough to move down into lower physical vulnerability categories. These areas should be prioritized for investment because an adaptation to climate change for the road infrastructure reduces physical vulnerability in areas with high social vulnerability.

Graphics 1 and 2: Census-tract level maps of the state of California. Vulnerability to climate change is mapped based upon a static 2012 social vulnerability to climate change rating paired with a physical infrastructure vulnerability metric based on the 2050 cumulative cost of climate change. See Table 1 for ranking definitions.



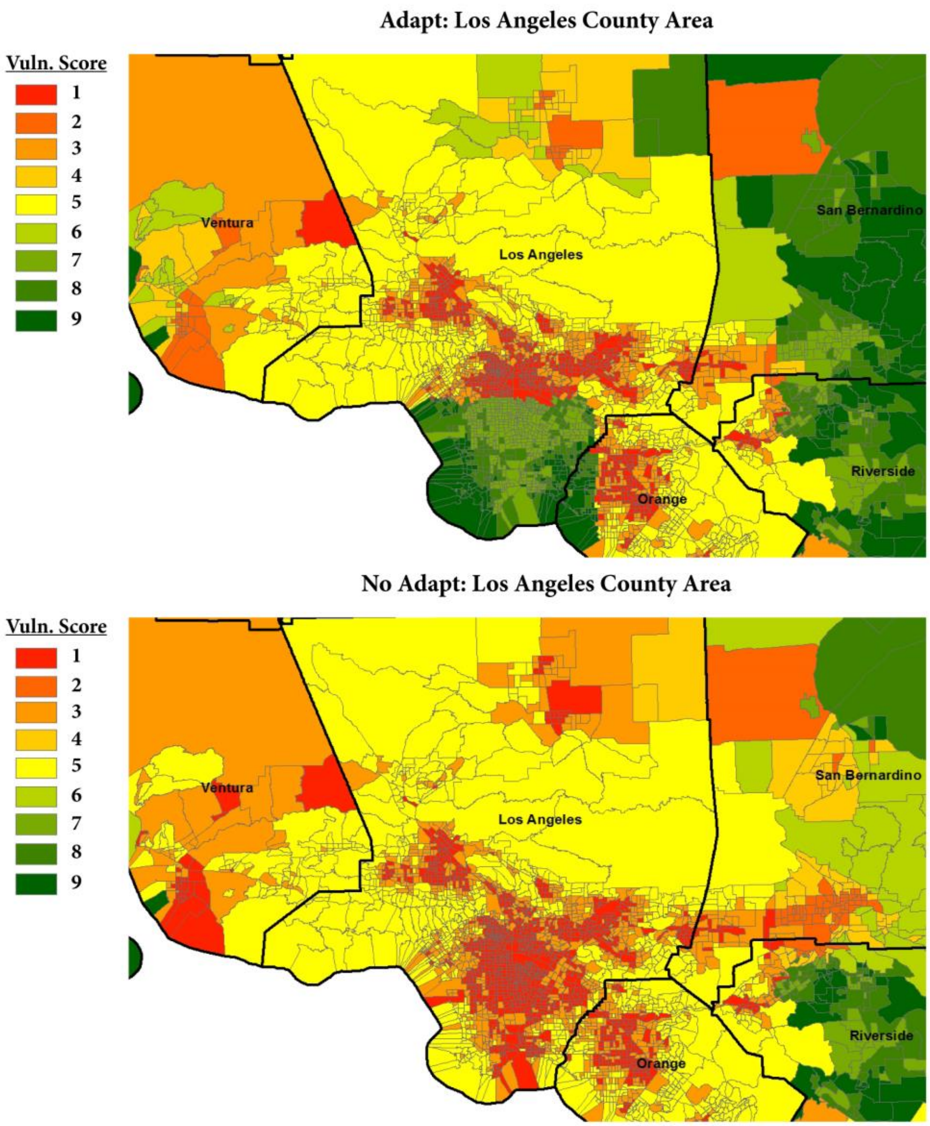
Graphics 1 and 2 show maps created using ArcGIS to visualize the adapt strategy compared with the no adapt strategy. The mapping data generally shows that the distribution of high vulnerability areas (rankings 1, 2, 3) are associated with highly populated urban areas. This is consistent with the expected results because urban areas have a large amount of road infrastructure relative to rural areas and generally have some populations that are more vulnerable to climate change. There are some rural areas, especially along the southern and eastern areas of the state, where the vulnerability to climate change is drastically reduced by an adaptation strategy. These rural areas show a large net benefit from adaptation.

