Design Standards for U.S. Transportation Infrastructure
The Implications of Climate Change

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This paper examines the changes to engineering design practice that might occur given climate-induced changes in environmental factors. A project design is separated into the individual components that might be affected by changing environmental conditions: subsurface conditions, materials specifications, cross sections and standard dimensions, drainage and erosion, structures and location engineering. A typical engineering design process including the use of design standards is described. The origin and use of design standards and guidance is presented with an assessment of how robust and flexible they are to incorporating climate-induced changes.

Climate change-induced design factors include temperature change, precipitation and water levels, wind loads, and storm surges and wave heights. Both the short- and long-term implications of these changing environmental factors are examined.

The paper concludes that there is a need for a broader systems perspective in looking at network-oriented infrastructure design to determine what design factors, if any, should be included to reflect network interdependencies. Risk-oriented, probabilistic design procedures should be used when defining design characteristics of components that could be affected by changing environmental factors. The design standard and guidance approach to current practice should be assessed to see how such procedures could be enhanced or further introduced into standard practice. The design considerations relating to the presence of water and the additional forces applied to engineering structures due to wave actions and storm surges appear to be the most pressing in the shorter term. In the longer term, temperature changes, increasing range of temperatures during a typical year and wind loads become important additional considerations. Non-design standard strategies for considering risk-oriented designs should be examined closely in a broader assessment of how to respond to climate change. The linkage between infrastructure provision and land use development patterns needs to be considered very carefully because of the development-inducing influence of infrastructure provision (and thus the corresponding multiplier of hazardous conditions to human population in the case of an extreme event). One of the most productive avenues of research might be the application of “smart” technologies to infrastructure to provide flexible responses to changing environmental conditions. There is clearly a need for research on the potential impacts of climate change on infrastructure design. This is a serious gap and a missing step for gaining agreement from the professional community that the issue deserves attention.

INTRODUCTION

The built environment is largely the product of the design standards and accepted practice adopted by engineering professions to guide how buildings and infrastructure are designed and constructed. Design standards provide uniform applications of the best engineering knowledge that has been developed over time through experimental studies and actual experience. Importantly, this design knowledge is based on an understanding of the underlying physical forces acting upon an engineered structure[1] and, in essence, compensates (or, in some cases, uses) these forces to assure a structure will not collapse. Examples of such forces for a civil engineered structure include the fixed loads that result from the weight of the materials used in the design and the dynamic loads associated with the movement of the structure due to external forces or to the use of the structure, for example, vehicles moving across a bridge. Other forces or loads acting upon civil engineered structures relate to such things as seismic events, winds, buoyancy, hydrostatic pressures, wave loads, and a change in material properties due to differences in pressure or temperature. Engineering design standards and professional practice are established to account for such forces.

Fundamental to the application of engineering design standards is an understanding of how environmental factors will affect both the behavior of the overall structure itself as well as of the individual material components of the design. Thus, for example, in road engineering, the freeze-thaw cycle for pavement materials in areas where temperatures can range widely over the year becomes an important consideration in the types of materials used and the design specifications for road pavements (and why states in winter regions often have a much greater challenge with pavement conditions than states in more temperate zones). Another example would be long span bridges, especially those designed with cables or other means of suspending the road deck, that face strong wind loads (in especially long bridges, wind loads can cause up to 10 meters of lateral movement in the bridge deck). It is a basic tenet of civil engineering that the design of structures cannot be divorced from the environment within which they are built. The risks of doing otherwise could be catastrophic.

This tenet of civil engineering leads to a challenging question of how such practice might vary given changes in this environment, such as those expected due to climate change. One has to look no further than the Gulf Coast experience with hurricanes in 2005 and the resulting damage to the built environment to know that environmental factors much more extreme than was assumed in the original design can have devastating effects. Over the longer term, more gradual changes in such things as temperatures, temperature ranges, level of precipitation, coastal water levels, storm surges, and wind speeds can create new risks with regard to the design of civil structures. Thus, civil engineers should be concerned about how transportation designs can withstand the physical forces resulting from so-called extreme events (although in most cases civil engineered facilities are designed to withstand either the most extreme or close to the most extreme event that will add abnormal stresses on a structure, for example, designing for the 100-year storm). In addition, however, they need to be thinking about how changing environmental conditions over a longer timeframe could affect how engineering design should occur, and in particular, whether current design standards and principles are adequate for infrastructure that could potentially last 100 years.

The purpose of this paper as defined by the organizing committee was to "provide a broad conceptual framework for the possible role and objectives of standards and guidelines for the planning, design and construction of the transportation infrastructure under the assumption that climate change is occurring and will impact U.S. transportation." Addressing this charge in the limited space available in this paper is, to put it mildly, daunting. Several aspects of this

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[1] For purposes of this paper, the term "structure" and "infrastructure" will be used interchangeably in a generic way to represent the facility or infrastructure being designed for. Technically, "structure" in civil engineering refers to such things as buildings and bridges, but would not be used, for example, in describing a road.

charge, in particular, provide challenges for a comprehensive discussion on the many facets that should be considered in how design standards and guidelines might change given climate change. These aspects lead to the following assumptions that serve as a point of departure for this paper.

First, "U.S. transportation" includes many different modes, thus different designs and thus different design standards. How one designs an oil pipeline, for example, is very different than how one would design an interstate highway. The approach adopted in this paper is to use a typical road segment, including both a surface road and a bridge, to represent the key elements of any type of design challenge for surface transportation. Considering such factors as drainage, materials properties, wind loads, changes in temperatures, and water pressures on such a road segment would likely raise similar concerns given environmental changes for all types of transportation infrastructure. The introduction of this "typical segment" is presented in the following section.

Second, design standards have been defined and adopted primarily to account for the risks associated with design failure, or more accurately, to avoid such failure. Uncertainty in environmental conditions and in the likely response of materials and system properties have led designers of different transportation facilities to adopt standards very specifically oriented to the design context being faced. Section 3 of this paper thus discusses the underlying principles and approaches adopted by engineering professional organizations that serve as the basis for design standards and guidance. This institutional context for the development and application of design standards is important to understand, especially if there is a need or desire to change such standards.

Third, different climatic changes will have varying effects on how civil engineered structures will respond. In other words, dramatic changes in temperatures and in temperature ranges will lead to one set of conclusions on what types of changes might be needed in design approaches versus say changes in the frequency and magnitude of storm surges. Section 4 of this paper lays out a typology of climate change-induced environmental factors that might have important influence on how engineers design future transportation infrastructure.

Finally, although this paper focuses on design standards and guidance, there might be other ways of assuring the viability of transportation infrastructure in the face of changing environmental conditions other than through the design process. For example, some of the environmentally-induced additional forces on infrastructure might be avoided if facilities were not built in locations that were susceptible to such forces, such as might occur in coastal or low-lying areas. This might suggest more emphasis on land use policies than on changing design standards. Similarly, one could envision technology applications (for example, the use of "smart" materials) or changes in insurance strategies that could result in reducing the risk associated with changing climatic conditions. Section 5 discusses these "other than engineering design" strategies.

