CLIMATE ADAPTATION

Literature Review: Climate Change Vulnerability Assessment, Risk Assessment, and Adaptation Approaches

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Table of Contents

Executive Summary

Incorporation of climate change impacts into transportation decisions is still a relatively new concept. As decision makers in various sectors grapple with information on climate change effects and how they may or may not impact their core mission(s), they are turning to existing tools and approaches for guidance. To date, three closely-related approaches are being used to help transportation decision makers consider and prepare for future climate impacts: vulnerability assessment, risk assessment, and adaptation assessment.

- Vulnerability assessment begins with the identification of existing stressors facing transportation systems and projects how climate change will impact and/or introduce new stressors in the future. The findings of the assessment can then be ranked to assess, prioritize, and address vulnerabilities.

- Risk assessment evaluates the likelihood and consequence of climate-related impacts on transportation and can be rooted in engineering applications. Many times this assessment will quantify the product of the probabilities of exposure and vulnerability. This assessment provides transportation policymakers with guidance based on quantitative analysis of the level of risk associated with changing climate conditions.
- Adaptation assessment identifies, plans, prioritizes, implements, and measures transportation management options available for effectively adapting to climate change impacts. This assessment may discuss ways to reduce transportation vulnerability, increase resilience and/or highlight regions of retreat.

These approaches have been applied at varying levels of sophistication in assessing climate change impacts on human and natural systems. This document details how these approaches have been or could be used to integrate climate change impacts into transportation decisions and ultimately increase the adaptive capacity of the highway system.

1. Overview

The Federal Highway Administration (FHWA) recognizes the importance of understanding and responding to information on impacts of climate change on the U.S. transportation system. FHWA further recognizes that this is a rapidly evolving area of research and that useful information may come from a wide variety of sources both inside and outside the United States . For that reason, FHWA has commissioned a review of U.S. and international approaches to address global climate change adaptation. FHWA recognizes that efforts to address adaptation are in their infancy and in some cases, adaptation efforts may be limited to a qualitative assessment of vulnerability. Thus, this literature review focuses on three major categories of activities: vulnerability assessments, risk assessments, and adaptation approaches. Ultimately, some combination of these actions will inform a new risk assessment framework for FHWA.

This remainder of this report presents the findings of a streamlined literature review for Task 2.1 (see Appendix A for a detailed discussion of the literature review methodology). Ultimately, this Task and the subsequent Tasks (2.2 and 2.3) are intended to inform the development of a risk assessment framework (Task 2.4). The framework will draw on several tools to assist policy makers in assessing and responding to projected climate change impacts. Transportation officials will likely begin by identifying the climate effects, assessing the climate impacts on transportation infrastructure, and evaluating/prioritizing adaptation options. In order to maximize the usefulness of the information presented in this report, examples from the literature are presented in three categories: (1) vulnerability assessment, (2) risk assessment, and (3) adaptation approaches. Each of these sections provides a general overview of the assessment or approach, the methodology that policymakers may utilize for applying the assessment or approach, and selected examples. In the absence of a framework, one or all of the methodologies discussed here may be utilized to address climate change impacts on transportation systems; the methodologies' relative usefulness in specific situations is highly dependent on several factors including the infrastructure in question, the design life, and available resources, among other considerations.

2. Vulnerability Assessment

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes" (IPCC, 2007). The vulnerability of a given system to climate change can vary with the unique characteristics of that system including its exposure, sensitivity, and adaptive capacity (Snover et al., 2007). Climate change can impact a study group (or system) by introducing new stressors into the system, and may also exacerbate existing stressors.

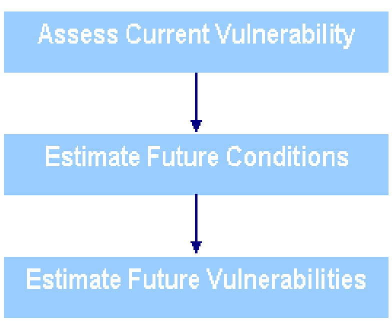
Depending on how "the system" is defined for the purpose of conducting a vulnerability assessment, factors external to the system itself may influence its vulnerability; these factors may include development patterns, the surrounding physical environment, the distribution of resources, and existing stressors (IPCC, 2007). Vulnerability analysis has evolved over time drawing on issues associated with entitlement, diversity, and resilience (Turner et al., 2003). The first relates to human needs that render a system more or less vulnerable. The second, diversity, addresses the need for redundant functions and the third has roots in ecology, alluding to a system's ability to maintain equilibrium (even if that equilibrium is dynamic) despite exposure to disturbance or stress. There is a rapidly growing body of literature addressing terms such as vulnerability, resilience, and adaptive capacity, particularly for natural systems. The remainder of this section focuses on how "vulnerability assessments" may be useful for FHWA in addressing climate change impacts on the U.S. highway system.

In this context, vulnerability to climate change and climate variability acts as a function of the structural strength and integrity of the infrastructure, as well as the potential for damage and disruption in transportation services (CCSP, 2008). While factors for determining the vulnerability of transportation infrastructure may vary across transportation agencies, common factors may include: the age of the infrastructure element; condition/integrity of the infrastructure element; proximity to other infrastructure elements/concentrations; and the level of service (CCSP, 2008). Currently, there is no comprehensive inventory of U.S. transportation infrastructure considered vulnerable to climate change, the degree of infrastructure vulnerability, or the estimated costs of associated damages (NRC, 2008). However, there are several local and regional studies available in the U.S. that utilize a bottom-up approach to evaluate infrastructure vulnerability that attempt to capture this information (Larsen et al., 2007; Kirshen et al., 2006). In addition, various international vulnerability assessments have been conducted at local and regional levels (Andrey and Knapper, 2003; Allen Consulting Group, 2005; Ibarrarán et al., 2008).

2.1 General Methodologies of a Vulnerability Assessment

The literature provides some guidance on the methodology of vulnerability assessments. Two reports provide the foundation for this described methodology (Mehdi et al., 2006 and Snover et al., 2007). In general, a vulnerability assessment can be broken into 3 key elements as illustrated in Box 1 . The available budget, time allocated for the study, the number of planning areas encompassed within the study, and the objective of the assessment will dictate the level of effort and detail appropriate as evidenced by the vulnerability assessment examples in section 2.2 (Snover et al., 2007). Once a vulnerability assessment has been assembled, continual monitoring and review is necessary to ensure the findings throughout each element of the process are up-to-date and relevant including integrating new information into the decision-making and planning process as it becomes available (Mehdi et al., 2006; Snover et al., 2007).

Box 1. Key steps of a vulnerability assessment



(Adapted from C-CIARN, 2006; Snover et al., 2007)

Element One: Assess Current Vulnerability. This element identifies the system's vulnerabilities to existing stressors, including relevant climate conditions that currently affect the system stressors. This assessment provides a roadmap for which climate variables (temperature, precipitation, etc.) are most likely to be of interest. The current vulnerabilities are apt to be affected by a complex number of factors including environmental (extreme weather), social (policy changes) and economic (market changes) factors (Mehdi et al., 2006). This step may draw heavily from historical data, experience, and past climate events to provide further insight into the potential responses and vulnerabilities of the system (Mehdi et al., 2006).

Element Two: Estimate Future Conditions. The future climate change effects within the assessment area are projected to a particular time period to determine the potential changes in relevant climate variables and climate variability (Mehdi et al., 2006). Questions for this step may include (Snover et al., 2007):

1. What is the projected change in the climate conditions identified (and by what time period)?
2. What is the projected climate change impact to the system (absent adaptation action)?
3. What are the projected changes in existing system stressors as a result of the projected climate change impacts?
4. Are they likely to get worse, stay the same, or improve as a result of climate change impacts? Or, do new system stressors emerge altogether?

Further, it is important to recognize that these climate effects may have strong seasonal and regional signatures (e.g., excessive summertime drought conditions in the Southwest); it is critical to capture these signals to adequately assess vulnerability (Mehdi et al., 2006).

Element Three: Estimate Future Vulnerabilities. How vulnerable a system is to climate change can be determined by (1) estimating how sensitive the system is to climate change and (2) how resilient the system is to change (Turner et al., 2003). A system is considered sensitive to climate change if the system is likely to be affected by the projected climate scenarios (Snover et al., 2007). This step will draw from the findings of element two which describes how the projected climate effects affect the current and newly introduced system stressors and uses this information to identify system vulnerabilities. This step may further rank the associated impacts through a quantitative or qualitative process, using rankings such as high, medium, or low, enabling decision makers to prioritize the future impacts (Snover et al., 2007). In addition, estimates of vulnerability will include the system's adaptive capacity (i.e., how well can the system sustain the climate effects with minimum disruption or cost) (Snover et al., 2007). Key considerations for evaluating adaptive capacity include (Snover et al., 2007):

1. Is the system already able to accommodate changes in climate?
2. Are there barriers to a system's ability to accommodate changes in climate?
3. Is the system already stressed in ways that will limit the ability to accommodate changes in climate?
4. Is the rate of projected climate change likely to be faster than the adaptability of the system?
5. Are there efforts already underway to address impacts of climate change related to the system?

Table 1 is an example of a vulnerability assessment conducted for various planning activities (Snover et al., 2007). The vulnerability scenarios may be broken into sectors such as the potential effects on environmental, social and economic systems. Here the vulnerability of pavement to extreme heat events is analyzed qualitatively: the pavement is considered to be extremely sensitive to the heat event, yet the decision makers have opportunities to cope with the consequences leading to a moderate level of vulnerability. Policymakers can use this type of ranking system to assess and prioritize the vulnerability of planning areas or impacted systems.

