Climate Change and Transportation Engineering: Preparing for a Sustainable Future

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Abstract: Climate change has been identified by many scientists, engineers, and public officials as one of the significant challenges facing society over the next several decades. And of civil engineered facilities, the transportation network is likely to be one of the systems most affected by changing climate, weather, and local environmental conditions. This paper examines the current practice of looking at transportation system adaptation to climate changes and develops a conceptual framework of the different components of transportation infrastructure that will be affected differently by a range of climate changes. An adaptive systems management approach is suggested as one approach for transportation engineers to anticipate likely climate changes, identify vulnerabilities in the transportation system, and assess different strategies for mitigating potential impacts. The result of this approach is a strategic perspective on what transportation agencies should do today and in the future to respond to changing environmental conditions. Developing an organizational strategy for dealing with the different elements of these changes is a critical component of this strategic perspective. **DOI: 10.1061/(ASCE)TE.1943-5436.0000108.** *© 2011 American Society of Civil Engineers.*

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Introduction

Climate change has received increasing attention worldwide as potentially one of the greatest challenges facing modern society. Although much of this attention has focused on how to reduce greenhouse gas (GHG) emissions entering the atmosphere (climate change mitigation), perhaps a more vital and uncertain issue for transportation engineers is how to prepare for a future world with changing climatic conditions (climate change adaptation). Most scientists believe that many climate-related changes will occur no matter the level of success in controlling GHG emissions simply because of the cumulative concentration of GHG gases that are already in the atmosphere, and the long-term effect of these gases in the climate system.

Climate changes could result in significant impacts on transportation facilities and systems. Sea-level rise threatens to inundate low-lying transportation facilities such as coastal highways, railways, and ports. Increased risk of flooding, however, may pose a more serious risk than sea-level rise. Climate change science suggests that the intensity of hurricanes, particularly the most powerful hurricanes, will increase in the future. This means stronger winds and higher storm surges on top of higher sea levels, which will put even more land and transportation facilities at risk.

Very high temperatures can cause concrete pavements to buckle and can soften asphalt roads, leading to rutting and subsidence. Higher winter temperatures will cause more precipitation to fall as rain rather than snow, which may increase drainage problems. The melting of permafrost in Arctic areas will create significant challenges to road maintenance and design (as is already happening in Alaska). Increased frequency of freeze/thaw cycles could significantly affect pavement designs.

Precipitation patterns and intensity could change dramatically, affecting the operation of transportation facilities and networks. Some regions may face increased precipitation and increased flooding. For example, climate models tend to project increased winter precipitation in the U.S. Midwest and Northeast, increasing the risk of early spring flooding as snow packs melt. In the summer months, precipitation intensity from convective thunderstorms is projected to increase in the future, thereby further increasing the risk of flooding.

In addition to directly affecting transportation infrastructure, changing climatic conditions can affect many of the ecological functions of lands surrounding transportation infrastructure and thus possibly influence existing environmental impact mitigation strategies (such as wetland habitat banks) that are commonly considered today by state transportation agencies as part of the project development process. Thus, future highway projects might face very different environmental mitigation requirements or goals than they do today.

This paper examines the different characteristics of expected climate/weather changes that could affect transportation infrastructure, with a focus on the highway network. Uncertainties, particularly with respect to the time frames associated with the impacts of climate changes and associated changes in extreme weather events (such as more heat waves or intense rain storms), lead to questions of whether and when it would be reasonable to modify planning, design, construction, maintenance, and operational practices. This paper identifies different approaches that have been used to account

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for such uncertainty. A strategic perspective is needed on how the transportation sector can best prepare for likely changes in environmental conditions over the next half century. The paper ends by discussing different approaches for adopting such a perspective.

Transportation Infrastructure: "Typical" Segment

Although different surface transportation modes will be served by different types of infrastructure, there are several components and design issues that are common to most (this includes roads and highways, rail lines, runways, and transit facilities). Fig. 1 will be used in this section to focus attention on those infrastructure components that will be critical in understanding potential impacts of climate change on infrastructure design. In addition, this figure becomes a point of departure for examining the underlying basis for the recommendations subsequently discussed in the paper.

Subsurface Conditions

The stability of a built structure depends on the soils on which it is built. Geotechnical engineers focus their attention on the properties of different soil types and their behavior given different design loadings [see, for example, Budhu (2000); Coduto (1999)]. The expected behavior of soils directly influences the design of foundations and support structures for the infrastructure itself. Various stresses act upon soil, including geostatic, horizontal, and shear stresses, as well as stress associated with the weight of structures built on the soil. The design of foundations for transportation facilities reflect the soil conditions, water table, dead weight of the structure, and forces that add to the dynamic loads being placed on the structure (Reese et al. 2006).

One of the important factors for subsurface design is the degree of saturation and expected soil behavior under saturated conditions. Changes in pore water pressure can have significant effects on the shear strength of soils; it is a change in soil shear strength that has caused many failures in ground slopes (e.g., mud slides). A good example of how subsurface conditions can affect design is the behavior of different soils under seismic forces and the resulting effects on built structures. The shifting or liquefaction of soils during a seismic event creates significant risks of unstable soil conditions and thus the destablization of structures built on top of the soils. Seismic codes have been enacted in many regions of the world, particularly focused on dealing with the changing characteristics of foundation conditions during such extreme events (National Research Council 2003).

Materials Specifications

Transportation structures are constructed of materials selected for their performance under design loads and environmental conditions. Much of the original research in transportation during the 1940s and 1950s focused on improving the ability of materials to withstand the loads associated with transportation use while still remaining resilient in response to changes in environmental conditions. Transportation research engineers continue to improve the physical properties of both asphalt and concrete pavements. Pavements, as a transportation facility component, affect facility performance at a considerably large spatial scale, and their performance can change dramatically given changing conditions, such as heavier vehicles, higher traffic volumes, more dramatic freeze/thaw cycles, or subgrade soil dynamics (e.g., saturation and erosion).

