Executive Summary

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The changing climate raises critical questions for the transportation sector in the United States. As global temperatures increase, sea levels rise, and weather patterns change, the stewards of our Nation's infrastructure are challenged to consider how these changes may affect the country's roads, airports, rail, transit systems, and ports. The U.S. transportation network – built and maintained through substantial public and private investment – is vital to the nation's economy and the quality of our communities. Yet little research has been conducted to identify what risks this system faces from climate change, or what steps managers and policy-makers can take today to ensure the safety and resilience of our vital transportation system.

This study: *The Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* has investigated these questions through a case study of a segment of the U.S. central Gulf Coast. The research, sponsored by the U.S. Department of Transportation (DOT) in partnership with the U.S. Geological Survey (USGS), has been conducted under the auspices of the U.S. Climate Change Science Program (CCSP). The study is one of 21 "synthesis and assessment" products planned and sponsored by CCSP. The interdisciplinary research team included experts in climate and meteorology; hydrology and natural systems; transportation; and decision-support.

A case study approach was selected for this research as an approach that would both generate useful information for local and regional decision-makers, while helping to develop research methodologies for application in other locations. In defining the study area, the DOT sought to design a project that would increase the knowledge base regarding the risks and sensitivities of all modes of transportation infrastructure to climate variability and change, the significance of these risks, and the range of adaptation strategies that can be considered to ensure a robust and reliable transportation network. The availability of reliable data, interest of local agencies and stakeholders, and transferability of findings were also important criteria in selecting the study area. While the methods presented in this report can be applied to any region, the modeled climate projections and the specific implications of these scenarios for transportation facilities are specific to the Gulf Coast study area.

This report presents the findings of the first phase of a three phase research effort. The ultimate goal of this research is to provide knowledge and tools that will enable transportation planners and managers to better understand the risks, adaptation strategies, and tradeoffs involved in planning, investment, design, and operational decisions. The objective of Phase I was to conduct a preliminary assessment of the risks and vulnerabilities of transportation in the region, after collecting and integrating the range of data needed to characterize the region – its physiography and hydrology, land use and land cover, past and projected climate, current population and trends, and transportation infrastructure. Subsequent phases will conduct more detailed analyses. Phase II will conduct an in-depth assessment of risks to transportation in a selected location, reporting on implications for long-range plans and impacts on safety, operations, and maintenance. This phase will also develop a risk assessment methodology and identify techniques to incorporate environmental and climate data in transportation decisions. Phase III will identify and analyze adaptation and response strategies and develop tools to assess these strategies, while enumerating future research needs.

■ The Gulf Coast Study Area

The Gulf Coast study area includes 48 contiguous coastal counties in four states, running from Houston/Galveston, Texas to Mobile, Alabama. This region is home to almost 10 million people living in a range of urban and rural settings, and contains critical transportation infrastructure that provides vital service to its constituent states and the Nation as a whole. It is also highly vulnerable to sea-level rise and storm impacts. A variety of physical datasets were compiled for review and use by the project research team. Most of the spatial data is organized in GIS formats or "layers" that can be integrated to assess the vulnerability and risks of the transportation infrastructure in the study area and inform the development of adaptation strategies.

Physical and Natural Environment

The coastal geography of the region is highly dynamic due to a unique combination of geomorphic, tectonic, marine, and atmospheric forcings that shape both the shoreline and interior land forms. Due largely to its sedimentary history, the region is low-lying; the great majority of the study area lies below 30 meters in elevation. Due to its low relief, much of the central Gulf Coast region is prone to flooding during heavy rainfall events, hurricanes, and lesser tropical storms. Land subsidence is a major factor in the region, as sediments naturally compact over time. Specific rates of subsidence vary across the region, influenced by both the geomorphology of specific locations as well as by human activities. Most of the coastline also is highly vulnerable to erosion and wetland loss, particularly in association with tropical storms and frontal passages. It is estimated that 56,000 hectares (217 square miles) of land were lost in Louisiana alone during Hurricane Katrina. Further, many Gulf Coast barrier islands are retreating and diminishing in size. The Chandeleur Islands, which serve as a first line of defense for the New Orleans region, lost 85 percent of their surface area during Hurricane Katrina. As barrier islands and mainland shorelines erode and submerge, onshore facilities in low-lying coastal areas become more susceptible to inundation and destruction.