Once future vulnerabilities are assessed, adaptive approaches can be developed in response to the increased vulnerabilities or new opportunities, and no-regrets adaptation strategies can be identified (Mehdi et al., 2006). Depending on the level of the assessment, the identification of adaptation options may occur as part of a more quantitative risk management approach and/or in the context of a dedicated adaptation planning effort; both of these approaches are described in the following sections. In fact, the Canadian Climate Impacts and Adaptation Research Network (C-CIARN) expanded upon this three element approach described above by prefacing these three elements with stakeholder involvement and adding a final step of identifying adaptation strategies when outlining the elements of a vulnerability assessment (Mehdi et al., 2006). This demonstrates the grey lines that exist between these different assessments and approaches.

Table 1 . Sample vulnerability assessment

Planning Area	**Current and Expected Stresses**	**Projected Climate Change Impacts**	**Vulnerability Assessment**		
			Sensitivity	**Adaptive Capacity**	**Vulnerability**
Water supply	Summer drought	Increases in summer droughts due to warmer, drier summers	High - water supply is very sensitive to changes in snowpack	Low - numerous regulatory constraints on reallocating water, options for expanding supply limited, summer demand already greater than supply	High
Stormwater management	Combined sewer overflows	More localized flooding, water quality problems	High - CSO events are sensitive to	Medium - can upgrade the system but costly; some	Medium

	(CSOs) during heavy rainstorms	possible if precipitation becomes more intense and/or frequent	changes in the intensity and frequency of rain events	upgrades already underway	
Road operations and maintenance	Pavement buckling on asphalt roads during extreme heat events	More required asphalt maintenance likely	High - pavement Buckling an existing problem on many roads	Medium - can replace asphalt more frequently but costly; dependent on industry-wide changes in asphalt for improved asphalt mixes	Medium

Source: Snover et al., 2007

2.2 Examples of Vulnerability Assessments

The following summarizes studies that have utilized some aspect of the vulnerability assessment methodology outlined above in the approach and highlights each study's key findings.

2.2.1 Synthesis and Assessment Product 4.7: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase 1 (CCSP, 2008)

Synthesis and Assessment Product (SAP) 4.7 focuses on the Gulf Coast and examines the potential impacts of climate change on vulnerable transportation systems and infrastructure. This study follows many of the steps described in the methodology section including the assessment of current vulnerabilities, estimating future climate conditions and identifying the associated projected vulnerabilities. Future projections of climate will vary depending on the choice of emission scenarios (i.e., various scenarios describing how emissions of greenhouse gases will change over the projected years in response to changes in policies, population growth, economic development, etc.). This report estimates future conditions using climate models driven by a variety of emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES), including the low-emissions B1 scenario, the mid-range A1B scenario, and the high-emissions A2 scenario. The AIFI scenario was also added to the SRES scenarios to assess the impacts of sea level rise.

These scenarios examined climate impacts in 2050 and 2100. The climate impacts on transportation infrastructure assessed in this study rely on the combination of an understanding of historical climate trends and future projections from general circulation models (GCM). Factors of existing transportation infrastructure were considered in assessing future climate changes. For example, sea level rise scenarios for 2050 and 2100 were factored against land surface elevation and subsidence rates of sample sites.

In the case of increasing temperatures, transportation analysts have identified several specific attributes of temperature change of concern in transportation planning: "changes in annual days above 32.2 °C (90 °F) and maximum high temperature, for example, will impact the ability to construct and maintain transportation facilities. Concrete loses strength if it is set at air temperatures greater than 32.2 °C and the ability of construction workers and maintenance staff to perform their duties is severely curtailed at temperatures above 32.2 °C degrees" (CCSP, 2008).

This study finds highways, ports, and rail infrastructure are particularly vulnerable to projected sea level rise and future storm surges (see Table 2 for sample results). In addition, the maintenance of infrastructure (such as rail and highways) is projected to be vulnerable to increasing temperatures while bridges are projected to be especially vulnerable to changes in precipitation and flooding.

Table 2 . A sample of the vulnerability assessment findings of the percent of highway facilities vulnerable to relative sea level rise and storm surge impacts.

Facility	Relative Sea Level Rise		Storm Surge	
	61 cm (2 ft)	122 cm (4 ft)	5.5 m (18 ft)	7.0 m (23 ft)
Arterials	20%	28%	51%	57%
Interstates	19%	24%	56%	64%
Intermodal connectors	23%	43%	73%	73%

Source: CCSP, 2008

In addition to assessing potential transportation infrastructure vulnerabilities based on climate scenario modeling, the report also presents case studies of the impacts of Hurricanes Katrina and Rita in 2005. It is understood that although changes in tropical cyclone activity have not been directly attributed to climate change, these case studies illustrate the types of impacts that would occur if the Gulf Coast experiences an increase of Category 4 and 5 hurricanes. Tropical cyclones at hurricane strength damage infrastructure through increased winds, storm surges, and wave action. This assessment focuses on how the elevation of roads and bridges are linked to the vulnerability to storm surges and sea level rise by examining actual damages to transportation infrastructure that occurred as a result of Hurricanes Katrina and Rita in 2005 and the associated costs of repairs (CCSP, 2008). This type of vulnerability assessment can be replicated in other regions as the climate scenarios are applicable worldwide and the results can be incorporated into regional vulnerability assessments relying on regional expertise and existing infrastructure inventories.

The bridges most impacted by the storms are found to be the numerous bay and river crossings throughout the region. Several bridges were completely destroyed, while others sustained significant damage. The vulnerability of these roads and bridges are attributed to the storm surge and wave action from the storms, as well as problems with structural design. Roadways were likewise inundated and damaged by these storms resulting in roadway weakening and sinkholes requiring reconstruction and improvements.

The analysis also includes a discussion of the cost of infrastructure repair. Requests for emergency repairs to Mississippi highways after Katrina totaled approximately $580 million. The Louisiana Recovery Authority estimates that the cost of rebuilding transportation infrastructure damaged by the hurricanes would cost $15-18 billion. These estimates provide some indication of the potential expense that would occur if hurricane frequency and/or intensity increase as the climate changes.

2.2.2 Impact of Climate Change on Road Infrastructure (Harvey et al., 2004)

This Australian report uses a vulnerability assessment to investigate how projected climate effects will affect road infrastructure. The climate effects were projected based on the IPCC SRES A2 scenario providing temperature, precipitation and moisture for 2100. This paper focuses on select road system components including: pavement performance, road use demand, and road design and maintenance; additional modeling tools were utilized to make the connection between climate projections and road system component (e.g., Pavement Life Cycle Costing (PLCC) model, and the Highway Development and Management Version 4 (HDM-4) model). In order to undertake the vulnerability assessment, the following road system datasets were utilized: road inventory data, traffic information (e.g., annual average daily traffic), pavement type (e.g., materials, strength, thickness), and pavement condition (e.g., age, initial pavement roughness).

This study finds significant state variations in the change of pavement maintenance and rehabilitation costs as a result of climate variation and population and transport demand levels. In addition, there is a small decrease (between 0% and -3%) in the required pavement maintenance and rehabilitation budget based solely on change in climate factors. This result reflects the generally warmer and drier Australian climate which reduces the rate of pavement deterioration.

2.2.3 Adapting to Climate Change: Canada 's First National Engineering Vulnerability Assessment of Public Infrastructure (Engineers Canada , 2008)

In 2008, Engineers Canada conducted this engineering vulnerability assessment on four categories of Canadian public infrastructure: stormwater and wastewater, water resources, roads and associated structures, and buildings. The report provides an assessment of vulnerability based on case studies. In the case of transportation infrastructure (i.e., roads and associated structures), the locations analyzed include the City of Greater Sudbury, Ontario, and the City of Edmonton, Alberta. The engineering vulnerability assessment conducted in these two case studies employed a sophisticated three-dimensional analysis of infrastructure components including how the components respond to climate events and the particular set of climate events under consideration. Examples of the factors considered in these case studies are presented in Table 3 below.

Table 3 . Factors considered in the roads and associated structures engineering vulnerability assessments

Relevant Infrastructure Elements	**Performance Response**	**Relevant Climate Events and other Environmental Factors**
Arterial roads Collector roads Local urban roads Local rural roads Bridges	Structural integrity Serviceability Functionality Operations & maintenance Emergency response risk Insurance considerations Policies & procedures Economics Public health & safety Environmental effects	High temperature Low temperature Extreme temperature range Precipitation as rain Precipitation as snow Wind Ice accretion Ice force Hail Freeze-thaw cycles Groundwater Flooding Fog Humidity

Source: Engineers Canada , 2008

Key findings of transportation infrastructure vulnerabilities to climate change include: (1) infrastructure systems studied were generally resilient to discrete, one-time, climate events; and (2) infrastructure systems were particularly vulnerable to long-term cumulative impacts.

2.2.4 Evaluating Climate Change Impacts on Low Volume Roads in Southern Canada (Tighe et al., 2008)

A Canadian study conducted a case study analysis of pavement sensitivity to temperature and precipitation. Specifically, this report analyzes pavement performance over a 20-year period using the Mechanistic-Empirical Pavement Design Guide (M-E PDG) to determine how climate changes in precipitation and temperature will affect the pavement performance indicators of international roughness index (IRI), longitudinal cracking, transverse cracking, alligator cracking, asphalt concrete (AC) deformation, and total deformation. This analysis requires traffic, and structure and material properties datasets to represent current stressors and pavement conditions. Climate effects were represented by temperature, wind speed, percent sunlight, precipitation, and relative humidity.

Large temperature and precipitation increases are shown to have a negative impact on the pavement performance in the Canadian environment. In most cases, a 1°C temperature increase did not significantly affect the pavement performance, while a larger temperature increase showed noticeable differences. Pavement deterioration will be significantly accelerated by climate change (Smith et al., 2008). Pavement performance will require maintenance, rehabilitation and reconstruction to occur earlier in pavement design life.

