5.0 How Can Transportation Professionals Incorporate Climate Change in Transportation Decisions?

Lead Authors: Kenneth J. Leonard, John H. Suhrbier, Eric Lindquist

Contributing Authors: Michael J. Savonis, Joanne R. Potter, Wesley R. Dean

As the previous chapters have demonstrated, there is benefit to including long-term climate considerations in the development of transportation systems. In fact, climate factors are likely to affect decisions in every phase of the transportation management process: from long-range planning and investment; through project design and construction; to management and operations of the infrastructure; and system evaluation (Figure 5.1). This chapter will explore how such concerns might be addressed in the continuing process of development and renewal of transportation infrastructure. To better understand this, an overview of the planning process as generally implemented today is provided, as well as specific consideration of transportation planning within the Gulf Coast States.

However, to rigorously address climate concerns, new approaches may be necessary. Since climate impacts occur into the future, and there is uncertainty as to the full magnitude and the timing of the impacts, deterministic methods as currently employed are ill suited to provide the type of information that current decision-makers need. Instead it may be more fruitful to consider these impacts through a risk management approach to more effectively give transportation executives, elected officials and the general public a more complete picture of the risks and potential solutions to climate impacts. The last section of this chapter begins the process of developing an alternate approach to planning with a conceptual framework for introducing more probabilistic approaches. Once fully operational, this type of methodology could lead to better information to address the changing climate.

[INSERT FIGURE 5.1 How will climate change affect transportation decisions?]

■ 5.1 Considering Climate Change in Long-Range Planning and Investment

This section discusses how transportation planning and investment decisions are made in state and local governments and to some extent in private agencies. It reviews in particular the planning and decision-making processes used by state departments of transportation (DOT) and metropolitan planning organizations (MPO). Specifically, it discusses the long-range planning taking place in the Gulf Coast Study region and provides the results of a number of state DOT and MPO interviews. Finally, it suggests how the planning process might be adapted to consider the potential impacts of climate change.

5.1.1 Overview of the Federal Surface Transportation Planning and Investment Process

Transportation planning processes vary with the type of agency (public or private), level of government (Federal, state, or local), mode of transportation, and other factors. This chapter will not attempt to provide an overview of all of them. But since the Federal government has specific requirements codified in law to cover the surface transportation planning process (for highways and transit investments), this chapter provides an illustrative example using the Federal process.

Surface transportation planning and investment decision-making, employed to make use of Federal transportation funding, is conducted within the framework and requirements defined by the planning provisions contained in Titles 23 and 49 of the United States Code (USC), most recently amended in August 2005 by the *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* (SAFETEA-LU).

State DOTs and MPOs have lead transportation planning responsibilities, working in coordination with local governments. States and local governments may implement transportation infrastructure without Federal funding. These projects may be included within the framework of the Federal transportation process, but could be implemented outside that framework.

Within the Federal process for highways and transit, state DOTs and MPOs must comply with the planning requirements to be eligible and to receive Federal transportation funds. The state DOTs within the study area are the Alabama Department of Transportation, Louisiana Department of Transportation and Development, Mississippi Department of Transportation, and Texas Department of Transportation. Ten MPOs exist within the study area, as identified in Table 5.1. Each MPO consists of one or more urbanized areas exceeding 50,000 in population with an urban area exceeding 200,000 in population also defined as a Transportation Management Area (TMA).

[Insert Table 5.1 Urbanized area Metropolitan Planning Organizations (MPO) in the Gulf Coast study area]

The MPO's planning activities are identified in the Unified Plan Work Program which covers a two-year period for the purpose of maintaining short- and long-term transportation plans. It is within this program that MPO staff collect data on traffic and pedestrian counts, building permits, planned developments, and accident rates, etc., analyze trends, and evaluate potential projects. Two principal products are produced in the transportation planning process: a long-range transportation plan and a transportation improvement program. These two products, then, provide the basis for more detailed project development – engineering, design, and construction.

Separate but coordinated long-range transportation plans are cooperatively developed on a statewide basis by a state DOT and for each urbanized area by an MPO. The long-range transportation plan is developed with a minimum of a 20-year forecast period, with many areas using a 30-year time horizon. The intent of a plan is to provide a long-range vision of the future of the surface transportation system, considering all passenger and freight modes and their interrelationships. As defined by SAFETEA-LU (23 USC 134 and 135) long-range plans, "shall provide for the development and integrated management and operation of transportation systems and facilities that will function as an intermodal transportation system." The transportation planning process for TMAs is essentially identical to that in urbanized areas having a population between 50,000 and 200,000 except that a Congestion Management Process (CMP) also is required.

The transportation improvement program (TIP) is a separate document for the immediate future. It must be consistent with the long-range plan and provides the list of short-term (three years) priorities for construction. A TIP must be developed for each metropolitan area and a Statewide Transportation Improvement Program (STIP) must be developed for the State that is consistent with the TIPs. The STIP must be approved by U.S. DOT.

Environmental considerations have long played a role in the planning and development of transportation projects. Changes over time, though, have occurred in the manner in which environmental analyses have been conducted and the underlying legal framework in which these analyses are conducted. SAFETEA-LU, in Section 6001, defines the following eight planning factors that should guide a transportation planning process and the development of projects, strategies, and services (Figure 5.2):[1]

1. "Support the economic vitality of the United States, the States, nonmetropolitan areas, and metropolitan areas, especially by enabling global competitiveness, productivity, and efficiency;

2. Increase the safety of the transportation system for motorized and nonmotorized users;

3. Increase the security of the transportation system for motorized and nonmotorized users;

[1] This list represents a refinement of a similar list contained in previous intermodal surface transportation legislation.

4. Increase the accessibility and mobility of people and freight;

5. Protect and enhance the environment, promote energy conservation, improve the quality of life, and promote consistency between transportation improvements and state and local planned growth and economic development patterns;

6. Enhance the integration and connectivity of the transportation system across and between modes throughout the State, for people and freight;

7. Promote efficient system management and operation; and

8. Emphasize the preservation of the existing transportation system."

[INSERT Figure 5.2 SAFETEA-LU Planning Factors]

The SAFETEA-LU legislation requires that long-range transportation plans be developed in consultation with agencies responsible for land use management, natural resources, environmental protection, conservation, and historic preservation. Further, this consultation is to consider, where available, conservation plans or maps and inventories of natural or historic resources. This is typically a time- and labor-intensive effort requiring years to complete with extensive public involvement which was made far more difficult by the 2005 hurricanes. The Gulfport MPO reports that in addition to the several years the overall effort took prior to 2005, the agency needed another year to reconsider the land use and demographic changes taking place as well as the Plan's regional goals to make them consistent with the Governor's Recovery Plan.

An interesting question is the manner in which the impacts of climate change can be addressed in the list of eight planning factors and the associated consultative process. As will be discussed later in this section, while climate change is not now named as part of any of the eight factors, a number of them reflect considerations that are directly related to climate change. In addition to protecting, enhancing, and mitigating impacts on the environment, these include system preservation, system management and operation, safety, and economic vitality (see especially Factors 1, 2, 6, and 8).

Transportation plans, programs, and projects historically have been developed to meet the needs of future projected or planned land use, including population and employment patterns. In recent years, though, transportation and land use are being addressed in a much more interactive or coordinated manner. Rather than land use being viewed as driving transportation decisions, transportation investment and management decisions are increasingly being made collaboratively and in concert with growth management and economic development decisions. In this view, the manner in which transportation infrastructure is developed and managed is seen as one "tool" for helping to achieve desirable growth objectives.

