TRANSPORTATION RESEARCH
CIRCULAR
Number E-C181 December 2013

Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector

A Synthesis of Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

TRANSPORTATION RESEARCH CIRCULAR E-C181

Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector

A Synthesis of Practice

Thomas A. Wall
Michael D. Meyer

Prepared for the
Climate Change, Energy, and Sustainability
Impacts on the Transportation Infrastructure Subcommittee

TRB Design and Construction Group

November 2013

Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001
www.TRB.org

TRANSPORTATION RESEARCH CIRCULAR E-C181

Transportation Research Board
500 Fifth Street, NW
Washington, D.C.
www.TRB

Javy Awan, Production Editor; Jennifer Correro, Proofreading and Layout

Preface

During its January 2008 meeting, the TRB Design and Construction Group approved the formation of a new subcommittee: Climate Change, Energy, and Sustainability Impacts on the Transportation Infrastructure. The subcommittee was charged with providing internal coordination within the Design and Construction Group, supplementing and supporting the activities of the existing TRB Special Task Force on Energy and Climate Change as well as other relevant TRB efforts and NCHRP projects, and promoting the interests of standing committees within the Design and Construction Group by sponsoring activities and events within TRB.

The formation of the subcommittee reflected a growing awareness that the committees within the Design and Construction Group cannot stand aloof from the climate change, energy, and sustainability initiatives within TRB. These committees oversee technical design or construction issues that are directly related to, or are affected by, climate change. For example, a changing climate and associated variations in weather patterns may affect the severity of storm events, and thus the design of infrastructure elements, including culverts, earthworks, pavements and structures, while changed thermal and moisture regimes will influence the life-cycle performance and maintenance requirements of many transportation elements.

Beginning in 2009, the subcommittee sponsored or cosponsored sessions and workshops at each TRB Annual Meeting. At the 2013 Annual Meeting of the Transportation Research Board it sponsored Workshop 141: Reducing Risks and Costs of Climate Change: Preparedness and Adaptation in the Face of Increasingly Extreme Weather and Session 509: Assessing Potential Impacts of Climate Change on Transportation Infrastructure. This circular is an expanded version of a paper presented in Session 509. During the paper review process, several reviewers recommended that this paper be further developed and published as a circular.

The information presented in this circular was gathered as part of a larger research project conducted at the Georgia Institute of Technology. Recent studies of the climate change adaptation frameworks emerging from the transportation sector show a strong focus on risk. However, the unique experiences and conditions associated with the development of individual frameworks have resulted in some variability in their specific approaches to risk. Recognizing this, the goal has been to review and synthesize how risk is approached by various transportation and infrastructure adaptation frameworks from around the world. The intent is to identify leading adaptation frameworks and to examine the unique aspects of each framework's development and approach. The result is a synthesis of a knowledge base that may be helpful to both researchers and practitioners. The contents of this circular contain the opinions of the authors and are not endorsed by TRB or AASHTO.

The TRB Subcommittee Climate Change, Energy, and Sustainability Impacts on the Transportation Infrastructure sincerely thanks the authors for their contributions to this circular. Critical reviews were provided by Jeffrey R. Keaton, AMEC Environment and Infrastructure; Stephen Lane, Virginia Center for Transportation Innovation and Research; David Orr, Cornell University; and Marie Venner, Venner Consulting. Special thanks are expressed to TRB staff representative G. P. Jayaprakash for providing continued support and assistance during the development of this circular.

—A. Keith Turner, *Chair*
Climate Change, Energy, and Sustainability Impacts on the Transportation Infrastructure Subcommittee

Contents

Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector

A Synthesis of Practice

THOMAS A. WALL
Georgia Institute of Technology

MICHAEL D. MEYER
Parsons Brinckerhoff

Consensus is growing within the scientific community that the global climate system is changing. Many of these global changes are projected to translate into regionally significant environmental impacts, including increases in precipitation, temperature, sea-level rise, and the intensity of extreme weather events. In the transportation sector, the design and management of infrastructure is heavily influenced by the surrounding environment. Given the uncertain future of regional environmental conditions and climate impacts, the current design and management practices of existing infrastructure may be inadequate over the coming decades. Research institutions and government agencies in the United States (e.g., TRB, FHWA) and abroad (e.g., the United Kingdom Highways Agency, New Zealand Transport) have begun to investigate adaptation strategies and evaluation frameworks for transportation infrastructure. Many of these adaptation strategies are heavily influenced by the tenets of risk analysis and risk management. This circular synthesizes several leading risk-based adaptation frameworks from the international transportation community. Commonalities among these frameworks were synthesized for four key areas: (*a*) the underlying motivation for initiating climate change adaptation planning, (*b*) the foundational risk-management standards–principles used to develop these frameworks, (*c*) the focus and approach of the frameworks, and (*d*) the barriers and limitations identified by the transportation agencies and organizations. The circular concludes with suggestions for future research priorities.

INTRODUCTION

The United Nation's Intergovernmental Panel on Climate Change (IPCC) has stated that the "warming of the climate system is unequivocal, as is now evident from observed increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (*1*). In the coming decades, it is expected that these changes will result in regional climate impacts, including, but not limited to, permafrost thawing, increased tropical cyclone intensity, shifting tropical storm tracks, and an increase in the frequency of heat waves and heavy precipitation (*1*). As a result of these findings, concern is growing both in the United States (*2*, *3*) and abroad (*4*–*7*) that these changes will have serious adverse impacts on transportation and civil infrastructure systems unless agencies take proactive steps to mitigate these issues.

In response to these concerns, governments and agencies in charge of managing infrastructure have begun to investigate ways to adapt—to reduce the vulnerability of their infrastructure systems and practices against potential climate change effects (*8*). In recent years, adaptation has attracted much attention in the transportation sector (*9–13*), and some formalized adaptation strategies have emerged.

Much of the transportation and infrastructure sector's approach to climate change impact analysis and adaptation planning is based on risk management: an approach broadly endorsed by the adaptation community (*2*, *14*, *15*). For the purposes of this discussion, we use the traditional definition of risk as the combination of the *likelihood* or *probability* of a negative event occurring, and the *consequences* of that negative event.

Risk and risk management are familiar to the transportation and infrastructure sectors that already utilize risk-based practices (*9*). For example, Meyer (*16*) notes that the AASHTO *Load and Resistance Factor Design* (LRFD) *Bridge Design Specifications* (*17*) "incorporates risk into the calculations of bridge design parameters." Also, parameters such as the "design storm" or the "100-year flood" are inherently risk-based parameters as they are attached to some likelihood of occurrence (e.g., a return period of approximately 100 years, or an annualized probability of occurrence of 0.01) to an event that reaches or exceeds a certain level of significance or magnitude.

Many transportation agencies and organizations around the globe have leveraged their familiarity with risk-based practices to develop risk-management frameworks that address climate change adaptation planning. Although no single unified approach has emerged, many approaches are built around common principles, follow similar procedures, and encounter similar problems.

This circular synthesizes the current state of practice in the transportation sector and provides a foundation of knowledge for future framework development. A two-stage process was followed. First, a number of the leading risk-based climate change adaptation frameworks from the international transportation community were identified. Then, commonalities among these framework strategies were identified by an iterative process and fell into four key areas. Initially only two key areas were used: (*a*) the focus and approach of the frameworks and (*b*) the barriers and limitations identified by the transportation agencies and organizations that must be addressed and overcome to move forward. However, as the process continued, two additional key areas were added because they provide valuable guidance and context. These are (*c*) the risk-management standards–principles used to develop these frameworks and (*d*) the underlying motivation for initiating climate change adaptation planning. This circular concludes with suggestions for future research to address the common issues encountered in climate change adaptation planning.