One final caveat on the material presented in this paper needs to be noted. Although the paper assumes that climate change is occurring, some of this change is likely to occur gradually (at least by engineering timelines), whereas others might already be upon us (such as the increasing frequency of violent storms). Transportation infrastructures have different design lives, that is, they are expected to last under normal loads for a specific number of years. Pavements, for example, depending on the type of materials, vehicle loads, and environmental factors can last anywhere from 10 to 20 years before being replaced. Bridges can have useful lives of 100 years or longer if designed with such a long time frame in mind. Thus, there might be a different level of professional concern for changing design and maintenance approaches to elements of transportation infrastructure that have a fairly short time frame than there is for something that will last a long time. We need to be thinking today of the potential impacts of climate change on infrastructure that will be still serving society 100 years in the future.

In addition, and perhaps more important for the broader discussion, the provision of transportation infrastructure is fundamental to the way we live and how our communities develop. If transportation infrastructure is provided to areas currently underserved or where demand for development is high, it will act as a catalyst for promoting land development in these areas. Thus, in the bigger picture, the effect of climate change on how we design transportation infrastructure also needs to address in a serious way the decisions of where we put this infrastructure in the first place.

TRANSPORTATION INFRASTRUCTURE: A "TYPICAL" SEGMENT

In order to discuss the different components of transportation infrastructure and how design standards are applied, it is first important to describe what transportation infrastructure consists of. As noted earlier, different surface transportation modes will be served by different types of infrastructure. However, there are several components and design issues that are common to most of this infrastructure (this includes roads and highways, rail lines, runways, and transit facilities). Figure 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 design standards. In addition, this figure becomes a point of departure for examining the underlying basis for the respective design approach and the standards that are applied in the design of each component.

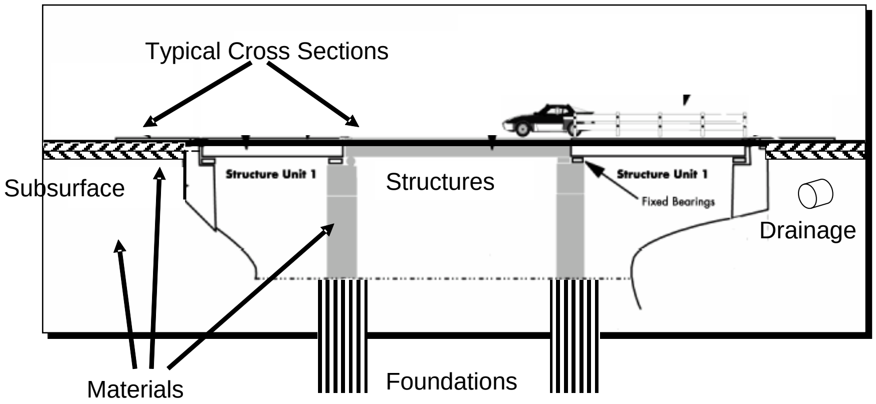

FIGURE 1 Critical components of infrastructure design.

Figure 1 suggests that there are several components of infrastructure design that will be common to most transportation infrastructure, and as will be seen later, can be affected significantly by changing environmental conditions. These key components include the following.

Subsurface Conditions

The stability of a built structure depends upon the soils upon 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 influences directly the design of foundations and support structures for the infrastructure itself. Different stresses act upon soil, ranging from geostatic stresses, 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, in particular, reflect the soil conditions, water table, dead weight of the structure itself, and forces that add to the dynamic loads being placed on the structure [Reese, Isenhower and Wang, 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, and in fact, is it the change in 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, causing structures built on top of the soils to sink. Seismic codes have been enacted in many regions of the world focused in particular on dealing with the changing dynamics of foundation conditions during such extreme events [National Research Council 2003].

Materials Specifications

Transportation structures are constructed of materials, all of which have their own set of properties with respect to how they behave under different environmental conditions and loads. In fact, much of the original research in transportation during the 1940's and 1950's 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. The best example of this for surface transportation has been the significant levels of research worldwide to improve the physical properties of both asphalt and concrete pavements. Pavements are the most visible component of a transportation facility whose condition can change dramatically given changing conditions, such as heavier vehicles, higher traffic volumes, more dramatic freeze-thaw cycles, and disruption of the subgrade foundation under the pavement due to moisture or some dynamic force acting upon it,

Bridge designs are also heavily influenced by the types of materials that will be used in construction. 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 above, the strength and protection of materials used in the design might have to be enhanced to account for expected wind loads on the superstructure itself, increased moisture or humidity (that could accelerate corrosion), and more violent storm surges if the bridge is located in a coastal region.

Transportation agencies have a long history of testing and developing specifications of the types of materials that can be used in the construction of transportation facilities. The American Society for Testing and Materials (ASTM) is often the definitive authority on the testing procedures for different materials. The Federal Highway Administration (FHWA) has tested materials for many years to determine the most cost effective strategy for the construction of transportation facilities. And almost every state department of transportation (SDOT) has a research and materials division or bureau that constantly examines the properties of materials under experimental and field conditions, and makes changes in contract specifications if needed. It is often very difficult to change materials specifications until significant testing of the properties of the new material is conducted, usually on a multi-state basis.

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 commonly found along major sections of the alignment. A typical transverse cross section for the road shown in Figure 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 noted above, 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 on the vehicles using the facility, 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 based on field or laboratory studies, many of which occurred decades earlier. However, they still represent the design approach that is expected to meet the functional requirements of the structure in the safest and most cost effective way. As will be discussed later, these design manuals and standards often become evidence in court cases where engineers are questioned as to whether a particular design conformed to accepted engineering practice, that is, was the design based on adopted design standards?

Although not the same as a cross section, 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 simply floated the decks off of their supports. The bridges are now being rebuilt with a higher clearance over the water surface. For bridges not over water bodies, the AASHTO *LFRD*[2] *Bridge Design Specifications* [2004a] states that the vertical clearance should be in conformance with the AASHTO *A Policy on Geometric Design of Highways and Streets* [2004b], for those agencies that have adopted this guidance manual for road design.

Drainage and Erosion

Water is one of the most challenging factors to design for in transportation engineering. As noted above, 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 which 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* [2004c] provides the most accepted guidance.

Structure

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 changed over time in response to abnormal loads being placed on a structure). 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 reflect such uncertainty. The primary focus of such an approach is to increase the reliability of the structure over its lifespan while considering the economic costs of failure. AASHTO's most recent bridge design manual, the *LFRD Bridge Design Specifications* [2004a] incorporates risk into the calculations of bridge design parameters, although the economic costs of failure are not totally considered.

