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Adapting Transportation to the Impacts of Climate Change

State of the Practice 2011

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State of the Practice 2011

Special Task Force on Climate Change and Energy

June 2011

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Contents

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Introduction

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Regardless of what climate change mitigation strategies are adopted, the shorter-term effects of climate change mean that transportation policy makers, planners, and operators—across all modes—need to make changes to adapt to these effects. This E-Circular on adaptation, developed under the auspices of the TRB Special Task Force on Climate Change and Energy, is a companion to the *TR News* Special Edition issue of May–June 2010 on climate change mitigation (*1*). This document focuses on transportation adaptation practices that can be implemented to yield benefits now and in the longer term. It highlights what climate change adaptation means for the transportation industry and why it is so important.

This document begins with an overview of adaptation issues and a summary of the numerous recommendations for adaptation identified in the 2008 TRB Special Report 290 (*2*). Following that is a series of articles addressing work currently underway at the federal level, at the state level, and in the United Kingdom. Projects at the federal level, being pursued by the FHWA's Sustainable Transport and Climate Change Team, address a broad range of adaptation issues facing state departments of transportation and metropolitan planning organizations, including the issue of risk and vulnerability, which is being addressed by an assessment tool that FHWA is testing in a number of states. The United Kingdom has established requirements for addressing climate change and adaptation that are currently being implemented at various levels of the government; its focus on coordination among various sectors (including transportation) provides interesting concepts for the United States to consider. The next article highlights quite a number of specific adaptation strategies that have been implemented by various states in the United States that are providing successful results and that bear consideration by agencies across the country. An article on aviation focuses on some of the unique aspects of dealing with adaptation in relation to airport operations, when many constituents are involved—the ideas on communication, cooperation, and collaboration will be of interest to those dealing with other transportation modes. The final feature article highlights the need for transportation planners and operators to work and plan in close cooperation with a range of agencies and across regional boundaries, and to include weather forecasters and emergency responders.

Sidebars throughout this E-Circular highlight the real impacts of flooding due to climate change, summarize the impacts of climate change on freight operations, and provide information about an upcoming international scan on climate change adaptation. The document concludes with a list of research needs and opportunities identified by the TRB Special Task Force on Climate Change and Energy.

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Adapting to Climate Change
Another Challenge for the Transportation Community

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The transportation planners, designers, and operators of this nation's transportation systems face many daunting concerns, not the least of which is funding to maintain and improve the country's infrastructure and competitiveness. To these concerns is now added climate change or global warming. This paper does not address the science of climate change or the issue of mitigation to reduce the emissions of greenhouse gases (GHG). Rather it accepts the current state of knowledge on global warming and focuses on adaptation. How does the transportation community develop solutions and approaches that will minimize or eliminate the impact of climate change? To many, this question is a paramount one as the nation builds, rebuilds, operates, and maintains its transportation infrastructure.

Even if there are major strides in the mitigation of GHG emissions, the world very likely will be facing a significantly altered climate in coming decades with impacts that test our current ability to forecast accurately. Nonetheless, one can develop scenarios of probable impacts and how the United States might adapt to conditions that could occur 25 to 50 years hence. While most of these scenarios deal with transportation, a few others are included to demonstrate the breadth of the impacts.

- **Rising sea levels will place people, homes, businesses, and infrastructure at risk, especially along the Atlantic and Gulf Coasts and Alaska.** Coupled with land subsidence, prevalent in many areas such as the Gulf Coast, the impacts will be felt tens of miles inland. More intense hurricanes packing higher wind speeds coming on shore on higher sea levels are a recipe for even greater disaster. Efforts to restore barrier islands to protect the mainland will be extensive and expensive. Sea walls along miles of shoreline may protect densely populated areas, but relocation inland of some communities may well be necessary. Transportation systems must be designed to permit faster and orderly evacuation of coastal communities. Are there new structural and nonstructural solutions to these problems? Can more resilient systems be developed that can withstand a certain amount of inundation during high storm surges, but restore service and utility rapidly?
- **Heat will be a growing concern throughout much of the United States.** Warmer temperatures and longer heat waves will create demand for more air conditioning, even in northern latitudes such as New England. By the end of the century, the climate in Illinois is forecast to be like Texas today. Sustained higher temperatures will stress pavement materials, bridge structures, and rails. The impact of prolonged heat waves will impact the most vulnerable of our population, the poor, the elderly, and the very young. With rising temperatures will come greater desertification and drought, particularly in the southwest. Water scarcity, already an issue in those regions, will necessitate changes in water laws and interstate compacts. Lower air densities will reduce aircraft takeoff payloads and require longer runways.
- **Water levels in the Great Lakes will drop, impacting shipping through the Saint Lawrence Seaway, but elsewhere higher temperatures of inland waterways and the Arctic will lengthen the shipping season.** Power plant efficiencies will decrease absent new

technologies to improve heat transfer systems. Construction and other outside work will increasingly be performed in evening and nighttime hours to protect workers' health. Are there more effective ways to protect the most vulnerable from the impacts of heat waves? Can more heat resistant materials be developed with which to pave our highways and build our infrastructure? Can new developments in aerodynamic design improve aircraft liftoff capacities?

- **With the shift in temperatures, there will be a concomitant migration of plant, insect, and disease vectors northward in the United States.** The unprecedented infestation by the log pole pine beetle in the Rocky Mountains and the spruce beetle in Alaska will have eliminated those native trees, creating a tinderbox for forest fires. As amply demonstrated in California, Florida, and Colorado, such fires directly impact transportation visibility and are invariably followed by rainstorms generating mudslides that destroy rail lines and highways. Crops once confined to southern climes will now be grown farther north, and the growing season may well permit two harvests per year in new locales. Conversely, drought and water reallocations may change the crops grown in some of the nation's most productive regions such as the southwest. Weeds and other invasive plant species will rapidly move northward as will disease vectors thereby placing larger populations at risk. It is likely that natural mutations of some of these diseases will create new problems. Plant science will be particularly challenged to arrest some of these migrations as will the health sciences. On a positive note, warmer winters may well reduce the need for and cost of snow and ice removal while improving vehicle safety.
- **Increased intensity of precipitation in many parts of the continental United States and perhaps Alaska will place new stresses on the environment.** Rainfall frequency–duration profiles will have changed very significantly: more frequent, heavier storms. Culverts, stormwater drainage systems, and natural drainage basins will all experience overloads with the increase in heavy rainfall. Infrastructure, such as bridges, levees, and dikes, will have to be designed to withstand greater hydraulic loads. Hydrological analyses will be revised, flood plains redefined, and new engineering standards developed. Social and environmental questions must be addressed as the nation wrestles with the entire issue of sustainable development especially in coastal communities. See the sidebar (page 10), which graphically shows effects of increased precipitation.
- **Alaska is a special case as temperatures are expected to rise much more rapidly in far northern regions.** The Arctic ice sheet will retreat even farther, opening the Northwest Passage to shipping but exposing the northern slope of Alaska to greater storm erosion. Many native villages will have to be relocated. Infrastructure built on permafrost will be endangered, necessitating new structural approaches and replacement. Cold weather roads will disappear, creating yet another challenge to accessing parts of Alaska by rail or road.

If these scenarios provide a window into the climate of the future, it behooves those involved with the planning, design, construction, and operation of infrastructure systems to understand how climate change will impact those systems. As we move through the 21st century, how can we rehabilitate, reconstruct, build, operate and maintain systems that are more resilient to the impacts of climate change? Nowhere will the impacts of climate change be more apparent than on the vast transportation network of this country.

CLIMATE CHANGE IMPACTS

In 2008, TRB *Special Report 290*: *Potential Impacts of Climate Change on U.S. Transportation* identified five specific concerns that will directly affect transportation systems over the next 50 to 100 years (*1*); most of these were alluded to in the climate scenarios above:

- Sea level rise (virtually certain, 99% probability);
- More very hot days with concomitant heat waves and fewer cold days (very likely, 90% probability);
- Rise in Arctic temperatures (virtually certain, 99%);
- Changes in precipitation patterns (very likely, 90%); and
- Increase in the intensity of strong hurricanes (likely, 67% probability).

The assessments and associated probabilities in the parentheses are from the Intergovernmental Panel on Climate Change report (*2*).

ADAPTATION AND RISK ANALYSIS

Mankind and the environment will adapt to climate change either as a reaction to short term impacts, sometimes with tragic consequences, or as a planned response. Planned adaptation must balance the risks with the benefits and costs in a rational manner. Situations will vary from high probability, low consequence events such as the flooding of agricultural lands or low traffic flood plain roads to low probability, high consequence events like Hurricane Katrina.

Risk analysis is the identification of the hazards of concern (sea level rise, intense precipitation, storm surge), the vulnerable infrastructure assets (bridges, highways, airports), the potential consequences (direct and indirect including cost to society and the economy), and the probability that the hazardous event will occur.

Applying risk analysis techniques to climate change and reaching sound adaptation conclusions is a very complex process. It is truly decision making under circumstances of great uncertainty.

UNCERTAINTY OF CLIMATE SCIENCE

There are the inherent uncertainties or lack of specificity surrounding the science of climate change and these can be divided into three major issues.

1. Natural variations occur with climate systems, even when there are no external forcing factors such as volcanic eruptions or GHG emissions. One of the most important is the El Nino–La Nina southern oscillation in the Pacific Ocean off California. Other factors include sunspots and the wobble in the Earth’s axis.
2. There is the uncertainty about the level of GHG emissions and what effect future mitigation measures may have on emissions.
3. There is the uncertainty about the response of Earth’s climate to various perturbations including, most specifically, increased GHG emissions

THE ISSUE OF SCALE

Another issue that must be addressed is that of scale. Climate scientists are most confident in projecting climate changes at the global scale, e.g., average temperatures of the Earth's oceans and land mass. As the scale decreases, their confidence level goes down and so too does knowledge about specific impacts. Infrastructure planners, on the other hand, can do little with global climate change information. They need information at the regional and local scale for it to be useful.

Developing finer scale models or downscaling the current global climate models is essential to understanding the impacts of global warming at a practical level.

GRADUAL CHANGES VERSUS EXTREME EVENTS

Of the five primary climate change impacts, it is readily apparent that some are gradual changes, such as sea level rise while others relate to extreme events such as floods and hurricanes. Indeed, one of the important characteristics of climate change will be the increased frequency of extreme weather events, i.e., surprises.

Planning, design, operation, and maintenance of transportation systems traditionally have been based on the analysis of historical weather data, but the climate is changing in ways not witnessed before. The once-in-100-years storm of yesterday may well become more frequent, say to a once-in-20-years event. To put it another way, the slope of historical data on temperature and precipitation has changed.

MULTIPLE STRESSES

Climate change cannot be considered in isolation. It must be considered in the context of multiple other stresses, both environmental and societal, that affect the human experience. For example, the impacts of sea level rise are influenced heavily by land subsidence, coastal population growth, institutional constraints, wealth, and other factors.

Climate change is an additional stress on the system, one that may become the tipping point wherein the system is permanently altered. Take coastal development where continued sea level rise coupled with storm surge is going to place coastal communities at greater risk—homes, businesses, and the infrastructure that supports them. As the intensity of storms rise on higher seas, it may well become prudent to abandon or move some of these coastal communities.

APPROACHES TO RISK MANAGEMENT

Given the inherent complexities in analyzing how to respond to climate change, planning for adaptation has to be flexible and responsive to new and better information. Figure 1 (*3*) is a somewhat simplified diagram of the basic steps to be taken to develop sound adaptation options coupled with a feedback loop to monitor and re-evaluate options.

The process begins with identifying the climate futures that are relevant to the transportation system in the region or locale under study. Is one concerned about coastal sea

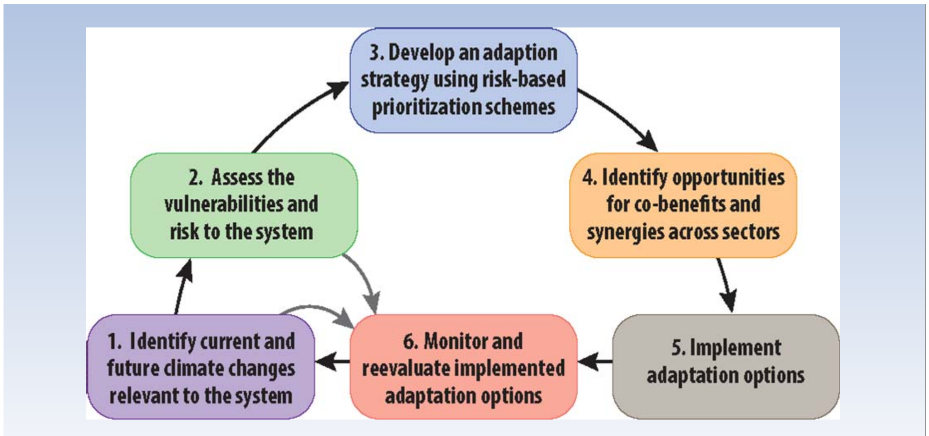

FIGURE 1 Adapting in the long term: a risk management approach (*3*).

level rise perhaps coupled with storm surge as in the Gulf Coast and Alaska? Or more intense storms and floods in the Midwest or Northeast? Or perhaps extended heat waves in the Southwest and Southeast? What is the magnitude of these impacts and over what period of time will they be manifest?

How do these climate changes impact the transportation assets? What are the systems or parts thereof which are at risk, i.e., what are the vulnerabilities? The next step is to develop alternative strategies that are responsive to different climate scenarios. These alternatives may well involve various technical solutions, but also institutional or market-driven changes.

Often there will be opportunities for cobenefits such as restoring barrier islands thereby providing protection for the mainland, but also recreating valuable wetlands and protecting barge traffic. At the same time, one has to be conscious of potential adverse impacts. Flood walls can destroy natural wetlands both on the coast and along inland waterways.

With adaptation options identified, the planning process shifts to implementation. As new and different approaches are tried and as more is learned about the climate threats, monitoring successes and shortcomings and modifying solutions are imperative—what some term adaptive management. The climate will be changing over decades and transportation systems are built to last 50 to 100 years. Improvements to our knowledge base and to our adaptation strategies will occur. Two different approaches to infrastructure adaptation planning are highlighted below as examples of the activities already under way in some communities.

In 2006, New York established a special Climate Change Adaptation Task Force made up of public and private stakeholders. Using climate forecasts prepared by the New York Panel on Climate Change, the Task Force created a risk matrix shown in Figure 2 (*4*). The horizontal axis is the likelihood that an event will happen during the lifetime of the infrastructure element and the ordinate is the magnitude of the consequence if the event occurs. Stakeholders decided where to place different infrastructure segments into the matrix. Those boxes shaded more darkly in the upper right are those where the probability and consequence are the greatest, i.e., the greatest risks, such as the flooding of the subway system.

The final step in New York's process was to relate urgency and cost as shown in this second matrix (Figure 3). Items that fall in the upper left hand box are of greatest urgency and lowest relative cost, i.e., the most cost effective. The city presumably will attack those first.

