Task 2.4: Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama
Impacts of Climate Change and Variability on Transportation Systems and Infrastructure

The Gulf Coast Study, Phase 2
Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama
Final Report, Task 2.4

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Introduction and Purpose

Project Context and Goals

One of the most important questions currently facing transportation officials is how to efficiently invest in and design improvements to transportation systems in order to reduce vulnerability to climate variability and change. Sensitivity, the degree to which an asset or a system responds to a given change in climate impact, is a key part of evaluating vulnerability and risk. Since sensitive assets will experience higher levels of damage when subjected to relatively small climate variations as compared to their non-sensitive counterparts, understanding the relative sensitivity of various assets can help transportation officials make targeted system improvements to reduce vulnerability.

The purpose of this report is to review transportation assets in Mobile, Alabama and to qualitatively assess their sensitivity to changes in climate. Two products were created to address these objectives: (i) a Sensitivity Matrix that identifies relationships, thresholds, and indicators of sensitivity for transportation assets, and (ii) a Sensitivity Screen that planners and decision makers can use to quickly assess whether transportation assets are sensitive to certain climate stressors. This final report describes these two products, presents the methodology for their development, and provides key conclusions derived from them.

The intended audience for the Sensitivity Matrix and Screen includes local and regional planners who are attempting to prioritize and focus climate risk analyses on the most sensitive assets under their purview. Planners can use the Sensitivity Screen to identify assets that are sensitive to a particular climate impact as part of a high-level screening process to determine areas of vulnerability within a system. The Sensitivity Matrix provides a deeper level of detail including information on the threshold at which assets become sensitive, historical precedents for climate-related damage to that asset type, and features of the asset which may be associated with increased sensitivity. Planners can use the Sensitivity Matrix as one piece of a more detailed climate vulnerability and risk assessment. While the specific results presented in this report are specific to Mobile and the Gulf Coast region, the methodologies, screens, and assessment techniques presented here are transferable to other regions.

Concurrently with this effort, the Gulf Coast Phase 2 project developed climate projections for Mobile. It is important to note that those climate projections will be used in conjunction with the sensitivity information contained in this report under Task 3 to...
conduct a vulnerability assessment of Mobile’s transportation system. As such, the results presented in this report consider overall sensitivities of transportation assets and operations, but do not evaluate the vulnerability of those assets and operations to the specific climate projections developed for this project. Such an assessment will occur in the next project task.

### Key Terms and Concepts

The Intergovernmental Panel on Climate Change (IPCC) describes the vulnerability of a system to climate change as a function of the character, magnitude, and rate of climate variation to which a system is exposed, the sensitivity of the system, and its adaptive capacity. This relationship is mathematically represented by the equation:

\[
\text{Vulnerability} = f(\text{Exposure, Sensitivity, Adaptive Capacity})
\]

- **Sensitivity**: The change in the condition of an asset given a change in a particular climate stressor.
- **Exposure**: The extent to which a system is subjected to a particular climate stressor.
- **Adaptive capacity**: 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.

**Climate variable**: Parameters used to measure and describe climate. For the purposes of this report, six different climate variables were examined: temperature, precipitation, wind, storm surge, waves, and relative sea level change.

**Climate stressor**: Variation in a climate variable that may lead to a climate impact (e.g., high temperatures, heavy rainfall, cyclical variations in temperature over a period of time).

**Climate impact**: The effect that climate has on a transportation asset.

* “Resilience” is sometimes used interchangeably with the term “adaptive capacity;” but is also used in the adaptation literature as a term related to, but distinct from, adaptive capacity; and sometimes as a concept representing the opposite of vulnerability. To avoid the confusion associated with the term “resilience,” this study exclusively uses the term “adaptive capacity.”

### Introduction to the Sensitivity Matrix

The Sensitivity Matrix and the Sensitivity Screen developed during this project are housed together in a single spreadsheet workbook. The Matrix documents the sensitivities of 28 transportation sub-modes to the following four major climate variables and associated stressors. The Matrix focuses on these particular stressors since research indicated that they are the most relevant to transportation assets in the Gulf Coast region.

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Waves and storm surge (increased storm surge height), and relative sea-level rise (incremental increase in sea-level rise)

- Wind (increased wind speed)

- Precipitation (heavy rain events, drought, incremental changes in the mean)

- Temperature (extreme heat events, incremental changes in temperature)

Multiple similar types of climate changes (e.g., waves, storm surge, and long-term sea-level rise) were aggregated into each category because the effects of these factors tend to be similar though not always identical. By reducing the number of categories, the size of the large Matrix is minimized. Another reason for grouping different types of climate changes is that empirical information on effects of the various sub-categories may be lacking. For example, there is much more empirical information on the sensitivity of transportation infrastructure to short-term flood-related impacts than long-term sea-level rise. The sensitivities specified in the Matrix are specific to each sub-category of climate change, where appropriate, and generalized where possible.

The Approaches for Characterizing Sensitivity section of this report discusses the definition of sensitivity and different approaches for characterizing it using an example from the Sensitivity Matrix. The Methodology section details the six step process that was used to develop the Sensitivity Matrix, the main information sources that were used, and the development of the Sensitivity Screen. The Results section of the report presents the major conclusions that can be drawn from the overall sensitivity assessment. Finally, the Next Steps section describes next steps for the Gulf Coast Phase 2 project and also explains how the Sensitivity Matrix and Screen can be used by transportation planners in regions outside of the Gulf Coast.

**Approaches for Characterizing Sensitivity**

**Defining Sensitivity Based on Damage Functions**

Sensitivity is a component of vulnerability that is difficult to define and assess. Exposure and adaptive capacity, the two other components of vulnerability, can be generalized more easily with indicators across a large region. For example, analyses often use a combination of models to estimate exposure over a wide region, such as the Gulf Coast. Similarly, climate change studies often use indicators of adaptive capacity (such as wealth, technology, and education indicators)\(^2\) in order to estimate overall adaptive capacity. However, sensitivity is locally-defined and depends on contexts and relationships that are difficult to generalize.

\(^2\) Although these adaptive capacity indicators are not directly applicable to transportation assets, indicators such as capital turnover cycles, maintenance periods, monitoring and reporting, redundancy, excess capacity, and the modularity of assets could be used to assess adaptive capacity in transportation.
The sensitivity of an asset is the change in the condition of the asset when it is exposed to a change in a climate variable (e.g., higher temperatures). Sensitive assets will experience a large degree of impact if the climate varies even a small amount. At the opposite extreme, assets that are not particularly sensitive could withstand high levels of climate variation before exhibiting any response.

Quantitatively, sensitivity is the slope of the functional relationship between the condition of an asset and a particular climate variable. For example, Figure 1 hypothetically describes the relationship between coastal bridges (the assets) and storm surge (the climate variable). The slope of this curve represents the sensitivity of bridges to storm surge. Figure 2 provides a mathematical description of this hypothetical relationship.

In the case illustrated in Figure 1, the sensitivity (or slope of the line) does not have a single value, but instead varies as a function of increased storm surge elevation. In other words, the damage associated with storm surge escalates dramatically once the surge elevation reaches the height of the low-chord bridge elevation. This important threshold point (indicated by the red dot in Figure 1) could occur when bridges are not designed to withstand direct wave action on the bridge superstructure. Bridges that are more highly prone to damage at this threshold (and thus become highly sensitive) are graphically represented by the steeply sloping tail of the sensitivity curve. Bridges that are better able to withstand surge that exceeds the low chord elevation are graphically represented by the more gradually sloping sensitivity curve. The example function in Figure 1 is only a hypothetical possibility of how damage to a bridge might vary as a function of storm surge elevation.