The basic approach in the LFRD specifications is to prevent the structure from reaching a "limit state," which is defined as the condition beyond which a bridge system or bridge component ceases to fulfill the function for which it was designed. [AASHTO 2004a; Barker 1997] Examples of limit states include deflection, cracking, fatigue, flexure, shear, torsion, buckling, settlement, bearing, and sliding. Mathematically, the relationship between designed resistances and expected loads is represented as:

$$\sum \eta_i \gamma_i Q_i \leq \Phi R_n$$

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[2] LFRD stands for Load and Resistance Factor Design

$\sum$	summation of the following factors
η_i	is a load modifier relating to ductility, redundancy and operational importance of the bridge
γ_i	is a load factor, statistically-based multiplier applied to force effects
Q_i	is the force effects for force i
R_n	nominal resistance
Φ	resistance factor a statistically-based multiplier applied to nominal resistance

This equation illustrates how uncertainty can be incorporated into design procedures, primarily in this case through the γ_i and Φ parameters. The engineering design process is thus based on understanding the likely loads or forces that will be applied to the structure (note the ability 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.

Bridges over water present a special challenge to bridge engineers. According to AASHTO's *LFRD Bridge Design Specifications*, waterway crossings should be studied with respect to the following factors:

- Increases in flood water 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 through the structure or long-term stream stability
- Clearances between the flood water 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
- Evaluations of capital costs and flood hazards associated with the candidate bridge alternatives through risk assurance 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) [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 DOT's 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 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 interstate, major structures and critical bridges that would consider a combination of wave and surge effects, as well as the likelihood of pressure scour (see below) 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 crossing 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 "forgiveness" 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 Figure 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 interesting question with respect to location studies is whether areas that might be susceptible to climate change effects such as coastal or low-lying areas might be considered as part of the criteria for where new transportation facilities should be avoided.

An interesting observation for infrastructure siting is the use of flood insurance maps. In many ways, these maps, created primarily to determine flood zone areas for individual buildings and residences (and thus the need for flood insurance if financing is being used to purchase or rebuild a structure) have become a quasi design standard, even though they were never intended for this purpose. Transportation facility designers use them to determine drainage and facility design parameters that are appropriate for the 100-year or 500-year flood zone, although the creation of the flood zone mapping is not done with infrastructure design in mind. There needs to be a more formal incorporation of flood zone mapping into the infrastructure design process.

The above 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. Before examining this potential effect, however, it is important to examine first the basis for design guidance---why are design standards used? and where do they come from?

DESIGN STANDARDS AND GUIDANCE: THE BIGGER PICTURE

Engineering design, in many ways, involves trade-offs. One will often find safety as the most important stated goal of an engineering design process. However, many other factors must be considered as well, many of which have cost implications associated with them. For example, AASHTO's *LRFD Bridge Design Specifications* states that "bridges shall be designed for specified limit states to achieve the objectives of constructability, safety, and serviceability, with due regard to issues of inspectability, economy and aesthetics." Achieving each of these objectives might require different approaches in the use of materials and in the how the subsurface and superstructure is designed. Such trade-offs often occur within a project budget constraint that limits the amount of flexibility that engineers have to achieve all of the objectives.

Given the importance of design standards and guidance to the engineering process, the following sections describe design standards come from and how they are used for both public and private sector infrastructure. In particular, this section discusses the issue of how robust design standards are in the context of significant environmental change.

Project Development Decision Making Context

All engineering projects proceed through a project development process in which the project design evolves from initial concept to the final preconstruction stage of developing plans, specifications and estimates (PSE's). In the context of major transportation projects, the project development process can also include environmental studies and assessments of likely project impacts on the natural and man-made environment. Environmental analyses that are part of the project development process usually entail an initial level of engineering design (referred to as the 25 or 30 percent engineering design) that provides a sufficient level of understanding of the projected alignment of the facility that engineers and planners can identify likely impacts. If the project proceeds after the environmental study, final engineering (or 100 percent engineering design) occurs on the preferred alternative.

As one could imagine, the application of design standards in the initial conceptual engineering phase can have significant impacts on later decisions and determinations of environmental impacts. For example, maximum allowable radii for road curves might very well cause road alignments to go through environmentally or community sensitive areas. Maximum allowable vertical road grades likewise could require the excavation of large amounts of material that must be disposed of or used elsewhere. Minimum vertical clearance of a bridge over a water surface might result in a bridge design that the surrounding community finds visually intrusive.

The typical approach for applying design standards and guidance is for the owner of the project, which could be either a government agency or a private entity, to specify the design guidelines and standards that will be used during the design process. In addition, the owner identifies the specifications for the materials that will be used in construction. Many transportation agencies have developed their own design manual that covers a wide range of design-related topics. Other transportation agencies adopt national guidelines as their own. For example, AASHTO's *A Policy on Geometric Design of Highways and Streets* [2004b] is often adopted by many states as the design guidance that will be followed for their projects.

Another important consideration in the application of design standards is the source of funding. For example, federally-funded road projects often have to satisfy federal guidance on what standards will be applied, e.g., 12 foot lanes and 10 foot shoulders on new interstate highways. Or has been mentioned previously, federal guidance can also influence the design for such special circumstances as bridge clearances over navigable waterways.

Although design standards are established to provide engineers with guidance on project characteristics that are considered by the professional community to be safe and defensible, clearly not all project contexts will be amenable to a blanket application of such standards. Especially in urban areas, where community structure often precludes the uniform application of infrastructure design standards, engineers sometimes consider exceptions to the adopted design standards. Design exceptions are used (sparingly) in those situations where the project context does not allow the application of the adopted design standards. So, for example, a design exception might be used for 12 foot lanes on urban interstates if having 12 foot lanes requires extraordinary expenditures for right-of-way acquisition or causes significant levels of disruption to the surrounding community.

One of the most significant changes in recent years in highway design has been the introduction of what is called context sensitive design (CSD) or context sensitive solutions (CSS) [see http://www.fhwa.dot.gov/csd/index.cfm for a national overview of current practice in CSD/CSS]. In this approach, the road engineer works collaboratively with the community to both satisfy the functional needs of the project while also attempting to incorporate into the project design characteristics that are more in-tune with the surrounding community context. Such projects often result in the application of design criteria and materials specifications that are not standard practice in that state. In Massachusetts, for example, the state highway agency has recently updated its highway design manual based on CSD principles, resulting in a very different engineering design philosophy than was present in previous versions. As noted in the new design guide, "an important concept in planning and design is that every project is unique. Whether the project is a modest safety improvement, or a ten mile upgrade of an arterial street, there are no generic solutions. Each project requires designers to address the needed roadway improvements while safely integrating the design into the surrounding natural and built environment."[Mass Highways 2005]

Private owners approach project development in a slightly different manner, especially for buildings.[3] For those transportation projects that are privately owned and funded, such as rail tracks and pipelines, firms have adopted their own guidelines on what historically has been needed for a safe and cost effective design of a facility. For example, typical cross sections of track and pipeline designs are used that represent accepted practice in that industry. If the company is large, it usually has an in-house staff that develops the design based on its proven

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[3] For buildings, developers and owners are subject to building codes that are often performance-based, which means that the structure must meet certain condition and performance requirements.

design guidelines. Otherwise, the company hires design firms to prepare a facility design. In this case, the desired performance of the structure is specified in the contract with the firm and the ultimate design reflects the most economical combination of design characteristics that still provide the desired function of the facility.