4.2 - Los Angeles County Area

The Los Angeles County Area (LAC) was chosen for analysis based upon two factors: the relatively high risk of southern California to climate change impacts (HVRI 2000) and the high proportion of residents with a high vulnerability to climate change (Cooley et al 2012). As seen in Graphic 2, LAC data is comprised of 9 full or partial physical infrastructure analyses (CRU level) and several hundred census tract level analyses. Graphic 5 and 6 show the benefit from an adapt strategy for the census tract levels. The overall level of vulnerability in the area is very high (rankings 1-5). The main benefit from adaptation is seen in the south western parts of LAC and the northwestern parts of Orange County. San Bernardino County and Ventura County see benefits from adaptation as well.

A critical aspect of investment strategy is spending the available budget efficiently. While the central areas of LAC see high vulnerability to climate change in terms of social vulnerability and physical vulnerability in both the adapt and no adapt approaches, an investment in these areas proactively combats the damages from climate change. This contributes to social resilience as well as daily life and economic transactions. LAC is well known for traffic jams as a main means of individual and commercial commuting; ensuring these roads are well-maintained with limited ongoing interruptions from maintenance increases could show positive net returns on adapting to climate change.

Graphic 5 and 6: Vulnerability to climate change for the LAC area for the adapt and no adapt strategies for physical infrastructure vulnerability



5.0 – DISCUSSION AND CONCLUSION

This paper presents a first step in quantitatively identifying specific adaptation options that can be implemented from an organizational planning perspective to reduce vulnerability to climate change. By combining robust, quantitative modelling data of social and physical vulnerability to climate change, the prioritization metric allows for a targeted investment strategy that reduces the vulnerability of infrastructure to climate change with a particular focus on areas with high social vulnerability. Particularly in areas where there is a high level of vulnerability to climate change and limited financial resources to address this challenge, prioritization of investments based on data-driven analysis can be an asset to project managers by allowing financial resources to be used most efficiently. This is a first-step in addressing the calls for more holistic and integrated assessment social and economic development (social vulnerability) and the recognition of a need for infrastructure planners to increase resilience to climate change.

This research has several limitations. A critical component of modelling climate change vulnerability is the climate models utilized. As data and forecasting becomes more accurate, the modelling should account for this updated accuracy. Another limitation is in the static snapshot of existing road infrastructure and current social vulnerability. The study could be expanded to include projected road projects. However, it is difficult to project with accuracy the changes in social and economic welfare that may occur over the coming decades; further, it is impossible to project what changes may occur if adaptation investments are made in road infrastructure. More research to understand the relationship between road infrastructure and socio-economic development could provide more information about these potential trends and enhance the cost-benefit (qualitative and quantitative aspects) analysis of this prioritization process.

Further research is needed to understand the most effective manner of presenting data to decision-makers as well as the social, economic, and political values and stakeholders that are most relevant to the road infrastructure planning process. Ascertaining a better understanding of this would allow for a more accurate and useful ranking process (see Table 1).