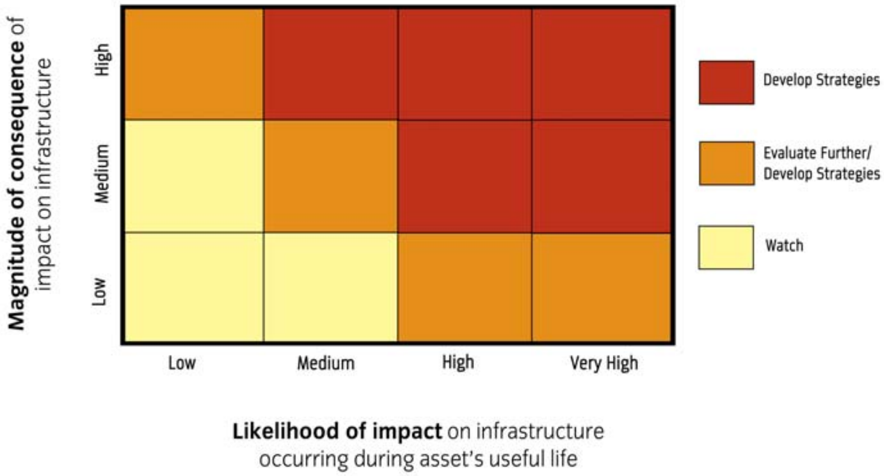

FIGURE 2 New York City risk matrix.

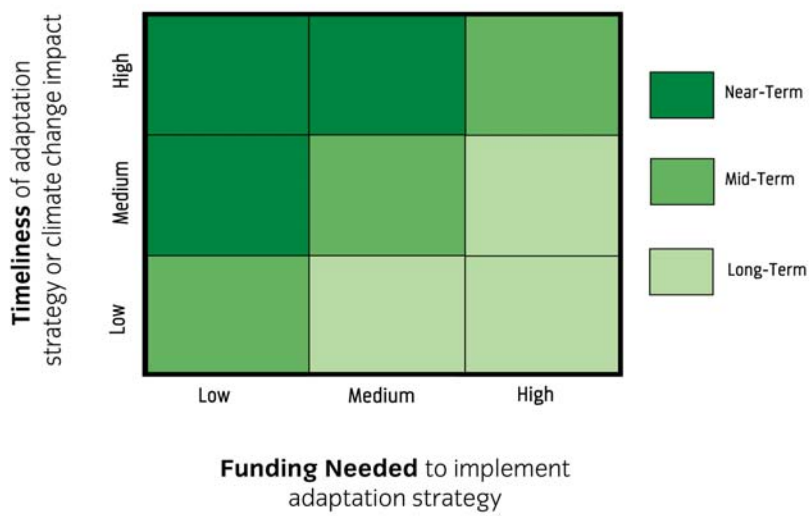

FIGURE 3 New York City prioritization matrix.

A quite different approach to adaptation decisions called robust decision making or RDM (*5*) is being used by some western water management authorities to address climate change. RDM has three key constructs. First, there are multiple views of the future both in terms of the climate and the user demands. Many different scenarios are constructed, in contrast to a limited number of "futures" in the New York City process. Second, there is the concept of robustness as opposed to optimization. That is, how well do alternative systems or strategies detect and react to changes? Will the alternative system function reasonably well under various scenarios, but not necessarily best under any specific scenario? Third, RDM inculcates the iterative ability to assess vulnerabilities as they develop and adjust responses much like classic control theory wherein an electronic controller monitors critical parameters and continually adjusts the process.

RDM and other new decision-making methodologies provide the water management agencies effective, new tools with which to evaluate the performance of their systems and alternative strategic approaches against many possible futures. The strategies encompass structural, operational, and institutional options ranging from increased importation of water, to greater reclamation and reuse, to restrictions on new landscaping.

To translate this RDM approach to transportation, consider a coastal community faced with rising sea levels and greater storm surge. Structural solutions such as elevating new bridges and highways are an obvious approach and may well have relatively modest marginal cost impacts. Retrofitting or reconstructing existing highways and bridges is a different matter. Here the criticality of the assets is of paramount importance. Indeed for many of these assets as well as ports and low-lying airports, the best solution may well be to monitor sea level rise and reconstruct or protect the assets only when sea levels or surge events reach some critical height.

TABLE 1 Illustrative Adaptation Measures for Transportation (*3*)

Sea Level Rise	• Protect infrastructure with dikes and levees. • Elevate critical infrastructure. • Abandon or move coastal transportation system. • Reduce or eliminate development in coastal flood plains by providing local or federal incentives or by legislative mandate. • Provide good evacuation routes and operational plans.
Heat Waves	• Research on new, heat-resistant or resilient materials. • Replacement of bridge and highway expansion joints. • Longer runways to account for lower lift-off capacities. • Design changes to reduce stresses in rail lines. • More nighttime construction to avoid undue heat stress for construction workers with the added benefit of less traffic disruption.
Increased Storm Intensity	• Revise Federal Emergency Management Agency flood plain maps which are badly out of date. • Update hydrological storm frequency curves. • Develop new design standards for hydraulic structures, e.g., culverts and drainage channels. • Protect existing and vulnerable structures, e.g., bridge piers. • Better land use planning in flood plains. • Construction of storm retention basins for short, high intensity storms, i.e., flash flooding.
Hurricane Intensity	• Move critical infrastructure systems inland. • Build or reconstruct more robust and resilient structures. • Design for higher storm surges that progress further inland. • Strengthen and elevate port and harbor facilities. • Install surge barriers on vulnerable rivers.
Arctic Warming	• Identify areas with accelerated permafrost thawing. • Develop new designs for constructing transportation systems on less stable soils. • Dikes or levees to protect vulnerable coastal communities. • Move at-risk coastal communities.

Institutional steps such as restricting development in flood prone areas or eliminating subsidies for homeowner insurance may well be initiated as sea levels rise decades hence. The response couples short-term structural solutions with longer-term adaptive management, somewhat predetermined actions to be taken as the climate actually changes and better estimates the magnitude and time scale of the changes become available.

ADAPTATION ALTERNATIVES

The Panel on Adaptation of America's Climate Choices provided some illustrations of adaptive measures that can be incorporated into transportation planning for new or retrofitted systems as shown in Table 1. This list is by no means all-inclusive and many of the suggestions will be quite obvious. Once the problem is defined, transportation professionals are good at developing solutions.

CONCLUSIONS

The potential impacts of global warming on transportation and other built infrastructure are sufficiently well defined to incorporate climate change into the long-term planning process for transportation systems. There are new techniques to learn and apply for dealing with problems with deep uncertainty. If we do so, the marginal cost of adapting to climate change can be readily accommodated. Further, the profession will have met its obligation to future generations of transportation users.

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SIDEBAR

Early Signs of Climate Change
2010 Flooding in Tennessee, Rhode Island, and Iowa

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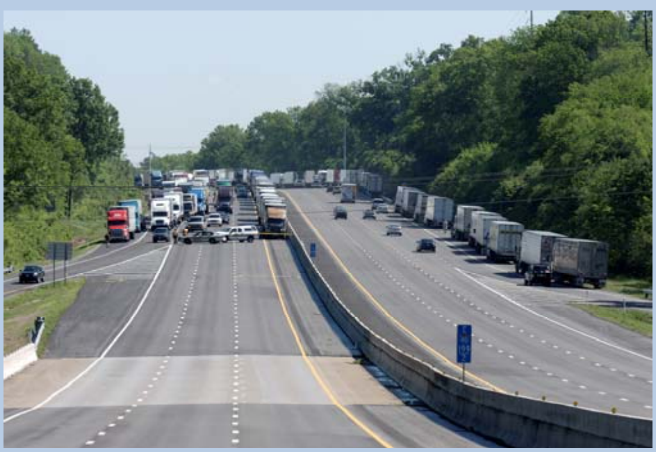
In 2010, transportation agencies in Tennessee, Rhode Island, and Iowa saw firsthand the effect of extreme rainfall events that brought severe flooding and a wide range of impacts to the transportation system. These effects are likely to be early signs of climate change.

- **March 2010:** Rhode Island experienced record flooding due to intense rainfall, not just once but twice. The unprecedented rainfall forced closure of 98 roads and 20 bridges, including closure of critical parts of Interstate 95 for 36 hours. To avoid having to also close nearby I-295, Rhode Island Department of Transportation (DOT) used thousands of sandbags and pumper trucks from the Warwick Fire Department. Ten days after the worst rainfall, 15 roads and bridges were still closed despite heroic efforts by 150 Rhode Island DOT maintenance crews and 50 engineering crews working around the clock to get them open.
- **July–August 2010:** In July, northeast Iowa saw torrential rainfall (as much as 9 in. in places) that pushed the Maquoketa River to 23.92 ft—more than 2 ft above its previous record of 21.66 ft in 2004. In August, intense waves of thunderstorms over 3 days fell on already-saturated ground and forced closure of I-35 northbound and southbound near Ames, Iowa, along with many other roadways. Just 2 years earlier, in 2008, Iowa experienced record



Traffic on I-40, a major east–west corridor across the United States, halted in West Nashville, Tennessee, due to flood waters after heavy rainfall in May 2010.

levels of flooding that closed roads and damaged roads and bridges. Iowa DOT's website carries sites that feature dozens of pictures of the impacts of the 2008 flooding and the 2010 flooding.

- **May 2010:** On May 1–2, rainfall in Nashville, Tennessee, was more than double the previous record for a 2-day period—and the previous record was set during a hurricane. Forty-one counties suffered highway and bridge damage, including a large landslide that covered parts of US-70. In Maury Country, two sections of State Route 7 sank as much as 20 ft below its original elevation due to ground saturation and collapse of pavement. Multiple sinkholes emerged, including a large sinkhole in eastbound I-24 that was 25 ft wide and 25 ft deep, which emerged 2 weeks after the flooding. Estimated impacts included 100 routes affected, $45 million in repair costs, and 83,000 state DOT maintenance hours to assess damage and recover.

Severe rainfall is one of the signs of climate change. Warmer temperatures put more moisture in the air and increase the probability of more severe precipitation—greater rainfall in short periods, occurring more often. Scientists and weather experts who track the climate are convinced that climate change is already happening, at a faster rate than climate models predicted a few years ago, and that many parts of the world will see this intensify over time.

The 2010 experiences of transportation agencies in Iowa, Tennessee, and Rhode Island are likely to be repeated there and elsewhere in future years, making it important to begin climate adaptation planning now to evaluate the new vulnerabilities and risks associated with climate change, to develop plans for coping with these events, and to incorporate these risks into asset management and infrastructure design for the future.

Planes and hangars at Cornelia Fort Airpark, East Nashville, under water on May 3, 2010.

Federal Highway Administration Activities Related to the Adaptation of Transportation Infrastructure to Climate Change Impacts

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The projected effects of climate change could have significant implications for the nation's transportation system. Rising sea levels, increasingly extreme temperatures, changes in the frequency and intensity of storm events, and accelerating patterns of erosion could damage infrastructure, flood roadways, and disrupt safe and efficient travel. Certain effects, such as sea level rise and increases in storm intensity, present obvious challenges. Storm surge can damage and destroy coastal roadways, rail lines, and bridges and sea level rise will only exacerbate such effects. Rising sea levels can also present flooding risks to underground infrastructure such as subways and road tunnels, allowing water to enter through portals and ventilation shafts. Subtle changes, such as those expected in temperature, will also necessitate changes in the design, construction, and maintenance of infrastructure—for instance, the incorporation of materials and building techniques that can withstand temperature extremes. Some climate change effects may positively impact transportation, as higher average temperatures in certain regions could reduce safety and maintenance concerns associated with snow and ice accumulation. Although mitigating the effects of climate change through reductions in greenhouse gases is an important element of the Federal Highway Administration's (FHWA's) climate change strategy, the agency places equal importance on acknowledging that certain changes may require appropriate adaptation strategies.

Recognizing the need for adaptive transportation systems, FHWA's Sustainable Transport and Climate Change Team has developed several programs and initiatives to provide FHWA Division Offices, state departments of transportation (DOTs), and metropolitan planning organizations (MPOs) with the data and tools needed to identify and adapt to climate-related impacts on vulnerable transportation infrastructure. Three initiatives described here illustrate the range of activities underway at FHWA: a report on regional climate change, an in-depth study of climate impacts in the Gulf Coast region, and pilot-testing of a conceptual model for risk and vulnerability assessments.

REPORT PROJECTS REGIONAL CLIMATE CHANGE EFFECTS

One of the key challenges in adaptation planning is the uncertainty of future projections regarding climate change and its impacts (Figure 1). Transportation planners must rely on such projections because anticipated climate changes will likely surpass past trends, which have

FIGURE 1 The anticipated effects of climate change on transportation include roadway flooding. (Photo courtesy of U.S. Global Change Research Program.)

traditionally been the basis for transportation decision making. Adaptation to climate change necessitates a shift in existing design and planning paradigms, as the demands placed on transportation will require more robust systems that can cope with an increasingly extreme and volatile climate.

To address the risks that climate change poses, state, regional, and local planning and transportation organizations first need to understand and evaluate the threats facing their systems. In the spring of 2010, FHWA released a report entitled *Regional Climate Change Effects: Useful Information for Transportation Agencies* (the *Effects* report), which provides planners with information on the climate changes likely to have the greatest impacts on transportation systems. Drawing on the expertise of multiple federal agencies, including the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Energy, the *Effects* report presents the science of climate change in the context of transportation at a regional level. The report is organized by region (Northeast, Southeast, Midwest, Great Plains, Southwest, Pacific Northwest, Alaska, Hawaii, Puerto Rico), time horizon (2010–2040, 2040–2070, 2070–2100), and climate effect (projected change in temperature, precipitation, storm activity, sea level) and includes the best available climate projections. These projections are presented through narrative descriptions, tables and maps, and a Climate Change Effects Typology Matrix, which aggregates projections by region and, in certain cases, subregions, states, and cities. In addition to summarizing the current understanding of projected climate change effects, the report includes a brief discussion linking these effects to potential impacts on infrastructure, such as flooded roads and damage to bridges. Although the *Effects* report does not present adaptation strategies, it does provide information that highway planners can use to begin to identify and address vulnerabilities and to generate discussion between the transportation and climate science communities.

Gulf Coast Phase 2 Study Targets Impacts of Climate Change in Mobile, Alabama

In 2008, FHWA, on behalf of the U.S. DOT Center for Climate Change and Environmental Forecasting and in coordination with other modes, released a groundbreaking assessment of potential climate impacts on the Central Gulf Coast transportation network, entitled *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase 1* (Figure 2). The study region, which stretched from Houston and Galveston, Texas, to Mobile, Alabama, was selected due to its combination of population centers, multimodal transportation systems—including critical infrastructure focused on freight and petroleum movement—and the low-lying region's vulnerability to sea level rise and storm impacts. The second phase of the study began in 2010 as an in-depth analysis of anticipated climate change effects and impacts on the transportation system of a single metropolitan area—Mobile, Alabama. The Gulf Coast Phase 2 study will generate tools and guidance for assessing vulnerability that can be transferred to other regions, and strategies for adapting transportation systems to anticipated changes in climate. In partnership with the USGS, FHWA is working with representatives from the Mobile MPO and the South Alabama Regional Planning Commission to complete the Gulf Coast Phase 2 study in 2013.