The overall transportation planning and investment process is illustrated in Figure 5.3 with an emphasis that is helpful in identifying where in this transportation planning process considerations related to climate change impacts potentially could be introduced. Using terminology that is consistent with current planning and strategic management approaches, separate steps are identified for establishing a long-range vision and for establishing goals, objectives, and performance measures. Developing an *understanding of the problem* is seen as occurring on a continuing and iterative basis throughout the planning process, including the analysis of data and evaluating tradeoffs and establishing priorities among candidate policies and projects. The process culminates with development of a long-range transportation plan, a short-range transportation improvement program, and project development and implementation.

In terms of introducing climate-related changes into the long-range transportation planning and investment process, the potential exists at each step illustrated in Figure 5.3. As shown, long-range environmental quality, economic development, mobility, and other desired conditions such as safety commonly are defined as part of a vision and accompanying mission statement and then translated into goals, objectives, and performance indicators. Thus, protection from climate change impacts could be introduced at these stages as well. Given these defined goals and objectives, strategies then are developed that are specifically designed to meet the agreed upon goals and objectives, and evaluated using the appropriate performance measures. Again, strategies could be developed that address climate change and variability. Similarly, climate change protection and mitigation strategies could be evaluated with respect to their potential impact on the transportation system.

[INSERT Figure 5.3 Steps in the transportation planning process]

5.1.2 Coordination in Transportation Planning

The Federal transportation planning and investment process is highly collaborative in which transportation agencies work in partnership with natural resource agencies, communities, businesses, and others throughout the period of planning, programming, developing, implementing, and operating transportation projects. Transportation agencies are charged with helping to accomplish multiple transportation, economic development, environmental, community, safety, and security objectives. Going beyond the Federally mandated process, the continued development and operation of the multimodal network requires extensive coordination.

Although planning and programming of the highway system, and its coordination with other modes of travel, are major responsibilities of the state DOT and the MPO, the actual development and operation of the transportation system is the responsibility of various levels of government and private agencies. States typically own and operate a relatively small portion of the road network but that portion (the Interstate System and Arterial Highways) usually accommodates the majority of the road travel. In some cases, states also own and operate local and state transit systems and freight rail lines. However, the majority of highway miles and transit systems are local responsibilities and most of the nation's freight system and air passenger system is owned by the private sector.

Meeting the requirements of the Federal planning process is necessary as a condition of receiving Federal financial assistance. However, for states and MPOs the number of different organizations who have independent roles makes it important to have a collaborative decision-making process, one that is based on valid and convincing information. At the MPO level, decisions are a collaboration of the individual local governments that comprise the MPO and serve on the policy board usually supported by the advice and analysis of a technical coordinating committee.

At the state level, the ultimate decisions are typically made by the Governor and the state legislature[2] with recommendations and advice coming from the state DOT. Decisions within the state DOT also occur at many levels and units within the organization. State DOT decisions encompass all aspects of the roadways under state jurisdiction: planning, engineering, operations, design, and construction.

Most of the freight and part of the aviation and passenger systems are owned by the private sector. State DOT and MPO plans that make recommendations for these systems must get the concurrence from the private sector for implementation. In the vast majority of the cases, the private sector invests in their current system or a new system if they feel it is cost-effective to do so. The state and MPO may have some influence through the planning process or through the provision of financial assistance. For instance, a railroad will not likely move a rail line unless it improves their return on investment or because the government helps finance it.

Since the freight network is largely owned by the private sector, the long-range transportation planning process for both states and metropolitan areas ensures that the private users and providers of transportation are represented and their comments considered. In fact, the Federal planning regulations discussed above requires that in developing or updating long-range transportation plans states and MPOs shall have a process to allow freight shippers and providers of freight transportation services a reasonable opportunity to review and comment on key decision points and the proposed transportation plan. Planning agencies normally include private shippers and transportation providers on their plan advisory committees to guarantee representation early and throughout the planning process.

For these systems to be effective at efficiently moving people and goods – as well as meeting the higher needs of society in terms of economic development and environmental enhancement – a high degree of coordination is crucial. In terms of meeting the particular challenges that climate change poses, each entity, whether public agency or private firm, needs to consider how climate stressors might affect their businesses. Further, these agencies need to work together to consider how climate changes affect the efficient movement of people, goods and services as a whole to take full advantage of system redundancy and resilience, explained later in this chapter.

---

[2] Some DOTs, such as Mississippi's, do not report to the Governor.

5.1.3 Current State of Practice in Incorporating Climate Change Considerations

In this Gulf Coast Study, representation of the private freight industry was sought during the development of the modal technical papers. For example, railroads were involved in the review of the rail technical paper and discussions were held with the Association of American Railroads about possible impacts to rail lines from climate change such as "sun kinks" and the importance of prestressed rail track. The CSX Railroad provided significant information on hurricane Katrina impacts and adaptation strategies through public comments and the sharing of information. The CSX reported that it cost about $250 million to repair damage from Katrina, and the damage caused them to further consider relocating the rail line. The CSX Railroad is exploring the feasibility of new construction within the existing corridor but further inland. Also, increased use of alternative Mississippi River crossings is under study (Baton Rouge/Vicksburg). Interviews included a private toll road authority and port employees for two separate ports (Galveston and Houston) that were publicly owned but operate privately owned facilities. The toll road representative expressed concern about potential impacts of sea level rise since the toll facilities do approach the coast line particularly in the Houston metropolitan area. The port representatives also were concerned about the impacts of possible seal level rise and the impacts of increased precipitation on sedimentation of port channels and port run-off that could cause local flooding. In the next phase of the Gulf Coast Study, the private sector involvement will be intensified to determine what specific climate change impacts are possible and in detailing likely adaptation strategies and costs.

Three approaches were utilized to determine how state DOTs and MPOs currently are addressing issues of climate change and also how climate change might be addressed in the future. The approaches involved:

1. Obtaining and reviewing current long-range transportation plans, and transportation improvement programs for the states and selected MPOs within the study area;

2. Interviewing state DOT and representative MPO officials responsible for transportation planning within the study area; and

3. Reviewing other recent documents from within the study area that address issues that are potentially related to the effects of climate change on transportation infrastructure development, operation, and management.

Some MPOs within the study region currently are in the process of updating their vision statements and long-range transportation plans. In some of these cases, MPOs are actively considering issues related to the potential effects of climate change and variability combined with the impacts of Hurricanes Katrina and Rita, not surprisingly the two aspects of climate that are receiving the most attention are: 1) evacuation planning and management; and 2) preventing infrastructure damage resulting from storm surge-related flooding.

Mission statements, long-range transportation plans, statewide transportation improvement programs, and annual reports were obtained, where available, from the Internet for the states of Alabama, Mississippi, Louisiana, and Texas. In addition, the corresponding documents were similarly obtained for the following urban areas:

- Mobile, Alabama (South Alabama Regional Planning Commission);
- Hattiesburg, Mississippi (Hattiesburg-Petal-Forrest-Lamar Metropolitan Planning Organization);
- Gulfport, Mississippi (Gulf Regional Planning Commission);
- Lake Charles, Louisiana (Imperial Calcasieu Regional Planning and Development Commission);
- Lafayette, Louisiana (Lafayette City-Parish Consolidated Government Metropolitan Planning Organization);
- New Orleans, Louisiana (Regional Planning Commission for Jefferson, Orleans, Plaquemine, St. Bernard and St. Tammany parishes); and
- Houston and Galveston, Texas (Houston-Galveston Area Council).