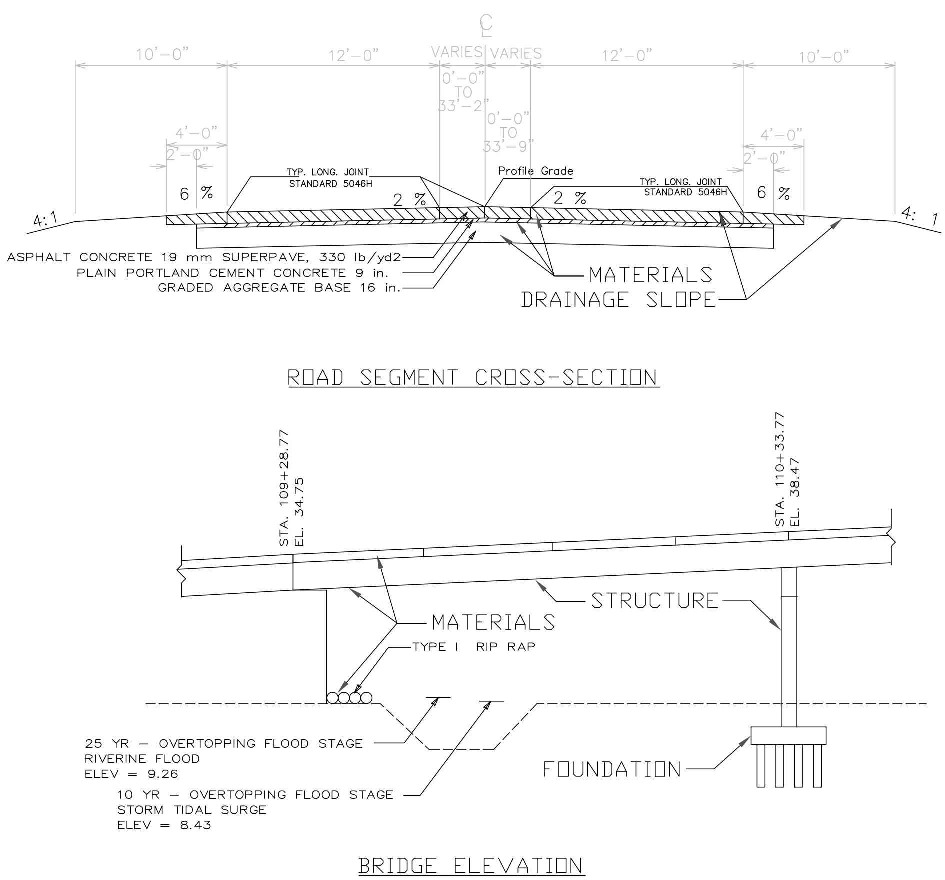

Fig. 1. Assets of a typical road segment

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Construction materials have a significant influence on the design and performance of bridges as well. Steel, concrete, or timber bridges must each handle the dead weight and dynamic loads they will be subject to, and thus the strength and resiliency of the bridge materials become of paramount concern to the bridge engineer. In addition to the changing conditions mentioned previously, the strength and protection of materials used in the design might have to be enhanced to account for expected wind loads, increased moisture or humidity (that could accelerate corrosion), and (for bridges located in coastal regions) more violent storm surges.

Cross Sections and Standard Dimensions

Given the complexity of designing a transportation facility, and of all the subcomponents that it consists of, engineers often identify typical sections that are applicable to much of a given design corridor. A typical cross section for the road shown in Fig. 1, for example, would show the depth of subgrade, pavement materials and thickness, width of lanes and shoulders, slopes of the paved surface, expected design of the area outside the paved surface, and other appurtenances that might be found in a uniform section of the road. As previously noted, the type of pavement and design of the subgrade would reflect the environmental conditions found along the alignment. The slope of paved surface would be determined not only by the physical forces from the vehicles using the facility (e.g. superelevation), but also by the need to remove water from the paved surface. In areas where one would expect substantial precipitation, the slope of pavement might be slightly higher to remove water to the side of the road as soon as possible. Cross sections would also be developed for areas where designs would be different from the typical section, such as locations for culverts, special drainage needs, bridges, and other structures that would be close to the side of the road.

The design of each of the key components of the cross section usually reflects design standards that have been adopted by the owner of the facility, such as a transportation agency. Thus, one can often find design manuals with standards for lane and shoulder widths, transverse slopes, radii for road curvature, dimensions of barriers, merge and exit areas, culverts, drainage grates, signing, and pavement markings. Most of these standards are developed on the basis of field or laboratory studies, many of which occurred decades earlier.

Design criteria are also associated with such things as the vertical clearance over waterways and other roads. For example, the U.S. Coast Guard establishes vertical clearance guidelines for bridges over waterways, with the vertical clearance dimensions depending on the type of navigation occurring on the river. One of the lessons learned from Hurricane Katrina was that the vertical clearance of many Gulf Coast bridges over water channels was too low; the storm surge that went over the bridge deck had floated the decks off of their supports. The bridges have been rebuilt with a higher clearance over the water surface along with improved fasteners to the bridge piers.

Drainage and Erosion

Water is one of the most challenging factors to design for in transportation engineering. As noted previously, saturated or near-saturated soils can be a critical consideration in the design of a facility's substructure and foundations. In addition, runoff from impermeable surfaces such as bridge decks or road surfaces must be handled in a way that redirects water flows away from the facility itself, but that does not harm the surrounding environment. Standard designs for drainage systems, open channels, pipes, and culverts reflect the expected runoff or water flow that will occur given assumed magnitudes of storms. Something as simple as the design of a culvert entrance would be affected by the assumed surge of water that would flow through it. For drainage considerations relating to highways, the AASHTO *Model Drainage Manual* (AASHTO 2004b) provides the most accepted guidance.