FHWA Conceptual Model Assesses Risks and Vulnerability for Transportation Infrastructure

In 2009, FHWA began developing a conceptual model to guide state DOTs and MPOs in evaluating the vulnerability of their existing and planned transportation infrastructure to climate-related risks (Figure 3). The model, which is currently in draft form, outlines the steps that an agency can follow to inventory its transportation assets, gather climate information, and conduct

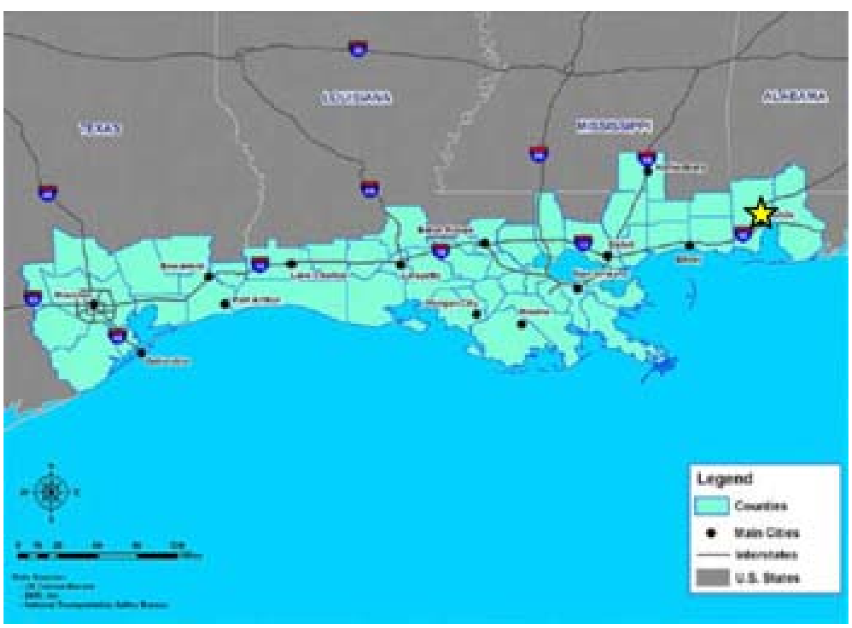

FIGURE 2 Gulf Coast Phase 1 Study area. Mobile, Alabama, on the eastern edge of the study area, serves as the focus of Phase 2. (Courtesy of FHWA.)

FIGURE 3 FHWA's Conceptual Risk Assessment Model will allow transportation agencies to identify critical assets that face the greatest risk of damage due to the effects of climate change. (Photo courtesy of U.S. Global Change Research Program.)

a systems-level analysis of the likelihood and consequences of climate change impacts on specific assets. Through their use of the conceptual model, agencies can develop a prioritized list of at-risk assets, allowing them to focus their initial adaptation efforts on assets that both have a high likelihood of suffering severe damage and are most critical to the transportation network.

In September 2010, FHWA selected five transportation agencies around the nation to pilot and provide feedback on the conceptual model. These five pilots will provide a diversity of experiences in testing the model, generating valuable feedback that will be incorporated into a final version suitable for implementation nationwide.

- **California.** The San Francisco Bay Metropolitan Transportation Commission, in partnership with the San Francisco Bay Conservation and Development Commission and other organizations, is leading a study of a relatively low-lying section of the East Bay, stretching from the Oakland Bay Bridge to the San Mateo Bridge. The study complements a NOAA-funded subregional project by adding a transportation component to an ongoing multisector study of the San Francisco Bay Area (Figure 4).
- **Hawaii.** The Oahu MPO is assessing the vulnerability of transportation infrastructure on the island of Oahu, the population and economic hub of Hawaii. The assessment includes an emergency management component, an important element given Oahu's isolated location and limited evacuation options (Figure 5).

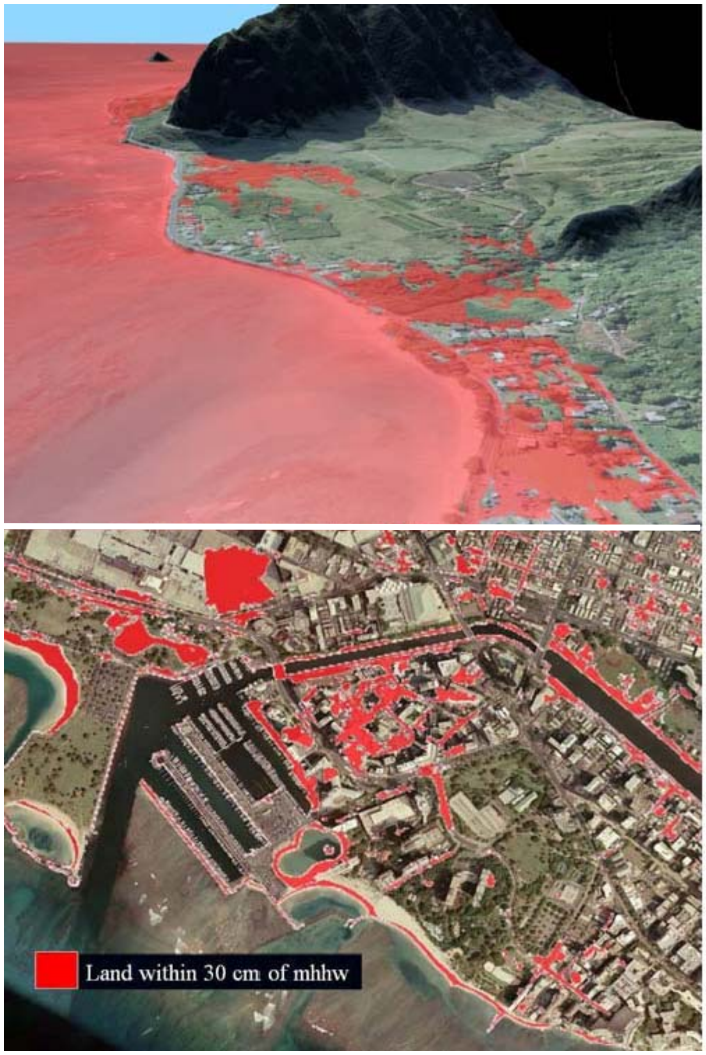

FIGURE 4 The Oahu pilot will conduct an analysis of areas with infrastructure potentially vulnerable to sea level rise on the island. (Source: *Grant Proposal: Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure*, July 2010, Oahu Metropolitan Planning Organization.)

- **New Jersey.** The New Jersey DOT and North Jersey Transportation Planning Authority, in partnership with the Delaware Valley Regional Planning Commission and the South Jersey Transportation Planning Organization, are leading an assessment of climate vulnerability to both coastal and riverine impacts along the Atlantic coast and in the Delaware River Valley.
- **Virginia.** Virginia DOT's study focuses on the Hampton Roads metropolitan area at the mouth of the Chesapeake Bay. The study area's transportation network must support a large urban area, one of the East Coast's leading freight ports, and a U.S. Navy base, but includes numerous potentially vulnerable coastal roads, bridges, tunnels, and other facilities.
- **Washington.** Washington State DOT is conducting the only statewide pilot of the conceptual model, as it examines a range of coastal and non-coastal climate impacts on the

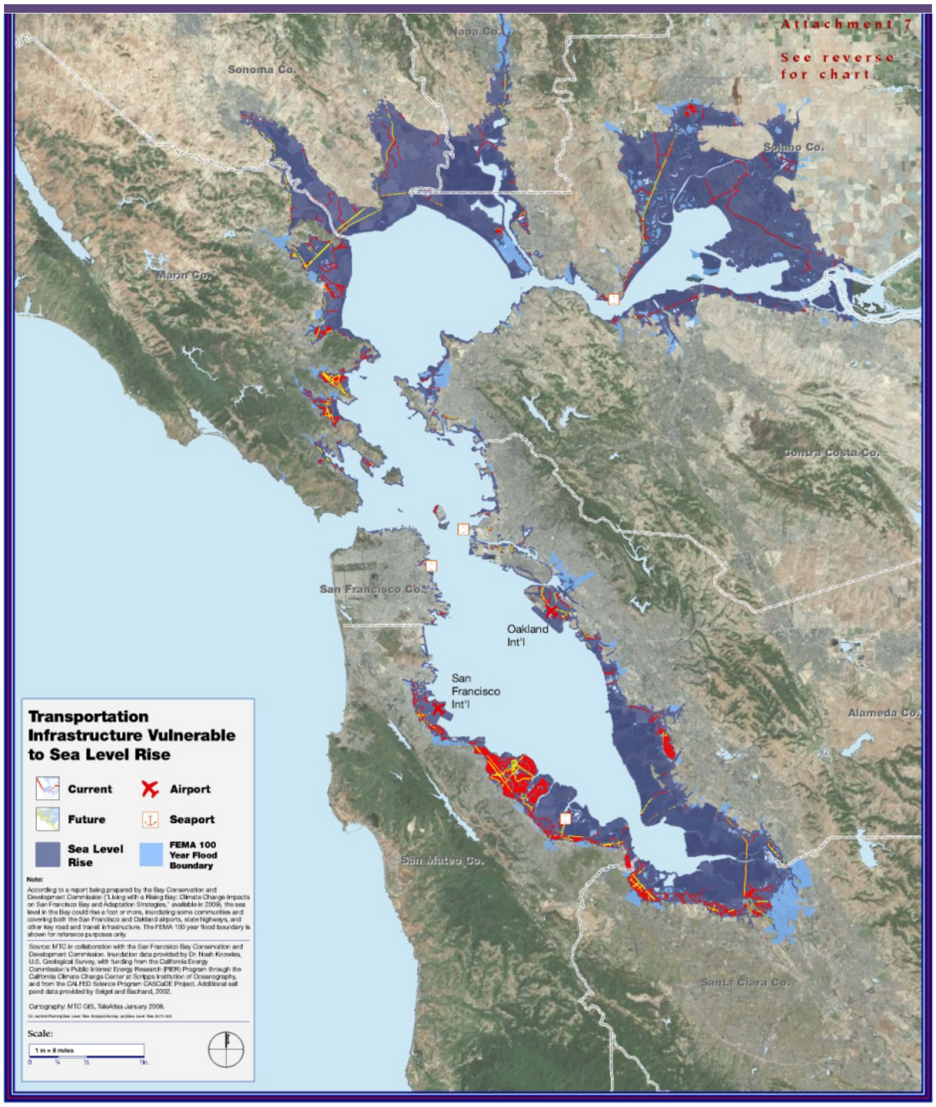

FIGURE 5 Shoreline areas potentially vulnerable to sea level rise in the San Francisco Bay area, 2040–2060. The pilot study will focus on a section of East Bay shoreline bounded by the San Francisco–Oakland Bay Bridge in the north and the San Mateo–Hayward Bridge in the south. (Source: Metropolitan Transportation Council.)

Washington State DOT operated highway network, including sea level rise, changes to river and stream systems, extreme temperature effects, precipitation changes, and drought impacts.

These agencies and locations were chosen in part on the basis of their existing climate change adaptation activities, which FHWA hopes will accelerate through the pilot. FHWA expects each pilot agency to generate a final report detailing its activities, partners, lessons learned, and recommendations for future applications of the conceptual model. Based on input from these agencies, FHWA will revise and finalize the model for use nationwide (Figure 6).

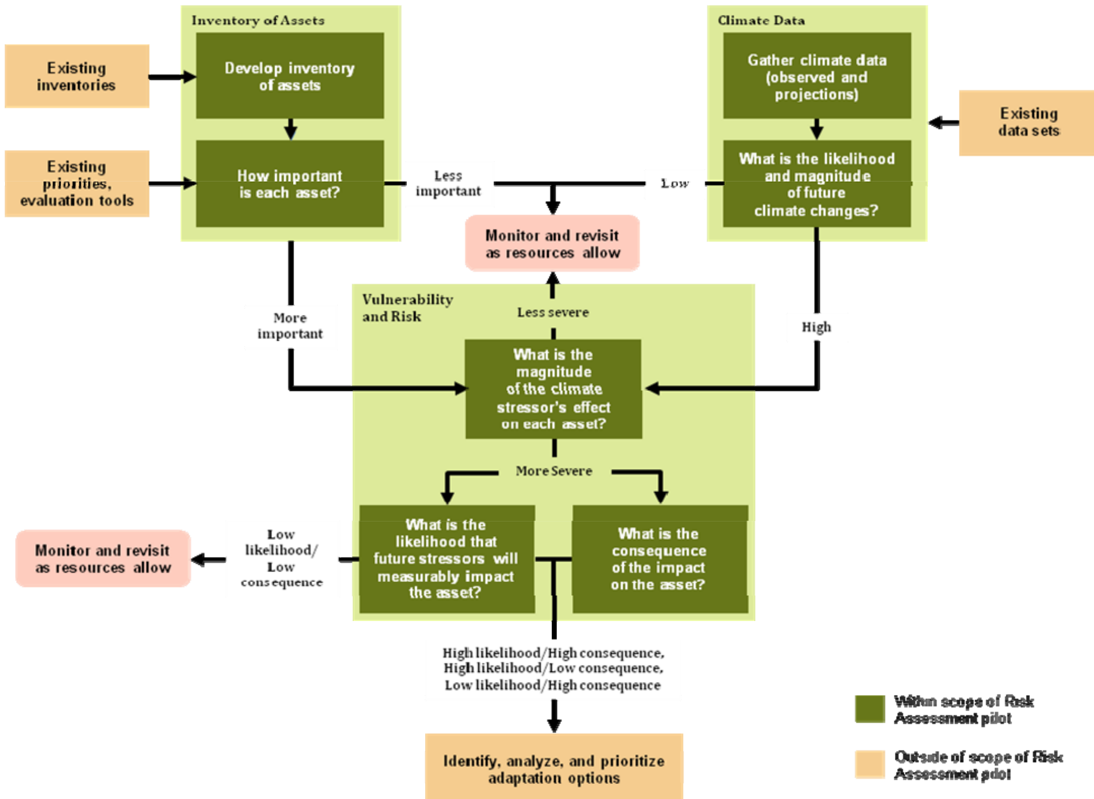

FIGURE 6 Structure of the FHWA Draft Conceptual Risk Assessment Model being tested by MPO and state DOT pilots.

ADDITIONAL INFORMATION

Climate adaptation planning is an issue that continues to grow in importance for FHWA. The White House Council on Environmental Quality has recently released guidance directing federal agencies to develop adaptation plans. Building on information generated by the initiatives above, FHWA is currently developing a draft agencywide *Strategy for Adaptation to Climate Change Effects*. An FHWA Adaptation Working Group established to promote communication and sharing of knowledge and ideas between FHWA offices will work to ensure that the strategy reflects the diverse needs of the agency and its partners. In turn, this strategy will become an integral component of the larger U.S. DOT adaptation planning strategy. For additional information about FHWA's climate change adaptation and mitigation activities as well as resources, publications, and frequently asked questions, please visit the FHWA Highways and Climate Change website.

