Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2

# Task 3.1: Screening for Vulnerability

U.S. Department of Transportation
Gulf Coast Study, Phase 2

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Impacts of Climate Change and Variability on Transportation Systems and Infrastructure

# The Gulf Coast Study, Phase 2

# Screening for Vulnerability

## Final Report, Task 3.1

*Prepared for:*

The U.S. DOT Center for Climate Change and Environmental Forecasting

*Project managed by:*

Office of Planning, Environment, and Realty
Federal Highway Administration, U.S. DOT
Robert Hyman, Robert Kafalenos, Brian Beucler

*Prepared by:*

ICF International
1725 Eye Street, NW
Washington, DC 20006

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## Principal Authors and Reviewers (in alphabetical order)

Anne Choate, Chris Evans, Beth Rodehorst, Ricardo Saavedra, Cassandra Snow, and John Snyder of ICF International; Robert Hyman, Robert Kafalenos, and Brian Beucler of the Federal Highway Administration (FHWA)

## Other Contributing Authors (in alphabetical order)

Zac Andereck, Miyuki Hino, Dr. Rawlings Miller, Thuy Phung, Emily Rowan, and Dr. Peter Schultz of ICF International

Chris Dorney, Michael Flood, and Dr. Michael Meyer of Parsons Brinckerhoff

Dr. Scott Douglass and Dr. Bret Webb of South Coast Engineers

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# 1. Summary for Policymakers

## 1.1 Introduction and Purpose

As part of Gulf Coast Study Phase 2, the U.S. Department of Transportation (U.S. DOT) sought to improve its understanding of how a metropolitan transportation system—including highways, ports, airports, rail, transit, and pipelines—could be affected by climate change. Building on previous work under this project that determined which transportation assets were critical and that developed climate projection data and scenarios,[1] the U.S. DOT developed and tested methodologies for conducting a transportation system-wide climate vulnerability assessment. The goals of this effort were two-fold: (1) to develop and pilot novel approaches for conducting system-wide climate change vulnerability assessments with the intention that the methodologies could be replicated by other transportation agencies, and (2) to understand where important transportation-related climate vulnerabilities may exist in Mobile, Alabama, the MPO serving as the pilot for all methodologies developed under the Gulf Coast project.

**Key Terms Used in this Summary for Policymakers**

- **Vulnerability***– The degree to which a transportation system or asset is susceptible to, and unable to cope with, adverse effects of climate change, variability, and extremes. Vulnerability is a function of *exposure, sensitivity*, and *adaptive capacity.*
- **Exposure***– The nature and degree to which a system or asset is exposed to significant climate variations.
- **Sensitivity***– The degree to which a transportation system or asset is affected by climate variability or change.
- **Adaptive Capacity***– The ability of the transportation system or asset to adjust to climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.
- **Indicators** – Characteristics that may indicate the degree to which an asset may be exposed, be sensitive, or have the capacity to adapt to changes in climate.
- **Climate Narratives** – Plausible climate futures developed for Mobile, Alabama. These narratives were developed *with consideration* of a variety of climate models, emission scenarios, global sea level rise assumptions, and storm modeling. The narratives are themselves not the result of model outputs, but are used to convey a reasonable range of the numerous modeling results.

**Derived from definitions established by the Intergovernmental Panel on Climate Change*

### 1.1.1 Transportation Climate Change Vulnerability Assessments: A Need for Streamlined Methodologies

The approaches developed for this work are meant to help overcome a barrier of transportation agencies wishing to prepare for climate change. In order to prepare for climate change, transportation practitioners must first understand how climate change could affect their transportation system and assets, so that they know where to focus their limited resources in preparing for climate change. However, transportation networks are comprised of many individual assets, each of which is differentially affected by the various climate stressors, and a comprehensive vulnerability assessment of any single asset can be a resource-intensive endeavor.

[1] For background information on the Gulf Coast Study, please see Section 2.

Evaluating vulnerability of each individual asset is simply not feasible for most transportation agencies. Therefore, it is important to consider ways to cost-effectively identify which assets are potentially more likely to be affected by projected changes in climate in order to get a bigger picture understanding of system-wide vulnerabilities, as well as to help determine where additional resources should be dedicated to better understand asset-specific vulnerabilities.

### Scope of Vulnerability Assessment Methodology

The methodology discussed in this report covers the following modes:

- Highways
- Ports
- Airports
- Rail
- Transit

Pipelines were also qualitatively evaluated, but lack of data prevented a quantitative vulnerability assessment.

The methodology also covers the following climate change stressors:

- Changes in temperature
- Changes in precipitation
- Sea level rise
- Increased severity of storm surge
- Winds associated with more severe storms

In order to overcome the infeasibility of doing detailed vulnerability assessments for all individual assets, this study developed a screening approach that helps identify which assets could be considered more likely to be vulnerable to future climate conditions. The hallmark of this approach is the use of "indicators," which are characteristics that may indicate the degree to which an asset is exposed, sensitive, or able to adapt to a particular climate stressor. Using indicators, each asset receives a score based on exposure, sensitivity, and adaptive capacity; these scores are then rolled up into an overall vulnerability score. Assets with high vulnerability scores should be the first assets to receive more detailed attention to determine their specific vulnerabilities and/or to begin adapting to their vulnerabilities. Meanwhile, assets with lower vulnerability scores may not need immediate action.

Indicators can be qualitative or quantitative, and may utilized existing datasets, spatial analysis, or stakeholder input. Example indicators include: scour condition rating of bridges from the National Bridge Inventory (a quantitative measure using an existing dataset); presence of asset in the 500-year flood zone (evaluated using spatial analysis); and stakeholder input on which assets have traditionally experienced climate-related damage (qualitative assessment based on stakeholder interviews). Regardless of their type and data source, indicators have one thing in common, in that they can be evaluated across large numbers of assets at relatively low cost.

The approach developed for this work also includes a methodology for identifying reasonable bounds to plausible future climate scenarios. To evaluate future vulnerabilities, it is important to understand how the climate may change over time. However, projecting future climate conditions involves a lot of uncertainty, and requires that assumptions be made about how much greenhouse gases humans continue to emit into the future, how the global sea level may rise, or what future storms could look like. Furthermore, different climate models will yield different results given the same inputs. Picking one emissions scenario or one climate model on which to base adaptation actions is risky, since a transportation practitioner cannot have a large degree of confidence that they selected the "right" one. However, considering a wide range of models and input assumptions yields an intimidating amount of climate projection data, with each data point being equally as likely to occur as the others. To overcome this challenge, this project developed a methodology that incorporated the results of different emission scenarios, models, and sea level rise and storm assumptions, while also harnessing these various climate projections into conceptually simple future "climate narratives" against which to evaluate vulnerabilities.

Detailed information on the methodology, including the use of indicators and development of climate narratives, is included in Section 3 and 4.

### 1.1.2 Using this Methodology in Other Analyses

The methodologies developed were piloted using Mobile, Alabama's transportation system as a test case. This pilot effort yielded important lessons learned regarding the application of the methodologies. These lessons may assist other transportation agencies in conducting similar assessments on their own transportation systems, and are discussed in Section 1.2. The intention of this work is that other transportation stakeholders can adapt and build upon these methodologies to conduct their own vulnerability assessments. The methodology was designed to be highly flexible and scalable to accommodate different situations in terms of resource and data availability, types of modes and assets being evaluated, and climate stressor types (e.g. temperature, precipitation) of concern. Detailed information on the methodologies employed can be found starting in Section 3.

As part of a larger effort of U.S. DOT to assist transportation agencies in preparing for climate change, U.S. DOT developed new tools and resource that will help other transportation practitioners conduct vulnerability assessments similar to the one described here. The first tool, the CMIP Data Processing Tool, enables transportation practitioners to download temperature and precipitation project data for their location and easily "translate" the raw data into terms that are more relevant to transportation assets, such as short-term temperature or precipitation extremes, rather than focusing on longer-term averages. The outputs of this tool can provide the basis of the temperature and precipitation exposure against which to evaluate vulnerability. The second tool, the Vulnerability Assessment Scoring Tool (VAST), automates the scoring methodology described in this report. Users enter information on their assets, select the parameters for the analysis, and select indicators to evaluate exposure, sensitivity, and adaptive capacity. Then, the tool calculates vulnerability scores based on these inputs. VAST significantly reduces the resources needed to complete the analysis described in this report.

The U.S. DOT has developed other tools and resources to assist transportation practitioners in conducting vulnerability assessments and adapting to climate change. These resources, including the CMIP Climate Data Processing Tool and VAST, are housed in the "Assess Vulnerabilities" section of FHWA's virtual adaptation framework at http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/.

### 1.1.3 Building on Mobile-Specific Findings

The pilot testing of these methodologies also yielded important findings related to the climate vulnerability of Mobile's transportation system. These findings may help Mobile better understand where and when climate vulnerabilities may need to be addressed. These results were also used to identify specific assets thought to be particularly vulnerable, which then underwent detailed engineering assessments of vulnerability and adaptation. These engineering assessments looked at the specific design and location characteristics of the assets in question, and evaluated how the asset might be affected under particular climate conditions. The assessments also considered viable adaptation options for mitigating the impacts of the projected future climate conditions.

This study is *not* intended to provide recommendations for specific actions that Mobile should undertake to prepare for climate change. Appropriate adaptation actions need to take into account available resources, community priorities, local tolerance for risk, and other factors—all of which also need to be weighed against local priorities outside the realm of climate change adaptation. However, the findings of this vulnerability assessment can help inform future discussions about how to prioritize adaptive actions.

The overarching Mobile-specific findings are discussed in Section 1.3. Detailed results of the vulnerability assessment are discussed in Section 5.

## 1.2 Key Lessons Learned in Evaluating Vulnerability Using an Indicators Approach

Due to resource constraints, climate change vulnerability assessments are often limited to small geographic areas, a single mode, and/or a single climate stressor. The approach described in this report provides a way to conduct more comprehensive vulnerability assessments by looking for specific characteristics (indicators) that may suggest that certain assets are particularly vulnerable. Although the results from this approach are not specific enough to provide definitive conclusions regarding the vulnerability of any specific asset, they can be used to identify specific assets, modes, or geographic areas that could be potentially vulnerable, as well as specific climate stressors that could be particularly problematic to a community.

The methodologies discussed here are highly flexible. They can be applied for a variety of modes and locations, and can be easily scaled for varying levels of resource constraints and data availability. It is the authors' belief that other transportation agencies will find these methods to be a solid foundation for their own analyses, but that those agencies may well find that different indicators, scoring methodologies, or evaluation methods work better for their particular needs. Furthermore, perfect information is not necessary to conduct a broad vulnerability assessment, and indicators and scoring methodologies can be easily customized to account for local priorities and knowledge.

## Key Findings in Methodology

The study team learned several key lessons while piloting this vulnerability assessment approach. These lessons are grouped into several key categories and discussed below:

*Scoping the Vulnerability Assessment*

- How "assets" should be defined and selected is an important consideration at the outset of the vulnerability process. This vulnerability assessment focused on specific broadly-defined assets within each mode (e.g., highway segments, rail segments, ports, airports, transit facilities). For other vulnerability assessments, the resolution could vary. For example, the vulnerability screen can be applied at the level of highway segments, or could focus on specific asset types within highways like culverts, bridges, and roadways. The chosen resolution affects the indicators and methods used to assess vulnerability.
- Determining which assets to include is also important. Some organizations may want to limit the scope of the assessment to fit time or resource constraints or focus results on a subset of assets. A criticality assessment, as done in this study, is one way to limit the number of assets considered.
- Determining which climate stressors to evaluate is another early scoping need, especially for organizations interested in limiting the amount of climate data they need to collect. As a pilot study testing replicable approaches, this study focused on several climate stressors. Other assessments, however, may choose to focus on stressors deemed most important based on general knowledge of exposure or sensitivities.

*Use of Climate Data*

- Trying to look at too many timeframes and climate narratives can result in an overwhelming amount of data to process. Narrowing the scope of the assessment through desktop exercises could be one way to simplify the process. For example, in some cases, highways may be identified as not sensitive to temperature because the pavement binders can withstand even the highest temperature ranges projected. If this is determined at the outset, temperature could be eliminated as a stressor to consider for highways, leaving more resources and time to focus on other climate stressors. As another example, a local transportation agency may determine that only the near or medium term timeframes are relevant to their local planning priorities and choose to not consider longer-term climate changes in their assessment.
- Evaluating the interactions between different climate stressors proved difficult in this vulnerability assessment, but in reality will be an important factor in how communities and transportation systems respond to climate change. This analysis explicitly considers such interactions in the storm surge analysis, where one narrative includes the impacts of storm surge combined with sea level rise. It was more difficult to explicitly assess interactions between other climate stressors, such as heavy downpours and high winds alongside storm surge during extreme events. Similarly, the study team did not have enough information to evaluate changes in humidity alongside changes in temperature, though humidity is an important aspect of heat stress.

*Scoring Vulnerability through Exposure, Sensitivity, and Adaptive Capacity Indicators*

- The concepts of *exposure* and *sensitivity* can be difficult to separate, as both help determine whether an asset would be damaged by climate change. Ideally, *exposure* refers only to whether an asset will experience a change and *sensitivity* refers only to whether it would be damaged if hypothetically exposed. In practice, however, this distinction can be difficult to make. This difficulty is illustrated in the exposure and sensitivity indicators used in the precipitation analysis, where location in flood zone is used as a sensitivity indicator. Other examples are discussed in text boxes throughout the report.
- *Adaptive capacity* can apply both to the adaptive capacity of a *specific asset* and to the adaptive capacity of the *system* as relates to that specific asset. This analysis considers both asset-specific and system-level adaptive capacity. The vulnerability scores for individual assets therefore provide some indication of the vulnerability of the overall system. For example, an airport with multiple runways has higher adaptive capacity than an airport with one runway, since this enables the airport to function in a wider range of wind conditions or in the event that one runway is unavailable. Meanwhile, having multiple airports in a region means that the regional system may have higher adaptive capacity; if one airport becomes unavailable, passengers or cargo may be transported using nearby airports (albeit at a lower level of performance than typical conditions). Both asset- and system-level adaptive capacity indicators are used to evaluate adaptive capacity of airports in this study.
- Transportation professionals interested in applying this approach face decisions about whether to incorporate definitive thresholds for asset sensitivity to different stressors. For an asset or system to be vulnerable, it must both be exposed and sensitive to climate change impacts. The study team did not designate any assets as definitively “not sensitive” in this analysis. Future vulnerability assessments may opt to incorporate thresholds of sensitivity in their scoring approach, below which a given asset is not sensitive to a given stressor and, therefore, not vulnerable. However, identifying such thresholds is difficult, depends greatly on one’s confidence in the indicators, and is an opportunity to bias vulnerability assessment results toward past experience. Care should thus be taken before applying a methodology that automatically deems assets not vulnerable because they are not sensitive under a chosen threshold.
- Having more indicators does not necessarily yield better results. Having many indicators that agree about how vulnerable an asset is increases the robustness of a result; however, disagreement among indicators can mask an asset’s vulnerability. This is because not all indicators are as telling about an asset’s vulnerability as others, nor do all indicators have consistently reliable data. The importance and accuracy of indicators will vary by study area. Weighting some indicators more strongly than others or grouping indicators can be a way to overcome this problem. For example, if an asset has been damaged in the past (and is clearly sensitive), but is in good condition, it may make sense to weight historical performance more heavily. Similarly, if detailed information is available for several indicators related to the condition of an asset, it may make sense to group these related indicators to limit how strongly the asset’s condition influences the overall score compared to other factors that can only be evaluated by one or two indicators. Consulting stakeholders and local experts can help to identify effective indicators and appropriate weights.
- Historical vulnerability can be a useful tool to begin evaluating future vulnerability. The study team arrived at several of the indicators used in this assessment by investigating the reasons behind previous weather-related damage in Mobile. On the advice of the local

transportation officials, this assessment weighted historical performance more heavily than other sensitivity indicators. The transportation officials indicated that looking at historical performance can help capture which assets would be affected first, or most significantly, as the climate changes.

That said, relying too heavily on historical vulnerability can be difficult when dealing with novel climate impacts. For example, under extreme scenarios, such as two meters of sea level rise, many assets that have never experienced tidal flooding before may be highly vulnerable. This can be taken into account by weighting historical performance lower or equal to other indicators when assessing vulnerability for the most extreme, "never-before-seen" narratives.

- The results of the indicator-based screen are heavily influenced by decisions about scoring approaches and how those scores are weighted – both by indicator and by vulnerability component. The scoring system and weights in this study were based on professional judgment and Mobile-specific considerations. A vulnerability assessment elsewhere would need to review and revise the specific methodology used. This also is a reminder that it is important to conduct a sensitivity analysis to validate the robustness of the screen's conclusions and identify which assumptions are driving results. The methodology used to evaluate the robustness of this study's results is described in Appendix F.

*Using Vulnerability Screen Results*

- These findings highlight the need for a "gut check" of the results. While most of the results from this analysis appeared reasonable, there were a small number of results that did not resonate with the experience of reviewers and stakeholders. It is important to remember that this type of broad, screening-level approach will inevitably have limitations. As an example, one adjustment made for this analysis related to the treatment of coastal highway segments in flood zones. There were a few cases where a small piece of a segment crossed a riverine flood zone and was therefore counted as non-coastal, even though the asset was clearly a coastal asset. The vulnerability scores for those assets appeared to be a bit skewed, so the default calculations were revised. In another example, scores of certain coastal highway segments to precipitation changes seemed to be unduly influenced by adaptive capacity scores. Upon further review of the sensitivity and adaptive capacity scores, it was apparent that high adaptive capacity scores were sufficient to propel these assets to the top of the vulnerability list, even though they were not believed to be particularly sensitive. Knowing the facets of these results allows decision-makers to judge the implications of the vulnerability score.
- Evaluating each component of vulnerability separately in addition to as part of a composite vulnerability score adds another dimension to the analysis of results. One way to separate these concepts is to view vulnerability as a relationship between likelihood of damage (a combination of exposure and sensitivity) and adaptive capacity, which allows decision-makers to make real-time decisions about the weight of each component in their decision-making, and potentially vary those decisions by asset (such as in the case of highway precipitation results discussed above).
- The complex interactions between the three components of vulnerability and vulnerability to different stressors make it important to think critically about the most effective ways to represent the results. Spatial representation (i.e., maps) of the vulnerability results through color-coding vulnerability can be one powerful way to illustrate the results of the screen (and

also facilitate the "gut check" process. Knowing decision makers needs can inform the appropriate outputs for a vulnerability assessment.

Related to these lessons are three key caveats to the final vulnerability screen scores, which need to be kept in mind when reviewing the results. These caveats are:

- It is difficult to make an apples-to-apples comparison of vulnerability scores to different climate stressors for specific assets. That is, an asset could end up with a vulnerability score of 3.3 for storm surge and 3.2 for sea level rise, but such scores do not necessarily mean that the asset is more vulnerable to storm surge than to sea level rise. Different indicators were used for each climate stressor, meaning the resulting vulnerability scores are not directly comparable. Still, the results can generally show which climate stressors may be more problematic than others. An asset scoring 3.3 for storm surge and 1.3 for temperature is likely more vulnerable to storm surge than temperature.
- Similarly, different indicators were used to evaluate each mode. A highway asset scoring 3.5 to wind is not necessarily more vulnerable than a port asset scoring 3.4 for wind. Order of magnitude, however, can still be useful. While the quantitative scores are not directly comparable across modes, they do provide an indication of which modes appear to be relatively more or less vulnerable.
- Vulnerability scores were based on readily available data, expert interviews, and spatial analysis. As with any quantitative analysis, the quality of the results is dependent on the quality of the input data.

Mobile-specific caveats and limitations are discussed in Section 1.3.

## Areas for Future Research

While this approach and its associated indicators were well vetted with transportation officials, engineers, and climate change vulnerability experts, there are specific areas that would benefit from additional research or evaluation by other localities. Such future analyses will help improve and build upon the methods presented in this document.

The authors have identified the specific areas that may benefit from future research include:

- Evaluation of additional indicators: This document discusses alternate indicators that were not used in this project, but that could be considered for other efforts. These alternate indicators often address characteristics that may be relevant to other locations but were not relevant to Mobile (such as cold-weather related indicators) or that rely on data that may be available elsewhere but that were not readily available for Mobile. As other transportation agencies evaluate their systems for climate vulnerability, additional indicators may be identified.
- Systematic evaluation of effectiveness of using the chosen indicators: It would be interesting to evaluate how effective these indicators are in actually identifying assets that are more vulnerable. This ground-truthing could be done by looking at past climate events and the associated impacts on the transportation system. That is, if a similar assessment were conducted 5 or 10 years ago, using the selected indicators, would it have accurately identified the areas that exhibited vulnerability to recent weather events? This evaluation was outside

the scope and resources of this study, but conducting this type of evaluation in the future could provide important insight into the selection and weighting of indicators.