None of the state and MPO documents directly addresses or acknowledges issues of climate change and variability. This is, in part, due to their age; most were developed two to fours years ago, prior to the recent increase of interest in climate change and the associated increase in the availability of climate change-related information. Also, each of these documents was prepared prior to Hurricanes Katrina and Rita so the many actions being taken by state DOTs and MPOs in response to these two storms have only recently been included in updated and published planning documents.

The following observations result from a review of these planning documents, organized into the following three categories: missions and goals, scope of planning activities, and prioritization criteria.

Mission and Goals – Most of the state and MPO plans in the region include a mission or goals that include statements about providing environmentally sound transportation systems or preserving the quality of the environment and enhancing the quality of life. There also are goals that include strategies to encouraging land use planning and incorporate public transportation, walking, and bicycles. In Mississippi, the flooding that resulted from Hurricane Katrina has resulted in new design standards for the bridges that are being rebuilt and is serving as a catalyst for considerable debate on the interrelationships between land use and transportation investment within the coastal areas of the State.

The Regional Planning Commission for the New Orleans urbanized area and the Mandeville/Covington and Slidell urbanized areas is refining its Metropolitan

Transportation Plan (MTP) for the New Orleans region so that it can provide a framework within which the projected climate change effects can be assessed and addressed. The Houston-Galveston Area Council (H-GAC) is in the process of conducting a visioning exercise, the results of which will then guide the development of an updated regional transportation plan. Since this is occurring post-Hurricane Rita, climate change and the means of reducing the risk of flooding have been raised in the outreach sessions and working meetings.

Scope of Planning Activities – In addition to including policies to provide maintain and improve the area's intermodal systems, the states and MPOs in the study area also are including consideration of future uncertainties and evacuation management. The Mississippi transportation plan and associated STIP both acknowledge uncertainty in future year conditions in areas such as growth, air quality, road maintenance, and congestion. The STIP contains a section on planning and research that states, "Planning is looking at what we have to do today to be ready for an uncertain tomorrow." While climate change and variability are not explicitly mentioned in either the plan or the STIP and the major effects of climate change may not occur within the plan's current 30-year timeframe, the stage certainly is set to both recognize and respond to potential issues of climate change.

Following Hurricane Rita, the Governor of Texas established a task force on evacuation, transportation, and logistics. The report of this task force was completed and submitted on February 14, 2006. Twenty recommendations are made, including the development of contraflow plans for nine major hurricane evacuation routes:

1. U.S. 69, north out of Beaumont to Lufkin;
2. I-10, west out of Houston to San Antonio;
3. I-45, north out of Galveston Island;
4. I-45, north out of Houston to Dallas;
5. U.S. 290, northwest out of Houston to Austin;
6. U.S. 59, northeast out of Houston to Nacogdoches;
7. I-37, northwest out of Corpus Christi to San Antonio;
8. U.S. 281, from Brownsville through McAllen to San Antonio; and
9. U.S. 83, from Harlingen to the intersection with U.S. 281 in McAllen.

Evacuation routes represent one element of the operations and system management portion of the long-range transportation plan for the Houston-Galveston metropolitan area, with extra points given to evacuation routes in the prioritization ranking of projects. Short-term recommendations to improve evacuation capabilities were developed in 2006. Longer-term evacuation priorities also are being assessed, "some of which may require significant public investment over many years." These may include new evacuation routes, reconstruction of existing evacuation routes, and reduction in the number and severity of traffic bottlenecks. The location of new development in flood and storm prone areas also is arising as an issue.

Essentially all of the plans recognize the environmental impacts (excluding climate change) and issues related to transportation growth and expansion. The Louisiana long-range transportation plan defines 57 "mega projects," whose evaluation criteria for development and implementation include environment, demonstrating context-sensitive design and/or sound growth management principles, and emergency evacuation capabilities. Nine of the 22 Priority "A" mega projects involve I-10, including construction of a six-lane I-10 Twin Span across Lake Pontchartrain. Other Priority "A" mega projects located in evacuation areas include upgrading I-49 south of Lafayette and construction of a new two-lane road between U.S. 90 and LA 3127.

The Houston-Galveston long-range transportation plan identifies eight distinct ecological zones within the region and pays particular attention to the wetlands, which protect shoreline areas from erosion and serve as buffers from flooding.

5.1.4 Interviews with Transportation Representatives in the Gulf Coast

To better understand some of the issues and concerns transportation planners face in the Gulf coast, two sets of interviews were conducted. The first was conducted in spring 2006 to get general impressions on the issues of adaptation and climate change in the transportation context. These interviews involved all four state DOTs and 6 of the 10 MPOs, including large, medium, and small MPOs.

The second set of interviews was conducted between December 15, 2006 and January 10, 2007 to understand in more specific terms the issues facing the area selected for more intense study in Phase 2 of this effort. These interviews included a representative of each of the transportation modes represented in the site study area. The objective of the study site interviews was to consider the potential climate impacts at the level of the individual decision-maker/planner. This information was used to develop and refine the conceptual framework for assessing potential impacts on transportation presented below. There were three general lines of inquiry used to generate a localized picture of climate change impacts and transportation decision-making:

1. **Interviewees' Perspectives on Climate Change –** Respondents were asked about their perception of climate change, its potential impact on the respondent's specific facility or system, and whether or not the respondent currently was incorporating climate change and variability science or indicators in their decision-making and planning.

2. **Decision and Planning Processes in which Respondents are Involved –** Interviewees were asked to describe the types of decisions they are engaged in at the facility and/or system level in their area of responsibility. The interview guide solicited responses in regard to the factors that were the most relevant to making facility or system decisions, the role of the respondent in the local decision and planning process and interactions

with the state and Federal processes, what information was used for informing these decisions, and what threshold or tipping point factors would facilitate changes in policy or planning, both from the climate perspective and in general.

3. **Utility of the General Project Report Findings –** Respondents were asked their opinions regarding the applicability of the climate scenarios and various report concepts that might be used in their analysis. The respondents were presented with a two-page summary of study findings – including climate scenarios for the study area, and the assessment of exposure, vulnerability, and resilience – for their review and input.

The interviews were designed and conducted according to standard social science research methodologies and practices. The questions were open ended in order to solicit as broad as possible a range of responses.

The interview subjects were contacted and interviewed using a questionnaire approved by the Texas A&M University Institutional Review Board. As such they were informed that their expressed opinions and any information they provide would be kept confidential and that they were free to refuse to answer any questions that made them uncomfortable. Because of the size and public nature of the research area, only limited references are made to the positions of these individuals within the hierarchy of their system or institution.

Fourteen individuals were interviewed, four of whom provided general context information on climate change and variability and the Galveston County area, and 10 of whom were formal interview subjects. These included:

- An employee of Transtar, the Houston Traffic Management Center;
- An individual responsible for evacuation in the Galveston County area,;
- A representative of a toll road authority;
- Employees of the City of Houston Aviation Department;
- A County Engineer;
- Employees of the Texas Department of Transportation (TxDOT); and
- Employees of the Ports of Galveston and Houston.