OTHER NOTABLE FHWA CLIMATE CHANGE ADAPTATION INITIATIVES

- Eastern Federal Lands: *Adapting the Nation's Refuge Roads System to Climate Change*.
- Western Federal Lands: *Assessing the Impact of Climate Variability on Transportation Infrastructure*.
- Participation in the Pacific Northwest Climate Change Collaboration and the Northeast Federal Partners.

United Kingdom's Experience with Climate Change Adaptation and Transportation

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DAMON FORDHAM
AEA Group

MIA STEPHENS
Consultant

Identifying the causes of climate change and addressing these causes through the implementation of mitigation measures is becoming common practice in policy development around the world. Adapting to the impacts of climate change is also becoming increasingly important in a policy context. The United Kingdom (U.K.) is currently leading the way when it comes to the implementation of climate change policy frameworks by being the first country to have a legally binding long-term framework to cut carbon emissions by 80%, enacted through the United Kingdom's Climate Change Act. The Climate Change Act also sets out the requirements for the country's response to climate change adaptation and the appropriate actions to be undertaken.

CLIMATE CHANGE ADAPTATION AND TRANSPORTATION AT THE NATIONAL LEVEL

Policy Drivers

The Climate Change Act sets out a number of requirements related to adaptation, including an obligation to prepare a national climate change risk assessment, the need to develop a national program focused on climate adaptation, and obligations for selected government and non-government authorities to report on the climate risks associated with their activities.

The United Kingdom's first Climate Change Risk Assessment (CCRA) is due to be completed by January 2012. It will draw together evidence and analysis that will enable all U.K. government agencies to understand the level of risk posed by climate change for the United Kingdom, where risk is a consideration of the likelihood of an impact and the magnitude of the consequences. Additionally, it will enable a comparison of the risks posed by a changing climate with other pressures on the government, as well as help in prioritizing adaptation policy measures and assessing the costs and benefits of adaptation actions.

Beyond the CCRA, a variety of other preparatory activities have been undertaken to explore the issues surrounding climate change and adaptation and the potential risks that the Unitd Kingdom may face. These activities have required consideration of, and inputs from, all sectors, including transportation. Some of the national- and local-level preparatory activities are discussed in more detail below, with a specific focus on U.K.-level activities and those that have been introduced in England. (Scotland, Wales, and Northern Ireland have their own climate adaptation strategies.)

City center floods, York, United Kingdom.

Program Drivers: The Adapting to Climate Change Program and Infrastructure-Related Activities

The cross-government Adapting to Climate Change (ACC) Program, coordinated by the Department for Environment, Food and Rural Affairs, has brought together the climate adaptation work already undertaken by the U.K. government and the public sector, and will coordinate and drive forward the future development of the government's work on adaptation. As part of the activities of the ACC Program, a cross-departmental 2-year project on infrastructure and adaptation has been set up with the aim of identifying and examining strategic solutions to "improve the long-term resilience of new and existing infrastructure in the energy, transportation, and water sectors due to future climate change impacts." The outcomes of the project will help the government take early adaptation action to minimize potential disruption and cost to the U.K. economy. A number of studies have already been published as a result of the program. These studies include research to examine whether market, policy, and regulatory models in the infrastructure sectors provide adequate incentives for infrastructure providers to consider climate change resilience in their future investment decisions. Other work includes an assessment of the vulnerabilities in different sectors of the national infrastructure to the effects of climate change and the modifications that would be required to increase resilience, while considering the vulnerabilities that affect the infrastructure system as a whole that arise as a result of interdependencies between sectors.

Storms and heavy rain, potentially causing delays at Gatwick Airport.

The cross-sector/departmental approach that is being taken by the U.K. government further demonstrates the linkages and interdependencies between the various sectors, including transportation, energy, water, and communications with respect to climate adaptation. This approach will ensure that adaptation in the transportation sector is not addressed in isolation. A 2010 URS Corporation report has identified two key types of interdependencies that are likely to have far greater impacts on infrastructure functionality than individual failures. The first interdependency is cascade failures, which refers to a series of linked impacts or failures, and the second is regional convergences of infrastructure, which, if impacted by an extreme weather event, could have consequences on functionality at a national scale in one or more of the sectors.

Ensuring that adaptation is embedded in key policies at the national level, the ACC Program requires each U.K. government department to produce Departmental Adaptation Plans (DAPs). The Department for Transport's (DfT) DAP highlights what has been done to date to understand and manage climate change related risk and the actions that will be taken in the period between 2010 and 2012. The ultimate aim of the plan is to ensure the delivery of the department's strategic aim ("transport that works for everyone") through a U.K. transportation system that continues to operate effectively because its infrastructure and operations have been planned, designed, and maintained to be resilient to future climate change.

While not part of the ACC Program or other adaptation initiatives, the U.K. government has also recently been responsible for producing the first U.K. National Infrastructure Plan. The plan outlines the scale of the challenges facing the U.K.'s infrastructure (including energy, transportation, digital communications, floodwater, and waste management) and the major investment required to underpin sustainable growth. The plan also addresses issues relating to climate adaptation across the range of infrastructure-related sectors, and identifies the need for transportation infrastructure to adapt to climate change in order to provide security and resilience against the increased risk from natural hazards, such as floods and heat waves.

Legal Drivers

Essential services and infrastructure are likely to be significantly affected by the impacts of climate change. With this in mind, the U.K. government has introduced a new regulation known as the Adaptation Reporting Power which obliges organizations responsible for providing or operating essential services and infrastructure to assess the potential impacts of climate change on their operations and to develop plans to minimize or eliminate those impacts. This allows the government and key stakeholders to better assess the degree to which the country's essential services and infrastructure providers are preparing for climate change. They will also be in a position to identify any potential barriers that could prevent adequate preparation from happening. The reports are in the public domain, which means that customers and stakeholders can also engage in the process.

The U.K. has a comprehensive approach for adapting to climate change in transportation and other sectors. In part inspired by the U.K. approach, the Federal Highway Administration (part of U.S. Department of Transportation) is developing a strategy to better prepare highways and on-road transportation to adapt to the impacts of climate change. In addition, FHWA and the other transportation modes of U.S. DOT are in the process of integrating climate change adaptation planning and strategies into transportation planning, programming and operations under recent guidance from the Council on Environmental Quality.

—Rob Kafalenos, FHWA Sustainable Transport and Climate Change Team

In terms of transportation, these new reporting requirements have enabled the DfT to learn directly from transportation operators–providers regarding potential risks associated with climate change, and identify the measures in place to adapt to these risks. There are currently nine statutory and two voluntary transportation-related reporting authorities, which include those responsible for road, rail, aviation, and marine–shipping infrastructure in the United Kingdom. It is the liaison with these key stakeholders that will ensure that DfT is in a position to identify the risks, issues, and barriers that the transportation sector faces.

To date, two of the reporting authorities (Network Rail, the authority responsible for Britain's rail infrastructure, and the Highways Agency, the authority responsible for freeways and other major roads) have produced interim climate change adaptation reports. The risks identified in these reports have been assessed and ranked according to potential severity of impacts, and planning has been initiated to address those impacts, along with monitoring and evaluation. The reports also identify potential opportunities that may arise from climate change. The process has enabled and encouraged the organizations to engage with a diverse group of customers, industry partners, and other key stakeholders, looking beyond their own responsibilities and towards the impacts of climate change on the U.K.'s transportation infrastructure as a whole.

Network Rail's report identifies a range of established plans and procedures already in place to respond to extreme weather events but also to deliver appropriate levels of infrastructure resilience and service continuity under current weather patterns. Substantial amounts of capital are being invested for renewal work on railway drainage at priority locations to protect the railway assets from the impact of severe weather. Through their work on adaptation to date, Network Rail has identified the importance of prediction in order to facilitate long-term management decisions.

Harbor floods during heavy storm, Cornwall, United Kingdom.

The Highways Agency (HA) is one of the voluntary reporting authorities. As such, the HA has produced a climate change adaptation strategy and framework independently from this process, while also reporting to the U.K. government on adaptation as required under the new regulation. A key driver for the HA is that it needs to ensure that it can continue to provide an effective strategic road network, but has recognized that many of its activities are either directly affected or influenced by climate. The HA has undertaken a host of activities in recent years, including the production of a Sustainable Development Action Plan, a Climate Change and Adaptation Strategy and Framework, and the development of a climate change risk assessment methodology. These activities will enable the HA to incorporate climate change considerations into design standards and specifications, routine maintenance, operating procedures, and the development of contingency plans to ensure that a robust network will continue.

The examples above highlight the valuable information available to the DfT on potential transportation infrastructure risks associated with future climate change. As more of the interim and final climate change adaptation reports are submitted from the transportation-related authorities, a more detailed picture of the United Kingdom’s transportation infrastructure, the risks, and its ability to cope will emerge.

CLIMATE CHANGE ADAPTATION AND TRANSPORTATION AT THE REGIONAL AND LOCAL LEVEL

While adaptation is being considered in terms of major transportation infrastructure and key transportation policies at the national level, important decisions regarding transportation are also made at the regional and local levels. These decisions may require the consideration of climate change adaptation. Each local transportation authority is required to prepare a Local Transport Plan (LTP), which is developed with key stakeholders and must include major policies and delivery plans relating to transportation for their areas. The Local Transport Act of 2008 expressly addresses adaptation, stating that when developing transportation policies, local authorities should take into account government policies on climate change adaptation and mitigation.

The DfT has produced Guidance on Local Transport Plans to aid local authorities in this area. While the guidance primarily refers to greenhouse gas mitigation measures, it also refers to the need to ensure that local authorities implement measures to improve the climate resilience of local transportation, including resilience to flooding and deterioration of roads. As a result of

SIDEBAR

International Scan on Climate Change Adaptation

EDWARD WEINER
Transportation Consultant

Many countries are taking action to adapt because they already recognize the vulnerability of their transportation infrastructure to climate changes. The Dutch are building more dunes to protect their low-lying country. They are dredging sand from the bottom of the North Sea about 15 km from shore and piping it to the beach. There, bulldozers create the dunes and broaden the beach, wresting territory from the sea meter by meter. The area behind the existing dikes and dunes is so densely populated there was no room left to extend coastal flood defenses, so they elected to extend the beaches toward the sea—having run out of space, they opted to enlarge the country.

Venice, Italy, has been vulnerable to rising water for many years. Venetians drove piles deep through the muck of the lagoon bottom to bedrock deep below. Then they built a city on top of those piles. But extracting industrial water through artesian wells driven into an underlying aquifer has caused the land (and the pilings) to subside. Coupling that with rising sea levels has caused periodic flooding of the city. Italy is spending $6.35 billion to overcome this problem. It is building a complex series of 78 mobile barriers across its three inlets that will be inflated when high tides or storms are forecast, causing them to rise and isolate the lagoon from the Adriatic Sea. It is also employing costal reinforcement, the raising of quaysides and paving, and other improvements in the area around the lagoon to reduce the impact of rising waters.

Two states in Germany are in danger of flooding from rising seas. The state of Schleswig–Holstein is at risk of flooding from the North Sea and Baltic Sea. The length of their North Sea coastline is 553 km. Almost the entire mainland coastline at the North Sea side is protected with a system of sea dikes. In case of flooding, evacuation is a problem because of the long distance to higher locations. The height of the dikes is evaluated every 10 years, with respect to the rising sea level. If the evaluation indicates a deficient dike height for a certain stretch, this stretch is reinforced by increasing the height of the dikes to account for a forecasted 2100 sea level. The coastline of the state of Niedersachsen has seven barrier sand islands that protect the coastline. The whole coastline is protected with a system of sea dikes (1143 km

(*continued*)

these requirements, local transportation authorities have started to undertake activities to consider the likely local impacts of climate change (such as undertaking Local Climate Impacts Profiles that provide insights into how local transport networks are currently coping with severe weather, vulnerabilities, how events were dealt with, and potential costs), and have begun to identify the actions necessary to protect existing and future infrastructure from the impacts of climate change in their developing LTPs.

INTERNATIONAL SCAN ON CLIMATE CHANGE ADAPTATION (*continued*)

total) and flood defenses in river arms and estuaries. The highest dikes have a height of about 9 m. The height line of the protected areas in Niedersachsen is up to 5 m above sea level.

FHWA, AASHTO, and NCHRP have initiated a scan to gather information on how other countries are addressing the adaptation of highway infrastructure to the future impacts of climate change. The results of this scan will provide engineers and planners in the United States with new ideas on approaches that they can use in their own communities to adapt transportation to climate changes. These countries' efforts include diversity in scope and application, reflecting their varied geographic, environmental, and societal conditions. It is anticipated that this same diversity will allow the scan to identify lessons that match the diversity found in the United States and that can be used to improve U.S. adaptation effort.

The wide-ranging and multidisciplinary implications of climate change on transportation infrastructure require an approach that is multidisciplinary, risk-based, and dynamic and that builds on a relationship of cooperation among varying levels of government. Therefore, the climate change adaptation scan will focus on the following important areas.

- Understanding how best to include climate change information in existing or new analysis techniques for planning new infrastructure and maintaining transportation systems.
- Assessing how climate change impacts will affect asset management investment cycles and the life cycles of major investments.
- Developing pavement, bridge, and other infrastructure design and materials specifications that account for expected climate change impacts, including climate change considerations in hydraulic modeling and design.
- Considering climate change adaptation in the transportation planning process.
- Developing policies and procedures for inventorying critical infrastructure and assessing vulnerabilities and risks due to climate change impacts.
- Developing options for risk analysis frameworks.
- Developing data collection standards to inform risk analysis, asset management, and decision making.
- Finding opportunities to improve the resiliency of transportation infrastructure naturally, through the benefits of ecosystem services.
- Documenting effective management strategies that are able to accommodate the climate change impacts on highway safety and operations.

EUROPEAN REQUIREMENTS RELATED TO CLIMATE CHANGE ADAPTATION AND TRANSPORTATION

At the European level, there are legislative requirements for environmental assessments to be carried out for new developments that are likely to lead to significant environmental impacts, including those that are transportation related. In such cases, a Strategic Environmental Assessment (SEA) is required. The SEA process requires U.K. transportation planners to identify and evaluate their plans' impacts on a number of environmental issues, including climatic factors. SEA then enables the development and implementation of appropriate adaptation and mitigation measures to deal with any significant impacts of climate change (and other environmental impacts) that have been identified. These impacts include secondary and cumulative effects. Climate change is often considered a cumulative effect in SEA, caused by the buildup of many actions, each of which only has a limited contribution, but which together may cause serious effects.