2.2.5 Living with a Rising Bay : Vulnerability and Adaptation in San Francisco Bay and on its Shoreline (San Francisco Bay Conservation and Development Commission, 2009)

This report assesses the vulnerability of San Francisco Bay and its shoreline to the impacts of climate change, identifies information needs for future vulnerability assessments, and suggests near-term and long-term strategies to address climate change impacts. For this assessment, two IPCC scenarios were used to report on climate change impacts in California : A2 (a higher emissions scenario) and B1 (a medium-low scenario). Researchers used the A2 and B1 scenarios to run multiple global climate computer models and performed additional research to project specific climate changes in California . Two sea level rise estimates were selected for analysis in this report: a 16-inch (40 cm) sea level rise by mid-century and a 55-inch rise in sea level by the end of the century (SFBCDC, 2009).

Many of the major roads and highways within the Bay region may be significantly impacted by sea level rise and extreme flooding events due to their proximity to the Bay and the Pacific Ocean . Approximately 99 miles of the major roads and highways within the region are vulnerable to a 16-inch rise in sea levels (by mid-century) and approximately 186 miles of major roads and highways are vulnerable to a 55-inch rise (by the end of the century). Some roads and highways will be subjected to other impacts, such as erosion from increased storm activity. These types of impacts have been shown to undermine existing structures, which can substantially increase maintenance costs. Supporting structures of many of the region's bridges may also be vulnerable to unanticipated, prolonged contact with corrosive salt water (SFBCDC, 2009).

This study considers the vulnerability of regional transportation infrastructure to climate change to be "High" as there are many highways are adjacent to the Bay and crossing the Bay. Flooding of these highway segments in the regional transportation network would disrupt the movement of goods from ports. Approximately 99 miles of the major roads and highways within the region are vulnerable to a 16-inch rise in sea levels (by mid-century) and approximately 186 miles of major roads and highways are vulnerable to a 55-inch rise (by the end of the century). Where rising sea level and storm activity do not actually flood roads and highways, it will further complicate maintenance and congestion relief projects (SFBCDC, 2009).

2.2.6 National Highway Hazards Tool (TRB, 2009)

The National Cooperative Highway Research Program (NCHRP) produced the *Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA)* report in order to provide transportation owners and operators with resource allocation guidelines for safety and security investments. The CAPTA methodology is available to the public as a computer-based spreadsheet model providing a means to analyze assets, relevant threats and hazards, and consequence levels of interest in a common framework (TRB, 2009).The report and accompanying tool consider natural hazards as potential risk to highway infrastructure, including: flooding, earthquakes, extreme weather (including extreme wind, rainwater, snow, ice, etc.), and mud/landslides (TRB, 2009). While this assessment does not take into account long-term climate changes or variability, this assessment may be useful for providing a vulnerability assessment methodology framework for the highway system.

3. Risk Assessment

The concept of risk is not new to transportation planners, designers, engineers, managers, community stakeholders and policymakers; however, the application of risk assessment methods in the context of climate change is relatively new. The purpose of a climate change risk assessment is to identify hazards that may be caused or exacerbated by climate change, and to assess the likelihood and relative consequence of these hazards in order to prioritize responses and mitigate risks (NZCCO, 2004); where the term "hazards" refers to perturbations and stresses (Turner et al., 2003). A climate change risk assessment can help identify no-regrets climate change adaptation options, that is, the uncertainty associated with the stressor is very low warranting implementation of adaptation options (Willows and Connell, 2003).

Box 2 . Important Concepts for a Climate Change Risk Assessment

Risks vary spatially and temporally. At present, risks are not consistent regionally or even locally, and will differ down to the specific asset in question. Additionally, risks faced today at a given location may change in the future, dependent upon climatic changes, management decisions, and the implementation of adaptation measures, for example.

Scale. As the ultimate goal of a climate change risk assessment is to inform the decision-making process, risk assessments need to be carried out at an appropriate scale in order to support that process-spatially (e.g., national, regional, local), temporally (e.g., present day to 2050, 2050 to 2100, etc.), and also in terms of ability to satisfy data requirements in order to complete the assessment.

Uncertainty. Natural variability and knowledge gaps are sources of uncertainty, which should be considered in the risk assessment process.

Communication. The outputs of a risk assessment should be communicated to relevant decision makers and to the public, as appropriate.

(adapted from NZCCO, 2004)

Climate change risk assessment can be a tool for enhancing the resilience of the transportation network (CCSP, 2008). Weather conditions are becoming increasingly variable due to climate change, which translates into additional risks that have the potential to carry financial, environmental, and social costs related to long-lived transportation infrastructure assets (Fankhouser et al., 1999). For example, a financial "side effect" of bearing this increased risk may include difficulty in financing climate-sesitive projects (Frankhouser, et al., 1999). Identifying potential climate-related hazards and prioritizing at-risk infrastructure in the context of other risks currently under consideration by policymakers is critical in assessing whether or not adaptation is appropriate, and if so, *when* and *where* to focus adaptation efforts.

In the context of climate change risk assessment, *risk*is best defined as the combination of two elements: (1) the likelihood of an event occurring (e.g., flooding, hurricane, heat wave, etc.), and (2) the consequence of such an event (e.g., moderate highway flooding resulting in disruption in services for several days) (NZCCO, 2004). In developing quantitative risk assessmentsand related risk-based indices as a tool for prioritizing risks, risk can be more precisely defined as the product of the probability and the consequence of a given event (i.e., risk = probability x consequence) (Snover et al., 2007). Several fundamental concepts apply to any climate change risk assessment process (see Box 2).

3.1 General Methodologies

Methodologies for conducting risk assessment (i.e., incorporating tools and approaches to prioritize the potential impacts of climate change) can vary depending upon resources and information available. In the literature, risk assessment approaches fall into two distinct classes based on the availability of data and effort and are discussed here as the Tier 1 assessment and the Tier 2 assessment.

3.1.1 Tier 1 Preliminary Risk Screening / Qualitative Risk Assessment

The primary elements of a preliminary risk screening, or a more detailed qualitative risk assessment include (Snover et al., 2007; NZCOO, 2004):

Box 3 . Key Questions for Identifying the Stressors on a Transportation System

- What is the land use or infrastructure and where does it occur?
- Is any lifeline infrastructure located within

the area (e.g., hospitals, ports, key transportation or network utilities which provide lifeline connections for which there is no alternative)?

- Are there particular environmental issues to be considered? (e.g., significant mangroves, wetlands or dune ecosystems).

(NZCCO, 2004)

- Defining the planning context including geographic parameters (e.g., highways, bridges, and tunnels by region or specific location);
- Identifying existing stressors that may be exacerbated by climate change, as well as the introduction of new stressors (see adjacent Box 3);
- Projecting climate-related effects including changes in climate variability and determining how these effects impact infrastructure (e.g., more asphalt rutting due to extended heat waves; more frequent/severe coastal highway inundation due to the combined effects of heavy precipitation, wind waves, and storm surge; more frequent/severe direct wind damage to exposed infrastructure due to more frequent/severe hurricanes);
- Identifying and evaluating the likelihood and consequence of climate-related impacts in order to characterize risks in the planning context;
- Characterizing uncertainty and assumptions; and
- Communicating risks to stakeholders.

The evaluation of the likelihood and consequence of climate-related impacts provides policymakers with some guidance on the level of risk and may be based upon a literature review or expert survey (Snover et al., 2007). The risk can be determined for a given system or program and focuses on a defined set of stressors (such as climate change effects). The analysis for a given system or program can be divided into endpoints of interest such as environmental, human health, and financial where each endpoint has its own risk table. The risk product for each stressor and endpoint reflects the level of risk for policymakers. Table 4 describes a qualitative approach of assessing risk of hazardous events and describes how risk associated with an event is categorized (adapted from NZCCO, 2004; CSIRO et al., 2007; IPCC, 2007). For example, an event that is very likely to occur and produce catastrophic consequences has a high level of risk associated with it (illustrated below in red). Alternatively, an event that is not likely to occur and, if it were to occur, would produce very little damage would be considered a very low risk (illustrated below in white). Ideally, the risk thresholds of the policymaker are also incorporated into the design of the evaluation. For example an extreme climate event such as intense rainfall events may be considered rare but the actual impacts may be very severe and may warrant a greater degree of associated risk than the findings of the evaluation (Willows and Connell, 2003).

Table 4 . Qualitative evaluation of likelihood and consequence of hazardous events

Likelihood	**Consequence**				
	1.Catastrophic	**2.Major**	**3.Moderate**	**4.Minor**	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Source: Adapted from NZCCO 2004; CSIRO et al., 2007; IPCC, 2007

The consequence of impact for the risk table can be determined for each endpoint of interest described in Box 4 .

The likelihood of impact and/or severity of the stressor on the system or program for each endpoint of concern can be assessed and described also according to a qualitative scale (Snover et al., 2007). For example, "very likely" may refer to an event or stressor that occurs repeatedly across multitude of regions and/or within one region but continually over time; "likely" may refer to an event or stressor that has occurred in a particular location more than once; and so on. For climate projections, it may be more appropriate to also include scientific literature that provides some indication of the potential magnitude of an event or stressor opposed to relying on historical observations.

A Tier 1 analysis can help ensure that climate-related stressors are included in the decision process at an early stage (Willows and Connell, 2003).