---

1 The bridge’s low chord elevation refers to the elevation of the portion of the bridge closest to the water (often the bottom of the girders).
2 During Hurricanes Rita and Katrina in 2004 and 2005, many bridges along the Gulf Coast experienced damage because their superstructures were directly exposed to wave forces. This exposure to wave loading was particularly damaging because in most cases, the bridges had not been designed to withstand that type of exposure. In order to improve design standards, the Federal Highway Administration and ten states sponsored the development of new guidance for bridges vulnerable to coastal storms. An AASHTO/FHWA Wave Task Force was established to oversee the development of the guidance. The resulting guidance includes new methods for calculating wave forces on superstructures that had not been presented in previous design provisions. The new guidance specifies that, “whenever practical, the vertical clearance of highway bridges should be sufficient to provide at least 1 foot of clearance over the 100-year design wave crest elevation, which includes the design storm water elevation.” The guidance also notes that where it is not possible to provide this level of vertical clearance, strategies such as venting cells that could entrap air, using large holes in concrete diaphragms, constructing continuous superstructures, and using solid or voided slab bridges could all help increase the resilience of the bridge to wave forces acting on the superstructure (AASHTO, 2008).
In this particular example the impacts are deleterious. However, it is also possible that changes in climate variables could benefit certain transportation assets. In other words, sensitivity, or the slope of the damage function, can be positive or negative. For example, roadways may experience fewer frost heaves and potholes if increases in seasonal temperatures reduce the frequency of freeze-thaw cycles.

**Figure 1: Possible Damage Function Representing the Relationship between Coastal Bridges and Storm Surge**

The sensitivity is the slope of the line (or derivative of the function) measured at a specific point. The red dot indicates the threshold, or the place where damage to the bridge begins to escalate.

**Figure 2: Equation Estimating the Sensitivity of Bridges to Storm Surge Elevation between Two Levels of Exposure**

\[
\text{Sensitivity} = \frac{\Delta \text{Damage}}{\Delta \text{Climate variable}} = \frac{d[f(\text{bridge elevation})]}{d(\text{storm surge})}
\]

**Difficulties with Damage Functions**

In some types of environmental impact analyses, it makes sense to articulate the concept of sensitivity through a quantitative damage function, such as in the case of the dose-response functions that are a cornerstone of air quality and groundwater quality regulation. However, in general, the information available at the present time in the transportation sector does not lend itself to representation in the form of continuous...
damage functions, as shown in Figure 1, that relate climate stressors to transportation impacts. There are a few reasons for this:

- **Damage functions require continuous information on the levels of damage experienced historically at a range of levels for each climate variable.** Although agencies collect information on failures or damage in major weather events, it is difficult to comprehensively obtain information on the damage or benefit resulting from more minor changes in climate variables since that information is typically not routinely collected. Furthermore, even when information on damage exists, stakeholders may not want to share the information. For example, privately-owned ports and rails consider this type of information to be proprietary.

- **Sustained exposure to low levels of stressors may have cumulative impacts over time not represented by a simple dose-response function.** For example, although Mobile County has a list of roads prone to flooding and a list of common overtopping points during storms, there is little information on the degree of erosive damage associated with storms of various magnitudes, the cumulative effects of those storms, and how much repair is typically required over time in relation to the cumulative effects.

- **Damage functions are unlikely to be linear, since sensitive assets tend to have a threshold at which sensitivity increases abruptly** (see Figure 1 as an example). Therefore, measuring sensitivity from a damage function requires estimating the derivative of the damage function at a particular level of exposure. In cases where the decision-maker would like to know the sensitivity of an asset in general, this approach is not helpful.

- **Finally, multi-stressor situations (e.g., high winds in conjunction with heavy precipitation, and storm surge during major storms) may lead to more serious impacts than if stressors were experienced in isolation.** Establishing relationships that are specific to a singular stressor are unable to capture this multi-stressor context. Multi-stressor effects can also make it difficult to isolate damage associated with individual climate effects in a simple relationship.

**Real-World Methods of Assessing Sensitivity**

To overcome the obstacles associated with developing quantitative damage functions, an alternate approach to assessing sensitivity was taken. This approach qualitatively identified the nature of relationships between asset classes and stressors, indicated thresholds (including quantitative thresholds, where possible), and provided indicators that can be used to quickly assess the sensitivity of a particular asset. The *Sensitivity*

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5 Exceptions to this statement exist. For example, see Powell and Reinhold (2007) for an example of a damage function that relates residential wind damage (claim to insured value ratio) to 10-m open terrain wind speed. See Padgett et al. (2009) for an analysis of bridge damage at different levels of storm surge during Hurricane Katrina.
Matrix framework presents the relationship between four climate variables and six major transportation modes: bridges, roads and highways, railroads, airports and heliports, oil and gas pipelines, and marine ports, terminals and waterways. In addition to these six transportation modes, electrical power systems were included in this analysis because the reliance of transportation modes on electrical systems can be a determining factor for sensitivity.

The Sensitivity Matrix is organized according to the four climate variable groupings that were identified to be most important in the region: waves and storm surge, wind, temperature, and precipitation. The matrix contains two tables for each variable: a main summary table and a second table containing any additional detail or notes. The following four columns make up each variable table: Important Impact-Asset Relationships, Threshold, Mobile-specific Detail, and Potential Indicators of Sensitivity.

Table 1 contains an illustrative excerpt of the Sensitivity Matrix describing the sensitivity of bridges, roads, and highways to wind. Starting from the left in the Matrix, the Important Impact-Asset Relationship column qualitatively describes stressors between the climate variable and the sub-mode. The Threshold column includes any specific information about the exposure level at which damage to the sub-mode may begin increasing. Historical context relevant to Mobile is placed in the Mobile-Specific Detail column, and the Potential Indicators of Sensitivity column contains a list of indicators that have been associated with increased sensitivity to that climate stressor in the past.

In the illustrative excerpt below, the Matrix reveals that wind can damage bridges directly or indirectly by increasing wave action or damaging operator houses. The ASCE 7-05 design standard recommends using a wind design speed of 130-150 for the majority of coastal Mobile County, indicating that damage to bridges may begin to increase at around that threshold.\(^6\) ASCE 7-10 recommends a three-second gust wind speed of 140-175 mph, depending on the structure's risk category (ATC 2012). However, the threshold column also points out that service on bridges is likely to stop at around 56 mph, potentially causing degradation of service due to traffic delays and freight disruptions. The Mobile-Specific Detail column notes that in the past, damage to bridges has occurred from debris-related collisions, rather than the direct impacts of wind on infrastructure. Finally, the indicators column states that the presence of operator houses and the age of the bridge may indicate increased sensitivity to wind in certain contexts.