Of interest to this paper is the issue of performance – cost tradeoffs that are inherent in project design. In other words, engineering design standards usually reflect the characteristics of safe design that incorporate a contingency factor to allow for unexpected design loads or pressures. This "extra" design has costs associated with it in that it usually means more material or often more expensive and stronger materials of construction will be used. The desired performance of a facility or of the component parts/materials is usually specified upfront in the construction bid documents, and it is then up to the bidder to determine how best to satisfy these performance conditions, subject to owner acceptance of the materials of construction that will be used. Another approach that emphasizes the performance – cost tradeoff is "value engineering." Value engineering has evolved over the past two decades as a way for engineers to examine a project design to see of the desired performance can be achieved through less costly means. What this means to a change in design standards that reflects a more robust design in light of potential climate-inducing environmental conditions is that the engineering community will want to see the cost implications of any such change and the corresponding change in performance. More will be said about this later in the paper when a risk-oriented design process is introduced.

Institutional Structure for Establishing and Modifying Standards

Because design standards are so important to engineering, a great deal of effort is put into their development and, in particular, into justifying any change to current ones. In most cases, design standards are based on experimental tests and practical experience that lead to an acceptance by the professional community that the standards do indeed represent safe practice. Major disagreements can occur when changes are proposed to existing standards because of differences of opinion over the impact of the proposed changes. In most cases, design standards and changes thereto are based on lengthy testing of the design application being investigated.

Figure 2, for example, shows the process that was used to introduce new pavement specifications into pavement design. Called Superpave, the program resulted from a large-scale research effort in the 1990s to identify innovative pavement specifications that would produce stronger, longer-lasting and more cost effective pavement applications. As noted in a Transportation Research Board report summarizing the implementation of the Superpave program, "the test methods, engineering practices, and standard specifications together comprise the Superpave system for selecting materials and designing pavement mixtures to meet specific climate and traffic conditions." [TRB 2005] Figure 2 shows the timeline that was followed in introducing the new specifications into practice. As shown, the initial decision to implement the research findings occurred in the early 1990s, and through a national testing program and several national conferences to disseminate the results of this testing, new specifications were finally adopted in 2005. Testing on the long-lasting effects of Superpave road sections is still on-going.

The implication of Figure 2 is that changing design standards and materials specifications is often a time-consuming and consensus-seeking process. Numerous professional organizations provide the testing and justification for design standards, depending on what infrastructure component one is talking about. For example, the following organizations are examples of groups that are professionally recognized as being sources of information for design guidance in transportation:

- American Association of State Highway and Transportation Officials
- American Concrete Institute
- American National Standards Institute
- American Society for Testing and Materials
- American Society of Civil Engineers
- American Institute of Steel Construction
- Federal Highway Administration
- National Fire Protection Association
- Transportation Research Board (although it does not issue design standards)
- U.S. Army Corps of Engineers
- U.S. Coast Guard

1991	AASHTO task force on implementation formed and round-robin testing began
1992	Superpave pooled fund test equipment purchase
1993	FHWA Superpave prototype equipment delivered
1993	Oversight groups established; Training contract signed; AASHTO establishes provisional standards
1994	First Superpave conference
1995	Superpave centers established
1996	First Superpave projects constructed by states; lead states activated
1997	FHWA technology delivery team formed
1998	Federal transportation law eliminates funding; Second Superpave conference
1999	AASHTO assumes funding; TRB forms Superpave committee
2000	Long-range research plan created; Superpave 2000 conference
2001	World of pavement conference; 14 projects started
2002	Lead States Team sunsets
2003	World of asphalt conference
2005	Superpave binder standard adopted, 52 DOTs
2005	Mix design adopted by 36 DOTs; Superpave committee sunsets

FIGURE 2 From research to design standards: the Superpave example.

As can be inferred with some of the organizations listed above, there is often a direct relationship between proposed design guidance and regulatory requirements. Many federal agencies, for example, have been mandated by Congress to either provide services and infrastructure or to protect natural resources that relate to the substance and form of the design guidance issued by these agencies. In particular situations, there is thus a direct link between design standards and regulatory requirements and risk mitigation.

The institutional structures within each organization for making changes to design standards vary from one group to another. However, the process usually includes committees composed of leading engineers in the respective field that review test results and other evidence justifying any change. AASHTO, for example, has an extensive committee structure relating to bridges and roads that review research results (often conducted under the auspices of the Transportation Research Board) and approves changes to guidance and standards. This guidance does change based on the findings of research and practical experience, but not before the proposed change is fully vetted in front of practicing engineers.

The time it takes to change design standards is also influenced by current design practice and the degree to which the particular design factor is accepted by the professional community. Thus, for example, changing design practice from assuming a 100-year storm to a 500-year storm would certainly cause much discussion and debate among the professional community, but at least the concept of a design storm is well known and accepted. If evidence can be found to suggest the validity of making such a change, engineering practice would be changed….eventually. However, something more traumatic to engineering practice, say, for example, adopting a risk-based design approach to all infrastructure components could be debated and discussed for a long time. Thus, it seems likely that the lead time needed for making changes to design standards that reflect potential climate change-induced environmental conditions could be very long. This further suggests that the research needed to lay the ground work for such changes needs to be done even earlier than this.

Another group that has some influence in project development, but not so much in the development of the design standards themselves, is the insurance industry. When a natural disaster occurs and buildings and structures are destroyed, insurance policies usually require replacement of the asset as it was….in other words, the insurance company will not fund the redesign of a structure to higher standards than what were applied in the original design. For private property owners, this can become a real challenge for reconstruction. The professional liability insurance industry, that is, those that insure professional engineers against lawsuits, also requires evidence that the professional engineer follows accepted practice when designing a project.

One of the important aspects of design standards and guidance is their use by the legal community as evidence of "good practice." In the event of death or injury, lawyers will often try to assign some degree of responsibility to parties that were associated with the incident. In the case of the physical design or operations aspects of the facility itself this often leads to an examination of whether the engineer followed design guidelines and accepted practice. Thus, in some ways, design standards become almost a form of liability insurance in that following accepted design practice will often be accepted in court as evidence of due diligence and an exercise of defensible engineering judgement. The reliance on design standards and guidance for liability reasons is one of the reasons why design exceptions are often avoided as much as possible, or when they do occur, the justification is well documented.