The Gulf Coast Transportation Network

The central Gulf Coast study area's transportation infrastructure is a robust network of multiple modes – critical both to the movement of passengers and goods within the region and to national and international transport as well:

- The region has 17,000 miles (27,000 km) of major highways – about 2 percent of the nation's major highways – that carry 83.5 billion vehicle miles of travel annually. The area is served by 13 major transit agencies; over 136 providers offer a range of public transit services to Gulf Coast communities.
- Roughly two-thirds of all U.S. oil imports are transported through this region, and pipelines traversing the region transport over 90 percent of domestic Outer Continental Shelf oil and gas. Approximately one-half of all the natural gas used in the United States passes through or by the Henry Hub gas distribution point in Louisiana.
- The study area is home to the largest concentration of public and private freight handling ports in the United States, measured on a tonnage basis. These facilities handle a huge share – around 40 percent – of the nation's waterborne tonnage. Four of the top five tonnage ports in the United States are located in the region: South Louisiana, Houston, Beaumont, and New Orleans. The study area also has four major container ports.
- Overall, more than half of the tonnage (54 percent) moving through study area ports is petroleum and petroleum products. New Orleans provides the ocean gateway for much of the U.S. interior's agricultural production.
- The region sits at the center of transcontinental trucking and rail routes, and contains one of only four major points in the United States where railcars are exchanged between the dominant eastern and western railroads.
- The study area also hosts the nation's leading and third-leading inland waterway systems (the Mississippi River and the Gulf Intracoastal) based on tonnage. The inland waterways traversing this region provide 20 states with access to the Gulf of Mexico.
- The region hosts 61 publicly owned, public-use airports, including 11 commercial service facilities. Over 3.4 million aircraft takeoffs and landings take place at these airports annually, led by the major facilities at George Bush Intercontinental (IAH), William P. Hobby, and Louis Armstrong New Orleans International. IAH also is the leading airport in the study area for cargo, ranking 17th in the nation for cargo tonnage.

Given the scale and strategic importance of the region's transportation infrastructure, it is critical to consider the potential vulnerabilities to the network that may be presented by climate change. A better understanding of these risks will help inform transportation managers as they plan future investments.

■ The Gulf Coast Climate Is Changing

The research team's assessment of historical and potential future changes in the Gulf Coast study region draws on publications, analyses of instrumental records, and models that simulate how climate may change in the future. The scenarios of future climate referenced in this report were generated by the National Center for Atmospheric Research (NCAR) using an ensemble of 21 different atmosphere-ocean coupled General Circulation Models (GCM) for the Gulf Coast region. Model results, climatic trends during the past century, and climate theory all suggest that extrapolation of the 20^{th} century temperature record would likely underestimate the range of change that could occur in the next few decades. While there is still considerable uncertainty about the *rates* of change that can be expected, there is a fairly strong consensus regarding the direction of change for most of the climate variables that affect transportation in the Gulf Coast region. Key findings for the study region include:

- **Rising relative sea levels –** Relative sea-level in the study area is likely to increase at least 0.3 meter (1 foot) across the region and possibly as much as 2 meters (6 to 7 feet) in some parts of the study area. Relative sea-level rise (RSLR) is the combined effect of the projected increase in the volume of the world's oceans (eustatic sea-level change), which results from increases in temperature and melting of ice, and the projected changes in land surface elevation at a given location due to subsidence of the land surface. The highest rate of relative sea-level rise will very likely be in the central and western parts of the study area (Louisiana and East Texas), where subsidence rates are highest. The analysis of a "middle range" of potential sea-level rise of 0.6 to 1.2 meters (2 to 4 feet) indicates that a vast portion of the Gulf Coast from Houston to Mobile may be inundated over the next 50 to 100 years. The projected rate of relative sea-level rise for the region is consistent with historical trends, other published region-specific analyses, and the IPCC 4^{th} Assessment Report findings, which assumes no major changes in ice sheet dynamics.
- **Storm activity –** Hurricanes are more likely to form and increase in their destructive potential as the sea surface temperature of the Atlantic and Gulf of Mexico increase. The literature indicates that the intensity of major storms could possibly increase by 10 percent or more. This indicates that Category 3 storms and higher may return more frequently to the central Gulf Coast, and thus cause more disruptions. Rising relative sea-level will exacerbate exposure to storm surge and flooding. Depending on the trajectory and scale of individual storms, facilities at or below 9 meters (30 feet) could be subject to direct storm surge impacts.
- **Warming temperatures –** All GCMs available from the Intergovernmental Panel on Climate Change (IPCC) for use in this study indicate an increase in average annual Gulf Coast temperature through the end of this century. Based on GCM runs under three different emission scenarios developed by the IPCC Special Report on Emissions Scenarios (SRES) (the low-emissions B1, the high-emissions A2 and the mid-range A1B scenarios), 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. Extreme high