Interview Responses

Significance of Climate Considerations – Although the respondents were comfortable with the idea that climate conditions would be changing in the Gulf Coast area, most respondents reported that climate was not an issue that they considered in development of the plans and TIPS. The perceptions of the respondents were that climate change is an issue that has been of limited concern to the state and Federal agencies that affect their decision-making. Yet responses varied. Representatives of at least one agency indicated a strong belief that climate change should be treated as an issue of importance in the transportation planning of the region. In contrast, others indicated that climate change is not an issue that has received any official treatment. Several interviewees felt that future consideration of climate change would be directed by guidelines established by the Federal government.

None of the interview subjects indicated they were using climate change data in their transportation decision-making. However, the entire sample of interview subjects was convinced that climate change is a matter of some concern.

Value of Climate Information – The general project synthesis report findings were of some use to the interview subjects. At least one interview subject indicated they had not concerned themselves with climate change until they saw the predictions for sea level and storm surge in the Galveston County area. The value of the specific predictions varied from one respondent to the next. Many respondents found sea level rise and storm surge information to be useful, however, they would like the projections to be for time periods more applicable to their own decision-making timeframes. At least one respondent suggested that the elevations for storm surge and sea level should be selected from a range more relevant to the Galveston County area. Much of Galveston County is at an elevation of 4.6 meters (15 feet); the 5.5 meter (18-foot) threshold used in the storm surge map was not as relevant as this decision-maker would like.

Perceived Importance of Individual Climate Factors – The degree to which respondents considered various climate stressors to affect the transportation infrastructure modes for which they were responsible is characterized in Table 5.2 with a scale of low, limited, moderate, high, and highest perceived concern.

[Insert Table 5.2 Level of decision-maker concern about climate stressors]

The high degree of concern exhibited by all respondents about *storm frequency and magnitude* as a stressor betrays the strong affective power of recent hurricanes on the hazard perceptions of respondents in the Galveston and Harris County area. The majority of subjects expressed their concern for storm frequency and magnitude in regards to the capacity of their infrastructure mode of responsibility to fully function during a hurricane evacuation, or in the case of the port, to be evacuated. An exception was the flood control subject who shared this fear, but was primarily concerned about the ability of the drainage system to cope with severe storms.

Temperature was of limited importance to the respondents with the exception of the Transtar subject who described his equipment as tested and hardened against temperature extremes and the airport representative who described temperature as a key variable in airport performance measures. The other airport representative was not as concerned about temperature. We account for this variation as a function of their respective roles. The second representative is involved in construction and does not directly grapple with operations logistics. Operations logistics are heavily determined by temperature as increased temperature reduces lift and results in an increase of the airport facility's average annual delay of departures.

Average precipitation was of limited importance to many of the respondents in comparison to *extreme precipitation* events. Of special interest was the flood control engineer who indicated increases or decreases in average precipitation have limited effect on flooding. His concern was principally with precipitation events that could be categorized as high in intensity, frequency, and duration. The one interview subject who was directly and seriously concerned with overall precipitation levels was the port engineer, who linked average levels of precipitation to the sedimentation of port channels. The second port engineer and manager were concerned with precipitation as well, especially with the consequences of port runoff for local flooding.

Sea level was of high importance to many of the interview subjects. The factor that governed the strength of this concern was proximity to the coast, moderated by the relative imperviousness of the infrastructure in question. For example, the toll road authority representative expressed a potential concern about sea level as the toll facility does approach the coast, however, this facility was designed to be elevated well above the surge levels predicted in the climate and vulnerability summaries, as well as the levels to which this respondent was previously familiar. Other respondents had broader purviews of responsibility such as multiple highways, the evacuation of residents, and facilities near sea level. These respondents expressed high concern about sea level rise. The port representatives characterized their concerns about sea level rise differently. One port engineer was highly concerned about sea level rise, but this respondent noted his concern was coupled with his concern about local subsidence. The second port interview subject could imagine sea level rise having an impact on the region, however, the infrastructure elements of concern – piers – were rebuilt often enough that only a catastrophic degree of sea level rise would have any impact. This respondent explicitly stated that such an event was highly unlikely.

The responses in regards to questions about decision-making thresholds were fairly uniform. Interview subjects suggested the impetus to make fairly radical policy shifts could only come from higher levels of government, and usually in response to a disaster. Otherwise, they simply did not have the autonomy, or the access to funding, to adopt new policies or planning approaches.

Since these interviews were conducted, however, there appears to have been a shift in some of the expressed opinions due to the impacts of Hurricanes Katrina and Rita. As detailed in Chapter 4.0, the rebuilding of certain facilities, like Highway 90 in Mississippi, have taken into account the likely impacts of future storms. Further the activities and opinions expressed to the study authors by state and local authorities indicate a much greater appreciation for the potential impacts of climate change than those of the interviewees.

The involvement of private users and providers of freight transportation in these interviews was limited. Employees at two public ports using private facilities and a private toll road authority representative were interviewed. However, the private sector's involvement in the next phase of the study will be substantially expanded to capture specific impacts and adaptation activities. Also, additional insight to private sector impacts and adaptation considerations were learned from other regions of the study area in the aftermath of Hurricane Katrina. As an example, the CSX railroad received extensive damage on the Gulf Coast particularly in Mississippi and Louisiana and had to consider alternative adaptation strategies such as rerouting, rehabilitation with strengthening or relocation further inland.

5.1.5 Challenges and Opportunities to Integrating Climate Information

Transportation agencies consider a broad range of future conditions, including demographic, environmental, economic, and other factors. It is within this broader context, that it is reasonable for some agencies to address the additional consideration of climate change over the lifetimes of their transportation facilities, to the extent possible.

Over time, fundamental and significant changes may be desirable in the manner in which long-range transportation plans are developed and investment decisions are made. Similar to what transportation agencies are now doing to address freight, safety, economic development, environmental mitigation, and other emerging issues, considerations of climate change can be incorporated in each step of the transportation planning process particularly during the earliest parts of the planning process – the formulation of a vision and the development of goals and objectives.

5.1.5.1 Timeframes

Long-range transportation plans are developed with a time horizon that typically extends 20 to 30 years into the future. Most long-range transportation plans being developed today have time horizons of 2030 or 2035. However, as illustrated in Figure 5.4, individual facilities being recommended in those plans will be designed with a considerably longer service life. For instance, bridges being built today should last 60 to 80 years or more. Furthermore, bridges being proposed in the long-range plans will be designed to last beyond 2100. Although the timeframe for significant climate change might appear to be longer than most plan horizons, studies have found that the effects of climate change are being experienced today. And while climate change is typically thought of as a gradual, incremental process over many years, scientists expect that climate changes are likely to include abrupt and discontinuous change as well. To begin to adequately consider the implications of climate change, transportation planners would benefit from consideration of longer time horizons. Climate changes over longer time periods could be addressed as part of a long-term visioning that helps determine where transportation investments are needed and should be located. It would thus inform the transportation planning process with supplementary information. For example, in the planning process depicted in Figure 5.3, climate change could be added to the vision step at the beginning of the process along with other factors such as economic and environmental considerations.

While it is difficult to know the planning horizons of private companies, given their proprietary nature, it is likely that their focus would benefit from an expanded time horizon, as well. Since the infrastructure likely affected by future climate impacts is currently under development, planners and decision-makers need to start now in considering how climate changes may affect them.

[Insert Figure 5.4: Relationship of transportation planning timeframe and infrastructure service life to increasing climate change impacts]

5.1.5.2 Land Use

Responding to the potential effects of climate change, as demonstrated by the ongoing discussions in Texas, Louisiana, and Mississippi, may involve changes in the location of transportation facilities, housing, and business. Transportation planning already attempts to forecast these types of demographic and economic shifts. Potential changes in the future climate and its resulting impacts on the existing ecology may make such forecasting far more difficult.