SYNTHESIS APPROACH

The first step in the synthesis approach was identifying the leading climate change adaptation frameworks proposed by the global transportation community. These frameworks were initially identified on a country-by-country basis by conducting Internet searches on relevant government agency websites [e.g., national departments of transportation (DOTs), national highway administrations], national engineering society websites, and regional planning organization (RPO) websites. Searches were limited to agencies with English-language websites and reports. Several European Union (EU) countries, such as the Netherlands and Scandinavian countries, provided English-language examples of European approaches. Most of these referenced regional smart-growth studies with strong climate elements or non-risk general climate vulnerability studies. However, the Risk Management for Roads in a Changing Climate (RIMAROCC) framework, discussed subsequently, is an EU framework, conducted by a partnership of SGI (Sweden), EGIS (France), Deltares (Netherlands), and NGI (Norway). Additional frameworks were then identified through a broader literature search.

The second step in the synthesis was screening of the identified climate change adaptation frameworks to identify leading frameworks. The frameworks were screened according to the general maturity of their climate change impact evaluation and management approach, and for those that incorporated elements of risk-based practices (e.g., risk analysis, risk management). This screening eliminated reports containing only generalized impact investigations and vulnerability analyses. Each of the selected adaptation framework reports were then read with a specific focus on the four key synthesis areas noted in the introduction, with a qualitative ranking made of the frequency and prevalence of commonalities and important themes.

ADAPTATION FRAMEWORKS

Adaptation frameworks that incorporate risk-based practices in the analysis and management of climate change impacts on transportation infrastructure were the focus of the synthesis. Two categories of risk-based adaptation frameworks were examined.

The first category contains adaptation frameworks that address general infrastructure system concerns, of which transportation infrastructure is one component. These frameworks were generally developed by agencies at the municipal and regional level, national engineering societies, or were incorporated into frameworks from intersecting fields (e.g., flood risk management). For example, the Canadian Council of Professional Engineers developed a risk-based vulnerability assessment framework (Figure 1) to evaluate climate change risks in building, roadway asset, stormwater–wastewater systems, and water resource management infrastructures (*18*). Table 1 lists the general infrastructure adaptation frameworks that were examined.

The second category contains risk-based adaptation frameworks that specifically address transportation infrastructure and management activities. These frameworks were typically developed by government transportation agencies for broad, national-level evaluations, or by independent and private-sector transportation organizations (e.g., airport, port, and rail operators) to evaluate their own infrastructure and management activities. For example, the U.K. Highways Agency's Climate Change Adaptation Strategy and Framework (Figure 2) is very specifically designed to identify and address climate change risks in highway infrastructure and agency practices (*19*). Table 2 lists the transportation infrastructure-specific adaptation frameworks that were examined.

Risk-based adaptation frameworks relevant to the global transportation sector exist beyond those identified in Tables 1 and 2. However, the intent is to provide an overview of the leading risk-based adaptation frameworks to enable a synthesis of commonalities, motivations, barriers, and limitations. The selected frameworks provide a sufficient sampling to draw conclusions of the current state of practice in the transportation community.

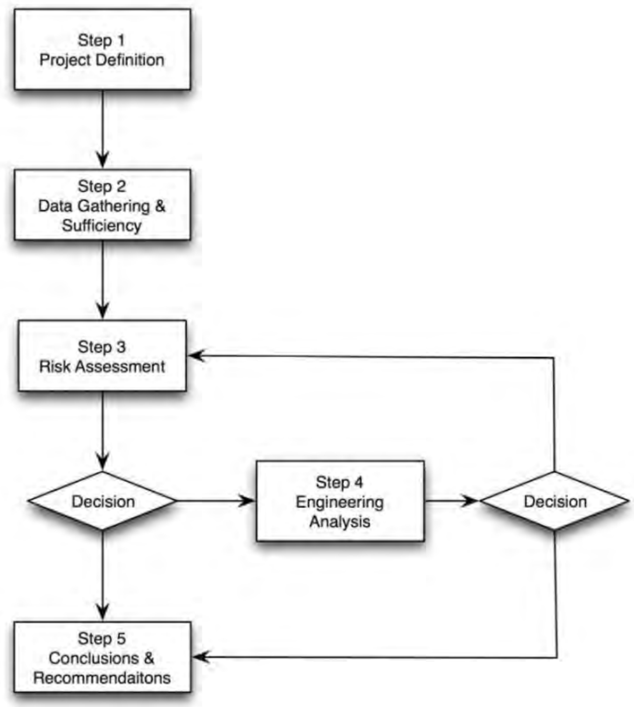

FIGURE 1 General infrastructure adaptation framework (*18*).

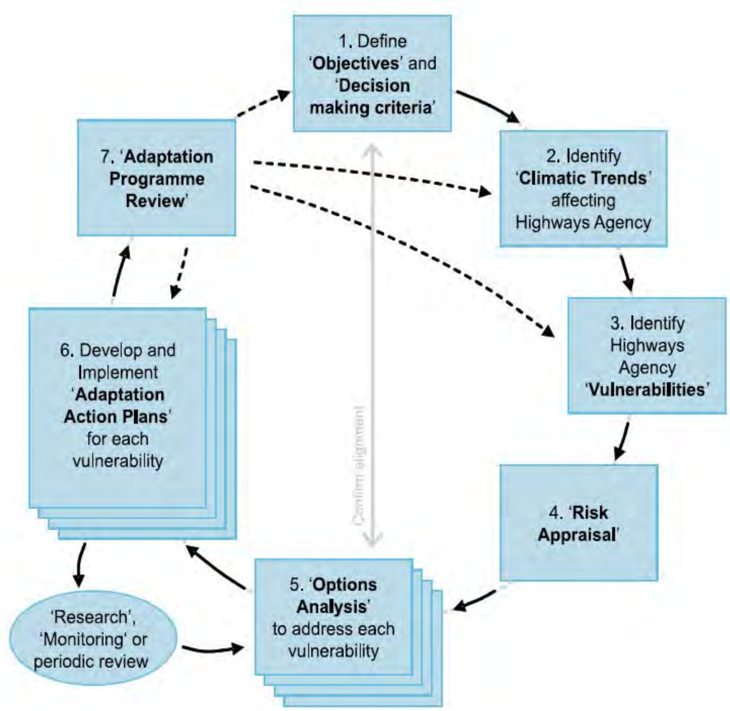

FIGURE 2 Highway infrastructure adaptation framework (*19*).