The combination of long time frames for developing the justification for new or changed design standards, the institutional procedures for approving such changes, and the use of design guidance as evidence in litigation often leads to a rather conservative approach to changing such guidance. Design standards and guidelines, in one sense, provide a collective sense of professional acceptance and individual comfort for engineering designers.

Treatment of Risk and Uncertainty

For most of the 20th century, engineering design guidance focused on the conditions allowed (e.g., deflections or deformations) before failure would occur given expected forces acting on the structure. Equations and tables would show design parameters based on such things as the length of the facility, soil conditions, and environmental factors. Engineers would then choose design parameters that best accounted for the combination of forces acting on the structure so as to minimize the chance of failure. The most important element that reflected some degree of uncertainty associated with the environmental context of the design was the so-called “design event” or “design unit.” Thus, road design characteristics would be defined based on the design vehicle, the vehicle that would have the most difficulty using the road with respect to geometric characteristics and that would place the greatest load on the facility itself (for major highways, this would most often be a truck). Other examples would be the 100-year storm (the characteristics of a storm so severe that it occurs on average once in 100 years) that is used to determine the capacity requirements for handling drainage and flooding, or a design wind speed for determining materials strength and cable placement on bridges.

In recent years, many engineering design analyses have been incorporating more probabilistic approaches into their design procedures that account for uncertainty in both service life and in environmental factors. In considering wind speeds, for example, probabilities of different wind speeds occurring based on an underlying distribution of historical occurrences are used to define a design wind speed. Other analysis approaches are incorporating risk management techniques into the trade-off between design criteria that will make a structure more reliable and the economic costs to society if the structure fails. Perhaps the two civil engineering fields that are most progressive in such applications are found in earthquake engineering and fire prevention. In both cases, the design procedures have been developed that examine design characteristics and the costs associated with failure. For example, if a major interstate highway bridge collapses during an earthquake, what will be the economic costs of diverted traffic or of traffic no longer traveling?, and over how many months will the costs last? These societal costs can be compared to the costs associated with retrofitting the bridge prior to an earthquake so as to provide more resiliency given the likelihood of a seismic event occurring.

Although some areas of civil engineering are applying risk management approaches and incorporating uncertainty more fully into the design process, in general, there is still a long way to go. By and large, the design guidance and design standards in use today reflect the risk-averse nature of public agencies and of the engineering profession. Safety factors are incorporated into design standards that are an attempt to account for unforeseen events or abnormal forces being applied to a structure. To the extent that input variables can be changed to reflect the possible effects of climate change (e.g., using the 500-year storm instead of the 100-year storm), these approaches are amenable to considering design characteristics that could make transportation facilities more resilient against the effects of climate change. However, this approach would likely result in much more costly designs, which would not be well received by the owners of the infrastructure, especially given the sharp increases in construction costs that have occurred in recent years.

The aftermath of Hurricane Katrina provides the best case for why design approaches should account for uncertainty associated with environmental conditions. It is doubtful that the roads, bridges, pipelines and railroads that were either destroyed or incapacitated during the hurricane were designed with the possibility of such a magnitude event occurring. And certainly the designs did not account for the economic cost to the region and to the nation of the disruption that would occur if the facilities were unable to serve their original purpose. The response in rebuilding the damaged infrastructure suggests that the original design approaches, in fact, did not assume the forces that actually occurred primarily via the storm surge. Vertical clearances on the replacement bridges are being increased and the design of the connections between the bridge decks and the bridge piers are being reconsidered.

It is the contention of this paper that design procedures are needed that more fully account for the uncertainty of environmental factors from both extreme events and over the longer term from more "gradual changes" in such conditions. Given the substantial economic costs associated with widespread failures of the transportation infrastructure, such risk should be incorporated into the analysis.

DESIGNING FOR CLIMATE CHANGE-INDUCED HAZARDS

Very few studies 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; Suarez et al 2005]. 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, sea level rise),
- Causeways and coastal roads (sea level rise and increased frequency and intensity of storm surges),
- Pavement surfaces (increased mean annual 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 due to increased levels of precipitation and rising sea levels.

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; and 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.

Another regional 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 accommodate 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, steam 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. Roads and railways 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 over 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 most 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 percent 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 most studied impacts of climate change on infrastructure is the research associated with increasing temperatures on permafrost. As noted by Wendler [2006],

> "The results from future warming concerning transportation will be strongest in Interior Alaska, where non-continuous permafrost exists and the mean annual

> temperature is a few degrees below freezing at about 27°F. On the North Slope the temperature will be, even assuming an increase of a few degrees, still too cold for melting of permafrost as the mean annual temperature in this region is about 10°F. The active layer, that is the layer that melts in summer and presently has a typical thickness of 30-50 cm, will increase by 10-20 cm. In Southern Alaska, the area south of the Alaska Range, there is no permafrost, while Interior Alaska can have areas of permafrost and non-permafrost next to each other, e.g. the south side of a hill is normally permafrost free, while on the north side of the hill permafrost is found. Relatively small changes in temperature can have large changes in the permafrost areas, and we are observing such changes presently. The implications are especially important for road and pipeline construction."

Another implication of changing temperatures on permafrost is the change in river flows and the corresponding impact on bridge scour. A study on streambed scour at bridge crossings in Alaska shows that the major effects of climate change is mainly on rivers in glacial systems. As noted by Jeff Conaway with the U.S. Geological Survey, "The hotter, drier summers have led to increased glacial output in summer months. The peak flows are not as high as from intense rainfall events, but the duration of the high flows is longer. This translates to increased sediment transport capability and scour at bridge crossings." [Conaway 2006]

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]

Although most of these studies have examined one or two aspects of the potential climate change-induced forces that could act upon transportation infrastructure, combined, they present the range of such effects that are different from those assumed in today's design approach. These forces are described in the following section.

Climate-Induced Changes Affecting Transportation Infrastructure

Depending on the type of infrastructure component one is designing for, environmental characteristics can have varying effects on the final design parameters. Thus, for example, wave motion is much more important to bridge design than say temperature changes, although even bridge designs in terms of the materials used reflect expected temperature ranges. Increases in precipitation would likely affect drainage and soil stability much more than changing freeze-thaw cycles would. The following climate-induced changes should therefore be viewed from the perspective that they will have varying effects on the design of the components of a transportation facility.

Temperature Change and Increased Temperature Range

Temperature change affects, in some way, every component of infrastructure design because the materials used in building a structure will usually exhibit some contraction and expansion due to temperature changes. Temperature change would include both maximum and minimum temperatures and the range between the two. 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 temperature will happen over a longer time frame than the average life of most transportation infrastructure, except perhaps bridges. In the long term, that is, from 40 to 100 years from now, temperature changes could have important effects on the procedures and materials used for infrastructure design.

Pavements will likely be the most affected by changes in temperature. Changnon et al [1996] reported that highways and railroads were damaged due to 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 average temperatures and 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 high temperature regimes.