\(^6\) AASHTO Load and Resistance Factor Design (LRFD) Bridge Specifications use a base design wind velocity of 100 mph, although they require that the base wind design velocity be investigated for tall structures to account for variations in local conditions (AASHTO 2012). The LRFD specifications were initially based on ASCE 7-88 wind load provisions, which have since been updated to reflect 3-second-gust wind speeds. NCHRP has indicated that there is a need to update the AASHTO LRFD wind load provisions to provide consistent reliability across different regions and locations (NCHRP 2012).
<table>
<thead>
<tr>
<th>Asset Categories</th>
<th>Important Impact-Asset Relationships</th>
<th>Threshold</th>
<th>Mobile-Specific Detail</th>
<th>Potential Indicators of Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridges</td>
<td>Winds stress bridges with additional horizontal loading. Bridges are designed with a certain amount of wind loading accounted for in the structure design. [1] Strong winds create more powerful waves which can stress the bridge superstructure and substructure. [8]</td>
<td>AASHTO LRFD bridge design specifications are based on a base design wind velocity of 100 mph, although the base design wind velocity investigated for tall structures to account for local wind speed conditions [79, 80]. ASCE 7-05 recommends using a wind design speed between 130-150 mph for majority of Mobile County [66]. ASCE 7-10 recommends a three-second gust wind speed of 140-175 mph, depending on the structure’s risk category [81]. Higher wind speeds are correlated with larger waves and, to a lesser extent, more frequent wave periods. The effect is continuous, so the threshold at which damage occurs depends on the elevation of the bridge deck and other conditions. [2]</td>
<td>During Hurricane Katrina, strong winds helped break a 13,000 ton semi-submersible drilling platform free from its dry-dock moorings. The drilling platform collided into the Cochrane-Africatown bridge. [4]</td>
<td>- Presence of operator houses with electrical and mechanical equipment - Age</td>
</tr>
</tbody>
</table>

| Bridge (Substructure) | Strong winds create high flow velocities (including high wave impact energy), which can lead to bridge scour. [8] | Higher wind speeds are correlated with higher kinetic energy of the water. The effect is continuous, so the threshold at which damage occurs depends on factors such as the substrate type, and the depth and geometry of footings. [2] | - | |

<p>| Operator Houses (movable bridges) and electrical parts | Wind damage to operator houses causes damage to the electrical and mechanical equipment of the bridge, and may exacerbate rain damage. [8] | Higher wind speeds are correlated with larger waves and, to a lesser extent, more frequent wave periods. The effect is continuous, so the threshold at which damage occurs depends on the elevation of the bridge deck and other conditions. [2] | - | |</p>
<table>
<thead>
<tr>
<th>Mode</th>
<th>Sub-Mode</th>
<th>Important Impact-Asset Relationships</th>
<th>Threshold</th>
<th>Mobile-Specific Detail</th>
<th>Potential Indicators of Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads and Highways</td>
<td>Paved road surface</td>
<td>Wind does not directly damage the physical structure of the road, but can severely disrupt road traffic and other service activities.</td>
<td>No documented relationship.</td>
<td>No documented relationship.</td>
<td>- Structure elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Road substructure</td>
<td>No documented relationship.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(gravel base, substructure)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unpaved roads</td>
<td>Wind can stir up dust from unpaved roads, causing eye irritation to residents and other health issues. [6]</td>
<td>Unknown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stormwater drainage (culverts, side drains, etc)</td>
<td>Wind damages trees, buildings, and other structures. Debris from this destruction can clog the stormwater drainage system, resulting in flooding impacts to the surrounding area. [6]</td>
<td>Non linear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway, road and street signs and traffic lights</td>
<td>Winds can blow over highway, street, and road signs.</td>
<td>The Alabama AASHTO wind design speed is 140 mph. If street signs (such as stop signs) are not buried deeply in strong soils they may not be in compliance with design standard and may fail at (much) lower wind speeds. [5]</td>
<td>DURING Hurricane Katrina and Wilma, a large proportion of street signs failed in Miami-Dade county and the vicinity. The majority of these street signs failed at their foundations - mostly by leaning more than 15 degrees sideways or falling over completely. [5]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Asset Categories | Wind – Summary

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sub-Mode</th>
<th>Important Impact-Asset Relationships</th>
<th>Threshold</th>
<th>Mobile-Specific Detail</th>
<th>Potential Indicators of Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway and road traffic and service</td>
<td>High winds cause safety risks and travel delays, a loss of visibility, impaired mobility, loss of communications and power, freight/cargo damage risk, increased risk of collisions/spills of hazardous cargo, and transport schedule delays. [7]</td>
<td>Winds become dangerous to road maintenance, truck operations, and other road users at around 39 mph and are very dangerous at 74 mph. [7] AASHTO LRFD wind load provisions assume that no traffic will be present on a bridge when wind speed exceeds 56 mph. [3]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[1] Chen and Duan (1999)  
[8] Padgett et al. (2009)

Although the Sensitivity Matrix does not quantitatively evaluate the sensitivity of an asset exposed to a climate stressor, this approach has advantages compared to damage functions. The matrix does not require extensive damage information across a range of climate stressors to identify key impact-asset relationships. It can accommodate the full range of available data from available literature, design standards and guidelines, analogues from historical data and case studies, and expert consultations. It is accessible to planners and policy makers, and can be used as a screen to identify important relationships between climate stressors and critical assets. Finally, it is designed to be transferable to other regions—both in terms of the approach itself, and the bulk of the information summarized within the Sensitivity Matrix.

The Sensitivity Matrix is limited to describing direct sensitivities of transportation infrastructure to climate change. There are, however, indirect ways in which climate change can affect infrastructure. For example, marshes may not be able to keep pace with long-term sea-level rise, depending on the marshes’ vertical accretion rate and the rate of sea-level rise. Elimination of marshes would tend to amplify the storm surge impacts on transportation because the marshes would no longer help to buffer a storm’s energy. Similarly, barrier islands may be affected by multiple factors associated with climate change and their storm buffering capacity may also be impaired. Any impact and/or risk analysis performed using the Sensitivity Matrix should consider such whole-system interactions.
The *Sensitivity Matrix* is an important step toward a more comprehensive understanding of the relationships between climate stressors and transportation assets. Due to the matrix’s reliance on qualitative data, however, it can be difficult to concisely summarize the information for planners and decision makers. To make the information in the *Sensitivity Matrix* more accessible, a *Sensitivity Screen* was developed from the relationships and thresholds identified in the *Sensitivity Matrix* to provide a tool that can be used to quickly assess whether transportation assets may be sensitive to certain climate stressors.

**Methodology**

**Developing the Sensitivity Matrix**

The *Sensitivity Matrix* was developed in a six-step process:

**Step 1: Define the climate variables.** The climate variables included in the *Sensitivity Matrix* were selected based on a general understanding of potential future changes in climate in the Mobile region. The five climate variables that were initially considered are: incremental relative sea-level rise, waves and storm surge, wind, precipitation (incremental changes in precipitation, heavy rain events, drought), and temperature (incremental changes in temperature, extreme heat events). However, based on the early analyses, the initial interviews with Mobile County transportation experts, and the results of the Gulf Coast Study Phase I, this set was narrowed to: waves and storm surge (including consideration of relative sea-level rise), wind, precipitation, and temperature. All climate variables were included in the *Sensitivity Screen*.

**Step 2: Define transportation modes and sub-modes.** There are several sub-modes defined within each of the six transportation modes (bridges; roads and highways; railroads; airports and heliports; oil and gas pipelines; and marine ports, terminals, and waterways) plus electricity. These sub-mode categories were broad enough to cover the wide range of assets and components within each category, but at a level of detail sufficient to identify climate stressor relationships on specific classes of assets. These modes and sub-modes included the following:

- **Bridges:** bridge deck and bearings, bridge girders and piers, bridge abutment and approach, operator houses (for movable bridges), and electrical components
- **Roads and highways:** paved road surface, road substructure (gravel base, substructure), unpaved roads, stormwater drainage (culverts, side drains, etc.), highway and road signage and traffic lights, and highway and road traffic and services
- **Railroads:** electrical equipment (gates, flashers, and signal bungalows), railroad ties, railroad tracks (steel and wooden), services, and operations
Airports and heliports: runway and navigational aids, aircraft, airfield buildings (terminal buildings, hangers, and air traffic control towers), and services and airport/heliport operations (flight departures and arrivals, baggage and cargo transfers, ground transportation)

Oil and gas pipelines: aboveground, underground, and offshore pipelines, and aboveground infrastructure (compressor stations, metering stations, other structures) Marine ports, terminals, and waterways: electrical equipment, terminal buildings, channels, piers, wharves, and berths, and port services and operations.