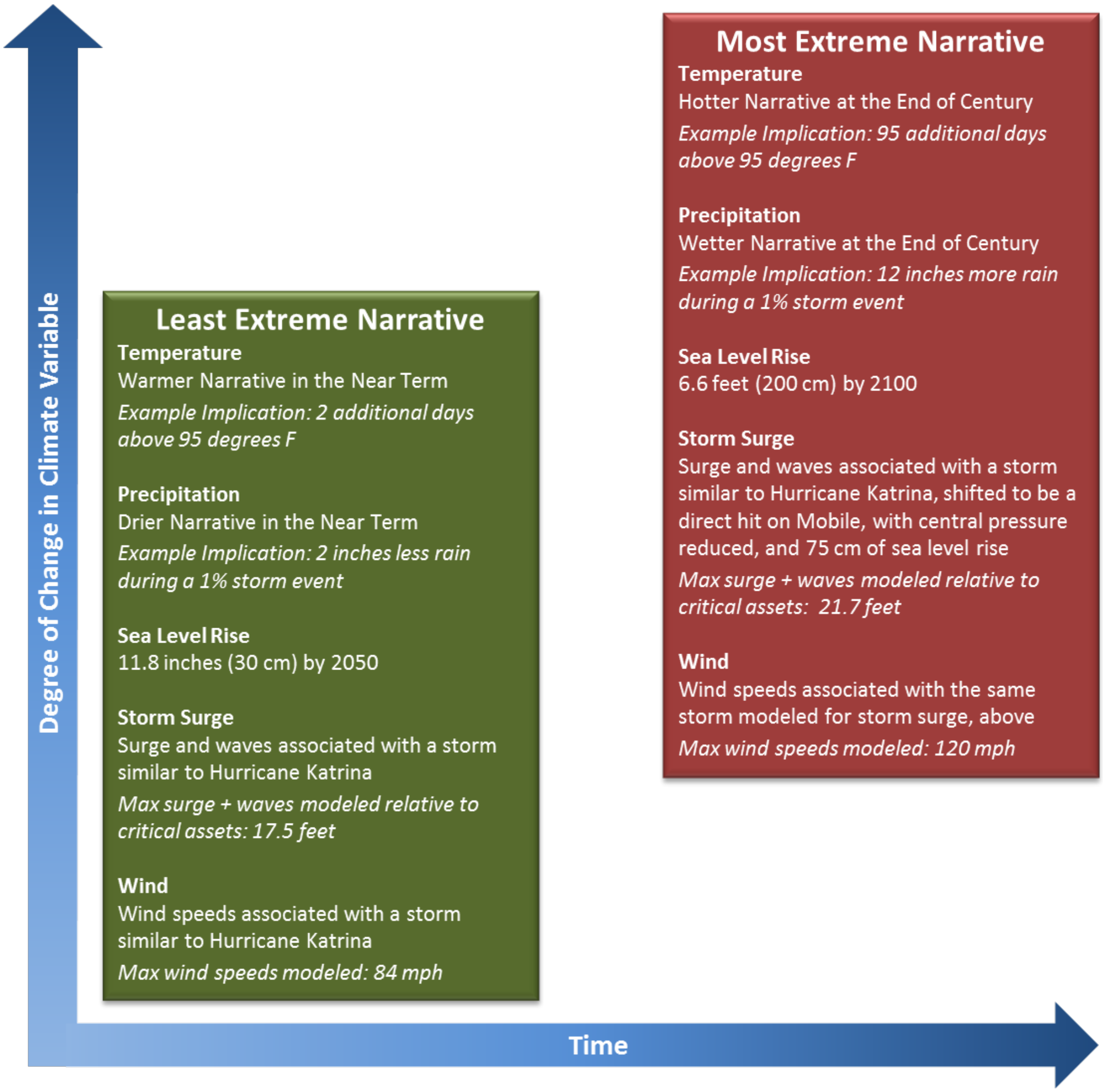
- Further review of scoring and weighting assumptions: As noted above, the assumptions on scoring and weighting are important influencers of the results. Future review of these assumptions and evaluating them in different contexts would help improve robustness of the methodology.
- Approaches for linking existing data collection structures with vulnerability assessments: This indicator-based vulnerability screening approach is heavily data-dependent. Therefore, it would be helpful to determine effective ways to link existing data collection systems (such as asset management systems) with vulnerability screens. For example, the fields available in an asset management system can determine the available pool of indicators. In addition, determining key vulnerability indicators can be a way of identifying data fields to collect and track in the future.

## 1.3 Key Findings in Mobile

This section provides a high-level summary of the findings for Mobile's transportation system, including specific findings for each mode. As noted previously, this work was intended to identify where climate change-related vulnerabilities may exist in Mobile's transportation system, but does not provide recommendations on how to mitigate these vulnerabilities.

Note that the discussion in this section refers to various climate narratives, which are discussed in more detail in Section 3.2. "Climate narratives" refer to the specific temperature and precipitation projections, as well as the modeled sea level rise, storm surge, and wind scenarios, assumed for this vulnerability assessment. For each climate stressor, two or three narratives were selected, representing a range in the degree of change. Furthermore, three time periods were assessed: near-term, medium-term, and end-of-century. References to the "least extreme narrative" represent (a) the least severe projection or modeled scenario for a given stressor and (b) the near-term timeframe. References to the "most extreme narrative" represent (a) the most severe projection or modeled scenario for a given stressor and (b) the end-of-century timeframe. The least extreme and most extreme narratives are meant to represent reasonable ranges in future climate. Figure 1 provides a graphical depiction of the least and most extreme narratives referenced throughout this report.

**Figure 1: Graphical Depiction of Least Extreme and Most Extreme Climate Narratives Used in this Report**



### 1.3.1 Overall Vulnerabilities of the Transportation System

In general, transportation assets in Mobile seem to be particularly vulnerable to sea level rise and storm surge. Under the most extreme narratives, all modes except airports have assets that scored as highly vulnerable, and most modes had assets scoring either moderately or highly vulnerable even under the least extreme narratives. The analysis indicates that there are highways and rail assets that are vulnerable to storms that could conceivably happen today; more intense storms, coupled with sea level rise, could cause significant impacts on all modes. Please see Figure 2 and Figure 3.

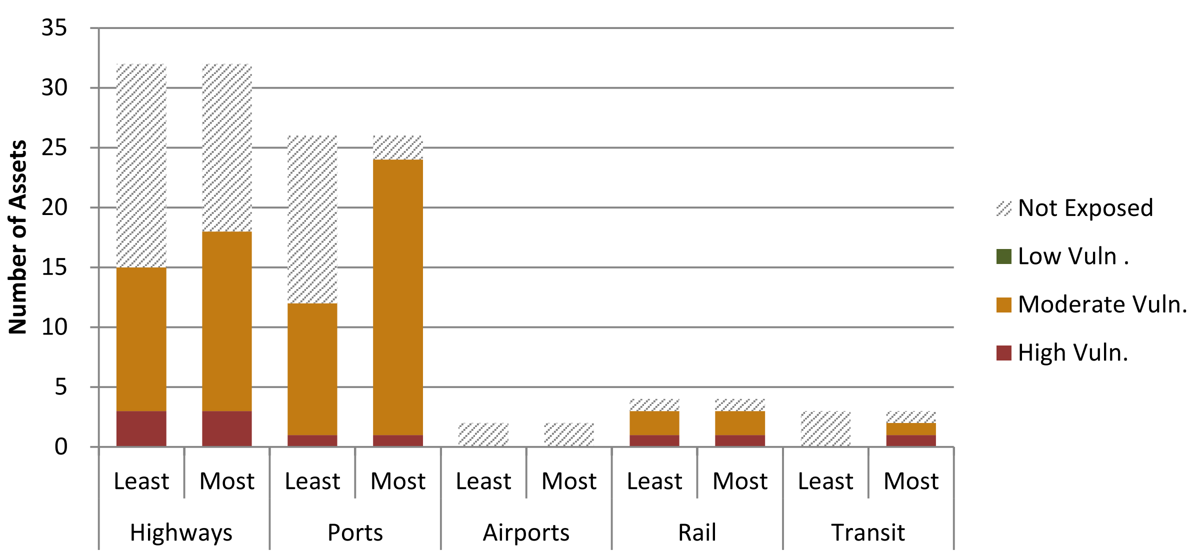
**Summary of Transportation System Vulnerabilities**

- Storm surge and sea level rise appear to pose the greatest threat to Mobile's transportation system. Parts of the system are highly vulnerable, even under lower sea level rise narratives and current storm conditions
- In general, coastal areas show greater vulnerability scores than inland areas for all climate stressors

**Key Caveats in Vulnerability Assessment Results**

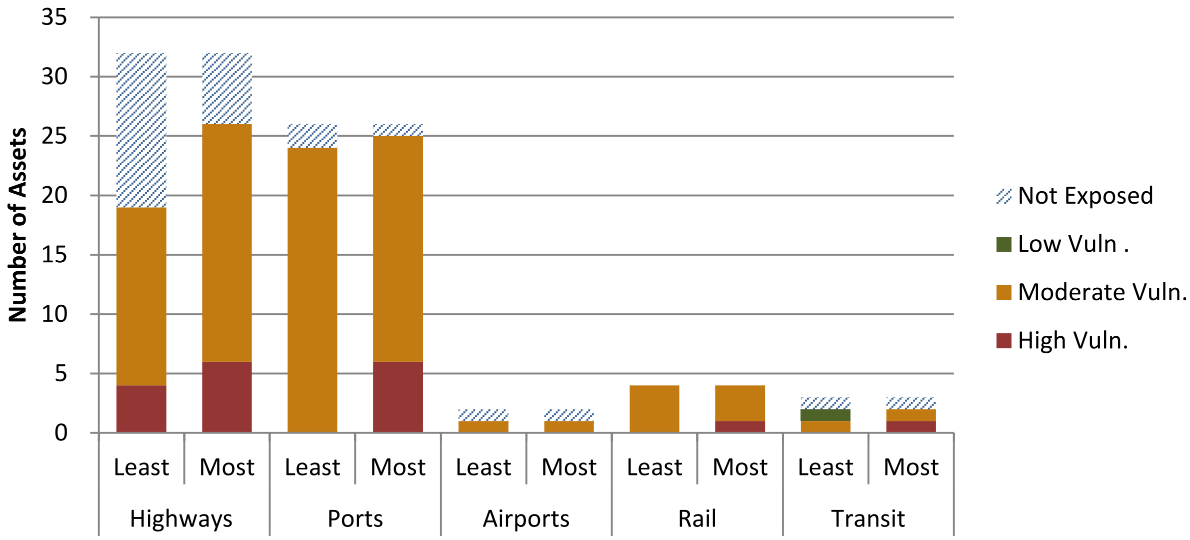
The vulnerability scores represent relative vulnerability within each type of mode to each type of stressor. Direct comparisons cannot be made between scores across modes or stressors, since different indicators and methodologies are used to generate them. However, the results, along with local context, can provide a sense of the key transportation system vulnerabilities in Mobile. See "Caveats" section on page 21 for a further discussion of the caveats in the vulnerability assessment results.

**Figure 2: Summary of Vulnerabilities to Sea Level Rise by Mode***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. Assets that are not exposed are considered to be not vulnerable. See Section 4 for detail on the scoring methodology used.

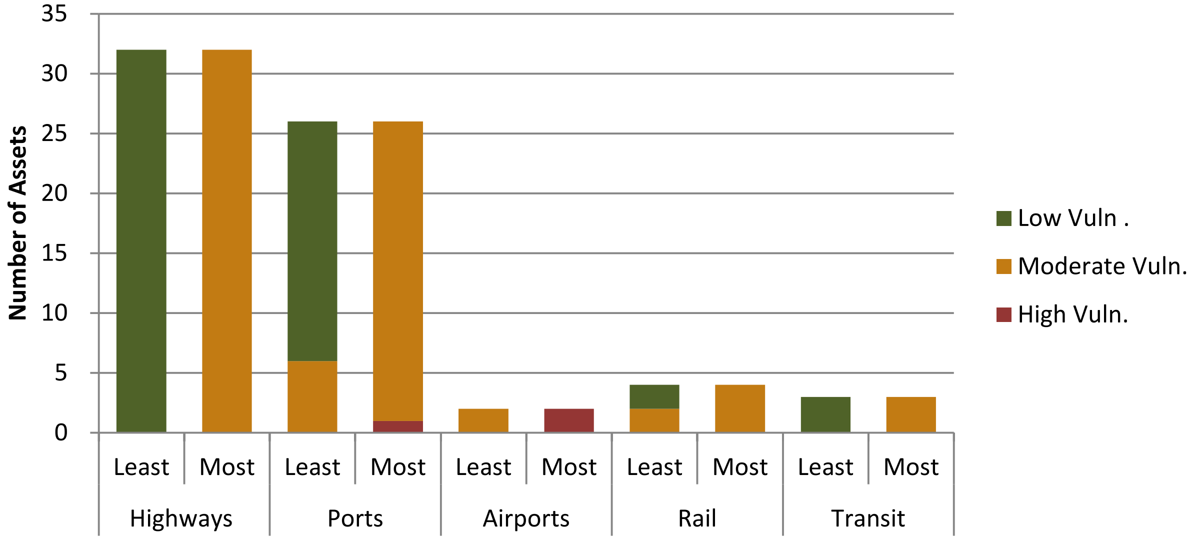
**Figure 3: Summary of Vulnerabilities to Storm Surge by Mode***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. Assets that are not exposed are considered to be not vulnerable. See Section 4 for detail on the scoring methodology used.

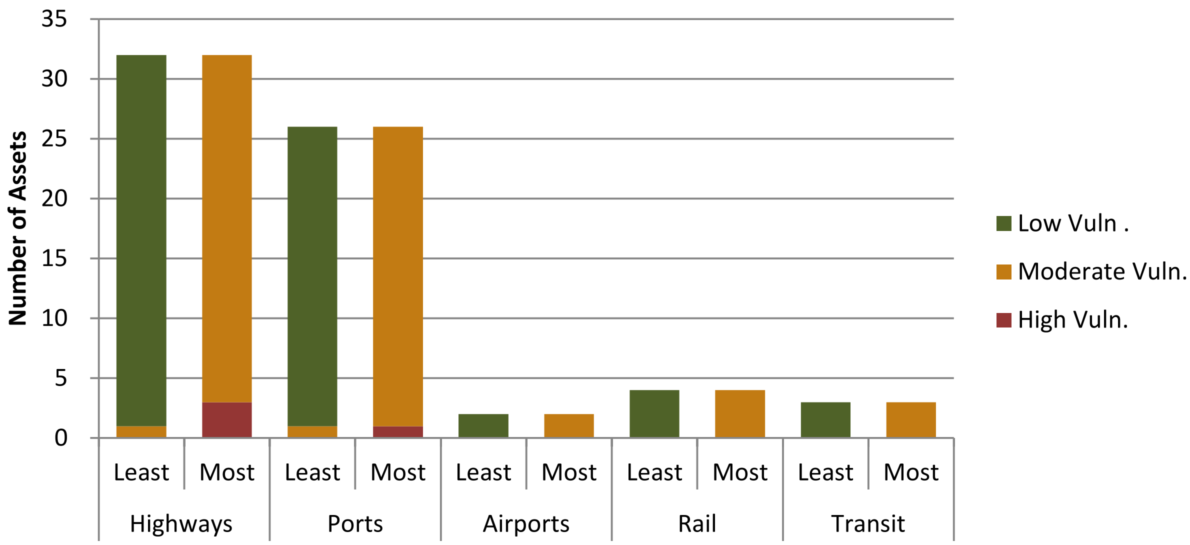
Vulnerability scores for temperature and precipitation are not as high. It is not until the most extreme narrative that any of the assets analyzed score as highly vulnerability to temperature or precipitation, and even then only a few of the total assets appear to be highly vulnerable. For temperature, certain marine port and airport assets exhibited high vulnerability scores under the most extreme narrative. For precipitation, only highways and ports have assets with high vulnerability scores under the most extreme narrative. Please see Figure 4 and Figure 5.

**Figure 4: Summary of Vulnerabilities to Temperature by Mode***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. See Section 4 for detail on the scoring methodology used.

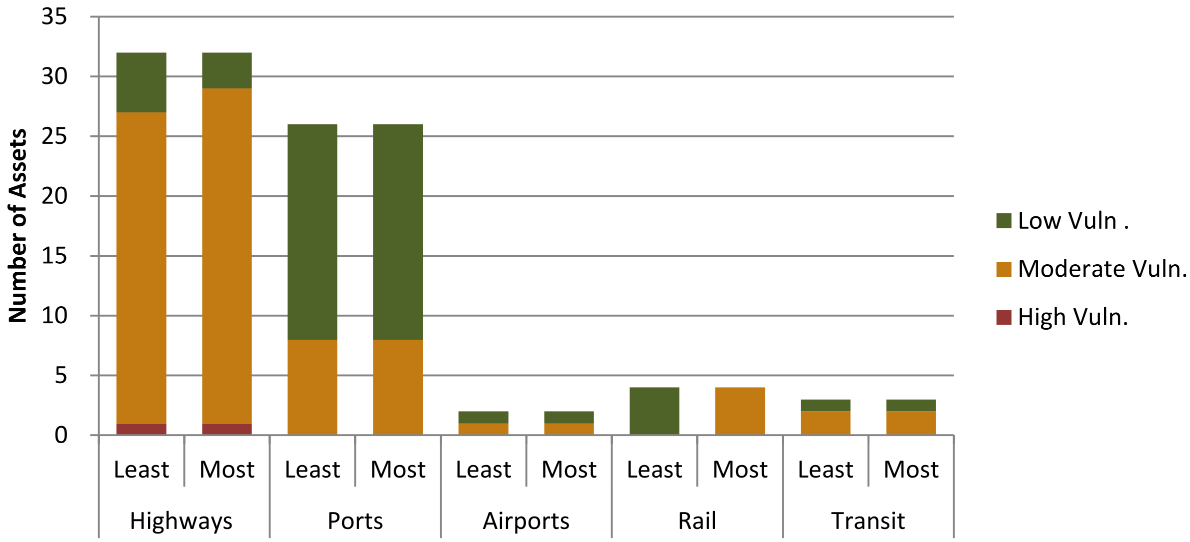
**Figure 5: Summary of Vulnerabilities to Precipitation by Mode***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. See Section 4 for detail on the scoring methodology used.

Among the modes, highways assets seem to have the highest vulnerability to winds associated with hurricanes. The high vulnerability scores for highways are due, in part, to the thresholds at which traffic is disrupted by winds, and in part to the potential for damage to the physical assets themselves. Please see Figure 6.

**Figure 6: Summary of Vulnerabilities to Wind by Mode***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. See Section 4 for detail on the scoring methodology used.

This research indicates that the highway and port assets studied are susceptible to a wider range of climate stressors than the other modes. Under the most extreme narrative, highways and ports each show high vulnerability scores to four out of five climate stressors. Rail and transit show high vulnerability scores under two of the five climate stressors under the most extreme narrative (i.e., sea level rise and storm surge), and airports show high vulnerability scores for just one of the stressors (i.e., temperature).

Not surprisingly, the vulnerability scores tended to increase as the narratives got more extreme. In the case of temperature, the most notable vulnerabilities occurred at the end-of-century timeframe. Thus, Mobile's transportation system may have limited vulnerabilities to changes in temperature in the near term. For precipitation, the less extreme narratives show only modest increases, or even decreases, in precipitation. Thus, while the scores indicate that many assets have low vulnerability to precipitation in the near-term, it is actually possible that the assets would experience a slight *decrease* in vulnerability relative to today. Under more extreme precipitation narratives, however, the precipitation exposure increases significantly, thereby increasing the overall vulnerability of the transportation system.

Geographically, the coastal areas appear to be particularly vulnerable. While this might not be surprising from a sea level rise and storm surge perspective (since it is the coastal areas being inundated), it is also interesting to note that precipitation vulnerability scores tend to be higher near the coasts. This finding is in line with input from Mobile stakeholders, and with the fact that the coastal areas tend to be lower lying, and that some of these areas have existing drainage issues. Some of the assets with particularly high vulnerability to temperature are also near the coast, although their vulnerability is driven by other characteristics rather than proximity to the coast. Wind is the only stressor not showing a concentration of vulnerable assets near the coastal regions. The assets with higher wind vulnerability scores extend inland from Downtown, and are also in the more inland, southern part of the County. Some of these segments are in areas with a larger number of traffic signals. Figure 7 through Figure 11 illustrate the spatial distribution of vulnerabilities for each climate stressor.