Box 4 . Characterizing Consequences

Catastrophic

Financial: Huge financial losses involving many people and/or corporations and/or local government; large long-term loss of services; permanent damage and/or loss of infrastructure service across sizeable region; high financial loss and/or environmental remediation costs; long-term impact on commercial revenue Health: Severe adverse human health with multiple events leading to disability or fatalities and requiring emergency response Environmental: Permanent loss of environmental service

Major

Financial: Major financial losses for many individuals and/or a few corporations; some long-term impacts on services; some homes permanently lost; existing infrastructure damage or loss requiring extensive repair Health: Permanent physical injury and fatalities from individual event Environmental: Significant impairment of environmental service; some species loss

Moderate

Financial: High financial losses, probably for multiple owners; disruption of services for several days; widespread infrastructure damage and loss of service requiring maintenance and repair Health: Adverse human health; most populations affected; people displaced from their homes for several weeks Environmental: Impairment of environmental service; species affected

Minor

Financial: Moderate financial losses for small number of owners; disruption of services for a day or two; localized infrastructure damage Health: Slight adverse human health effect; vulnerable populations affected Environmental: Short duration and intensity of impairment to environmental service; minimal effect on species

Insignificant.

Financial: No infrastructure damage; Minimal financial losses; short term inconvenience Health: No adverse human health effect or complaint Environmental: Minimal impact on environmental services

(adapted from NZCCO, 2004; CSIRO, 2007)

3.1.2 Tier 2: Quantitative Risk Assessment

Fewer examples of quantitative climate change risk assessment exist. Deterministic "what if" or "worst case" scenario analyses are based on historical data without consideration of recurrence or probability. Probabilistic Risk Assessment (PRA) does attempt to associate probabilities with specific hazardous events (e.g., storm surge). Further, some approaches attempt to superimpose incremental climate-related hazards on existing hazards in order to assess potential changes in frequency and severity in the future (Jacob et al., 2000).

Methods or frameworks for quantitatively assessing and prioritizing risks and direct and indirect consequences, or probable losses, due to climate-related impacts are not well established. However, models do exist to help understand existing natural hazards that may be exacerbated by climate change and to quantify damage-e.g., the HAZUS-MH Hurricane Wind Model is a scenario-based model that draws upon National Weather Service forecasts and enables analysis of economic and social losses from hurricane winds at the state and local levels; or, for example NOAA's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, which is used to estimate storm surge heights and wind speeds based on historical, hypothetical, or predicted hurricanes (CCSP, 2008).

Additionally, some state DOTs have developed mathematical models to prioritize bridges for retrofitting based on their seismic vulnerability and their importance as "lifelines" (see WSDOT Bridge Seismic Retrofit Planning Program). For example, the WSDOT "priority index" is expressed as:

$$I = A \times C$$

Where "A" describes the criticality of the route, "C" describes the vulnerability of each bridge to seismic failure and "I" is between zero and 100 representing the relative priority of Washington state.

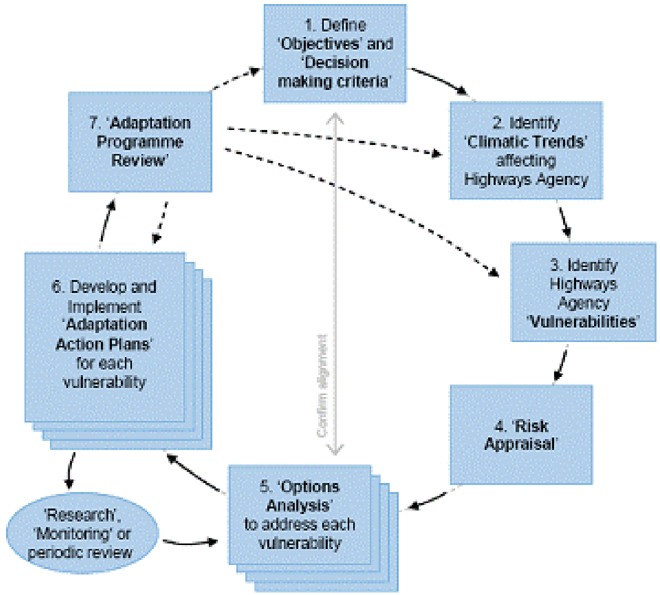
- The sub-components of the criticality factor "A", which are represented as numerical coefficients, include: interstate route vs. all other routes; length of available detour routes; criticality of the route itself as a detour route; whether or not the bridge carries essential utility lines; etc. This methodology for assessing criticality may be a useful approach when prioritizing climate-related risks to transportation infrastructure.
- The coefficients for the seismic vulnerability factor "C" are: a coefficient describing the likelihood and severity of seismic activity within state sub-regions based on historical data; a factor representing the remaining service period of the bridge; and, a factor representing the structural vulnerability to seismic activity of the bridge, which involves an assessment of the superstructure, substructure, foundation, and soil conditions for each.

In contrast to managing seismic risks, climate change impacts usually involve complex interactions of multiple climate-related effects. For example, in some areas coastal flooding will become more frequent and more severe due to the confluence of rising sea levels, storm surge, and heavy precipitation events, which introduces a high degree of uncertainty in judgments about specific climate-related impacts. While assessing seismic risks is a similar exercise to assessing climate-related risks in terms of uncertain timing, location, and severity of the hazard, data on seismic activity is more readily assimilated into impactanalysis because the singular *effect*(i.e., an earthquake of a given magnitude) more directly translates into a given *impact*(i.e., infrastructure damage due to the earthquake) based on historical data. For these reasons, while the framework outlined above is instructive, it may not be feasible to follow precisely without thorough consideration of interacting climate-related effects, and consideration of how these effects might accelerate or otherwise change in the future.

3.2 Examples of Risk Assessments Conducted on Infrastructure

3.2.1 Highways Agency Adaptation Strategy Model (U.K. HACCAS, 2008)

The United Kingdom has developed a seven-phase process for assisting transportation decision-makers in addressing climate change impacts on highways. This approach provides methodologies for vulnerability assessment, risk assessment, and adaptation. Developed by the United Kingdom Department for Transport (DfT) Highways Agency, Highways Agency Adaptation Strategy Model *(*HAASM) is a seven-phase, systematic approach that identifies and manages the transportation-related activities projected to be affected by a changing climate to assist transportation decision-makers in the development of the Highways Agency Climate Change Adaptation Strategy (see Box 5).



This framework draws upon UK climate projections and practical templates, schedules, and guidance of assessments for vulnerability, risk, and adaptation options. The first step of the framework defines the objectives and decision making criteria to then be used throughout the process. The next two steps help transportation decision-makers identify the climatic trends that may impact the highway agency and the associated vulnerabilities.

In step 4, each vulnerability identified receives a risk-ranking based on a risk appraisal scoring using four primary criteria: (1) uncertainty, (2) rate of climate change, (3) extent of disruption, and (4) severity of disruption (see Table 5).

Table 5 . Risk Scoring of Primary risk criteria.

Primary risk criteria	**Risk Source**	**Risk Score (numerical)**
Uncertainty	Low	1
Rate of Climate Change Criterion	Medium	2
Extent of Disruption	Medium	2
Severity of Disruption	High	3

Source: U.K.HACCAS, 2008

Step 5 and 6 then prioritize the results of step 4 determining the timescales for action and highlighting the priority areas requiring early involvement through adaptation strategies (see Table 6).

Table 6 . Prioritization criteria and respective indicator score.

Prioritisation Criteria	Indicator score
Time-criticality	2/3=0.67
High Extent	2/3=0.67
High disruption duration	3/3=1
Potential research need (asset or activity)	1/3=0.33
Highly disruptive, time-critical with high confidence	[2x2x3x(4-1)/81=0.44

Source: U.K. HACCAS, 2008

Early rounds of implementation of the HAASM have identified more than 80 Highways Agency activities that may be affected by climate change. A preliminary appraisal of the risks associated with these vulnerabilities has been undertaken finding that over 60% of them are expected to be affected by current predicted levels of climate change within the relevant asset life or activity time horizon.

3.2.1 Infrastructure and climate change risk assessment for Victoria , Australia

(CSIRO et al., 2007)

This report includes a Tier I infrastructure risk assessment for Victoria , Australia and implements the New Zealand risk management guidebook (NZCOO, 2004). The study assesses the risk for various types of infrastructure against a range of climate change variables. Each climate change variable in the report is described in terms of a worst-case scenario for low and high climate change projections for 2030 and 2070 while assuming no adaptation between now and then.

Each infrastructure category, including transportation infrastructure, was assessed in terms of the impact of climate change on physical infrastructure assets, the services they provide, their value as a "social amenity", and the impact on operations, maintenance, repair, and replacement. The primary transportation infrastructure types include roads, rail, bridges, tunnels, airports and maritime ports.

In the transportation infrastructure risk summary, risk scenarios and ratings (i.e., low, moderate, high risk) were assigned to each transport type for 2030 and 2070. Road-related risks include: asphalt degradation due to increased solar radiation and increased variation in wet/dry spells and decrease in available moisture; flood damage to roads due to increases in extreme daily rainfall and increases in frequency and intensity of storms (see Table 7 and Table 8).

3.2.2 Metropolitan East Coast Study (Jacob et al., 2000)

This study reviews the current understanding of the risks posed by climate stressors to the Metropolitan East Coast infrastructure with a focus on coastal storm surge inundation and then looks at the incremental hazards associated with projected sea level rise including risks associated with coastal storm surge.

This approach represents a partial probabilistic risk assessment (Tier 2) while building upon elements of the Tier 1 approaches. Due to a lack of detailed, regionally-specific data on historic storms-including the height and duration of storm surge by location and data on the damage that past storms have caused-a "comprehensive" probabilistic risk assessment was not performed as part of this study. This risk assessment found an increase of sea level rise of less than 1 meter by 2100 increases the frequency of coastal flooding by factors of 2 to 10 by 2100.

The report appendix provides a description of a, "…basic probabilistic hazard definition," and its applicability in probabilistic risk assessment, which is a more detailed, mathematical approach to probabilistic risk assessment. However, as previously noted, a more detailed probabilistic approach requires detailed, location-specific data on climate-related effects, physical infrastructure characteristics (including detailed vulnerability data), and direct and indirect infrastructure value.