Structures

In the context of this paper, structures will primarily refer to bridges. Consistent with the previous discussion on how engineers account for different physical forces when developing a design, civil engineering has a long history of research and practical experience with understanding how such forces act upon buildings and bridges [see Ellingwood and Dusenberry (2005) for an overview of how building codes have evolved over time in response to new types and degrees of structural loading]. The engineering design process is exercised on the basis of understanding the likely loads or forces that will be applied to the structure (note the practice of assigning a factor that represents how important the bridge is) and developing a design that provides a level of resistance to these forces that will exceed expected loads. The current approach toward bridge design is to consider the inherent uncertainty in expected loads and resistance factors that a bridge will be exposed to, and thus probabilistic methods are used to incorporate such uncertainty. The primary focus of such an approach is to increase the reliability of the structure over its life span while considering the economic costs of failure. AASHTO's most recent bridge design manual, the *LFRD Bridge Design Specifications* (AASHTO 2004a) incorporates risk into the calculations of bridge design parameters, although the economic costs of failure are not totally considered.

Bridges over water present a special challenge to bridge engineers. According to the AASHTO manual (AASHTO 2004a), waterway crossings should be studied with respect to the following factors:

- Increases in floodwater surface elevations caused by the bridge;
- Changes in flood flow patterns and velocities in the channel and on the floodplain;
- Location of hydraulic controls affecting flow under the structure or long-term stream stability;
- Clearances between the floodwater elevations and low sections of the superstructure to allow passage of ice and debris;
- Need for protection of bridge foundations and stream channel bed and banks; and
- Evaluations of capital costs and flood hazards associated with the candidate bridge alternatives through risk assessment or risk analysis procedures.

As can be seen in this list, the assumed behavior of the water body below the bridge significantly affects how the design of the bridge proceeds.

The design of bridges in coastal areas has received renewed attention given the experience with Hurricane Katrina. According to a recent position paper of the Federal Highway Administration (FHWA) (Federal Highway Administration 2005), "in the coastal environment, design practice assumes that flood events would essentially behave in a manner similar to a riverine environment. However, bridge failure mechanisms associated with recent storm events have resulted in a reevaluation of these assumptions. The result is a need to differentiate how FHWA considers the state-of-practice to hydraulically design bridges in the coastal environment." As noted in the paper, the hurricane damage to the Gulf Coast bridges resulted primarily from the combination of storm surge and wave crests. However, most state DOTs assume a riverine environment when designing bridges, which assumes a 50-year storm event (this approach is codified in state drainage manuals, AASHTO drainage guidance, and in FHWA floodplain

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regulations). The result of this assumed frequency of storm is that designs do not consider the effect of wave actions on the bridge. In other words, according to their own regulations and design guidelines, state DOTs can consider a storm surge, but not additional wave actions. As noted by the FHWA, "state DOTs find themselves in the position that their own regulations and guidelines do not permit them to consider alternative bridge design frequency criteria." The FHWA recommended that a 100-year design frequency be used for interstates, major structures, and critical bridges that would consider a combination of wave and surge effects, as well as the likelihood of pressure scour during an overtopping event (water levels going over the structure). The consideration of a super flood frequency surge and wave action (that is, the 500-year design frequency) was also suggested. It was also recommended that risk and cost assessments be conducted.

Long-span bridges, especially over water, present a special challenge in two respects. First, very long bridges have to account for wind forces, which can be quite substantial in areas where the topography results in a "canyon effect," that is, high hills or cliffs that concentrate and thus make more powerful the winds striking the bridge. For suspension or cable-stayed bridges, these wind forces must be accounted for in the design strength of the support structure and in the level of deflection or flexibility designed into the bridge itself (Simiu and Scanlon 1996). For long-span bridges, engineers conduct wind tunnel tests of different sections of a proposed design to assess section behavior under varying wind conditions.

Second, columns or piers that are located in water are subject to scour, that is, the erosion of the river or stream bed near the column foundation. The majority of bridge failures in the United States are the result of scour (AASHTO 2004a) in that the flow of water currents at the column base can erode the stability of the column foundation. The FHWA requires that bridge owners evaluate bridges for potential scour associated with the 100-year event (known as the base flood) and to check scour effects for the 500-year event (known as the superflood). If floods or storm surges were expected to occur more frequently or channel flows were to become more turbulent, one would potentially have to rethink the design of such foundations (Sturm 2001).

Location Engineering (Where to Put the Facility to Begin with)

Technically, location engineering is not a generic characteristic of the road segment shown in Fig. 1. However, designs for new or relocated transportation facilities always include location studies to determine where to build the facility. Such efforts are often associated with much broader environmental impact analyses that examine a range of alternative alignments and design characteristics. Location studies themselves often do not have specific design criteria associated with where facilities will be located, although factors such as right-of-way width, roadway curve radii, and vertical slope limitations for different types of facilities will constrain designs to certain design footprints. In addition, as part of environmental analyses, a fatal flaw analysis often identifies areas or sites so environmentally sensitive that the designer will stay clear of these locations. The important question with respect to transportation facility location studies is how areas that might be susceptible to climate change effects, such as coastal or low-lying areas might be evaluated for suitability.

The previous description of the different components of a typical transportation facility design does not cover all of the different considerations that would enter into the design thought process of the engineer. However, it does illustrate the important influence of standards and guidelines in the design process. In addition, the discussion suggests some of the design categories where changes in environmental conditions, in particular those related to climate change, could affect how engineers design a transportation facility.