**Figure 7: Geographic Distribution of Vulnerabilities to Temperature, All Modes**

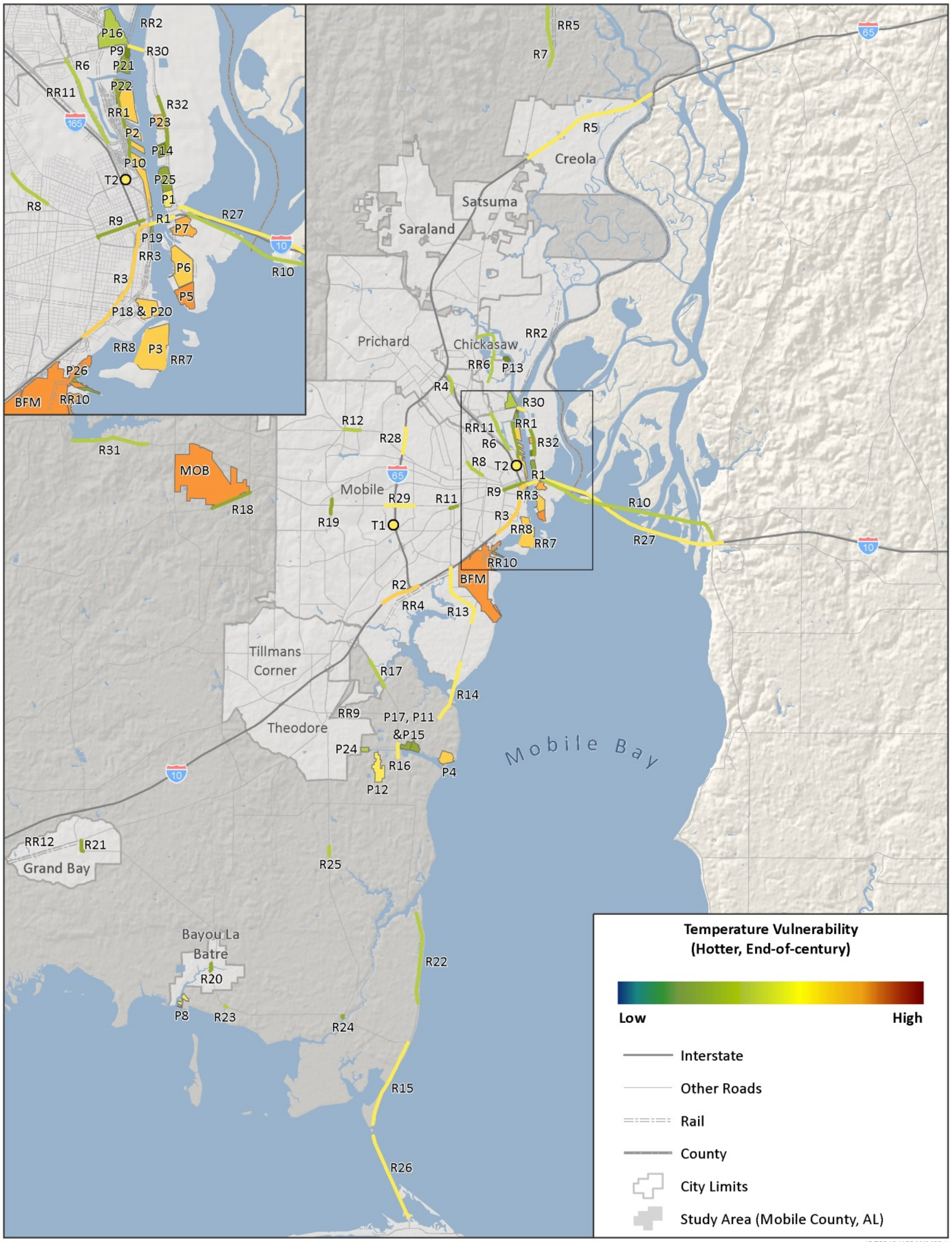


**Figure 8: Geographic Distribution of Vulnerabilities to Precipitation, All Modes**

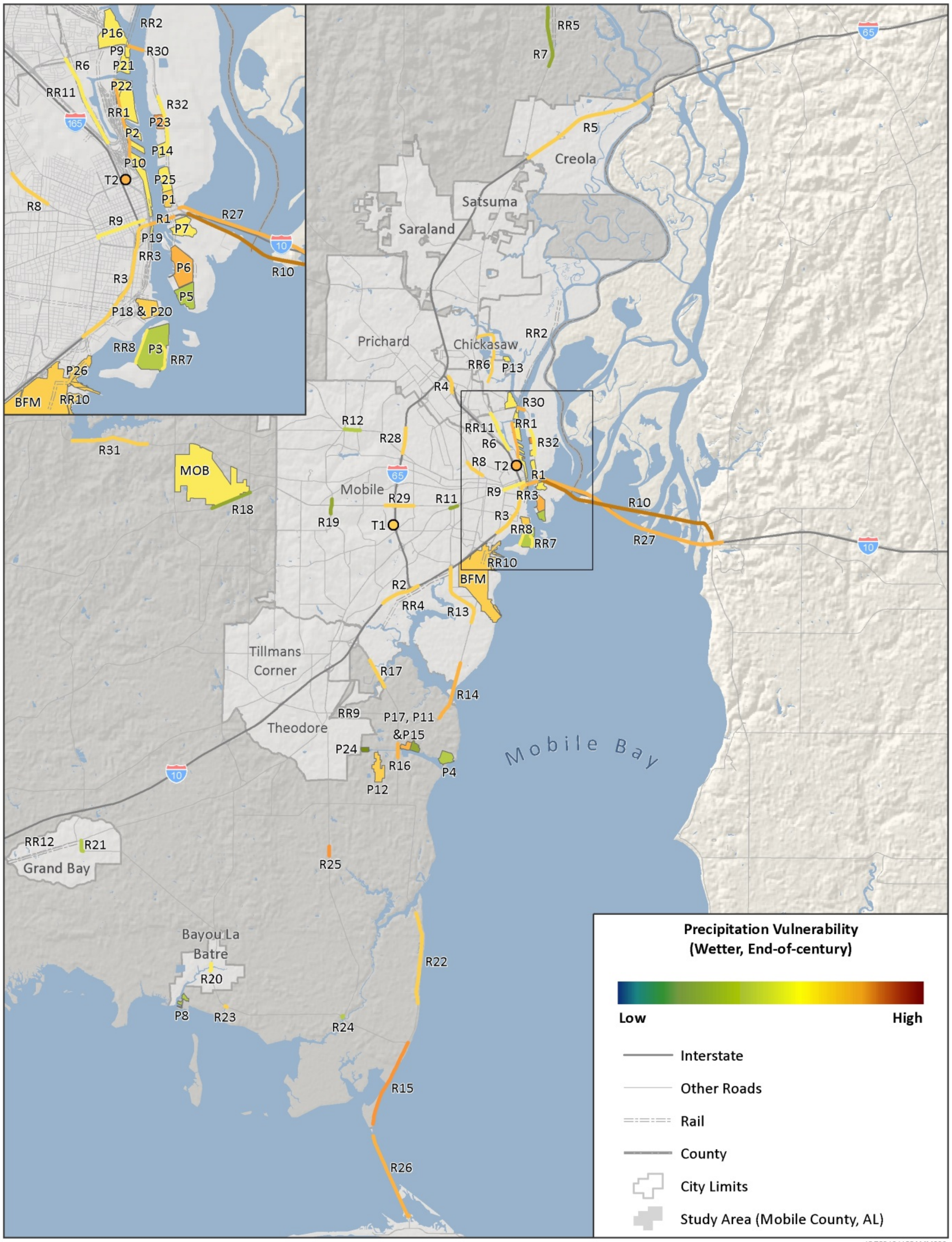


**Figure 9: Geographic Distribution of Vulnerabilities to Sea Level Rise, All Modes**

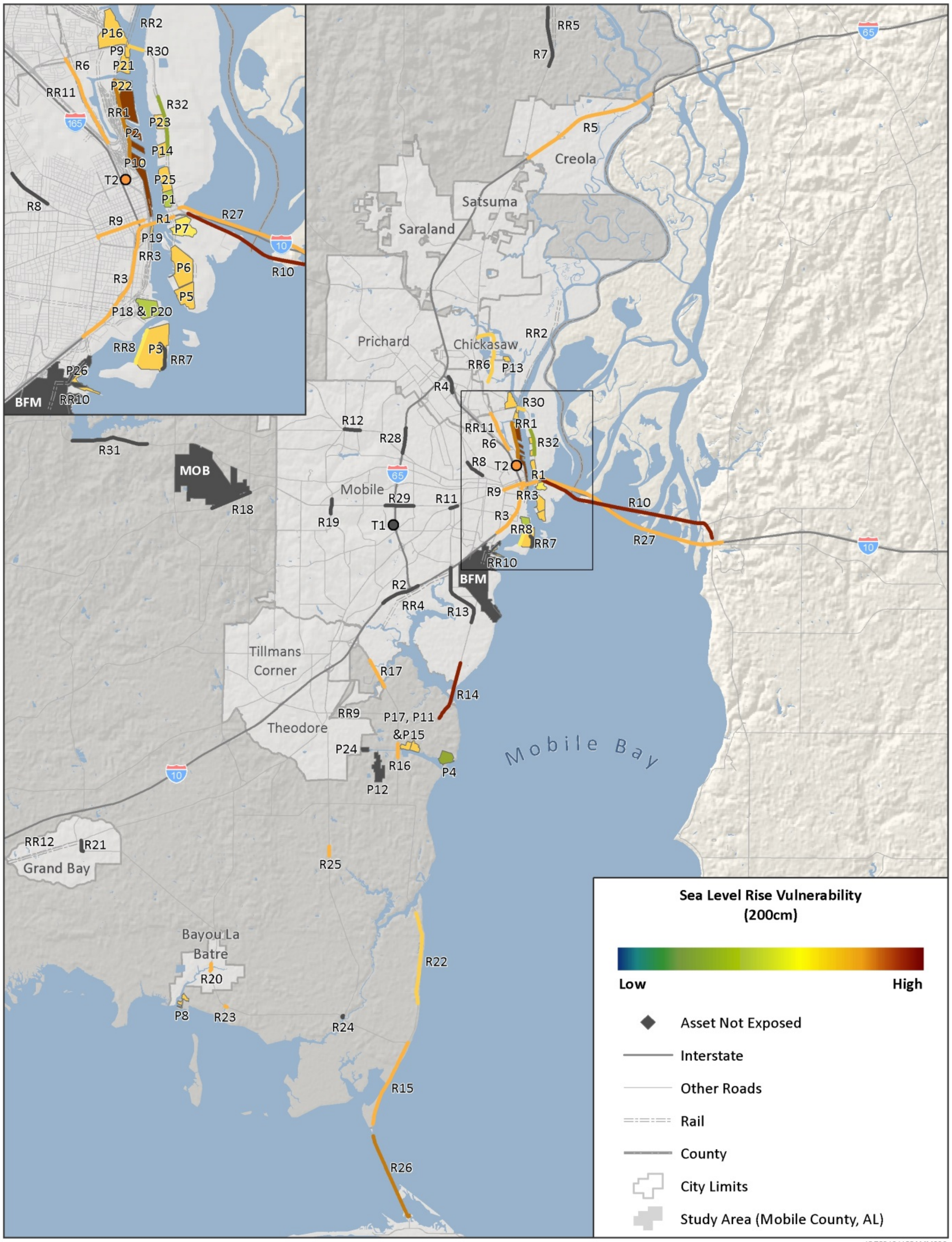


**Figure 10: Geographic Distribution of Vulnerabilities to Storm Surge, All Modes**

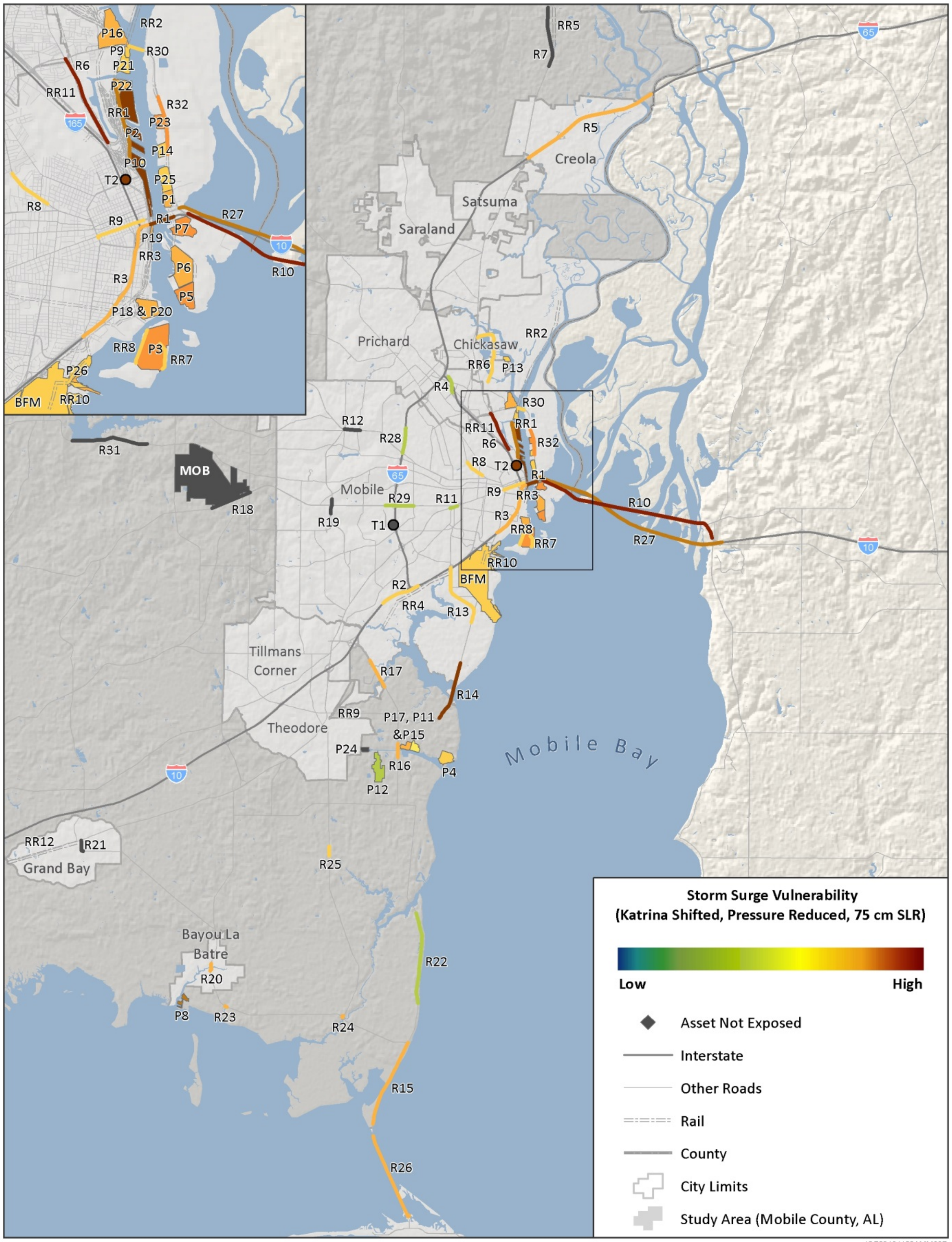
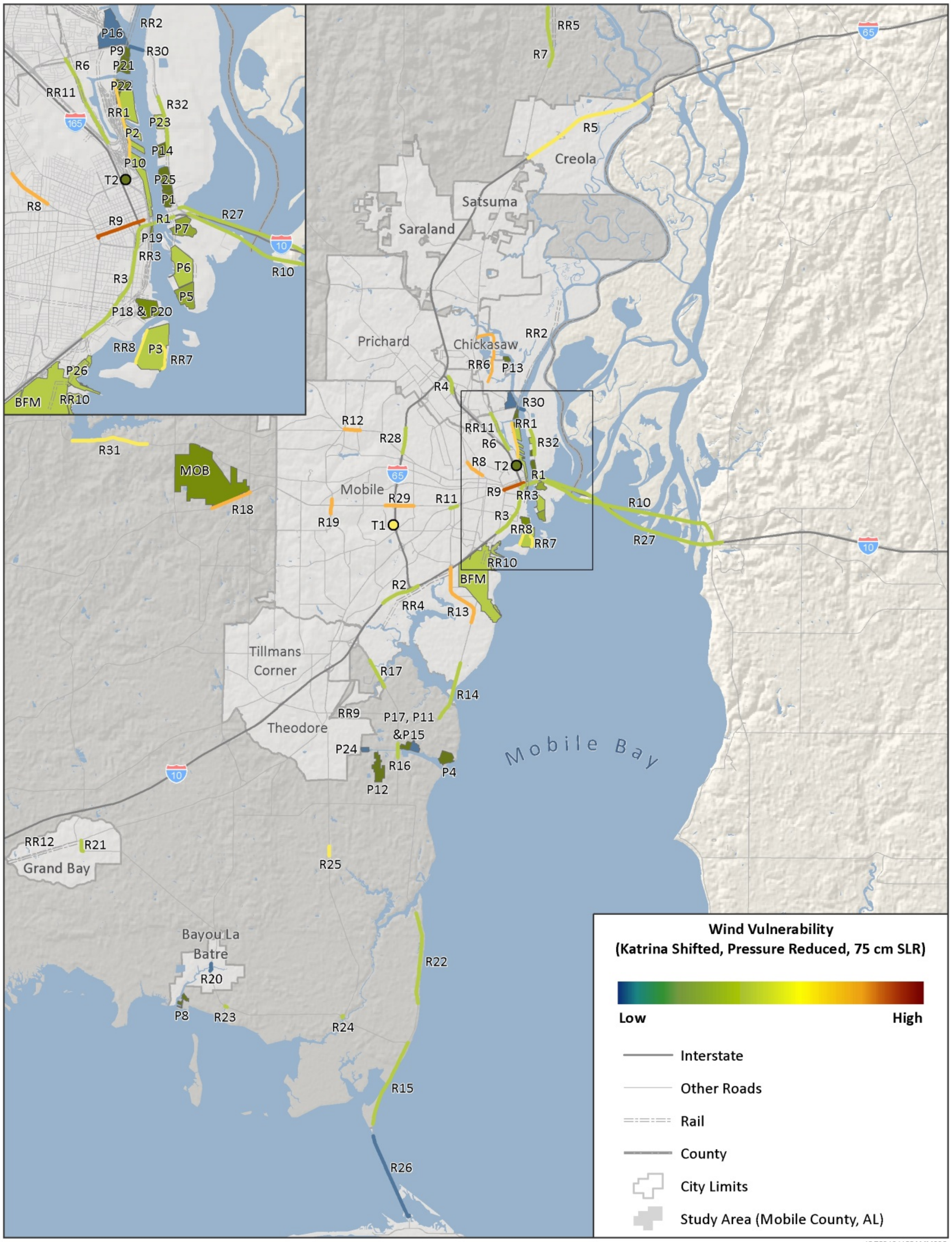


**Figure 11: Geographic Distribution of Vulnerabilities to Wind, All Modes**



Maps of all vulnerability scores—for any combination of assets, climate stressors, and narratives—are available in the web viewer that accompanies this report at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

## Caveats

Vulnerability results presented in this report are derived from an indicator-based scoring system. This is the first large-scale attempt to systematically evaluate and score vulnerability based on readily available data, expert interviews, and threshold analysis. The results presented are subject to inaccuracies and gaps in the data. In recognition of this limitation, results of this study include a "data availability score" so that decision-makers are aware of instances where incomplete data may have influenced the results. The specific effects of data gaps on the results are discussed in Section 5.

"Historical performance" is a sensitivity indicator frequently used across modes and climate stressors. Upon advice from local stakeholders, this indicator was generally weighted 15 percent points more heavily than other indicators. This increased weighting represents the fact that assets that have demonstrated vulnerabilities in the past are likely to be among the first, or the most severely, affected under increasingly severe weather impacts. However, this weighting assumption may bias the results somewhat against assets that have historically *not* been affected, but that have other characteristics that suggest they may be particularly vulnerable in the future.

Also, as discussed within the mode-specific sections of this report, sufficient data to complete the analysis for rail segments were available only for rail segments maintained by the Alabama State Port Authority (ASPA); these segments are referred to as Terminal Rail at Alabama State Docks (TASD), and represent rail yards and segments immediately surrounding the ports. Therefore, the vulnerability results for rail exclusively represent coastal segments; findings are not representative of segments elsewhere in the County. Furthermore, there were only two critical airports and only three critical transit facilities in Mobile, AL, so the results presented in this report may be limited in their applicability elsewhere. However, the process for identifying indicators of vulnerability should be applicable broadly and could be calibrated to reflect a broader range of example facilities.

Given the range of climate models and emission scenarios available to support analyses of future climate, it is challenging to synthesize and communicate vulnerability information in a way that is useful to practitioners. This research provides insight into which stressors may be particularly problematic for Mobile and for specific assets, and for which stressors there may be less vulnerability; these vulnerability findings hinge on a small set of climate "narratives" that are chosen from a rich set of climate information developed for Mobile in order to provide decision makers with information about the *range* of possible vulnerabilities rather than to pinpoint vulnerability under any single set of future climate conditions.

Finally, it is difficult to make an apples-to-apples comparison of vulnerability scores of specific assets to the different climate stressors and across modes. In this analysis, different indicators were used for each stressor; thus, too much stock should not be taken in the fact that an underlying vulnerability score for one stressor is just slightly higher/lower than the score for a different stressor. Similarly, different indicators were used for each mode, making it difficult to compare vulnerability across modes. The results show relative vulnerability within each mode and climate stressor.

The following sections detail vulnerabilities found for highways, ports, airports, rail, and transit.

### 1.3.2 Overview of Vulnerabilities of Critical Highway Segments

According to the analysis, the highway system in Mobile is vulnerable to storm surge, sea level rise, extreme precipitation events, extreme winds, and heat waves, in order of descending vulnerability. The assets that appear to be most vulnerable tend to have one or more of the following characteristics:

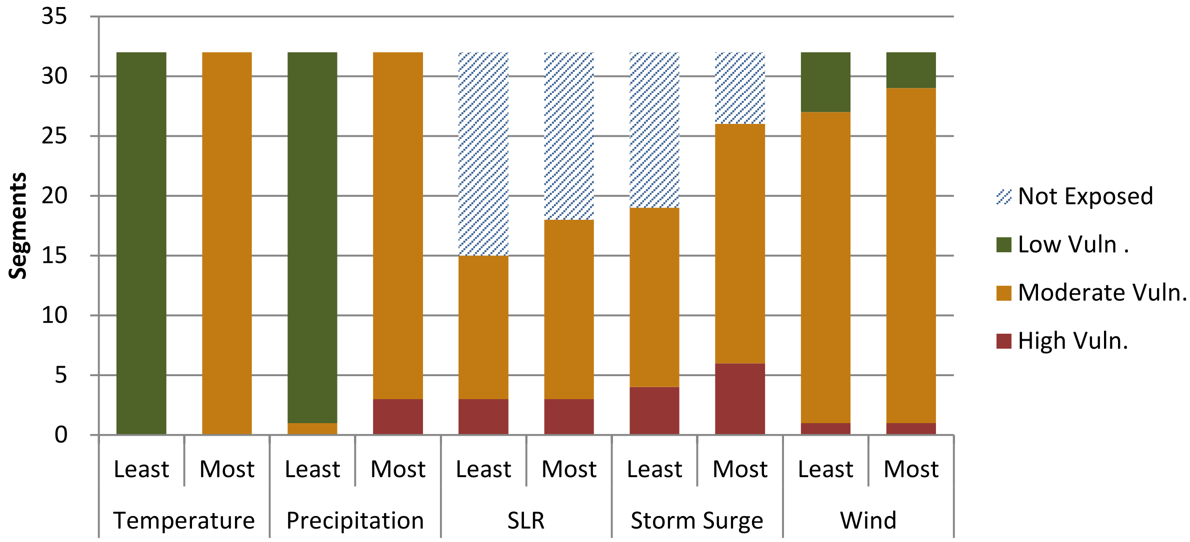
- Location close to the coastline or water bodies
- Low elevation
- Advanced age or sub-optimal condition
- Lack of system redundancy

Please see Figure 12 for a summary of highway vulnerability results.

