SPECIAL REPORT 299:
REDUCING TRANSPORTATION GREENHOUSE GAS EMISSIONS AND ENERGY COMSUMPTION:
A RESEARCH AGENDA

# Adaptation Research Programs and Funding

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## EXECUTIVE SUMMARY

This paper presents a proposed research program and activities to assist transportation agencies, owners and users to adapt to climate change as outlined in (but not limited to) Transportation Research Board (TRB) Special Report 290: *Potential Impacts of Climate Change on U.S. Transportation.* The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Adaptation activities can be technological (such as increased sea defenses), policy-based (such as improved risk management), behavioral (such as the sparing use of water in times of drought) or managerial (such as improved forest management)".

A review of global initiatives, research in Australia, the European Union, New Zealand and the United Kingdom reveals a rich body of experience, guides, assessment tools and case studies of adaptation options. Recent research in the United States by foundations, federal, state and local government also provides a base of experience. Common elements of the research programs are the importance of sharing information, engaging stakeholders, building capacity and providing advice.

Selecting adaptation strategies is made more difficult by the uncertainties surrounding climate change, the range of climate change phenomena and the range of impacts on transportation facilities and processes. Candidate adaptation activities can be technological, policy-based, behavioral or managerial. Desirable adaptations are characterized as "no regret" (benefits occur even if climate change does not occur), "low regret" (provide benefits at relatively little cost or risk), or "win-win" (reduces the impact of climate change while providing other social or economic benefits.) Using the same climate change impacts as Special Report 290, the proposed program is intended to address temperature changes, sea level rise, precipitation changes, and increasing intensity of storms.

The proposed program is organized around three areas: 1) foundational research; 2) applied research; and 3) support functions. Specific research areas are described as follows:

- Foundational Research
  - Identification of vulnerable assets and vulnerable locations
  - Identification of opportunities for adaptation
  - Understanding changes in the life of facilities
  - Identifying the modes and understanding the consequences of failure
  - Assessing the costs and benefits of adaptation
  - Understanding stakeholder/ community response
- Applied Research
  - Infrastructure planning and environmental decision making
  - Infrastructure design standards and practices

- Infrastructure construction
- Infrastructure maintenance
- Infrastructure operations
- Infrastructure renewal/ rehabilitation
- New infrastructure to support mitigation measures
- Tool and model development
- Sensing and monitoring
- Best practices
- Long range planning related to transportation and land use
- Influencing land use decisions
- Funding adaptation

These research areas address or partially address seven of the fourteen recommendations in Special Report 290.

Support functions include:

- Information clearinghouse
- Dissemination
- Stakeholder engagement
- Cross cutting issues and coordination, and
- Evaluation

For each area of foundational and applied research, an objective, timeframe and cost estimate has been developed. A modest program of $120 million over 20 years recognizes that there are opportunities to leverage this research through other programs. However, almost 50% of the research budget will be expended in the first five years. Related programs include ongoing efforts by American Association of State Highway and Transportation Officials (AASHTO), Federal Highway Administration (FHWA), National Oceanographic and Atmospheric Administration (NOAA), the University Transportation Centers program and the National Science Foundation (NSF).

Drawing on global and international efforts to determine the need for adaptation and then developing feasible responses, the proposed research program is structured around information sharing, stakeholder involvement and support tools for all levels of government and public and private sector stakeholders. The program recognizes the uncertainties associated with the climate change, the importance of probabilistic analysis, the range of adaptation options possible, the importance of understanding local needs and conditions, and the importance of avoiding unintended consequences.

The intent is to be cautious but proactive. The program is modest but effective.

While the timing and magnitude of climate change is unknown, climate change is occurring. To adapt, agencies, owners, and users must make rational well informed decisions. Research is necessary to make these decisions and this research must begin now. The impacts of delay are likely to be far more costly and disruptive than the costs of action.

## INTRODUCTION

Climate change is occurring and mitigation measures cannot be implemented in time to forestall the impacts of climate on transportation infrastructure in the United States. Strategies are urgently required to adapt our infrastructure, travel behavior, development and investment policies and management to reduce the impacts of climate change. This paper presents a proposed research program and activities to assist transportation agencies, owners and users to adapt to climate change as outlined in (but not limited to) TRB Special Report 290: *Potential Impacts of Climate Change on U.S. Transportation* (*1*). The paper begins by defining adaption, reviewing Special Report 290, and describing the approach used to develop the research program.

### Defining Adaptation and Scope

As a foundation for this paper, two definitions of adaptation are provided. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as (*2*) "an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Adaptation activities can be technological (such as increased sea defenses), policy-based (such as improved risk management), behavioral (such as the sparing use of water in times of drought) or managerial (such as improved forest management)." The United Nations Framework Convention on Climate Change (UNFCCC) defines adaptation as (*3*) "actions by individuals or systems to avoid, withstand, or take advantage of current and projected climate changes and impacts. Adaptation decreases a system's vulnerability, or increases its resilience to impacts". Both definitions stress the role of systems and the interaction among human and natural systems.

While adaptation is focused on response to climate change, adaptation of infrastructure in response to mitigation efforts is also required. This paper also briefly looks at infrastructure for alternative fuels and market mechanisms to force mitigation to pay for adaptation. However, infrastructure and policy to support reduced VMT are beyond the scope of this paper.

### The Role of Special Report 290

Special Report 290 is the culmination of significant research, discussion and synthesis of information on issues for planning, designing, operating and maintaining highway, rail, pipeline, marine, and aviation transportation systems due to climate change. Special Report 290 identified potential climate changes in terms of four phenomena: (1) temperature changes (increases, decreases, increases in Arctic temperatures, and shorter winters), (2) sea level rise, (3) precipitation changes (increases in intense precipitation events, increases in drought conditions, and changes in seasonal precipitation), and (4) increasing intensity of hurricanes. For each potential climate change phenomenon, adaptation options are identified focusing on changes in operations and changes in infrastructure design and materials, and other options. The report summarizes the findings and makes fourteen recommendations. The findings and recommendations recognize the high levels of uncertainty surrounding climate change, the importance of location specific strategies (local and regional) and the long planning horizons involved.

The fourteen recommendations in Special Report 290 range from inventorying transportation infrastructure to recognizing the consequences of climate change, to better communication, coordination, and exchange of information with other agencies such as National Oceanographic and Atmospheric Administration (NOAA), US Geological Survey (USGS) and Federal Emergency Management Agency (FEMA). While some recommendations serve as a foundation for adaptation decisions or adaptation research, others have a supporting or enabling role. Table 1 attempts to summarize the recommendations in terms of the role these recommendations play in adaptation and adaptation research. This paper focuses on adaptation research related to recommendations 2, 3, 7, 8, and 9 and to some extent recommendations 13 and 14 in terms of exploring land use changes and policies. Other areas of relevant research are also identified.

## Approach

The proposals for research programs and activities related to adaptation to climate change presented in this paper were developed through a systematic process based on the following tasks:

- Develop criteria for inclusion of projects in research programs drawing on documents such as the "Seven Keys to Developing a Robust Research Program" (*4*) and "Performance Measurement Tool Box and Reporting System for Research Programs and Projects" (*5*). For example, the projects must be driven by economics, and they should draw on non-traditional partnerships.
- Review existing research programs and conduct a literature review of published and documented research.
- Explore the characteristics and attributes of adaptation actions including policy and construction alternatives for adaptation.
- Identify opportunities to link the research programs with existing programs and emerging areas such as international work on adaptation to climate change, the University Transportation Centers, and other regional efforts. For example in Australia and New Zealand work on adaptation to climate change has been tightly linked with asset management and sustainability.
- Identify research programs, projects and activities that are needed to implement successful adaptation strategies.
- Map potential programs to the recommendations of Special Report 290.
- Develop a matrix of programs and the criteria for successful research programs to understand which programs are feasible and likely to have a high impact.
- Develop cost estimates and timelines for each of the programs.
- Develop a draft paper documenting existing research programs and past research and outlining a proposed research program.
- Present the preliminary research program at the Transportation Research Board Annual Meeting in January 2009.
- Seek comments on the draft paper.
- Revise the paper to reflect the comments on both the presentations and the written paper.