Table 7 . Victoria , Australia transportation infrastructure risk assessment summary, 2030 Low (excerpt)

Transport Risk Assessment 2030 Low

Transport	Risk Scenario	Climate Variable (Cause)	Climate Change Impact	Risk Description for Multiple Causes	Risk Rating (likelihood x consequence)				
					Risk Rating	Infrastructure Service	Social	Governance	Finance
1.1 Roads	1.1.1 Asphalt Degradation	Increased Solar Radiation	**Majority of Victoria experiences an increase in radiation by 0.5-2%.** Increased rate of degrading the asphalt and road surface. Materials breakdown and dispersion	• Increased maintenance and renewal of road and pavement surfaces in localised regions. • Increase in short term loss of public access or increased congestion to sections of road and highway (regional and Melbourne) during repair and replacement. • Increase in road replacement costs due to greater rate of degradation. • Likely financial impact to local councils, Vic Roads.	Moderate	M (B2)	M (B2)	L (B1)	M (B2)
		Increased Temperature and Heatwaves	**0.5-1°C increase in temp over majority of the state and increase of 1 (Melbourne) to 4 (Rutherglen) days over 35 and an increase in the number of heatwaves events over 30 C° by 0.5 (Melbourne) to 2 (Rutherglen) p.a..** Increased rate of degradation to asphalt and road surface integrity.						
	1.1.2 Road Foundations Degradation	Increased Variation in Wet/Dry Spells	**An increase in variation of short intensive wet spells and prolonged dry spells.** Increased in fluctuation in groundwater levels, changes to soil composition and foundation structures	• Degradation, failure and replacement of road structures due to increases in ground and foundation movement, shrinkage and changes in groundwater. • Increased maintenance and replacement costs of road infrastructure. • Short term loss of public access or increased congestion to sections of road and highway (regional and Melbourne) due to increase maintenance and replacement regime. • Regional cost to councils and VicRoads.	Moderate	M (B2)	M (B2)	L (B1)	M (B3)
		Decrease in Available Moisture	**The frequency of drought increases by up to 20% for the majority of Victoria, with the exception of the Great Dividing Range. The annual reduction in the moisture balance for majority of Vic is between -50 and -100mm.** Soil movement generated in prone soils. Foundation failure generated through both increases in movement stresses and increased fatigue from changing of conditions more often over time.						
	1.1.3 Flood Damage to Roads	Increase in Extreme Daily Rainfall	**Increases in extreme daily rainfall by up to 27%.**	• Degradation, failure and replacement of road structures due to increased damage from flooding, inundation of foundations and changes in	Moderate	M (D3)	M (D3)	L (D2)	M (D3)

Table 8 . Victoria , Australia transportation infrastructure risk assessment summary, 2030 High (excerpt)

Transport Risk Assessment 2030 High

Transport	Risk Scenario	Climate Variable (Cause)	Climate Change Impact	Risk Description for Multiple Causes	Risk Rating (likelihood x consequence)				
					Risk Rating	Infrastructure Service	Social	Governance	Finance
2.1 Roads	2.1.1 Asphalt Degradation	Increased Solar Radiation	**Majority of Victoria experiences an increase in radiation by 2-4%.** Increased rate of degrading the asphalt and road surface. Materials breakdown and dispersion	• Increased maintenance and renewal of road and pavement surfaces in localised regions. • Increase in short term loss of public access or increased congestion to sections of road and highway (regional and Melbourne) during repair and replacement. • Increase in road replacement costs due to greater rate of degradation. • Likely financial impact to local councils, Vic Roads.	Moderate	M (B2)	M (B2)	L (B1)	M (B2)
		Increased Temperature and Heatwaves	**1-1.5°C increase in temp over majority of the state and increase of 3 (Melbourne) to 10 (Rutherglen) days over 35 and an increase in the number of heatwaves events over 30 C° by 1 (Melbourne) to 5 (Rutherglen) p.a.** Increased rate of degradation to asphalt and road surface integrity.						
	2.1.2 Road Foundations Degradation	Increased Variation in Wet/Dry Spells	**An increase in variation of short intensive wet spells and prolonged dry spells** Increased in fluctuation in groundwater levels, changes to soil composition and foundation structures	• Degradation, failure and replacement of road structures due to increases in ground and foundation movement, shrinkage and changes in groundwater. • Increased maintenance and replacement costs of road infrastructure. • Short term loss of public access or increased congestion to sections of road and highway (regional and Melbourne) due to increase maintenance and replacement regime. • Regional cost to councils and VicRoads.	Moderate	M (B3)	M (B2)	M (B2)	M (B3)
		Decrease in Available Moisture	**The frequency of drought increases by up to 20% for the majority of Victoria, with a 1/5 of the state experiencing up to a 40% increase. The annual reduction in the moisture balance for majority of Vic is between -100 and -200mm with a 1/3 between -200 and -400mm.** Soil movement generated in prone soils. Foundation failure generated through both increases in movement stresses and increased fatigue from changing of conditions more often over time.						
	2.1.3 Flood Damage to Roads	Increase in Extreme Daily Rainfall	**Increases in extreme daily rainfall by up to 27%.**	• Degradation, failure and replacement of road structures due to increased damage from flooding, inundation of foundations and changes in	Moderate	M (D3)	M (D3)	L (D2)	M (D3)

3.2.3 Caltrans Seismic Retrofit Program for Bridges (NRC, 2008)

As indicated previously, transportation professionals currently take into account a variety of risks outside the context of climate change, including seismic risks and other natural hazards, as well as human-induced risks such as terrorist attacks. Methods currently used in assessing these risks and prioritizing responses could be augmented and employed in the context of climate change risks.

For example, the Transportation Research Board Special Report 290, *Potential Impacts of Climate Change on U.S. Transportation* (2008)highlights the California Seismic Retrofit Program as a strategic, risk-based approach that could be considered in the context of climate change risks. The program was designed to identify and rank roughly 25,000 California bridges based on vulnerability to earthquakes in order to prioritize limited state resources in carrying out retrofits.

The general approach of the Seismic Retrofit Program is as follows:

- Establish minimum performance standard for bridges (i.e., "no collapse" for most bridges);
- Develop risk algorithms for screening bridges with respect to the minimum performance standard, evaluating seismic activity by location, seismic hazard, potential impact, and the vulnerability of the structure;
- Perform a series of "desk study" screenings to determine which bridges should be considered further in the program or if a retrofit should be deferred;
- Perform a final field inspection to verify that the subset of bridges identified as needing retrofits as a result of the initial screenings indeed failed to meet the minimum performance standard, and thus, should be retrofitted;
- Implement retrofits;
- Conduct ongoing assessments and prioritization of retrofit needs and include additional bridges in the retrofit program as needed.

Phase I of the program was implemented after the 1989 Loma Prieta earthquake and included the retrofitting of 1,039 state highway bridges through May 2000. Following the 1994 Northridge earthquake, an additional 1,155 state-owned bridges were deemed in need of retrofits, which are nearly complete but presently ongoing (CALTRANS, 2009).

3.2.4 New York City Climate Risk Assessment (Rosenzweig and Solecki., 2009)

The New York City Panel on Climate change investigated the likelihood and potential impacts on infrastructure. Global climate models (GCM) projections of temperature, precipitation, sea level rise and extreme events for three scenarios were combined with qualitative projections of heat indices, frozen precipitation, intense precipitation, lightning and large-scale storms to determine the potential climate hazards over the 21st century. This study finds:

- It is "very likely" that NYC will experience an increase in the number of hot days, heat waves, warmer winters, and less extreme cold waves leading to a number of implications for NYC infrastructure including transportation service disruption, increase in the construction season, and a reduction of road damage associated with freezing surfaces.
- It is "likely" snowfall amounts will reduce in the coming years while increases in the frequency of rainfall intensity will lead to flooding of low-elevation transportation, delays of public transportation and low-lying highways, and a reduction in winter weatherizing.
- It is "very likely" sea level rise will lead to more frequent and intense coastal flooding delaying public transportation and low-lying highways and wave action causing infrastructure damage.

The findings of this study are considered applicable to other coastal urban areas.

3.2.5 Mudslide Hazard Assessment (Winter et al., 2008)

This study investigates the potential impacts of mudslides associated with the recent and projected increase in seasonal intense storm events in Scotland . Changes in the frequency and annual timing of heavy precipitation events have a direct impact on the debris flow that causes mudslides. The risk assessment is a GIS based assessment using maps to represent debris flow as a function of water conditions, vegetation and land cover, stream flow, and slope angle. Ground-truthing was employed through site specific studies. The study suggests two approaches for reducing the climate impact: exposure reduction through outreach and road closures, and hazard reduction through road protection, minimizing the opportunity of debris flow, and road realignment. Mudslides are not confined to Scotland but are of global concern. The Canadian Climate Impacts and Adaptation Research network (C-CIARN) hosted a workshop to discuss and identify the impacts of landslides, adaptation and risk management and future needs associated with future climate projected in Canada to include increased water, steepness, and intensity of storms (CCIARN, 2004).

4. Adaptation**Assessment**

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2007); that is, adaptation enhances resilience or reduces vulnerability to observed or projected changes in climate (PPIC, 2008). Reducing vulnerability may address one or many of the projected impacts of climate change. For example, elevating coastal roads reduces vulnerability to the impacts of anticipated sea level rise; or investing in coastal protection infrastructure reduces coastal vulnerability to storm surges and anticipated sea level rise (IPCC, 2007). Alternatively, adaptation may increase a system's resilience to future impacts through the fortification of structures or implementing measures to increase a system's ability to bounce back after an impact (Turner et al., 2003).

An adaptation assessment is defined by the IPCC as "the practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency and feasibility" (IPCC, 2007). Long-term planning can prepare for potential climate changes and address the uncertainty with changing conditions. For example, roads and bridges are designed to be maintained and replaced in a certain time frame. Incorporating improvements in design and maintenance can enhance the lifetime expectancy of this infrastructure, and improve resilience to climate impacts.