**Summary of Highway System Vulnerabilities**

- According to the analysis, storm surge represents the source of the greatest vulnerability for Mobile's transportation system. Vulnerability scores are greatest for low-lying coastal roads and bridges
- Proximity to water is a major driver of the vulnerability scores—particularly to storm surge, sea level rise, and heavy precipitation
- The most vulnerable areas appear to be those closest to Downtown as well as in the southern tip of Mobile, near Dauphin Island
- The components of the highway system that score highest for vulnerability are those that are (a) susceptible to damage because of their construction, location, or condition, and/or (b) difficult to repair or replace if they are damaged because of high replacement costs or little redundancy in the highway system
- Mobile's highways do not appear to be very vulnerable to projected increases in temperature

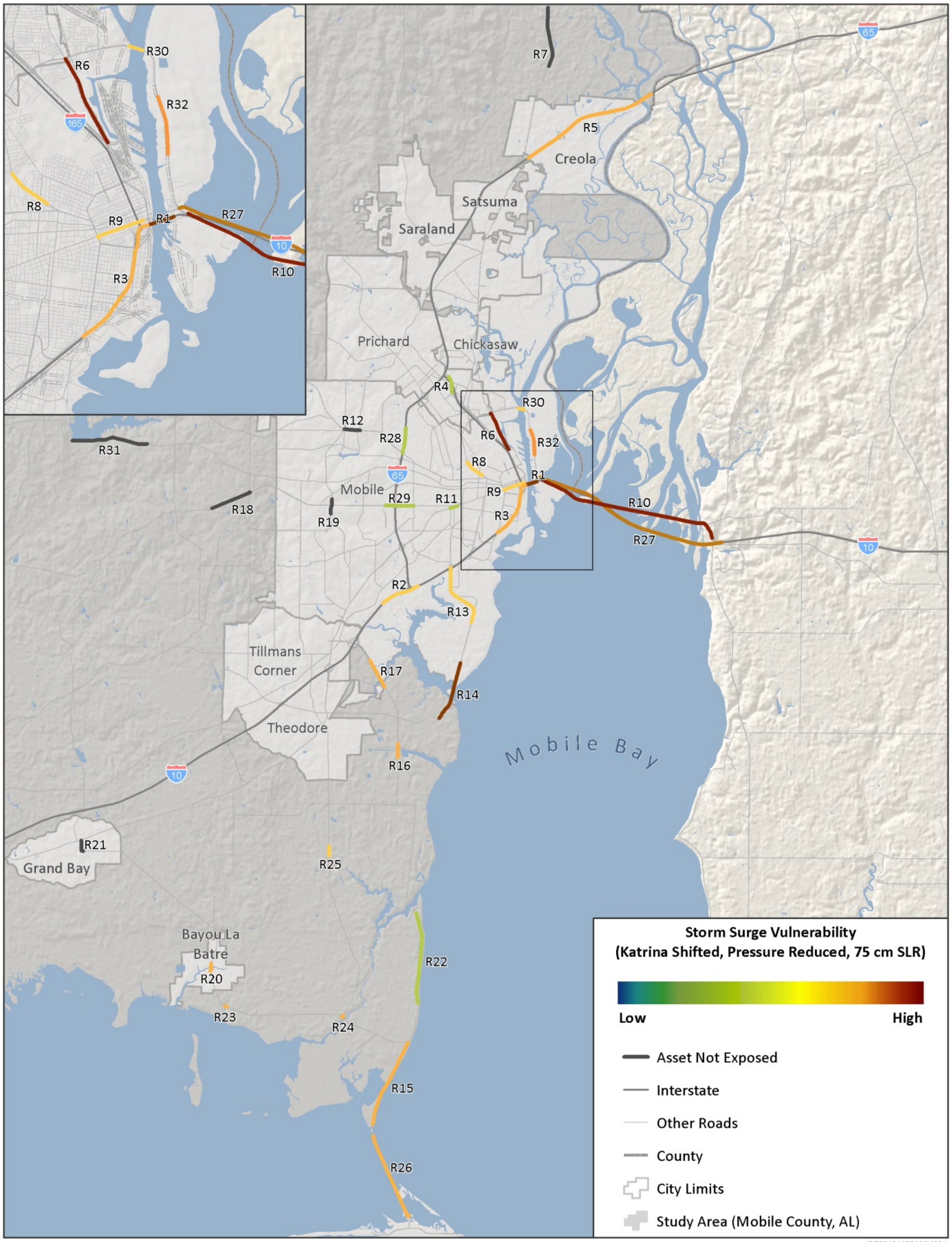
**Figure 12: Number of Highway Segments that are Not Exposed or have Low, Moderate, or High Vulnerability, by Stressor***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Segment vulnerability is calculated using the maximum vulnerability score across sub-segments. Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. Assets that are not exposed are considered to be not vulnerable. See Section 4 for detail on the scoring methodology used.

According to the analysis, the highway system's most significant vulnerabilities relate to coastal assets experiencing **storm surge**. Telegraph Road (R6) is highly vulnerable, due to its exposed location, which has already demonstrated coastal flooding in the past. The Wallace Tunnel (R1) and the Causeway (R10) are also highly vulnerable to storm surge because of their coastal location and low elevation. The Dauphin Island Parkway is another highly vulnerable coastal asset, particularly the segment just south of Mobile Downtown Airport. It scores as highly vulnerable due in part to its exposed location. The vulnerability scores of these assets also reflect the fact that they are highly important to Mobile, and losing service along these segments would greatly affect the overall transportation system. Figure 13 shows a map of highway asset vulnerabilities to storm surge. Similar maps for all assets and climate stressors are available in the web viewer that accompanies this report at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Figure 13: Vulnerabilities of Highway Representative Segments to Storm Surge (most extreme narrative)**



Mobile's highways also appear to be quite vulnerable to **sea level rise**. Half of all representative segments studied in this analysis are projected to be inundated under the lowest sea level rise narrative of 30 centimeters by 2050 (see Figure 9). Among those assets, the ones scoring as most vulnerable have two key traits: they have flooded in the past during high tide events and are relatively difficult to repair or replace. For example, the five bridges with the highest vulnerability scores are along the Causeway—expensive assets that have low approach and deck heights and have flooded in the past from tidal events.

The highway vulnerability analysis for **precipitation** changes focused on whether highways would be vulnerable to precipitation-induced inland flooding; since direct projections of inland flooding were not available, the potential impacts of projected changes in extreme precipitation events were evaluated. Highway precipitation vulnerability scores depend greatly on whether today's extreme rain events become more frequent and severe. If they do, as projected under the more extreme narratives in this study, then portions of Mobile's highway system appear to be vulnerable to these changes (see Figure 8). One important driver of the vulnerability score is whether the roadway has historically flooded during heavy rain events. Assets that are vulnerable under today's conditions would still be vulnerable if conditions worsen. Other factors affecting precipitation vulnerability scores are whether assets are located in flood zones, if they are bridges with low approach heights, and whether they are situated to collect runoff. The assets with the highest precipitation vulnerability scores are the Causeway (R10), the Dauphin Island Parkway (R15), the Dauphin Island Bridge (R26), the I-10 Bridge across Mobile Bay (R27), and a segment of Bellingrath Road where it crosses Fowl River (R25). The Dauphin Island Bridge and I-10 Bridge across Mobile Bay are major coastal bridges that do not, intuitively, seem vulnerable to precipitation-driven flooding. Their high vulnerability is driven by three traits that they share: they are sensitive because the approaches to the bridges are very low in elevation, meaning they are more susceptible to flooding. In addition, they both have very low adaptive capacity, as indicated by their high cost and lack of detours. Thus, if they were to be damaged by flooding, Mobile's transportation system would be severely affected.

Mobile's highway system appears to be only moderately vulnerable to extreme **winds** from hurricanes that may affect the area. Most bridges in Mobile are designed to withstand wind speeds of 100 to 150 mph depending on whether they are coastal, but wind speeds can negatively impact signs, power lines, and service at lower thresholds, generally starting at around 74 mph. The projected wind speeds associated with the most extreme storm narrative ranged from 108 to 120 mph. Therefore, highways in Mobile appear to have low vulnerability to wind from a structural standpoint. The roads with the highest wind vulnerability scores are those closest to downtown (see Figure 11), because they have the highest density of signs and signals; damage to signs and signals can impair use of the road.

Finally, the screen shows that the Mobile highway system is not very vulnerable to projected **temperature** increases (see Figure 7). According to ALDOT, most assets in Mobile are paved using an asphalt binder (PG 67-22) designed to withstand ambient air temperatures up to about

130°F. Temperatures in the Mobile region are not projected to reach these levels even under the most extreme narrative, so road surfaces in Mobile are unlikely to be greatly damaged by temperature increases. I-10 (R2 and R3) is more vulnerable than other highways because it experiences high volumes of truck traffic, which increases the likelihood of pavement rutting during high temperatures.

Table 1 indicates the assets that rank in the "top 10" most vulnerable highways for each stressor. The table is sorted by the number of stressors for which the highway is one of the most vulnerable. The five segments that score among the most vulnerable for all climate stressors are all coastal assets highly exposed to extreme weather stressors and that would burden the entire transportation system if they were closed after damage. For example, they are highways that serve areas with little redundancy in the system or that have very high replacement costs. Further, many of these assets are ones that have been damaged from extreme weather in the past, demonstrating that they are susceptible to damage. Figure 14 shows these assets on a map.

Vulnerabilities are not necessarily uniform across the study area. The coastal areas of Mobile appear to be, unsurprisingly, most vulnerable to sea level rise and storm surge, particularly in the areas closest to Downtown as well as the southern tip of Mobile, near Dauphin Island. Precipitation vulnerability scores tended to be higher near the coast, which is where the land elevation is lower and where more water features are found. Wind vulnerability scores were higher in more developed areas, as the number of intersections, traffic lights, and signage increases. Maps of highway vulnerability scores to all climate stressors are available in the web viewer that accompanies this report at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Table 1: Most Vulnerable Highway Assets to All Climate Stressors**

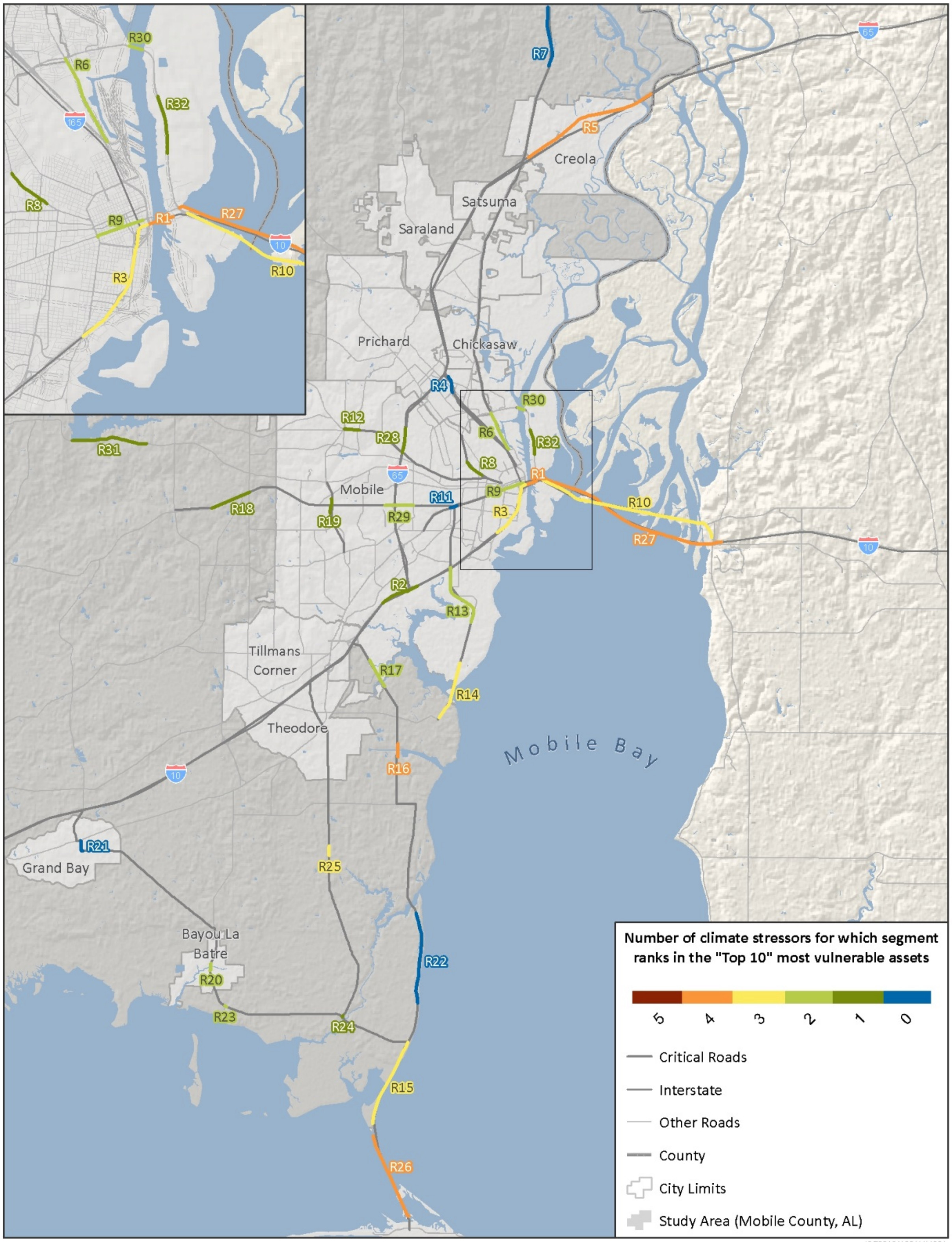
●● in Top 10 under both the least and most extreme narratives

● in Top 10 under most or least extreme narrative only

| ID | Segment Name | Stressors for Which Asset Ranks Within the Top 10 Most Vulnerable Highway Assets | | | | |
|---|---|---|---|---|---|---|
| | | Temp | Precip | SLR | SS | Wind |
| R1 | I-10 Tunnel (Wallace Tunnel) | ●● | ●● | ●● | ●● | ● |
| R16 | SR-193 (Range Line Road), running about 0.5 mile on either side of Theodore Industrial Canal | ●● | ●● | ●● | ●● | ● |
| R27 | I-10 Bridge across Mobile Bay | ●● | ●● | ●● | ●● | ● |
| R26 | Dauphin Island Bridge | ●● | ●● | ●● | ●● | |
| R5 | I-65, between US-43 and County boundary | ●● | | ●● | ●● | ● |
| R10 | The Causeway (Battleship Parkway) | | ●● | ●● | ●● | ● |
| R14 | SR-163 (Dauphin Island Parkway), from Island Road to Terrell Road | | ●● | ●● | ●● | ● |

| ID | Segment Name | Stressors for Which Asset Ranks Within the Top 10 Most Vulnerable Highway Assets | | | | |
|---|---|---|---|---|---|---|
| | | Temp | Precip | SLR | SS | Wind |
| R15 | SR-193 (Dauphin Island Parkway), from Dauphin Island Bridge to CR-188 | | ●● | ●● | ●● | ● |
| R3 | I-10, from Wallace Tunnel to S Broad Street | ●● | | ●● | ● | ● |
| R17 | SR-193 (Range Line Road), between Rabbit Creek Drive and Tufts Road | | | ●● | ●● | ● |
| R23 | SR-188, river crossing near Coden | | | ●● | ●● | ● |
| R25 | CR-59 (Bellingrath Road), 0.5 mile on either side of large stream crossing north of Plantation Woods Drive | | ●● | ● | | ●● |
| R6 | Telegraph Road from downtown to Bay Bridge Road | | | ● | ●● | ● |
| R9 | US-90 (SR-16), section east of Broad Street | | | ●● | | ●● |
| R13 | SR-163 (Dauphin Island Parkway), from I-10 to Brill Road | ●● | | | | ●● |
| R20 | SR-188, where it crosses the river just North of Bayou la Batre | | | ●● | ●● | |
| R29 | Intersection of Airport Blvd and I-65, near drainage areas | | ●● | | | ●● |
| R30 | Cochrane Bridge (Bay Bridge Road) | ●● | ●● | | | |
| R2 | I-10, intersection with I-65 | ●● | | | | ● |
| R24 | Intersection of SR-188 and CR-59 (Bellingrath Road), near Fowl River | | | | ●● | ● |
| R28 | I-165, near intersection with Route 98 | ●● | | | | ● |
| R32 | Old Spanish Trail, between Cochrane Bridge and the tunnels | | | | ●● | ● |
| R8 | US-45 (St. Stephens Road), between Rylands Street and Simington Drive | | | | | ●● |
| R12 | Route 98 near the Stickney Filtration Plant | | | | | ●● |
| R18 | Airport Blvd, between CR-31 (Schillinger Road) and airport | | | | | ●● |
| R19 | South University Blvd, 0.5 mile segment either side of CR-56 (Airport Blvd) | | | | | ●● |
| R31 | CR-70 (Tanner Williams Road), along the J.B. Converse Reservoir dam and covering access to the Palmer S. Gaillard Pumping Station | | | | | ●● |
| R4 | I-165, 1 mile before intersection with I-65 | | | | | ● |
| R11 | US-90, intersection with SR-163 and Government Street | | | | | ● |
| R21 | SR-188, from Douglas Road to US-90 West | | | | | ● |
| R22 | SR-193 (Dauphin Island Parkway), from Old Cedar Point Road to Day Springs Road | | | | | ● |
| R7 | US-43 (Saraland Blvd N), northernmost portion | | | | | |

**Figure 14: Number of Climate Stressors for which a Highway Segment Ranks in the "Top 10" Most Vulnerable Segments (most extreme narrative)**



### Caveats

Many, but not all, of the highway representative segments studied include bridges that are "sub-segments" of the highway. The National Bridge Inventory (NBI) provided data about useful vulnerability indicators for these bridges that were not available for roads. As a result, this analysis used two sets of methodologies to evaluate vulnerability within highways: one for bridges that included NBI indicators, and one for roads. The final vulnerability score for each highway segment was taken using the maximum vulnerability score across its sub-segments, which included both bridges and roads. The bridge scores are based on more indicators and are thus more robust, but the differences in indicators used can propel certain highways without bridges to the top of vulnerability lists (i.e., the vulnerability of the Wallace Tunnel to storm surge and sea level rise), since they rely on fewer indicators.

## 1.3.3 Overview of Vulnerabilities of Critical Ports

The port and marine waterway system in Mobile appears to be highly vulnerable to storm surge and moderately vulnerable to sea level rise and precipitation. According to the analysis, exposure to storm surge is high; even in the least extreme narrative, nearly all of the port assets experience flooding. On the other hand, port vulnerability scores to sea level rise depend on the narrative. With only 30 cm of sea level rise, less than half of the port assets are exposed and vulnerability remains moderate due to extensive shoreline protection. However, in the 200 cm narrative, all of the port assets are exposed except for Evonik Industries (P12) and Standard Concrete Products (P24), both of which are on the Theodore Ship Canal. According to the analysis, vulnerability to temperature and precipitation is low to moderate, and vulnerability to wind is low.

**Summary of Port System Vulnerabilities**

- Critical ports in Mobile, AL appear to be most vulnerable to storm surge; vulnerability scores are relatively high even under the less extreme storm scenario
- ASPA's State Docks facility is ranked most vulnerable to both storm surge and sea level rise; this vulnerability ranking is driven primarily by high exposure and high sensitivity scores
- Port facilities score as moderately vulnerable to temperature and precipitation, but only under the most extreme narratives
- Port vulnerability scores to wind are low because port buildings are designed to withstand high wind speeds

The Alabama State Port Authority (ASPA) State Docks facility (P2) appears to be the most vulnerable asset across stressors with particularly high vulnerability to storm surge and sea level rise. This older facility has a lower elevation, little shoreline protection, and may not be in as good condition or constructed with the latest standards and materials as compared to other, newer ports.

The results are caveated in that the vulnerability screen for ports had inconsistent data availability. The project team was able to assemble a more complete dataset for the ASPA ports, based on stakeholder interviews and information from ASPA. This pattern of data availability influenced the vulnerability scores of the ASPA facilities.