Designing in a Changing Environment

An ever increasing number of state and local officials have begun to examine how activities in their jurisdiction could be affected by changes in such environmental conditions. Examples include, but are not limited to Maryland (Maryland Commission on Climate Change 2008), Florida (Florida Governor's Action Team on Energy and Climate Change 2008), California's Climate Adaptation Strategy (CAS), as required by Executive Order S-13-08 (Nov. 14, 2008) (California Natural Resources Agency 2009), Alaska (Alaska Adaptation Advisory Group 2010), New Hampshire (New Hampshire Department of Environmental Resources 2009), and Berkeley (City of Berkeley 2009). In almost all of these efforts, the transportation system has been identified as one of the most important sectors that could face significant impacts of a changing climate. Very few studies, however, have examined the likely effects of climate change on the *design* of transportation facilities. From a regional perspective, three cities in the United States have been the subject of climate change studies: Boston, New York, and Seattle.

Tufts University conducted a study of climate changes on different parts of the Boston metropolitan area and concluded that transportation systems would be affected especially by flooding (Tufts University 2004). Another Boston study assessed the risks to transportation network performance from climate change-induced flooding by overlaying National Flood Insurance Program flood map projections with the transportation network and then using the regional travel demand model to estimate future lost trips and trip diversions attributable to both coastal and riverine flooding (Suarez et al. 2005). The assessment concluded that the estimated disruptions caused by climate change-induced flooding do not justify infrastructure adjustments or improvements, largely because of an adequate degree of redundancy in the transportation network. However, this assessment did not account for potential damage to or destruction of the transportation facilities.

Studies of New York City concluded that transportation systems in the New York metropolitan area would be significantly affected by floods and rising water tables, especially given that many of the critical facilities are in tunnels. (Jacob et al. 2000, 2001, 2007) The 2001 study, in particular, was one of the first to examine quantitative time-dependent hazards and risk assessment, especially with respect to sea-level impacts.

More recently, the New York City Panel on Climate Change has performed a risk assessment of major elements of New York area transportation (and other) infrastructure in changing climatic conditions. In their study "Climate Risk Information," the panel characterized the risk of climate change impacts in terms of generalized risk factors derived from the Intergovernmental Panel on Climate Change (IPCC) (New York City Panel on Climate Change 2009). These risk factors do not quantify the magnitude or consequences of impacts but rather prioritize the impacts through expert judgments of potential consequences and assign a likelihood of occurrence in accordance with IPCC probabilities (e.g., virtually certain: 99% probability of occurrence, extremely likely: 95% probability of occurrence). For example, higher average sea levels are found to be extremely likely, and a potential impact on transportation is "increased rates of coastal erosion and/or permanent inundation of low-lying areas." Although quantified infrastructure

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component impacts are lacking, the New York report provides quantified projections (with uncertainties) of regional environmental conditions in future decades, relative to an existing average baseline. Example projected conditions include number of days per year with maximum temperature exceeding 100°F, average reoccurrence of 100-year flood, and flood heights associated with 100-year flood. The flood projections were sourced from the U.S. Army Corps of Engineers' Metropolitan East Coast Assessment, which provides a spatial analysis of coastal flood areas. The flood height, location, severity, and location data, coupled with additional data on infrastructure conditions and costs, would enable a focused assessment of risks to discrete transportation infrastructure components.

The City of Seattle's auditor's office assessed the impact of climate change on Seattle's transportation system and concluded that the following components of this system were most vulnerable (Soo Hoo 2005):

- Bridges and culverts (increased mean annual rainfall, increased intensity of rainfall events, and sea-level rise);
- Causeways and coastal roads (sea-level rise and increased frequency and intensity of storm surges);
- Pavement surfaces (increased mean annual surface temperature);
- Surface drainage (increased intensity of rainfall events); and
- Hillside slope stability (increased mean annual rainfall and increased intensity of rainfall events).

Seattle's bridges were identified to be at greatest risk from thermal expansions caused by warmer temperatures, increased erosion at bridge foundations, and pavement deterioration attributable to increased levels of precipitation and rising sea levels.

Another study was conducted by Cambridge Systematics, Inc. (2006), which comprehensively examined the effect of climate changes and their impacts on the Gulf Coast's transportation system. With respect to the types of changes expected in environmental conditions, this study concluded that:

- By 2100, temperatures will be approaching those of current design standards; design changes should be developed now (for long-life infrastructure such as bridges) to ensure that facilities will be able to accommodate higher temperatures in the future;
- The impact of sea-level rise is significant for some, but not all, parts of the region. Highways in high risk areas should be redesigned to accommodate changes as part of a comprehensive urban redesign strategy;
- The most severe and pervasive impacts to highways will be the increase in the number of intense storms; the impacts from storm waves can be so severe that efforts to identify and protect the bridges should be a priority.

In a study of the impact of climate change on road and bridge maintenance practices, Smith (2006) concluded that "bridges and culverts seem most vulnerable to changing patterns of rainfall, storm intensity, runoff, stream sediment transport load, and sea level rise. These rigid structures have much longer lives than the average road surface and are much more costly to repair or replace. Road surfaces and railway tracks on the other hand are typically replaced every 20 years or so and can readily accommodate actual change in the local environment at the time of replacement."

Smith also reported on two studies by Transit New Zealand, that country's ministry of transport. In one of the most aggressive responses to potential effects of climate change on the design of transportation infrastructure, Transit New Zealand's bridge design specifications are now requiring risk analysis for increased flood flows and consideration of bridge retrofit for changing hydrology (Rossiter 2004). Transit New Zealand officials have also committed to monitor climate change data and to revise policies and standards accordingly. Another New Zealand study (Kinsella and McGuire 2005) examined climate change impacts on bridges and culverts. A first phase of the study concluded that currently applied design approaches might not protect bridges and culverts with a design life of more than 25 years from climate change impacts. A second phase identified methods for including probabilistic approaches to account for larger climate change-induced flows under major new bridges. The study also concluded that the retrofitting of existing or smaller bridges and culverts was deemed a practical choice for many of the prospective climate change impacts.