TABLE 1 General Infrastructure Adaptation Frameworks

Framework	Country of Origin	Agency or Organization
Climate Change Risks to Australia's Coast: A First-Pass National Assessment	Australia	Department of Climate Change (*5*)
Climate Change Risks for Coastal Buildings and Infrastructure: Supplement to the First-Pass National Assessment	Australia	Department of Climate Change and Energy Efficiency (*7*)
Infrastructure and Climate Change Risk Assessment for Victoria	Australia	Victorian Government; CSIRO (*20*)
Adapting To Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure	Canada	Engineers Canada–Public Infrastructure Engineering Vulnerability Committee (PIEVC) (*21*)
PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment	Canada	Engineers Canada–Public Infrastructure Engineering Vulnerability Committee (PIEVC) (*18*)
Adapting to Climate Change: A Risk-Based Guide for Ontario Municipalities	Canada	Ontario Ministry of Municipal Affairs and Housing (*22*)
Adapting to Climate Change: A Risk-Based Guide for Local Governments	Canada	National Resources Canada (*23*)
Ahead of the Storm: Preparing Toronto for Climate Change	Canada	Department of Climate Change Adaptation Strategy (*24*)
Climate Change Risk Management Strategy for Halifax Regional Municipality	Canada	Halifax Regional Municipality (*25*)
National Flood Risk Assessment	Scotland	Scottish Environmental Protection Agency (SEPA) (*26*)
Flood Risk Management Strategies and Local Flood Risk Management Plans	Scotland	Scottish Environmental Protection Agency (*27*)
Climate Change Adaptation in New York City: Building a Risk Management Response	United States	New York City Panel on Climate Change (*28*)
Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments	United States	King County (Wash.) Executive (*29*)

TABLE 2 Transportation Infrastructure-Specific Adaptation Frameworks

Framework	Country of Origin	Agency or Organization
Impact of Climate Change on Road Infrastructure	Australia	Austroads (*30*)
Risk Management for Roads in a Changing Climate: A Guidebook to the RIMAROCC Method	European Union	ERA–NET (*31*)
Climate Change Uncertainty and the State Highway Network: A Moving Target	New Zealand	Transit New Zealand (*32*)
Climate Change Effects on the Land Transport Network, Volume 1: Literature Review and Gap Analysis	New Zealand	NZ Transport Agency (*10*)
Climate Change Effects on the Land Transport Network, Volume 2: Approach to Risk Management	New Zealand	NZ Transport Agency (*33*)
Scottish Road Network Climate Change Study	Scotland	Scottish Executive (*34*)
Scottish Road Network Climate Change Study: Progress on Recommendations	Scotland	Transport Scotland (*35*)
Scottish Road Network Landslides Study	Scotland	Scottish Executive (*36*)
Adaptation Reporting Powers received reports[a]	United Kingdom	Department of Environment, Food and Rural Affairs (*37*)
Climate Change Adaptation Strategy	United Kingdom	U.K. Highways Agency (*38*)
Climate Change Adaptation Strategy and Framework	United Kingdom	U.K. Highways Agency (*19*)
Climate Change Risk Assessment	United Kingdom	U.K. Highways Agency (*39*)
Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual Model[b]	United States	FHWA (*40*)
Climate Change and Extreme Weather Vulnerability Assessment Framework	United States	FHWA (*41*)

[a] Twenty-three agency reports were reviewed under the U.K. Department for Environment, Food, and Rural Affairs (DEFRA) reporting powers requirement. A full agency list can be found at http://www.defra.gov.uk/environment/climate/sectors/reporting-authorities/reporting-authorities-reports/.
[b] This includes five pilot program case study reports: MTC (*42*), NJTPA (*43*), Oahu Metropolitan Planning Organization (MPO) (*44*), Virginia DOT (*45*), and Washington State DOT (*46*).

FRAMEWORK COMMONALITIES

Commonalities among these framework strategies were synthesized for four key areas of these strategies: (*a*) the underlying motivation for initiating climate change adaptation planning; (*b*) the foundational risk-management standards–principles used to develop these strategies; (*c*) commonalities in the focus and approach of the frameworks; and (*d*) the barriers and limitations that must be addressed and overcome to move forward. For each of these four key areas, the following sections present commonality aspects in descending order of their prevalence or frequency within the framework reports reviewed.

Underlying Motivation for Framework Development

Among the frameworks reviewed, it was frequently difficult to determine the exact underlying forces motivating their development. However, three themes emerged as common motivating factors in many of the frameworks:

1. Government acts, laws, or legislation;
2. Initiatives motivated by extreme weather events; and
3. Self-motivated agency initiatives.

Numerous frameworks, most notably in the United Kingdom and Australia, were motivated by a government act, law, or similar legislation. In 2008, the United Kingdom Parliament passed the U.K. Climate Change Act (*47*), a part of which granted reporting power to government departments. This enabled departments to require climate change adaptation reports from various agencies under their oversight. In 2010, DEFRA issued direction to numerous transport, infrastructure, and utility agencies requiring that they submit adaptation reports (*48*). By October 2011, more than 90 agencies, organizations, and authorities had submitted reports outlining adaptation actions and the evaluation frameworks developed. Twenty-three of these came from the transportation sector (e.g., road and rail operators, port authorities, airports) (*37*).

In 2007, the Council of Australian Governments (COAG) agreed to the National Climate Change Adaptation Framework (*49*), one goal of which was to assess climate change risks to Australia's coastline. This initiative led to the development of a national assessment of coastal climate change risks (*5*, *7*). Also in 2007, the Australian government established the Department of Climate Change (now the Department of Climate Change and Energy Efficiency) to lead "an effective national response and global contribution on climate change" (*50*).

In some cases, adaptation framework development was motivated by extreme weather events, which were taken as indicators of potential future climatic conditions. For example, the Scottish Executive noted that "the landslide events of August 2004 had a substantial impact on Scotland's road network" (*34*) and responded by commissioning the Scottish Road Network Climate Change Study (*34*) and the Scottish Road Network Landslides Study (*36*). It also seems likely that the Gulf Coast studies sponsored by FHWA (*11*, *13*) were in part motivated by catastrophic effects of major hurricanes along the U.S. Gulf Coast.

Most other adaptation frameworks were motivated by internal agency planning and research initiatives. For example, internal adaptation planning and framework development initiatives at the New Zealand Transport Agency (*10*, *33*) were directly motivated by concerns identified in reports from the Ministry of Environment. The RIMAROCC framework developed in the EU (*31*) was developed by an internally motivated research consortium (ERA–NET ROAD) funded by the European Commission. The report *Preparing for Climate Change: A Guidebook for Local, Regional and State Governments* (*29*) is an example of a framework developed as part of an independent research initiative motivated by climate-related concerns in Washington state.

Risk Standards Used in Framework Development

To develop their adaptation frameworks, most agencies and organizations drew from existing risk-management practices. Independent and private-sector transportation organizations (i.e., port authorities, airports) frequently reported that enterprise risk management was already a part of their existing business management activities, and that climate change adaptation planning would be incorporated into these existing practices.

Some noted that specific standards had been used in developing their enterprise risk-management practices. For example, in the United Kingdom, both the Port of Dover (*51*) and NATS Holdings (formerly National Air Traffic Services), the main air navigation service provider in the United Kingdom, reported that the standard, ISO 31000:2009 Risk Management: Principles and Guidelines (*52*), was a major resource used in developing their risk management programs (*53*).

In Canada, the Ontario Ministry of Municipal Affairs and Housing (*22*) and National Resources Canada (NRCAN) (*54*) both reported that the standard, CAN/CSA-Q850-01 – Risk Management: Guidelines for Decision-Makers, was used in developing their frameworks. The Halifax Regional Municipality (*25*) used an earlier edition of the same standard, as well as CAN/CSA-Q634-M91: Risk Analysis Requirements and Guidelines.