The ability to make targeted investment decisions which enhance the community capacity to withstand, respond and recover to climate change yet which pose a very low 'regret' factor if the predicted changes do not occur is a necessity for city, state, and national level planners. This can be characterized as building 'resilience' – investments which enhance the well-being of populations and are more flexible, redundant, and able to absorb shock and slow-onset stress from climate change. There are many frameworks that provide guidance in terms of the sectors to examine and questions to ask, but there remains a paucity of resources that can guide specific, data-driven, targeted investments that will enhance the resiliency of communities, particularly of the most vulnerable. This paper presents a foray into combining these impacts in a quantitative method which allows for a practical, policy-driven climate-wise investment strategy which emphasizes minimizing the impacts on those whom are least able to respond. From the perspective of decision-makers, this prioritized adaptation strategy helps direct investments in a manner which accounts for current and future vulnerability, long-term sustainability, and cost-effective life-cycle management.

REFERENCES

"100 Resilient Cities" Rockefeller Foundation. 2014. http://100resilientcities.rockefellerfoundation.org/

Arndt, C., Chinowsky, P., Strzepek, K., and Thurlow, J. (2013) 'Climate Change and Infrastructure Investment in Developing Countries: The Case of Mozambique', *Climatic Change*.

Berdica, Katja. 2002. "An Introduction to Road Vulnerability: What Has Been Done, Is Done and Should Be Done." *Transport Policy* 9 (2) (April): 117–127. doi:10.1016/S0967-070X(02)00011-2. http://www.sciencedirect.com/science/article/pii/S0967070X02000112.

Bohle, Hans G., Thomas E. Downing, and Michael J. Watts. 1994. "Climate Change and Social Vulnerability: Toward a Sociology and Geography of Food Insecurity." *Global Environmental Change* 4 (1) (March): 37–48. doi:10.1016/0959-3780(94)90020-5. http://www.sciencedirect.com/science/article/pii/0959378094900205.

Burkett, V.R. (2002) 'Potential Impacts of Climate Change and Variability of Transportation in Gulf Coast/Mississippi Delta Region', *The Potential Impacts of Climate Change on Transportation Research Workshop.* US Department of Transportation Center for Climate Change and Environmental Forecasting.

Chakraborty, J., G. Tobin, and B. Montz. 2005. "Population Evacuation: Assessing Spatial Variability in Geophysical Risk and Social Vulnerability to Natural Hazards." *Natural Hazards Review* 6 (1): 23–33. doi:10.1061/(ASCE)1527-6988(2005)6:1(23). http://ascelibrary.org/doi/abs/10.1061/%28ASCE%291527-6988%282005%296%3A1%2823%29.

Chi, Cheryl, Inkeri Ruuska, and Wang Guangbin. 2013. "Identifying Governance Challenges of Sustainable Infrastructure." *Engineering Project Organization Conference Working Paper Proceedings* (July 9–11).

Chinowsky, P. and Arndt, C. (2012) 'Climate Change and Roads: A Dynamic Stressor–Response Model', *Review of Development Economics*, 16(3), pp. 448-462

Chinowsky, Paul S., et al. (2012) 'Infrastructure and Climate Change: Impacts and Adaptations for South Africa', UNU-WIDER Research Paper WP2012/105.

Chinowsky, Paul S., et al. (2013) 'Infrastructure and climate change: Impacts and adaptations for the Zambezi River Valley', UNU-WIDER Research Paper WP2013/041.

Chinowsky, P., Schweikert, A., Manahan, K., Strzepek, K., and Schlosser, C.A. (2013) 'Climate change adaptation advantage for African road infrastructure', Climatic Change, 117.1-2, pp. 345-361.

Chinowsky, Paul S., Hayles, Carolyn, Schweikert, Amy and, Strzepek, Niko (2011). 'Climate Change As Organizational Challenge: Comparative Impact On Developing And Developed Countries,' Engineering Project Organization Journal, 1(1).

Chinowsky, Paul, Amy Schweikert, Niko Strzepek, Kyle Manahan, Kenneth Strzepek, and C. Adam Schlosser. "Climate change adaptation advantage for African road infrastructure." *Climatic change* 117, no. 1-2 (2013): 345-361.