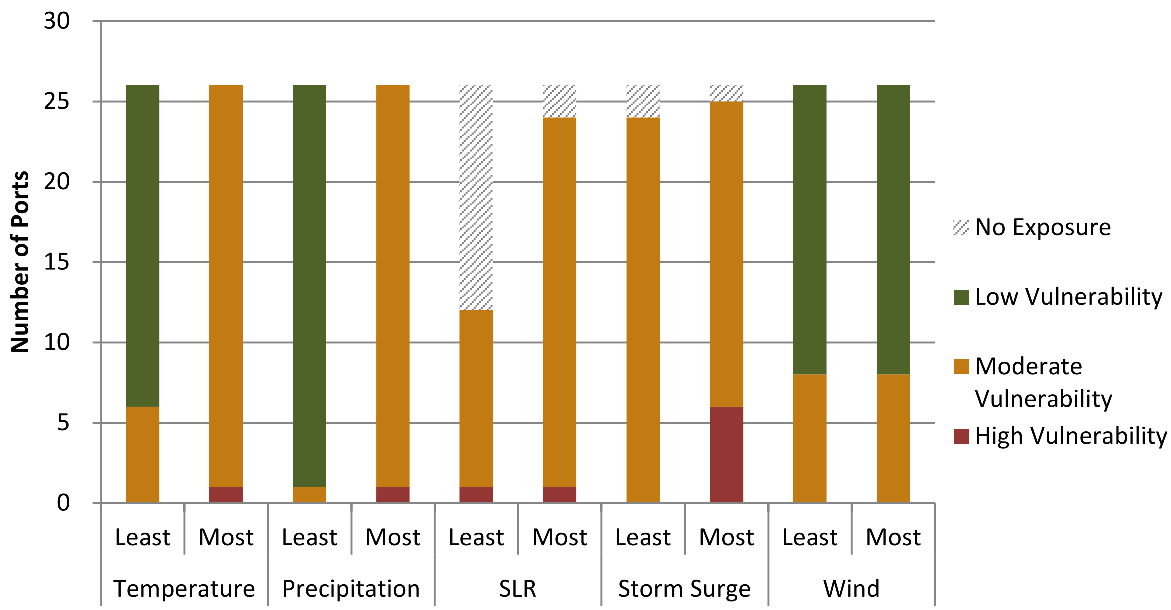
Figure 15 summarizes the vulnerabilities of critical port facilities.

Overall, ports scoring as highly vulnerable tend to share the following characteristics:

- Low elevation
- Advanced age or sub-optimal condition
- Reliance on electricity
- History of damage due to flooding or storm surge
- Inability to shift operations to other facilities or within the same facility

Furthermore, vulnerability scores tend to be higher from climate stressors that may take a long time to recover from (such as storm surge) compared to other stressors that may cause less dramatic service disruption or cost of repairs (like temperature).

**Figure 15: Number of Port Facilities that have No Exposure or have Low, Moderate, or High Vulnerability, by Climate Stressor***




*"Least" and "Most" refer to the Least Extreme and Most Extreme scenarios/timeframes.

Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. Assets that are not exposed are considered to be not vulnerable. See Section 4 for detail on the scoring methodology used.

Mobile's port system is largely coastal, and vulnerability of facilities to **storm surge** appears to be very high. Even in the least extreme storm surge narrative, nearly all critical facilities experience at least some degree of inundation. Under the most extreme storm narrative, average projected flooding depths at ports are nearly 25 feet, including wave height. This high exposure results in high vulnerability scores for those exposed facilities that are also sensitive and have a low capacity to adapt. For example, ports such as the Alabama State Docks Main Complex (P2), McDuffie Terminal (P3), and Austal (P7) score as highly vulnerable because of their location, lack of redundancy, history of flooding, and reliance on electricity. For more information on the vulnerability of port facilities to **storm surge**, please see Figure 10 or the web viewer that accompanies this report featuring maps of all results, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

Mobile's ports appear to be moderately vulnerable to **sea level rise**. Under the 30 cm scenario, just under half of the critical port facilities are projected to be inundated. However, despite relatively high exposure scores, port sensitivity scores tend to be low, due to a high degree of shoreline protection. Interviews with stakeholders indicated that port facilities do not currently experience flooding during high tide events. The assets that appear to be more vulnerable tend to be older facilities with less shoreline protection and little ability to shift operations to another facility or area. For more information on the vulnerability of port facilities to **sea level rise**, please see Figure 9 or the web viewer that accompanies this report featuring maps of all results, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

According to the analysis, the port system's vulnerability to changes in **precipitation** events depends greatly on whether today's extreme rain events become more frequent and severe, or not. If they do, as projected under the more extreme narratives, then portions of Mobile's port system are vulnerable to these changes. Two important drivers of vulnerability scores are whether the port has historically flooded during heavy rain events and the location of the port in the 100-year flood zone. Differences in the adaptive capacity of ports also drive vulnerability results. For example, the only asset that scored as highly vulnerable to changes in precipitation is Shell Chemical Co. This facility has an unusually low adaptive capacity score because it is reliant on import of feedstocks and export of products via marine movements. In the event of a disruption, the facility may be unable to operate once the limited amount of crude oil in inventory was consumed. For more information on the vulnerability of port facilities to changes in **precipitation**, please see Figure 8 or the web viewer that accompanies this report featuring maps of all results, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

Even under the most extreme scenario, Mobile's port system appears to exhibit a low to moderate vulnerability to projected **temperature** increases. Sensitivity of ports to temperature appears to be low, partially because ports have not historically experienced noticeable impacts during heat events. In addition, the ability of ports to recovery from and adapt to increased temperatures seems to be high. ASPA's Pinto Island facility is the only asset that exhibits a high vulnerability score under the most extreme temperature narrative. The facility's lack of operational redundancy and high reliance on electricity (which is in turn vulnerable to brownouts or blackouts during extreme temperatures) drive its vulnerability score. For additional information on the vulnerability of ports to changes in **temperature**, see Figure 7 or the web viewer that accompanies this report featuring maps of all results, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

Mobile's port system appears to have low vulnerability to extreme **winds** from hurricanes that may affect the area. Most coastal buildings, including port facilities, in Mobile are designed to withstand wind speeds of 130 to 150 mph. The projected wind speeds associated with the most extreme storm scenarios used in this study ranged from 108 to 120 mph. Therefore, in this analysis, ports in Mobile are considered to have low vulnerability to wind from a structural standpoint. The assets with the highest vulnerability scores for wind tend to have a high reliance on electricity, a history of wind damage, and a lack of operational redundancy. For example, Shell Chemical Co. has a very low adaptive capacity score because it is reliant on import of feedstocks and export of products via marine movements. In the event of a power outage, the facility may be unable to operate after the limited amount of crude oil in inventory was consumed. For more information on the vulnerability of port facilities to **wind,** please see Figure 11 or the web viewer that accompanies this report featuring maps of all results, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

Table 2 and Figure 16 indicate the ports that most frequently rank in the "top 10" most vulnerable assets for each stressor, according to the results of the analysis. The ports that appear most frequently in the "top 10" appear at the top of Table 2. The five ports that appear most vulnerable across all climate stressors are facilities at low elevations with a history of flooding, a high reliance on electricity, and low adaptive capacity. For example, these ports may be constrained in their ability to shift operations either within the facility or to another location. Further, many of these assets are ones that have been damaged from extreme weather in the past, demonstrating that they are susceptible to damage. The Alabama State Docks Main Complex (P2) scores as the most vulnerable asset across climate stressors. This facility is the site of one of the most extreme projected inundations under the storm surge modeling, 29 feet (9 meters). In addition, it is an older facility in less-than-optimal condition with little shoreline protection.

**Table 2: Most Vulnerable Port Assets to All Climate Stressors**

●● in Top 10 under both the least and most extreme narratives

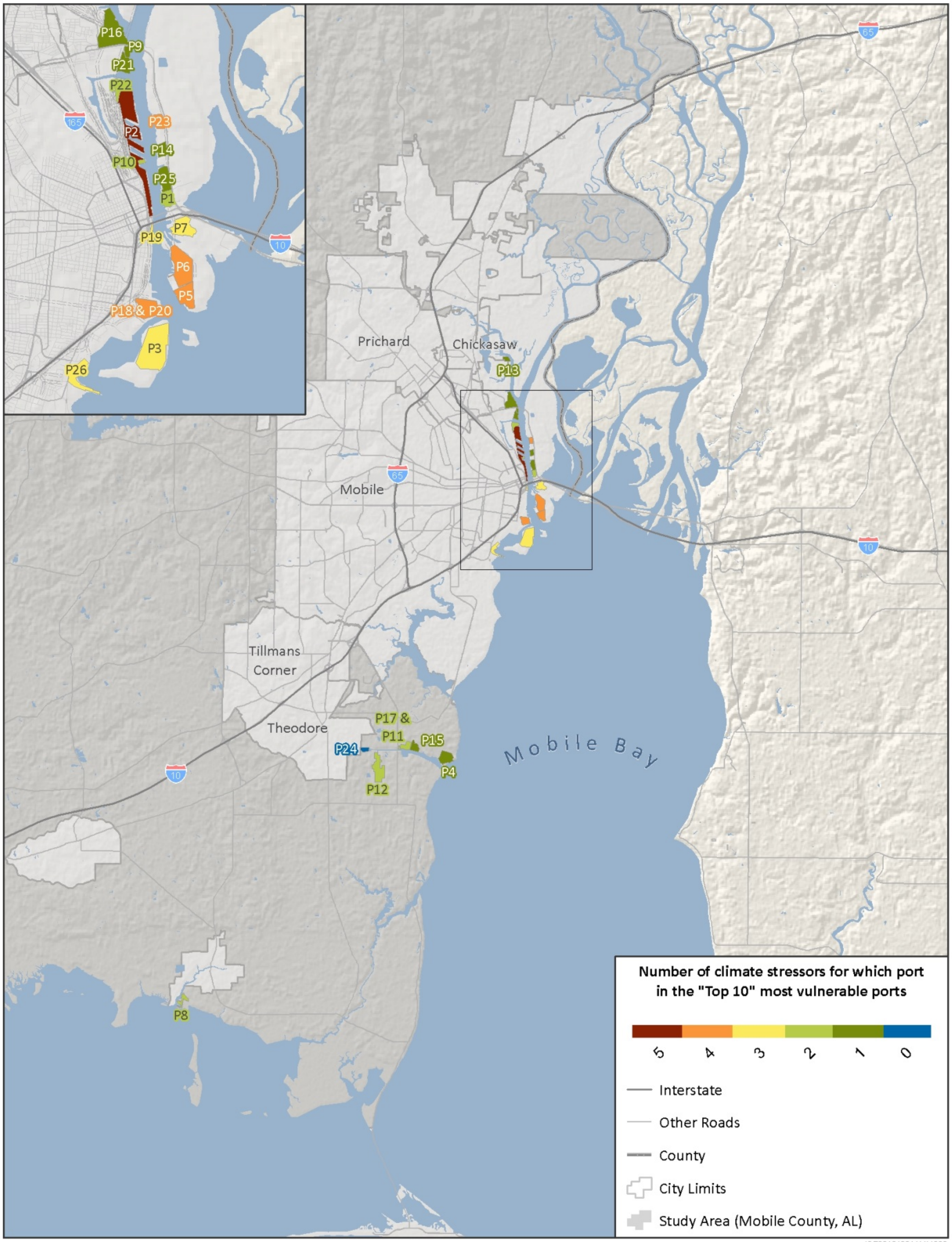
● in Top 10 under most or least extreme narrative only

| ID | Port Name | Stressors for Which Asset Ranks Within the Top 10 Most Vulnerable Ports | | | | |
|---|---|---|---|---|---|---|
| | | Temp | Precip | SLR | SS | Wind |
| P2 | Alabama State Port Authority (ASPA) - Alabama State Docks Main Complex | ●● | ●● | ●● | ●● | ●● |
| P6 | Atlantic Marine (BAE Systems Southeast Shipyards) | ●● | ●● | ● | ● | ●● |

| ID | Port Name | Stressors for Which Asset Ranks Within the Top 10 Most Vulnerable Ports | | | | |
|---|---|---|---|---|---|---|
| | | Temp | Precip | SLR | SS | Wind |
| P18 | Mobile Container Terminal | ●● | ●● | ● | ● | ●● |
| P23 | Shell Chemical Co. | ●● | ●● | ● | ● | ●● |
| P5 | Alabama State Port Authority (ASPA) - Pinto Island | ●● | ● | ● | ● | ●● |
| P26 | U.S. Coast Guard Pier | ● | ● | ●● | ●● | ● |
| P3 | Alabama State Port Authority (ASPA) - McDuffie Terminal | ●● | ● | | ● | ●● |
| P7 | Austal | ●● | ● | | ● | ●● |
| P11 | Environmental Treatment Team Wharf | ● | ● | ●● | ●● | |
| P8 | Bayou La Batre | ● | | ● | ●● | ● |
| P20 | Oil Recovery Co. of Alabama, Mobile Terminal Pier | ● | ● | ● | ●● | |
| P10 | Crescent Towing & Salvage Co., River A Wharf | ● | ● | ● | ● | |
| P22 | Plains Marketing - South Terminal | ● | | ● | ● | ● |
| P1 | Alabama Bulk Terminal Co. (Hunt Refining Company) | ●● | ●● | ● | | |
| P12 | Evonik Industries | ●● | ●● | ● | | |
| P19 | Mobile Cruise Terminal | ● | | | ●● | ●● |
| P16 | Kimberly-Clark Corporation | ● | | ● | ●● | |
| P13 | Gulf Atlantic Oil Refining Co., North Terminal | ● | | ● | ● | |
| P14 | Gulf Coast Asphalt Co., Mobile Terminal Wharf | ● | | ● | ● | |
| P15 | Holcim Cement Wharf | ● | | ● | ● | |
| P17 | Martin Marietta Aggregates | ● | | | ● | ● |
| P4 | Alabama State Port Authority (ASPA) - Mobile Middle Bay Port | ●● | ● | | | |
| P9 | BP Oil Co., Mobile Terminal Barge Wharf | ● | | | ● | |
| P21 | Plains Marketing - North Terminal | ● | | | ● | |
| P25 | TransMontaigne Product Services | ● | | | ● | |

| ID | Port Name | Stressors for Which Asset Ranks Within the Top 10 Most Vulnerable Ports | | | | |
|---|---|---|---|---|---|---|
| | | Temp | Precip | SLR | SS | Wind |
| P24 | Standard Concrete Products | ● | | | | |

**Figure 16: Number of Climate Stressors for which a Port Ranks in the "Top 10" Most Vulnerable Ports (most extreme narrative)**



#### Caveats

The vulnerability screen for ports had inconsistent data availability. For example, the project team was able to assemble a more complete dataset for the ASPA ports, based on stakeholder interviews and information from ASPA. This pattern of data availability influenced the vulnerability scores of the ASPA facilities.

### 1.3.4 Overview of Vulnerabilities of Critical Airports

Only two airports in Mobile were considered to be highly critical and therefore assessed for vulnerability: Mobile Downtown Airport, which primarily serves cargo and private aircraft, and Mobile Regional Airport, the primary passenger airport in Mobile.

Overall, the vulnerability assessment indicates that Mobile's two critical airports are only moderately vulnerable to the climate impacts analyzed. Across stressors, Mobile's airports appear most vulnerable to increases in temperature, strong winds, and increases in heavy precipitation. The key traits that drive vulnerability scores for Mobile's airports are:

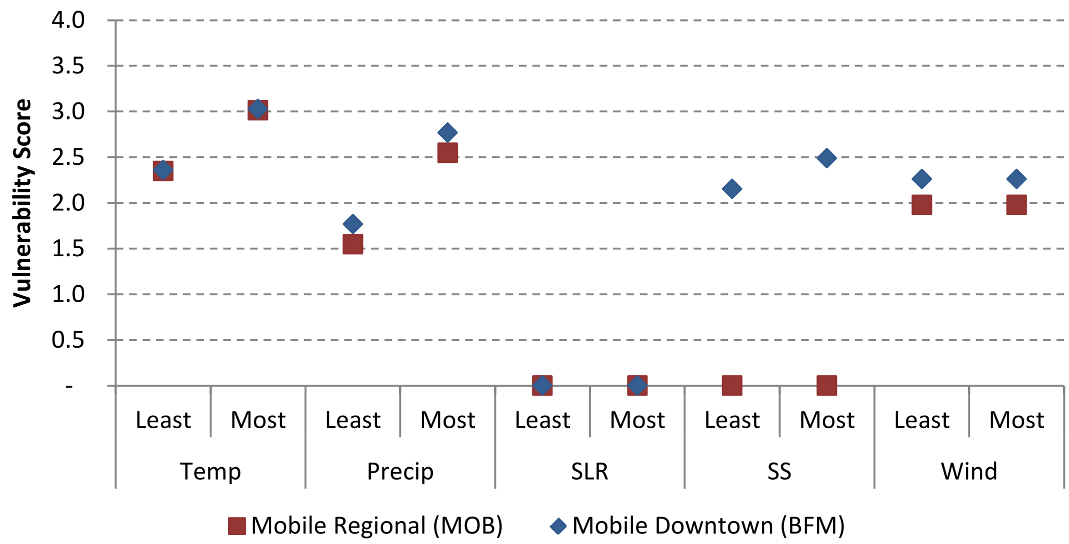
- Location relative to the coastline or water bodies
- Lack of system redundancy
- Extensive asphalt pavement

#### Summary of Airport Vulnerabilities

- The airports appear to be particularly vulnerable to temperature, due to sensitivity of runways and taxiways to damage from heat.
- Neither airport is considered vulnerable to sea level rise. Though on the coast, Mobile Downtown airport is not exposed to modeled sea level rise since it is elevated high enough above the current sea level. Mobile Regional airport is too far inland to be exposed to sea level.
- Under more extreme storm surge narratives, Mobile Downtown scores as somewhat vulnerable; again, the Regional airport is too far inland to be exposed.
- Mobile Downtown airport appears slightly more vulnerable to temperature, precipitation, and wind than the Regional airport.
- Exposure is a major driver of vulnerability scores, as sensitivity and adaptive capacity scores are moderate for all stressors.

Mobile Downtown airport appears to be more vulnerable than Mobile Regional airport to all climate stressors. Mobile Downtown airport has lower adaptive capacity scores, since it is the only airport of its kind in the area. Another reason is that the Mobile Regional airport is not coastal, and therefore not exposed or vulnerable to modeled storm surge and sea level rise. Mobile Downtown airport is partly inundated under the most extreme storm narrative, but is otherwise not exposed to modeled storm surge or sea level rise. Other driving vulnerability scores for airports include low redundancy in the local airport system, and aged infrastructure. The vulnerability scores are summarized in Figure 17.

**Figure 17: Airport Vulnerability Scores by Climate Stressor, under Least and Most Extreme Narratives***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.

The airports' highest vulnerability scores relate to changes in extreme **temperature**. Even with relatively low exposure in the least extreme narrative, Mobile's airports (specifically, runways and taxiways) appear sensitive to damage from heat, as demonstrated through existing heat-related damage—especially to runway markings important to plane navigation—and potential for pavement expansion and degradation.

**Wind** is another important vulnerability of Mobile's airports. Though neither airport is projected to be exposed to wind speeds above their building ratings, Mobile's airport buildings have demonstrated sensitivity to damage from winds, especially to building roofs.

Mobile's airports are moderately vulnerable to changes in heavy **precipitation**. As heavy rain events become more frequent, Mobile's airports may experience flooding or other damage, as indicated by limitations to their drainage systems. In addition, there is relatively low redundancy in the area, meaning that any damage to the airports could have widespread implications for transportation.

Mobile's airports do not appear vulnerable to **sea level rise** or **storm surge**. Though on the coast, Mobile Downtown airport is not exposed to modeled sea level rise since it is elevated high enough above the current sea level. It is also not exposed to modeled storm surge, except for small areas under the most extreme narrative. Mobile Regional airport is too far inland to be exposed to modeled sea level rise or storm surge.

The vulnerability results in the most extreme narrative are summarized in Table 3, as well in the maps in Figure 7 through Figure 11, and in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Table 3: Vulnerability of Airports to All Climate Stressors under the Most Extreme Narrative**

| ID | Airport Name | Temp | Precip | SLR | SS | Wind |
|---|---|---|---|---|---|---|
| BFM | Mobile Downtown Airport (Brookley Field) | **High** | **Moderate** | **NE** | **Moderate** | **Moderate** |
| MOB | Mobile Regional Airport | **High** | **Moderate** | **NE** | **NE** | **Low** |

NE = Not Exposed; Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. See Section 4 for detail on the scoring methodology used.

### Caveats

The vulnerability assessment for Mobile's airports focused on only two airports and relied on information collected during interviews with the Mobile Airport Authority. The vulnerability assessment should be considered specific to these two airports, and the results may not be broadly applicable. However, the indicators used to determine vulnerability could apply to airports nationwide.

## 1.3.5 Overview of Vulnerabilities of Critical Rail Segments

There were twelve representative rail segments included in the Gulf Coast Study, including segments from CSX, Norfolk Southern, and the Terminal Rail at Alabama State Docks (TASD). However, CSX and Norfolk Southern are private companies, and limited information was available for their rail assets in Mobile. Furthermore, the information that was available for these segments could not be verified with the rail companies. Meanwhile, good quality information was available for the TASD segments, which are maintained by the Alabama State Port Authority, and which represent the rail and rail yards that are within the boundaries, or immediately adjacent to, the ports. Therefore, the vulnerability assessment evaluated only the four TASD assets. The vulnerability of these assets is not necessarily representative of the entire Mobile rail system, but some findings may be relevant.