A further challenge for transportation planners and climate scientists is to better understand the interplay of the built environment with the local ecology toward the betterment of both. For example, barrier islands serve to protect existing infrastructure by reducing the impacts of major storms. Preservation of these ecologically sensitive coastal wetlands areas is one way of minimizing damage from hurricanes by restoring critical buffer areas that absorb storm energy. Similarly, a variety of human activities are contributing to the current and projected rate of land subsidence, including, but not limited to the location and management of navigation channels. The impacts of climate change will likely make understanding and protecting these natural systems even more important not only for their own sake, but to prolong the viability of transportation infrastructure. The development of the full range of port, pipeline, shipping, and their supporting land transportation infrastructure can be examined for their potential to either directly or indirectly affect coastal areas. In essence, this is extending the concept of “secondary and cumulative effects” to include coastal ecology and storm protection. Similarly, strategies proposed to protect coastal areas should be screened for potential implications on the transportation system.

5.1.5.3 Institutional Arrangements

Existing institutional arrangements may not be sufficient for transportation agencies to fully address and respond to issues of climate change. Increased collaboration may be necessary for transportation planning and investment decision-makers to effectively respond to climate change issues, including, partnering with climate change specialists. State DOTs and MPOs already are consulting with resource agencies such as natural resources, conservation, and historical preservation in the planning process. Collaborating on climate change might be a natural extension of that consultation process.

It also will be necessary for state DOTs to collaborate within their agencies so that planning, engineering and programming have a common understanding of the potential for climate change and the alternative responses possible. Likewise, the MPOs need to accomplish a similar effort with their members – local governments. Finally, for the vast amount of the transportation system owned by private agencies, climate change information must be made available to them so that their decisions can be coordinated with and compliment those of the public sector. In some cases, this may lead to public/private investment options.

5.1.5.4 A New Approach

Based on currently available climate change information, there appear to be important implications of climate change for the manner in which transportation investments are planned, developed, implemented, managed, and operated. This report shows that these implications are sufficiently significant that transportation planners should develop an improved understanding of climate change issues and reflect them in their decision-making today.

Yet the long timeframe for climate change, as compared to the existing 20-year view of most transportation plans, makes the specification of its impacts considerably more difficult. Instead of relatively precise estimates of potential impacts needed for many aspects of transportation planning, broad ranges are more typically what climatologists currently can provide. Given this lack of certainty, climatologists are moving toward the determination of probabilities of potential impacts.

Currently, the transportation planning process does not consider probabilities in determining future travel demand and ways to meet it.[3] Instead, transportation professionals generally rely on more deterministic methods that yield a single answer based on the inputs, well accepted engineering, construction, and other standards, and professional judgment.

Such methods are ill-equipped to addressing the uncertainties associated with the timing and magnitude of many climate change impacts. What is needed are new tools that can address the uncertainties associated with climate change and yet provide more useful information to the transportation community that would be used to create a more robust and resilient system.

The following section provides a conceptual approach that represents the first step toward development of such a tool. It suggests a new approach to viewing both individual transportation facilities and the system as a whole, borrowing concepts and relationships from ecology, risk management, decision theory, and transportation practice. It proposes a way to help planners, designers, and engineers think through the potential harm that changing conditions in the natural environment might cause and the ability of the existing and proposed facilities to withstand such harm.

[3] Steps have been made in this direction with the development of TRANSIMS, which employs sampling and statistical methods to generate future travel demand. However TRANSIMS is not yet in general use.

■ 5.2 Conceptual Framework for Assessing Potential Impacts on Transportation

While climate factors are not usually considered for transportation planning purposes, as shown in the previous section, some agencies are beginning to explore how they might be incorporated. This section attempts to provide a conceptual approach to how climate concerns – with their inherent uncertainties – might be addressed in a transportation context. This is a first step toward creation of a way to consider risk and uncertainty in transportation planning as an alternative to the largely deterministic approaches currently employed. Further refinement will be necessary in Phase 2 of this study to make this approach operational in a pilot test area.

While the focus of this project is on a portion of the U.S. Gulf Coast, the intent is to develop a conceptual framework that lays the groundwork for an assessment linking climate change and transportation, and to focus on this nexus using a specific case as an illustration. Climate change impacts vary by region, with some areas being more vulnerable to some aspects of exposure than others. Regardless of the specific site characteristics related to this chapter, the general framework and relationships between information, decision-maker, and process will be transferable to other situations. Developing a conceptual framework at this stage in the research, rather than a static tool or model, provides the transportation sector with the basic understanding of these relationships at this early stage of recognition of the potential impacts of climate change and variability on transportation infrastructure.

This section focuses on: 1) a description of the basic factors that can be useful in an assessment of the potential impacts of climate change on transportation; and a 2) description of the development of a conceptual framework incorporating these basic components.

5.2.1 Factors of Concern: Exposure, Vulnerability, Resilience, and Adaptation

There are four major conceptual factors to consider climate concerns in transportation: exposure to climate stressors, vulnerability, resilience, and adaptation. These concepts and their definitions are borrowed from, and consistent with, ecological and hazard assessment practices and represent transportation infrastructure's probable levels of exposure to damage from climate change factors, its capacity to resist such damage or disruption of service, and its ability to recover if damaged. For purposes of this project, we adapted the Intergovernmental Panel on Climate Change (IPCC) definitions of these concepts, in general, with reference to applied and theoretical applications for more specific or articulated examples. It was determined by the research team to closely approximate the IPCC terminology and methodology, as this also informs many other regional and sectoral assessments conducted in the United States and elsewhere.

With specific regard to climate change, *exposure* comprises the "nature and degree to which a system is exposed to significant climatic variations" (IPCC, 2001). Exposure also is often articulated as the probability of occurrence (the probable range of climate change stressors, such as sea level rise or increased rainfall) and the physical characterization of the local area. In this study, *exposure* is the combination of stress associated with climate-related change (sea level rise, changes in temperature, frequency of severe storms) and the probability, or *likelihood*, that this stress will affect transportation infrastructure.

While there are different kinds of exposure, (see Tobin and Montz, 1997, for a discussion), two types are applicable to this approach: perceived (based on the situational perspective of the particular decision-maker) and predicted (based on "objective" measures). For predicted exposures, the following environmental impacts appear to be most relevant in the Central Gulf Coast Region, depending on the specific infrastructure component and location:

- Sea level rise, historic trends, and predicted range (including rates of subsidence and/or erosion;
- Temperature range, scenarios, and probability distribution functions (with special consideration to changes in extreme temperatures);
- Precipitation range, scenarios and probability distribution functions and intensity; and
- Major storm characteristics (projected magnitude of storm surge and winds, and frequency).

Vulnerability, in general, refers to the "potential for loss" (Tobin and Montz, 1997) due to *exposure* to a particular hazard. The IPCC defines vulnerability as: "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC, 2001). More specifically for this project, vulnerability considers the structural strength and integrity of key facilities or systems and is defined as the resulting potential for damage and disruption in transportation services from climate change stressors. The vulnerability of a facility or system then depends on the level of exposure to which it is subject.

The risk that a transportation facility or a system faces can be defined from these notions of exposure and vulnerability. It is the product of the probability that a facility will be exposed to a climate stressor of destructive (or disruptive, at the systems level) force times the damage that would be done because of this exposure.