"Climate Change: FHWA Role in Climate Change". Federal Highway Administration. 2014. http://www.fhwa.dot.gov/environment/climate_change/

Cooley, Heather; Moore, Eli; Heberger, Matthew; Allen, Lucy. 2012. "Social Vulnerability to Climate Change in California". Pacific Institute; California Energy Commission. http://www.pacinst.org/wp-content/uploads/2013/02/full_report31.pdf.

Cutter, Susan L. 1996. "Vulnerability to Environmental Hazards." *Progress in Human Geography* 20 (4): 529–539.

Cutter, Susan L., Bryan J. Boruff, and W. Lynn Shirley. 2003. "Social Vulnerability to Environmental Hazards*." *Social Science Quarterly* 84 (2): 242–261. doi:10.1111/1540-6237.8402002. http://onlinelibrary.wiley.com/doi/10.1111/1540-6237.8402002/abstract.

Cutter, Susan L., Lindsey Barnes, Melissa Berry, Christopher Burton, Elijah Evans, Eric Tate, and Jennifer Webb. 2008. "A Place-based Model for Understanding Community Resilience to Natural Disasters." *Global Environmental Change* 18 (4) (October): 598–606. doi:10.1016/j.gloenvcha.2008.07.013. http://www.sciencedirect.com/science/article/pii/S0959378008000666.

Cutter, Susan L., Bryan J. Boruff, and W. Lynn Shirley. 2003. "Social Vulnerability to Environmental Hazards*." *Social Science Quarterly* 84 (2): 242–261. doi:10.1111/1540-6237.8402002. http://onlinelibrary.wiley.com/doi/10.1111/1540-6237.8402002/abstract.

Dow, Kirstin, and Thomas E. Downing. *Vulnerability research: where things stand*. National Emergency Training Center, 1995

Downing, Thomas E. 1991. "Vulnerability to Hunger in Africa: A Climate Change Perspective." *Global Environmental Change* 1 (5) (December): 365–380. doi:10.1016/0959-3780(91)90003-C. http://www.sciencedirect.com/science/article/pii/095937809190003C.

duVair, P., Douglas W., and Burer, M.J. (2002) 'Climate Change and the Potential Implications for California's Transportation System', *The Potential Impacts of Climate Change on Transportation Research Workshop.* US Department of Transportation Center for Climate Change and Environmental Forecasting.

Erath, Alex, James Birdsall, Kay Axhausen, and Rade Hajdin. 2009. "Vulnerability Assessment Methodology for Swiss Road Network." *Transportation Research Record: Journal of the Transportation Research Board* 2137 (-1) (December 1): 118–126. doi:10.3141/2137-13. http://dx.doi.org/10.3141/2137-13.

Fellows, Richard. 2014. "Towards Satisfying the Client: Optimizing, Satisficing or Disappointing?" *Engineering Project Organization Journal* 0 (0): 1–18. doi:10.1080/21573727.2013.873718. http://dx.doi.org/10.1080/21573727.2013.873718.

Feng, Wen, Donald Lessard, Bruce Cameron, and Edward Crawley. 2013. "Stakeholders, Issues and the Shaping of Large Engineering Projects." *Working Paper Proceedings, Engineering Project Organization Conference* (July 9–11).

Flanagan, Barry E., Edward W. Gregory, Elaine J. Hallisey, Janet L. Heitgerd, and Brian Lewis. 2011. "A Social Vulnerability Index for Disaster Management." *Journal of Homeland Security and Emergency Management* 8 (1) (January 5). http://www.degruyter.com/view/j/jhsem.2011.8.issue-1/jhsem.2011.8.1.1792/jhsem.2011.8.1.1792.xml.