Frameworks in Australia (*10*, *20*, *33*) were predominantly informed by AS/NZS 4360:2004: Risk Management and the superseding standard, AS/NZS 31000:2009 (*55*). This latter standard is also specified by the ISO as ISO 31000:2009 (*52*). The development of the RIMAROCC framework in the EU (*31*) is also based on ISO 31000:2009 (*52*). Figure 3 shows the general risk management process specified by ISO 31000:2009.

Commonalities in the Focus and Approach of Frameworks

Commonalities in Focus

The frameworks reviewed focused on adaptation in three primary areas: (*a*) physical infrastructure and assets; (*b*) operations and maintenance; and to a lesser degree, (*c*) organizational management.

Adaptation of Physical Infrastructure and Assets Adaptation of physical infrastructure and assets was a primary focus of the frameworks reviewed. Generally speaking, this type of adaptation seeks to evaluate the impacts and vulnerabilities of existing physical infrastructure and assets, and then identify and implement actions that seek to minimize or mitigate climate change vulnerabilities. An example would be a state DOT replacing drainage culverts with larger structures, or better maintaining existing structures, where runoff flows are expected to increase. Many adaptation planning frameworks examine infrastructure at the system and corridor levels; however, some frameworks, for example, the FHWA conceptual framework (*40*) and related

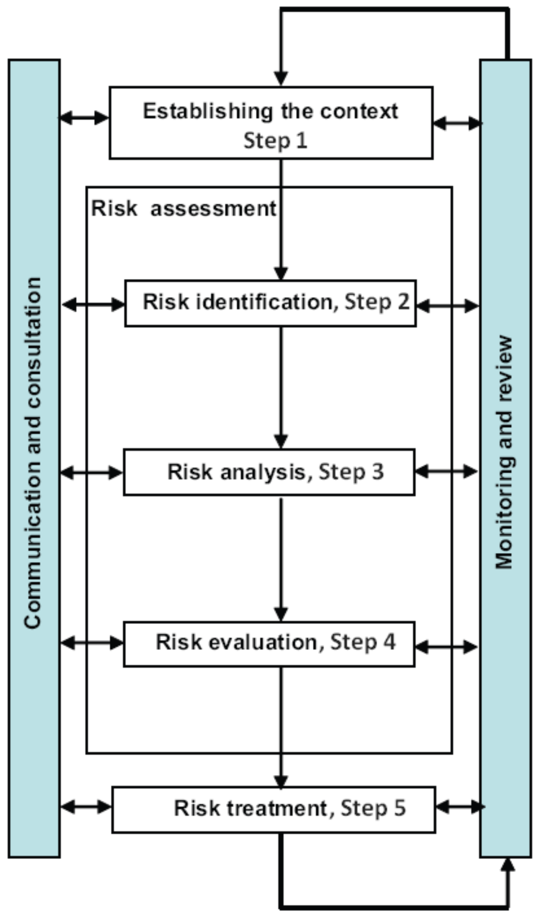

FIGURE 3 ISO 31000:2009: risk management process (*52*, *55*).

pilot studies (*42*, *45*), evaluated infrastructure at the individual asset or project levels. Additionally, the RIMAROCC framework (*31*) from the EU was designed to enable adaptation analysis and planning at the system, corridor, and individual asset levels by examining various "domains of expertise," including

- Pavements;
- Bridges;
- Equipment (e.g., road signs, lighting, safety barriers);
- Small hydraulics (drums) and drainage;
- Geotechnics;
- Environment;
- Large hydraulics (culverts); and
- Sea level.

Adaptation of Operations and Maintenance Practices Adaptation of operations and maintenance practices was also a primary focus of the adaptation frameworks reviewed. This type of adaptation seeks to evaluate the impacts of future climate conditions on operations and maintenance practices, and identify and implement strategies to mitigate the impacts of future climate conditions. An example would be an airport operator purchasing additional snow-clearing equipment to ensure that increases in winter storm events do not significantly disrupt airport operations. Particularly in the United Kingdom, several of the DEFRA-reporting power agency frameworks explicitly considered climate change impacts on operations and maintenance (*37*). For example, every U.K. airport operator who submitted an adaptation report to DEFRA identified significant impacts of climate-induced changes in weather on airport operations and maintenance, ranging from an increasing number of extreme weather periods (impacting operations) to longer growing seasons for vegetation (impacting maintenance).

Adaptation of Organizational Management A limited number of frameworks evaluated the broader impacts of climate change on organizational management. An important example is the U.K. Highways Agency (*39*) that considered how increases in mean temperature would affect the amount of energy consumed to heat and cool their offices, control centers, and outstations.

Commonalities in Approach

The common approach of the developed frameworks was generally consistent with practices outlined in the ISO 31000: 2009 standard shown in Figure 3, with only minor alterations or expansions of the steps outlined. Several of the steps were commonly altered or expanded to tailor the generic approach to the unique aspects of climate change planning (e.g., need for qualitative likelihood in risk analysis).

Step 1. Establishing the Context This step generally consisted of defining goals and objectives, collecting infrastructure inventory and projected climate data, and assembling expert panels. The use of expert panels, or expert workshops, in the risk assessment activities (Steps 2 through 4) was nearly universal across the frameworks reviewed.

Step 2. Risk Identification This step commonly consisted of identifying relevant climate change hazards–impacts, identifying vulnerabilities within the infrastructure system or agency's activities, and identifying likely consequences of climate impacts. This frequently involved the identification of regional focus areas or priorities (e.g., focus only on coastal sea-level rise, specific regions), and critical infrastructure systems. Agencies often developed matrices to aid in this effort across multiple infrastructure types, agency activities, and impact types (*19–21, 31, 56*).

Step 3. Risk Analysis This step consisted of assigning qualitative (e.g., low, medium, high) or semiquantitative (e.g., 1 through 5) scores to the aspects of the climate impact. Typically this was simply the risk's likelihood and consequences. In some cases, the analysis examined other elements. For example, the U.K. Highways Agency (*19*) framework asks experts to rank (low, medium, high) four specific risk criteria: (*a*) uncertainty, (*b*) rate of climate change (i.e., time horizon associated with predicted changes), (*c*) extent of disruption (i.e., number of locations, extent of network), and (*d*) severity of disruption (i.e., recovery time or disruption time). In another example, the Washington State DOT (*46*) examined two elements: (*a*) impact severity (e.g., reduced capacity, temporary failure, complete failure) and (*b*) asset criticality.

Step 4. Risk Evaluation The evaluation of risks constitutes some type of ranking of the risk analysis results to identify priorities for adaptation. Most commonly this consisted of inputting the scores from Step 3 into a risk matrix to evaluate and prioritize risks. Risk matrices position the variables (e.g., likelihood and consequence, criticality and impact) associated with a climate change impact on the *x* and *y* axes of a Cartesian coordinate system; those events with higher combined likelihood and impact receive higher risk prioritization scores than those with lower rankings. Matrices range from simple matrices with discrete low–medium–high regions (Figure 4) to much more complex matrices with less discrete heat map regions (Figure 5), or multidimensional matrices that incorporate additional criteria (Figure 6).