In the United States, Kirshen et al. (2002) studied the impact of long-term climate change on bridge scour by examining the possible effects of a 10 to 30% increase in the 100-year flood discharge. The study then recommended design strategies to account for increased scour at the column base.

One of the more closely studied impacts of climate change on infrastructure is the occurrence and effect of melting permafrost. The most significant melting of permafrost is expected (and has occurred) in Interior Alaska, where much of the noncontinuous permafrost that is susceptible to an increase in atmospheric temperatures exists (Meyer 2008). The implications for road and pipeline construction will be (and currently are) significant.

Another implication of melting permafrost is the change in river flows and the corresponding impact on bridge scour. Studies of streambed scour at bridge crossings in Alaska show that the major effect of climate change is mainly on rivers in glacial systems (Meyer 2008). Increased duration of peak flow flows from melting glaciers in summer months have resulted in increased scour at bridge crossings (Meyer 2008).

The Arctic Climate Impact Assessment effort has similarly focused on the issue of changing temperatures and this impact on permafrost. The most detrimental effects to transportation facilities were considered to be an increase in the number of freeze/thaw cycles, such as pavement cracking, rutting, formation of potholes, and formation of black ice on pavement surfaces (Instanes et al. 2005).

Increased Design Temperature Range

Temperature change affects the deformation and/or stress of every component of infrastructure design, because the materials will experience contraction and expansion in response to temperature changes. For structures, temperature fluctuations can be separated into two major components: a uniform change and a gradient (difference in temperature between the top of a structural member and the bottom). Both kinds of temperature effects produce a strain on bridge materials.

It is likely that changes in ambient temperature ranges or extremes will happen over a longer time frame than the average life of most affected transportation infrastructure components, except perhaps bridge structures. In the long-term, that is, from 40 to 100 years from now, ambient temperature range changes could have important effects on the procedures and materials used for infrastructure design.

Changnon et al. (1996) reported that highways and railroads were damaged because of heat-induced heaving and buckling of joints during the 1995 heat wave in Chicago. They also noted that a train wreck was linked to heat-induced movement of the rails. As noted in the Cambridge Systematics report (2006), the likely temperature change up to 2050 will not create a significant challenge to pavement design, but that the range in temperatures by 2100 would clearly make today's pavement design approach ineffective. One should expect, however, that research in materials properties and characteristics would provide solutions to pavement design in higher temperature conditions.

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Increased Precipitation

Changes in precipitation and water levels are another consequence of global climate change that will occur over a time span longer than the average lives of most infrastructure components built today. More moisture in the soil and the hydrostatic pressure buildup behind such structures as retaining walls and abutments might cause a rethinking of the types of materials used in construction and in dimensions such as slab thickness. The consolidation of saturated soils would also have to be considered in the context of pavement subgrades. Higher groundwater levels could affect the design of column foundations for bridges and other structures dependent on deep foundation support.

Increasing precipitation levels will have an important impact on drainage designs. The design water discharge that is currently assumed for culvert design and drainage systems might have to be changed, resulting in larger capacity systems to be put in place. Larger and faster velocity flows through culverts could also affect the design of culvert entrances and grates, which would be affected by the speed of the water flow entering the drainage.

Flooding because of extreme events such as stronger and more frequent storms could affect how overflow systems are designed, the design of water channels flowing underneath bridges, and the manner in which bridge foundations are protected from bridge scour.

Increased Wind Loads

Given an increasing frequency of more powerful storms, changing wind loads is a phenomenon that can affect engineering design in the short-term. Likely increases in storm intensities will most probably be accompanied by higher and more sustained wind speeds. Increasing wind speeds will certainly affect buildings and other structures built above ground, and will likely affect transportation signage and signal installations. Increased wind speeds could have an important effect on long-span bridges, and in particular, suspension and cable-stayed bridges. Design wind speeds are part of the engineering calculations used to identify different bridge designs and materials specifications. With increased wind speeds, bridge cable strengths may have to be increased, wind profiles may have to be streamlined, and wind tunnel protocols used to test such structures may have to be adjusted.

Storm Surges and Increased Wave Height

Wave forces on bridge piers, columns, and abutments are part of the design considerations for such components. Increased forces on these components because of higher and more forceful waves could result in changes in component dimensions and materials, reinforcing, foundations, or protective mechanisms.

Storm surges will be of great concern to engineers designing for coastal environments. Not only does the storm surge create forces on parts of transportation structures that were typically not designed for such forces, but it also may carry with it the debris of all the other structures that have been destroyed in its path. Surprising to many, but the most damage caused to the highway bridges during Hurricane Katrina was attributable to the buoyancy force on the bridge decks resulting from the storm surge and wave action. This force effectively lifted the decks off of their supports; the previous design assumed that the weight of the bridge deck would be sufficient to keep the deck in place. Storm surges thus create significant design challenges in the way bridges are designed, both in terms of the bridge superstructure and the foundations.

Table 1 shows the types of changes in climate that might have an effect on roadway design and some of the strategies that have been reported in the literature. New and innovative strategies will be added to this list as engineers identify new challenges associated with changing climatic conditions.

Adopting an Adaptive System Management Approach

Considering the broad and disparate impacts shown in Table 1, it seems likely that some components of transportation infrastructure systems will be more vulnerable than others to the risks associated with changing environmental conditions. Probable future loss because of an extreme weather- or climate-induced event (otherwise known as risk) is related to the expected level of hazard occurrence and the vulnerability of the infrastructure to damage. Given that hazard occurrence is likely to change over time (varying by type of climate-induced change; for example, higher levels of occurrence of sea-level rise versus wind changes), the level of risk is also likely to change over time. Given the uncertainty associated with the varying types of climate change-induced environmental conditions, one of the best strategies might be to develop an approach toward system management that monitors changing conditions and takes appropriate action when certain impact thresholds are reached.