**TABLE 1 Role of Recommendations from Special Report 290 in Adaptation Research**

| Special Report 290 Recommendation | Role in Adaptation | Role in Adaptation Research |
|---|---|---|
| 1. Inventory transportation infrastructure to determine consequences of climate change | Enables decision making | Supports |
| 2. Incorporation of climate change into capital improvement plans, facility designs, maintenance practices, operations, and emergency response plan | Foundation for decision making | Foundation |
| 3. Use more probabilistic investment analyses and design approaches | Foundation for decision making | Foundation |
| 4. Better communication among agencies and establish a clearinghouse for transportation relevant climate change information | Supports adaptation | Supports |
| 5. Include the needs of transportation decision makers in research | Supports adaptation | Supports |
| 6. Integration of transportation into emergency response and evacuation plans | Supports adaptation of operations | Supports |
| 7. Development and implementation of monitoring technologies | Supports adaptation | Foundation |
| 8. Share best practices | Foundation for dissemination | Foundation |
| 9. Reevaluation of existing and development of new design standards | Foundation for adaptation | Foundation |
| 10. Build projects in vulnerable areas to higher standards and provide for redundancy | Demonstration of adaptation | Foundation |
| 11. Develop interagency working group | Supports adaptation | Supports |
| 12. Include climate change in long-range transportation plans | Enables adaptation | Foundation |
| 13. Reevaluate the risk reduction effectiveness of the National Flood Insurance Program and the FIRMs | Supports adaptation | One element of influencing land use decisions |
| 14. Include incentives for addressing and mitigating impacts | Supports adaptation | Requires innovation |

The proposed research recognizes uncertainty, the need to understand local and regional effects, and the long timeframes involved. Where possible the research programs are structured to recognize that adapting to climate change is a dynamic process and policies, changes in design standards and decision making processes must be able to respond to changes in climate change trends or other evidence of change. Any secondary impacts of mitigation in terms of the need for less emphasis on adaptation are ignored.

## Overview of the Paper

This paper is organized as follows. This section briefly discusses adaptations needed to support mitigation. The following section reviews ongoing global, international and U.S. based research and initiatives. The paper then develops criteria for selecting research areas and identifying program elements. The next section then describes the characteristics of adaptation options and

adaptation research. The next section "Developing a Research Program" documents the assumptions made and the strategies used to identify the research areas in the following two sections. These sections describe the foundational and applied research areas. Finally, cost estimates and timelines are developed, and conclusions presented.

## RELATED ONGOING RESEARCH AND INITIATIVES

In the US research on adaptation has just begun. Much work has been done on adaptation to climate change in other countries. This work provides a foundation for structuring the proposed research. This section briefly reviews global efforts by the UNFCCC and non profits; work in Australia, Canada, the European Union, New Zealand and the United Kingdom; and by US agencies, and other US-based organizations, as well as a recent initiative by the state of California. While this review is not exhaustive, it illustrates the range of research being undertaken and the common themes emerging.

### Global Efforts

The UNFCCC is an international treaty to address climate change. The UNFCC has broadly addressed adaptation, particularly in lesser developed countries and the adaptation website provides a broad array of strategies and experiences that provide insights on risk assessment, the integration of strategies and regional experiences rather than sector or transport specific experiences (*3*).

A report on international policy options for adaptation produced for the Pew Center on Global Climate Change focuses on the need for funding, information, capacity building and the development of both proactive and reactive adaptation strategies for vulnerable countries. The report recommends actions in three areas – within the UNFCCC, through risk assessments integrated with development aid, and through the use of insurance instruments (*6*).

These global efforts serve as a resource for examples of adaptation actions and also define much of the common vocabulary used to describe adaptation options.

### International Efforts

The international sources reviewed were limited to English language publications. Fortunately, much of the work in Europe is published in English through the European Commission. This subsection reviews work in Australia, Canada, the European Union, New Zealand and the United Kingdom. Much of this work was begun over a decade ago.

Like the United States, Australia has many levels of government. The Council of Australian Governments (COAG) endorsed the *National Climate Change Adaptation Framework*, at its meeting on 13 April 2007. Roads, bridges, railways and ports are addressed in the section on "Settlements, Infrastructure and Planning" including revision of planning guides and design codes and standards and assessment of the vulnerability of transport infrastructure (*7*). At the federal level, the Department Climate Change was established in December 2007. The National Climate Change Adaptation Programme is a four year effort to (*7*):

> (1) advise Government on policy issues related to climate change impacts and adaptation, including key risks to and opportunities for Australia; (2) build capacity to support the development of effective and targeted adaptation strategies; (3) engage stakeholders and provide targeted and scale-relevant information and tools to industry sectors and regions; and (4) integrate climate change impacts and adaptation considerations into key policies and programmes, including into risk management practices across vulnerable sectors.

In October 2008, the Australian government announced the commitment of over $10 million over four years to establish research networks investigating the effects of climate change, including adaptation in several areas including emergency services, and infrastructure.

At the state level, individual states have also undertaken research and studies. For example, the Victorian Government has released a study on the potential impacts of climate change on the State's infrastructure. The study examines the potential risks to key infrastructure areas such as water, power, telecommunications, transport and buildings (*8*).

At the local level local, governments have begun to understand the need to respond to climate change. For example, the Sydney Coastal Councils Group Inc (SCCG) has examined their vulnerability to climate change and exploring adaptive strategies to respond (*9*). The Local Government Association of Queensland has produced a guide to climate change focused on adaptation for local governments (*10*).

While considerable progress has been made on raising awareness, exploring options, much research is still required. Engineers Australia states (*11*):

> Action is needed to establish the legislative frameworks and to provide the essential scientific parameters for the planning authorities such as safe setbacks, sea level limits, bunded zones, infrastructure replacement and aquifer management plans etc. Effective legislative action requires strong political will, while the identification of the threats and treatment options requires the harnessing of appropriate engineering and related scientific expertise and provision of research and investigation funding.

The objective of the Government of Canada's Climate Change Impacts and Adaptation Program is to reduce Canada's vulnerability to climate change through research. As part of this program the Canadian Climate Impacts and Adaptation Research Network (C-CIARN) facilitates interaction between stakeholders and researchers, and helps disseminate information. In 2004 the program produced (*12*) "Climate Change Impacts and Adaptation: A Canadian Perspective." The report identifies three research directions: understanding vulnerability, scenarios and costing climate change. Subsequent reports document the findings from ongoing research addressing regions (*13*), local government (*14*), and risk assessment (*15*). A database of ongoing research projects identified fourteen transportation projects (http://www.adaptation.nrcan.gc.ca/projdb/index_e.php). In addition individual provinces have initiated climate change research. For example, Quebec is a leader in climate change with a well defined action plan and regular reports on progress (*16*).

The European Commission, as part of the European Climate Change Programme II, is exploring impacts and adaptation strategies. While no specific reports focus on transportation, the reports recognize the regional and local nature of planning, the complex interactions among

land use, climate change and infrastructure, and the impacts of climate change such as heave, flooding, and temperature changes on physical infrastructure (*17*) (*18*). The Programme recognizes the importance of research on adaptation. The European Commission's Green Paper states (*19*): "An integrated, cross-sectoral and holistic approach is to be promoted together with internalisation of environmental costs of physical and biological system degradation. Research should address the complexity of interrelated factors, which cannot be analyzed independently. The EU's 7th Framework Programme for Research (2007-2013) places a strong emphasis on climate change, both in terms of predictive capacity, modelling and adaptation strategies."

Relevant research initiatives include (*19*):

- Develop comprehensive and integrated methodologies for the assessment of impacts, vulnerabilities and cost effective adaptation.
- Develop indicators to measure the success of responses. Improve European-wide risk, impact and cost/benefit assessment for adaptation responses, as compared with "no action".
- Compare integrated EU-wide responses with sectoral approaches including analysis of socio-economic costs and benefits.
- Improved integrated assessment and the development and use of tools for demonstrating economic, environmental and social benefits of adaptation for European regions crossing national boundaries.
- Launch Europe-wide studies on the present and future plans of coastal regions to strengthen coastal protection, the environmental and economic costs involved in these plans, the impacts they may have on the community budget and on the economy of coastal regions. This should include the assessment of costs involved for ports and waterways to continue delivering basic transport functionalities.

Initiatives in individual countries are summarized by Climate Change Impact Research for a Larger Europe (CIRCLE) (http://www.circle-era.net/recent-country-news/). Common themes include vulnerability assessment, risk management and location specific studies such as the Dutch Delta Commission.

Transit New Zealand has taken a proactive approach to adaptation to climate change. In 2004, Transit New Zealand published an Adaptation Position Paper, *Climate Change Impacts on the State Highway Network: Transit New Zealand's Position*, which outlined Transit's response to the potential impacts of climate change (*20*). Their research has shown that climate change can be accommodated in the existing asset management framework and that particular attention should be paid to assets with lives longer than 25 years. Transit New Zealand also uses a two stage approach first evaluating the necessity of acting and then the feasibility of acting (*21*).

The United Kingdom Climate Impacts Programme (UKCIP), formed in 1997, works with public, private and non-profit organizations to help them respond to climate change. UKCIP is a stakeholder driven research program and focuses on partnerships in two areas related to adaptation (*22*):

- "Building adaptive capacity" to create the information and conditions (regulatory, institutional, and managerial) that are needed before adaptation actions can be undertaken.
- "Delivering adaptation actions" to reduce vulnerability to climate risks, or to exploit opportunities.

