6.0 What Are the Key Conclusions of This Study?

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The primary objectives of this phase of the Gulf Coast Study were to assemble the data needed for an analysis of the potential impacts on transportation; determine whether climate and ecological data could be usefully employed in such an assessment; identify and implement an assessment approach; and provide an overview of the potential impacts. The results are striking. They show that the data can provide useful information to transportation decision makers about the natural environment as it exists today, as well as the likely changes stemming from climate shifts. By using the historical data on the natural environment, an ensemble of climate models, a range of emissions scenarios, well-established literature on climate impacts, and a conservative approach toward interpretation, this study indicates that the potential impacts on transportation in the Gulf Coast are highly significant, as summarized below.

While further study is needed to examine in more detail the impacts on specific transportation facilities, such as individual airports or rail terminals, this preliminary assessment finds that the potential impacts on infrastructure are so important that transportation decision makers should begin immediately to assess them in the development of transportation investment strategies. Phase II of this effort will examine one small part of the Gulf Coast study region in much more detail. While the significance of climate factors will vary across regions of the United States, responsible transportation agencies in other areas would do well to consider these types of impacts as well, since the decisions they make today may result in infrastructure that will last 50 to 100 years. While the timing and pace of these impacts cannot be specified with precision, the central Gulf Coast already is vulnerable to certain impacts, as demonstrated by the 2005 hurricane season.

Given the characteristics of the climate system – especially the long periods of time greenhouse gases remain in the atmosphere and the virtually certain increases in carbon dioxide concentrations in the coming decades – some degree of impacts cannot be avoided. Based on analysis of different emissions scenarios, the magnitude of future impacts will depend on the amount of greenhouse gases emitted. While the modeled scenarios demonstrate very similar levels of climate impacts over the next 40 years, lower emission scenarios show lesser impacts in the longer term (60 to 100 years). If aggressive measures result in reduced emission levels globally, the climate impacts identified here may be on the lower end of the anticipated ranges.

The study authors believe that prudent steps can be taken to fortify the existing transportation system, as warranted, after an evaluation of impacts on critical transportation facilities and systems. Structures can be hardened, raised, or even relocated as need be, and where critical to safety and mobility, expanded redundant systems may be considered as well. What adaptive strategies may be employed, the associated costs, and the relative effectiveness of those strategies will have to be determined on a case-by-case basis, based on studies of individual facilities and systemwide considerations. As transportation agencies struggle to meet the challenges of congestion, safety, and environmental mitigation – as well as maintaining transportation infrastructure in good repair – meeting the challenges posed by a changing climate poses a new and major hurdle toward creation of a more resilient transportation network in a time of increasingly scarce resources. Phase III of this effort will examine potential response strategies and develop methods to assist local decision makers in assessing the relative merits of various adaptation options.

■ 6.1 Trends in Climate and Coastal Change

The central Gulf Coast is particularly vulnerable to climate variability and change because of the frequency with which hurricanes strike, because much of its land is sinking relative to mean sea level and because much of its natural protection – in the form of barrier islands and wetlands – has been lost. While difficult to quantify, the loss of natural storm buffers will likely intensify many of the climate impacts identified in this report, particularly in relation to storm damage.

- **Relative Sea Level Rise –** Since much of the land in the Gulf Coast is sinking, this area is facing much higher increases in relative sea level rise (the combination of local land surface movement and change in mean sea level) than most other parts of the U.S. coast. Based on the output of an ensemble of general circulation models (GCM) run with a range of Intergovernmental Panel on Climate Change (IPCC) emissions scenarios, relative sea level in the study area is very likely to increase by at least 0.3 m (1 ft) across the region and possibly as much as 2 m (6 to 7 ft) in some parts of the study area over the next 50 to 100 years. The analysis of even a middle range of potential sea level rise of 0.3 to 0.9 m (2 to 4 ft) indicates that a vast portion of the Gulf Coast from Houston to Mobile may be inundated in the future. The projected rate of relative sea level rise for the region during the next 50 to 100 years is consistent with historical trends, region-specific analyses, and the IPCC 4th Assessment Report (2007) findings, which assume no major changes in ice-sheet dynamics.

  Protective structures, such as levees and sea walls, could mitigate some of these impacts, but considerable land area is still at risk to permanent flooding from rising tides, sinking land, and erosion during storms. Subsidence alone could account for a large part of the change in land area through the middle of this century, depending on the portion of the coast that is considered. Sea level rise induced by the changing climate will substantially worsen the impacts of subsidence on the region.