While transportation is frequently thought of as the built infrastructure, transportation's value to society is the service or performance this system of facilities and operations provides to move goods and people. Loss of capacity is the reduction from full performance capacity for a particular transportation system or facility. For example, Berdica (2002) defines vulnerability to the road system as a "problem of reduced accessibility." System vulnerabilities to specific locational risks will vary based on the performance expectations of those specific system segments. The loss in performance would be the reduction of system capacity measured according to the relevant metrics. For example, highway capacity would be measured in volume of traffic flow; a loss in performance would be gauged by the reduction of traffic flow capacity.

It is important to note that vulnerability, like exposure, may be perceived differently among stakeholders and across modes. Key factors for the determination of transportation facility or system vulnerability may include:

- Age of infrastructure element;
- Condition/integrity;
- Proximity to other infrastructure elements/concentrations; and
- Level of service.

The concept of *resilience* is used to refer to the restoration capacity of the infrastructure at the facility and system level. In general, resilience is defined as the "amount of change a system can undergo without changing state" (IPCC, 2001). In the climate change context, resilience also refers to regenerative capacity, the speed of response and recovery of various system elements, and mitigation and adaptation efforts. It also is generally considered to be a "multidimensional concept, encompassing biogeophysical, socioeconomic and political factors" (Klein et al., 1998). Adger, et al., define resilience more specifically as the capacity of a system to absorb disturbances and retain essential processes (2005).

We can apply these concepts to the transportation context. System-level resilience is particularly important in the transportation sector because of the inherent connectivity of transportation facilities. Resilience can be looked at as the ability of a transportation network to maintain adequate performance levels for mobility of goods and services through redundant infrastructure and services. The fact that one component is out of service may not be crucial in areas where alternative transportation facilities or services are available. For an individual facility such as a road or bridge, resilience can be thought of as how quickly full service can be restored either through repair or replacement.

Key factors influencing resilience in our conceptual framework can be categorized across three dimensions: mode or structure (highway segment or port, for example), socioeconomic (political will and resources), and system-level factors. These factors may include:

1. Mode/structure:
   - Repair/replacement cost; and
   - Replacement timeframe.

2. Socioeconomic:
   - Public support;
   - Interorganization cooperation;
   - Economic resources; and
   - Social resources.

3. System level:
   - Redundancy among components;
   - Essential service resumption;
   - System network connectivity;
   - Institutional capacity; and
   - Relevance of existing plans for response to events (e.g., floods).

Transportation planners and decision-makers may consider these factors (either formally or informally) and generate a basic perception of resilience. For example, for any given facility the relevant decision-maker would have a general idea as to: 1) how much replacement would cost; 2) how long it would take; 3) the economic resources available for replacement; 4) public sentiment regarding replacement (or not); 5) how essential the facility is to system performance; and 6) whether or not plans exist for dealing with disruption of facility and/or system performance over the duration of the replacement time. This understanding of the resilience of the facility or system can be based on either a general feeling and experience of the decision-maker, of it can be developed systematically with quantifiable measures.

The IPCC defines *adaptation* as the: "adjustment to natural or human systems to a new or changing environment. Adaptation to *climate change* refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2001). An associated concept, *adaptive capacity*, refers to "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC, 2001).

In this project, we are interested in understanding adaptation as a decision that officials can make in response to perceptions or objective measurements of vulnerability or exposure. For example, given a certain climate change scenario, a decision-maker may choose to advocate for certain adaptive policy responses beyond the status quo. This can be determined through interviews by asking such questions as: what is the planning horizon for this specific area, what factors (political and resource) constrain or encourage adaptive behavior in this area of concern, and what are the stakeholder perceptions of uncertainty in regard to the data and information provided and available for informed decision-making (see Jones, 2001, for an example).

Adaptive strategies can be further delineated into three possible alternatives: protect, accommodate, and retreat. These adaptive responses are derived from the IPCC framework for assessing coastal adaptation options (Bijlsma et al., 1996). Within the context of our case study which is in a coastal region, the *protection* strategy might aim to protect the land from the sea so that existing land uses can continue, by constructing hard structures (e.g., seawalls) as well as using "soft measures" (e.g., beach nourishment, wetland restoration). *Accommodation* may call for preparing for periodic flooding by having operational plans in place to redirect traffic, for example, or cleaning up roadway obstacles to return to normal service. The *retreat* option would involve no attempt to protect the facility from the climate stressor. In an extreme case along a coastal area, for example, a facility or road segment could be abandoned under certain conditions (sea level rise, persistent storm surges that reduced the feasibility of replacement). From a system perspective, it could be determined that retreat is the best decision if the road segment could be relocated without loss of system service, if performance can be maintained through other system components, or if service is no longer required due to shifts in population and commerce.

A related concept, *threshold*, also will be considered in the framework. Threshold has been defined as "the point where a stimulus leads to a significant response" (Jones, 2001; Parry, Carter, and Hulme, 1996). In the case of transportation decision-making, we are interested in determining at what point within an assessment or decision process change is induced. A threshold can be quantified under certain circumstances (for example, the impact of temperature on pavement construction decisions), or it may be subjective, depending on the situation. Jones (2001) suggests two general thresholds for infrastructure: 1) economic write-off, or when replacement costs less than repair; and 2) a standard-derived threshold, when the condition of the infrastructure component falls below a certain standard. These variables can have both quantitative and qualitative characteristics. In this phase of the research, the focus is on determining qualitative characteristics and their general utility to decision-makers (see Cutter, et al, for a similar approach).

In summary, the following are working definitions that were applied in this section of the research. These definitions were developed in conjunction with the research team, the Federal Advisory Committee, and other experts.

Exposure – The combination of stress associated with climate-related change (sea level rise, changes in temperature, frequency of severe storms) and the probability, or *likelihood*, that this stress will affect transportation infrastructure.

Vulnerability – The structural strength and integrity of key facilities or systems and the resulting potential for damage and disruption in transportation services from climate change stressors.

Resilience – The capacity of a system to absorb disturbances and retain essential processes.

Adaptation – A decision that stakeholders can make in response to perceptions or objective measurements of vulnerability or exposure. Included in this concept is the recognition that *thresholds* exist where a stimulus leads to a significant response.

Each of these four factors is critical in our understanding of how climate change may impact transportation in the study region. As illustrated in Figure 5.5, an initial risk assessment for a facility or system will include analysis of the first three factors: exposure, vulnerability, and resilience. Once a risk assessment is conducted, choices for an appropriate adaptation strategy can be considered. The implementation of a particular adaptation strategy – to protect, accommodate, or retreat – will in turn affect subsequent risk assessments by changing one or more aspects of risk. The effectiveness of the adaptation strategy can be assessed by the degree of success in maintaining system or facility performance.

[INSERT FIGURE 5.5: A risk assessment approach to transportation decisions]

5.2.2 Framework for Assessing Local Climate Change Impacts on Transportation

Having introduced the major factors for consideration in a climate change impact assessment, this section introduces the conceptual framework and outlines the input and outputs. This is followed by a description of an approach to implementing such a framework.

In general, the objective is to illustrate how climate change/variability can be integrated into existing transportation policy- and decision-making processes toward the development of adaptation strategies. Even at the conceptual level, this process can assist transportation decision-makers in considering the potential impacts from climate change and variability on a wide range of transportation infrastructure components of any type, including air, rail, marine, transit, or highway, as well as the overall intermodal system. It is intended to be implemented primarily at the state or local scale, since climate impacts differ by region of the country.