4.1 General Methodologies

The IPCC discussed adaptation strategies in its first assessment report in 1995. Despite acknowledgement that adaptation strategies were needed, action on climate change adaptation is still in its infancy. The literature is relatively sparse, but growing with respect to systematic descriptions of adaptation approaches compared to vulnerability and risk assessment methodologies (Heinz, 2007). Through our literature review, we have compiled a series of core steps that may be considered within an adaptation approach based on the information gathered from a limited number of reports (IPCC, 2007; Willows and Connell, 2003; Snover et al., 2007; U.S. EPA, 2009). It is assumed this methodology will continue to evolve as planners begin to incorporate climate change into their decision making processes. Interestingly, adaptation approaches are extremely broad and are likely to include qualitative screening assessments, some quantitative risk assessments, policy and implementation actions, as well as outreach and communication efforts. As officials and managers of natural and human systems are finding, adaptation is an extremely far-reaching concept, requiring a wide range of activities and skillsets. As the literature has noted, planning for climate change requires building and improving partnerships, soliciting expert assistance, partnering with funding organizations, and convening advisory groups (Snover et al., 2007).

Identify Adaptation Responses.There are three types of adaptation responses relevant to transportation planning which address climate impacts at varying time scales: protect, retreat and accommodate (CCSP, 2008). These responses can be put into practice through investing in infrastructure and technology or changes in management approaches (PPIC, 2008; CCSP, 2008):

- Protect includes such options as redesigning the infrastructure or instituting measures to reduce the climate impact (such as armoring against storm surges).
- Retreat includes abandonment of the infrastructure.
- Accommodate includes operational strategies that can be implemented to reduce the climate impact (such as pumping water after a flood event).

In some cases, these options are not implemented until pre-determined climate change thresholds are observed or are until an established time frame is reached**.**

Proactive or anticipatory options take place before the impacts of climate change are observed, this includes a "no regret" option (IPCC, 2007). A no regret option applies to a decision option that is determined to be worthwhile now (in that its immediate benefits exceed its costs), and continues to be provide benefits with or without changing climate conditions (Willows and Connell, 2003). This is in contrast to the generally more expensive reactive adaptation which describes actions that take place in response to already occurring climate change (Mehdi et al., 2006).

Box 6 . Implementation tools for adaptation actions

- Zoning rules and regulations,
- Taxation (including tax incentives),
- Building codes/design standards,
- Utility rates/fee setting,
- Public safety rules and regulations,
- Issuance of bonds,
- Infrastructure development,
- Permitting and enforcement,
- Management practices,
- Outreach and education,
- Emergency management powers, and
- Partnership building with other communities.

(Snover et al., 2007)

Determine Appropriate Adaptation Action. Adaptation actions may be either incorporated into existing policies, practices and procedures through some modification or, in some cases, new policies, practices, and procedures will need to be created (Snover et al., 2007). According to the Climate Impacts Group (CIG) at the University of Washington (2007), modification to existing policies, practices and procedures should: allow regular reevaluation and adjustment in accordance with changing conditions; require planning that is not based strictly on the past, and does not restrict certain decisions to certain periods or seasonal patterns; and reinforce trends that reduce vulnerability or increase adaptive capacity. On the other hand, climate change adaptation can be incorporated into existing planning through modifying zoning codes, land use planning guidance, or emergency planning.

Select and Prioritize Actions.Adaptation assessments may identify a wide variety of potential options for considered action. In order to prioritize and select among these options, planners may consider a range of criteria including: the timeframe of risk; design life of the infrastructure at risk; cost of action/inaction; the likelihood of the action to reduce risk; the timeframe for implementation; and other constraints or limitations (Snover et al., 2007) (see Box 7 for more discussion).

Implementing Actions. Once particular actions have been identified, a plan for implementation is developed. Implementation may include near-term operational and maintenance responses or longer-term design strategies (see Box 6). Implementation is often the most difficult stage of adaptation to accomplish. Plans may languish on the shelf unless the actions identified in the plan are tied to specific actors and timelines for implementation. In many cases, implementation will require input and cooperation from several actors inside and outside the relevant transportation agency.

Box 7 . Tools for Determining Appropriate Adaptation Actions

Timeframe of risks: The timeframe for projected impacts (e.g., short-term, mid-term, long-term) can be assessed relative to the timing of management decisions and actions (U.S. EPA, 2009). The severity and probability of projected impacts can also be factored into this analysis (see section on risk assessment) and compared to the timeframe available for implementation of action.

Cost-benefit considerations: The potential costs associated with an action is compared to the potential benefits the action will provide (Bueno et al., 2008; Stanton and Ackerman, 2008; Williamson et al., 2008). Decision makers will have to determine the time frame to be considered for benefits (i.e., some benefits of adaptation options may not be seen until climate impacts occur).

Constraints or limitations: Various limitations or constraints may affect the decision-making process. These factors can be considered prior to implementation. These may include regulatory, operational, political, or legal constraints. In many cases, planners will develop strategies for overcoming these barriers in preparation for implementing adaptation actions (U.S. EPA, 2009).

Measuring Progress*.*Ideally, any adaptation plans will incorporate regular evaluation of adaptation effectiveness and consideration of new or better information on climate effects (U.S. EPA, 2009). Standards for evaluating effectiveness may need to be developed and re-evaluated in order to facilitate the periodic evaluation process. The timeframe for measuring progress in climate change preparedness will depend on: the nature of the

vulnerabilities and risks that are addressed in priority planning areas; the planning horizon, investment rules and/or other factors related to a given capital project or system in a priority planning area; and organizational planning and budget cycles (Snover et al., 2007). Over time, climate change data and information used to develop planning goals may need to be updated based on new research. Climate change plans and actions will also need to be regularly updated once new information has been reviewed and basic assumptions have been examined (Snover et al., 2007).

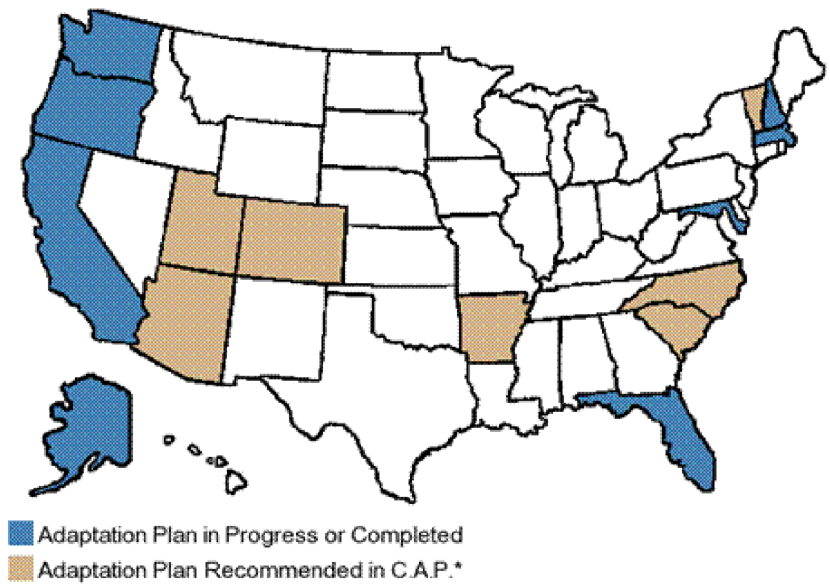
While these considerations provide a general methodology for assessing adaptation options, individual organizations may vary in the specific application of this process. For example, the United Kingdom Climate Impacts Programme (Willows and Connell, 2003) identifies a three-tiered approach for analyzing actions:

- Tier 1 - a systematic qualitative analysis, where the size, significance and relative importance of the risks, costs and benefits for each option are described. There should be an emphasis on ranking the options in terms of costs and benefits, but this may not involve quantification.
- Tier 2 - a semi-quantitative analysis, where some aspects of the risks, costs and benefits are assessed in quantitative terms while others are assessed qualitatively; the assessment would aim to assess uncertainty by placing upper and lower bounds on the risks, costs and benefits.
- Tier 3 - a fully quantitative analysis, where the probable performance of each option in managing the risk is quantified in terms of costs and benefits and, in some cases or where possible, converted into monetary terms.

4.2 Examples of Adaptation Action in the United States

Some states and communities have begun to integrate climate change adaptation into their planning process as illustrated in Box 8 .

Box 1. States Taking Action
15 states have either already begun adaptation planning or are likely to in the near future.



(Pew Center on Global Climate Change, 2009)

4.2.1 Alaska Climate Change Strategy (Alaska Climate Change Strategy, 2008)

Alaska 's Public Infrastructure Technical Working Group identified the following actions as part of the Alaska Climate Change Strategy (2008) in order to address climate impacts on Alaska 's transportation infrastructure:

- Ensure that climate change is considered as part of Alaska 's State Transportation Plan;
- Develop an inventory of potentially impacted infrastructure;
- Evaluate and address damage to highways, roads, and bridges from thawing permafrost and coastal and river erosion;
- Add additional planning scrutiny to future infrastructure investments in undeveloped hazard-affected coastal areas;
- Integrate critical area planning requirements with comprehensive planning laws, including emergency planning, emergency evacuation routes, and infrastructure planning requirements.

4.2.2 King County , Washington Climate Plan (Snover et al., 2007)

King County , Washington has been considering adaptation activities since 2005, and many are currently underway. Strategic focus areas for adaptation include: climate science; public health, safety and emergency preparedness; surface water management; freshwater quality and water supply; land use, building and transportation; economic impacts; and, biodiversity and ecosystems. The King County Climate Plan (2007) outlines strategic goals and actions under each focus area. Examples of King County 's strategic adaptation actions include:

- Creating a climate change technical advisory group within the climate adaptation team;
- Investing in education and outreach to raise awareness and build public support for adaptation in the region;
- Developing proactive strategies to reduce known public health risks of climate change;
- Continuing to analyze the potential impacts of climate change on natural hazards, and updating emergency plans and activities in response to projected changes;
- Tracking and collaborating with local climate change researches to better understand the effects of climate change on fall and winter precipitation patterns; and,
- Incorporating climate change impacts information into construction, operations and maintenance of infrastructure projects.