Foster, Vivian. "Africa Infrastructure Country Diagnostic: Overhauling the Engine of Growth Infrastructure in Africa". September 2008. http://go.worldbank.org/SWDECPM5S0

Füssel, Hans-Martin. 2007. "Vulnerability: A Generally Applicable Conceptual Framework for Climate Change Research." *Global Environmental Change* 17 (2) (May): 155–167. doi:10.1016/j.gloenvcha.2006.05.002. http://www.sciencedirect.com/science/article/pii/S0959378006000525.

Füssel, Hans-Martin, and Richard J. T. Klein. 2006. "Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking." *Climatic Change* 75 (3) (April 1): 301–329. doi:10.1007/s10584-006-0329-3. http://link.springer.com/article/10.1007/s10584-006-0329-3.

Hambly, D., Andrey, J., Mills, B., and Fletcher, C. (2013) 'Projected implications of climate change for road safety in Greater Vancouver, Canada', *Climatic Change*, 116(3-4), pp. 613-629.

Industrial Economics (2010). 'Costing Climate Impacts and Adaptation: A Canadian Study on Public Infrastructure', Report to the National Round Table on the Environment and the Economy, Canada.

Infrastructure Planning Support System (IPSS). Institute of Climate and Civil Systems. http://clicslab.org/ipss

Intergovernmental Panel on Climate Change (IPCC). 2014. http://www.ipcc.ch/

Jenelius, Erik, Tom Petersen, and Lars-Göran Mattsson. 2006. "Importance and Exposure in Road Network Vulnerability Analysis." *Transportation Research Part A: Policy and Practice* 40 (7) (August): 537–560. doi:10.1016/j.tra.2005.11.003. http://www.sciencedirect.com/science/article/pii/S096585640500162X.

Keener, V.W., Marra, J.J., Finucane, M.L., Spooner, D., and Smith, M.H. (2013) *Climate Change and Pacific Islands: Indicators and Impacts: Report for the 2012 Pacific Islands Regional Climate Assessment*. Island Press.

Kwiatkowski, Kyle P., Irina Stipanovic Oslakovic, H. W. ter Maat, Andreas Hartmann, Paul Chinowsky, and G. P. M. R. Dewulf. "CLIMATE CHANGE ADAPTATION AND ROADS: DUTCH CASE STUDY OF COST IMPACTS AT THE ORGANIZATION LEVEL."

Levitt, R. E., Henisz, W., Scott, W. R., & Settel, D. 2010. Governance Challenges of Infrastructure Delivery: The Case for Socio-Economic Governance Approaches. In J. Ruwanpura, Y. Mohamed, & S. Lee (Eds.), Construction Research Congress 2010, Vol. 2: 757-767. Banff Canada: American Society of Civil Engineers.

Liverman, Diana M. "Vulnerability to global environmental change. "Understanding global environmental change: The contributions of risk analysis and management (1990): 27-44.

"Living with Risk: A Global Review of Disaster Reduction Initiatives" United Nations Office for Disaster Risk Reduction. 2004. ISBN: 9211010640.

Lucas, Karen. 2011. "Making the Connections between Transport Disadvantage and the Social Exclusion of Low Income Populations in the Tshwane Region of South Africa." *Journal of Transport Geography* 19 (6): 1320–34. doi:10.1016/j.jtrangeo.2011.02.007.

"Map: Social Vunlerability Index: GIS Data Downloads" Pacific Institute. 2014 http://pacinst.org/mapping-social-vulnerability-to-climate-change-in-california/map-social-vulnerability-index/gis-data-downloads/

Moselhi, O., A. Hammad, S. Alkass, C. Assi, M. Debbabi, and M. Haider. 2005. "Vulnerability Assessment of Civil Infrastructure Systems: A Network Approach." *1st CSCE Specialty Conference on Infrastructure Technologies, Management and Policy* (June 2–4). http://users.encs.concordia.ca/~hammad/papers/C37.pdf.