While SEA is a useful tool for embedding adaptation into the plan-making process, there are further considerations that often must be addressed at the project level. Specific transportation projects, while contained within LTPs, are subject to an Environmental Impact Assessment (EIA). The European Union's EIA Directive requires that an EIA should identify, describe and assess "…the direct and indirect effects of a project on the…interaction between: human beings, fauna and flora, soil, water, air, climate, the landscape, material assets and cultural heritage (Article 3)." However, assessing the resilience of proposed developments, including transportation infrastructure, to the effects of climate change is not clearly required. The European Commission has recently reviewed the application and effectiveness of the EIA Directive and concluded that adaptation to climate change is not sufficiently considered within EIA. Because projects required to undertake an EIA are likely to be vulnerable to climate change impacts, it is the European Commission's view that the EIA process should consider climate resilience (both positive and negative). The Commission has launched a consultation on this topic, which will likely lead to the development of a revised EIA Directive.

SUMMARY

It is clear from the foregoing discussion that there are many actions already in place for addressing transportation-related climate adaptation at the national and local levels in the United Kingdom. A key aspect of the U.K.'s framework for adaptation is the cross-sectoral approach that is being taken. This is important, given the wide range of sectors potentially affected by climate impacts. It is also clear that the U.K.'s approach involves enabling both public and private-sector organizations to start the process of planning for climate adaptation. While the U.K.'s policy framework for climate adaptation is still in the early phases of implementation, it is apparent that organizations are already benefitting from the process of developing plans and strategies to maximize their climate resilience, and as each organization improves its own climate resilience, then so too does the United Kingdom as a whole.

State Departments of Transportation Working to Adapt to a Changing Climate

CAROLINE PAULSEN
American Association of State Highway and Transportation Officials

with support from
AMY PHILLIPS
BNA, Inc.

Changing weather patterns, increasing storm intensities and flooding, rising sea levels, and increasing temperatures are presenting a “new normal” under which transportation agencies across the country are starting to weigh the potential vulnerability of their transportation infrastructure and come up with plans to adapt.

Many coastal states, while experienced with severe weather and effects of storm surge, are now preparing for more permanent effects—including disinvestment and abandonment of some transportation infrastructure, and in some cases, relocation of entire communities.

For some non-coastal states, increased frequency and intensity of storm events—and the associated flooding and wind damage—have become critical issues.

Across the nation, states are seeing the need to plan for adaptation. At least 21 states either have begun planning for climate change adaptation or have announced their intention to do so as part of a broader climate change action plan. According to a recent assessment by the Pew Center on Global Climate Change, eight states—Arizona, Colorado, Iowa, Michigan, North Carolina, South Carolina, Utah, and Vermont—have called for comprehensive adaptation plans as part of their climate action plans. Thirteen other states are already conducting adaptation planning efforts alongside their mitigation actions. These states include Alaska, California, Connecticut, Florida, Maine, Maryland, Massachusetts, New Hampshire, New York, Oregon, Virginia, Washington, and Wisconsin (*1*).

Transportation agencies are in various stages of addressing adaptation needs. For state departments of transportation (DOTs) that have addressed the issue, climate change planning efforts often were prompted by a state legislative or administrative mandate. Some efforts began as increasing concerns over environmental conditions. For Alaska in particular, climate change effects that already are occurring—such as loss of sea ice and melting permafrost—made adaptation a necessity rather than a choice, forcing agencies to take action to protect shorelines and relocate residents.

Increases in severe weather events and unprecedented flooding have forced transportation agencies in many states into crisis mode. While climate change had not been a major priority in Rhode Island, transportation officials in the state took notice after severe flooding in March 2010 shut down local roads, bridges, and Interstates and caused some $20 million in damages. While no one can say with certainty that such events are caused by climate change, this event got the attention of officials in Rhode Island. Rhode Island DOT’s Robert Shawver told a climate change symposium sponsored by AASHTO “…there’s a pretty good chance that’s what we’ll be dealing with in the future.…Everything we learned we have to relearn.”

States including California, Florida, Maryland, and Washington have aggressive efforts underway on adaptation, including strategies to inventory their infrastructure and identify risks, coordinate with other agencies and jurisdictions, address design standards to improve resiliency, and focus on planning and risk assessment.

But even in states like Maryland, which has given priority attention to adaptation, transportation agencies face difficult decisions in determining how, and in some cases, whether, to protect vulnerable infrastructure as the oceans rise and weather patterns change. “We feel we are way ahead, but behind at the same time,” Maryland DOT official Greg Slater told an audience at the 2011 TRB Annual Meeting.

Tools have been developed to help transportation agencies with vulnerability and risk assessments, including the framework outlined in TRB *Special Report 290* as well as the FHWA’s Conceptual Model for Vulnerability and Risk Assessment and Regional Climate Change Effects report. And states are developing their own tools for adaptation planning, including geographic information systems to help identify and prioritize vulnerable infrastructure.

But the uncertainties surrounding climate change impacts remain a challenge, as transportation agencies continue to cite the need for consistent and reliable data to help predict sea level rise, temperatures, and storm events, and to protect vulnerable infrastructure.

EXAMPLES OF STATE DOT ACTIONS

The following provides a sample of some of the efforts underway by state DOTs on adaptation.

Alaska

Alaska has become a leading example of the challenges a warming climate can pose for transportation infrastructure. Coastal areas in the state face increasingly frequent and intense storms and flooding, and increased erosion due to loss of sea ice and to sea level rise. Officials with Alaska’s Department of Transportation and Public Facilities (ADOT&PF) have been dealing with a range of effects as rising temperatures cause unprecedented thawing of

Damage on the Richardson Highway after unexpectedly high flood surges from the 2006 South Central Alaska storm.

Typical permafrost damage on the
Glenn Highway near Glennallen, Alaska.

permafrost, including longitudinal shoulder cracking along roadsides, thaw settlement, and buckling and cracking of road structures.

Aside from being an inconvenience for travelers, these changes threaten some 180 coastal communities and the subsistence way of life for many Alaskan Natives.

Alaska Department of Transportation and Public Facilities (DOT&PF) has been active in implementing shoreline protection efforts, relocations, evacuation routes and shelters, drainage improvements, and permafrost protection for roadways. But these emergency efforts come at a great cost. Alaska DOT&PF reports that their northern region spends upwards of $10 million annually due to the effects of melting permafrost, and this represents only a fraction of what is needed. Those costs are expected to increase as warming trends continue.

Adopted in January 2010, Alaska’s Climate Change Strategy provides background on projected climate impacts in the state and calls for actions to protect the state’s public infrastructure. These include development of a coordinated statewide system for key data collection, analysis, and monitoring; promotion of improvements that use the current best practices; and focusing on building resiliency into the state’s infrastructure.

From a practical perspective, Alaska officials note that existing infrastructure has limited capacity for adapting to the effects of climate change. The fixed infrastructure does not lend itself to revised alignment, elevation, or structural foundation. When modification of existing infrastructure is possible, it can be prohibitively expensive. Alaska’s strategy emphasizes planning for projected climatic changes and updated design and siting in new infrastructure and construction, even though these techniques increase the cost of projects.

California

Adaptation concerns are vital in California, which faces significant impacts along its vast coastline as well as inland areas. The most significant climate impacts to California's infrastructure are predicted to be from higher temperatures and extreme weather events, reduced and shifting precipitation patterns in Northern California, and most predominantly, effects of sea-level rise including storm surge, erosion, and flooding.

A preliminary assessment of potential effects of sea level rise on transportation infrastructure in California found that a projected 55-in. rise in sea level by 2100 would threaten some 350 mi of major state highways, in addition to local streets and roads in vulnerable areas (*2*).

In November 2008, California Gov. Arnold Schwarzenneger signed an Executive Order (Order S-13-08) directing state agencies to plan for sea level rise and climate impacts. As a result, the state's 2009 Climate Adaptation Strategy outlines how state agencies should start considering such impacts.

The strategy includes a call for California DOT (Caltrans) to undertake a vulnerability assessment for the state's transportation infrastructure. The assessment will include a "hot spot map" of areas that are susceptible to climate change impacts and an adaptation plan that assesses adaptation options and prioritizes projects based on projected climate change risks. Caltrans has contracted with University of California at Davis to prepare this geographic information system (GIS) -based map to identify these areas. The assessment should be completed in 18 months and will use data available from the National Academy of Sciences' ongoing Pacific Coast Sea Level Rise Assessment as well as current sea-level rise data. Once this hot spot map is completed, the data will be used to assist in the development of a plan to address these climate change impacts.

Caltrans also is working on a number of guidance documents—including guidelines on incorporating sea level rise in project initiation documents and guidance to metropolitan planning agencies on how to address climate change in long-range planning. The agency also plans to conduct a baseline assessment of Caltrans' efforts to reduce greenhouse gases as well as a climate action plan for Caltrans.

Transportation Adaptation Strategies in California

- Develop a detailed climate vulnerability assessment and adaptation plan for California's transportation infrastructure.
- Incorporate climate change vulnerability assessment planning tools, policies, and strategies into existing transportation and investment decisions.
- Develop transportation design and engineering standards to minimize climate change risks to vulnerable transportation infrastructure.
- Incorporate climate change impact considerations into disaster preparedness planning for all transportation modes.

—2009 California Climate Adaptation Strategy

Delaware

Sea level rise is a major concern in Delaware and is expected to cause increased inundation and shoreline erosion, increased tidal surge, flooding from severe weather events, accelerated saltwater contamination of ground water and surface water supplies, elevated water tables, and expedited loss of critical habitats.

To help adapt to these changes, Delaware DOT is working with the state Department of Natural Resources and Environmental Conservation (DNREC) and with the Wilmington region MPO on a sea-level rise scenario study. DNREC adopted the sea-level rise predictions of the 2007 report by the Intergovernmental Panel on Climate Change, the leading international body for the assessment of climate change, established by the United Nations Environment Programme and the World Meteorological Organization (*2*). The levels were localized to Delaware: 0.5 to 1.5 m of sea-level rise by 2100 for the state. The ongoing study—a simple geographic inventory of assets and population that may be affected under three sea-level rise scenarios—will likely set the methodology and format that will be used for statewide sea-level rise evaluations. In addition, DNREC has convened a Sea-Level Rise Committee comprised of state, county, municipal, and private groups to guide state agencies in planning and investing in assets and programs that officials say will be "adaptable as well as adaptational."

Florida

Florida is another state facing significant challenges in adapting to climate change impacts—with particular vulnerabilities to rising temperatures, rising sea-levels, increases in heavy rainfall and hurricanes, and associated storm surge, erosion, and flooding.

In 2008, Florida adopted its Energy and Climate Change Action Plan with a framework for adaptation strategies, including protecting transportation and other infrastructure. The Action Plan also acknowledges the need for additional scientific data, analyses, mapping, and predictive modeling for climate change effects in Florida. The recommendations include inventorying critical transportation infrastructure at risk; determining whether, when, and where project impacts from climate change might be significant; and evaluating the costs and benefits of alternatives. It also calls for state, regional and local governments, and modal partners in Florida to work together to identify and protect at-risk transportation infrastructure.

The 2060 Florida Transportation Plan, updated in December 2010, calls for development of "refined data and decision making tools to better integrate climate trends and their potential impacts into decisions about designing, constructing, maintaining, and operating transportation infrastructure." The plan covers the state's entire transportation system, not just those facilities owned and operated by Florida DOT.

In addition, the state's 2010 Strategic Intermodal System (SIS) Strategic Plan, updated in January 2010, calls for Florida DOT to evaluate SIS infrastructure at risk from sea level rise and other climate trends.

Florida DOT addresses adaptation within the broader context of asset management. The department routinely monitors and maintains state roadways and bridges to achieve established preservation and maintenance standards. In addition, the state's investment policy is to fund its preservation needs first before investing in capacity improvements.

Florida DOT is working to decrease vulnerability of state bridges and roads that are at particular risk from extreme weather events—retrofitting infrastructure damaged by hurricanes and flooding to withstand future events—and the agency is developing a statewide inventory and action plan for high-risk bridges.

Research is underway with Florida Atlantic University to make recommendations for sea level forecasting methods and how existing data sources can be integrated with Florida DOT information to assess infrastructure vulnerability. The research is expected in August 2011.

Maryland

Maryland also has seen a range of climate-related impacts, including increased temperatures, increased precipitation in the spring, and a different makeup of winter storms. The state faces serious challenges with sea level rise, with some areas in and around the Chesapeake Bay already facing inundation and abandonment.

A range of aggressive actions are underway in Maryland related to climate change, both on mitigation and adaptation. On adaptation, the agency is working to assess vulnerable infrastructure and to build adaptation considerations into the agency's business practices, as outlined in the recently issued Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change, Phase II: Building Societal, Economic, and Ecological Resilience by the Maryland Climate Change Commission. This strategy document represents continued efforts to implement Maryland's 2008 Climate Action Plan.

The Maryland State Highway Administration (SHA) also is working to develop its own adaptation plan. According to state transportation officials, planning and engineering efforts must be adapted to address effects such as pavement rutting and buckling, increased rain and snow, more frequent and costly evacuations, scouring of bridge foundations and failure of bridge decks, and flooding, power loss, and traffic disruptions as well as inundation of coastal areas from rising sea levels. Maryland SHA's adaptation planning process includes identifying climate changes, assessing vulnerabilities and risk, developing a risk-based adaptation strategy, and identifying opportunities for co-benefits, implementation, and monitoring.

Like Florida DOT, Maryland SHA is approaching its adaptation efforts with an asset management approach. The agency is working to prioritize assets, taking into account factors such as anticipated sea level rise ranging from 2 to 10 ft as well as anticipated increase in 100-year storm events to every 20 years.

Maryland SHA also is developing a GIS tool which will allow the agency to track specific assets and determine which ones will be vulnerable.

Oregon

Like other coastal states, Oregon's transportation infrastructure is vulnerable to climate change impacts including increased erosion along coastal highways and more intense precipitation events that have the potential to overrun culverts and stormwater systems.

Oregon DOT has work underway to develop adaptation strategies. On a state level, Oregon DOT participated in the process to create the Oregon Climate Change Adaptation Framework. Issued in January 2010, the framework gives broad guidance to state agencies in assessing the impacts of climate change, identifying the basic adaptive capacity of Oregon to deal with risk of climate change, and identifying a list of state-level priority actions.

Within Oregon DOT, a Climate Change Technical Advisory Committee is identifying the potential impacts of climate change on the transportation system and strategies to adapt to those

Climate Risks in Oregon

- Increase in average annual air temperatures and likelihood of extreme heat events.
- Changes in hydrology and water supply; reduced snowpack and water availability in some basins; changes in water quality and timing of water availability.
- Increase in wildfire frequency and intensity.
- Increase in ocean temperatures, with potential for changes in ocean chemistry and increased ocean acidification.
- Increased incidence of drought.
- Increased coastal erosion and risk of inundation from increasing sea levels and increasing wave heights and storm surges.
- Changes in the abundance and geographical distributions of plant species and habitats for aquatic and terrestrial wildlife.
- Increase in diseases, invasive species, and insect, animal, and plant pests.
- Loss of wetland ecosystems and services.
- Increased frequency of extreme precipitation events and incidence and magnitude of damaging floods.
- Increased incidence of landslides.

impacts. A more comprehensive Oregon DOT Adaptation Strategy Report will specifically address the potential strategies and actions to reduce the vulnerability and increase resilience of Oregon DOT's infrastructure and systems to climate change impacts. The committee is in the process of developing this strategy document, with the ultimate goal of creating an Oregon DOT Climate Change Adaptation Plan that will help guide planning, project development, and emergency response to prepare for the impacts of climate change.