The UKCIP has assembled research tools, including databases, guides, tools and reports that are relevant to US research (*23*). These include:

- Database of research activities, and adaptation actions. The database, Base for Research, Adaptation, Impacts and News (the BRAIN), can be accessed online http://www.uk8cip.org.uk/index.php?option=com_content&task=view&id=226&Itemid=324
- Guide to introducing climate change into decision making. http://www.ukcip.org.uk/images/stories/Pub_pdfs/Risk.pdf
- Research projects, workshops and tool development funded through the research arm of the UKCIP - Building Knowledge for a Changing Climate (BKCC). This initiative was completed in 2006. A comprehensive research report documents the projects (*24*). Of particular interest are three projects:
  - BIOlogical and eNgineering Impacts of Climate change on Slopes (BIONICS)
  - Adaptable Urban Drainage – Addressing Change in Intensity, Occurrence and Uncertainty Of Stormwater (AUDACIOUS)
  - Building Economic and Social information for Examining the Effects of Climate cHange (BESEECH).
- "Adaptation Wizard" – a 5-step web-based tool to help organizations adapt to climate change (http://www.ukcip.org.uk/index.php?option=com_content&task=view&id=147&Itemid=297, http://www.ukcip.org.uk/images/stories/Wizard/Wizard_pdfs/whole_wizard.pdf)
- Dissemination effort - Sustaining Knowledge for a Changing Climate (SKCC)
- Evaluation of stakeholder involvement. http://www.ukcip.org.uk/images/stories/Pub_pdfs/BKCC_evaluation.pdf

Key next steps include:

- Publication of "UK 21st Century Climate Scenarios" or UKCIP08 – scenarios to help refine climate change uncertainties
- Assessment of adaptation options that may be applied across a range of sectors in the built environment and infrastructure systems
- Integrating adaptation with measures to mitigate greenhouse gas emissions
- Costing climate impacts and adaptation

The subsequent research program Adaptation and Resilience to a Changing Climate (ARCC) was launched in March 2008. While the program explicitly identifies transport infrastructure as an area of interest no funded research projects are in this area. However, much can be learned from the structure of this research program (*22*).

Other UK based agency led efforts include Department for Transport and Transport for London. The Department for Transport has undertaken some of the most relevant research. A report documents the issues and options (*25*). The report identifies sector specific research initiatives that have been undertaken and should be reviewed as part of further research. These are:

- Rail – "Engineering and Safety Implications of Weather, Climate and Climate Change" commissioned by the Rail Safety and Standards Board. The report can be found at: http://www.railwaysafety.org.uk/pdf/ClimateChangeFR.pdf
- Ports – "Climate Change: The Implications to Associated British Ports."
- Highways – "Climate Change and the Highways Agency" by TRL Limited.

Transport for London established the climate change partnership in 2001 and published (in cooperation with the Greater London Authority) a report on "Climate change and London's transport systems" in 2005. The report recommended the inclusion of climate change in risk management, the inclusion of adaptive strategies in planning, and all infrastructure renewal and upgrade projects (*26*).

These international research efforts and others provide a wealth of information on adaptation options and evaluation.

**US Efforts**

Interest in mitigation of and adaptation to the climate change in the United States has risen dramatically in the past five years. However, as a 2008 report to the Federal Highway Administration (FHWA) states (*27*) "MPOs [Metropolitan Planning Organizations] and DOTs [Departments of Transportation] have little if any information on precisely what impacts they can expect, where, and in what time frames. As a result, agencies are largely not acting to adapt the transportation system to climate change, or are waiting for further guidance on the topic." No Department of Transportation participating in a 2008 peer exchange has any specific programs and policies on climate change in place, and a 2008 survey of all state DOTs, Puerto Rico and the District of Columbia indicated that only eight jurisdictions had policies in place (*27*). At the same time, US-based research programs are evolving to address these issues and it is important not to duplicate efforts.

Current programs and studies demonstrate interest and some of the challenges as illustrated by the following examples:

- The Urban Leaders Adaptation Program by the Center for Clean Air Policy engages stakeholders and links adaptation, policy and urban planning (http://www.ccap.org ).
- The American Association of State Highway and Transportation Officials (AASHTO), as part of the preparation for transportation reauthorization, has released a series of policy briefs, including one on climate change and sustainability. The brief is focused on mitigation and is silent on adaptation (*28*). Similarly, the AASHTO Primer on Climate Change only briefly mentions adaptation and refers to the studies by the Pew Climate Change Center and the TRB Special Report 290 (*29*).
- A report from the Pew Center on Global Climate Change provides a good summary of the current state of the practice and poses research needs that include building capacity, disseminating best practices, developing tools to support policy change and decision making (*30*). A review of climate change impacts by the Center for Integrative Environmental Research (CIER) at the University of Maryland found that (*31*) "climate change will cost the public sector a lot." The report included a series of regional analyses that each included a section on "Missing Information and Research Needs". Research needs related to transportation include:

- Logistics and supply chain implications of climate change in the specific region
- Strategies for identifying investment and policy options for reducing vulnerability and costs of infrastructure as a result of flooding, subsidence and sea level rise.
- Recognition of infrastructure interdependences, for example, transportation and flood control, and emergency preparedness and transportation.

- Rich sources of information on guides, frameworks, experiences, and institutions are a Heinz Center survey of adaptation planning (*32*) and "Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments" (*33*). The guidebook lays out a strategy for adaption in a variety of sectors including transportation, and also provides examples of experiences and organizational structures in a variety of states and communities.
- The most comprehensive regional study is the Gulf Coast Study (*34*). This multimodal study demonstrates the important of recognizing climate change in planning and decision making in a particularly vulnerable area where the impacts of climate change are regional and national, and the value of federal agencies, in this case US Department of Transportation and US Geological Survey, cooperating. The Gulf Coast Phase II is being launched in 2009 and will focus on adaptation.

State, regional and local government interest in adaptation is also growing. The governor of California has recently (November 2008) issued an executive order (EXECUTIVE ORDER S-13-08) that sets an agenda for climate change focusing on adaptation. An earlier report also set a research agenda including four questions (*35*):

- What level of climate change (or risk of change) is society willing to accept (thus also raising questions about the extent of greenhouse gas mitigation)?
- What goals should adaptation achieve, e.g., preserving the status quo, actively managing change toward new conditions, promoting deeper societal changes required for sustainability?
- What is an acceptable level of individual vs. public risk and how should the responsibility in case of impact be shared?
- What are the social justice, environmental, economic, and other trade-offs associated with allocation of scarce resources as more systems come under growing pressure from climate and other stresses?

The report also recognizes research directions:

- Encourage research that uses a vulnerability approach to help identify the risks of climate change within the context of multiple stressors
- Encourage collaborative and participatory research that seeks to expand the knowledge of resource managers regarding climate and weather risks, and how risks affect coping/adaptation options
- Encourage research that identifies critical thresholds in climate-sensitive sectors; for example, species-specific thresholds of landscape connectivity would help in the design of protected areas that would afford species habitat protection as environmental conditions change
- Encourage research into the socioeconomically and racially differentiated vulnerabilities to, and capacities to deal with, the impacts of climate change

- Encourage research into the feasibility of adaptation options against the backdrop of climatic, economic, technological, institutional, social, legal, ecological, or other constraints and stressors; as well as research on how to overcome the obstacles or minimize these constraints
- Encourage further sector-specific empirical research into resource managers' specific information needs: how they process information about climatic risks, identify and assess coping strategies, and choose whether, when, and how to employ them
- Respond to these identified information needs of different decision-makers by providing information that is directly relevant and easily accessible to different stakeholders' decisions

A series of recent MPO Peer exchanges, sponsored by FHWA, identified six key issues of common concern to participants (*27*):

- Making climate change a national planning priority
- Planning for adaptation to climate change
- Educating the public and policy-makers about climate change and transportation
- Articulating the relationship of land use patterns to climate change
- Need for tools to address climate change planning challenges
- Need for continuous communication and information sharing among planning partners

Several University based research centers are conducting relevant research on climate change and transportation including:

- Alaska Center for Climate Assessment at Policy at University of Alaska Fairbanks focusing on off-shore transportation, and the impact of climate change on public infrastructure (http://www.uaf.edu/accap/research.htm)
- Alaska University Transportation Center
  - Impacts of Climate Variability and Change on Flood Frequency Analysis for Transportation Design http://www.alaska.edu/uaf/cem/ine/autc/projects.xml
- Oregon Transportation Research and Education Consortium (OTREC)
  - Future Flooding Impacts on Transportation Infrastructure and Traffic Patterns Resulting from Climate Change (http://otrec.us/research.php )
- South West Region University Transportation Center (SWUTC) (http://swutc.tamu.edu/research.htm)
  - Climate Change/Variability Science and Adaptive Strategies for State and Regional Transportation Decision Making
  - Transportation Planning, Policy and Climate Change: Making the Long Term Connection

These US efforts are particularly important as they begin to define a research agenda that can be used to identify the research areas.