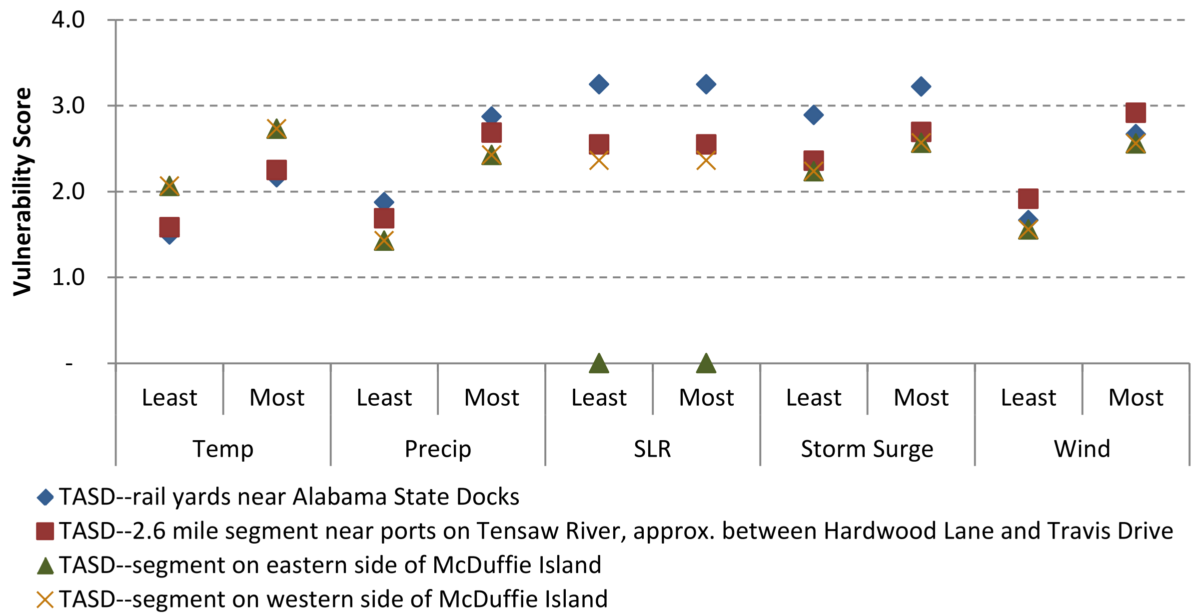
**Summary of Rail System Vulnerabilities**

- According to the analysis, sea level rise and storm surge are associated with the highest vulnerability scores for TASD rail yards
- The rail lines on McDuffie Island are the most vulnerable rail assets to changes in temperature
- The system overall appears to be vulnerable to extreme winds, especially if winds exceed 85 mph, as they may under hurricane conditions
- The rail system does not score as particularly vulnerable to near-term changes in temperature and precipitation. However, the system may be vulnerable to longer-term changes

The four TASD assets are the TASD rail yards near Alabama State Docks, the TASD rail segment near the ports on Tensaw River, the TASD rail segment on the eastern side of McDuffie Island, and the TASD rail segment on the western side of McDuffie Island. Figure 20 shows the locations of these segments.

Overall, the TASD assets scored moderately vulnerable to climate changes. Vulnerability scores are highest for sea level rise and storm surge and relatively lower for temperature, precipitation, and wind. The rail yards score as highly vulnerable to sea level rise and storm surge, primarily as a result of their known tendency to flood. The TASD rail segments also experience the highest storm surge depths in the study area, averaging 28.8 feet (8.8 meters) of storm surge. The lines on McDuffie Island appear to be relatively less vulnerable to all climate impacts except for changes in high temperatures; the corrosiveness of coal dust on the rail ties, as well as fewer track joints to accommodate expansion indicate that these rail segments may be more vulnerable to higher temperature; past experience with frequent repair/replacement needs on these tracks supports this assertion.[2] The rail segment near ports on Tensaw River appears to be moderately vulnerable across all climate impacts. The vulnerability scores are summarized in Figure 18.

**Figure 18: Rail Vulnerability Scores by Climate Stressor, under Least and Most Extreme Narratives***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.

According to the analysis, TASD rail assets appear to be most vulnerable to **sea level rise** and **storm surge**, primarily due to their proximity to water bodies and lack of elevation or protective structures. In addition, adaptive capacity scores are low for all four assets because the disruptions caused by sea level rise and storm surge are so severe (taking months, rather than a few hours or days, to recover).

---

TASD 2012.

According to the analysis, hurricane-force **wind** similarly may pose a threat to Mobile's rail system, because the system may be exposed to heavy winds during tropical storm or hurricanes, and rail signals and aerial lines may be particularly prone to wind damage.

Mobile's rail system also appears to be moderately vulnerable to projected changes in **temperature** and **precipitation**. Specific assets have already demonstrated sensitivity to heat-related track buckling and precipitation-driven flooding.

The TASD rail asset vulnerabilities in the most extreme narrative are summarized in Table 4, as well in the maps in Figure 7 through Figure 11, and in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Table 4: Vulnerability of TASD Rail Segments to All Climate Stressors (most extreme narrative)**

| ID | Asset Name | Temp | Precip | SLR | SS | Wind |
|---|---|---|---|---|---|---|
| RR1 | TASD--rail yards near Alabama State Docks | **Moderate** | **Moderate** | **High** | **High** | **Moderate** |
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive | **Moderate** | **Moderate** | **Moderate** | **Moderate** | **Moderate** |
| RR7 | TASD--segment on eastern side of McDuffie Island | **Moderate** | **Moderate** | **NE** | **Moderate** | **Moderate** |
| RR8 | TASD--segment on western side of McDuffie Island | **Moderate** | **Moderate** | **Moderate** | **Moderate** | **Moderate** |

NE = Not Exposed; Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. See Section 4 for detail on the scoring methodology used.

## Caveats

As mentioned, the vulnerability results for rail focus only on the TASD assets, since reliable data were not available for the privately-owned rail assets in Mobile. The results are thus based on a small sample size of assets, which are concentrated around the ASPA ports along the Mobile River. It is thus difficult to draw broad conclusions about the overall rail system's vulnerability, including inland rail lines.

### Exposure of Privately-Owned Rail Assets

Though data were too limited to evaluate the sensitivity and adaptive capacity of Mobile's privately-owned rail assets, this analysis did evaluate their exposure. Of the eight private representative rail segments, three are not exposed to sea level rise under any scenario. Three are also not exposed to storm surge.

| ID | Asset Name | Sea Level Rise | | Storm Surge* | |
|---|---|---|---|---|---|
| | | 30 cm | 200 cm | Katrina Base | Katrina Shifted, Pres Reduced, 75 cm SLR |
| RR2 | CSX M&M subdivision--segment along Mobile River between Cochrane Bridge and Twelvemile Island | **YES** | **YES** | **Moderate** | **High** |
| RR3 | CSX NO&M subdivision--1.2 mile segment running along eastern edge of Downtown, between St. Louis St. and Elmira Street | **NO** | **YES** | **Moderate** | **High** |
| RR4 | CSX NO&M subdivision--3.9 mile segment running along I-10, near Dog River and its tributaries, between Dauphin Island Parkway and Cypress Shores Drive | **YES** | **YES** | **Moderate** | **High** |
| RR5 | Norfolk Southern--1.6 mile segment running along US-43, near Le Moyne | **YES** | **YES** | **Not Exposed** | **Not Exposed** |
| RR9 | CSX NO&M subdivision--0.7 mile segment that is bisected by Hamilton Blvd., near Theodore | **NO** | **NO** | **Not Exposed** | **Not Exposed** |
| RR10 | CSX NO&M subdivision--1.2 mile segment on eastern side of Brookley airfield | **YES** | **YES** | **Low** | **High** |
| RR11 | Norfolk Southern--segment running along Telegraph Rd, crossing Three Mile Creek | **YES** | **YES** | **Moderate** | **High** |
| RR12 | CSX NO&M subdivision--segment running along US-90, between Grand Bay Wilmer Road and western edge of Grand Bay | **NO** | **NO** | **Not Exposed** | **Not Exposed** |

*Exposure score of 3 or 4 = High; 2 = Moderate; 1 = Low

### 1.3.6 Overview of Vulnerabilities of Critical Transit Facilities

Three of Mobile's transit assets were considered critical and assessed for vulnerability. These consisted of two facilities, the Beltline operations and maintenance facility and the GM&O Terminal, as well as the Mobile area bus fleet and service.[3]

Overall, the vulnerability assessment indicates that transit's vulnerability is highest to sea level rise and storm surge—when exposed. In fact, the inland location of the Beltline facility and the ability to move routes and the fleet out of harm's way help mitigate the vulnerability scores of transit for sea level rise and storm surge. However, the GM&O terminal is located closer to the Bay, making it score as highly vulnerable to the more extreme storm surge and sea level rise narratives, but only moderately vulnerable to the less extreme narratives. The bus fleet and service has a relatively high vulnerability score for wind. Finally, Mobile's three critical transit "assets" score as only moderately vulnerable to changes in temperature and precipitation. Figure 19 illustrates the relative vulnerability scores of the three transit assets to the five climate stressors.

**Summary of Transit Vulnerabilities**

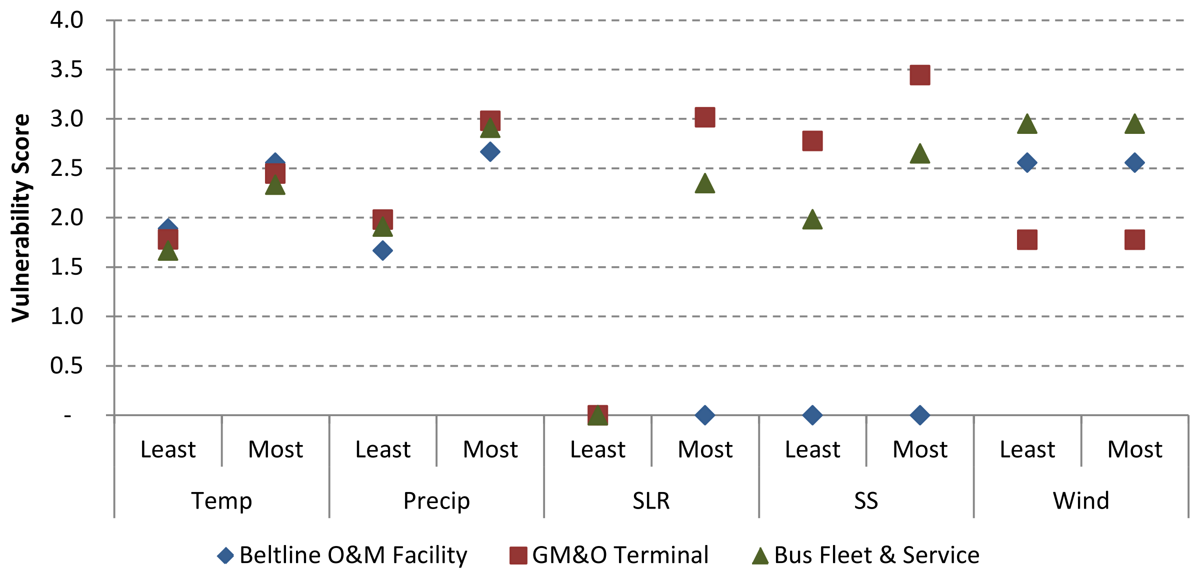
- All three assets have low to moderate vulnerability scores for changes in temperature and precipitation.
- Under the most extreme storm surge and sea level rise narratives, the GM&O Terminal scores as highly vulnerable. The Beltline O&M facility is not exposed and therefore scores as not vulnerable.
- The GM&O Terminal has low vulnerability scores to wind, but the Beltline O&M facility and the bus fleet and service score as moderately vulnerable under all wind narratives.
- In general, Mobile's fleet and routes have the ability to adapt to climate change, given the ability to relocate routes and buses. Buildings are less easily located, although the operations run out of these buildings could conceivably be relocated in the long term.

The key trait that drives vulnerability scores for Mobile's transit assets is:

- Location relative to the coastline or water bodies

[3] Bus and fleet service consists of the 38 critical buses and 33 critical demand response vehicles in the Wave Transit system, along with the services they provide. As described in Appendix B, the exposure of the bus fleet and service "asset" was calculated based on the percent of the systems 907 bus stops that were exposed to inundation under the storm surge and sea level rise scenarios.

**Figure 19: Transit Asset Vulnerability Scores by Climate Stressor, under Least and Most Extreme Narratives***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.

According to the analysis, **sea level rise** threatens the critical transit assets only under the long-term, 200 cm rise narrative. None of the transit assets is exposed under less extreme sea level rise narratives. The GM&O Terminal scores as highly vulnerable to 200 cm of SLR, particularly because it is not otherwise protected from inundation. Access to the building may be impeded in the future since Government and Water Streets are already prone to flooding. The Beltline O&M facility is not exposed to sea level rise, even under the most extreme.

The GM&O Terminal is the transit asset that scores as most vulnerable to **storm surge** because it is situated closer to the coast and is located near streets that have been inundated by previous instances of flooding. In addition, it has been damaged by storm surges in the past, which may indicate sensitivity to future storm surge events. While the bus fleet and service asset is highly exposed to storm surge (in the most extreme narrative, over 50% of bus stops are inundated), the bus fleet has a high adaptive capacity since stops could be relocated as needed, which limits its overall vulnerability score for storm surge.

Both the Beltline O&M facility and the bus fleet and service score as moderately vulnerable to **wind** under the most extreme storm surge narrative. The GM&O terminal has low vulnerability scores, even under the more extreme narratives, because it has low sensitivity scores for wind. The Beltline facility's moderate vulnerability scores are due to the fact that its construction materials and roof type may be sensitive to high winds. In addition, the facility experienced wind damage previously during Hurricane Katrina.

Vulnerability scores of all critical transit assets to changes in **temperature** are low in the least extreme narrative and moderate in the most extreme narrative. The Beltline facility appears to be most vulnerable to temperature increases because operations that take place in that facility cannot easily be moved during extreme events. However, these operations can be moved over time, meaning the WAVE has time to adjust operations before the end-of-century temperature increases would be realized.

The vulnerability scores of the transit assets are slightly higher to changes in **precipitation** increases than to temperature increases. The GM&O facility appears to be the most vulnerable, but scores moderately so even under the most extreme narrative. This asset is located in the 100-year flood zone, and access to the building from Government Street and Water Street is impaired during heavy downpours. The Beltline O&M facility, located at higher elevation and away from major water bodies, exhibits a very low sensitivity score for precipitation, which limits its vulnerability score.

The vulnerability results in the most extreme narrative are summarized in Table 5, as well in the maps in Figure 7 through Figure 11, and in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

The GM&O Terminal scores as most vulnerable to both sea level rise and storm surge, but exhibits a low vulnerability score for wind. Low wind vulnerability could also mean it may experience less damage during storms, since debris is a major cause of storm damage.

**Table 5: Vulnerability of Transit Assets to All Climate Stressors (most extreme narrative)**

| ID | Asset Name | Temp | Precip | SLR | SS | Wind |
|---|---|---|---|---|---|---|
| T1 | Beltline O&M Facility | **Moderate** | **Moderate** | **NE** | **NE** | **Moderate** |
| T2 | GM&O Terminal | **Moderate** | **Moderate** | **High** | **High** | **Low** |
| T3 | Bus Fleet & Service | **Moderate** | **Moderate** | **Moderate** | **Moderate** | **Moderate** |

NE = Not Exposed; Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. See Section 4 for detail on the scoring methodology used.

## Caveats

The sensitivity and adaptive capacity scores for the three transit assets relied heavily on stakeholder interviews due to a lack of readily accessible data.

# 2. Background

## 2.1 Overview of Gulf Coast Study

Despite increasing confidence in global climate change projections in recent years, projections of climate effects at local scales remain scarce. Location-specific risks to transportation systems imposed by changes in climate are not yet well known. However, consideration of these long-term factors is highly relevant for infrastructure components, such as rail lines, highways, bridges, and ports, that are expected to provide service for up many years.

To better understand climate change impacts on transportation infrastructure and to identify potential adaptation strategies, the U.S. Department of Transportation's Center for Climate Change and Environmental Forecasting is conducting a comprehensive, multiphase study of climate change impacts on transportation in the Central Gulf Coast region. This study, formally known as *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study* (hereafter, "the Gulf Coast Study"), is the first such study of its magnitude in the United States and represents an important benchmark in the understanding of what constitutes an effective transportation system adaptation planning effort.

The Gulf Coast region was selected as the focal point due to its dense population and complex network of transportation infrastructure, as well as its critical economic role in the import and export of oil, gas, and other goods. The study is funded by the U.S. DOT Center for Climate Change and Environmental Forecasting and managed by FHWA. The U.S. Geological Survey (USGS) has provided support for much of the climate science work. The Gulf Coast Study includes two phases:

- **Phase 1** (2008)—During Phase 1, U.S. DOT partnered with the USGS and the U.S. Climate Change Science Program to investigate potential climate change risks and impacts on coastal ports, road, air, rail, and public transit systems in the region from Mobile, Alabama to Houston/Galveston, Texas. The study assessed likely changes in temperature and precipitation patterns, sea level rise, and increasing severity and frequency of tropical storms. Phase 1 then explored how these changes could impact transportation systems. It found that a local sea level rise of four feet would permanently inundate 27% of the Gulf Coast region's roads, 9% of its railways, and 72% of its ports; higher temperatures would likely lead to more rapid deterioration of infrastructure and higher maintenance costs; more intense precipitation events could overwhelm drainage systems and cause damage and delays; and increased hurricane intensity coupled with sea level rise would pose a significant threat to infrastructure.
- **Phase 2** (currently underway)—The purpose of Phase 2 is to provide a more detailed assessment of

### Phase 2 Study Area

While Phase 1 took a broad look at the entire Central Gulf Coast region (between Houston/Galveston, Texas and Mobile, Alabama) with a 'big picture' view of the climate-related challenges facing infrastructure, the current effort in Phase 2 focuses on Mobile, Alabama. The area of the study includes Mobile County (including Dauphin Island) and the crossings of Mobile Bay to the east to landfall in Baldwin County (Figure 20).

the vulnerability of the most critical components of the transportation system to weather events and long-term changes in climate. This work is being conducted on a single metropolitan area—the Mobile, AL region (see box)—with the intention of making the processes used in the study replicable to other areas. U.S. DOT is conducting Phase 2 in partnership with the Mobile Metropolitan Planning Organization, part of the South Alabama Regional Planning Commission (SARPC).

Phase 2 is divided into the tasks below. The first three tasks form the basis of a vulnerability screen and assessment of the Mobile transportation system, while the other tasks focus on tool development, coordination with stakeholders, and communication of project results.