- **Storm Activity –** The region is vulnerable today to transportation infrastructure damage during hurricanes and, given the potential for increases in the number of hurricanes designated as Category 3 and above, this vulnerability will likely increase. This preliminary analysis did not quantitatively assess the impact of the loss of protective barrier islands and wetlands, which will only serve to make storm effects worse. It also did not consider the possible synergistic impacts of storm activity over a sea that has risen by 0.6 to 1.2 m (2 to 4 ft). This potential would likely make a bad situation even worse, as well.

- **Average Temperature Increase –** All GCMs used by the IPCC in its Fourth Assessment Report (2007) indicate an increase in average annual Gulf Coast temperature through the end of this century. Based on GCM runs under three different IPCC emission scenarios (A1B, A2, and B1), the average temperature in the Gulf Coast region appears likely to increase by at least 1.5 °C ± 1 °C (2.7 °F ± 1.8 °F) during the next 50 years, with the greatest increase in temperature occurring in the summer.

- **Temperature Extremes –** With increases in average temperature also will come increases in extreme high temperature. Based on historical trends and model projections, it is very likely that the number of days above 32.2 °C (90 °F) will increase significantly across the study area; this has implications for transportation operations and maintenance. The number of days above 32.2 °C (90 °F) could increase by as much as 50 percent during the next 50 years.

- **Precipitation Change –** Future changes in precipitation are much more difficult to model than temperature. Precipitation trends in the study area suggest increasing values, with some climate divisions, especially those in Mississippi and Alabama, having significant long-term trends. Yet while some GCM results indicate that average precipitation will increase in this region, others indicate a decline in average precipitation during the next 50 to 100 years. Because of this ambiguity, it is difficult to reach conclusions about what the future holds regarding change in mean precipitation. Even if average precipitation increases slightly, average annual runoff in the region could decline as temperature and evapotranspiration rates increase.

- **Extreme Rainfall Events –** Average annual precipitation increased at most recording stations within the study area since 1919, and the literature indicates that a trend towards more rainfall and more frequent heavy downpours is likely. At this stage, climate modeling capacity is insufficient to quantify effects on individual precipitation events, but the potential for temporary flooding in this region is clear. In an area where flooding already is a concern, this tendency could be exacerbated by extreme rainfall events. This impact will become increasingly important as relative sea level rises, putting more and more of the study area at risk.

■ 6.2 Transportation Impacts

Based on the trends in climate and coastal change, transportation infrastructure and the services that require them are vulnerable to future climate changes as well as other natural phenomena. While more study is needed to specify how vulnerable they are and what steps could be taken to reduce that vulnerability, it is clear that transportation planners in this region should not ignore these impacts.

- **Inundation from Relative Sea Level Rise –** While greater or lesser rises in relative sea level are possible, this study analyzed the effects of relative sea level rise of 0.6 and 1.2 m (2 and 4 ft) as realistic scenarios. Based on these levels, an untenable portion of the region's road, rail, and port network is at risk of permanent flooding.

  Twenty-seven percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports are at or below 122 cm (4 ft) in elevation, although portions of the infrastructure are guarded by protective structures such as levees and dikes. This amounts to more than 3,900 km (2,400 mi) of major roadways that are at risk of total inundation for the highway system alone. While flood protection measures will continue to be an important strategy, rising sea levels in areas with insufficient protection may be a major concern for transportation planners. Furthermore, the crucial connectivity of the intermodal system in the area means that the services of the network can be threatened even if small segments are inundated.

  While these impacts are very significant, they can be addressed and adaptive strategies developed if transportation agencies carefully consider them in their decisions. The effectiveness of such strategies will depend on the strategies selected and the magnitude of the problem because scenarios of lower emissions demonstrate lesser impacts. It may be that in some cases, the adaptive strategy may be wholly successful, while in others further steps may need to be taken. Adaptive strategies that can be undertaken to minimize adverse impacts will be assessed in phase III of this study.

- **Flooding and Damage from Storm Activity –** As the central Gulf Coast is already is vulnerable to hurricanes, so is its transportation infrastructure. This study examined the potential for short-term flooding associated with a 5.5- and a 7.0-m (18- and 23-ft) storm surge. Based on these relatively common levels, a great deal of the study area's infrastructure is subject to temporary flooding. More than half (64 percent of interstates; 57 percent of arterials) of the area's major highways, almost half of the rail miles, 29 airports, and virtually all of the ports are subject to flooding.

  The nature and extent of the flooding depends on where a hurricane makes landfall and its specific characteristics. Hurricanes Katrina and Rita demonstrated that that this temporary flooding can extend for miles inland.