The effect of temperature change on the behavior of permafrost could also create significantly different approaches to engineering design in areas where permafrost has historically been a defining environmental factor.

Precipitation and Sea Level Rise

Changes in precipitation and water levels are another consequence of global climate change that will occur over a longer time span than most average lives of infrastructure built today. The effect of changing levels of precipitation would most affect foundation and pavement design, especially if precipitation levels increase significantly over today's levels. More moisture in the soil and the hydrostatic pressure build-up 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 ground water levels could affect the design of column foundations for bridges and other structures dependent upon deep foundation support.

Perhaps the most important impact of increasing precipitation levels will be 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. More and faster velocity flows through culverts could also affect the design of culvert entrances, which would be affected by the speed of the water flow passing the entrance point.

Flooding due to 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.

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. Increasing storm strengths will likely be accompanied by increasing and sustained wind speeds. Increasing wind speeds will certainly affect buildings and other structures built above ground, but will not likely affect surface transportation structures.[4] The most important effect of increased wind speeds on surface transportation structures will be 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, changes might have to occur to the strength of the materials used in bridge cables, and in the wind tunnel protocols used to test such structures.

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 due to higher and more forceful waves could result in changes in component dimensions, materials used in construction, deeper foundations, or in the use of protective mechanisms.

The most extreme force, and one that creates the most concern to engineers, is the storm surge. Not only does the storm surge create forces on parts of transportation structures that were not designed for such forces, but it more than anything else causes the most disruption because it carries 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 due to the buoyancy force on the bridge decks resulting from the storm surge and wave action. This force simply 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 as well as the foundations.

Table 1 summarizes the information presented in this section. As can be seen in this table, climate-induced changes will likely affect those transportation design elements that are most associated with forces resulting from water flows. This is not surprising given that much of the evidence from recent extreme events indicates that it is flooding and storm surges that create the most damage to buildings and infrastructure.

Changes to the Design Standard-Oriented Project Development Process

If the platform for considering climate-change induced factors into the transportation design process is through the currently accepted design standard and guidance process, what changes if any should occur to provide for more robust designs in response to changing environmental conditions?

How should engineering decisions for structures with lifetimes of many decades to perhaps a century be influenced today for likely climate-induced hazards?

As shown in Table 1, it seems likely that some components of transportation infrastructure will likely be more vulnerable than others to the risks associated with changing environmental conditions. Many of the procedures that are used to develop engineering designs include

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[4] However, greater wind speeds could require a rethinking of the support structures and design for traffic signs and signals.

TABLE 1 Climate-Induced Forces That Could Influence Transportation Design

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

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

approaches that could simply incorporate a greater incidence of abnormal behavior, such as assuming a greater frequency and magnitude of extreme events. By doing so, design procedures and design standards allow for the sensitivity of input variables to reflect the possibility of changing environmental conditions. However, the problem with this approach is it will often result in more expensive designs due to greater strength and resiliency being incorporated into the final design product. There are two approaches that could be adopted to incorporate greater uncertainty into the design process: using shorter useful life targets for infrastructure design, and adopting a probabilistic approach toward design that explicitly takes into account risk.

Infrastructure is designed for a specific useful life, for example, 100 years for a bridge and 10 to 15 years for pavements. The overall facility design, materials of construction and preservation/maintenance requirements are then chosen to achieve such a useful life. One of the approaches that could be taken to account for climate change is simply to design infrastructure for shorter useful lives. Thus, in coastal areas where some level of risk might be associated with the design of transportation facilities, bridge design could target a 50-year design life rather than 100 years. In some ways, this is exactly the approach that has been taken in New Zealand where Transit New Zealand, in examining the potential impacts of climate change, considered that many state highway assets have shorter intended design lives (for example, pavement surfaces have 8 to 10 years expected life) and that standards and the assets themselves would be able to be incrementally adjusted to manage the impacts of climate change. This was particularly the case with causeway heights, slopes, pavement surfaces, roadside vegetation and facility protection designs.

The life-cycle costs of infrastructure designed using this approach would depend very much on the assumed climate change actually occurring. In the short term, the costs of a 50-year bridge would be less than the costs for a 100-year bridge. And if environmental conditions have changed as expected in the design over the 50-year time frame, the costs of replacing the bridge could include the new design characteristics that reflect the changed environmental conditions. If a 100-year bridge had been built and the environmental conditions did change, the costs of retrofitting the bridge or even of replacing it would be much greater than if a 50-year bridge had been built to begin with. However, if the environmental conditions have not changed as expected, the owner of a 50-year bridge is faced with building a replacement bridge at the inflated expense of what the original bridge cost. As can be seen in this example, the level of risk and infrastructure vulnerability has associated with it a level of uncertainty, which suggests another approach toward design for potential climate change conditions.

A probabilistic approach to infrastructure design explicitly trade offs design considerations with the risks associated with structure failure, where this risk is defined broadly to include societal costs of not having the structure or infrastructure available. At a minimum, the structures that will have longer useful lives should be designed with such an approach. To a limited extent, the current design approach to some transportation infrastructure already permits uncertainty to be included in the design process. For example, the concept of design storms, and the resulting levels of precipitation and water rise, is based on a statistical assumption of the average occurrence of storms of such strength. To the extent that such allowances are incorporated into the design process, the challenge is to get the design engineer to consider such changes in the project development process, even if chosen design characteristics result in a more costly design. If the design approach does not allow for such a consideration, and some do not, then there is a need to examine current design practice for such components (such as culverts) and determine if the designs that result from current procedures are sufficient to handle additional demands due to changes in environmental conditions.

In a formal sense, probable future loss due to an extreme weather or climate-induced event (otherwise known as risk) is related to the expected level of hazard occurrence times 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, how to incorporate a risk assessment approach toward infrastructure design in general applications is unclear. However, the characteristics of such a risk assessment approach for long-lived infrastructure in particularly sensitive areas seem more obvious. These characteristics could include:

1. Focus on infrastructure that has long lives (greater than 40 to 50 years); infrastructure designed for a shorter life has flexibility incorporated into the facility replacement schedule to account for significant changes in environmental conditions and thus do not need to be included in this approach.
2. Identify geographic areas in a jurisdiction that have particular sensitivity to changes in climate, such as coastal or low-lying areas.
3. Assign a likely occurrence probability for environmental changes occurring in these sensitive areas that reflect the likelihood that such changes will occur over the useful life of the facility.
4. Undertake different designs for the facility with varying degrees of design standards applied to account (or not) for changing environmental conditions. Estimate the cost (both replacement and economic cost due to facility disruption) of each design.
5. Apply the hazard occurrence probability to the different cost components of the design that will be affected by changing environmental conditions. Estimate the likely costs in present dollars of each design. The design with the lowest net present value cost would be the desired alternative.