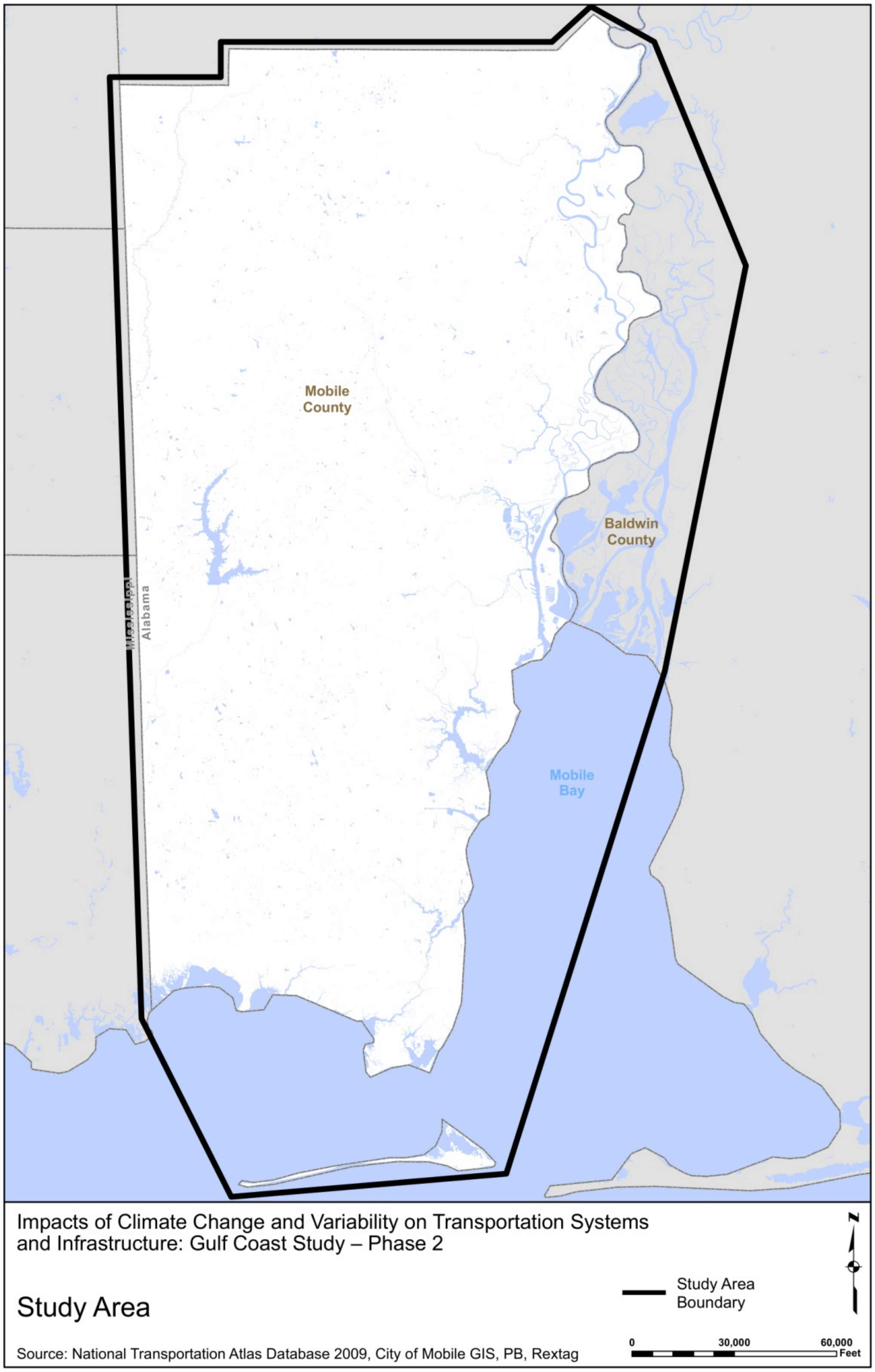
- **Task 1: Identify critical transportation assets in Mobile.** This task (completed) served as a first level screen for the vulnerability assessment, by identifying which transportation assets are highly critical to Mobile. The results were published in the report *Assessing Transportation for Criticality in Mobile, Alabama.*[4]
- **Task 2: Develop climate information.** Task 2 (completed) focuses on characterizing how temperature, precipitation, streamflow, sea level, and storms and storm surge in Mobile could change due to climate change. The results were published in the report *Climate Variability and Change in Mobile Alabama*.[5] This task also investigated the sensitivities of different transportation assets to each of these climate stressors, which is discussed in the companion report, *Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama*.[6]
- **Task 3: Determine vulnerability of critical assets.** This task (partly covered in this report) evaluates how the highly critical assets identified in Task 1 could be vulnerable to the climate information developed under Task 2. The purpose of this task is to develop a clearer understanding of the key vulnerabilities of Mobile's transportation system due to climate change. This report covers the methodology and findings of a high-level vulnerability assessment of the transport system. A more detailed engineering look at selected vulnerable assets is currently underway and results will be published in a report titled "Gulf Coast Study, Phase 2: Engineering Analysis and Assessment," available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3.
- **Task 4: Develop risk management tool(s).** Based on the findings and lessons learned during the first three tasks, FHWA has prepared and will be launching a suite of tools and resources that build on lessons learned in the Gulf Coat Study. These resources will be published on FHWA's website at http://www.fhwa.dot.gov/environment/adaptationframework/modules/index.cfm?moduleid=4
- **Task 5: Coordinate with planning authorities and the public.** Ongoing throughout the project, this task focuses on engaging key local transportation stakeholders, as well as members of the public. Efforts under Task 5 have included interactions with the South Alabaman Regional Planning Commission, a public meeting, a regional climate risk

[4] U.S. DOT, 2011
[5] U.S. DOT, 2012b
[6] U.S. DOT, 2012a

management workshop for regional transportation planners, briefings to DOT Technical Advisory Committee members representing all modes, and will soon be expanded to include training on key tools and resources developed under Task 4. These efforts serve to inform and shape the methods and analytical approaches used in the study and provide venues for describing and disseminating lessons learned to key audiences.

- **Task 6: Disseminate and publish results.** There will be a brief synthesis report that covers all of Phase 2, as well as associated presentations of the findings.

**Figure 20: Study Area**



## 2.2 Purpose of the Vulnerability Screen

This report discusses the methodology and results of a broad vulnerability assessment of the highly critical transportation assets in Mobile. This assessment begins with the specific transportation assets identified under Task 1 as being “highly critical to Mobile”, and considers how they may be vulnerable to the projected changes in Mobile’s climate identified under Task 2.

Because of the large number of assets considered to be highly critical to Mobile, it was not possible to do a detailed engineering assessment of each individual asset to determine their precise vulnerabilities. Therefore, one goal of this high-level assessment, or screen, is to determine which assets are *likely* to be particularly vulnerable, and which assets are probably *not* particularly vulnerable, to climate change. The results of this assessment are not meant to be the final word on any one asset’s vulnerability to climate change. Rather, the results indicate which assets deserve a closer look at their particular vulnerabilities. A selected group of the assets considered highly vulnerable is currently undergoing a more detailed engineering assessment to consider their more specific vulnerabilities, and possible strategies for reducing those vulnerabilities.

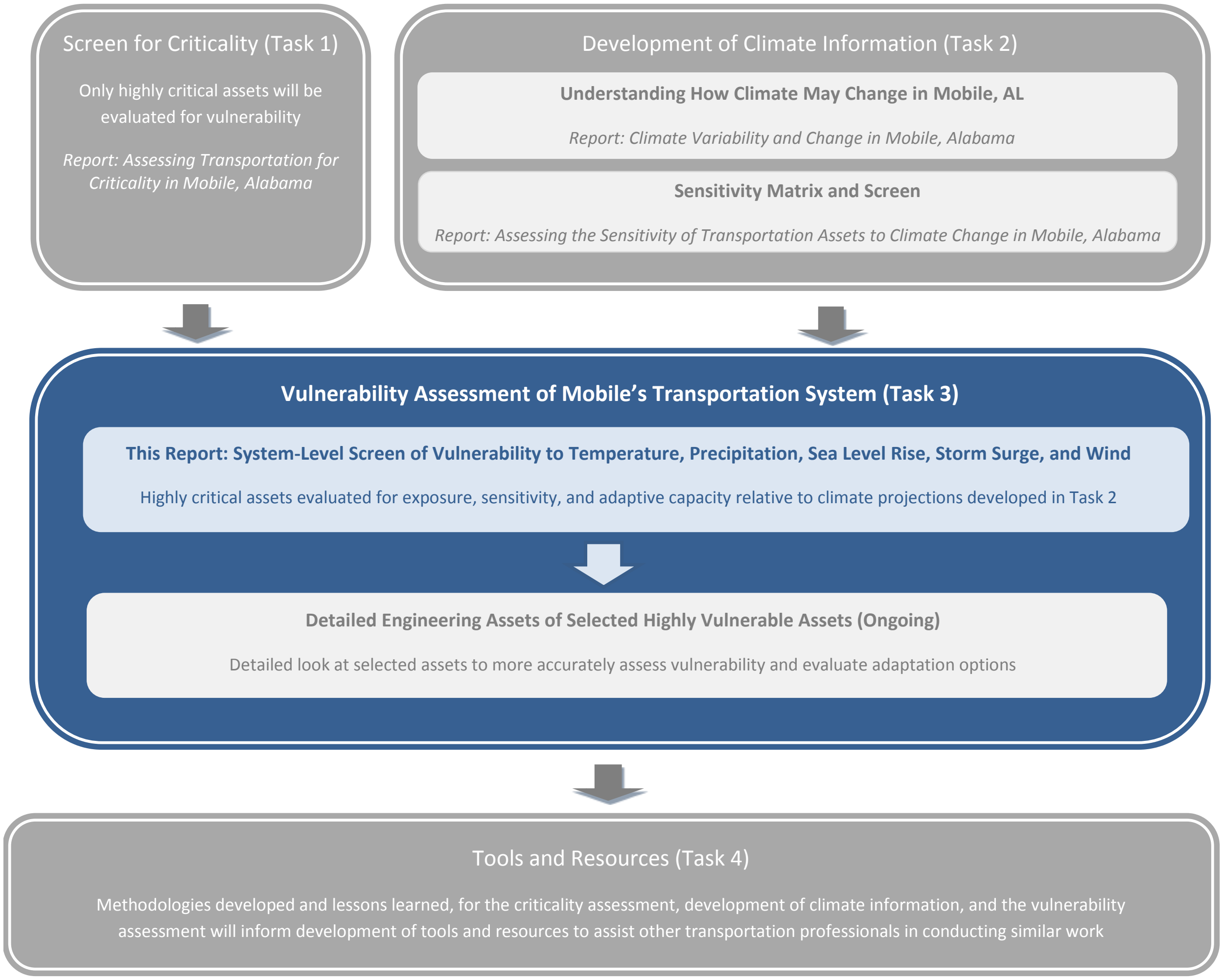
A related goal of this high-level vulnerability assessment is to identify system-wide vulnerabilities in Mobile. For example, it seeks to answer the following questions:

- Which climate change stressors (temperature, precipitation, sea level rise, storm surge, or wind) could be particularly problematic for Mobile in the future?
- Which modes are particularly vulnerable to climate change?
- Are certain geographic areas particularly vulnerable?
- What are the key vulnerabilities that need to be addressed immediately? In the medium- or longer-term?

A third and overarching objective of this work is to develop and test out methodologies that can be deployed by other local transportation agencies interested in conducting their own vulnerability assessments. In hopes that this approach can inform efforts nationwide, important lessons learned on the methodology are articulated throughout this report.

Figure 21 shows how the vulnerability assessment fits in with the other tasks under Phase 2.

**Figure 21: Roadmap for Phase 2 of the Gulf Coast Project**




*Note: The components covered by this report are indicated with blue shading. The gray shading indicates other components of the Phase 2 study that are covered under other tasks and reports*

## 2.3 Report Roadmap

This report is structured as follows:

- Overview of the approach used to assess for vulnerability, including refining the climate data, identifying representative critical segments, and employing an "indicators" approach to evaluate exposure, sensitivity, and adaptive capacity
- Specific approaches employed for each transportation mode to evaluate vulnerability
- Detailed results of the vulnerability assessment
- Evaluating vulnerability of pipelines, which were treated differently than the other transportation modes
- Next steps in the project

- References
- Appendices that provide more detail on specific methodologies and results:
  - Adaptation efforts underway in Mobile
  - Detailed methodology for evaluating exposure
  - Detailed methodology for evaluating sensitivity
  - Detailed methodology for evaluating adaptive capacity
  - Methodology for scoring data availability
  - Analysis to evaluate robustness of results
  - Detailed projections for temperature, precipitation, and storm surge

# 3. Overview of Approach

The purpose of this vulnerability assessment was to analyze a set of highly critical transportation assets against a common set of criteria in order to prioritize vulnerabilities. The direct outcome was a ranked list of vulnerable assets, highlighting assets that are most likely to experience expensive and disruptive impacts due to climate change. Overall system vulnerabilities were also identified.

Before a vulnerability assessment could be completed, however, several initial steps needed to be taken. First, the elements of vulnerability needed to be clearly defined in order to establish a framework for the methodology. Next, the voluminous climate data developed under Task 2 of this project needed to be packaged into intuitive climate narratives against which vulnerability would be assessed. Simultaneously, the large number of miles of highways, rail, and pipelines deemed to be highly critical needed to be broken down into a smaller number of representative segments that would be more manageable to assess. Then, the components of assets deemed relevant to this vulnerability assessment needed to be defined. Finally, criteria against which vulnerability would be assessed (called "indicators" in this report), also needed to be defined. The rest of this chapter discusses the processes for completing these initial activities.

## 3.1 Key Components of Vulnerability

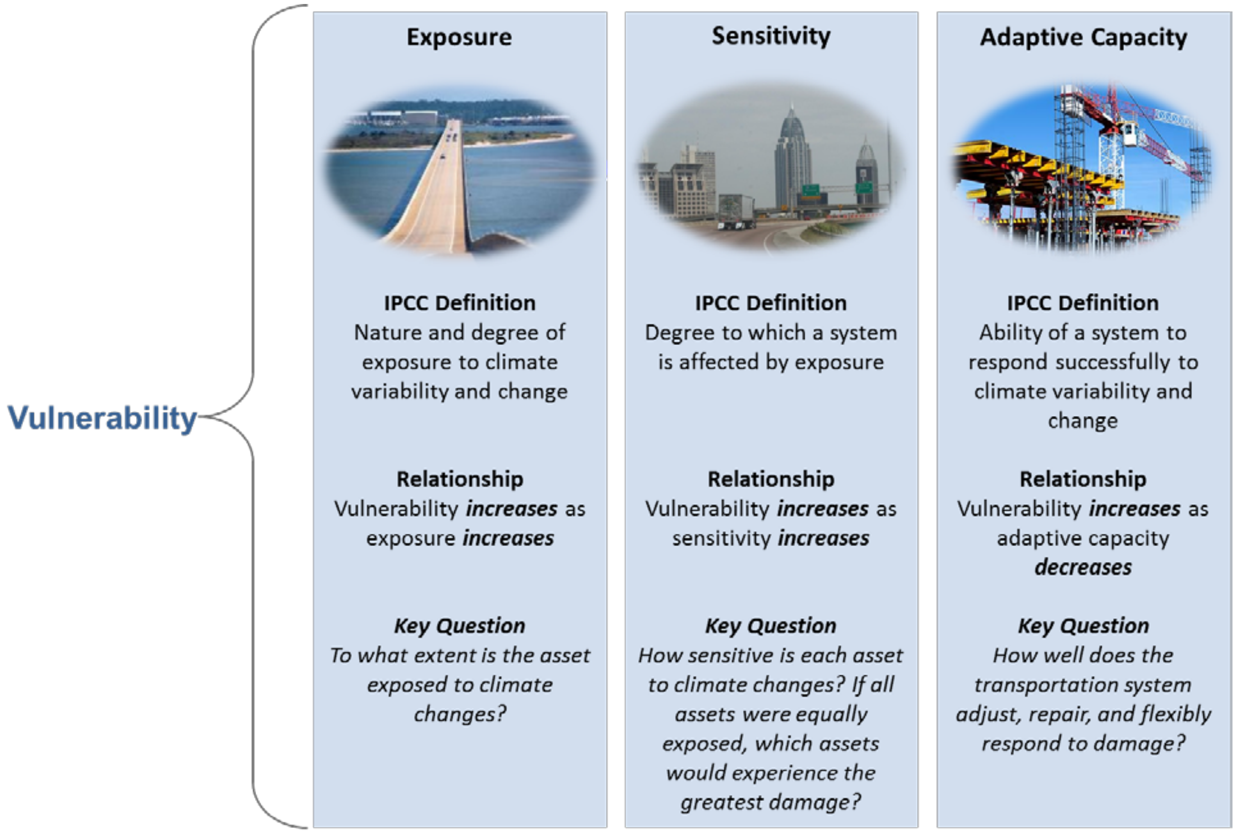
Climate change vulnerability refers to the degree to which systems are susceptible to, and unable to cope with, the adverse impacts of climate change.[7] Vulnerability is comprised of the following three elements:

- **Exposure**, which is the nature and degree to which an asset is exposed to significant climatic variations. For example, inland highways are usually not exposed to storm surge and coastal flooding. By definition, assets that are not exposed to a given climate stressor are not vulnerable to that stressor;
- **Sensitivity** is the degree to which an asset is affected, either adversely or beneficially, by climate-related stimuli. Not all assets and systems respond uniformly to climate stressors and extreme weather. During a storm, for example, some assets may experience more damage than their counterparts even if they were equally exposed to the same conditions; and
- **Adaptive capacity,** which is the ability of a system (or asset) to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. For example, a port with multiple docks may have more adaptive capacity than a port with a single dock, if operations can be easily shifted if one dock becomes incapacitated.

These elements are depicted in Figure 22.

[7] Definitions for vulnerability, exposure, sensitivity, and adaptive capacity are adapted from the International Panel on Climate Change (IPCC)'s Third Assessment Report. Please see "Annex B: Glossary of Terms" at http://www.ipcc.ch/pdf/glossary/tar-ipcc-terms-en.pdf.

**Figure 22: Definitions of the Three Components of Vulnerability: Exposure, Sensitivity, and Adaptive Capacity**




The Gulf Coast vulnerability assessment described in this report evaluates each of the three elements of vulnerability by defining and quantitatively assessing specific characteristics that could indicate different degrees of exposure, sensitivity, and adaptive capacity.

## 3.2 Developing Climate Narratives

### 3.2.1 Purpose

Under Task 2 of this study, detailed modeling projections of changes in temperature, precipitation, sea level rise, storm surge, and wind levels were developed for Mobile. These projections included temperature and precipitation changes under three emission scenarios and three time periods, sea level rise under three scenarios, and storm surge and wind speeds under 11 storm scenarios.[8] Within these different scenarios, various measurements evaluating exposure were developed; for example, for temperature alone, 32 different measurements of changes in temperature were developed (called “secondary variables”), ranging from annual and monthly averages, to hottest and coolest day of the year, to length of heat waves.

8 Please see page 37 of U.S. DOT 2012b for additional information on the climate information developed for this vulnerability assessment, including the emission scenarios, climate models, and storm modeling parameters employed.

The detailed climate projection effort resulted in a significant volume of data. However, for the purposes of a broad vulnerability screen, it was not necessary (nor possible) to evaluate vulnerability against every single projection metric available.

To streamline the high volume of climate projections into to a more manageable set of information for discussion and inclusion in the vulnerability screen, climate narratives were developed. Climate narratives condense the multiple outputs from different emission scenarios and climate models into more straightforward and intuitive datasets of potential climate futures.

### 3.2.2 Development of Narratives

Two to three narratives were developed for each climate stressor using the methods below. The narratives were selected through an iterative stakeholder process. Initial suggestions for narratives were presented to stakeholders in Mobile through a meeting of the Climate Change Work Group and a series of individual stakeholder meetings. Stakeholders were asked to consider any key weather thresholds and planning practices in determining narratives. For more information on the projections and how they were developed, please see: *Climate Variability and Change in Mobile Alabama*[9] and *Temperature and Precipitation Projections for the Mobile Bay Region*.[10]

#### Temperature

Two narratives were created to describe projected temperature changes, each representing a plausible climate future: Hotter and Warmer. These narratives were constructed out of the climate model outputs from Task 2 in order to convey the information in terms more readily understandable to the general public (rather than in emission scenarios, for example), and capturing the range of model projections.

**Process of Developing Narratives**

The narratives were selected through an iterative stakeholder process. Initial suggestions for narratives were presented to stakeholders in Mobile through a meeting of the Climate Change Work Group and a series of individual stakeholder meetings. Stakeholders were instructed to consider any key weather thresholds and planning practices in determining narratives.

Narratives were developed by identifying the points that approximately 90% of the model outputs fell between. These two points represent almost the full range of results, but exclude potential extreme values on either end. Projected temperature changes were calculated for the Hotter and Warmer narratives from the full set of climate model outputs using the following methodology. First, climate models were run to develop projected future temperature data for various timeframes and emission scenarios. “Secondary variables”—such as number of days above 95 degrees, hottest day of the year, etc.—were derived from these modeled temperature

9 U.S. DOT, 2012b
10 U.S. DOT, 2012c

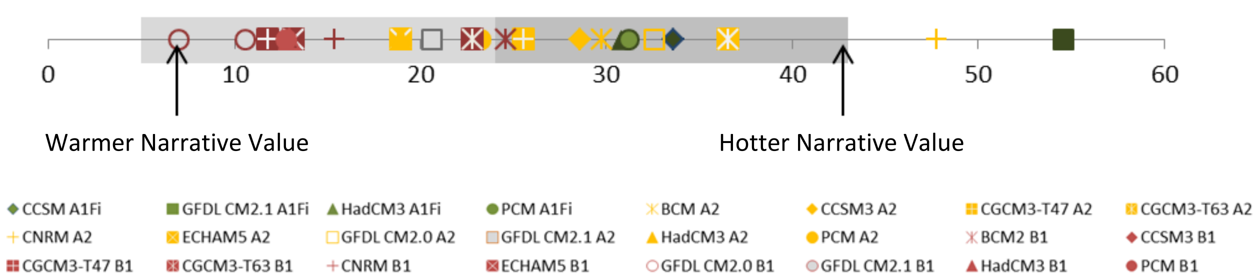
projections. For each timeframe, ten climate models were run using two emission scenarios and four models were run using a third emission scenario; thus, each secondary variable was associated with a total of 24 data points for temperature projections.

Simply taking the mean of these data points would be potentially misleading, as it would disregard the ranges in the results; also, the mean could potentially be skewed by a single outlier value.  Meanwhile, simply taking the highest and lowest values for each secondary variable could mean that extreme outliers could cause the range of plausible projects to appear quite large or extreme.  Therefore, the points at which 5% and 95% of modeled results are greater were identified, and used to bound the range of secondary variable values.

Put another way, the Hotter narrative represents the value at which approximately 5% of model results are greater, and the Warmer narrative represents the value at which approximately 95% of model results are greater. This approach is graphically represented in Figure 23 and corresponds to calculating 1.6 times the standard deviation either direction from the mean. In cases where 1.6 times the standard deviation falls outside the actual range of model results, the narrative value equals the most extreme (high or low) value modeled for that variable (see Figure 23).

Using this approach, a Hotter and Warmer value for each temperature secondary variable was calculated for each of the three time frames modeled: Near-term (2010-2039), Mid-century (2040-2069), and End-of-century (2070-2099). These values are presented in Appendix G.

**Figure 23: Example of the Distribution of Model Projections and the Warmer and Hotter Narratives for the Change in the Number of Days per Year above 95°F**




Note: Each icon represents a model and emission scenario projection. The gray bars show the mean plus and minus 1.6 standard deviations (SD) across those points. The value used for the hotter narrative (43) is the end of the dark gray bar, showing the mean + 1.6SD. The value used for the warmer narrative (7) is the lowest modeled value (since the mean—1.6SD is 5, which is lower than the most extreme model).

### Climate Model Projection Details

For both temperature and precipitation narratives, the ultimate value used in the narrative was based on a combination of climate model projections and observed local weather conditions. Projected changes in conditions are based on the change between a modeled baseline (1980-2009) and modeled future conditions (2010-2039, 2040-2069, and 2070-2099). To calculate the value used in the vulnerability assessment, the projected change in conditions (e.g., the increase in number of days above 95°F) is added to observed conditions from local weather stations over the same base time period (1980-2009) to generate approximate estimates of the future condition (e.g., total number of days per year above 95°F). This provides a way to translate climate model projections into a frame of reference familiar to stakeholders.