## CRITERIA FOR SELECTING RESEARCH AREAS AND IDENTIFYING PROGRAM ELEMENTS

Defining criteria for selecting research areas and identifying program elements are important as the process of defining and then evaluating criteria helps to determine whether research projects are feasible, and useful, and also provide an objective yardstick for evaluating the projects as the research progresses. The criteria are particularly important in times of limited resources.

The research efforts described in the proceeding section and documents such as the "Seven Keys to Developing a Robust Research Program" (*4*) and "Performance Measurement Tool Box and Reporting System for Research Programs and Projects" (*5*) serve as a starting point for defining these criteria.

Proposed criteria for selection are:

- Interdisciplinary,
- Driven by economics, and
- Draws on non-traditional partnerships including stakeholder involvement.
- Leverages existing and ongoing research
- Provides clear deliverables
- Specifies the relevant geographic coverage and aspect of climate change covered
- Recognizes interconnections and interdependencies, and
- Can be generalized

## CHARACTERIZING ADAPTATION ACTIVITIES AND ADAPTATION RESEARCH

Research programs require some structure to organize the research activities to prevent duplication of effort and to help achieve the objectives. The research may be structured into functional projects that either use a common methodology, are applied in a single or similar sector, address a similar issue or relate to a particular transportation function. This section briefly reviews different ways of characterizing adaptation activities and adaptation research.

We begin by reviewing the range of adaptation activities. The UNFCCC describes adaptation activities as technological, policy-based, behavioral or managerial (*3*). From the perspective of transportation technological activities can be distinguished as monitoring activities, and infrastructure construction activities. Examples are shown in Table 2. Special Report 290 classifies adaptation options as changes in operations, changes in infrastructure design and materials and other.

Adaptation activities are also characterized by their impact as (*33*):

- No regret - benefits occur even if climate change does not occur
- Low regret – provide benefits at relatively little cost or risk
- Win-win – reduce impact of climate change while providing other social or economic benefits.

This strategy is particularly relevant in the context of the Transportation Research Board (TRB) as many of these benefits will address critical issues (congestion, emergencies, energy and environment, equity, finance, human and intellectual capital, infrastructure, institutions, and

safety) identified by TRB (*36*). Alternatively activities are described as reactive or proactive (*6*). Proactive strategies reduce future risks, whereas reactive strategies address existing risks. Ideally, our research addresses all types of adaptation activities.

Adaptation actions and strategies are most often tailored to a specific location or region, type of infrastructure, process or sector. Table 3 summarizes these different characteristics. The climate change phenomena considered also map into the various regions as shown in Table 4. Research on adaptation activities must recognize these characteristics and the particular attributes.

**TABLE 2 Examples of Adaptation Activities**

| Activity | Example |
|---|---|
| Technological – Monitoring | Sensors to monitor pore water pressure in levees |
| Technological – Infrastructure | Sea wall construction |
| Policy based | Consideration of climate change in environmental impact statements |
| Behavioral | Alaskan winter roads are impassible |
| Managerial | Change in vegetation management on roadside right-of-way |

**TABLE 3 Characteristics of Adaptation Strategies**

| Characteristics (Source) | Attributes | |
|---|---|---|
| Sector (1) | • Land Transportation (Highway, Transit, Rail, Pipeline | • Marine<br>• Aviation |
| Climate Change Phenomena (1) | • Increase in very hot days and heat waves<br>• Increases in Arctic temperatures | • Rising sea levels<br>• Increases in intense precipitation events<br>• Increases in hurricane intensity |
| Region (31) | • Northeast and Mid-Atlantic<br>• Midwest<br>• West<br>• Great Plains | • Southeast<br>• Pacific Northwest<br>• Alaska<br>• Hawaii and US Affiliated Islands |
| Transportation Function | • Phase in the infrastructure life cycle (Planning, Design, Construction, Maintenance, Operation)<br>• Trip generator / attractor | |

**TABLE 4 Relationships Among Regions and Climate Change Phenomena**

| Climate Change Phenomena/Region | Northeast and Mid-Atlantic | Midwest | West | Great Plains | Southeast | Pacific Northwest | Alaska | Hawaii and US Affiliated Islands |
|---|---|---|---|---|---|---|---|---|
| Increase in very hot days and heat waves | X | X | X | X | X | | | |
| Increases in Arctic temperatures | | | | | | | X | |
| Rising sea levels | X | | X | | | X | X | X |
| Increases in intense precipitation events | X | X | X | X | X | | | X |
| Increases in hurricane intensity | | | | | X | | | X |

## DEVELOPING A RESEARCH PROGRAM

The proposed research program is founded on several assumptions:

- The research will make use of the best science currently available on climate change to understand the extent, magnitude and severity of climate change impacts.
- Where possible recent, ongoing, and proposed research will be integrated into the proposed research on adaptation.
- Research is broken into foundational, applied and supporting research. The foundational research is consistent with the discussion in the introduction and the characterization in Table 1 that recognizes that some research serves as a foundation for other projects. The applied research is either specific to a particular function of the provision of transportation services, or a sector. Supporting research are management elements common to all areas and projects including the information clearinghouse, dissemination, stakeholder engagement, cross cutting issues and coordination, and evaluations.
- Areas are identified that are consistent with current organizational structures, organizational functions and common research foci. However this does not preclude a more integrated model or a completely different research structure.
- A timeframe is assumed that is consistent with the research proposed in Special Report 290.

Research areas are distinguished as foundational and applied. The foundational research areas serve as a basis for the applied research and the knowledge gained is applicable to many of the applied research areas. To some extent these areas can be characterized as basic research as the intent is to create new knowledge given the highly uncertain environment and long timeframes involved in this research. This is particularly challenging because the climate change scenarios are not forecasts of climate change impacts at the level of spatial and temporal detail that is required for the types of infrastructure decisions that need to be made. Although the term "basic research" was initially used, the term "foundational research" was adopted to recognize that tools and techniques from other ongoing research efforts are likely to be adopted.

While the applied research builds on the foundational research, the two areas will advance in the same timeframe recognizing the large base of research already completed and the urgency with which some of the issues must be addressed. Both the foundational and applied research are intended to produce data, processes and tools that can be integrated with ongoing research, or research from other related programs, as well as updated information about climate change. The foundational research areas identified are:

- Identification of vulnerable assets and vulnerable locations
- Identification of opportunities for adaptation
- Understanding changes in the life of facilities
- Identifying the modes and understanding the consequences of failure
- Assessing the costs and benefits of adaptation
- Understanding stakeholder/ community response

The applied research focuses on integrating concepts of adaptation and adaptation strategies into the decision making process. As such this research fits within the strategic asset

management framework (*37*) – "Asset management is a systematic process of maintaining, upgrading, and operating physical assets, cost effectively" and adaptation to climate change is part of an integrated approach to risks associated with transportation assets that is practiced in several countries (*38*). The applied research areas must also integrate the ongoing and evolving foundational research. Specific applied research areas are:

- Infrastructure planning and environmental decision making
- Infrastructure design standards and practices
- Infrastructure construction
- Infrastructure maintenance
- Infrastructure operations
- Infrastructure renewal/ rehabilitation
- New infrastructure to support mitigation measures
- Tool and model development
- Sensing and monitoring
- Best practices
- Long range planning related to transportation and land use
- Influencing land use decisions
- Funding adaptation

Consistent with (*30*), the timeframe for short term adaptation actions is defined as being the next 30 to 40 years; and the timeframe for longer term actions is from 40 to 100 years. Also consistent with the idea that many of these adaptation actions should be proactive (protecting against current and future risks) the timeframe for the proposed research activities is the next 5 years for short term actions and 5 to 20 years for long term activities. This overall structure is also consistent with the research needs and framework identified in the 2008 state DOT peer exchange (*27*).

Several basic premises serve as a foundation for the research:

- Each area will build on ongoing and related work and each area should begin with the task of synthesizing the existing literature to demonstrate the need for additional research.
- Adaptation should be focused on the performance of the transportation system. For example, increasing the elevation of bridges to accommodate sea level change without changing the elevation of the connecting roads is of no value.
- Adaptation requires balancing the risk representing the probability of failure and the consequence of failure, with the costs and benefits of adaptation.
- Mitigation of climate change will likely cause structural changes in our transportation systems that in turn will influence how we adapt to climate change. For example, changes in some manufacturing industries will change the freight industry.
- Timing matters. For example, a company electrifying a rail line to reduce emissions, should carefully look at the need to elevate the track prior to the electrification.