temperatures are also expected to increase – with the number of days above 32.2°C (90°F) very likely to increase significantly across the study area. Within 50 years the probability of experiencing 21 days a year with temperatures of 37.8°C (100°F) or above is greater than 50 percent.

- **Changes in precipitation patterns –** Some analyses, including the GCM results from this study, indicate that average precipitation will increase in this region while others indicate a decline of average precipitation during the next 50 to 100 years. In either case, it is expected that average runoff could decline, due to increasing temperature and resulting higher evapotranspiration rates. While *average* annual rainfall may increase or decrease slightly, the *intensity* of individual rainfall events is likely to increase during the 21st century.

In the near term, the direction and scale of these modeled outcomes are consistent regardless of the assumptions used for level of greenhouse gas emissions: Model outputs are relatively similar across a range of IPCC SRES emission scenarios for the next four decades. However, long-range projections (modeled to 100 years) do vary across scenarios, with the magnitude of impacts indicated being more severe under higher-emission assumptions.

■ Climate Change Has Implications for Gulf Coast Transportation

The four key climate drivers in the region: rising temperatures, changing precipitation patterns, rising relative sea levels, and increasing storm intensity, present clear risks to transportation infrastructure in the study area. These factors can be incorporated into today's transportation decisions to help prepare for and adapt to changing environmental conditions.

- **Warming temperatures may require changes in materials, maintenance, and operations.** The combined effects of an increase in mean and extreme high temperatures across the study region are likely to affect the construction, maintenance, and operations of transportation infrastructure and vehicles. Higher temperatures may also suggest areas for materials and technology innovation to develop new, more heat tolerant materials. Some types of infrastructure deteriorate more quickly at temperatures above 32.2°C (90°F). As the number of very hot days increases, different materials may be required. Further, restrictions on work crews may lengthen construction times. Rail lines may be affected by more frequent rail buckling due to an increase in daily high temperatures. Ports, maintenance facilities, and terminals are expected to require increased refrigeration and cooling. Finally, higher temperatures affect aircraft performance and the runway lengths that are required. However, advances in aircraft technology are expected to offset the potential effects of the temperature increases analyzed in this report, so that current runway lengths are likely to be sufficient. The effects of increases in average temperatures and in the number of very hot days will have to be addressed in designing and planning for vehicles, facilities, and operations.

- **Changes in precipitation patterns may increase short-term flooding.** The analysis of annual precipitation trends is inconclusive: models project scenarios of both more and less average annual precipitation. In either case, the hotter climate may reduce soil moisture and average run-off, possibly necessitating changes in right-of-way land management. The potential of changes in heavy rainfall may have more significant consequences for transportation; more frequent extreme precipitation events may result in more frequent flooding, stressing the capacity of existing drainage systems. The potential of extreme rainfall events and more frequent and prolonged flooding may disrupt traffic management, increase highway incidents, and impact airline schedules – putting additional strain on a heavily used and increasingly congested system. Further, prolonged flooding – inundation in excess of one week – can damage pavement substructure.