Another common approach to risk evaluation consists of quantitatively determining risk scores or priority rankings. One motivation for this approach is the examination of additional criteria, which is beyond the capacity of a two- or three-dimensional risk matrix. The risk score is generally computed using a simple equation of the relevant criteria. For example, the U.K. Highways Agency (*19*) assigns low, medium, and high criteria ratings scores of 1, 2, and 3, respectively. These are then input into the following equation to arrive at an "indicator score":

$$\frac{[\text{Rate of climate change}] \times [\text{Extent of disruption}] \times [\text{Severity of disruption}] \times (4 - [\text{Uncertainty}])}{81}$$

More complicated evaluations of risk were found, for example the Virginia DOT pilot study of the FHWA Conceptual Model (*45*) computed scores incorporating climate, economic, deterioration, ecological, and traffic demand criteria, which were then input into a multicriteria decision analysis (MCDA) model to evaluate risks under multiple climate scenarios.

In many of the frameworks reviewed, steps 3 and 4 were frequently combined into a single step, called a risk appraisal (*19*), or a risk assessment (*18*).

Step 5. Risk Treatment The treatment of risk concerns the development, selection, and implementation of an adaptation action. This step was commonly broken into two discrete steps:

1. Identification, evaluation, and selection of adaptive action options, and
2. Implementation of the selected option.

The identification, evaluation, and selection of an adaptation action generally consisted of a multistep options analysis. To identify viable adaptation options, some frameworks contained tables with generic classes of adaptation options (*19*, *31*); others offered examples for certain types of infrastructure and suggested a site analysis for the affected assets (*57*).

The United Kingdom Climate Impacts Programme (*15*), which presents a nontransportation-specific risk-based adaptation framework, classifies adaptation option evaluation techniques in three tiers: (*a*) systematic qualitative analyses; (*b*) alternative methods (i.e., semiquantitative); and (*c*) quantitative and economics-based methods. They present 26 separate evaluation methods that might be used to evaluative adaptation options (Table 3). The synthesis, however, revealed that the evaluation of adaptation options and the selection of a preferred option most frequently involved a benefit–cost analysis (*19*, *31*, *57*). However, other selection methodologies included multiattribute analysis (*33*), ad-hoc multiattribute evaluation matrices (*23*, *28*), or general recommendations to consider "effectiveness, cost, residual risks and stakeholder acceptance" (*22*).

		Impact			
		Catastrophic	Major	Moderate	Minor
Likelihood	Very Likely	High	High	Med	Med
	Likely	High	High	Med	Low
	Medium	High	Med	Med	Low
	Unlikely	Med	Med	Low	Low
	Very Unlikely	Med	Med	Low	Low

FIGURE 4 Simple risk prioritization matrix (*56*).

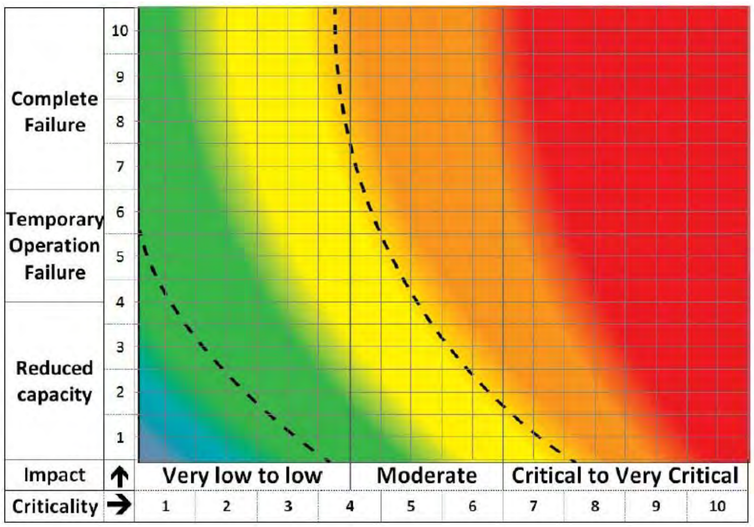

FIGURE 5 Complex risk prioritization matrix (*46*).

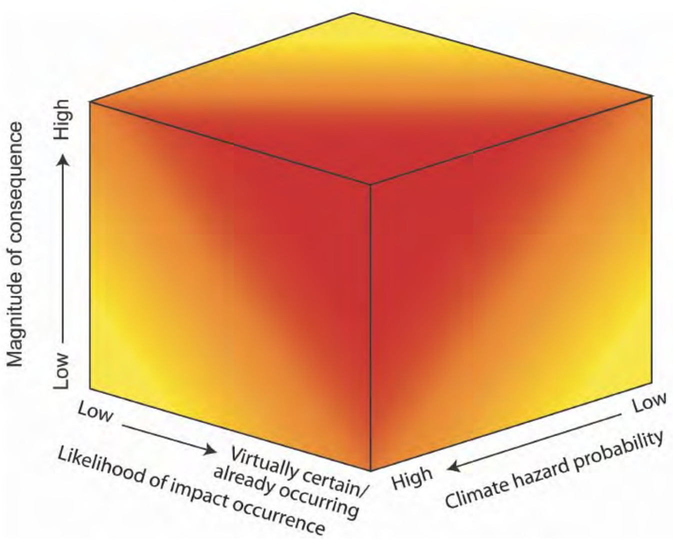

FIGURE 6 Multidimensional prioritization matrix (*28*).

TABLE 3 General Adaptation Option Evaluation Methods (*15*)

Tool–Technique	Qualitative Methods	Alternative Methods	Quantitative or Economics-Based Methods
Consultation exercises	x		
Focus groups	x		
Ranking–dominance analysis	x		
Screening		x	
Scenario analysis	x	x x	
Cross-impact analysis	x		
Pairwise comparison	x		
Sieve mapping	x		
Maximax, maximin, minimax regret			x
Expected value			x
Cost-effectiveness analysis			x
Cost–benefit analysis			x
Decision analysis			x
Bayesian methods			x
Decision conferencing			x
Discounting			x
Environmental impact assessment–strategic environmental assessment		x	
Multicriteria analysis (scoring and weighting)		x	
Risk–risk analysis		x	
Contingent valuation			
Revealed performance			**x**
Stated performance		**x**	**x**
Fixed rule-based fuzzy logic	**x**	**x x**	
Financial analysis			**x**
Partial cost–benefit analysis	**x**	**x**	
Preference scales	**x**		
Free-form gaming	**x**		
Policy exercise	**x**		

In some cases, this step was further broken down to identify synergies with other agency activities. For example, the FHWA framework (*41*) identifies synergies with several practices:

1. Asset management,
2. Emergency and risk management,
3. Hazard mitigation plans,

4. Transportation planning project selection criteria, and
5. Environmental review.

More broadly, the framework developed by the New York City Panel on Climate Change (*28*) discusses the need to identify opportunities for coordination among various city offices and stakeholders.

Implementation of the selected adaptation option(s) forms the second component of Step 5. In some cases, the implementation plan and delivery were discretized into specific steps and responsibilities (*19*, *22*, *23*). Implementation frequently included the development of a monitoring framework to periodically collect data on climate, asset performance, and agency activities. It was frequently noted in the frameworks reviewed (*10*, *31–33*, *36*, *41*, *45*, *46*, *57*), and has also been noted elsewhere (*58*, *59*) the importance of linking climate change adaptation planning with transportation asset management (TAM) programs due to the data-driven nature of those programs, which could be synergistic with adaptation monitoring.