These characteristics imply that the desirability of one design over another that more comprehensively includes the risk associated with climate change can be defined through relative design costs. To the extent of the author's knowledge, this approach has not been tried in practice, but it seems that there is some merit into linking alternative design costs that take into account possible changes in environmental conditions. More research and technical guidance is needed on the design implications of climate-induced environmental changes, and on risk-based approaches to designing the most cost effective and resilient facility.

How can climate-related design factors be combined with other accepted extreme event design considerations? Can these factors be considered simultaneously or should they be applied cumulatively?

In many ways, the approach toward climate-induced changes in the design process described above follows the 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, many 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. Of course, this works only when the project is found in one of the other special design contexts. If the project is not located in a seismic zone, and is not subject to collisions, fires or heavy snows, then the defining design criteria would be those adopted by the engineer that reflects the best approach to risk management.

How does one account for the interdependence of critical infrastructure links that are part of infrastructure networks or systems?

The first step in recognizing the interdependence of critical infrastructure links is to conduct a network or systems analysis of the performance of the network itself, and identify those links that are most critical in providing the best performance levels. In other words, the design of a critical infrastructure project should not be conducted in isolation of the broader system within which it occurs. For example, the desired traffic-carrying capacity of a road or bridge project is usually determined by forecasting the traffic demand given future expectations of travel flows due to economic, population and employment growth. This approach depends on models that largely look at historic trends and relationships and predicts the future based on the same underlying assumptions. But the world as envisioned in this paper could be very different. Suppose for example that this road or bridge project lies along a major evacuation route from coastal areas….it might be appropriate to provide additional capacity over what is projected to be needed to handle traffic flows that are not reflected in historical trends.

The second step once the criticality of a link is established is to define the types of design strategies that might be considered. For example, one might consider designing in extra redundancy into the project or provide above normal reserve capacity. Or the design could include a greater sensitivity to the protection of critical elements of the project design, such as better protection against bridge scour or high winds. Or the design could exceed normal design standards such as recommended bridge clearances in consideration of abnormal environmental conditions (e.g., storm surges). In essence, what is being suggested is that design standards for critical facilities would be subject to more robust standards that take risk and performance into account. Taking into account the risks associated with changing environmental conditions, one design approach for all facility types does not make sense (this is exactly the conclusion Transit New Zealand has reached for those elements of the transportation infrastructure that could be in most jeopardy from climate change - bridges and culverts).

The incorporation of climate-induced risk factors into engineering design will require professional leadership, and quite frankly, a convincing argument. As was noted in the section on the institutional structure for establishing new standards and design guidance, the process is designed to be deliberate and comprehensive (and some might say conservative). Decisions to change design procedures are data-driven…the facts must be clearly known before the professional community responds to changing demands. It seems that we are at the beginning of the fact-finding portion of this process. Not much attention has been paid to the possible engineering design implications of changing environmental factors. The attention that has been paid has focused on the nature of the environmental change itself (e.g., what is happening to the permafrost?), but with little serious attention paid to the implications to engineering design practice. Leadership in such an endeavor needs to come from the scientific and engineering research community in collaboration with leading professional organizations such as ASCE, AASHTO, and FHWA. The Transportation Research Board (TRB) also has an important role in keeping this issue before the transportation professional community and in supporting research on related topics. Given the time lag that usually occurs between research findings, acceptance of these findings by the professional community and the eventual adoption of related design standards, there is a strong need for a federally supported research effort (that is, the National Science Foundation and the U.S. Department of Transportation) to provide the impetus for such an effort.

Other organizations, such as those listed earlier, will follow with new testing procedures and materials specifications once the transportation community itself states there is a need. The challenge is to get these organizations to focus on a possible scenario 100 years in the future…something that most engineering-oriented organizations have difficulty doing. The focus is rather more often on what can we do to improve today's processes and design efficiencies.

OPTIONS OTHER THAN CHANGING DESIGN STANDARDS AND GUIDANCE

Previous sections have focused on the influence of design standards and guidance on the built environment. The discussion on the different components of infrastructure, that is, subsurface conditions, materials specifications, cross sections, drainage, structures, and location engineering, was founded on a point of departure that the design considerations associated with these components would likely be affected by changing climatic conditions. The previous section described how changes in environmental conditions could indeed affect the design of these different components. This section will examine means other that design standards that might be considered to reduce the risk associated with failure due to environmental factors.

One of the most effective strategies for reducing the engineering risk associated with climate change is to avoid the potential of risk to begin with. As noted earlier in the discussion on location engineering, infrastructure and land use are closely linked to one another. Indeed, the typical approach to modeling future travel demand and thus the need for new facilities is to begin with expected land use patterns over the next 25 to 30 years. [Meyer and Miller 2001] Expanded transportation networks are then modeled based on their ability to handle the forecasted demand. This transportation planning process seldom considers the external conditions of building such facilities at this step in the process, and there are few if any cases where planners have considered the likely effects of climate change on location of facilities and on the land development that results. Some areas like Lake Tahoe, NV and Cape Cod, MA have identified environmentally sensitive areas such as coastal zones and low lying areas that are considered "off limits" when future transportation is contemplated, but by far the vast majority of transportation planning organizations seldom include such considerations into their network modeling [Amekudzi and Meyer 2005].

This strategy would thus provide land use guidelines for areas that are at high risk due to changing conditions over time. These guidelines could mandate building codes that must be followed to put in place a building stock that can respond to such changes or they might prohibit any development from occurring in areas particularly prone to hazards or in areas that disrupt the natural ameliorating effect of such things as rising water levels. At the regional level, these strategies could be reinforced with infrastructure investment policies and tax incentives to encourage the development patterns that are desired.

However, one of the challenges in adopting a more environmentally sensitive land use/infrastructure approach relates to the current governance system of land use decisions in the United States. Decisions on land use are primarily the prerogative of local governments, which attempt to influence such decisions through zoning laws, ordinances and comprehensive plans. Large-scale infrastructure decisions, however, are the responsibility of state, regional, or special purpose agencies, each often having a specific focus or mandate on providing such infrastructure. One of the continual laments of the professional planning community is the disconnect between local development decisions and state/regional infrastructure decisions. It seems likely that any strategy for minimizing risk to climate-induced changes that combines land use and infrastructure components will have to be done at least at a regional level, with a regional consensus on appropriate development patterns and corresponding infrastructure investments.

A second strategy is primarily reactive and follows closely the approach taken in response to earthquake risks. Following several major earthquakes in California, civil engineers and the building construction industry worked toward changing the way structures were designed by modifying building codes and design standards. In the interim, however, most bridges in California were retrofit with "collars" around the columns that provided greater strength and resiliency in the event of an earthquake. This strategy thus depends on new building codes to provide the longer term solution as the building stock turns over, while the shorter term fix, the bridge retrofits, is designed to handle the more immediate risk. There are some types of infrastructure designs where a retrofit strategy might work, such as connecting the bridge deck to the deck piers so that buoyant forces due to storm surges do not lift the decks off of their supports. However, most of the climate-induced changes discussed in the previous section such as temperature change, increased precipitation, and rising water levels are not conducive to this strategy.