Fig. 2 illustrates an adaptive systems management approach to managing transportation facilities that are potentially vulnerable to negative (and inherently uncertain) impacts of climate change. The approach is developed on the basis of the general concept of adaptive management, which has been formulated from the evolving philosophies and practices of environmental managers. Adaptive management is more than simply monitoring management outcomes and adjusting practices accordingly; it involves predicting future conditions and the outcomes of related management policies as well as testing alternative management practices designed to address new and uncertain conditions. An adaptive systems management approach to transportation infrastructure management provides a structured framework for characterizing future risks and developing new and evolving strategies to minimize system risk over time. Such a risk assessment approach is particularly vital for infrastructure systems and components that have long service lives (greater than 40 to 50 years); infrastructure designed for a shorter service life has inherent adaptation opportunities incorporated into the facility replacement schedule to account for significant changes in environmental conditions. Nonetheless, a process of identifying vulnerabilities and performance deterioration in changing environmental conditions will be required for infrastructure with short service lives so that appropriate adjustments in design, construction, operation, and maintenance practices can be effectively implemented over time.

Step 1: Identify Critical Transportation Assets

Changes in climate can affect many different components of a transportation system. Depending on the type of hazard or threat, the impact to the integrity and resiliency of the system will vary. Given limited resources and thus a constrained capacity to modify an entire network, the first step in the adaptive system management approach is to identify those assets that are critical to network performance or are important in achieving other objectives (e.g., economic development). The criteria for identifying such assets might include: (1) high volume flows, (2) linkage to important centers such as military bases or intermodal terminals, (3) function includes emergency response or evacuation routes, (4) condition (e.g., older assets might be more vulnerable than newer ones), and (5) an important role in the connectivity of the national or state

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Table 1. Illustrative Listing of Climate Impacts and Adaptation Strategies

Impact category	Adaptation strategies	References
Sea level rise: storm surges	• Protective designs • Relocation of facilities	Burton et al. 2006; Cambridge Systematics 2006; Easterling 2004; Luers and Moser 2006; Meyer 2008 National Committee on Coastal and Ocean Engineering 2004; New York City Panel on Climate Change 2009; Pew Center 2011; Transportation Research Board (TRB) 2008
Sea level rise: inundation of infrastructure	• Relocate assets • Develop redundancy in travel routes near the shoreline • Disinvest in infrastructure too costly to protect • Elevate or hardscape the most critical infrastructure • Expand drainage and pumping capacity	AASHTO 2009; Attwater and Witte 2008; Australian Greenhouse Office 2004; Burton et al. 2006; Center for Integrative Environmental Research 2007; Transit New Zealand 2004; Council of Australian Governments 2007; Dept. for Transport 2004; European Union 2006; Greater London Authority 2005; Highways Agency 2009; Meyer 2008; National Committee on Coastal and Ocean Engineering 2004; U.S. Climate Science Program 2006a; Cambridge Systematics 2006
Precipitation and sea level rise: increased incidence of flooding events	• Resite or flood-proof infrastructure • Greater protections and construction limitations for floodplains and coastal areas	Council of Australian Governments 2007; Local Government Association of Queensland 2007; New York City Panel on Climate Change 2009; Suarez et al. 2005
Precipitation: accelerated asset deterioration	• Conduct early vulnerability assessments • Incorporate increased ground subsidence in design of infrastructure • Accelerate replacement cycles • Shift to materials with greater resistance to moisture and hot/cold cycles • Incorporate design features such as increased pavement sloping to reduce precipitation-related effects (e.g., drainage)	Coduto 1999; Council of Australian Governments 2007; Easterling et al. 2004; Pew Center 2011; TRB 2008
Precipitation: water scarcity and loss of winter snowpack	• Shift to less water-intensive construction methods • Shift right-of-way plantings to drought-resistant species and designs that reduce runoff	Coduto 1999; Dept. for Transport 2004; Solomon et al. 2007
Precipitation: increased incidence of wildfires	• Vulnerability assessments incorporated into infrastructure location decisions • Use of fire-resistant construction materials and landscaping	Highways Agency 2009; Local Government Association of Queensland 2007; Luers and Moser 2006
Precipitation: shift in ranges of endangered species	• Keep abreast of ecological studies on a regional basis to detect observed shifts in habitat	Easterling et al. 2004
Temperature: arctic asset and foundation deterioration	• Install insulation or cooling systems in roadbeds to prevent thawing • Relocate facilities to more stable ground • Remove permafrost before construction for new facilities	Burton et al. 2006; Easterling et al. 2004; Meyer 2008; TRB 2008
Temperature: increase in the frequency and severity of heat events	• Plan for more frequent maintenance • Use of heat-resistant roadway materials • Greater use of expansion joints in roadways, bridges, and rail guideways	AASHTO 2009; Australian Greenhouse Office 2004; Dept. for Transport 2004; Center for Integrative Environmental Research 2007
Temperature: reduction in frequency of severe cold	• Capitalize through the extension of construction and maintenance season	Center for Integrative Environmental Research 2007; Highways Agency 2009; Pew Center 2011
More intense weather events: damage to assets	• Retrofit assets early for greater resistance to extreme weather • Incorporate storm-resistant features into future designs • Minimize water-impervious surfaces in designs and design infrastructure to slow runoff from heavy rain events	Burton et al. 2006; Greater London Authority 2005; Meyer 2008; U.S. Climate Science Program 2006b

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Table 1. (*Continued.*)