For each of the research areas, the following descriptions identify the research issue, briefly state the research objective, describe the nature of the research and define the timeframe.

## FOUNDATIONAL RESEARCH

The foundational research requires close cooperation with climate scientists and other relevant agencies such as the National Oceanic and Atmospheric Administration (NOAA), and the US Geological Survey (USGS) as stated in Recommendation 4 of Special Report 290. The foundational research elements of the proposed program will establish what is known (for example, climate change is occurring), and distinguish that from what is assumed (for example, specific climate change scenarios) and what is not known (for example, the exact timeframe over which specific changes will occur). The results from the foundational research serve as inputs to the applied research in terms of identifying issues for current practice (and therefore of some urgency), scenario tools, triggers for action, and remedies.

### Identification of Vulnerable Assets and Vulnerable Locations

*Sectors – Land Transportation, Marine and Aviation*

**Issue** Most climate change predictions have been fairly generic and as such make it difficult for any unit of government to develop a response. This research area is consistent with Special Report 290 Recommendations 1 and 3.

**Objective** To develop a process for identifying assets and locations that are vulnerable to climate change.

**Research** The proposed process will use specific local information and knowledge, and climate change scenarios for a specific region. Such risk assessment processes have been used in Canada to develop maps of vulnerable areas (*15, 39*). Another example is the mapping work done for New York City indicating subway lines flooded under various scenarios of sea level rise (http://dels.nas.edu/dr/docs/dr22/Jacob.pdf). This research helps to focus attention on highly vulnerable areas. The research also requires interaction with climate scientists and modelers to understand the time scale, severity and extent of climate change. The process envisaged will also make use of Geographic Information Systems (GIS) to take advantage of the spatial relationships among topography, development and climate. Identifying vulnerable assets is important for identifying which assets require adaptation and identifying vulnerable locations is important for locating assets and development to proactively minimize future risks.

**Timeframe** Near term.

### Identification of Opportunities for Adaptation of Specific Facilities

*Sectors – Land Transportation, Marine and Aviation*

**Issues** While much has been written about adaptation strategies in general, the specifics generally relate to individual case studies. For example, Annex 5-1A of Special Report 290 documents adaptation options for each of the three different sectors (land transportation, aviation and marine) in response to each of the six different potential climate changes. A database of

these options as they relate to infrastructure is needed to serve as a foundation for decision making tools.

**Objective** To develop a database of adaptation options for specific facilities and regions.

**Research** Research is required to structure the database, define appropriate parameters for each of the options and provide a mechanism for maintaining, adding to and removing options from the database. This will require understanding the attributes of the options. For example, options will be classified using a schema such as technological, policy, behavioral or managerial to aid in supporting the decision making process. This activity is particularly important as state and local governments do not have experience with adaptation.

**Timeframe** Near term.

**Understanding Changes in the Life of Facilities**

*Sectors – Land Transportation, Marine and Aviation*

**Issue** The expected life of a facility influences the economic evaluation of any investment in infrastructure. Climate change can either foreshorten or extend the life of the facility.

**Objective** To quantify the impact of climate change on facility life.

**Research** Assessing the life of a facility is challenging in the absence of climate change. Concepts such as design life, service life, and remaining service life are already in use and research is proposed to refine these concepts (*40*). Initially research can focus on expert judgment but it is expected that over time, data will be used to refine these estimates. Programs such as the Long Term Pavement Performance Program (LTPP) and the recently launched Long Term Bridge Performance Program (LTBP) serve as an opportunity to leverage data collection efforts.

**Timeframe** Initiation – immediate. Updating – continuous.

**Identifying the Modes and Understanding Consequences of Failure**

*Sectors – Land Transportation, Marine and Aviation*

**Issue** Failure may be structural, functional, or economic. Failure is rarely catastrophic as transportation professionals focus on the delivery of safe, secure and reliable transportation services. However, climate change promises to accelerate the process of degradation and increase the opportunities for catastrophic failure due to natural hazards such as floods, and hurricanes.

**Objective** To identify the modes of failure and understand the consequences of failure.

**Research** Identifying the modes of failure and understanding the consequences of failure are key to the evaluation of adaptation options. While it is generally recognized that "do-nothing" is not an option, little work has quantified the impacts of a "do-nothing" option because the modes of failure and the consequences of failure are not understood. Research identifying the modes of failure is a synthesis of existing knowledge and ongoing research and more importantly the communication of that knowledge. Understanding the consequence of failure can also draw on existing tools such as HAZUS-MH – FEMA's tool for estimating the impacts of natural hazards (http://www.fema.gov/plan/prevent/hazus/hz_overview.shtm), and similar models in bridge management software, such as PONTIS (http://www.transportation.org/?siteid=28&pageid=74). A recently completed NCHRP project on "Asset Management of the Interstate" also explores risk and offers some ideas for managing failure (*41*). Marine transportation and aviation may require special consideration.

**Timeframe** Intermediate

**Assessing the Costs and Benefits of Adaptation**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Adaptation is identified as a costly consequence of climate change but little is understood of the costs and benefits of adaptation. The concept of "no-regret", "low regret" and "win-win" strategies recognizes these costs but eventually, proper evaluation of alternatives by all stakeholders will require more concrete estimates of costs and benefits of adaptation (*33*).

**Objective** To develop a framework for developing and refining estimates of the costs and benefits of adaptation.

**Research** The framework for developing estimates of the costs and benefits of adaptation recognizes that as more knowledge is accumulated the estimates will be refined and improved. The estimates need to be consistent with the structure of the database of climate change adaptation options identified above. One approach is to estimate values based on expert judgment and rules of thumb, and refine these estimates based on data and experiences as they are incurred. The unintended consequences of adaptation should also be considered. For example, adaptations such as sea walls to protect infrastructure may prevent landforms and ecosystems from adapting to changing sea level. Similarly constructed features such as sea walls may change the appeal of a location to residents and visitors. Benefit estimation is particularly challenging and work in Australia provides a good starting point (*42*), as well as research in Canada (*12*) and the United Kingdom (*24*).

**Timeframe** Initiation – immediate. Updating – ongoing.

### Understanding Stakeholder/Community Response

*Sectors – Land Transportation, Marine and Aviation*

**Issues** The selection of climate change options will vary depending on your point of view. For example, one could argue that some coastal areas should be abandoned or complete towns relocated. On the other hand, the residents are likely to strongly disagree with this perspective.

**Objective** To understand the responses of stakeholders and communities to the range of adaptation options.

**Research** Understanding stakeholder/community response will require some foundational social science research into perceptions, impressions and the relative importance of different issues. Focus groups followed by interviews and perhaps surveys can be used to obtain data that can then be analyzed. Various guidebooks provide ideas for building the appropriate partnerships (*14*, *33*).

**Timeframe** Intermediate

## APPLIED RESEARCH

The applied research focuses on the needs of owners and operators of our transportation systems. The research is intended to develop processes and tools that can be updated to reflect the inputs from the foundational research as they become available. The objectives and research descriptions in each of the areas are intended to illustrate the nature and scope of the research. These research areas would be further developed in collaboration with stakeholders and experts.

### Infrastructure Planning and Environmental Decision Making

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Transportation infrastructure planning and environmental decision making involves setting policy, locating and configuring new and existing transportation facilities to meet current and future demands. Planning recognizes the context in which the transportation infrastructure must deliver service, the regional and local objectives and priorities, and the constraints imposed by the site(s). Planning also involves assessing the expected life of those facilities so that capacity is provided to match the needs for the service and physical life of the infrastructure. Locating physical facilities requires knowledge of vulnerable locations, and understanding the impacts of catastrophic events and more severe environments on the expected life of facilities. This must be accomplished while continuing to address the broader goals of Infrastructure planning related to mobility, accessibility and economic development recognizing the impacts on communities, quality of life, environmental quality, and equity. This research area must be particularly attuned to the unintended consequences of various mitigation strategies and the close relationship between mitigation strategies and the need for adaptation. For example, mitigation strategies may change the demand for transportation; mitigation may decrease the demand for adaptation; and individual adaptation projects must be viewed as part of the larger transportation

network. Infrastructure planning occurs in the context of an existing project development process and under well-defined environmental regulations such as the National Environmental Protection Act (NEPA).

**Objectives** To integrate climate change into infrastructure planning and environmental decision making through:

- Identifying vulnerable locations
- Identifying facility configurations that are less vulnerable to climate change due to new designs, or new materials
- Understanding the changes in facility life due to climate change and catastrophe events
- Exploring policy changes by reviewing existing processes and regulations and understanding the impacts of climate change.

**Required Research** Research is required to integrate several foundational research activities into the planning process. While the specifics may vary from sector to sector the process should be generic to all sectors. This research will build on the ongoing research on vulnerability, the opportunities for adaptation, the modes of failure and the stakeholder response.