Electric power systems and services

Step 3: Establish impact-asset relationships. This step identified the relationships between climate stressors and their impacts on specific assets. For each of the sub-modes isolated in Step 2, relevant relationships with each of the four climate variables were qualitatively described. This information was populated in the Matrix, using a combination of historical data, case studies, literature, design standards and guidelines, and expert consultations.

Step 4: Identify thresholds. Although the relationships between climate stressors and sub-modes are described qualitatively in the Sensitivity Matrix, sub-modes often have thresholds above which climate stressors are likely to cause significant damage. Drawing upon information from design standards and guidelines, and historical data and case studies from previous weather events, known thresholds were identified.

Step 5: Develop region-specific detail. In this step, information from historic data and case studies in the Mobile region was incorporated into the Matrix. This information allowed the evaluation of the sensitivity and, in some cases, exposure of specific transportation in Mobile to the impact-asset relationships described in the Matrix. For example, using data on the elevation of airport runways in Mobile airports, it was possible to evaluate the exposure of local airports to impacts from storm surge and waves. Similarly, based on damage assessments from Hurricanes Andrew, Ivan, and Katrina, the historical sensitivity exhibited by bridges, highways, and oil and gas pipelines in the Mobile area to these events was assessed.

Step 6: Identify indicators of sensitivity. Finally, the information summarized in the Matrix was evaluated to identify potential indicators of sensitivity. These indicators are design-related features that are relevant to the sensitivity of an asset. In combination with information on thresholds, indicators of sensitivity could help assess whether assets within a specific category may be more or less sensitive to projected climate stressors.

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7 Electrical power systems and services are a separate sector from transportation modes. Electrical power systems were included in this analysis because the reliance of transportation modes on electrical systems can be a determining factor for sensitivity; however, this sector was not analyzed in sufficient detail to distinguish between sub-categories.

8 In some cases, features were included that influence the exposure of assets to climate stressors. For example, the use of flood protection (e.g., dikes, retaining walls) to shield runways from waves and storm surge.
Steps 3 through 5 relied heavily on three primary sources of information: expert consultations, design standards, and analogues from historical data and case studies. Each data source is described in sub-sections below.

**Expert Consultations**

The sensitivity analysis began by identifying and consulting key transportation mode experts inside Mobile County and elsewhere. These meetings proved to be integral to the rest of the analysis since the modal experts were able to quickly identify locally important hazards and also describe the nature of the causal relationships. Many of the state and county engineers consulted seemed to be most concerned and informed about the hazards posed by heavy precipitation events. In contrast, there was very little concern expressed about increased temperatures or heat waves.

**Design Standards and Guidelines**

Transportation infrastructure is designed according to standards and guidelines that are based on detailed sets of empirical tests, asset-specific quantitative models, and other engineering analyses. Engineers use these documents to ensure that a design meets the functional specifications of a project within accepted limits and factors of safety. Design standards and guidance consider relevant climate variables—both typical climate characteristics in which the design will operate, as well as infrequent events such as violent storms, floods, and hurricanes, whose occurrence is estimated through design return periods for each hazard. As a result, design standards and guidelines can be used to isolate specific climate stressors relevant to a particular asset. The relationships provided within design standards can also be used to provide quantitative indicators of an asset’s sensitivity to a particular climate stressor. For example, the ASCE 7-05 3-second gust basic wind speed for the Mobile region is between 130 and 150 mph, depending on proximity to coastal areas; ASCE 7-10 recommends a three-second gust wind speed of 140-175 mph, depending on the structure's risk category (ATC 2012). Although other parameters influence building design—such as the Occupational Category of the building—this wind speed threshold provides an indication of the operating conditions that are used in the design of buildings and other structures, and can be used to identify whether there may be potential sensitivities that should be investigated in more detail.

Standards and guidelines can be useful in identifying the thresholds or limits of a design, beyond which damage is likely to occur. For example, when determining the low chord elevation of bridges, engineers use numerical and computational tools that roughly estimate storm surge and wave height associated with a storm of a particular return period (e.g., a 50- or 100-year storm). While assets tend to have a factor of safety built into the design, climate hazards that exceed the design limits can cause damage. In addition, climate change may change the probabilities of the design return periods for hazards; for example, the probability of what is currently considered a 50-yr storm could change.
Analogues

Analyzing historical data and case studies from other areas along the Gulf Coast provided some of the most-detailed information on sensitivity for this analysis. For example, a significant body of research exists on the impacts of Hurricane Katrina on transportation in the Gulf Coast. During the sensitivity assessment, the existing literature on hurricane damages to Mobile and surrounding regions was analyzed in order to detect any patterns in damage. For example, studies investigating the performance of the I-10 Twin Bridge as compared to the neighboring U.S. 11 and railroad bridges over Lake Pontchartrain during Hurricane Katrina provided evidence that certain features of the superstructure (girders and diaphragms) can influence the sensitivity of bridges to storm surge. The impacts documented for Hurricane Frederic—the most devastating hurricane to have struck Mobile in the past several decades—were also important in the development of the Sensitivity Matrix.

Developing the Sensitivity Screen

The Sensitivity Screen is a complementary tool developed from the Sensitivity Matrix. Although the Matrix contains a wealth of information on relationships, thresholds, Mobile-specific details, and indicators of sensitivity, it is difficult to quickly apply this descriptive information to evaluate which assets may exhibit sensitivity to climate stressors. The Sensitivity Screen extracts information from the Matrix to show two layers of information in an accessible, easy-to-use format. The Sensitivity Screen consists of:

1. A grid listing the climate variables in columns, and the transportation modes and sub-modes in rows;
2. A color-coded mapping of the sub-modes that were found to exhibit sensitivity to specific climate stressors in the Sensitivity Matrix, and
3. A layer of quantitative information on climate variable thresholds above which impacts may be more severe (also extracted from the Sensitivity Matrix).

Together, these elements allow planners and decision makers to: (i) screen out sub-modes that were not found to exhibit sensitivity to certain climate stressors in the Sensitivity Matrix, and (ii) layer climate projections onto the screen to identify where future climate variables are likely to exceed current thresholds.

The method used to assemble the Sensitivity Screen is depicted in Figure 3. The color-coded mapping of sub-modes that exhibit sensitivity to certain climate stressors distinguishes between two levels of sensitivity: (i) sensitive (color-coded in orange), and (ii) not sensitive. Sub-modes that have orange-shaded cells were affected—either adversely or beneficially—by the stressors corresponding to each climate variable. Grey-shaded cells denote sub-modes that were not affected by the climate stressor. On top of
this information is a layer of quantitative data on climate thresholds above which impacts may become more pronounced.

**Figure 3: Illustrative Framework for Developing the Sensitivity Screen**

<table>
<thead>
<tr>
<th>Modes</th>
<th>Sub-modes</th>
<th>Climate Stressors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Storm Surge and SLR</td>
</tr>
<tr>
<td>Bridges</td>
<td>Superstructure</td>
<td>Wind</td>
</tr>
<tr>
<td></td>
<td>Substructure</td>
<td>Precip.</td>
</tr>
<tr>
<td></td>
<td>Operator houses</td>
<td>Temp.</td>
</tr>
<tr>
<td>Highways and roads</td>
<td>Paved roads</td>
<td>Designed to 100-year storm surge...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Designed to 100-year flood...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Closure at wind speeds of 40 mph...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damage when surge overtops road...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Designed to 50- to 100-year flood...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pavement may soften above 108°F...</td>
</tr>
</tbody>
</table>

Background: Sensitivity Matrix Grid

Layer 1: Mapping of Sensitive Sub-modes

Layer 2: Climate stressor thresholds
Applying the Sensitivity Screen and Matrix: Practical Tools for Planners

Understanding which asset types and subtypes are sensitive to certain climate stressors is essential to helping planners evaluate and prepare for the risks of future climate changes. The Sensitivity Screen was developed to convey the results from the Sensitivity Matrix in a format that can be used as a tool to support rapid screening and vulnerability assessments. The Sensitivity Screen is shown in Table 2.