Oregon DOT is taking an active role to share information with the public, including a website providing state-specific information and background on climate change adaptation and mitigation efforts at www.climatechangeodot.com.

Vermont

Vermont DOT (VTrans) is working with other sectors in the state to gather climate change adaptation information. The transportation sector will provide an overview of the climate science for the Northeast, including known science, data, and information gaps related to changes in weather and the associated effects including stream flow changes, flooding, increases in freeze–thaw events, increases in wind intensity, and snow levels. VTrans will collect information and map locations where it is spending resources addressing storm event flooding and other damages. The analysis also will provide a summary of how predicted weather changes and associated effects are expected to affect transportation infrastructure and operations, laying the groundwork for development of a risk management based approach to decision making related to these effects as well as actions to address them.

Washington

Washington State DOT has been very active in assessing the effects that climate change may have on infrastructure in the state, where key impacts include sea level rise, transition from snow-dominant to rain-dominant watersheds, wildfires, changing river dynamics, and landslides.

In 2009 the legislature directed state agencies to begin planning for climate change and formed Topic Advisory Groups. Washington State DOT, along with five other state agencies and the University of Washington (UW), are looking at the potential impacts to infrastructure and operations in the state. Washington State DOT's adaptation strategy includes scenario planning, sea level rise mapping, scour monitoring, vulnerability assessment, and risk assessment.

The UW Climate Impacts Group has taken the global climate change models and scenarios and downscaled them to a regional level covering Washington, Oregon, Idaho, and a portion of British Columbia. This regional evaluation allows the jurisdictions to share costs for analysis of areas with similar physical characteristics, and it allows an assessment of impacts beyond the state's boundaries that may have effects within Washington.

Changes in river dynamics: Hoh River flooding, channel migration, and avulsion. (Photo courtesy of Washington State DOT.)

Scour and damage to structures, US-12 Davis Creek.
(Photo courtesy of Washington State DOT.)

Washington State DOT is one of the state agencies that received grant funds to test the FHWA's conceptual model for vulnerability and risk assessment. (See the related article about FHWA's climate change programs.) As part of that process, the agency is continuing to update its inventory of infrastructure, including road center lines, bridges, buildings, pit and quarry sites, radio sites, stormwater treatment facilities, wetland mitigation sites, culverts, hydraulic conveyance features, rest areas, rail lines, and ferry terminals. This data is or will be geospatially referenced for use in a GIS system. Washington State DOT will be looking at the likely changes to sea level rise, precipitation, flooding, temperature, fire, sediment loading in rivers due to glacial recession, soil moisture, coastal erosion, snowpack, and wind. By overlaying maps of these anticipated changes on its infrastructure, Washington State DOT will analyze which locations will be at risk.

Washington State DOT will use this information and hold risk analysis workshops with local staff and subject matter experts to assess the vulnerability of the state's infrastructure. In turn, the agency will use that information to evaluate design guidelines and inform future planning efforts, allowing the agency to prioritize actions to address the state's most vulnerable assets.

Washington State DOT's efforts on climate change are documented on its website, http://www. wsdot.wa.gov/environment/climatechange/.

BARRIERS AND NEEDS

Even in states that are addressing adaptation, obtaining reliable data is a challenge. Common assumptions are needed to determine the projected climate change impacts from sea level rise, precipitation, and heat. More information and training is needed on risk-based decision making with respect to climate change, especially changes in storm frequency and intensity.

State officials report that the public continues to be misinformed and confused regarding climate change science. Better models are needed to provide a clear prediction of local climate change effects, as well as more accurate timeframes for sea-level rise scenarios, better hydrologic models, and environmental "tipping points" to trigger policies and actions. Better information also is needed on increasing storm intensities so that structures can be protected.

Those state DOTs that have not addressed adaptation have cited a range of factors for not doing so, including

- A perceived lack of urgency, particularly for non-coastal states;
- Focusing on day-to-day system operations, rather than longer-term climate change impacts;
- Lack of political support;
- Lack of funding; and
- Difficulties in planning for the uncertainties of climate change.

DOTs have suggested a range of tools to help with adaptation efforts, including

- Updating federal emergency response requirements so that dedicated resources can be used toward improving existing infrastructure rather than simply replacing it;
- Gathering additional lidar data for more accurate climate change projections;
- Asset management tools;
- Identifying best practices for emergency response communication efforts;
- Updates to 100-year storm projection maps and 100-year flood boundaries;
- A collection effort of best practice adaptation strategies;
- A tool for conducting a cost–benefit analysis on adaptation efforts, particularly the costs of inaction; and
- Identification of materials that are best able to handle potential effects of climate change.

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Climate Change Adaptation and Preparedness Planning for Airports

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Airports across the United States and throughout the world are a vital part of a metropolitan area's transportation infrastructure and play a large part in linking the global economy for passengers, mail, and freight. The airport community has already developed skills and resources for adapting to significant changes, such as new larger aircraft, security screening, airline mergers, environmental and community expectations, funding cutbacks, global safety regulations, and rapidly evolving technologies. Climate change is likely to have subtle long-term as well as dramatic short-term effects on airports in the future, introducing yet another challenge —one of adapting operations and development to changing climate conditions. That said, adaptation thinking, planning, decision making and investment is in its infancy in the airport world.

Unlike most public transportation assets in the United States and in other developed countries, most airports are owned and operated by a municipality, government authority, or state government and used by private airlines and other private tenants. This relationship often results in airport managers and tenants focusing on investments that will produce relatively near-term return, and not on adaptation that may take decades to come into full use. This article lays out the essence of how climate change is likely to affect airports in the future, the adaptation actions that airport operators can start taking to prepare and adapt to these coming changes, and some of the research needed to help the industry adapt more quickly and efficiently.

AIRPORT CONTEXT

Obviously, airports occupy large acreage. Many often encompass multiple watersheds, and are sited in many diverse landscapes and communities around the world. They vary from sprawling complexes like Dallas–Fort Worth and Denver to very compact facilities like New York's LaGuardia or San Diego. Thus the potential climate change impacts and adaptation actions will vary widely. Some aspects of airports that are particularly important for climate change adaptation include:

- Infrastructure investments often last more than 50 years. Utility and storm water infrastructure could become overloaded, and be among the first victims of climate changes. It will be important for airport operators to develop long-range infrastructure management plans and potentially consider changes to the designs and locations of facilities to avoid future costly relocations.

- In addition to aircraft flight, airport function depends on connectivity to ground transportation systems such as road and rail connectors. These facilities may or may not be owned or controlled by the airport, yet the impacts to the continuity of airport operations would be severe if the consequences of climate events were to frequently sever the airport from the community.
- Aircraft, airport, and airspace operations are weather dependent. Aircraft assets are extremely expensive precision machines that must be protected from salt water, excessive wind-borne dust, etc. Adapting to climate change is as much about protecting aircraft as it is about protecting airport infrastructure, and as the climate evolves, this may lead to completely new facility requirements and operating procedures.
- Airports often host emergency city or regional command center operations during times of crisis, and are a focal point for rescue, evacuation, and emergency supply chains. These expected roles are both an opportunity for the airport to play a critical role in facilitating regional climate change adaptation and preparedness, as well as a potential vulnerability if the airport were severely damaged by storms or sea-level rise in ways that compromised its command-center and distribution hub role.

These important aspects of airports suggest that climate change adaptation programs need to include a variety of elements, including the planning, development, and redevelopment of facilities and infrastructure, new operational requirements, procedures and standards, and new and extensive community communications and collaboration processes for ensuring that the entire region is involved in adapting to climate change.

POTENTIAL CLIMATE CHANGE IMPACTS

In general, there are three levels of potential effects of climate change on airports: the direct climate changes such as temperature and precipitation, the secondary effects of those changes on the ecosystem, and the tertiary effects of the ecosystem changes on human management processes like insurance costs. The direct climate changes are expected to be

- Increases in average temperatures (air and ocean) in many parts of the world,
- Increases in average sea level and in the maximum extent of storm surges,
- Changes in average precipitation amounts and increases in precipitation intensity, and
- Increases in wind speeds and storm intensities.

The secondary effects of climate and weather changes on ecosystems include

- Dryer soils and more runoff and erosion. These effects may change various parameters of the airport environment such as increased airborne dust which can damage aircraft machinery and affect operations, and changes in wildlife–aircraft hazards. Moreover, depending on the severity, airports would have to adapt water conservation and management practices.
- More forest and grassland fires. Smoke from these events affects aircraft operations.

Intense climate changes will necessitate new facility construction and design specifications and operating procedures at airports.

- Reductions in mountain snowpack and associated changes in stream flow timing and volume. These effects may change the timing of water availability, increase erosion through the airport watershed, and change habitats local to the airport environment which results in changes in wildlife–aircraft hazards.
- Changes in plant and animal species migration, disease, extinctions, and habitats. The obvious immediate implication is the potential for change in aircraft–wildlife hazards, but more subtle effects may occur over time.
- Changes in human migration and the creation of refugees from severely affected areas of the world to more habitable areas of the world. The implication of this effect is changes in demand for air travel, which would result in changes to aircraft size and frequency in operations.

Finally, the tertiary effects of these direct and secondary effects on human management processes include issues such as

- Changes in populations and air service market dynamics,
- Significantly higher insurance costs for property and liability coverage,
- An increased role for the airport in regional emergency management, and
- Significant public expectations for airports to both prevent climate change impacts and to reduce the greenhouse gas emissions that cause them.

All of these effects have roles to play in identifying and prioritizing the best climate change adaptation actions for a particular airport to focus on, and for shaping industry research programs.

CRAFTING ADAPTATION STRATEGIES

A comprehensive approach to an airport climate change adaptation strategy, then, needs to consider both the unique characteristics of the airport and the combination of potential effects noted above. While climate change adaptation programming at airports is at an early stage in its development, it is clear that adapting to the various effects will involve three broad areas of work:

- Hardening and redeveloping the physical plant,
- Assessing and adapting to a variety of operational risks and opportunities, and
- Building communications, collaboration, and strategic alignment with the full range of airport stakeholders to carry the load together.

Hardening the Physical Plant

The potential serious physical damage to the facilities and infrastructure of an airport mainly result from the changes in precipitation, temperature, sea level, storm surge, and winds. The risks include flooding, heat buckle and other forms of expansion stress, permafrost thaw buckle in northern regions, perimeter security breaches, and fuel contamination or spills from pipe ruptures. As noted in the previous section, secondary effects of climate change may also cause new risks, such as extreme erosion, soil depletion, wild land fires, and facility damage from new species of animals and plants.

Addressing potential physical damage from future climate change can generally be done by progressively incorporating the consideration of the risk factors into existing design specifications, asset management systems, and maintenance work order systems. Airports can take their existing inventory of facilities and infrastructure and assess each component for its susceptibility to the various risk factors, and then the best remedial actions can be programmed and performed. Examples of adaptation actions that could be identified include

- Revising design standards for higher average temperatures and design day temperatures, which could affect the selection or specification of materials and the design of expansion joints;
- Developing plans for lengthening runways to account for future higher density altitudes and the degradation of future aircraft takeoff performance;
- Rebuilding stormwater infrastructure to withstand greater peak flows, where these are expected based on climate model projections;
- Hardening facilities for higher wind loads (e.g., building shell replacement, aerodynamic load analysis of building complexes, and extra tie-downs for aircraft and containers); and

- Rebuilding, relocating, or abandoning shoreline facilities (e.g., seawalls, sewage treatment outfalls, and building and runway foundations) to accommodate expected future higher sea levels

It would be unusual for these types of physical improvements to be carried out in isolation from the regular process of continuous planning, design, development, and maintenance that typically goes on at any airport. Climate change adaptation actions for the physical plant can be seen as one of many objectives to be incorporated into the master planning and asset management process. This approach ensures that solutions are thought through in an integrated and comprehensive manner, to minimize the costs of the improvements and maximize the efficiency of the development process over time. The goal is to adapt to this new consideration of climate change in a way that still maximizes the utility of the often very long lived components of the airport infrastructure.

Addressing Operational Risks

The second broad area of adaptation work is to assess and adapt to a variety of operational risks and opportunities that affect the airport. Here again, there are usually well-developed operational programs for assessing operational risks and doing something about them, and climate change risks would simply be added to the mix. The terms “irregular operations” and “incident management” are being increasingly used to help integrate the many operational considerations that need to be brought together to manage an airport when one or more excursions from normal are happening. Increasingly the functional groups at an airport—operations, fire, police, finance, environmental, health and safety, human resources, and so forth—work together as a team to manage both the day-to-day operations and the unusual accidents or incidents. At many airports, business continuity plans are being developed and amended to address all manner of anticipated irregular operations. In the event that the uses of irregular operations plans are invoked more frequently, these plans will essentially be adapted to the changing local climates. Therefore, there is every reason to include the potential climate change risks into these plans and drills. Some of the climate related potential risks include

- Operational impacts from airport closure and delayed aircraft operations due to flooding or storm water overload,
- Increased energy consumption for heating, ventilation, and air conditioning due to extreme heat events,
- Water quality violations from increased deicing,
- Computer system downtime or data loss and cyber security risks due to power failures or building damage related to wind,
- Operations and maintenance disruptions due to all of the above,
- Public health risks (air, water, sanitation, infectious disease) during mass strandings and extended disruptions,
- Airport employee chaos due to regional and family demands for their services,
- Tenant or contractor lack of performance due to equipment, supplies, or labor unavailability, and
- Economic loss to regional businesses.

While there is a great deal of science being deployed to better understand climate change, it is also true that it is no more possible to predict exactly when a particular storm, overnight sea level rise, or other climate effect not yet anticipated will occur, than it is to predict the date of an earthquake or major fire. It makes a great deal of sense to incorporate the potential of climate change events into the existing system of planning for irregular operations, so that they are understood and prepared for by all the functional groups that keep an airport running.

Communications and Collaboration

The third broad area of climate change adaptation work is building communications, collaboration, and strategic alignment with the full range of airport stakeholders. Climate change is a global concern with many local implications, so there are stakeholders at the international, national, state, regional, and local levels bringing a variety of resources, needs, regulations, partnerships, and obstacles to the table. The best course is to over-communicate the airport's interests and concerns to all who will engage, and to develop the most robust possible approach to understanding and adapting to climate change. The airport is such a key part of every region's transportation infrastructure that it has a tremendous opportunity to engage and help drive the region's approach to climate change adaptation, rather than be driven by it.

Churchill's famous quotation, "We have nothing to fear but fear itself," applies to climate change adaptation. It is not easy to contemplate the possibility of having to tear out and rebuild, or relocate, facilities which have not been paid for yet. Insurance companies have been among the first businesses to start doing research and holding customer seminars on climate change, because they know it is in their best interests to minimize risk. An airport is no different. What makes "over-communicating" a winning strategy is that it maximizes the process of collaboration and consensus building that will be necessary to raise the funds and make the tough decisions to address the various adaptation issues.