- **Relative sea-level rise may inundate existing infrastructure.** To assess the impact of relative sea-level rise (RSLR), the implications of rises equal to 61 cm and 122 cm (two and four feet) were examined. As discussed above, actual RSLR may be higher or somewhat lower than these levels. Under these scenarios, substantial portions of the transportation infrastructure in the region are at risk of inundation: 25 percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports are at or below 122 centimeters (4 feet) in elevation. While protective structures, such as levees and dikes, will continue to be an important strategy in the area, rising sea levels significantly increase the challenge to transportation managers. Further, inundation of even small segments of the intermodal system can render much larger portions impassable, disrupting connectivity and access to the wider transportation network.

- **Increased storm intensity may lead to greater service disruption and infrastructure damage.** This study examined the potential for flooding and damage associated with storm surge levels of 5.5 meters and 7.0 meters (18 feet and 23 feet). The specific location and strength of storm surges are of course determined by the scale and trajectory of individual tropical storms, which are difficult to predict. However, substantial portions of the region's infrastructure are located at elevations below the thresholds examined, and recent storms have demonstrated that major hurricanes can produce flooding miles inland from the location of initial landfall. At 7 meters (23 feet), more than half of the area's major highways (64 percent of Interstates; 57 percent of arterials), almost half of the rail miles, 29 airports, and virtually all of the ports are subject to flooding due to storm surge.

  Other damage due to severe storms is likely, as evidenced by the damage caused by Hurricanes Katrina and Rita in 2005. Damage from the force of storm surge, high winds, debris, and other effects of hurricanes can be catastrophic, depending on where a specific hurricane strikes. This study did not examine in detail these effects; the cumulative direct and indirect impacts of major storms need to be further analyzed. However, given the expectation of increasing intensity of hurricanes in the region, consideration should be given to designing new or replacement infrastructure to withstand more energy-intensive, high category storms.

■ Climate Change Considerations Need to Be Incorporated in Transportation Decisions

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. The effects of potential climate changes, particularly when combined with other factors such as subsidence, are likely to be significant. These changes threaten to cause both major and minor disruptions to the smooth provision of transport service through the study area. As transportation agencies work to meet the challenges of congestion, safety, and environmental stewardship – as well as maintaining transportation infrastructure in good repair – addressing the risks posed by a changing climate can help ensure that the substantial investments in the region's infrastructure are protected in the coming decades by appropriate adaptation strategies.

While several of the impacts of climate change identified above are significant, transportation planners and managers can incorporate effective adaptation strategies into transportation decisions today. Some level of adaptation will be required in the near-term to address the effects of climate change processes that are underway. Concentrations of greenhouse gases already in the atmosphere will further force climate changes for the next three to four decades. The scale of adaptation required over the longer term – through this century – will be shaped in part by future emissions levels, as projections of lower-emission scenarios demonstrate lesser impacts.

Transportation Planning Processes

Transportation decisions are made by a number of different entities, both public and private, and transportation infrastructure is financed through a range of government and private investments. Within the study area, four state departments of transportation (DOTs) – for Texas, Louisiana, Mississippi, and Alabama – and 10 Metropolitan Planning Organizations (MPOs) lead surface transportation planning, in close coordination with local governments. To use Federal funding, these agencies must adhere to Federal requirements for surface transportation planning and investment. These laws are contained in Titles 23 and 49 of the United States Code (USC), and most recently amended in August 2005 by the *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* (SAFETEA-LU), the latest six-year authorization of Federal funding for surface transportation.

In surface transportation separate but coordinated long-range transportation plans are cooperatively developed on a statewide basis by each 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 timeframe. These plans provide a long-range vision of the future of the transportation system, considering all passenger and freight modes and the intermodal system as a whole. The planning and investment process is highly collaborative; transportation agencies need to work in partnership with natural resource agencies, communities, businesses, and others as they chart a course for the transportation network that will meet multiple goals, supporting mobility, economic development, community, safety, security, and environmental objectives.

While climate and environmental projections inherently have a degree of uncertainty, this is not unusual to transportation. Transportation decision-makers are well accustomed to planning and designing systems under conditions of uncertainty on a range of factors – such as future travel demand, vehicle emissions, revenue forecasts, and seismic risks. In each case, decision-makers exercise best judgment using the best information available at the time. In an ongoing iterative process, plans may be revised or refined as additional information becomes available. Incorporating climate information and projections is an extension of this well developed process.