Common Barriers and Limitations

In discussing the development of their frameworks, many agencies reported the limitations of their risk-based adaptation frameworks, as well as barriers, both internal and external, which could inhibit the framework's implementation. We have characterized common barriers and limitations as falling into five categories. These categories can be divided into two classifications: those that were more predominant (categories 1 through 3), and those that were less predominant (categories 4 and 5) in the framework literature:

1. Data limitations;
2. Treatment of risk;
3. Availability of sufficient resources;
4. Legal, political, and regulatory barriers; and
5. Uncertain future system demand.

Data Limitations

Of the barriers and limitations noted, limited data was the most prevalent and applies to two types of data: (*a*) infrastructure system and asset data and (*b*) climate data. Primarily three types of limitations apply to infrastructure asset and system data:

- Unavailable. No inventory or database exists for certain types of assets (e.g., culverts).
- Incomplete–inconsistent. Data does not contain all necessary or relevant fields (e.g., asset condition), or contains information for some assets but not others.
- Not easily accessed. Necessary or relevant data may be available, but is spread across multiple departments within an agency and must be coalesced.

The predominant limitation noted for climate data was that the projections available to agencies for planning purposes are not downscaled to a level of detail sufficient for decision making at the local or regional level. Some agencies also noted that some types of climate impacts are better characterized in projections than others. For example, port authorities in the United Kingdom noted that changes in wind and fog conditions could significantly impact their operations, yet their projections contain significantly more uncertainty than other projected impacts (*60*, *61*).

Treatment of Risk

The way in which risk is perceived and characterized was the second most commonly listed limitation or barrier. Most significantly, numerous agencies noted that it is difficult to define acceptable levels or risk, relevant types of risks, and the critical thresholds of risk. Furthermore, in the decision-making process, difficulty was noted in linking the immediate need for action with risks that are perceived to be of long-term or distant consequence.

The difficulty in linking risk levels to the decision-making process is further compounded by what many agencies discussed as the qualitative treatment of risk. As noted in the previous section, risk analysis and prioritization is primarily conducted using expert opinion and risk matrices. This qualitative approach, although necessitated by data limitations, was found to be politically unacceptable in determining priorities and infrastructure asset criticality (*42*).

Availability of Sufficient Resources

The third most commonly discussed barrier inhibiting framework development and implementation was insufficient financial and staffing resources. With respect to financial barriers, agencies noted that sufficient financial resources were not available to implement adaptation planning as specified in the frameworks developed. In addition, several agencies noted that sufficient financial resources were not available to develop further or refine the adaptation planning frameworks themselves.

Agencies also noted that they, themselves, often do not have sufficient staff available to undertake adaptation planning in addition to their other planning efforts. Furthermore, agencies reported that availability of insufficient staff is closely related to insufficient financial resources, as additional funding would enable additional staff to be hired.

Interdependency and Regulatory Barriers

When conducting climate change risk assessments, it was difficult for agencies to completely characterize their own risk without some knowledge of the climate risks faced by interdependent agencies. For example, Mersey Docks (United Kingdom) noted that the operations of their facilities are dependent upon the supply of utilities (e.g., water, gas, electricity), the surrounding highway infrastructure, and adjacent properties leased from third parties (*61*). However, as climate risks are not fully characterized within these three interdependent sectors, Mersey Docks noted that this will have to be "further addressed over time through engagement with those organizations with which there are interdependencies" (*61*) to understand fully the climate-related risks that they face.

Regulatory barriers also pose a significant challenge to private and independent transportation organizations, such as airport operators and port authorities, whose funding and investment programs must be approved by their regulating agencies. For example, London Gatwick Airport noted that any plans to "develop, improve and grow the airport" must be agreed upon by the United Kingdom Civil Aviation Authority (CAA) and the airlines for each 5-year investment cycle (*62*). However, airport officials also noted that this short investment approval cycle is difficult to reconcile with long-term climate projections that predict environmental conditions well beyond the timeframe of the 5-year cycle. This temporal discrepancy makes it difficult to justify investment in projects whose benefits are uncertain and may occur well after the current investment cycle.

Uncertain Future System Demand

The uncertainty associated with future transportation demand was noted as a difficulty in determining the need for adaptive actions, and forced many agencies to make assumptions as to future demand circumstances. For example, Associated British Ports predicts throughput and cargo flows up to the year 2030 in their master planning process, but noted that "it is difficult to accurately predict the way that world trade and, hence, international cargo flows will change" (*63*). Therefore, the uncertainty associated with climate change-related adaptation needs is compounded by the uncertainty associated with future demand-related needs. Some agencies, for example the New Zealand Transport Agency, chose to not consider the impacts of climate change on travel demand and land use to simplify their analysis and thus enabled the focus of their analysis to be directed towards physical impacts on infrastructure and assets (*10*).

SUGGESTIONS FOR FUTURE RESEARCH

Data limitations were noted to be the most significant barrier to progress in risk-based adaptation planning and evaluation. The need for better infrastructure asset and inventory information can be addressed by mainstreaming adaptation-related data collection efforts with existing asset management programs. Meyer et al. (*64*) have discussed international examples where climate change concerns have begun to be incorporated into transportation asset management programs. The need for more regionally relevant, actionable climate change information suggests that transportation agencies, regional climatologists, and scientists from intersecting fields should form partnerships that could pursue multiple outcomes. For example, dialog between transportation agencies and climatologists could help identify the level of resolution, detail, and type of information necessary for adaptation, and ensure that projections more directly support the decision-making process. More importantly, such partnerships could also lead to the development of more-effective ways of characterizing and communicating the climate risks associated with current projections. One example of this may be improved information about the range of possible impacts to support scenario assessments. Additionally, partnerships with scientists in intersecting fields could help to better characterize impacts, and how those impacts are influenced by other physical, nonclimate systems. For example, coastal subsidence is a geologic process that is independent of climate change, yet it is a compounding factor to sea-level rise in several locations, including the Gulf Coast of the United States. Drought-stressed vegetation is more susceptible to wildfire. Burned areas on steep hillsides are susceptible to severe erosion resulting in clogging of drainage devices and diversion of sediment-laden discharge into locations that formerly were "safe" from all but the largest storms. From an operational impacts perspective, a need also exists to pursue climate impact projections that are not as well understood (and more difficult to model), for example, fog and wind patterns.

Numerous agencies noted that methods for identifying risk are also important. Specifically, agencies found it difficult to define acceptable levels of risk, types of risk, and critical thresholds. The Climate Impacts Group (United States) suggests that "community meetings and interviews with government leaders may provide insight into what risks are and are not acceptable, and at what thresholds these distinctions are made" (*29*). Acceptable levels of risk are likely to differ among agencies; however, it may be helpful for researchers and transportation professionals to develop common guidelines, or processes, to assist transportation agencies and organizations in establishing their own unique acceptable risk thresholds.

Inadequate resources, particularly financial resources, were a common barrier listed. In addition to the need for identifying or establishing new funding streams for adaptation planning, mainstreaming adaptation planning with current programs may also be needed. As with infrastructure asset information, mainstreaming with existing asset management programs may enable physical and operational adaptation in financially constrained environments. Other opportunities [for example, a "real options" type of approach (*65*)] could enable physical adaptation of existing infrastructure by building adaptive design elements into new infrastructure, or into reconstruction–rehabilitation projects.