  This study did not examine in detail the potential for damage due to storm surge, wind speeds, debris, or other characteristics of hurricanes since this, too, greatly depends on where the hurricane strikes. Given the energy associated with hurricane storm surge, concern must be raised for any infrastructure in its direct path that is not designed to withstand the impact of a Category 3 hurricane or greater.

Climate change appears to worsen the region's vulnerability to hurricanes, as warming seas give rise to more energetic storms. The literature indicates that the intensity of major storms may increase 5 to 20 percent. This indicates that Category 3 storms and higher may return more frequently to the central Gulf Coast and thus cause more disruptions of transportation services.

The impacts of such storms need to be examined in greater detail; storms may cause even greater damage under future conditions not considered here. If the barrier islands and shorelines continue to be lost at historical rates and as relative sea level rises, the destructive potential of tropical storms is likely to increase.

- **Effects of Temperature Increase –** As the average temperature in the central Gulf Coast is expected to rise by 0.5 °C to 2.5 °C (0.9 °F to 4.5 °F), the daily high temperatures, particularly in summer, and the number of days above 32.2 °C (90 °F) also will likely increase. These combined effects will raise costs related to the construction, maintenance, and operations of transportation infrastructure and vehicles. Maintenance costs will increase for some types of infrastructure because they deteriorate more quickly at temperatures above 32 °C (90 °F). Increase in daily high temperatures could increase the potential for rail buckling in certain types of track. Construction costs could increase because of restrictions on days above 32 °C (90 °F), since work crews may be unable to be deployed during extreme heat events and concrete strength is affected by the temperature at which it sets. Increases in daily high temperatures would affect aircraft performance and runway length because runways need to be longer when daily temperatures are higher (all other things being equal). While potentially costly and burdensome, these impacts may be addressed by transportation agencies by absorbing the increased costs and increasing the level of maintenance for affected facilities.

- **Effects of Change in Average Precipitation –** It is difficult to determine how transportation infrastructure and services might be impacted by changes in average precipitation since models project either a wetter or a drier climate in the southeastern United States. In either case, the changes in average rainfall are relatively slight, and the existing transportation network may be equipped to manage this.

- **Effects of Increased Extreme Precipitation Events –** Of more concern is the potential for short-term flooding due to heavier downpours. Even if average precipitation declines, the intensity of those storms can lead to temporary flooding as culverts and other drainage systems are overloaded. Further, Louisiana Department of Transportation and Development reports that prolonged flooding of 1 to 5 weeks can damage the pavement substructure and necessitate rehabilitation (Gaspard et al., 2007). The central Gulf Coast already is prone to temporary flooding, and transportation representatives struggle with the disruptions these events cause. As the climate changes, flooding will probably become more frequent and more disruptive as the intensity of these downpours will likely increase. As relative sea level rises, it appears likely that even more infrastructure will be at risk because overall water levels already will be so much higher. While these impacts cannot be quantified at present, transportation representatives can monitor where flooding occurs and how the sea is rising as an early warning system about what facilities are at immediate risk and warrant high-priority attention. In a transportation system that already is under stress due to congestion, and with people and freight haulers increasingly dependent on just-in-time delivery, the economic, safety, and social ramifications of even temporary flooding may be significant.

■ 6.3 Implications for Planning

The network in the study area provides crucial service to millions of people and transports enormous quantities of oil, grain, and other freight. It is a network under increasing strain to meet transportation demand as the American public's desire for travel and low-cost goods and services continues to grow. Even minor disruption to this system causes ripple effects that erode the resources of transportation agencies as well as the good will and trust of the public. Good stewardship requires that the transportation network be as robust and resilient as possible within available resources.

This preliminary assessment raises clear cause for concern regarding the vulnerability of transportation infrastructure and services in the central Gulf Coast due to climate and coastal changes. These changes threaten to cause both major and minor disruptions to the smooth provision of transport service through the study area. Transportation agencies – bearing the responsibility to be effective stewards of the network and future investments in it – need to consider these impacts carefully.

Steps can be taken to address the potential impacts to varying degrees. This study demonstrates that there is benefit to examining the long-term impacts of climate change on transportation. Climate data and model scenarios may be productively employed to better plan for transportation infrastructure and services, even if there is not as much information or specificity as transportation planners might prefer. State and local planners need to examine these potentialities in greater detail within the context of smaller study areas and specific facilities. But to effectively consider them, changes are likely necessary in the timeframes and approaches taken.

- **Planning Timeframes –** Current practice limits the ability of transportation planners to examine potential conditions far enough into the future to adequately plan for impacts on transportation systems resulting from the natural environment and climate change. As such, insufficient attention is paid to longer-term impacts in some cases. The longevity of transportation infrastructure argues for a long timeframe to examine potential impacts from climate change and other elements of the natural environment.