The framework can help direct local decision-makers in raising and to some extent answering such questions as: what are the likely changes in sea level (for example) in my area, how vulnerable is the transportation infrastructure related to this probability in my area, and at what point should decision-makers seek adaptive strategies to address this? The resulting information can then be utilized for making adaptation decisions.

5.2.2.1 Needed Data

Previous chapters outlined the physical, infrastructure, and socioeconomic data that was collected and aggregated specifically for the Gulf Coast study area. This section discusses how this data serves to help assess the exposure and vulnerability of any transportation network. While not all of the data collected for this project would be available to local transportation stakeholders, much of the data is available and is being update on a regular basis.

Within this conceptual framework, the analysis begins with an assessment of what climate impacts can be determined with a relatively high degree of confidence. This is the basis for the exposure analysis, including some idea as to the probability that transportation facilities will be exposed to particular impacts. For the Gulf Coast Study, various climate scenarios were analyzed and probable impacts identified at the regional level, including sea level rise, increased storm intensity, extreme temperature increases, and potential ranges quantified. The infrastructure and services will be exposed to these impacts.

The vulnerability of specific portions of the transportation infrastructure will depend on its location relative to the location of the impacts, as well as other characteristics. Sea level rise is a good example, as coastal infrastructure will be more vulnerable than inland facilities. Based on location, the physical characteristics of the region, and socioeconomic data, the vulnerability of transportation facilities can be assessed.

From the probability of an exposure to a climate impact and the assessment of vulnerability, some idea of the risk the facility or the system faces can be determined. In order to do this, repair or replacement costs, economic losses, or other metric of potential damage must be developed. In addition, precise estimates of risk would require quantitative estimates of exposure would be needed. Whether risk can be quantitatively determined remains to be seen.

Resilience was not addressed in the first phase of the Gulf Coast analysis, but will be in the second phase. The analysis of resilience requires different data for systems versus facility consideration. At the systems level, an in-depth knowledge of the movement of goods and people is necessary to assess the potential for redundant services that can at least minimally maintain service. For facilities, the time and cost needed to bring damaged infrastructure to full performance would be critical.

5.2.2.2 Outcomes

Having considered how transportation facilities might be exposed and determined their vulnerability and the resilience of the network, decision-makers can then consider ways to improve transportation in the region to be more robust to the climate impacts identified.

The primary outputs from the conceptual framework are policy recommendations or changes derived from the decision-makers understanding and interpretation of the major factors (exposure, vulnerability, and resilience and adaptation) associated with climate change. Where appropriate, these recommendations should lead to capital, maintenance, or operational improvements that will result in a more robust and resilient network.

The process of following the framework can be used to characterize the exposure of particular facility or system component to climate hazards, the vulnerability, and resiliency of these elements, and the adaptation options available to the decision-maker. Examples of potential thresholds or tipping points indicated for each of these factors targeted at each relevant transportation infrastructure element can then be used as input into the planning and decision processes available to the user. This output from the conceptual framework could be designated for the local level or state DOT level of planning. It will be up to the stakeholder or decision-maker to determine how the assessment output would impact existing or proposed decision and planning processes at the relevant scale.

Figure 5.6 illustrates the relationship between risk assessment and the value of performance to the type of adaptation strategy that may be selected. As the importance of maintaining uninterrupted performance increases, the appropriate level of investment in adaptation should increase as well, taking into account the degree of risk facing the specific facility or system. For example, maintaining a specific bridge may be essential to ensure safe evacuation of a particular community, because no other feasible evacuation routes or back-up strategies are available. In this instance, transportation and regional planners may recommend that more conservative (and possibly more expensive) design standards be applied to protect that bridge in the event of a low probability – but high consequence – storm event in that location. Conversely, although a road segment may be assessed to be highly at risk, it may warrant less extensive adaptation investment because alternatives to that road are available to provide access and mobility, or a moderate disruption in service performance is not considered to be critical.

[INSERT FIGURE 5.6: Degree of risk and value of performance inform level of adaptation investment]

5.2.2.3 Making Use of Risk Assessment in Transportation Decisions

The concepts presented in this chapter can be employed to begin the assessment of climate impacts in transportation planning and investment. Additional detail will be required for implementation, but this discussion offers an initial step toward a more complete consideration of risk and uncertainty in this type of assessment. As demonstrated, probabilities for some climate impacts are now available on a regional level, but probabilities for specific impacts on individual facilities or network components cannot yet be assigned with confidence. Furthermore, while some climate impacts can be reliably identified, data are lacking for others that may be important for transportation. Nonetheless, even at the conceptual level, this discussion may be useful for transportation planners as they begin to incorporate climate concerns in their consideration of new investments.

Consider the following example of a bridge located near the coast that is scheduled for rehabilitation in five years. Based on the conceptual framework, the first step is to determine its exposure to stressors that may significantly impede the service it provides.

If the bridge were located within the Gulf Coast study area, the analyses in Chapters 3.0 and 4.0 indicate the four main stressors of concern: sea level rise, storm surge, temperature increases, and heavy downpours giving rise to flooding. There may be others as well, and the analyst would do well to consider other potential impacts in consultation with natural resource experts.

If the bridge falls within the area identified as likely to be flooded by a 61 to 122 cm (2- to 4-foot) rise in sea level, more specific examination of the particular terrain is warranted to assess in greater detail the likelihood of flooding. If there are no mitigating factors, there is a relatively high probability that the area will flood within a 50- to 100-year time period.

The next step is to determine the bridge's vulnerability to sea level rise. How high is the bridge? How high are the approaches? How critical is the service it provides? Based on these and other considerations, the bridge's vulnerability, in the context of its role within the larger network, can be assessed. If the bridge, or critical elements of it, are below 122 cm (4 feet), it will likely flood within its projected lifespan. While more objective measures of vulnerability to the service flowing over the bridge would be desirable, at a minimum the analyst should be able to derive a qualitative determination of the bridge's vulnerability.

Judgment must be applied to assess the risk (probability of exposure x vulnerability) posed by flooding with current knowledge. Precise estimates of its components are not possible but the direction and likely ranges are known and from this a general sense of the risk can be inferred. If the bridge is heavily trafficked and it is vulnerable, the risk is high because the sea is rising leading to permanent flooding and the bridge's period of service will be cut short before it reaches the end of its useful life. Since in the example, the bridge is scheduled for rehabilitation, now would be an appropriate time to consider options.

The adaptation options are to protect, accommodate, or retreat. Accommodation, which might include operational strategies to work around the flooding or simply living with it, does not appear to be viable since the flooding is permanent and operational strategies like pumping the water out do not seem viable. Protection may include raising the bridge or its approaches or relocating the facility. Retreat, which in this case amounts to abandonment of the bridge, is likely the option of last choice since the bridge presumably provides a critical service. Engineering, design, landscape, and regional considerations will play crucial roles in the determination of the best option, as will the consideration of the additional resources necessary to best protect the bridge. Transportation agencies have extensive experience in exercising the judgment necessary to make these determinations.

In similar fashion, each of the stressors can be assessed for their likelihood and the bridge examined for its vulnerability. Risk can be determined and options identified to prolong the bridge's useful life and minimize disruptions to the critical service it provides. For stressors whose impacts are well understood, a higher level of analysis can and should be done to consider the potential for synergistic impacts that may be more severe than the individual effect. The end result of the analysis will be recommendations for investment whose implementation will result in a more robust and reliable transportation facility and system. Experience indicates that the total cost to transportation agencies will probably be lower than failing to consider these impacts when the full costs – capital, operating and economic loss due to disrupted service – are included.