**Timeframe** Immediate. This is a "no-regret" strategy

**Infrastructure Design Standards and Practices**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Climate change will also cause changes in the loads on structures, the environment in which transportation facilities operate, and the behavior of facilities (for example, the thermal expansion of bridge decks and rail).

Table 5 provides examples of these impacts for different climate change phenomena. New design methodologies, such as probabilistic methods that recognize the uncertainty in the loads and environment, are required. New materials and configurations are required for landscaping, asphalt concrete, drainage capacity, elevation of bridges, and pumping capacity for tunnels (road, rail and subway). Protective structures will be required for roads, railroads, bridges, airports and ports. New environmental information needs to be added into existing standards (e.g. where permafrost is no longer permafrost, ice bridges that are no longer ice bridges). This area addresses Special Report 290 Recommendations 3 and 9.

**Objective** To develop strategies and tools to change methods, codes and standards to respond to climate change.

**Research** Design standards and practices are slow to change and given the uncertainty surrounding climate change it is unrealistic to consider frequent changes. Research on infrastructure design standards and practices is required at five different levels:

- Development of probabilistic design methods

- Application of probabilistic design methods to particular facilities
- Development of new configurations consistent with the adaptation options identified under foundational research.
- Development of new materials.
- Revision of design parameters to reflect climate change phenomena at specific locations.

**Timeframe** Long term.

**Infrastructure Construction**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Transportation construction has traditionally been organized around the "construction" season. In northern climates, this is limited by cold weather. Climate change is likely to lengthen the construction season in cold climates. However, the construction season may be limited by

**TABLE 5 Climate Induced Forces That Influence Transportation Design (*43*)**

| Climate-Change Phenomenon | Changes in Environmental Condition | Design Implications |
|---|---|---|
| Temperature change | Rising maximum temperature; lower minimum temperature; wider temperature range; possible significant impact on permafrost | Over the short term*, minimal impact on pavement or structural design; potential significant impact on road, bridge scour and culvert design in cold regions |
| | | Over the long term, possible significant impact on pavement and structural design; need for new materials; better maintenance strategies |
| Changing precipitation levels | Worst case scenario, more precipitation; higher water tables; greater levels of flooding; higher moisture content in soils | Over the short term, could affect pavement and drainage design; greater attention to foundation conditions; more probabilistic approaches to design floods; more targeted maintenance |
| | | Over long term, definite impact on foundation design and design of drainage systems and culverts; design of pavement subgrade and materials impacts |
| Wind loads | Stronger wind speeds and thus loads on bridge structures; more turbulence | Over the short term, design factors for design wind speed might change; wind tunnel testing will have to consider more turbulent wind conditions |
| | | Over the long term, greater materials strength and design considerations for suspended and cable-stayed bridges |
| Sea level rise | Rising water levels in coastal areas and rivers; increases of severe coastal flooding | Over the long term, greater inundation of coastal areas; more stringent design standards for flooding and building in saturated soils; greater protection of infrastructure needed when higher sea levels combine with storm surges |
| Storm surges and greater wave height | Larger and more frequent storm surges; more powerful wave action | Over short term, design changes to bridge height in vulnerable areas; more probabilistic approach to predicting storm surges |
| | | Over long term, design changes for bridge design, both superstructure and foundations; change in materials specifications; more protective strategies for critical components |

* For purposes of this table, short term is defined as being the next 30 to 40 years; longer term is from 40 to 100 years

high temperatures in the south. Many of the issues relate to the organizational structure of the institutions involved. In some cases, due to changes in extremes, new methods must be used and contractors and agencies will need to understand these methods and training will be required.

**Objective** To understand institutional issues related to shortened construction schedules to avoid heat and longer construction seasons due to shorter winters.

**Research** This issue is very specific to particular regions or states. Most transportation institutions have elaborate organizational structures that balance the workloads in construction, maintenance and operations. Construction planning (advertising and awarding contracts, construction inspection, and contract documentation) is organized around a fixed calendar that will require modifications. Research will address strategies to balance workloads and develop educational and training programs to respond to the need for new construction methods, schedules, and contracting practices. This research area will draw from experiences in other parts of the country.

**Timeframe** Long term.

**Infrastructure Maintenance**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Climate change requires reallocation of resources based on changing needs (less freeze-thaw damage, more mowing and vegetation control, more heat damage, less snow removal). New strategies for vegetation management, debris management, and silt management due to increased flooding are also required

**Objective** To develop strategies to manage changing maintenance needs due to climate change.

**Research** Existing maintenance management systems track resources requirements, schedule preventive maintenance, and monitor expenditures. Research is needed to understand how these systems must change to respond to climate change. Areas to consider are:

- Changes in the expected life of facilities and treatments
- Changes in the expected frequency of activities such as mowing and pavement patching
- Changes in maintenance policies including changes in levels of service and triggers or thresholds
- Changes in the period during which specific maintenance activities, such as crack sealing or slurry seals, can be undertaken

Again, experiences in other parts of the country may serve to provide innovative solutions.

**Timeframe** Long term.

## Infrastructure Operations

*Sector – Land Transportation*

**Issues** Climate change is expected to increase the severity and intensity of hurricanes, floods, droughts and heat waves. Operations needs to be prepared to respond to these events including emergency evacuation and the integration of emergency planning and response into transportation operations including better communications with users. Ongoing Intelligent Transportation Systems (ITS) and the SHRP 2 Travel Time Reliability projects are already addressing some of these issues. Reduced seasonal weight restrictions also need to be recognized and communicated.

**Objective** To develop strategies to integrate emergency response into operations and implement other changes in operations that respond to climate change.

**Research** Considerable activity is already underway in this area although in general the research is not specifically addressing climate change. Research needs to understand how climate change may intensify or accelerate ongoing projects, or what changes are required to ensure that these efforts recognize the role of climate change. Specifically, coordination of emergency response, additional resources for emergency response, obtaining access to better short and long term forecasting of weather related events such as winter storms and hurricanes is needed. Public sector agencies will need to continually update their plans for emergency preparedness (evacuation), response, recovery (debris removal, detours and alternate routes and rapid repair) and ultimately mitigation of catastrophic events and disasters.

**Timeframe** Immediate.

*Sector –Marine*

**Issues** Access to facilities and the navigability of channels and shipping routes will change due to changes in ice coverage, river flows due to drought and flood, and changed clearance under bridges and at ports. Longer ice free shipping season, the possibility of a Northern Sea Route, and sea access to northern communities can significantly change operations. In other regions reduced river flows, can increase summer load restrictions. Increasing severity and intensity of storms also has implications for emergency evacuation of ports, and inland and coastal waterways, as well as strategies for dealing with storms at sea.

**Objective** To develop a systematic process for recognizing and communicating changes in marine facilities and navigable waterways.

**Research** The changes have safety, and economic implications. Local operators are likely to respond quickly and effectively based on local knowledge but ultimately, maps and charts must be updated, restrictions should reflect actual conditions and facilities of national significance (such as major ports) need to respond accordingly. A plan is required to organize this response. Similarly, plans are required for offshore enterprises.

**Timeframe** Intermediate.

*Sector –Aviation*

**Issues** Like marine transportation, aviation operations will be impacted by more restrictions due to high temperatures, fewer restrictions due to low temperatures and snow and ice, and more disruptions due to severe weather.

**Objective** To develop a systematic process for accommodating changes in aviation operations due to climate change.

**Research** The airline industry has historically changed operations due to economic factors, new technology and new regulations. Therefore there is a broad base of experience with change. However, climate change offers an opportunity to be more proactive rather than reactive. The proposed research should look at potential changes in operations strategically also recognizing other adaptations that will be required such as relocated facilities due to sea level rise.

**Timeframe** Intermediate

**Infrastructure Renewal/Rehabilitation**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Infrastructure renewal and rehabilitation provides an opportunity to implement climate change adaptation to create a "no-regrets" situation. Transit New Zealand has used this strategy within the context of their existing asset management approach to managing their transportation infrastructure. This requires consideration of climate change in the decision making process and then in the strategy design process. The identification of and development of rapid repair techniques in response to floods and wind damage, and modular construction techniques for rapid repair are also important strategies. Research is needed to on both processes and techniques.

**Objective** To determine how to integrate consideration of climate change into existing asset management practices and to identify and develop rapid repair techniques.

**Research** Based on observations of asset management practices in Canada, New Zealand, Australia and the United Kingdom from the 2005 International Asset Management scan, recent NCHRP funded asset management projects have integrated risk into asset management (*38, 41*). However, no documented projects have explicitly explored the risks from climate change. The proposed research will review more recent international experiences to identify opportunities to complement and supplement existing and developing asset management guides and research to address climate change in this context. Relevant NCHRP projects include:

- Project 08-69: Supplement to AASHTO Transportation Asset Management Guide, Volume 2--A Focus on Implementation.