  The current practice for public agencies of examining 20 to 30 years in the future to plan for transportation infrastructure may represent the limits of our sight for social, economic, and demographic assessments, as well as for consideration of fiscal constraint and other Federal planning requirements. However, the natural environment, including the climate, changes over longer time periods and warrants attention – perhaps as part of a long-term visioning process that helps to determine where transportation investments are needed and should be located. Such an approach would inform the long-range planning process with valuable supplementary information.

This study could not examine transportation decision making in the private sector in detail due to proprietary concerns and the numerous companies involved. Clearly, some companies, such as CSX Railroad, have responded to issues posed by the 2005 hurricane season and made contingency plans to reroute service. Since the concerns are every bit as real for the private sector, these companies also would do well to plan for and implement adaptive strategies related to climate and other natural environment impacts.

- **Connectivity –** In addition to analysis at the level of particular facilities – such as an airport, bridge, or a portion of rail line – it would be useful for planners to examine the connectivity of the intermodal system for vulnerability assessed at the local, regional, national, and international levels to long-term changes in the natural environment, including changes induced by climate. This helps to identify critical links in the system and ways to buttress them against exposures to climate factors or other variables, or to create redundancies to maintain critical mobility for directly and indirectly affected populations alike.

- **Integrated Analysis –** From a transportation planning perspective, it is unnecessary and irrelevant to separate impacts due to climate change from impacts occurring from other naturally occurring phenomena like subsidence or storm surge due to hurricanes. In fact, such impacts are integrally related. Climate change is likely to increase the severity or frequency of impacts that already are occurring. Any impact that affects the structural integrity, design, operations, or maintenance that can be reasonably planned for should be considered in transportation planning. Efforts to restore ecological systems to redevelop protective buffers and reverse land loss may likewise help to protect transportation infrastructure from future climate impacts.

■ 6.4 Future Needs

The analysis of how a changing climate might affect transportation is in its infancy. While there is useful information that can be developed, the continued evolution of this type of study will serve to enhance the type of information that planners, engineers, operators, and maintenance personnel need to create an even more robust and resilient transportation system, ultimately at lower cost. This study begins to address the research needs identified in chapter 1.0 based on the current literature, but much more investigation is required. Based on the experience gained in conducting this study, research gaps are indicated in several chapters and specifically identified in chapter 4.0. Taken together, they indicate the following areas where more information is critical to the further estimation of the impacts of a changing climate on transportation infrastructure and services.

- **Climate Data and Projections –** The transportation community would benefit from the continued development by climatologists of more specific data on projected future impacts. Higher resolution of climate models for regional and subregional studies would be useful. More information about the likelihood and extent of extreme events, including temperature extremes, storms with associated surges and winds, and precipitation events could be utilized by transportation planners.

- **Risk Analysis Tools –** In addition to more specific climate data, transportation planners also need new methodological tools to address the uncertainties that are inherent in projections of climate phenomena. Such methods are likely to be based on probability and statistics as much as on engineering and material science. The approaches taken to address risk in earthquake-prone areas may provide a model for developing such tools.

  This study proposes a conceptual framework that may provide one way of approaching the development of new tools. More effort is needed to make the concepts presented here operational and thus useful to planners in the region. Specifically, more effort is needed to identify thresholds at which adaptive actions are warranted and taken. Monitoring short-term flooding due to increased downpours; relative sea level rise; and operating, maintenance, and construction costs serves as a good first step toward the identification of these thresholds. Eventually, it would be most useful to have standards of transportation service based on societal needs to guide future investments, and in some instances, changes in design standards may be indicated to ensure the desired levels of service.

- **Region-Based Analysis –** Future phases of this study will examine in more detail the potential impacts specific to the Gulf Coast and determine possible adaptation strategies. In addition, information developed either in this or subsequent studies would be valuable on freight, pipelines, and emergency management in particular. Additional analysis on demographic responses to climate change, land use interactions, and secondary and national economic impacts would help elucidate what impacts climate will have on people and the Nation as a whole, should critical transportation services in the region be lost. However, the impacts that a changing climate might have depends on where a region is and the specific characteristics of its natural environment. The research conducted in this study should be replicated in other areas of the country to determine the possible impacts of climate change on transportation infrastructure and services in those locations. Transportation in northern climates will face much different challenges than those in the south. Coastal areas will similarly face different challenges than interior portions of the country.

- **Interdisciplinary Research –** This study has demonstrated the value of cross-disciplinary research that engages both the transportation and climate research communities. Continued collaboration will benefit both disciplines in building methodologies and conducting analyses to inform the Nation's efforts to address the implications of climate change.

6.5 References

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