Once planners have identified the critical transportation assets under their jurisdiction, they use the Sensitivity Screen to preliminarily identify which critical assets are not only important, but also sensitive to particular climate stressors. This step will screen out those assets that are not sensitive, thereby leaving a more manageable list of assets. This screening step can also be used to identify cases where individual assets are sensitive to multiple climate stressors, indicating the potential for compounding effects. The assets that are screened out using the Sensitivity Screen and Matrix should be monitored and revisited over time as resources allow.

Next, planners can use the Sensitivity Matrix to better determine which of the preliminarily identified assets may be impacted by climate change in a subsequent, rigorous vulnerability assessment. The Matrix provides information at a level of detail intermediate between the Screen and detailed design, performance, and maintenance information possessed by individual modal engineers. One of the particular advantages of the Matrix is that it provides cross-modal information to help focus subsequent detailed engineering analyses of potential impacts. This focusing can be done in part through the Matrix's information on indicators of sensitivity that can be used to bore down from sub-mode classes to individual assets to assess their sensitivity. The indicators information can also be used to help initiate consideration of adaptation measures that might be taken to reduce sensitivity and thus vulnerability. The threshold information contained within the Matrix also provides a resource that can be used by transportation planners as they review their design standards, particularly the “100-year storm” in light of changing climate conditions and consequent exposure of transportation assets.

In a comprehensive climate change vulnerability assessment, the critical assets that passed through the Screen should subsequently be assessed for exposure to climate stressors, and their adaptive capacity. Assessments of this type are being carried out in other parts of the Gulf Coast Phase 2 project. The previous section of this report discussed the assessment of the exposure of critical and sensitive assets to storm surge, waves, and long-term inundation due to sea-level rise and subsidence/uplift. The upcoming vulnerability assessment is combining the exposure, sensitivity, and adaptive capacity of critical assets to qualitatively assess vulnerability. These analyses will determine conditions under which the thresholds identified in the Sensitivity Screen are crossed, and the conditions under which other key aspects identified in the Matrix are encountered. The results from these steps will be used to prioritize a short list of assets/stressors for detailed engineering analysis in later efforts under this project.
Results

Sensitivity Relationships in Mobile, Alabama

Local policymakers and transportation decision-makers can use the Sensitivity Matrix to target specific sensitivities in the transportation system with adaptive planning and design in order to decrease vulnerability. This work on the matrix revealed three main conclusions about the sensitivity of the transportation system to climate stressors.

- Transportation assets tend to be more sensitive to extreme events, like heat waves, heavy rain events, and high wind events, than to incremental changes in the mean of climate variables. For example, the impacts associated with incremental average temperature increases in Mobile over time will be moderate and long-term. However, an increased frequency of severe heat waves will have potentially serious consequences for pavement deterioration, demand on electrical power systems, and the ability to perform construction or maintenance work. There are some gradual long-term changes that can be significant, such as gradually rising sea level that places transportation lines out of service.

- Services, such as maintenance and the conveyance of traffic, and safety are often more sensitive to climate stressors than physical assets. Thresholds for delaying or cancelling service are lower than thresholds for damage to infrastructure. Workers on offshore oil and gas infrastructure are evacuated in storm conditions that are much milder than those required to damage platforms, risers, or pipelines. Similarly, healthy and safety restrictions for road maintenance and construction workers begin at around 85°F, but actual pavement damage does not begin until much hotter conditions (approximately 108°F in Mobile, Alabama, particularly if combined with high truck traffic). Delays in the provision of critical services will therefore occur more frequently and may warrant a similar level of attention as high-consequence, low-risk physical impacts, even though their consequences may not be as great as the failure of a critical physical asset.

- An asset is often sensitive to stressors whose occurrence is relatively unlikely in comparison to typical weather variability. For example, during Hurricane Katrina, bridges in the Gulf Coast proved to be susceptible to the large loading from direct wave impacts on the superstructure of the bridge due to the unprecedented storm surge elevation. Similarly, the electrical components of a wide range of assets are usually very sensitive to salt water if exposed, but are generally not exposed except under extreme conditions.

It is important to bear in mind that sensitivity is only one component of overall vulnerability. So, even though a particular asset may be sensitive to a climate stressor, the

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9 OFCM (2002)
consequence of that sensitivity is equally important. For example, the impact may be enormous (e.g., shut-in of offshore oil and gas production for several days), or it may be minor (e.g., a two-hour delay of commercial air flights). The integrated analysis of sensitivity together with criticality, exposure, and adaptive capacity will occur during the vulnerability assessment later in the Gulf Coast Study. Information on criticality of assets was previously assessed in an earlier stage of the study.\textsuperscript{10} Information on exposure is being drawn from the efforts discussed earlier in this report. These factors will be jointly and systematically considered in the upcoming vulnerability assessment.

**Results by Climate Variable**

Each of the four sections below details the sensitivities of transportation assets to stressors corresponding to the four main climate variables considered in this study. Note that more information on the thresholds and impacts mentioned below can be found in the *Sensitivity Matrix*.

**Waves and Storm Surge**

Many assets are sensitive to low levels of exposure to storm surge. Since sensitivity is so high, damage often begins when the asset is exposed to the storm surge and escalates when the asset is directly exposed to wave action. In some cases, once the storm surge is elevated to the point where it has overtopped the structure by a significant depth, the structure may actually be protected from wave damage. For example, during Hurricane Frederic in 1981, about 80% of the roads on the western side of Dauphin Island and 20% of the roads on the eastern side of the island were damaged. Three feet of sand covered Bienville Boulevard, the main east-west road on the island, and may have helped to protect it from the storm surge, since the road experienced only minor damage.\textsuperscript{11}

The effects of storms including surge, high winds, and saltwater spray can severely damage electrical systems and electric parts of assets (e.g., control rooms of movable bridges, port machinery). For example, the majority of the bridges damaged in Hurricane Katrina were movable bridges, although in over one third of these cases, the damage was to a component of the bridge unrelated to the movable spans.\textsuperscript{12} Damages to electrical systems can also magnify the damage experienced by other transportation assets. For example, energy infrastructure is highly interdependent and the electricity outages from hurricanes often result in the closing of refineries, gas processes, pipelines, ports, and other facilities.\textsuperscript{13}

Many coastal assets such as coastal bridges, floating piers, dry docks and offshore oil and gas infrastructure have been designed to withstand exposure to the 100-year storm.

\textsuperscript{10} U.S. Department of Transportation (2011)
\textsuperscript{11} USACE (1981)
\textsuperscript{12} Padgett et al. (2008)
\textsuperscript{13} U.S. DOE (2009)
Engineers also use the 500-year storm as a “check storm” to check that a bridge can withstand scour created by an extreme event. The level of exposure to storm surge for most airports and heliports in the Mobile area is low, although facilities on Dauphin Island are already subject to flooding during extreme weather events, and are at high risk of exposure to relative sea-level rise.