Impact category	Adaptation strategies	References
More intense weather events: increased frequency of road traffic disruption, including interruption of emergency routes	• Develop more stringent design and operations standards • Develop redundancy in travel routes near the shoreline • Elevate or hardscape the most critical infrastructure • Create transportation management centers, improve monitoring of conditions and real-time information made available to the public • Greater emphasis on emergency evacuation procedures, making them routine	Cambridge Systematics 2006; Center for Integrative Environmental Research 2007; Council of Australian Governments 2007; Dept. for Transport 2004; European Union 2006; Highways Agency 2009; Meyer 2008; TRB 2008
Climate change legislation: increased planning, construction, or operating costs	• Early adoption of energy-saving measures to minimize the impacts of rising energy costs	Greater London Authority 2005; Highways Agency 2009; Meyer 2008; TRB 2008
Organizational adjustments: replace outmoded procedures, acquire new competencies	• Conduct early reevaluation of procedures in advance of new requirements	Greater London Authority 2005; Highways Agency 2009; Meyer 2008; TRB 2008

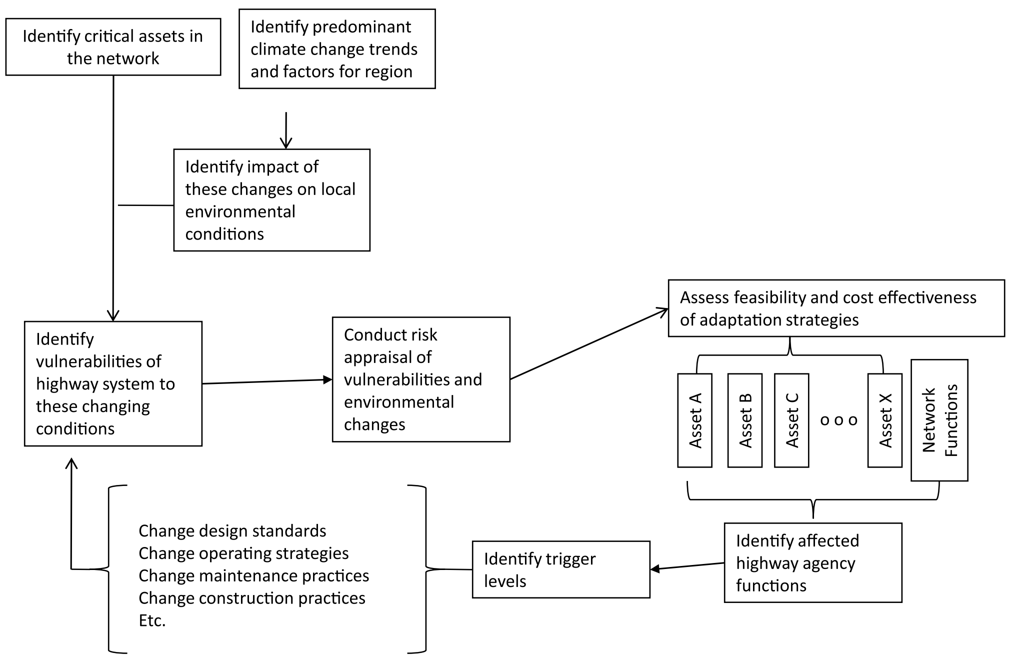

Fig. 2. Adaptive systems management approach

network. Given competition for limited resources, critical transportation assets should be ranked according to system performance priorities.

Step 2: Identify Climate Changes and Effect on Local Environmental Conditions

Climate change will result in a range of impacts in different parts of the world and throughout the United States. For example, coastal cities will likely face very different changes in environmental conditions than inland cities. This step identifies over the long-term those changes in climate and the corresponding changes in local environmental conditions that could affect transportation design and operation. To identify climate changes and the effects on local environmental conditions, transportation infrastructure managers will need to review updated regional and local climate modeling studies, or at the very least, deduce local impacts from national and global climate studies. At the local level, transportation agencies may perform a statistical analysis of historical variations and trends in weather event data, such as rainfall durations, intensities, and frequencies. Doing so may reveal that existing design guide standards, such as 24-hour rainfall intensities or rainfall intensity-duration-frequency curves, are inconsistent with recent trends. Historical weather data are widely available from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center and the Natural Resources Conservation Service's (NRCS) National Water and Climate Center, as are relevant stream flow data from the USGS National Water Information System. However, modeling of current and future environmental conditions will require improvements upon legacy products like the Federal Emergency Management Agency's flood mapping. An example of the type of modeling required may be found in

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the Maine Department of Transportation's effort to develop and calibrate rainfall/runoff models that incorporate historical increases in flood flows and sensitivity to potential climatic changes (Transportation Research Board 2010).

Step 3: Identify the Vulnerabilities of the Transportation System/Facilities to These Changing Conditions

This step matches the results of the previous two steps and assesses how vulnerable the critical assets are to likely changes in environmental conditions. This might entail, for example, examining potential flooding and the ability of drainage systems to handle greater flow demands or the likelihood of some segments of a facility being inundated with more frequent and severe storms. The vulnerability assessment might entail engineering analyses of the different elements of an asset and the likelihood of different asset elements failing because of environmental factors. The State of California has performed an assessment of its risk to coastal flooding, which includes an assessment of risks to its transportation infrastructure. The risk assessment utilizes flood mapping studies from the Scripps Institution of Oceanography and probability calculations of 100-year flood events. This statewide vulnerability assessment represents only a partial example of the level of total assessment needed—all climate change impacts need to be considered comprehensively and assessment should be detailed for particular types of infrastructure components. California's coastal flooding study identifies the miles of roadways affected by estimated flood events, but it does not quantify the costs associated with flood damage. A logical next step for this or any vulnerability assessment is to fully quantify the risk to infrastructure so that engineering decisions are adequately informed.