- Project 20-74: Developing an Asset Management Framework for the Interstate Highway System (*41*)
- Project 20-74A: Development of Service Levels for the Interstate Highway System

**Timeframe** Intermediate.

**New Infrastructure to Support Mitigation Measures**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Many measures proposed to mitigate climate change require significant adaptation of existing infrastructure and behavior to be effective. For example, the use of hydrogen as automobile fuel requires the development of a production and distribution network. Experience with LPG and LNG for taxis and buses indicates that significant investment in the infrastructure is required to support these alternative fuels. Attention to unintended consequences is also required. (For example, does the production of the fuel impact the environment; does the production of the fuel require more energy than the fuel generates; what constitutes a safe distribution system?) For hydrogen, infrastructure considerations include production and storage facilities, structures and methods for transporting hydrogen, and fueling stations. Institutional arrangements are also important. This work should leverage ongoing research as part of the 2005 National Energy Plan (Public Law 109-58).

**Objective** To understand the needs for new infrastructure to support mitigation measures and to develop a plan for R&D strategies and support, and build the necessary public and private partnerships.

**Research** The first phase of this research is a synthesis of past and ongoing research. This will then serve as a foundation for developing a plan to move forward.

**Timeframe** Intermediate

**Models and Tools to Support Decision Making**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Most transportation organizations do not have the resources or organizational capacity to develop processes, models or tools to support decision making. While many models, several guides and some tools already exist, they are not tailored to transportation needs. Research is needed in several areas to develop these processes, models and tools. This area supports Special Report 290 Recommendations 1, 2, 3, and 14.

**Objective** To develop models and tools to support decision making.

**Research** Several separate tasks are required that build on the foundational research already identified. For example, this research might develop software that takes the data on adaptation strategies and their costs and benefits and puts in a useful format – a spreadsheet, a table, or adds

an interface to a database, or customized software to map the information. Models and tools include:

- Tools to support identification of infrastructure facilities and systems impacted by climate change (Special Report 290 Recommendation 1). These tools should be linked to existing asset management inventories.
- Economic analysis (cost-benefit) models and tools. Cost benefit strategies require consideration of the timeframe for climate change and implementation of adaptation strategies, the areas considered in foundational research (identification of alternatives, costs and benefits, failure modes, and community response) (*44, 45*).
- Processes for identifying alternatives recognizing that alternatives must be tailored to local conditions and uncertainty
- Vulnerability assessment tools
- Risk communication tools/ visualization/ mapping
- Processes, rather than plans, for emergency response (recognizing the importance of adaptation, improvisation, innovation) that can provide better models for emergency evacuation

**Timeframe** Immediate

**Monitoring and Sensing**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** Climate change causes changes in the material properties of facilities and in indicators of events. At the same time, advances in technology provide the ability to detect and interpret these changes. Sensors and devices to monitor pore water pressures, saturated soils, land slopes, flood levels, thermal stresses, subsidence and scour are available. Similarly, improved information, to provide hurricane, surge and flood warnings, is available. The challenge lies in how, where and when to deploy the sensors and how to interpret the signals from the sensors and then how to communicate the information provided by the signals. This area is consistent with Special Report 290 Recommendation 7.

**Objective** To develop and deploy monitoring and sensing systems to provide useful information related to the condition of transportation facilities and local weather.

**Research** Recent advances in sensors and monitoring provide rich information on the condition and status of both facilities and the environment. However the information must be tailored to produce the appropriate response (for example, the decision to evacuate a transit station due to high temperatures, or close a bridge due to foundation scour). Ongoing projects on structural health monitoring or the development of new types of weather radar serve as models for this research as they are multidisciplinary efforts to develop and deploy the technology. This research could be organized around several smaller projects focusing on specific application or atypical behavior.

**Timeframe** Long term

**Best Practices for Adaptive Features**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** As for models and tools, transportation agencies do not have the resources to experiment with new techniques. Having easy access to document experiences and best practices helps agencies to adopt practices that have been tested and fit their needs. This area is consistent with Special Report 290 Recommendations 8 and 14.

**Objective** To identify and document current, evolving and emerging best practices for adaptive features.

**Research** Criteria for selecting best practices will be developed in consultation with stakeholders. A review of the literature, and surveys of organizations known to be leaders in adaptive practices will provide a core set of best practices. The collection of best practices will continue to evolve in the long term as the research progresses and experience is gained. This project is a key part of the information clearinghouse, dissemination and stakeholder engagement discussed in the criteria for selecting research priorities.

**Timeframe** Immediate with continued updating.

**Long Range Planning Related to Transportation and Land Use**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** While the inclusion of adaptation strategies into capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans has been discussed in other research areas, the complex interrelationships between transportation and land use have not been addressed. Transportation agencies are often challenged in this area as they have little control over land use. Therefore integrating land use and transportation into long range planning requires stakeholder engagement. Limiting development, or abandoning communities and facilities in vulnerable areas such as flood plains and coastal areas are feasible adaptation options that require the cooperation of all stakeholders in long range planning. This area addresses Special Report 290 Recommendation 2 and 14.

**Objective** To work with stakeholders to understand the implications of climate change on land use and transportation and identify appropriate adaptations.

**Research** This research requires identifying stakeholders, discussing the adaptation options (including the costs and benefits) in the context of various climate change scenarios, and the risks involved. Given that most agencies have little control over land use, this research requires a partnership between agencies providing transportation services and organizations influencing land use. In some areas, this may be exploring how to integrate climate change issues into the long range regional plans.

**Timeframe** Long range.

**Influencing Land Use Decisions**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** In addition to working with stakeholders, transportation agencies can work with other agencies to develop disincentives for development. This includes revising the flood insurance program, the flood insurance risk maps, imposing tax disincentives and development fees for developing in vulnerable areas, and imposing more stringent building codes for developing in vulnerable areas. These disincentives are applicable at the federal, state and local level. In some cases the disincentives are applied to floodplains or watersheds, and must cross jurisdictional boundaries to be applied at a regional level. Reducing development in vulnerable areas reduces the need to provide transportation services. FHWA is already working with other agencies on this topic. This research area addresses Special Report 290 Recommendations 13 and 14.

**Objective** To work with other agencies at all levels of government to influence land use decisions by developing disincentives for development.

**Research** Using up-to-date climate scenarios to update flood insurance maps and the consequences of climate change to update insurance rates can influence land use. Similarly local governments can impose development restrictions either through development fees or zoning or development regulations to discourage development. These activities require coordination and cooperation with other agencies and units of government building on existing coordination efforts.

**Timeframe** Long term.

**Funding Adaptation**

*Sectors – Land Transportation, Marine and Aviation*

**Issues** The Center for Integrative Environmental Research (CIER) at the University of Maryland states that “climate change will cost the public sector a lot.” Despite the concept of “win-win”, “no regret” or “low regret”, the stakeholders incurring the benefits are not the same as the stakeholders incurring the costs. There is a disconnect between who benefits and who pays. Identifying strategies for funding climate change adaptation is critical. Like many transportation improvements, there are institutional and political barriers to the use of existing and new revenue streams to pay for adaptation. Research is needed to understand these barriers and explore new revenue streams. For example, a carbon impact fee could be used to fund adaptation (*46*). This research area addresses Special Report 290 Recommendation 14.

**Objective** To identify strategies to fund climate change adaptation.

**Research** This research should begin by identifying various principles that apply to different funding mechanisms. For example, should those who benefit from the adaptation be those that pay? Innovative financing mechanisms should be explored and evaluated including the link between mitigation and adaptation.

**Timeframe** Immediate

## COST ESTIMATES AND TIMELINES

Climate change is fraught with uncertainty. One of the real research challenges is embracing this uncertainty. This is also true in attempting to estimate the cost and timeframe for the research. Many research successes have been opportunistic – the right combination of people, issues, technology and institutional support at the right time. Table 6 provides an approximate timeline for the various research areas. The timeline reflects research priorities and constraints in terms of research activities that support later activities. In particular, the timeline recognizes that initiating and managing all research topics at the same time is probably not feasible and attempts to stage various topics to recognize resource constraints. The staging should eventually reflect not only stakeholder priorities but the relationships among ongoing related research areas.

Similarly, Table 7 provides cost estimates in terms of expected cost. A total expected cost is also included. These estimates are based on expert judgment and are intended to serve as a guide for seeking funding and support for these critical research activities. The total expected cost of $120m is reasonable considering damaged inflicted by Atlantic hurricanes in 2005 was over $100 billion (*37*). The proposed distribution of research expenditures by year (in 5 year intervals) is shown in Figure 1. Research expenditures are concentrated in Years 1 to 5.