Every airport will have a different approach to working with its stakeholders, but, as with hardening the physical plant and mitigating operational risks, communication and collaboration about climate change adaptation is best done by incorporating it into existing channels. Master plans, bond prospectuses, lease negotiations, mutual aid agreements, community meetings, tenant meetings, and annual reports are all available avenues for describing and eliciting understanding and collaboration about mutual climate change issues and priorities. Each of these vehicles will be part of the communications package as airports begin to broaden their understanding of climate change vulnerabilities and risks and establish risk assessment frameworks for identifying, prioritizing, and implementing adaptation changes to airport infrastructure and operations–maintenance–emergency response planning and protocols.

Global challenges, like adapting to climate change, tend to be led not by government and business but by the emergence of self-empowered groups that form into powerful non-governmental organizations (NGOs). They tend to start out as observers outside the process, and become effective through lobbying and other kinds of public engagement. An example is the U.S. Green Building Council which started as a volunteer board and has grown to become the de facto regulator of sustainable building codes, even though it still has no contractual or governmental authority to do so. The LEED green building checklist and verification process is increasingly considered a standard practice. While it is too early to discern standard practice in climate change adaptation practice, it is likely that NGOs will play a leading role in developing them. Airports and their industry associations would do well to get involved early in any volunteer collaboration that arises around adaptation, such as the focus promulgated through TRB, and to make sure that those volunteers have the full picture of the role airports can play in adaptation strategy.

In addition, airports are only part of the aviation system which includes airlines, ground transportation providers, air traffic control, and aircraft and engine manufacturers. Each of these groups of stakeholders will be working on their approaches to adapting to climate change which may include new needs and uses for airport facilities. An effective two-way collaboration between the airport and its stakeholders will mean that the airport will get support for its needs while helping its key stakeholders with theirs. A robust communication program will ensure that the airport's adaptation actions takes everyone's needs into account for the most efficient long term results.

RESEARCH NEEDS

The recent 2011 mid-year meeting of the TRB AV-030 Environmental Effects of Aviation Committee focused on developing a framework and roadmap for climate change adaptation. In addition, the 2011 Airport Cooperative Research Program synthesis topic 02-06 will be a synthesis of current literature and practices in airport climate change adaptation and preparedness. The outcomes of these two efforts are expected to be

- A just-in-time literature summary to ramp-up airports' knowledge base of the issues and applicable lessons from other modes and industries;
- A matrix of risks, potential solutions, feasibility, and co-benefits applicable to the airport context;
- A generic work plan for developing a holistic adaptation plan for an airport or airport system; and
- A prioritized list of research needs to accelerate airports adaptation toolbox development.

Examples of research needs in airport and aviation climate change adaptation include

- Understanding and accounting for regional variations in the expected effects of climate change;
- Methods for regional data-sharing of climate change related data and forecasts;
- Effects of sea level rise on water tables and soil and structure foundations;
- Effective building shell treatments for higher velocity winds and precipitation densities;
- Materials science implications for higher average temperatures and higher extremes;
- Public health implications of new invasive species and vector-borne diseases;
- Efficient methods for storing and handling alternative fuels;
- Methods for valuing and pricing climate change adaptation actions;
- Ways to incorporate climate change considerations into risk management and asset management systems; and
- Community mapping and other ways to assure comprehensive stakeholder involvement in adaptation planning and implementation.

CONCLUSION

The field of airport climate change adaptation is emerging in importance. It stems from the need to address predicted future changes in climate and weather, their effects on airport infrastructure and an efficient air transportation network, and the role of the airport in the regional economy, society, and ecosystem. The three broad areas of adaptation actions are hardening the facilities, preparing for irregular operations, and engaging stakeholders in adaptation planning. Industry research and collaboration are ramping up to address these needs.

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SIDEBAR

Climate Change Impacts on Ports

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The impact of climate change on specific U.S. ports may not only disrupt regional economies, but have nationwide implications as well. For example, seven of the top 10 U.S. ports based on tonnage are located on the Gulf Coast between Houston, Texas, and Mobile, Alabama. Collectively, the approximately 1,000 freight ports in this region handle more than 60% of U.S. oil imports, and convey about 40% of U.S. marine tonnage—especially grains from the country's interior. Gulf Coast ports are served by a complex network of 17,000 mi of highways, rail lines, and inland waterways that provide 20 states with access to the Gulf of Mexico and global markets. The resilience of ports in this region is critical both to the country's energy security and economic vitality.

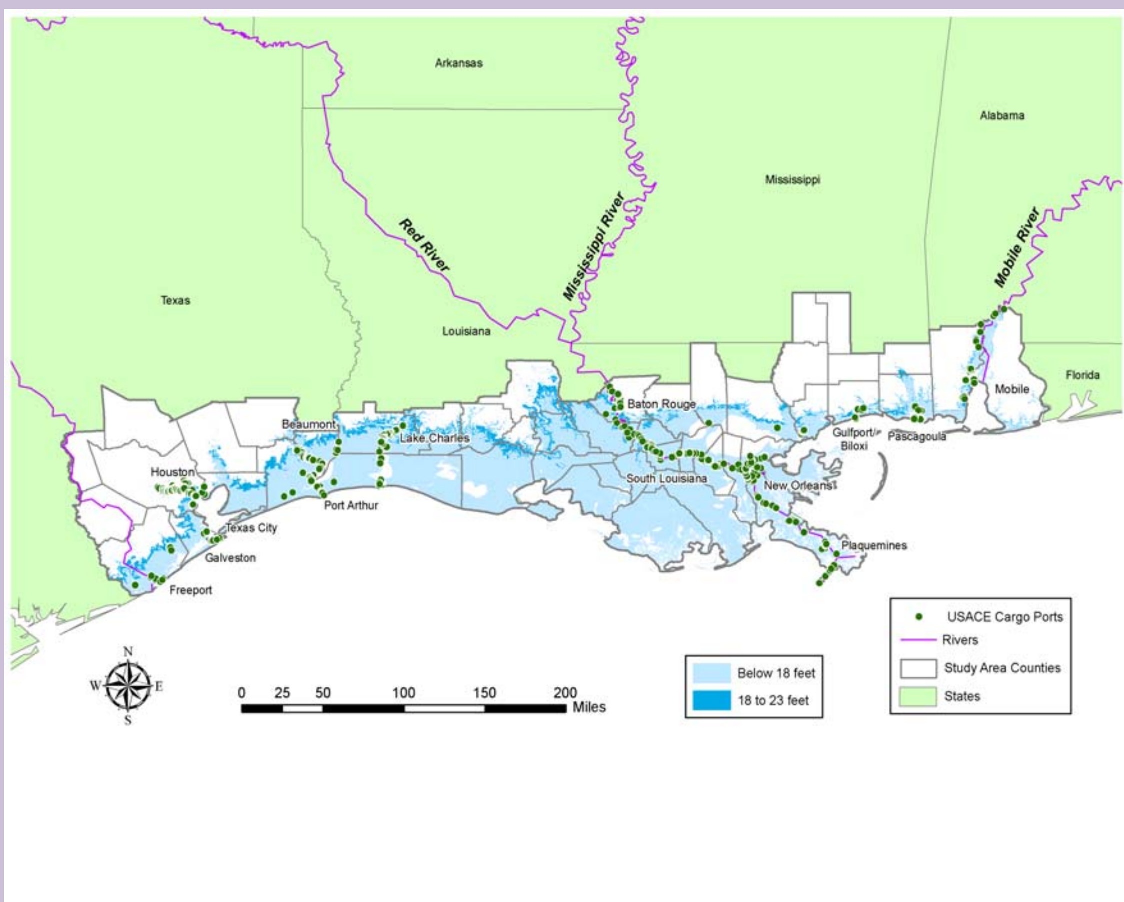
A study of climate impacts to transportation in the coastal Gulf Coast region examined the effect on regional ports of sea level rise, storm surge, increasing intensity of storm events, and greater numbers of "high heat" days. Among the findings of the U.S. Global Change Research Program's (USGRP) Gulf Coast Study (*1*):

- Rising sea levels will cause increased flooding and exacerbate the damage to ports from storm surge during severe weather events. Projected increases in relative sea-level rise by 2100 range from a low estimate of 47.8 cm (19 in.) in 2050 to a high of 199.6 cm (79 in.). Of freight port facilities in the study area, about 72% are vulnerable to a 122-cm (4-ft) rise in relative sea level, as well as nearly half of the region's intermodal connector miles, and 10% of its rail miles. [More recently, the USGCRP estimated a 91 cm to 122 cm (36 to 48 in.) rise taking into account ice sheet melt.]
- Simulated storm surge (at today's elevations and sea levels) demonstrated a 6.7- to 7.3-m (22- to 24-ft) potential surge for major hurricanes of Category 3 or greater. Based on recent experience, even these levels may be conservative. Hurricane Katrina had a 28-ft storm surge at landfall, causing an estimated $134 billion in damage and claiming 1,800 lives. Fully 99% of all study area marine facilities are vulnerable to temporary and permanent impacts resulting from a 7.0-m (23-ft) storm surge.
- The increasing intensity of individual rainfall events is likely to have significant implication for wind damage, flooding, and stormwater management. Fast moving water can be incredibly damaging to marine facilities. Water can physically dislodge containers and other cargo from open storage areas, knock down terminal buildings, damage or destroy

specialized terminal equipment, damage wharf and pier structures, temporarily inundate and submerge large areas, and undermine or damage pavement and foundations. Wind has its most damaging effects on unreinforced terminal structures, such as metal warehouses that feature large surface areas and relatively light construction. Much of Katrina's damage to the Port of New Orleans—which mostly escaped water damage—was due to wind tearing off warehouse roofs and doors.

- The number of very hot days (>100ºF) in the Gulf Coast could exceed 90 days per year by 2080. Higher temperatures will increase costs of terminal construction and maintenance, particularly of any paved surfaces that will deteriorate more quickly. And higher temperatures will lead to higher energy consumption and costs for refrigerated warehouses or "reefer slots".

Although the impacts to ports from climate change will vary from region to region, the Gulf Coast Study illustrates the potential magnitude of risk confronting our nation's ports. By assessing the vulnerability of individual ports and regional networks, we can take action today to protect these vital facilities.



Seven major U.S. ports are located on the Gulf Coast between Houston and Mobile; rising sea levels, elevated storm surges, severe rainfall events, and very hot temperatures will challenge the resilience of ports in the region.

Transportation Adaptation's Bearing on Planning, Systems Management, Operations, and Emergency Response

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State and local governments and private infrastructure providers should incorporate climate change into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans. In fact, one of the recommendations from TRB *Special Report 290* is that climate change be incorporated in these plans. This will require that transportation providers work more closely with weather forecasters and emergency planners and assume a greater role in planning and emergency response. Moreover, adaptation also may become an important criterion both for determining the form of the system and prioritization of projects.

According to the Intergovernmental Panel on Climate Change (IPCC), "…warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (*1*). Statistics from the National Climate Data Center (NCDC) indicate that of the 10 warmest years on record—since such record keeping began in 1880—nine occurred in the last decade (2001 to 2010), with 2008 ranking 11th. (The non-2000 year included in the top 10 is 1998.) Moreover, temperature reconstructions indicate that the global mean surface temperatures over the last 25 years have been higher than any comparable period since 1600 CE, and probably since 900 CE (*2*).

Recent weather events certainly demonstrate this warming trend and the associated consequences that wet places tend to get wetter while dry places tend to get drier. For example

- The December 2010 snowstorm in New York City left many subway and train riders stranded on unheated trains. This was followed by the second snowiest January in southern New England, resulting in many collapsed roofs.
- The early February 2011 storm paralyzed states from the Midwest to New England leaving many motorists and users of transit stranded in many states across the country. Associated Press articles noted that the storm left as much as 2 ft of snow across its 2,000-mi path, crippling airports and stranding drivers from Texas to South Dakota, where authorities rescued motorists from more than 150 vehicles that had become trapped.
- Before the winter season, there was record level flooding in Tennessee, Rhode Island, Iowa, and Wisconsin.
- California's blistering fall 2010 heat wave sent temperatures to an all-time record high of 113°F degrees in downtown Los Angeles, causing power outages and raising wildfire concerns.
- According to Ian Morris, the fire season in the western United States is now 78 days longer than it was in the 1970s (*3*).

- Heat waves have become significant issues.
- 1995 Chicago heat wave: 750 deaths.
- 2003 European heat wave: 40,000 deaths. A map showing the temperature anomaly for that time period can be found at http://en.wikipedia.org/wiki/2003_ European_heat_wave.
- 2010 Moscow heat wave: 11,000 deaths (*4*).
- Although great variation exists in hurricane seasons from year to year, a 2005 study in the journal *Nature* found that hurricanes and typhoons have become stronger and longer-lasting over the past 30 years. These changes correlate with a rise in sea surface temperatures. A 2010 article in the journal *Nature Geoscience* (*5*) summarizing a study conducted by a special World Meteorological Organization panel of 10 experts in both hurricanes and climate change, concluded that the world is likely to get stronger but fewer hurricanes in the future because of global warming.
- The 2010 floods in northern New South Wales and southern Queensland which ended a decade of drought (said to be Australia's worst in a century), followed by another flood in Queenstown in January 2011 with three quarters of the state declared a disaster zone.

Just as climate change has impacted the history of economic and social development, the transportation network—and the access it provides (or fails to provide)—also influences these development processes. Recent reports such as *Potential Impacts of Climate Change on U.S. Transportation* (*6*) and *Global Climate Change Impacts in the United States* (*7*), lay out the case that climate change has already begun to also affect the transportation network, and will continue and, most likely, increase in the years ahead. The U.S. Department of Transportation (DOT) has long paid attention to this issue. For example, the DOT's Transportation and Climate Change Clearinghouse is designed as a one-stop source of information on transportation and climate change issues. It includes information on greenhouse gas (GHG) inventories, analytic methods and tools, GHG reduction strategies, potential impacts of climate change on transportation infrastructure, and approaches for integrating climate change considerations into transportation decision making at http://climate.dot.gov/. More specifically, with regard to climate change and adaptation, climate change is expected to have an impact on transportation infrastructure. Issues such as rising sea level and changes in regional temperature may change the nation's road and rail network that could eventually require strategic adaptation planning to respond to the impacts (http://climate.dot.gov/impacts-adaptations/index.html).

Regional metropolitan planning organizations MPOs and state and local DOTs will therefore need to consider appropriate near-term operational approaches and long-term planning processes to "adapt" to the changes in the transportation network resulting from global warming, and to minimize the potential impacts on the transportation system from climatic changes, either through decreasing the system's vulnerability, increasing its resilience, or some combination. As was noted at the March 30, 2011, DOT-sponsored session, Transportation and Climate Change Adaptation, preparedness for climate change can include building in redundancy for storm surges to be prepared for evacuations. Or, for those southern states less accustomed to major snow falls, adaptation may mean a rethinking of equipment purchases. A single snow storm every few years may have meant inconvenience but no major shifts in agency decisions in the past. Now and in the future, when the frequency and severity of snowstorms in the southern tier may be more likely, and even a regular occurrence, the type of equipment, the number of vehicles, and the training needed to maintain the vehicles are among the many issues the state and local DOTs will be forced to address.