Last, a need exists for general knowledge sharing within and among agencies. Centralizing infrastructure asset and inventory data within agencies eliminates the need for planners to collect and synthesize the required data with various iterations of their adaptation planning framework, while also providing a central resource for the various departments within each agency. Although many reports were found that discuss the development of agencies' adaptation frameworks, few reports discuss the implementation process, successes, shortcomings, further development, and continual improvement of the frameworks. Some frameworks were applied in case studies to test their efficacy (*31*, *40*, *66*), but these instances, and their reporting, are rare. From a framework development perspective, communication of case study and implementation outcomes are vital components to inform the efforts of other agencies in developing new frameworks or revising existing frameworks.

SUMMARY AND CONCLUSIONS

The purpose of this circular is to synthesize the current state of adaptation planning and evaluation in the transportation sector, with a focus on risk-based frameworks. We first identified a number of the leading risk-based climate change adaptation frameworks from the international transportation community. We then analyzed these frameworks to enable a synthesis of commonalities in four key areas from these strategies: (*a*) the underlying motivation for initiating climate change adaptation planning; (*b*) the foundational risk-management standards–principles used to develop these strategies; (*c*) the focus and approach of the frameworks; and (*d*) the barriers and limitations identified by the transportation agencies and organizations that must be addressed in moving forward. From this synthesis, a number of conclusions can be drawn regarding the current state of risk-based adaptation planning in the transportation sector, as well as the actions necessary to move forward.

The development of adaptation frameworks by transportation agencies and organizations were motivated by one of three factors: (*a*) government acts, laws, or legislation requiring that some adaptation planning action be taken; (*b*) extreme weather events seen as indicators of future conditions; and (*c*) self-motivated internal agency initiatives. In some cases, the motivations were not as singular or as clear cut; that is, in certain instances motivation may have come from several factors. For example, the U.K. Climate Change Act 2008 caused the DEFRA Reporting Power agencies to report, explicitly, their adaptation planning. However, many of these agencies indicated that risk management was already a part of their daily business activities, and that some consideration of climate change was already implicit therein. Similarly, extreme weather events in 2004 motivated the Scottish Executive to exercise its powers and commission the Scottish Road Network Climate Change Study (*34*) and the Scottish Road Network Landslides Study (*36*).

All of the frameworks reviewed followed the general structure or best practices of recognized risk management standards. We have highlighted the ISO 31000:2009 standard (*52*) as it provides one of the most generalized risk-management structures for comparison. The two primary differences between the frameworks reviewed and this standard were:

1. In some cases the risk analysis and risk evaluations steps were combined as a "risk appraisal."
2. Many frameworks expanded the final step (risk treatment) into several steps to identify and select adaptation options, identify synergies with other programs, and implement the selected option.

The frameworks reviewed were primarily focused on two types of adaptation planning: physical infrastructure and assets and operations and maintenance. However, a limited number of cases were found in which agencies and organizations also considered the need for adaptation in their organizational management practices.

A particularly striking outcome of this synthesis was the broad agreement on the limitations of the frameworks developed, and the barriers preventing further development and implementation. Agencies and organizations widely agreed upon three primary limitations or barriers:

1. Data limitations: limited or inaccessible infrastructure data; limited usable climate data.
2. Inadequate treatment of risk: reconciling the immediate need for action with the perception of distant consequences; the qualitative treatment of risk; defining acceptable levels of risk.
3. Lack of sufficient financial resources.

Transportation agencies and organizations, particularly independent and private-sector organizations, identified additional limitations or barriers:

4. Interdependencies and regulatory barriers.
5. Uncertainty in future system demand; this causes uncertainty in the need for adaptation.

A number of suggestions to address these limitations and barriers have been described. Many suggestions are within the current state of practice of many agencies, such as mainstreaming with asset management programs.

Despite the limitations and barriers listed, it is encouraging that transportation agencies have developed common and consistent approaches to climate change adaptation planning, using widely accepted risk standards as a guide. The strong similarities in their approaches will enable information-sharing among agencies, helping to inform framework development in those agencies that are newer to adaptation planning while helping those agencies with more mature frameworks to further refine their practices. Additionally, although significant limitations and barriers exist, their commonality among agencies allows transportation and climate researchers to focus their efforts on a set of very specific issues, which will be of very broad and meaningful benefit to the transportation sector.

REFERENCES

1. IPCC. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (R. K. Pachauri and A. Reisinger, eds.), Cambridge University Press, Cambridge, Mass., 2007.
2. America's Climate Choices: The State of Climate Change Science and Options for Limiting Future Climate Change. *TR News*, No. 268, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 6–9.
3. USGCRP. *Global Climate Change Impacts in the United States* (T. R. Karl, J. M. Melillo, and T. C. Peterson, eds.). Cambridge University Press, Cambridge, Mass., 2009.
4. IPCC. *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, et al., eds.). Cambridge University Press, Cambridge, Mass., 2010.
5. Department of Climate Change. Climate Change Risks to Australia's Coast: A First-Pass National Assessment. Department of Climate Change and Energy Efficiency, Canberra, Australia, 2009.
6. UKCIP. Climate Change: Assessing the Impacts—Identifying Responses: Highlights of the First Three Years of the UK Climate Impacts Programme. University of Oxford, 2000.
7. Climate Change Risks to Coastal Buildings and Infrastructure: A Supplement to the First-Pass National Assessment. Department of Climate Change and Energy Efficiency, Canberra, Australia, 2011.
8. IPCC. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (B. Metz et al., eds.) Cambridge University Press, Cambridge, Mass., 2007.
9. *Special Report 290: Potential Impacts of Climate Change on U.S. Transportation*, Transportation Research Board of the National Academies, Washington, D.C., 2008.
10. Gardiner, L., et al. Climate Change Effects on the Land Transport Network, Volume 1: Literature Review and Gap Analysis. New Zealand Transport Agency, Wellington, 2008.
11. Savonis, M. J., V. R. Burkett, and J. R. Potter. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I: A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Climate Change Research. U.S. Department of Transportation, 2008.
12. Meyer, M., and Parsons-Brinkerhoff. NCHRP 20-83(05): Climate Change and the Highway System—Impacts and Adaptation Approaches. Transportation Research Board of the National Academies, Washington, D.C., 2009.
13. ICF International and Parsons-Brinkerhoff. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase II: Assessing Infrastructure for Criticality in Mobile, AL. Final Technical Memo Task 1. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, 2011.