4.2.3 Florida's Energy and Climate Change Action Plan (Florida Action Team on Energy and Climate Change, 2008)

The Governor's Action Team on Energy and Climate Change, established by the Executive Order 07-128, is tasked it with creating a comprehensive Florida Energy and Climate Change Action Plan. The Plan (2008) provides a framework for climate change adaptation strategies. The adaptation recommendations are a comprehensive first look at the issues and opportunities facing the State of Florida, as well as an analysis of actions that can be taken in the now versus in the future. The framework and major objectives for adaptation outlined in the Plan are:

- Advancing science data and analysis for climate change
- Comprehensive planning
- Protection of ecosystems and biodiversity
- Water resources management
- Built environment, infrastructure and community protection
- Economic development
- Insurance
- Emergency preparedness and response
- Human health concerns
- Social effects
- Organizing State government for the long haul
- State funding and financing
- Coordination with other regulatory and standards entities
- Education

4.2.4 Comprehensive Strategy for Reducing Maryland 's Vulnerability to Climate Change (MCCC, 2008)

The Maryland Climate Change Commission (MCCC) developed an action plan to address the causes of climate change, prepare for the likely consequences and impacts of climate change to Maryland , and establish firm benchmarks and timetables for implementing the Commission's recommendations. The Adaptation and Response Working Group (ARWG) was created within the MCCC to develop a Comprehensive Strategy outlining specific policy recommendations for reducing the vulnerability of the State's natural and cultural resources and communities to the impacts of climate change. The initial focus of the Strategy (2008) encompasses sea level rise and coastal hazards, including shore erosion and coastal flooding. This report lays out the specific priority policy recommendations of the ARWG to address short-and long-term adaptation and response measures, planning and policy integration, education and outreach, performance measurement, and, where necessary, new legislation and/or modifications to existing laws. Key recommendations outlined in the Strategy include:

- Take action now to protect human habitat and infrastructure from future risks.
- Minimize risks and shift to sustainable economies and investments.
- Guarantee the safety and well-being of Maryland 's citizens in times of foreseen and unforeseen risk.
- Retain and expand forests, wetlands, and beaches to protect us from coastal flooding.
- Give state and local governments the right tools to anticipate and plan for sea-level rise and climate change.
- State and local governments must commit resources and time to assure progress.

4.3 Adaptation Options for Transportation Infrastructure

According to the National Research Council's (NRC) *Potential Impacts of Climate Change on U.S. Transportation: Transportation Research Board Special Report 290* (2008), adaptation to climate change within the transportation sector falls into three categories of actions: operational changes, design changes, and other actions. Table 7 demonstrates the findings of a number of studies investigating adaptation options for transportation infrastructure and is organized by climate impact.

Climate variability and extreme events, such as storms and precipitation of increased intensity, will require changing operational responses from transportation providers. While U.S. transportation providers already address the impacts of weather on transportation system operations in a diverse range of climatic conditions, existing planning does not take into account long-term changes in climate. Operational changes may include (NRC, 2008): adjusting maintenance (both in the timing and type of maintenance); improved monitoring of conditions (both climatic and infrastructure conditions); incorporating climate scenario modeling into infrastructure planning; modifying procedures for emergency management; and altering construction schedules. In general, operational changes will apply to procedural planning at varying degrees of adjustment. For example, greater use of technology such as climate scenario modeling can enable infrastructure providers to monitor climate changes and receive advance warning of potential failures due to changing conditions (such as water levels and currents, wave action, winds, and temperatures) exceeding what the infrastructure was designed to withstand (NRC, 2008).

While transportation planning efforts do take weather conditions into account in the design of infrastructure, there is less examination of whether current design standards are sufficient to accommodate climate change (NRC, 2008). For example, the drainage capacity of road infrastructure often incorporates consideration of a 100-year storm event. However, climate projections indicate that current 100-year storm events are likely to occur more frequently (such as every 50 or perhaps even every 20 years) by the end of the current century (NRC, 2008). In this case, design standards for drainage would need to be updated to consider these changing conditions. Examples of design strategies include (NRC, 2008): improving materials or developing new materials; using alternative methods; upgrading current systems with improvements in design; and enhancing protection. Similarly, FEMA maps are often used to support development decisions, including citing roads. Because FEMA maps do not reflect projected climate change impacts, including effects of climate change on floodplain designations, roads may be established in areas that are highly vulnerable to flooding in the future.

Larsen et al. (2007) employs a bottom-up approach to monetize the costs and benefits of adapting through strategic redesign and replacement in Alaska . This study uses climate change projections for the near-term and far-term to estimate the replacement of statewide infrastructure and compares these estimates with what would be anticipated in the absence of climate change. The study determines the cost of adaptation through the redesign and replacement of airports, bridges, harbors, major roads, and railroads in response to permafrost melt, sea level rise, accelerated coastal erosion, increased flooding and increased fire risk. Benefits are realized over the long term as agencies will have greater opportunity to incorporate adaptation options into the state infrastructure planning (as planning practices evolve and infrastructure replacement opportunities arise) and include the reduction of costs that would have been realized had proactive adaptive strategies not been implemented. Kirshen et al. (2006) also uses a bottom-up approach to estimate the impact of climate change on various infrastructure sectors in metro Boston . The study compares three adaptation scenarios including a proactive scenario, a reactive scenario, and no adaptation scenario. The costs of the climate impact sustained through loss of service and repair/replacement are calculated as well as the adaptation costs associated with adjusting infrastructure systems and services to avoid the climate impact. Interestingly, this study allows for the inter-relation of climate impacting one infrastructure sector that in turn adversely impacts a secondary infrastructure structure, suggesting studies which focus on a single sector may minimize the actual costs. This study finds proactive adaptation optimally minimizes the costs associated with climate impacts

In addition to operational and design changes, other types of adaptation options are available for transportation infrastructure. Transportation planning and land use controls, especially concerning new construction and development, can integrate projected climate changes into the planning process. For example, development can be restricted or prohibited in zones most at risk from storm surges, flooding, and sea level rise. In addition, long-range planning and promoting cross-agency collaboration are two examples of other potential adaptation actions for transportation planning (NRC, 2008). Simpson et al. (2007) investigates the suitability of current culvert infrastructure in the White Brook watershed in Keene , NH to meet the projected increased frequency of heavy precipitation events. GCM projections are used to represent the changing climate. The assessment finds almost half of the culverts were undersized and will require upgrading.

Table 9 . Adaptation Options for Transportation Infrastructure

Climate Impact	**Potential Infrastructure Impact**	**Operational responses**	**Design strategies**	**Other**
Increased summer temperatures, increases in very hot days and heat	Highway asphalt rutting, possible movement of liquid asphalt (NRC, 2008)	• More maintenance (CCSP, 2008)	• Development of new, heat-resistant paving materials • Greater use of heat-tolerant street and highway	

waves			landscaping (NRC, 2008) • Proper design/construction, milling out ruts • Overlay with more rut-resistant asphalt (CCSP, 2008)	
	Thermal expansion of bridges (NRC, 2008)	• Increased ongoing maintenance (CCSP, 2008)	• Ensure that bridge joints can accommodate anticipated thermal expansion • Designing for higher maximum temperatures in replacement or new construction (NRC, 2008)	
	Limitation on construction periods during summer (NRC, 2008)	• Shifting construction schedules to cooler parts of day (NRC, 2008)		
Decreases in very cold days	Regional changes in snow and ice removal costs and environmental impacts from salt and chemical use (NRC, 2008)	• Reduction in snow and ice removal (NRC, 2008)		
	Fewer cold-related restrictions for maintenance workers (NRC, 2008)	• Extension of construction and maintenance season (NRC, 2008)		
Later onset of seasonal freeze and earlier onset of seasonal thaw	Improved mobility and safety associated with a reduction in winter weather (NRC, 2008)			
	Regional reduction in pavement deterioration resulting from less exposure to freezing, but possibility of more freeze-thaw in some locations (NRC, 2008)			