Similarly, environmental considerations have long played a role in the planning and development of transportation projects. As awareness of the complex interactions among environmental factors and transportation systems has grown, the transportation community has assumed increasing responsibilities for environmental stewardship. Integration of climate factors into transportation decisions continues this trend. However, interviews with a number of transportation managers in the region confirmed that most agencies do not consider climate change projections per se in their long-range plans, infrastructure design, or siting decisions. This appears to be changing, spurred in part by the devastating effects of Hurricanes Katrina and Rita. The damage caused by these storms highlighted the need to incorporate more information and model data related to climate change and other long-term shifts in environmental conditions as transportation plans are developed and implemented.

New Approaches to Incorporate Climate Information

The incorporation of climate factors into transportation decisions may require new approaches.

- **Planning timeframes –** The timeframes generally used for the Federal transportation planning process – 20 to 30 years – are short compared to the multidecadal period over which climate changes and other environmental processes occur. The longevity of transportation infrastructure – which can last beyond a century – argues for a long timeframe to examine potential impacts from climate change and other elements of the natural environment. While the current timeframe is realistic for investment planning, agencies need to consider incorporating longer-term climate change effects into their visioning and scenario planning processes that inform their long-range plans.
- **Risk assessment approach –** Given the complexities of climate modeling and the inherent uncertainties regarding the magnitude and timing of impacts of climate factors, the deterministic methods currently used to support decisions cannot fully address the range of potential environmental conditions transportation managers need to consider. Adopting an iterative risk management approach would provide transportation

decision-makers, public officials, and the public a more robust picture of the risks to – and level of resilience of – various components of the transportation network.

A conceptual framework and taxonomy for consideration of climate factors was developed. This approach incorporates four key factors that are critical to understanding how climate change may impact transportation:

- *Exposure:* What is the magnitude of stress associated with a climate factor (sea-level rise, temperature change, severe storms, precipitation) and the probability that this stress will affect a transportation segment or facility?
- *Vulnerability:* Based on the structural strength and integrity of the infrastructure, what is the potential for damage and disruption in transportation services from this exposure?
- *Resilience:* What is the current capacity of a system to absorb disturbances and retain transportation performance?
- *Adaptation:* What response(s) can be taken to increase resilience at both the facility (e.g., a specific bridge) and system levels?

Adaptation Strategies

Ultimately, the purpose of a risk assessment approach is to enhance the resilience of the transportation network. Analysis of these factors can help transportation decision-makers identify those facilities most at risk and adopt adaptation strategies to improve the resilience of facilities or 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 adaptation strategies are employed, and for which components of the system, will be determined considering the significance of specific parts of the network to the mobility and safety of those served, the effects on overall system performance, the cost of implementation, and public perceptions and priorities. Generally speaking, as the importance of maintaining uninterrupted performance increases, the appropriate level of investment in adaptation for high-risk facilities should increase as well. This study does not make recommendations about specific facilities or adaptation strategies, but rather seeks to contribute to the information available so that states and local communities can make more informed decisions.

■ Future Research Is Needed

The analysis of how a changing climate might affect transportation is in its infancy. While there is sufficient information today to begin to assess risks and implement adaptation strategies, further development of data and analysis will help planners, engineers, operators, and maintenance personnel as they create an even more robust and resilient transportation system, ultimately at lower cost. Key research needs include:

- **Integrated climate data and projections –** It would be useful to the transportation community if climatologists could continue to develop more specific data on future impacts. Higher resolution of climate models for regional and subregional studies are needed, to integrate with region-specific data on transportation infrastructure. More information about the likelihood and extent of extreme events, including temperature extremes, storms with associated surges and winds, and precipitation events could be put to excellent advantage 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 materials science. The approaches taken to address risk in earthquake-prone areas may provide a model for developing such tools.
- **Region-based analysis –** The impacts that a changing climate might have on an area depends on where the region is and its natural environment. This study needs to 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. Further, 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 the people and the nation as a whole should critical transportation services in the region be lost.
- **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 analysis to inform the nation's efforts to address the implications of climate change.