**Wind**

As wind speed increases, damage to structures increases nonlinearly. Based on the analysis of historical damage to residential areas from storms, Powell and Reinhold (2007) assigned the following damage levels to the following wind speed ranges: between 22 and 91 mph (light damage), between 91 and 123 mph (moderate damage), and over 123 mph (severe damage). These damage thresholds correspond to loss levels of around 2%, 12%, and 60% of insured value in residential areas respectively. The destructive power of wind increases drastically upon reaching the threshold value of 123 mph – winds above the severe threshold produced about 30 times more loss to the insured value of residential areas than moderate winds. While this analysis was conducted using residential insurance losses as the measure of damage, it is a reasonable assumption that damage to transportation assets that have a large vertical profile (e.g., buildings, signs, signals, etc.) would follow a similar pattern; most flat profile roads and rails are not likely to exhibit a similar sensitivity. Damage to buildings increases in proportion to at least the second power of wind speed. The 3-second gust basic wind speed required by ASCE 7-05 is between 130-150 mph for majority of Mobile County. This is the wind speed that is used in ASCE 7-05 to determine the pressures that buildings and other structures must withstand, although other factors such as the Occupational Category of the building also influence design. ASCE 7-10 recommends a three-second gust wind speed of 140-175 mph, depending on the structure's risk category (ATC 2012).

The findings in the Sensitivity Matrix identified two important sensitivities at relatively low wind speeds. First, there is evidence that electrical power systems may be significantly sensitive to damage from wind. For example, Reed et al. (2010) analyzed power outages during Hurricane Rita and found that outage fragility (defined as the ratio of outages in a parish to the total number of customers in the parish for the date of hurricane landfall) was 50% even when the wind speed was only around 51 mph, although some of these outages could be due to ancillary impacts of the hurricane. Similarly, lower wind speeds create dangerous conditions for road maintenance and truck operations. For example, at wind speeds between 45 and 60 mph, traffic limits on bridges

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14 See Sensitivity Matrix for specific design specifications and references.
15 Data were from zip code locations during Hurricanes Andrew, Hugo, and Opal.
16 Powell and Reinhold (2007)
17 Pielke and Landsea (2002)
are often imposed, electrical damage increases, and larger aircraft are prevented from taking off if winds have strong crosswind components.

In addition to direct damage, wind often serves as an ancillary stressor to storm surge and precipitation. Wind speeds increase wave action, are the major drivers of storm surge elevation, and can expose sensitive machinery and electronics to damage from precipitation, flooding, and storm surge.

**Temperature - Heat Waves**

Road pavement and steel railroad tracks are two transportation sub-modes that exhibit sensitivity to extreme heat events and diurnal temperature cycling. For paved roads, sensitivity to temperature depends in large part on the binder Performance Grade (PG) in use and the traffic loading experienced at that site. FHWA created a database tool called LTTPBind\(^\text{18}\) to help highway agencies select the most suitable asphalt binder PG based on historical temperature variation and an acceptable level of risk (usually 50% reliability or 98% reliability). PG 64-22 is the common asphalt grade recommended for Alabama and other states in the southeast. However, Alabama recommends the use of PG 67-22 for important roads in order to provide a higher margin of error against the possibility of rutting during particularly hot summers. Mobile County currently does not experience a lot of damage due to pavement softening. However, during extreme heat waves where the temperature can remain above 100°F, with relatively little cooling at night, the pavement can soften. Areas with high truck traffic (particularly areas where trucks stop) experience shoving during heat waves.\(^\text{19}\) Similarly, the risk of railroad track buckling increases significantly at around 110°F, though railroads may slow train speed when the temperature reaches 90°F to avoid buckling and derailments.\(^\text{20}\)

Maintenance work is also sensitive to extreme heat events. For example, in addition to the aforementioned temperature limitations on operations, restrictions that limit the number of hours that road crew maintenance can work begin at 85°F.\(^\text{21}\) Concerning airport operations, higher temperatures also decrease air density, which may require cargo or passenger adjustments to lower plane weight for takeoff.\(^\text{22}\)

**Precipitation – Heavy Rain Events**

Heavy rain events can flood local roads, wear out pavement, and scour bridge foundations. While extremely heavy rain events in combination with high wind speed or storm surge can rapidly damage assets, a series of moderately heavy precipitation events can also significantly degrade an asset over time. For example, precipitation will worsen

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\(^{18}\) Federal Highway Administration (2012)
\(^{19}\) Mitchell (2010)
\(^{20}\) Aggarwal and Wickensham (2010); OFCM (2002)
\(^{21}\) OFCM (2002); NRC (2008); US CCSP (2008)
\(^{22}\) Ang Olson (2009)
existing pavement cracks and can expose the sensitive subgrade to moisture.\textsuperscript{23} Mobile County routinely experiences flooding issues during storms and heavy rainfall events. Due to a variety of factors, certain roads and bridges flood more easily than others. For example, county bridges that are elevated above the roadway can cause rainwater to runoff and flood either side of the road during heavy rain events.\textsuperscript{24}

Stormwater drainage helps to protect road pavement and service from exposure to flooding. In Mobile County, stormwater drains are designed according to a 10-25 year storm depending on the drain type and road size. However, Mobile County engineers confirmed that flooding generally does not occur until a 50-100 year storm, indicating that stormwater drains may perform above their designed capacity.\textsuperscript{25} Debris can cause local flooding problems when small culverts or drains are blocked by tree limbs or other types of debris.\textsuperscript{26}

Heavy precipitation events can increase stream flow velocity and width, which can erode supporting material from bridge foundations, resulting in scour-critical conditions. AASHTO LRFD specifications require that scour at bridge foundations be designed for the 100-year flood storm surge tide or for an overtopping flood of a lesser recurrence interval. The Alabama Department of Transportation has reported no serious problems with bridge scour in the area, even to bridges that are deemed scour-critical.\textsuperscript{27}

Heavy rain events also impact road and airport services. For example, even light rain slows traffic and decreases the capacity of a road to handle traffic. Rain also increases safety risk on the road by impairing visibility and mobility and increasing the likelihood of hydroplaning.\textsuperscript{28} Heavy rain can flood runways, lower the crosswind takeoff and landing limits for aircraft, and thunderstorms can lead to flight delays or cancellations. Hail can cause significant damage to aircraft, hangars, and buildings.

\textsuperscript{23} The sensitivity of pavement depends on the pavement design. For example, in Mobile County, most county roads are thin bituminous pavements, which are more sensitive to water than other types of roadway. If moisture breaches the subgrade from the pavement shoulder, it deforms the subgrade which is then subjected to high stress loads during traffic. In thick bituminous pavements, the thicker pavement layers mean that less stress is transmitted to the subgrade. As a result, the pavement is less sensitive to moisture in the subgrade (Dawson, 2008).

\textsuperscript{24} Mitchell (2010)
\textsuperscript{25} Mitchell (2010)
\textsuperscript{26} Mitchell (2010)
\textsuperscript{27} Powell and Reach (2010)
\textsuperscript{28} OFCM (2002)
Table 2: Sensitivity Screen developed during this project.
Dark orange indicates a sensitive relationship between the sub-mode and the climate variable. Grey indicates a non-sensitive relationship. Where available, information about thresholds is included.