Thawing Permafrost, increased temperatures in the Arctic	Road embankments will fail and shallow pile foundations could settle; cave-in of bridge supports; shortened ice road season (NRC, 2008)	• Increased use of sonars to monitor streambed flow and bridge scour (NRC, 2008) • Rehabilitation, relocation, mechanically stabilize embankments against ground movement • Remove permafrost before construction (CCSP, 2008)	• Use of insulation in the road prism • Use of different types of passive refrigeration schemes, including thermosiphons, rock galleries, and "cold culverts" (NRC, 2008) • Crushed rock cooling system • Insulation/ground refrigeration systems (CCSP, 2008)	
	Exacerbated rutting and cracking of roads (Tighe et al., 2008)	• Relocation of section of roads to more stable ground (Tighe et al., 2008)	• Development of a protocol for incorporating climate change into the development of maintenance programs (Tighe et al., 2008)	
	Increased pavement deterioration as a result of high summer temperatures (southern Arctic areas) (Andrey, 2005)		• Losses due to pavement deterioration in summer likely to be outweighed by winter benefits, allowing leveraging of benefits (Andrey, 2005)	
	Increased scouring on bridges (CCSP, 2009)			
Increased Precipitation	Flooding of roads (frequency and magnitude will increase)	• Ensure bridge openings/culverts sufficient to deal with flooding • Improve drainage • Improved asphalt/concrete mixtures • Perform adequate maintenance • Minimize repair backlogs (CCSP, 2008) • Increases in real-time monitoring of flood levels • Integration of emergency	• Protection of critical evacuation routes • Upgrading of road drainage systems • Increases in culvert capacity • Increases in pumping capacity for tunnels • Increases in the standard for drainage capacity for new transportation infrastructure and major rehabilitation projects (NRC, 2008)	• Se alt rou • Im pro • Ris ass for • Em co pla (C • Gr of mo wa • Re de in

		evacuation procedures into operations (NRC, 2008)		(N
Sea Level Rise	Bridge scour	• Speed restrictions • Closure to traffic • Better maintenance (CCSP, 2008) • Expansion of systems for monitoring scour of bridge piers and abutments (NRC, 2008)	• Protection of bridge piers and abutments with riprap (NRC, 2008)	
	Inundations of roads in coastal areas and coastal erosion (San Francisco Bay area, New Orleans , Norway) (CCSP, 2009; CCSP, 2008; Deyle et al., 2007)		• Increased base elevation of infrastructure • Change in selection of building materials • Incremental elevation of roads with fill (NRC, 2008) • Addition of drainage canals near coastal roads (CCSP, 2008) • Bridges rebuilt with high elevations when cost effective • Relocation of sections of road to mainland • Strengthening and heightening of existing levees, seawalls and dikes (CCSP, 2009) • Appropriate zoning of residential, commercial and recreational areas • Combination of hard and soft engineering measures to protect coastline (ICF, 2007)	
Storms: More Frequent Strong Hurricanes (Category 4-5)	Highway embankments at risk of subsidence/heave	• Fill cracks • Carry out more maintenance (CCSP, 2008) • Increase in monitoring of land slopes and drainage systems (NRC, 2008)	• Addition of slope retention structures and retaining facilities for landslides (NRC, 2008)	

	Erosion of coastal highways		• Elevation of streets, bridges, and rail lines • Addition of drainage canals near coastal roads • Elevation and protection of bridge, tunnel, and transit entrances • Additional pumping capacity for tunnels (NRC, 2008)	• Co of (C • Re se roa lin • Pro hig coa sta lev sea dik • Str an he of lev sea dik • Re mo vu coa fro de • Inc flo ins rat res de • Re so are na 20
	Greater probability of infrastructure failures			• Str an he of • Re fur de in coa loc (N
Increases in intense precipitation events	Increases in weather-related delays and traffic disruptions (NRC, 2008)			
	Increases in flooding of roadways; Increases in road	• Expansion of monitoring systems of bridge scour, land	• Upgrading of road drainage systems (NRC, 2008)	

	washout, landslides and mudslides that damage roadways, increased bridge scour in the short term, compromised integrity of roads and bridges due to increased soil moisture (Department for Transport, 2004; NRC, 2008; CCSP, 2008)	slopes and drainage systems (NRC, 2008)	• Increases in the standard for drainage capacity for new structures (CCSP, 2009) • Pavement grooving and sloping • Greater use of sensors for monitoring water flows (CCSP, 2008)	
Changes in seasonal precipitation and river flow patterns	Potential benefit if frozen precipitation shifts to rainfall (NRC, 2008)			
	Increased risk of floods, landslides and damage to roads (areas where precipitation changes from snow to rain in winter and spring thaws) (NRC, 2008)		• Conduct risk assessments for all new roads (Department for Transport, 2004) • Encourage cooperation among drainage authorities (CSIRO, 2007) • Improved essential services planning (NRC, 2008)	
	Increased variation in wet/dry spells and decrease in available moisture may cause degradation of road foundations (CSIRO, 2007)			
Increases in drought conditions	Increased risk of mudslides in areas deforested by wildfires (NRC, 2008)	• Vegetation management (NRC, 2008)		
Storm Surges	Increased threat to stability of bridge decks		• Changes in bridge design to tie decks more securely to substructure and strengthen foundations (NRC, 2008)	
	Decreased expected lifetime			

	of highways exposed to storm surge			
Increased Wind Speeds	Coastal road flooding	• Improvements in monitoring of road conditions and issuance of real-time messages to motorists • Improvements in modeling of emergency evacuation (NRC, 2008)	• Design and material changes • Pumping of underpasses • Raise roads (CCSP, 2008) • Increases in drainage capacity for new transportation infrastructure or major rehabilitation projects • Removal of traffic bottlenecks on critical evacuation routes and building of more system redundancy • Adoption of modular construction techniques where infrastructure is in danger of failure • Development of modular traffic features and road sign systems for easier replacement (NRC, 2008)	• Se • Bu re int • Su us tha dis de on (C • Inc flo ins rat res de • Re so are na 20
	Bridges at risk		• Design structures for more turbulent wind conditions • Build with better material • Use "smart" technologies to detect abnormal events (CCSP, 2008)	
Increased risk of dryland salinity	Shallow, saline groundwater damages to roads and bridges (Australia) (CSIRO, 2007)			

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Appendix. Literature Research Approach

The approach for the literature review and analysis that informed this report was broken into three distinct tasks which are discussed below.

1. Conduct Literature Search

We established search terms for the literature search based upon guidance from our in-house adaptation experts. The goal was to gather information on climate change adaptation approaches, including risk assessments and vulnerability assessments.

The search terms selected include:

- infrastructure risk assessment
- infrastructure vulnerability assessment
- climate change infrastructure risk assessment
- climate change infrastructure vulnerability assessment
- climate change infrastructure adaptive capacity
- climate change infrastructure exposure
- climate change infrastructure exposure
- climate change infrastructure adaptation benefit
- climate change infrastructure sensitivity
- climate change infrastructure screening assessment
- climate change infrastructure tiered approach
- climate change infrastructure qualitative risk estimation
- climate change infrastructure quantitative risk assessment
- infrastructure hazard assessment
- infrastructure hazard scenarios
- infrastructure hazard risk
- climate change infrastructure response
- climate change infrastructure consequence
- Climate change adaptation decision matrix
- Climate change infrastructure management?
- Climate change infrastructure benefit-cost analysis
- Climate change infrastructure cost-effectiveness analysis
- Climate change infrastructure implementation analysis

The search was repeated replacing infrastructure with each of the following: highway, bridges, roadways, transportation, freight, built environment. It was determined the hazard assessment searches would most likely demonstrate work done in flooding and seismic activity.

The search was conducted using the DIALOG database system. DIALOG allows us to "multi-file" search which allows for searching across relevant data base files simultaneously including environmental, energy, governmental, sci/tech and other related files. The search found over 300 hits.

Box 9. DIALOG Database

"A collection of more than 550 data base files from a broad range of disciplines. A variety of more than 800 million full text or abstracted documents drawn from more sources than any other online service, including business and industry journals and trade press, scientific and technical literature, company directories, local/international newspapers, U.S. and foreign patents, financial statistics, demographic data, and chemical records. DIALOG is particularly noted for its focus on business, science, technology and intellectual property. Other major areas of interest include agriculture, biosciences, company/industry data, computers, energy and environment, government and law, medicine and health care, pharmaceuticals, local/regional/national/ international news, patents/trademarks/copyrights, people, consumer news, physical science and technology, and social sciences and humanities."

(DIALOG software)

2. Literature Screening

The literature identified in the search was then quickly screened and prioritized by title and information within the abstract, as available, for inclusion: thirty-two sources were identified as most relevant to this report; seventy-one sources were identified as second-tier relevance and have been marked for future reference; nine sources had already been identified through other in-house searches and were available in-house; and two hundred and eleven articles were viewed to be unlikely to be relevant for this work. The thirty-two likely relevant documents were then retrieved and placed on the ICF hard drive.

3. Evaluate Screened Literature

The thirty-two sources were then examined for useful report information and an excel spreadsheet was created to house the literature and identify the assessments discussed. Useful information retrieved from each document was placed into a table from each to provide the notes for this report (see Table 8 below).

Table 10 . Sample excerpt taken from the Excel Spreadsheet used to organize the collected literature

Mostly risk assessment
Mostly vulnerability assessment
Mostly adaptation

[actual report title]			[yes/no]	[yes/no]	[yes/no]	[yes/no]	[location of file]	[open; indicate usefulness]
Title	Author(s)	Date	Risk	Vulnerability	Adaptation	Cross-cutting	Folder	Notes
SAP 4.7: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I	USCCSP	March, 2008	yes	yes	yes	yes	cross-cutting	key synthesis report relevant to transport infrastructure
Adapting Infrastructure to Climate Change in Canada's Cities and Communities: A Literature Review	Infrastructure Canada	December, 2006	no	no	yes	no	adaptation	Assesses adaptation responses for infrastructure in Canada, and reviews literature and research related to infrastructure and climate change adaptation in Canada
Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure	Canadian Council of Professional Engineers (Engineers Canada)	April, 2008	no	yes	no	no	vulnerability	Engineering vulnerability assessment of four categories of Canadian public infrastructure: stormwater and wastewater; water resources; roads and associated structures; and buildings
Applying an index of adaptive capacity to climate change in North-Western Victoria, Australia	Remy Stekhiping	2006	no	no	yes	no	adaptation	Discusses how adaptive various communities and industries are to climate change in Victoria
Climate change and extreme weather events: can developing countries adapt?	M. Monirul Qader Mirza	2003	yes	yes	yes	yes	cross-cutting	Reviews various vulnerability and adaptation assessment strategies; discusses studies of extreme weather events and coping capacity and adaptation measures
Climate change and London's transport systems	London Climate Change Partnership	September, 2005	yes	no	yes	yes	cross-cutting	Impacts of climate change on London's transport and how to adapt; provides case studies
Climate change uncertainty and the state highway network: A moving target	Kinsella and McGuire	No date	yes	no	yes	yes	cross-cutting	Assesses the potential climate change impacts on state highways and develops potential responses