OPERATIONS

Transportation Systems Management and Operations (TSMO) is an "integrated program to optimize the performance of existing infrastructure through the implementation of systems, services, and projects designed to preserve capacity and improve security, safety, and reliability of the transportation system" (*8*). TSMO includes a broad range of multimodal activities, operational strategies, and supporting technologies.

Table 1 identifies many of these operational strategies in terms of how they may be applied to help manage and possibly reduce transportation impacts resulting from climate change. The columns identifying climate changes and their potential impacts on the transportation network are taken directly from the aforementioned TRB *Special Report 290*.

TABLE 1 Operational Considerations for Climate Change Impacts

Climate Change	Impacts on Transportation	Operations Considerations
Increases in very hot days	• Softening and buckling of pavements • Thermal expansion of bridge expansion joints • Rail–track deformities • Limitations on periods of construction activity due to health and safety concerns • Vehicle overheating (resulting in roadway incidents)	• Reduced (and variable) speed limits • Truck restrictions • Road and transit diversions • Work zone management (accommodate additional lane closures) • Increase in incident management activities
Rising sea levels	• Flooding of coastal roads, tunnels, and rail lines • Erosion of road base and bridge supports (scouring)	• Road and lane closures • Disruption of transit service • Road and transit diversions
Increases in intense precipitation events	• Increases in weather-related delays and traffic disruptions • Increased incidents • Erosion of road base and bridge supports (scouring)	• Reduced (and variable) speed limits • Road and lane closures • Truck restrictions • Diversions • Increase in incident management activities
Increases in drought conditions for some regions	• Increased susceptibility to wildfires and reduced visibility	• Reduced (and variable) speed limits • Road closures • Diversions • Increase in incident management activities
Increases in hurricane intensity	• More frequent and potentially more extensive emergency evacuations	• Contraflow lane operations • Ramp management • Integrated Corridor Management (along evacuation routes)

An underlying element in all of the operational considerations and strategies shown in Table 1 is that of traveler information—providing real-time information to travelers about the on-going transportation impacts, how they may affect their travels, and warning them as to any changes to the norm (e.g., reduced speed limits, closed lanes), thus allowing travelers make better decisions about how they travel (mode), when they travel (time), where and whether they travel (location), and which route they travel (path). This information can be provided pre-trip and en route through a variety of devices, including e-mail, text alerts, websites, in-vehicle navigation systems, and dynamic message signs.

In addition, given the broad geographical range of climate change impacts, operational solutions for reducing transportation impacts need to be addressed on a regional basis through Regional Transportation Systems Management and Operations, or RTSMO.

Many RTSMO strategies are becoming more proactive and dynamic in their application. One such example is Active Transportation and Demand Management, which includes variable speed displays, travel time signage, and lane control signals that are automatically set (and varied) according to prevalent roadway and operating conditions, including visibility, weather, lane constraints (e.g., work zones), incidents, and real-time traffic flows and congestion levels. As climate change continues increasingly to impact the transportation network, it will become even more important to incorporate weather-related data, as well as information on the condition of the transportation infrastructure, into the automated and predictive algorithms and related decision support tools for operations. Table 2 identifies some of the existing and emerging technologies and algorithms for collecting real-time data on weather and monitoring infrastructure conditions.

Real-time weather and infrastructure condition information will also need to be shared among the appropriate agencies involved in operating the transportation system (e.g., the transportation management center) and in responding to an extreme weather event (e.g., the emergency operations center), to aid in the decision-making processes. Figure 1 shows the

TABLE 2 Technologies and Algorithms for Monitoring Transportation Infrastructure

Environmental sensor station	• A roadway location with one or more fixed sensors measuring atmospheric, pavement and/or water level conditions. • Atmospheric data include air temperature and humidity, visibility distance, wind speed and direction, precipitation type and rate, and air quality. • Pavement data include pavement temperature, pavement freeze point, pavement condition (e.g., wet, icy, flooded), pavement chemical concentration, and subsurface conditions (e.g., soil temperature). • Water level data can also include levels of streams, rivers, and lakes near roads.
Bridge scour monitoring	• Bridge scour is the removal of soil, sand, and rocks form around bridge foundations, compromising the integrity of the structure; it is a common cause of bridge failure in the United States. • Increased intensity of precipitation events may increase scouring and potential failures.
Embedded nanotechnology monitoring	• Checking condition of joints and for structural fatigue, which may be accelerated by an increase on very hot days.

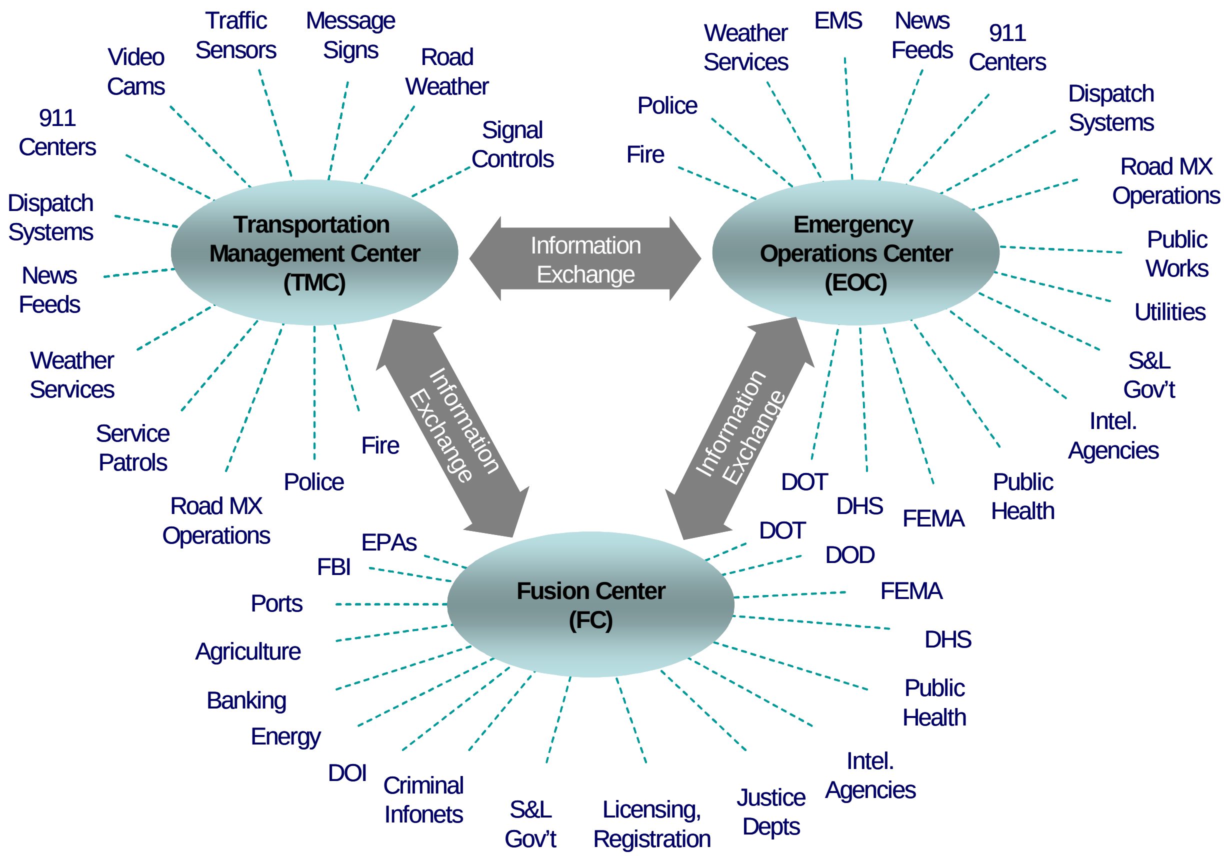

FIGURE 1 Interagency cooperation is necessary (*9*)

possible agencies, entities and activities that can be expected to play a role in operation and response events, and the required information exchange. Given recent climate trends, the interdependencies among the activities are likely to increase and thus be less appropriate for an ad hoc approach. The establishment and use of interagency standard operation procedures may support the sharing of time-sensitive data.

PLANNING

Emergency Planning

Many of the climate change events and transportation impacts identified in previous Table 1 constitute emergencies, and are often treated on an ad hoc basis. There are climate-related situations where U.S. transportation providers already plan for and address the impacts of weather on transportation system operations. For example, hurricane evacuation planning has become a major focus of transportation operations in the Gulf Coast states, where transportation providers are forging close relationships with emergency responders to handle such severe weather events.

As climate change induces more and new extremes, resulting in even greater impacts on the transportation network (refer to Table 1), operational responses and the associated planning are likely to become more routine and proactive than today's approach of treating severe weather on more of an ad hoc, emergency basis. For example, should hurricanes increase in intensity as predicted, the establishment of evacuation routes and use of contraflow operations may become as commonplace in other parts of the country as they are in the southeast. Similarly, the current use of snow emergency routes in the Northeast and Midwest may spread to more southerly locations. Another consideration is that, depending on the magnitude of such weather-related events, emergency transportation operations are likely to be hampered. With the possibility of evacuation routes curtailed, emergency responders may be limited in provide safe passages for those in affected areas. A rethinking of how best to advise those who are affected may require shelter-in-place to be the more likely "default" option.

Planning for Operations

Traditionally, planning the transportation infrastructure and operating the transportation system have been two relatively detached sets of activities with different requirements and different cultures. In the traditional model, transportation planning focuses on infrastructure projects, relying on an analysis of long-range travel demands, transportation system goals, and funding constraints, but often with limited consideration of short-term and ongoing operational issues. Management and operation of the transportation system typically involves a different set of practitioners with a short-term or real-time focus, often with limited consideration of how activities relate to regional transportation system goals and objectives. Linking planning and RTSMO is vital to improving transportation decision making and the overall effectiveness of transportation systems. Coordination between planners and operators (i.e., "planning for operations") helps ensure that regional transportation investment decisions reflect full consideration of all available strategies and approaches to meet regional goals and objectives, including those related to addressing climate change.

Planning for Operations is a joint effort between the FHWA's Office of Operations, FHWA's Office of Planning, and FTA's Office of Planning, and was developed to promote multimodal planning practices that support 21st-century transportation system management and operations. Per the website (http://plan4operations.dot.gov/), Planning for Operations includes three important aspects.

- Regional transportation operations collaboration and coordination activity that facilitates RTSMO;
- Management and operations considerations within the context of the ongoing regional transportation planning and investment process; and
- The opportunities for linkage between regional operations collaboration and regional planning.

A fourth aspect should be added to this: planning for operations in support of adaptation to climate change.

Infrastructure Planning

The long-term solution to adapting to climate change—apart from climate change mitigation strategies to reduce GHG emissions and thereby reduce climate change and its impacts—is to make the infrastructure more robust. This will involve a number of activities over the next several decades, including developing new design standards, redesigning and retrofitting transportation infrastructure to adapt to the potential impacts from climate change, and possibly rebuilding or relocating infrastructure that is in vulnerable locations.

An example of adaptation planning for infrastructure is the Boston Region Metropolitan Planning Organization's 2010 Work Program for Emergency Evacuation and Hazard Mitigation Mapping, available at http://www.ctps.org/bostonmpo/5_meetings_and_events/2_past/2010/020410_TPPC_Materials2.pdf.

Two of the three objectives for the 2010 work plan specifically acknowledge climate change (boldface emphasis added):

1. The first objective is to provide information that can help the MPO determine if planned transportation projects would improve infrastructure for emergency management functions and evacuation, serve critical infrastructure, **or include adaptation measures to protect against climate change impacts**. This information will be used for the security evaluation for projects proposed for the Transportation Improvement Program (TIP) and Regional Transportation Plan and **for future evaluations regarding projects' benefits in terms of climate change adaptation**.
2. The second objective is to provide planning information that can be used to protect transportation infrastructure from natural hazards and **climate change impacts**. The study will determine if planned or existing facilities lie in areas prone to flooding or hurricane storm surges, for example. This information could be used to plan adaptive measures to protect infrastructure from extreme weather impacts.
3. The third objective is to provide information for evacuation planners that can be used to plan alternate evacuation routes in the event that infrastructure fails or is impassible due to flooding or other extreme weather events, and to assess which areas might need to be evacuated in advance of a weather event, such as a hurricane. This mapping may be used to inform contract preparation for TIP projects so as to facilitate a convergence of construction planning with consideration of emergency preparedness needs at key evacuation locations or infrastructure.

RESEARCH NEEDS

The issues of climate adaptation are many. In these years when there still appears to be time for discussion and research, several topics should be considered for future research. These include the ways the transportation community can address the layers of organizational interdependencies (for example, how the many state and local governments facing fiscal constraints can incorporate adaptation into their overall planning processes, addressing inter-agency communications during emergencies, planning for operations, and infrastructure needs), the development and testing of new and emerging technologies to better monitor the impacts of climate change on the transportation network in real time, and new construction techniques and materials that are more durable and can better withstand climate change impacts.

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TRB Special Task Force on Climate Change and Energy Identifies Research Needs

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In spring of 2010, the TRB Special Task Force on Climate Change and Energy (A0020T) published a set of 40 research need statements on climate change and transportation. Universities, students, research organizations, government agencies, and other interested parties may wish to use these statements as part of their consideration for funding and conducting research on this important topic. Research needs related to climate change and transportation are available in several categories, including policy, energy and alternate fuels, planning and environment, design and construction, operations and maintenance, system users, aviation, freight, marine, rail, and public transportation.

A sample of the Research Need Statements developed for this effort is listed below. Research Need Statements specifically related to climate change adaptation are listed at the top.

- **Climate Change Adaptation**
  - Develop a collaborative decision-making framework for climate change mitigation and adaptation.
  - Explore adaptation as a defensive strategy to address climate variability impacts on critical transportation infrastructure.
  - Identify and develop climate change modeling outputs and climate scenarios to support transportation agencies in assessing climate risks and adaptation strategies.
  - Explore the effects of aspects of climate change on transportation infrastructure.
  - Identify and explore the implications of climate change for rail and barge freight demand, services, and networks.
- **Planning and Environment**
  - Develop a standardized process to incorporate climate change into the planning process.
- **Energy and Alternate Fuels**
  - Explore life-cycle analysis of alternative fuels for trains, planes, and ships.
- **Design and Construction**
  - Quantify and incorporate environmental benefits into life-cycle costing models for common roadway construction practices.
- **Operations and Maintenance**
  - Explore Induced Demand from Operational Efficiency and Its Impact on GHG Emissions: Part 1—Synthesis and Part 2: Analysis.
- **Aviation**
  - Develop Strategies for understanding and reducing the contribution of landside traffic to GHG emissions at airports
- **Freight, Marine, and Rail**

– Explore reducing GHG emissions from freight movements through comprehensive port and gateway planning.

The complete list of research needs statements is available online in *Transportation Research Circular E-C144* at http://onlinepubs.trb.org/onlinepubs/circulars/ec144.pdf.

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