<table>
<thead>
<tr>
<th>Asset Categories</th>
<th>Mode</th>
<th>Sub-Mode</th>
<th>Sea-level rise and Storms</th>
<th>Precipitation</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridges</td>
<td></td>
<td></td>
<td>Relative Sea-level rise (Gradual)</td>
<td>Storm Surge (including increased wave action and sea-level rise impacts)</td>
<td>Wind</td>
</tr>
<tr>
<td>Bridges (Superstructure)</td>
<td>Bridge</td>
<td>Damage increases substantially when storm surge height equals low chord bridge elevation. At this point, the bridge is usually exposed to direct wave impacts on the superstructure. Recent guidance specifies that the vertical clearance of highway bridges should provide at least 1 foot of clearance over the 100-year design wave crest elevation.</td>
<td>AASHTO LRFD specifications are based on a base design wind velocity of 100 mph, although the base design wind velocity investigated for tall structures to account for local wind speed conditions. ASCE 7-05 recommends a three-second gust basic wind speed of 130 to 150 mph in the Mobile area; ASCE 7-10 recommends 140 to 175 mph, depending on the structure’s risk category.</td>
<td>Scour can make bridge more susceptible to collisions, wave action, and other impacts.</td>
<td>Bridge pavement is usually concrete and may exhibit similar sensitivities as road concrete pavement.</td>
</tr>
<tr>
<td>Asset Categories</td>
<td>Sea-level rise and Storms</td>
<td>Precipitation</td>
<td>Temperature</td>
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<tr>
<td>Mode</td>
<td>Sub-Mode</td>
<td>Relative Sea-level rise (Gradual)</td>
<td>Incremental change in the mean (+/-)</td>
<td>Incremental increase in the mean</td>
<td>Increase in frequency or duration of heat events</td>
</tr>
<tr>
<td>Bridge</td>
<td>(Substructure, Abutment and Approach)</td>
<td>Storm Surge (including increased wave action and sea-level rise impacts)</td>
<td>Wind</td>
<td>Increase in frequency or duration of heavy rain events</td>
<td>Drought</td>
</tr>
<tr>
<td></td>
<td>Sea-level rise increases the base elevation of water during storm surge, thereby increasing damage due to scour, wave action, uplift and other stressors.</td>
<td>Design standards require that bridge foundations withstand scour resulting from a 100 year storm.</td>
<td>Strong winds create more powerful waves which can stress the bridge superstructure and substructure.</td>
<td>Scour at bridge foundations is generally designed to withstand the 100-year flood storm surge.</td>
<td></td>
</tr>
<tr>
<td>Operator Houses</td>
<td>(movable bridges) and electrical parts</td>
<td>If exposed, electrical components are very sensitive to low levels of salt water flooding.</td>
<td>Movable bridges may begin to close operations at wind speeds of around 40 mph. Physical damage to operator houses has occurred historically at wind levels of 125 mph. Damage from wind tends to be minor.</td>
<td>Damage would require wind or storm damage to expose operator house and electrical equipment.</td>
<td></td>
</tr>
<tr>
<td>Roads and Highways</td>
<td>Paved roads (surface and substructure)</td>
<td>Direct damage to road begins</td>
<td>While lower functional class</td>
<td>No documented</td>
<td>In Mobile, pavement</td>
</tr>
<tr>
<td></td>
<td>Sea-level rise increases the base elevation of water.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Asset Categories</td>
<td>Mode</td>
<td>Sub-Mode</td>
<td>Sea-level rise and Storms</td>
<td>Precipitation</td>
<td>Temperature</td>
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<td></td>
<td></td>
<td></td>
<td>Relative Sea-level rise (Gradual)</td>
<td>Incremental change in the mean (+/-)</td>
<td>Incremental increase in the mean</td>
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<tr>
<td>subsurface</td>
<td></td>
<td></td>
<td>Storm Surge (including increased wave action and sea-level rise impacts)</td>
<td>Increase in frequency or duration of heavy rain events</td>
<td>Increase in frequency or duration of heat events</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>occurring once storm surge overtops road, particularly if waves are in direct contact with road structure. There is some protection from wave action if road is deeply overtopped or covered with sand.</td>
<td>roadway are typically designed for the 10-25 year storm, Mobile County roads tend to not experience damage from flooding until 50-100 year storms.</td>
<td>relationship, but some sensitivity may exist.</td>
</tr>
<tr>
<td>Unpaved roads</td>
<td></td>
<td></td>
<td>Most coastal roads do not have unpaved surfaces. However, if exposed, unpaved roads are more sensitive to erosion and damage caused by sea-level rise than paved roads.</td>
<td>Moderate winds stir up dust from unpaved roads, resulting in minor discomfort and damage.</td>
<td>High sensitivity to washout from flooding.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Most coastal roads do not have unpaved surfaces. However, if exposed, unpaved roads are more sensitive to storm surge damage than paved roads.</td>
<td>No documented relationship, but some sensitivity is likely.</td>
<td>No documented relationship, but some sensitivity is likely.</td>
</tr>
<tr>
<td>Asset Categories</td>
<td>Sea-level rise and Storms</td>
<td>Precipitation</td>
<td>Temperature</td>
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<tr>
<td><strong>Mode</strong></td>
<td><strong>Sub-Mode</strong></td>
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</tr>
<tr>
<td><strong>Relative Sea-level rise (Gradual)</strong></td>
<td><strong>Storm Surge (including increased wave action and sea-level rise impacts)</strong></td>
<td><strong>Incremental change in the mean (+/-)</strong></td>
<td><strong>Increase in frequency or duration of heavy rain events</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stormwater drainage (culverts, side drains, etc)</td>
<td>Storm surge can flood the stormwater drainage system beyond its design capacity.</td>
<td>Damage from wind creates debris, which can clog stormwater drainage systems,</td>
<td>Culverts: 25 year storm capacity Cross drains: 10 year storm capacity Side drains: 10-25 year storm capacity (Mobile County design standards)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stormwater drainage increases potential for flooding of the stormwater drainage system.</td>
<td>exacerbating flooding damage.</td>
<td>In Mobile, destructive flooding generally does not occur until around 50 to 100 year storm. Culverts, cross drains, and side drains are designed to 25-, 10-, and 10 to 25-year storm capacity, respectively.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway, road and street signs and traffic lights</td>
<td>Flooding can damage electrical components, causing traffic lights and other signals to malfunction.</td>
<td>Alabama AASHTO wind design speed is 140 mph; if signs are not buried deep enough, failure can occur at lower wind speeds (e.g., sign failures at 90 mph have been recorded in Miami-Dade county).</td>
<td>No documented relationship, but some sensitivity may exist.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Heavy rainfall can impact visibility of signs.
<table>
<thead>
<tr>
<th>Asset Categories</th>
<th>Sea-level rise and Storms</th>
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<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mode</strong></td>
<td><strong>Sub-Mode</strong></td>
<td><strong>Relative Sea-level rise (Gradual)</strong></td>
<td><strong>Storm Surge (including increased wave action and sea-level rise impacts)</strong></td>
</tr>
<tr>
<td>Road Work and Maintenance, Driver Safety, and Traffic and Service</td>
<td></td>
<td>If exposed to storm surge, road usually closed or rendered inoperable.</td>
<td>Danger to road maintenance workers and road users at wind speeds of 40 mph; conditions become very dangerous at wind speeds of 75 mph.</td>
</tr>
<tr>
<td>Railroads</td>
<td>Electrical Equipment (gates/flashers and signal bungalows)</td>
<td>Equipment may become inundated.</td>
<td>Exposure to storm surge can cause failure of electrical components, such as signals.</td>
</tr>
<tr>
<td>Railroad Tracks, Ties, and Ballast</td>
<td>Rail lines may become inundated</td>
<td>Wave action can strip rail, ties, and ballast off of railroad bridges if they are exposed.</td>
<td>Immersion of wooden ties in water softens/expands the wood, weakening its ability to support tracks. Erosion of supporting</td>
</tr>
<tr>
<td>Asset Categories</td>
<td>Sea-level rise and Storms</td>
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</tr>
<tr>
<td><strong>Mode</strong></td>
<td><strong>Sub-Mode</strong></td>
<td>Relative Sea-level rise (Gradual)</td>
<td>Storm Surge (including increased wave action and sea-level rise impacts)</td>
</tr>
<tr>
<td>Railroad services (i.e., operations)</td>
<td></td>
<td>Service may be terminated if lines are inundated.</td>
<td>Storm surge can scour the railbed, derail rail cars, and damage railway bridges over streams, all of which can disrupt service.</td>
</tr>
<tr>
<td>Asset Categories</td>
<td>Mode</td>
<td>Sub-Mode</td>
<td>Sea-level rise and Storms</td>
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</tr>
<tr>
<td>Airports and Heliports</td>
<td>Runway and navigational aids</td>
<td>Runway and navigational aids</td>
<td>Sea-level rise exacerbates storm surge elevation.</td>
</tr>
<tr>
<td>Aircraft</td>
<td></td>
<td></td>
<td>Cross-wind landing and take-off speed limit for most small aircraft is 23 mph; limit for larger aircraft can range from 46 mph in dry conditions to 20 mph on iced runways.</td>
</tr>
</tbody>
</table>
## Gulf Coast Study, Phase 2—Task 2.4: Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama

<table>
<thead>
<tr>
<th>Asset Categories</th>
<th>Sea-level rise and Storms</th>
<th>Precipitation</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mode</strong></td>
<td><strong>Sub-Mode</strong></td>
<td><strong>Relative Sea-level rise</strong></td>
<td><strong>Storm Surge</strong> (including increased wave action and sea-level rise impacts)</td>
</tr>
<tr>
<td><strong>Airfield buildings and structures (e.g., terminal buildings, hangers, air traffic control tower)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Asset Categories</td>
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</tr>
<tr>
<td><strong>Mode</strong></td>
<td><strong>Sub-Mode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Relative Sea-level rise (Gradual)</strong></td>
<td>Storm Surge (including increased wave action and sea-level rise impacts)</td>
<td>Wind</td>
<td>Incremental increase in the mean (+/-)</td>
</tr>
<tr>
<td>Services and airport/ heliport operations</td>
<td>Airport services are sensitive to low levels of flooding; the storm surge threshold is therefore essentially equal to the airport elevation.</td>
<td>Airports close in hurricane conditions (i.e., wind speeds greater than 74 mph)</td>
<td>Increase in frequency or duration of heavy rain events</td>
</tr>
<tr>
<td>Oil and Gas Pipelines</td>
<td>Sensitivity generally low</td>
<td>Wind speeds above 60 mph can damage pipeline systems.</td>
<td>Damage caused by weakened soil structure due to precipitation or inundation from storms.</td>
</tr>
<tr>
<td>Pipelines, aboveground</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipelines, underground</td>
<td>Sensitivity generally low</td>
<td></td>
<td>Damage caused by weakened soil structure due to precipitation or inundation from storms. Pipeline may be unearthed from flooding.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td><strong>Sub-Mode</strong></td>
<td><strong>Relative Sea-level rise (Gradual)</strong></td>
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</tr>
<tr>
<td>Pipelines, offshore</td>
<td></td>
<td>Offshore oil and gas infrastructure is designed to withstand the 100 year storm. Historically in the Gulf Coast, damage to pipelines has drastically increased at around a Category 4 hurricane (Cat 4 storms are characterized by 130-155 mph winds and 13-18 foot storm surges).</td>
<td>Wind can damage buildings at speeds greater than 30 to 40 mph; basic wind speed used to determine the pressures that buildings and other structures must withstand according to ASCE 7-05 is 130 to 150 mph in the Mobile area. ASCE 7-10 recommends a three-second gust wind speed of 140 to 175 mph, depending on the structure’s risk</td>
</tr>
<tr>
<td>Aboveground infrastructure (e.g., compressor stations, metering stations, other buildings, structures)</td>
<td>No documented relationship, but some sensitivity is likely.</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Mode</td>
<td>Sub-Mode</td>
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<tr>
<td></td>
<td><strong>Relative Sea-level rise</strong></td>
<td>(Gradual)</td>
<td>Storm Surge (including increased wave action and sea-level rise impacts)</td>
</tr>
<tr>
<td>Electric Power Systems</td>
<td>Electric Power Systems</td>
<td></td>
<td>Wind, storm surge, and waves damage essentially every component of electric power systems (transmission lines, towers, insulators, generating plants) through direct flooding impacts, damage from debris, and other effects such as salt spray contamination.</td>
</tr>
<tr>
<td>Marine Ports, Terminals, and Waterways</td>
<td>Electrical Equipment</td>
<td></td>
<td>If exposed, high sensitivity.</td>
</tr>
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<td><strong>Storm Surge (including increased wave action and sea-level rise impacts)</strong></td>
</tr>
<tr>
<td>Terminal Buildings</td>
<td></td>
<td>Damage is likely to occur when wave height overtops elevation of port.</td>
<td>Design wind speed for Mobile port structures ranges from 130-140 mph (3-second gust). ASCE 7-10 recommends a three-second gust wind speed of 140 to 175 mph, depending on the structure’s risk category.</td>
</tr>
<tr>
<td>Channels</td>
<td>No documented relationship, but some sensitivity is likely.</td>
<td>Storm surge can wash debris and sediment into the shipping channels, necessitating dredging following the storm.</td>
<td></td>
</tr>
<tr>
<td>Piers, wharves, and berths</td>
<td></td>
<td>Damage is likely to occur when wave height overtops elevation of port.</td>
<td>Indirect impacts due to increased wave height.</td>
</tr>
</tbody>
</table>
### Gulf Coast Study, Phase 2—Task 2.4: Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama

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<td></td>
</tr>
<tr>
<td><strong>Port services</strong></td>
<td><strong>Relative Sea-level rise (Gradual)</strong></td>
<td><strong>Storm Surge (including increased wave action and sea-level rise impacts)</strong></td>
<td><strong>Wind</strong></td>
</tr>
<tr>
<td>(i.e., operations)</td>
<td>No documented relationship, but some sensitivity is likely.</td>
<td>Storms cause damage to marine port services by disrupting the power and communications networks, displacing port workers, washing away channel buoys, and submerging debris in ship channels.</td>
<td>Berthing large vessels is affected when wind speeds exceed 23 mph; high-speed ferries stop operating at wind speeds of roughly 46 mph; container and gantry-type cranes at affected by sustained wind speeds greater than 29 mph.</td>
</tr>
</tbody>
</table>
Replicability, Gaps, and Lessons Learned

Both the Sensitivity Matrix and the Sensitivity Screen offer an important step towards assessing the risks posed by future changes in climate, and identifying adaptation options for responding to these risks. As outlined above, the results from this sensitivity analysis will be coupled with a variety of complementary analyses to identify key vulnerabilities posed by climate change to transportation in Mobile County. This information will then be used to identify adaptation options to help cope with these risks.

As noted previously, the Screen and Matrix are also intended for application in coastal communities outside the Mobile MPO. However, these products are shaped by Mobile-specific priorities and do not include hazards such as permafrost and snow, or a detailed discussion of public transportation. Those issues and a few others of regional importance would need to be addressed for comprehensive applicability of this framework outside the Gulf States. While the analysis is still quite applicable to localities across the United States, each community should begin by determining its most important climate hazards and modes and the extent to which climate sensitivity information for them is contained in this Matrix. If relevant information is not included here, it must be independently gathered.

Significant benefit could be obtained by providing even more detail in the Matrix, particularly with respect to the indicators of sensitivity. More detail about these indicators would be particularly beneficial in supporting the identification and analysis of adaptation options. Some of this detail is likely to be available following the engineering analyses that will be undertaken later in this project.

It would be useful to merge the analysis conducted here to the FEMA HAZUS²⁹ model to make the results readily available to transportation planners that use this standard disaster risk planning model.

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²⁹ HAZUS is a methodology and software that FEMA developed for estimating losses from natural disasters in the United States. For more information, see http://www.fema.gov/plan/prevent/hazus/index.shtm.
References


Mitchell, R. (2010). Personal Communication between Emily Rowan (ICF International) and Ricky Mitchell (Mobile County Public Works).