■ 5.3 Conclusions

Climate change and variability have not historically been considered in the planning and development of transportation facilities, and this was clearly expressed in the interviews conducted as part of this study. Until recently, it may not have been possible to effectively use climate data to serve as the basis of considerable capital investment due to its relative uncertainties. That appears to be changing. The destructive force of Hurricanes Katrina and Rita have underscored the need to carefully consider the effects of the natural environment on transportation to a much higher degree. State, local, and possibly private (though less is known about their myriad approaches) transportation agencies are beginning to incorporate more information about the natural environment, including those effects wrought or exacerbated by climate change.

With the advent of increasingly greater certainty about the regional effects of climate change and better tools to assist their examination, the prospects for analyzing the impacts of climate and the natural environment has become possible. Clearly there is benefit to do so. Subsidence and climate-induced sea level rise, coupled with the likely increased severity of hurricanes, threaten infrastructure potentially causing severe disruptions to essential transportation services or cutting short the useful lives of important facilities. Transportation planners across the United States would do well to follow the lead of progressive agencies in the Gulf Coast and other places to begin immediately to consider the impacts of climate change on the natural environment and thus on transportation facilities under their purview.

This chapter introduces a taxonomy and conceptual approach toward fulfilling this need. Standard deterministic approaches used in transportation planning will not suffice to address the timeframes and uncertainties that a changing climate poses. The approach is based on the quantitative or qualitative assessment of exposure to potentially disruptive impacts, examination of a facility's (or a network's) vulnerability, the risk of its loss, and possible adaptation strategies to mitigate these impacts and prolong service. It is premature to consider any formal changes to the established Federal transportation planning process. If for no other reason, the timeframes and other requirements such as fiscal constraint do not mesh well. Nonetheless, the consideration of climate impacts is possible and useful to transportation plans at all levels of government and the private sector. For instance, in the planning process shown in Figure 5.3, climate change could be considered early on as part of a visioning process and later in the development and evaluation of alternative improvement strategies which consider future services and their location. Climate change could be considered in the project development process when design and engineering are addressed. Likewise, the concept of uncertainty and the use of risk analysis could be incorporated into the entire planning and project development process.

5.4 References

Adger, W. N., T.P. Hughes, C. Folke, S.R. Carpenter, and J. Rockström, 2005: Social-Ecological Resilience to Coastal Disasters. *Science*, 309 (5737):1036-1039.

Baumert, K., and J. Pershing, 2004: *Climate Data: Insights and Observations*. Pew Center on Global Climate Change, Washington, D.C.

Berdica, K., 2002: An Introduction to Road Vulnerability: What Has Been Done, Is Done, And Should Be Done. *Transport Policy*, 9(2):117-127.

Bijlsma, L., C.N. Ehler, R.J.T. Klein, S.M. Khlshrestha, R.F. McLean, N. Mimura, R.J. Nicholls, L.A. Nurse, H Perez Nieto, E.Z. Stakhiv, R.K. Turner, and R.A. Warrick, 1996: Coastal Zones and Small Islands. In: *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analysis*. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. [Watson, R.T., M.C. Zioyowera, and R.H. Moss, eds.] Cambridge University Press, Cambridge, United Kingdom, and New York, New York, USA, pages 289-324.

Cutter, S.L., 2003: The Vulnerability of Science and Science of Vulnerability. *Annals of the Association of American Geographers*, 93(1):1-12.

Cutter, S. L., J.T. Mitchell, and M.S. Scott, 2000: Revealing the Vulnerability of People and Place: A Case Study of Georgetown County, South Carolina. *Annals of the Association of American Geographers*, 90(4):713-737.

IPCC, 2001: *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. J.J. McCarthy, O.F. Canziani, N.A. Leary, et al. (Eds.). Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. New York, New York: Cambridge University Press. Page 944 [Available on-line at: http://www.ipcc.ch/]

Jones, R.N., 2001: An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessment. *Natural Hazards*, 23: 197-230.

Kelly, P.M., and W.N. Adger, 2000: Theory and Practice in Assessing Vulnerability to Climate Change and Facilitating Adaptation. *Climatic Change*, 47:325-352.

Klein, R.J.T., M.J. Smit, H. Goosen, and C.H. Hulsbergen, 1998: Resilience and Vulnerability: Coastal Dynamics or Dutch Dikes? *The Geographical Journal*, 164(3):259-268.

Levina, E. and D. Tirpak, 2006: *Adaptation to Climate Change: Key Terms*. Paris: Organisation for Economic Cooperation and Development/International Energy Agency.

Llort, Y., 2006: Transportation Planning in Florida. In: *Statewide Transportation Planning: Making Connections.* Transportation Research Circular E-C099, Transportation Research Board, Washington, D.C.

Omenn, G.S., 2006: Grand Challenges and Great Opportunities in Science, Technology, and Public Policy. *Science*, 314:1696-1704.

Parry, M., and T. Carter, 1998: *Climate Impact and Adaptation Assessment: Guide to the IPCC Approach*. Earthscan Publications, Ltd., London, United Kingdom.

Parry, M.L., T.R. Carter, and M. Hulme, 1996: What is Dangerous Climate Change? *Global Environmental Change*. 6(1):1-6.

Power, M., and L.S. McCarty, 1998: A comparative Analysis of Environmental Risk Assessment/Risk Management Frameworks. *Policy Analysis*, 32(9):224 A – 231 A.

Presidential/Congressional Commission on Risk Assessment and Risk Management, 1997: *Framework for Environmental Health Risk Management: Final Report*. The Presidential/Congressional Commission on Risk Assessment and Risk Management, Washington, D.C.

Scheraga, J.D., and J. Furlow, 2001: From Assessment to Policy: Lessons Learned from the U.S. National Assessment. *Human and Ecological Risk Assessment*, 7(5):1227-1246.

Schneider, S., J. Sarukhan, J. Adejuwon, C. Azar, W. Baethgen, C. Hope, R. Moss, N. Leary, R. Richels, J.P. van Ypersele, K. Kuntz-Duriseti, and R.N. Jones, 2001: Overview of Impacts, Adaptation, and Vulnerability to Climate Change. In: *Climate Change: Impacts, Adaptation, and Vulnerability, the Contribution of Working Group II to the IPCC Third Assessment Report (TAR) of the Intergovernmental Panel on Climatic Change* [J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White, eds.] Cambridge University Press, Cambridge, United Kingdom, 75-103.

Smit, B., I. Burton, and J.T.K Klein, 1999: The Science of Adaptation: A Framework for Assessment. *Mitigation and Adaptation Strategies for Global Change*, 4(3-4), 199-213.

Stern, P.C., and H.V. Fineberg, Eds., 1996: *Understanding Risk: Informing Decisions in a Democratic Society*. National Academies Press, Washington, D.C.

Tobin, G.A., and B.E. Montz, 1997: *Natural Hazards: Explanation and Integration*. Guilford Press, New York City.

U.S. Department of Transportation, 2006: *SAP-4.7, Prospectus for Impacts of Climate Variability and Change on Transportation Systems and Infrastructure – Gulf Cast Study*. Department of Transportation, Washington, D.C.

VTPI, 2006: *Online TDM Encyclopedia*. Victoria Transport Policy Institute, Victoria, BC, Canada. [On-line at: http://www.vtpi.org/tdm/index.php]