A third strategy focuses on network design itself. One of the reasons why there is often significant long term economic loss after a major event like Hurricane Katrina is due to the disruptions associated with loss of economic flows through a region. If a highway or pipeline is the critical link in the transportation network that provides for the flow of people and goods in a region, then the cutting of this link will have significant economic effects until the link is restored. One of the ways of reducing this impact is to design redundancy into the networks themselves, that is, providing other paths that can be followed in the event that an important bridge or highway segment is out of service. In a dense urban environment where the transportation network provides such a potential for redundancies, this strategy entails once again modeling the network from the perspective of identifying multiple paths for the most critical traffic flows. Implementing such a strategy would include coordinated traffic operations, communications, and perhaps targeted infrastructure investment. Such a strategy is more challenging in rural areas where network design doe not have such redundancies already incorporated into the network definition. But even here, one could plan ahead to establish alternative origin-destination paths in key corridors that might once again require targeted investment (for example, fixing a weight restricted bridge that is on a key detour route).

A fourth strategy would rely on the application of new technologies and construction approaches to respond to abnormal pressures being applied to structures and infrastructure. Many of these technologies are probably not yet invented, but it seems likely that the advances in material sciences (with special application of nano-technologies), sensors, computer processing and communications abilities could have a significant impact on the way we design infrastructure. Sensors that monitor changing pressures on a building or bridge and thus issue a warning when pressures become abnormal are already available and in limited use. One could envision "smart" infrastructure that directs highly turbulent and fast water flows away bridge columns and thus reduce the potential for bridge scour. Sensors could be embedded in pavements and bridge decks that monitor the changing stress and strain as temperatures change, allowing remedial action to be taken before failure occurs. Similar sensors could be applied to bridge structures in high wind conditions to change material properties that allow the bridge to survive abnormal wind speeds. And one could even consider sensors on buoys that would communicate warnings to sensitive infrastructure that would then be "lifted" above storm surges. It seems to me that one of the exciting areas of research and brainstorming will be in this linkage between design guidance and the application of "smart" technologies. This linkage could revolutionize the way we do engineering design.

Another factor to this strategy is developing new construction approaches to provide for more cost effective replacement of infrastructure components that are particularly vulnerable to higher stress environmental conditions. For example, one might consider modular construction techniques (such as for bridge decks) that allows quick replacement both when changing circumstances merit replacement and when catastrophic events cause the existing component to fail.

Finally, there might be appropriate changes in the institutional framework within which engineering design occurs that could influence the products of the process. For example, insurance policies could promote changes over and above the status quo when considering reconstruction payments or professional liability. This includes both the federal flood insurance program as well as insurance for privately-provided infrastructure. The National Flood Insurance Program (NFIP), established by Congress in 1968, requires that to get financing to buy, build or improve structures in Special Flood Hazard Areas, one must purchase flood insurance. A community must agree to adopt and enforce floodplain management ordinances as part of the strategy to provide flood loss reduction building standards for new and existing development. Buildings that are improved or repaired after floods must be brought into compliance with these ordinances if the repair costs 50 percent or more of the market value of the building. Significant questions have been raised about the various influences of the federal program on land development decisions, ranging from it providing a hidden incentive for further development in high risk areas (that is, it reduces the individual investment risk to catastrophic loss) to having little influence at all (many beach properties, for example, are purchased without loans, and thus no financing is necessary). [see, for example, (Center on Federal Financial Institutions 2005)] The federal flood insurance program should be assessed from the perspective of what impacts it has on development decisions in high risk areas, especially from the perspective of the different types of climate-induced changes that might occur in the future.

Another institutional change might include incentives in federal tax policy that would encourage extra design considerations for areas that are particularly vulnerable to changing environmental conditions (similar to the federal tax incentive to purchase an alternative-fueled vehicle).

CONCLUSIONS

This paper has attempted in a very ambitious way to identify the boundaries around the challenge facing designers of transportation infrastructure in light of potential changes in climate change-induced environmental factors. The paper has shown that there are environmental factor-related variables that are part of the engineering design process for different project components. It has also suggested that some of the environmental changes possible with climate change would indeed, even using today's design practices, have some effect on resulting designs. With a more robust design approach that accounts for uncertainties in these environmental factors, it seems likely that the impact on design approaches might be even more profound.

The major conclusions from this paper include:

1. There is a need for a broader systems perspective in looking at network-oriented infrastructure design to determine what design factors, if any, should be included to reflect network interdependencies.
2. Risk-oriented, probabilistic design procedures should be used when defining design characteristics of components that could be affected by changing environmental factors. The design standard and guidance approach to current practice should be assessed to see how such procedures could be enhanced or further introduced into standard practice.
3. The design considerations relating to the presence of water and the additional forces applied to engineering structures due to wave actions and storm surges appear to be the most pressing in the shorter term. In the longer term, temperature changes, increasing range of temperatures during a typical year and wind loads become important additional considerations.
4. Non-design standard strategies for considering risk-oriented designs should be examined closely in a broader assessment of how to respond to climate change. The linkage between infrastructure provision and development patterns needs to be considered very carefully because of the land use development-inducing influence of infrastructure provision (and thus the corresponding multiplier of hazardous conditions to populated areas in the case of an extreme event). One of the most productive avenues of research might be the application of "smart" technologies to provide flexible responses to changing environmental conditions.
5. There is clearly a need for research on the potential impacts of climate change on infrastructure design. This is a serious gap and a missing step for gaining agreement from the professional community that the issue deserves attention. The lead organizations in establishing such a research program should include those most at the forefront of civil engineering practice, that is, AASHTO, ASCE and FHWA, and those responsible for more basic research, for example, the National Science Foundation. In addition, the challenges associated with changing environmental conditions and the potential impact on the transportation system is not an issue solely for the transportation community. There is a serious need for the climate research community and the more applied transportation research community to work together to develop the research foundation for any changes in design standards. This should include joint research projects and research meetings/conferences where information can be exchanged. The U.S. Department of Transportation potentially has a critical leadership role in this regard in that it is viewed as a credible and influential player in transportation infrastructure decisions.

The country is celebrating the 50th anniversary of the interstate highway system in 2006, one of the most impressive engineering feats of the modern era. The design of this system was based on research and engineering practice that evolved over the 40 years prior to 1956, when the interstate program was authorized by Congress. In looking at the next 50 years, and what the United States should be doing in developing the transportation system of the future, it is appropriate to question whether the design standards and assumptions of environmental conditions that resulted in today's interstate system are appropriate given likely future conditions. Hopefully, this paper has provided some motivation to examine such an issue in more detail. It is only through professional discussions and debates, informed through research and data, that progress can be made on an issue that potentially has significant consequences on how we function as a society.

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