14. Carter, T. R., et al. *New Assessment Methods of the Characterisation of Future Conditions*, in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry et al., eds.). Cambridge University Press, Cambridge, Mass., 2007, pp. 133–171.
15. Willows, R., and R. Connell. Climate Adaptation: Risk, Uncertainty and Decision-Making. UKCIP Technical Report, UKCIP, Oxford, U.K., 2003.
16. Meyer, M. Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change. Georgia Institute of Technology, 2006.
17. AASHTO. *LRFD Bridge Design Specifications*. American Association of State Highway and Transportation Officials, Washington, D.C., 2004.
18. PIEVC and Engineers Canada. PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment. Canadian Council of Professional Engineers, Ottawa, 2009.
19. U.K. Highways Agency and Parsons-Brinkerhoff. Climate Change Adaptation Strategy and Framework. Highways Agency, London, 2009.
20. Victorian Government et al. *Infrastructure and Climate Change Risk Assessment for Victoria* (P. Holper et al., eds.). Victorian Government, Victoria, 2007.
21. PIEVC and Engineers Canada. Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure. Canadian Council of Professional Engineers, Ottawa, 2008.
22. Bruce, J. P., I. D. M. Enger, and D. Noble. Adapting to Climate Change: A Risk-Based Guide for Ontario Municipalities. Ontario Ministry of Municipal Affairs and Housing, Toronto, 2006.
23. Black, R. A., J. P. Bruce, and I. D. M. Egener. Adapting to Climate Change: A Risk-Based Guide for Local Governments, Volume 1. National Resources Canada, Ottawa, 2010.
24. Department of a Climate Change Adaptation Strategy. Ahead of the Storm: Preparing Toronto for Climate Change. Department of a Climate Change Adaptation Strategy, Toronto, Canada, 2008.
25. Dillon Consulting and de Romilly and de Romily Ltd. Climate SMART: Climate Change Risk Management Strategy for Halifax Regional Municipality. Halifax Regional Municipality, Halifax, 2007.
26. SEPA. The National Flood Risk Assessment. Scottish Environment Protection Agency, Stirling, 2011.
27. SEPA. Flood Risk Management Strategies and Local Flood Risk Management Plans: December 2011: Flood Risk Management (Scotland) Act of 2009. Scottish Environmental Protection Agency, Stirling. 2011.
28. Major, D., and M. O'Grady. Appendix B: Adaptation Assessment Guidebook. New York City Panel on Climate Change, New York, 2010.
29. Sonover, A. K., et al. Preparing for Climate Change: A Guidebook for Local, Regional and State Governments. Climate Impacts Group, Seattle, 2007.
30. Norwell, G. Impacts of Climate Change on Road Infrastructure. Austroads Inc., Sydney, 2004.
31. Bies, T., et al. Risk Management for Roads in a Changing Climate (RIMAROCC). ERA-NET ROAD, 2010.
32. Kinsella, Y., and F. McGuire. Climate Change Uncertainty and the State Highway Network: A Moving Target. Presented at New Zealand Institute of Highway Technology and Transit New Zealand Symposium. New Zealand Institute of Highway Techology, Christchurch, 2005.
33. Gardiner, L., et al. Climate Change Effects on the Land Transport Network, Volume 2: Approach to Risk Management. NZ Transport Agency, Wellington, 2009.
34. Galbraith, R. M., D. J. Price, and L. Shackman. Scottish Road Network Climate Change Study. Scottish Executive, Edinburgh, 2005.
35. Galbraith, R. M., et al. Scottish Road Network Climate Change Study: Progress on Recommendations. Transport Scotland, Edinburgh, 2008.
36. Winter, M. G., F. Macgregor, and L. Shackman. Scottish Road Network Landslides Study. Scottish Executive, Edinburgh, 2005.

37. DEFRA. Adaptation Reporting Powers Received Reports. 2012. Available at http://www.defra.gov.uk/environment/climate/sectors/reporting-authorities/reporting-authorities-reports/. Accessed May 16, 2012.
38. Highways Agency and Parsons-Brinkerhoff. Climate Change Adaptation Strategy. Highways Agency, London, 2008.
39. U.K. Highways Agency. Highways Agency Climate Change Risk Assessment. U.K. Highways Agency, London, 2011.
40. FHWA. Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual Model. *Climate Change Vulnerability Assessment Pilots*. Available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/conceptual_model62410.cfm. Accessed Feb. 1 and May 17, 2012.
41. FHWA. Climate Change and Extreme Weather Vulnerability Assessment Framework. U.S. Department of Transportation, 2012.
42. Nguyen, A., et al. Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project.Technical Report 2011. Metropolitan Transportation Commission, San Francisco, 2011.
43. NJTPA. Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure. North Jersey Transportation Planning Authority, Newark, 2011.
44. SSFM International. Transportation Asset Climate Change Risk Assessment. Oahu Metropolitan Planning Organization, Honolulu, 2011.
45. Virginia DOT. Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot. Virginia DOT, Richmond, 2011.
46. Maurer, M., et al. Climate Impacts Vulnerability Assessment. Washington State DOT, Olympia, 2011.
47. Parliament of the United Kingdom. Climate Change Act 2008.United Kingdom, 2008, p. 108.
48. DEFRA. Reporting Power Guidelines. Department for Environment, Food, and Rural Affairs, London, 2010.
49. COAG. National Climate Change Adaptation Framework. Council of Australian Governments, Canberra, 2007.
50. Department of Climate Change and Energy Efficiency. Incoming Government Brief: Administrative Brief: The Climate Change and Energy Efficiency Portfolio. Department of Climate Change and Energy Efficiency, Australian Government, Canberra, 2010.
51. Port of Dover. Climate Change Adaptation Report. Department for Environment, Food, and Rural Affairs, London, 2011.
52. International Organization for Standardization. Risk Management—Principles and Guidelines ISO 31000:2009. International Organization for Standardization, Geneva, 2009.
53. NATS. Climate Change Adaptation Report. Department for Environment, Food, and Rural Affairs, London, 2011.
54. NRCAN. *Climate Change Adaptation Planning: A Handbook for Small Canadian Communities*. Natural Resources Canada, Ottawa, 2011.
55. Standards Australia and Standards New Zealand. AS/NZS ISO 31000:2009 Risk Management: Principles and Guidelines. Standards New Zealand and Standards Australia, Wellington, New Zealand, and Sydney, 2009.
56. MacArthur, J., et al. Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska. Oregon Transportation Research and Education Consortium and Washington State DOT, Olympia, 2012.
57. Meyer, M., et al. Climate Change, Extreme Weather Events and the Highway System: A Practitioner's Guide, Transportation Research Board of the National Academies, Washington, D.C., in press.
58. Woolston, H. Climate Change Adaptation for London's Transport System. Available at http://www.sd-research.org.uk/wp-content/uploads/cc_adaptation.pdf. Accessed Feb. 20, 2013.

59. Meyer, M., A. A. Amekudzi, and J. P. Ohar. Transportation Asset Management Systems and Climate Change: An Adaptive Systems Management Approach. Presented at 89th Annuual Meeting of the Transportation Research Board, Washington, D.C., 2010.
60. Harwich Haven Authority. Adapting to Climate Change: Harwich Haven Authority Report to the Secretary of State. Jan Brooke Environmental Consultant Ltd., Department for Environment, Food, and Rural Affairs, London, 2011.
61. Gardiner, J., D. Beeden, and M. Hunt. Mersey Docks and Harbor Company Ltd. Climate Change Adaptation Report: Report to DEFRA Under the Adaptation Reporting Powers. Peel Ports Group, Department for Environment, Food, and Rural Affairs, London, 2011.
62. Gatwick Airport Limited. Climate Change Adaptation Report at Gatwick Airport. Department for Environment, Food, and Rural Affairs, London, 2011.
63. Associated British Ports. Climate Change Adaptation Report: Humber, Hull, Immingham and Southampton Harbor Authorities. Associated British Ports, London, 2011.
64. Meyer, M. D., A. Amekudzi, and J. P. Ohar. Transport Asset Management Systems and Climate Change: An Adaptive Systems Management Approach. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2160*, Transportation Research Board of the National Academies, Washington, D.C., pp. 12–20.
65. de Neufville, R. Real Options: Dealing With Uncertainty in Systems Planning and Design. *Integrated Assessment*, Vol. 4, No. 1, 2003, pp. 26–34.
66. UKCIP. M25 Maintenance and Operations: Connect Plus. *Business Case Studies*, University of Oxford, 2011.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. (Dan) Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. (Dan) Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

TRB

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001