Step 4: Conduct Risk Appraisal

Risk appraisal is the process of determining the degree to which assets are likely to be vulnerable given the likelihood of climate change and the uncertainty associated with such change. England's Highways Agency (2009), for example, developed a risk appraisal process on the basis of the following four elements:

> Uncertainty—compound measure of current uncertainty in climate change predictions and the effects of climate change on the asset/activity.
>
> Rate of climate change—measure of the time horizon within which any currently predicted climate changes are likely to become material, relative to the expected life/time horizon of the asset or activity.
>
> Extent of disruption—measure taking account of the number of locations across the network where this asset or activity occurs and/or the number of users affected if an associated climate-related event occurs. Therefore, an activity could be important whether it affects a high proportion of the network or a small number of highly strategic points on the network.
>
> Severity of disruption—measure of the recovery time in the event of a climate-related event e.g., flood, or landslip. This is separate from 'how bad' the actual event is when it occurs e.g., how many running lanes you lose; it focuses on how easy/difficult it is to recover from the event i.e., how long it takes to get those running lanes back into use.

In England's Highways Agency risk appraisal framework, these elements are scored separately by assigning a "High/Medium/Low" rating and are used to identify and prioritize lists of vulnerabilities according to the following criteria (Highways Agency 2009):

- "Time-criticality" (function of the rate of climate change);
- "High extent" (function of the extent of disruption);
- "High disruption duration" (function of severity of disruption);
- "Potential research need" (function of uncertainty level and the effects of climate change on asset/activity); and
- "Highly disruptive, time-critical with high confidence" (function of rate of climate change, extent of disruption, severity of disruption, and uncertainty).

Each of these prioritization criteria identify needs for action, with the understanding that there is more than one reason why a vulnerability should be acted on (Highways Agency 2009). The last of the aforementioned criteria identifies the asset/activity vulnerabilities that warrant action for multiple reasons.

Step 5: Assess Feasibility and Cost Effectiveness of Strategies

Identifying and assessing appropriate strategies for the challenges facing critical infrastructure assets is a core component of the process shown in Fig. 2. Such strategies might include modifying operations and maintenance practices (such as reducing train speeds or conducting more frequent track inspections on high temperature days that pose a risk of rail heat kinks), designing extra redundancy into a project, providing above-normal reserve capacity, incorporating a greater sensitivity to the protection of critical elements of the project design (such as better protection against bridge scour or high winds), or designing with different design standards that reflect changing conditions (such as higher bridge clearances for storm surges). In particular, with respect to design standards, a more robust approach could be adopted that takes into account risk and uncertainty.

In many ways, considering climate-induced changes in the design process follows a model that has been applied in earthquake engineering. Building codes and design standards have been changed to reflect the forces that will be applied to a structure during a seismic event. Substantial research on the response of materials, soils, and structures themselves has led to a better understanding of the factors that can be incorporated into engineering design to account for such extreme events. Similarly, other design contexts reflect forces that might be applied during collisions, fires, or heavy snows. The logical approach for considering the best design for climate-induced changes is to examine the relationship among the many different design contexts that a structure might be facing and determine which one "controls" the ultimate design.

This stage in the adaptive systems management approach also involves identifying which agency functions will be affected the most by changes in infrastructure management practices. Furthermore, it is reasonable to expect that the new challenges imposed upon transportation infrastructure managers by climate change will require new adaptive efforts that are dependent upon interagency cooperation. For example, an analysis of the impact of riverine flooding on transportation and other infrastructures may determine that the most cost-effective adaptation will involve a combination of bridge design adjustments and river channel widening, thus necessitating coordination between the local department of transportation and the U.S. Army Corps of Engineers.

Step 6: Identify Trigger Levels

Many of the changes in climate considered as part of this assessment will likely not occur for decades, and it is also likely that the full extent of the estimated impacts of such changes on transportation facilities or systems may not occur until even further into the future. This step in the adaptive systems management process establishes trigger mechanisms that serve as an "early warning system" for agency officials to examine alternative ways

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of designing, constructing, operating, and maintaining transportation infrastructure in light of higher likelihoods of changed environmental conditions. For example, precipitation levels might not change significantly enough over the expected life of drainage structures to change culvert designs today, but at some point in the future higher levels of precipitation would "trigger" a new culvert design because the new precipitation levels have now become the norm. The adaptive systems management approach to transportation infrastructure management is foremost an iterative process. Realization of the intended benefits of this approach (minimization of risk and development of cost-effective adaptation strategies) requires that the latest available information on changing environmental conditions and system performance priorities are incorporated into the process.

Conclusions

Most climate scientists agree that climate change is a near certainty. However, the degree of climate change impacts is very much uncertain, particularly over the long time scales that major transportation infrastructures are planned for. By starting early, and by integrating the strategies and actions needed to address anticipated effects of climate change as part of an ongoing process of adaptive system management, transportation engineers and the communities that they serve can be prepared for these impacts. Uncertainty regarding the performance of complex and vast transportation systems threatened by climate change will characterize the infrastructure design, construction, maintenance, and operation decisions facing today's and tomorrow's transportation engineers. Failure to deal effectively with this uncertainty could result in far more costly approaches of delayed and short-term "crash programs", or even worse, the need to rebuild long-life facilities that suffer sudden and potentially catastrophic damage as a result of climate-related occurrences.

This paper has reviewed the current thinking on climate change and transportation system adaptation. Very limited attention has been given to this topic in the United States, whereas other countries, most notably Australia, The Netherlands, New Zealand, and the United Kingdom, have undertaken fairly extensive studies to prepare their transportation organizations for likely climate changes. Although many of the changes in climate are not likely to occur in any significant way for several decades, others are already occurring (e.g., melting of the permafrost). The adaptive system management approach outlined in this paper is an effort to assess systematically the vulnerabilities of the transportation system to likely climate changes. The result of this approach is a strategic perspective on what transportation agencies should do today and, more likely, in the future to respond to changing environmental conditions. Developing an organizational strategy for dealing with the different elements of these changes is a critical component of this strategic perspective.

Ultimately, as stewards of the transportation investment that has occurred over generations, transportation engineers must be prepared to deal with threats or challenges that could reduce the effectiveness of this investment. When taking a long-term perspective, it is not likely that one will find a more serious challenge than that relating to a changing climate.

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