**TABLE 6 Proposed Research Timeline**

| | Years | 1 | 2 | 3 | 4 | 5 | 6 - 10 | 11-15 | 16-20 |
|---|---|---|---|---|---|---|---|---|---|
| Foundational | Identification of vulnerable assets and vulnerable locations | ■ | ■ | ■ | | | | | |
| | Identification of opportunities for adaptation | ■ | ■ | ■ | | | | | |
| | Understanding changes in the life of facilities | ■ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | Identifying the modes and understanding the consequences of failure | | | ■ | ■ | ■ | | | |
| | Assessing the costs and benefits of adaptation | ■ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | Understanding stakeholder/ community response | | | ■ | ■ | ■ | | | |
| Applied | Infrastructure planning and environmental decision making | ■ | ■ | ■ | | | | | |
| | Infrastructure design standards and practices | | | | | | ■ | | |
| | Infrastructure construction | | | | | | ■ | ■ | ■ |
| | Infrastructure maintenance | | | | | | ■ | | |
| | Infrastructure operations | | | ■ | ■ | ■ | | | |
| | Infrastructure renewal/ rehabilitation | | | ■ | ■ | ■ | | | |
| | New infrastructure to support mitigation measures | | | ■ | ■ | ■ | | | |
| | Tool and model development | ■ | ■ | ■ | | | | | |
| | Sensing and monitoring | | | | | | ■ | | |
| | Best practices | ■ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | Long range planning related to transportation and land use | | | | | | ■ | ■ | ■ |
| | Influencing land use decisions | | | | | | ■ | ■ | ■ |
| | Funding adaptation | ■ | ■ | ■ | | | | | |
| Support | Information clearinghouse | ■ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | Dissemination | ■ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | Stakeholder engagement | ■ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | Cross cutting issues and coordination | ■ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | Evaluation | | ■ | ■ | ■ | ■ | ▨ | ▨ | ▨ |

**Legend:** ■ Initiated ▨ Ongoing

**TABLE 7 Expected Research Costs**

| Areas | | Expected Costs 000's $ |
|---|---|---|
| Foundational | Identification of vulnerable assets and vulnerable locations | 3,000 |
| | Identification of opportunities for adaptation | 3,000 |
| | Understanding changes in the life of facilities | 7,000 |
| | Identifying the modes and understanding the consequences of failure | 3,200 |
| | Assessing the costs and benefits of adaptation | 8,800 |
| | Understanding stakeholder/ community response | 1,500 |
| Applied | Infrastructure planning and environmental decision making | 3,000 |
| | Infrastructure design standards and practices | 10,000 |
| | Infrastructure construction | 5,500 |
| | Infrastructure maintenance | 3,000 |
| | Infrastructure operations | 3,500 |
| | Infrastructure renewal/ rehabilitation | 2,000 |
| | New infrastructure to support mitigation measures | 2,000 |
| | Tool and model development | 10,000 |
| | Sensing and monitoring | 3,000 |
| | Best practices | 7,000 |
| | Long range planning related to transportation and land use | 7,500 |
| | Influencing land use decisions | 7,500 |
| | Funding adaptation | 2,000 |
| Support | Information clearinghouse | 5,600 |
| | Dissemination | 3,600 |
| | Stakeholder engagement | 3,200 |
| | Cross cutting issues and coordination | 11,500 |
| | Evaluation | 3,600 |
| Total | | 120,000 |

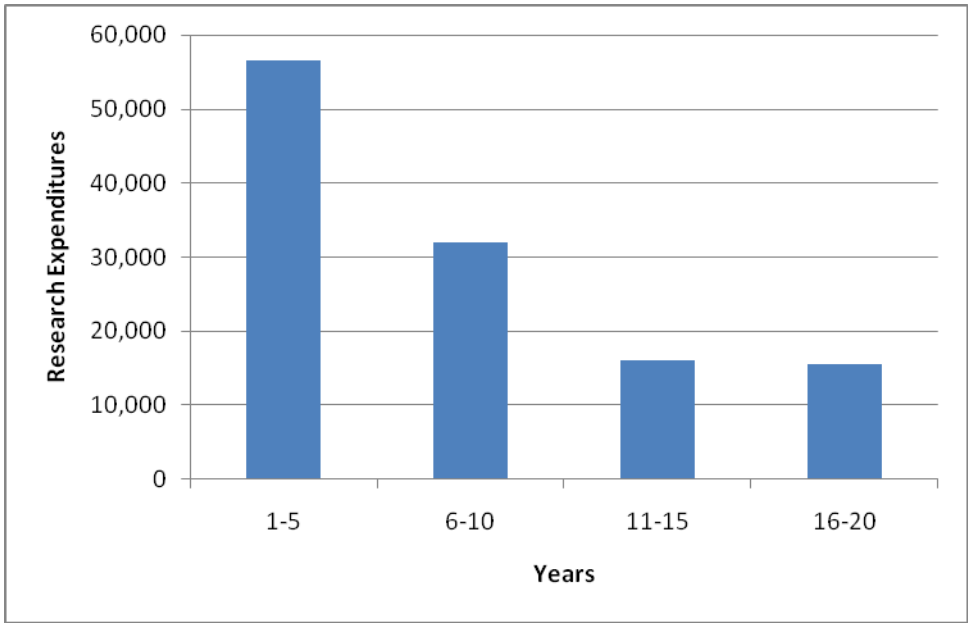


**FIGURE 1 Proposed research expenditures.**

## DEVELOPING LINKS TO ONGOING RESEARCH PROGRAMS

Many of the proposed adaptation activities to respond to climate change simply represent good practice in designing, operating, maintaining and renewing transportation facilities. In several cases existing and proposed research programs are addressing similar issues and the research on adaptation for transportation should coordinate with these programs rather than duplicate any effort. Examples of these programs include:

- Strategic Highway Research Program 2 – This multi-year program, managed by the Transportation Research Board, includes work on the Identification and Analysis of Best Practices to improve travel time reliability and several infrastructure renewal initiatives. (http://www.trb.org/shrp2/SHRPII_About.asp)
- NCHRP Long Term Strategic Research including NCHRP 20-83(04) Effects of Changing Transportation Energy Supplies and Alternative Fuel Sources on Transportation
- DOT's Center for Climate Change and Environmental Forecasting (http://climate.dot.gov/)
- AAHSTO Reauthorization efforts (http://www.transportation1.org/policysummaries/)
- FHWA's Gulf Coast II study (34)
- The University Transportation Center program (http://utc.dot.gov/utc_about.html)The National Oceanographic and Atmospheric Administration's Climate Change Office Regional Integrated Science Assessments (RISA) program (http://www.climate.noaa.gov/cpo_pa/risa/)
- Asset management research on the inventory of assets, assessment of risk (next step vulnerability) (http://assetmanagement.transportation.org/)
- Intelligent Transportation Systems (ITS) within the Research and Innovative Technology Administration undertakes research on communication with motorists, emergency evacuation and travel time reliability, and works on dissemination, capacity building and stakeholder involvement (http://www.its.dot.gov/index.htm)
- Long Term Pavement Performance (LTPP) program includes data from 20,000 pavement test sections over a 20 year period (http://www.trb.org/Studies/Programs/LTPP.asp)
- Long Term Pavement Performance (LTBP) program, launched in 2008, is intended to collect data on bridges over a 20 year period (http://www.tfhrc.gov/ltbp/about.htm)
- National Science Foundation supports basic research. Existing programs on human and social dynamics, decision making, and resilient and sustainable infrastructure offer provide opportunities for collaboration (http://www.nsf.gov)

These examples are neither comprehensive nor complete but are intended to illustrate the opportunities for collaboration.

## CONCLUSIONS

Drawing on global and international efforts to determine the need for adaptation and then developing feasible responses, the proposed research program is structured around information sharing, stakeholder involvement and support tools for all levels of government and public and private sector stakeholders. The program recognizes the uncertainties associated with the climate change, the importance of probabilistic analysis, the range of adaptation options possible,

the importance of understanding local needs and conditions, and the importance of avoiding unintended consequences.

The intent is to be cautious but proactive. The program is modest but effective.

While the timing and magnitude of climate change is unknown, climate change is occurring. To adapt, agencies, owners, and users must make rational well informed decisions. Research is necessary to make these decisions and this research must begin now. The impacts of delay are likely to be far more costly and disruptive than the costs of action.

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This paper covers a wide range of topics. The paper is intended to capture key ideas that serve as a starting point for a more holistic research. In developing the paper, I greatly benefited from the background materials developed by Laura Black, graduate student in Urban Affairs and Public Policy, and the comments received from members of the TRB Executive Committee and the PIARC Technical Committee on Preserving the Environment, TRB's Special Task on Climate Change and Energy, and Federal Highway Administration. Of course, errors and misstatements in this paper are my responsibility.

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