Moss, Richard H., Jae A. Edmonds, Kathy A. Hibbard, Martin R. Manning, Steven K. Rose, Detlef P. van Vuuren, Timothy R. Carter, et al. 2010. "The next Generation of Scenarios for Climate Change Research and Assessment." *Nature* 463 (7282): 747–56. doi:10.1038/nature08823.

Nemry, F. and Demirel, H. (2012) 'Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures', European Commission, Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS).

Nicholson, Alan, and Zhen-Ping Du. 1997. "Degradable Transportation Systems: An Integrated Equilibrium Model." *Transportation Research Part B: Methodological* 31 (3) (June): 209–223. doi:10.1016/S0191-2615(96)00022-7. http://www.sciencedirect.com/science/article/pii/S0191261596000227.

Oswald, M.R., and McNeil, S. (2012) 'Climate Change Adaptation Tool for Transportation: Mid-Atlantic Region Case Study', *Journal of Transportation Engineering*, 139(4), pp. 407-415.

Revi, Aromar, and David Sattherwaite. 2013. "IPCC WGII AR5 Chapter 8". Intergovernmental Panel on Climate Change Working Group II AR5. http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap8_FGDall.pdf.

Robinson, Richard. 2006. "A Perspective on Road Sector Restructuring in Developing and Transitional Countries." *Public Administration and Development* 26 (3): 265–78. doi:10.1002/pad.408.

Rothman, Dale S., and John B. Robinson. 1997. "Growing Pains: a Conceptual Framework for Considering Integrated Assessments." *Environmental Monitoring and Assessment* 46 (1-2) (June 1): 23–43. doi:10.1023/A:1005779717065. http://link.springer.com/article/10.1023/A%3A1005779717065.

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

Schlosser, A., Gao, X., Strzepek, K., Sokolov, A., Forest, C., Awadalla, S., and Farmer, W. (2011) 'Quantifying the Likelihood of Regional Climate Change: A Hybridized Approach', Report 205, MIT Joint Program on the Science and Policy of Global Change, October 2011.

Schweikert, A., Kwiatkowski, K., Chinowsky, P., and Espinet, X. (In Review) "The Infrastructure Planning Support System: Analyzing the Impact of Climate Change on Road Infrastructure and Development." *Transport Policy*, In Review.

"Social Vulnerability Index for the United States (42 Variable Technique)" Hazards and Vulnerability Research Institute. Departmnet of Geography. University of South Carolina. Updated 30 October 2013. http://webra.cas.sc.edu/hvri/products/sovi_42/sovi.aspx

Taylor, Michael A. P., and Glen M. D'Este. 2007. "Transport Network Vulnerability: a Method for Diagnosis of Critical Locations in Transport Infrastructure Systems." In *Critical Infrastructure*, edited by Professor Alan T. Murray and Professor Tony H. Grubesic, 9–30. Advances in Spatial Science. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/978-3-540-68056-7_2.

Tierney, Kathleen. 2012. "Disaster Governance: Social, Political, and Economic Dimensions." *Annual Review of Environment and Resources* 37 (1): 341–363. doi:10.1146/annurev-environ-020911-095618. http://www.annualreviews.org/doi/abs/10.1146/annurev-environ-020911-095618.

Timmerman, Peter. "Vulnerability, Resilience and the Collapse of Society." A Review of Models and Possible Climatic Applications. Toronto, Canada: Institute for Environmental Studies, University of Toronto (1981).

Tyler, Stephen, and Marcus Moench. 2012. "A Framework for Urban Climate Resilience." *Climate and Development* 4 (4): 311–326. doi:10.1080/17565529.2012.745389. http://www.tandfonline.com/doi/abs/10.1080/17565529.2012.745389.

UEA, 2013. "Data." Climate Research Unit. University of East Anglia (UEA). <http://www.cru.uea.ac.uk/data> Accessed January 31, 2014.

United States Census. 2014. http://www.census.gov/#