## Precipitation

Similar to temperature, two narratives were created to represent possible changes in precipitation: Drier and Wetter. The estimated changes for the narratives were calculated for each precipitation secondary variable based on the mean plus or minus 1.6 standard deviations (see Temperature discussion and Figure 23) to capture the range of model projections. The narrative projections for all secondary variables (such as the inches of precipitation falling within 24 hours during what would be considered a 100-year event) are presented in Appendix G.

## Sea Level Rise

Three sea level rise narratives are used to represent a low, medium, and high scenario of sea level rise (SLR) in Mobile. The narratives are 0.3 meters (1.0 foot), 0.75 meters (2.5 feet), and 2.0 meters (6.6 feet). These narratives correspond to the three scenarios selected under Task 2 based on a range of potential changes in sea level.[11] The 2.0-meter scenario corresponds to the high end of scientific projections, 0.75 meters corresponds to the mid-range of National Research Council estimates, and the 0.3-meter scenario corresponds to 2050 sea levels assuming a linear trend toward 0.75 meters by 2100.[12]

## Storm Surge and Wind

Stakeholders suggested that the storm narratives focus exclusively on Hurricane Katrina, as its impacts are readily understandable to a broad audience. Of the seven available Hurricane Katrina simulations, three were selected to represent a range of exposure levels while condensing the quantity of data considered. The following narratives were used to assess vulnerability to both storm surge and wind:

- Katrina Base—Based on the actual intensity and track of Hurricane Katrina, to ground the vulnerability assessment and results from other narratives in actual experience.
- Katrina Shifted—Based on the actual intensity of Hurricane Katrina, but modeled as if it directly hit Mobile. This narrative represents a storm that created a surge greater than any

[11] These values represent global sea level rise values, but local conditions (including subsidence and uplift) were taken into account when evaluating Mobile's exposure to sea level rise.

[12] U.S. DOT, 2012b

experienced in recent history in Mobile, but that is similar to a storm that recently occurred elsewhere on the Gulf Coast.

- Katrina Shifted, Pressure Reduced, with 0.75 meters sea level rise—This storm represents a direct hit to Mobile of a storm even stronger than Katrina, plus sea level rise. This narrative represents a storm stronger than Katrina but that could conceivably occur in the near future, plus the addition of future sea level rise. The storm surges and wind speeds associated with this storm are greater than for the other two storm narratives.

Two important notes regarding selection of the storm narratives: First, the most extreme storm narrative does not include the most extreme sea level rise modeled for this project. Stakeholders suggested basing the storm narratives on Hurricane Katrina, and the Hurricane Katrina storms had previously been modeled assuming either zero or .75 meters of sea level rise, but not 2 meters. Furthermore, the most extreme Katrina scenario that was modeled (which held the storm's maximum wind speed constant until landfall, and also added 0.75 meters of sea level rise), was not selected for use in the vulnerability assessment. The project team believed that the Katrina Shifted, Pressure Reduced, with 0.75 meters of sea level rise sufficiently represented a storm that is feasible under future climate change conditions without seeming to be too extreme.

### Summary

Table 6 summarizes the narratives used for each climate stressor. These narratives represent a simplified way of presenting model outputs and a way to more directly engage local stakeholders in understanding vulnerability.

**Table 6: Summary of Climate Narratives and Example Implications**

| Climate Stressor | Narrative | Sample Implication |
|---|---|---|
| Temperature | Warmer | 2 additional days above 95°F in near-term (2010-2039)<br>7 additional days above 95°F by mid-century (2040-2069)<br>9 additional days above 95°F by end-of-century (2070-2099) |
| | Hotter | 13 additional days above 95°F in near-term<br>43 additional days above 95°F by mid-century<br>95 additional days above 95°F by end-of-century |
| Precipitation | Drier | 2 inches less rain in the 1% storm in near-term<br>No change in the 1% storm by mid-century<br>No change in the 1% storm by end-of-century |
| | Wetter | 11 inches more rain in the 1% storm in near-term<br>10 inches more rain in the 1% storm by mid-century<br>12 inches more rain in the 1% by end-of-century |
| Sea Level Rise | 0.3 meters | 4% of critical roadways inundated |
| | 0.75 meters | 5% of critical roadways inundated |
| | 2.0 meters | 13% of critical roadways inundated |
| Storm Surge | Katrina Base | 28% of critical roadways inundated |
| | Katrina Shifted | 46% of critical roadways inundated |
| | Katrina Shifted + Pressure Reduced + 0.75 m SLR | 60% of critical roadways inundated |
| Wind | Katrina Base | Peak gusts of 84 mph |
| | Katrina Shifted | Peak gusts of 113 mph |
| | Katrina Shifted + Pressure Reduced + 0.75 m SLR | Peak gusts of 120 mph |

## 3.3 Identifying Representative Segments

The criticality assessment conducted earlier in this project[13] identified over a thousand highly critical assets in the Mobile region. Collecting the data necessary to evaluate this number of assets was not feasible given resource constraints. In addition, it is likely that many of the critical highway, rail, and pipeline routes share common characteristics, such that individual analyses of every asset would be redundant. Therefore, the project team selected a sub-set of highly critical assets that represent the larger set of highway, rail, and pipeline miles. The project team worked closely with stakeholders to identify these representative segments and revised the segments following Climate Change Work Group meetings and stakeholder consultants held in Mobile

13 U.S. DOT, 2011.

throughout 2012. It was not necessary to select representative segments for transit, port, and aviation facilities because the number of critical assets was small enough to be manageable for data collection purposes.

Sections 3.3.1 and 3.3.2 describe the criteria used to identify representative highway and rail segments. While using these criteria led the project team to select some segments that are likely to be at high risk, the team did not use anticipated vulnerability as a screening criterion for this exercise. Investigating segments that are resilient or not likely to be exposed to climate impacts can be as valuable as pinpointing segments that require adaptation measures. For a map and list showing the final representative highway, rail, and pipeline segments, please see page 61.

### 3.3.1 Representative Highway Segments

The criticality assessment conducted under Task 1 of this study[14] identified 152 miles of highway and 71 bridges in the study region as being highly critical. In addition, after the completion of Task 1, stakeholders emphasized the importance of two key evacuation routes that did not meet the original criticality criteria. The project team selected representative highway segments from these critical assets and additional evacuation routes.

For each one of the critical routes identified, as well as for the two additional evacuation routes, the project team identified between 1 and 4 representative highway segments. The project team selected for assets with the following characteristics:

- Together, represented the full geographic diversity within Mobile, including coastal and inland locations
- Intersections of multiple critical routes
- Multi-modal connectors
- Areas already prone to flooding during heavy precipitation events
- Located near various water bodies, including the Bay, rivers, and channels
- Co-located with major stormwater drainage structures
- Located near water and sewer facilities
- Social and cultural relevance to stakeholders

Using these criteria, the project team identified a total of 32 road segments for the vulnerability assessment, with an approximate mileage of 61 miles. These segments included 92 bridges and 15 culverts. This vulnerability assessment applies to all of these highway assets.

[14] U.S. DOT, 2011. Criticality was evaluated using a variety of socioeconomic, operational, and health and safety factors.

### 3.3.2 Representative Rail Segments

The criticality assessment[15] identified 347 miles of rail and 7 rail facilities in the study region as being highly critical. The project team selected representative rail segments from these critical assets.

For each one of the critical routes, the project team identified up to 4 representative rail segments. The team also identified opportunities to group critical facilities together based on relative proximity; for example, the dockside yards for TASD, CSX, and Norfolk Southern are all right next to each other, and could be evaluated together. The project team selected for assets with the following characteristics:

- Together, represented the full geographic diversity within Mobile, including locations relative to the Bay, ocean, and inland
- Multi-modal connectors, such as the segments near the Brookley airfield and the segments near the McDuffie coal terminal and the main port
- Connect to key industrial/manufacturing sites
- Social and cultural relevance to stakeholders

After applying these criteria, the project team identified a total of 12 representative rail segments for the vulnerability assessment with an approximate mileage of 25 miles.

### 3.3.3 Representative Pipeline Segments

The project team went through a similar process to identify representative pipeline segments. However, pipeline segments were ultimately analyzed separately from this vulnerability screen. The qualitative pipeline vulnerability assessment is found in Section 6, which includes a discussion of the criteria used to identify representative pipeline segments.

### 3.3.4 Final Group of Assets Studied

Figure 24 provides a map of the final group of assets included in this vulnerability assessment. These assets are also listed in Table 7. This list reflects the representative segments for highways and rail, as well as the critical assets for ports, airports, and transit.

[15] U.S. DOT, 2011

**Figure 24: Map of Assets Included in Vulnerability Assessment**

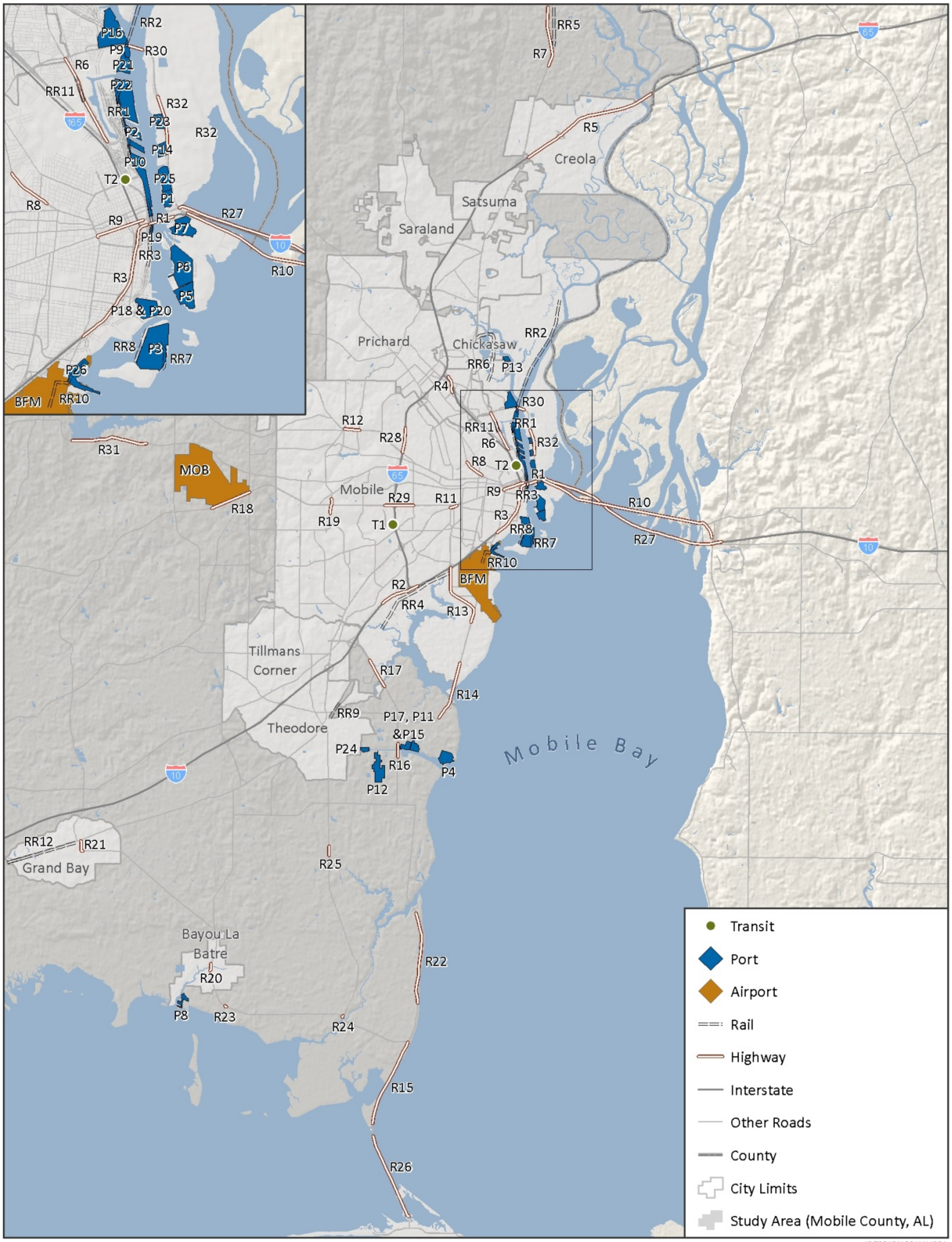


**Table 7: List of Assets Evaluated in Vulnerability Assessment, by Mode**

| ID | Asset |
|---|---|
| **Highways** | |
| R1 | I-10 Tunnel (Wallace Tunnel) |
| R2 | I-10, intersection with I-65 |
| R3 | I-10, from Wallace Tunnel to S Broad Street |
| R4 | I-165, 1 mile before intersection with I-65 |
| R5 | I-65, between US-43 and County boundary |
| R6 | Telegraph Road, from Downtown to Baybridge Road |
| R7 | US-43 (Saraland Blvd N), northernmost portion |
| R8 | US-45 (St. Stephens Road), between Rylands Street and Simington Drive |
| R9 | US-90 (SR-16), section east of Broad Street |
| R10 | The Causeway (Battleship Parkway) |
| R11 | US-90, intersection with SR-163 and Government Street |
| R12 | Route 98 near the Stickney Filtration Plant |
| R13 | SR-163 (Dauphin Island Parkway), from I-10 to Brill Road |
| R14 | SR-163 (Dauphin Island Parkway), from Island Road to Terrell Road |
| R15 | SR-193 (Dauphin Island Parkway), from Dauphin Island Bridge to CR-188 |
| R16 | SR-193 (Range Line Road), running about 0.5 mile on either side of Theodore Industrial Canal |
| R17 | SR-193 (Range Line Road), between Rabbit Creek Drive and Tufts Road |
| R18 | Airport Blvd, between CR-31 (Schillinger Road) and airport |
| R19 | South University Blvd, 0.5 mile segment either side of CR-56 (Airport Blvd) |
| R20 | SR-188, where it crosses the river just North of Bayou la Batre |
| R21 | SR-188, from Douglas Road to US-90 West |
| R22 | SR-193 (Dauphin Island Parkway), from Old Cedar Point Road to Day Springs Road |
| R23 | SR-188, river crossing near Coden |
| R24 | Intersection of SR-188 and CR-59 (Bellingrath Road), near Fowl River |
| R25 | CR-59 (Bellingrath Road), 0.5 mile on either side of large stream crossing north of Plantation Woods Drive |
| R26 | Dauphin Island Bridge |
| R27 | I-10 Bridge across Mobile Bay |
| R28 | I-165, near intersection with Route 98 |
| R29 | Intersection of Airport Blvd and I-65, near drainage areas |
| R30 | Cochrane Bridge (Bay Bridge Road) |
| R31 | CR-70 (Tanner Williams Road), along the J.B. Converse Reservoir dam and covering access to the Palmer S. Gaillard Pumping Station |
| R32 | Old Spanish Trail, between Cochrane Bridge and the tunnels |
| **Ports** | |
| P1 | Alabama Bulk Terminal Co. (Hunt Refining Company) |
| P2 | Alabama State Port Authority (ASPA) - Alabama State Docks Main Complex |
| P3 | Alabama State Port Authority (ASPA) - McDuffie Terminal |
| P4 | Alabama State Port Authority (ASPA) - Mobile Middle Bay Port |
| P5 | Alabama State Port Authority (ASPA) - Pinto Island |
| P6 | Atlantic Marine (BAE Systems Southeast Shipyards) |
| P7 | Austal |
| P8 | Bayou La Batre |
| P9 | BP Oil Co., Mobile Terminal Barge Wharf |

| ID | Asset |
|---|---|
| P10 | Crescent Towing & Salvage Co., River A Wharf |
| P11 | Environmental Treatment Team Wharf |
| P12 | Evonik Industries |
| P13 | Gulf Atlantic Oil Refining Co., North Terminal |
| P14 | Gulf Coast Asphalt Co., Mobile Terminal Wharf |
| P15 | Holcim Cement Wharf |
| P16 | Kimberly-Clark Corporation |
| P17 | Martin Marietta Aggregates |
| P18 | Mobile Container Terminal |
| P19 | Mobile Cruise Terminal |
| P20 | Oil Recovery Co. of Alabama, Mobile Terminal Pier |
| P21 | Plains Marketing - North Terminal |
| P22 | Plains Marketing - South Terminal |
| P23 | Shell Chemical Co. |
| P24 | Standard Concrete Products |
| P25 | TransMontaigne Product Services |
| P26 | U.S. Coast Guard Pier |
| **Airports** | |
| BFM | Mobile Downtown Airport (Brookley Field) |
| MOB | Mobile Regional Airport |
| **Rail** | |
| RR1 | TASD--rail yards near Alabama State Docks |
| RR2 | CSX M&M subdivision--segment along Mobile River between Cochrane Bridge and Twelvemile Island |
| RR3 | CSX NO&M subdivision--1.2 mile segment running along eastern edge of Downtown, between St. Louis St. and Elmira Street |
| RR4 | CSX NO&M subdivision--3.9 mile segment running along I-10, near Dog River and its tributaries, between Dauphin Island Parkway and Cypress Shores Drive |
| RR5 | Norfolk Southern--1.6 mile segment running along US-43, near Le Moyne |
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive |
| RR7 | TASD--segment on eastern side of McDuffie Island |
| RR8 | TASD--segment on western side of McDuffie Island |
| RR9 | CSX NO&M subdivision--0.7 mile segment that is bisected by Hamilton Blvd., near Theodore |
| RR10 | CSX NO&M subdivision--1.2 mile segment on eastern side of Brookley Airfield |
| RR11 | Norfolk Southern--segment running along Telegraph Rd, crossing Three Mile Creek |
| RR12 | CSX NO&M subdivision--segment running along US-90, between Grand Bay Wilmer Road and western edge of Grand Bay |
| **Transit** | |
| T1 | Beltline O&M Facility |
| T2 | GM&O Terminal |
| T3 | Bus Fleet & Service |

## 3.4 Refining Assessment based on Asset Components and Lifetime

Phase 2 of the Gulf Coast Study looks at six transportation modes: highways, ports, airports, rail, transit, and pipelines. However, when considering what causes a particular mode to be vulnerable, one must consider the various subcomponents of its infrastructure and operations. For example, relevant aspects of highways include pavement, sub-pavement, drainage structures, bridges, medians, nearby vegetation, usage, etc. Similarly, a port is comprised of docks, berths, storage facilities, operational offices, cranes, rail and trucking connections, container yards, and more. Before an assessment of vulnerability can be done, it is essential to define which components of each mode are being evaluated.

To do so, the project team consulted with modal experts and Mobile stakeholders to identify the most important components of each mode that could potentially be vulnerable to climate and weather events. These components helped focus the vulnerability assessment on the important components of each mode.

As the modal components were defined, the project team also gathered information on the expected lifetime of each component, relative to the climate projection timeframes (near-term, medium-term, and end-of-century). For example, pavement has a relatively short lifetime and will be replaced multiple times by the end of the century. Meanwhile, other components (such as bridge superstructure) may have expected lifetimes that reach into the medium-term and end-of-century timeframes. Defining the expected lifetimes of asset components helps frame the overall vulnerability results. For example, if pavement is considered highly vulnerable to temperatures at the end-of-century, it is important to know that there will be opportunities to change pavement mixes many times before those end-of-century temperatures are reached. Meanwhile, if bridge superstructure is considered to be highly vulnerable to end-of-century temperatures, it is more important to take long-term projected temperatures into account when designing or upgrading an asset.

The final modal components and their assumed lifetimes are shown in Table 8.

**Table 8: Modal Components and Assumed Lifetimes**

| Mode | Component | Assumed Lifetime<br>*Short = <30 years*<br>*Medium = 30-60 years*<br>*Long = >60 years* |
|---|---|---|
| Bridges | Superstructure | Long |
| | Substructure and roadway approaches | Long |
| | Operator/Bridge Tender's house and electrical parts | Short |
| | Location | Long |
| Roads | Pavement | Short |
| | Subsurface | Long |
| | Stormwater drainage | Long |
| | Traffic signs/lights | Short |
| | Road work/maintenance | Short |
| | Traffic/service/driver safety | Long |
| | Location | Long |
| Ports | Electrical Equipment | Short |
| | Terminal Buildings | Medium |
| | Channels | Medium |
| | Piers, wharves, and berths | Medium |
| | Port services (i.e., operations) | Short |
| | Cargo handling equipment | Short |
| | Storage areas | Short |
| | Location | Long |
| Airports | Runway (length and materials) | Short |
| | Aircraft | Short |
| | Buildings | Medium |
| | Services | Long |
| | Utilities/Navigational Aids | Short |
| | Location | Long |
| Rail | Electrical equipment, signals | Medium |
| | Tracks, ties, ballasts | Medium |
| | Operations | Short |
| | Location | Long |

| Mode | Component | Assumed Lifetime<br>*Short = <30 years*<br>*Medium = 30-60 years*<br>*Long = >60 years* |
|---|---|---|
| Transit | Bus Fleet | Short |
| | Service/Operations | Short |
| | Facilities | Long |
| Pipelines | Aboveground | Medium |
| | Underground | Medium |
| | Offshore | Medium |
| | Aboveground Infrastructure | Medium |
| | Location | Long |

## 3.5 Using an Indicators Approach for Evaluating Exposure, Sensitivity, and Adaptive Capacity

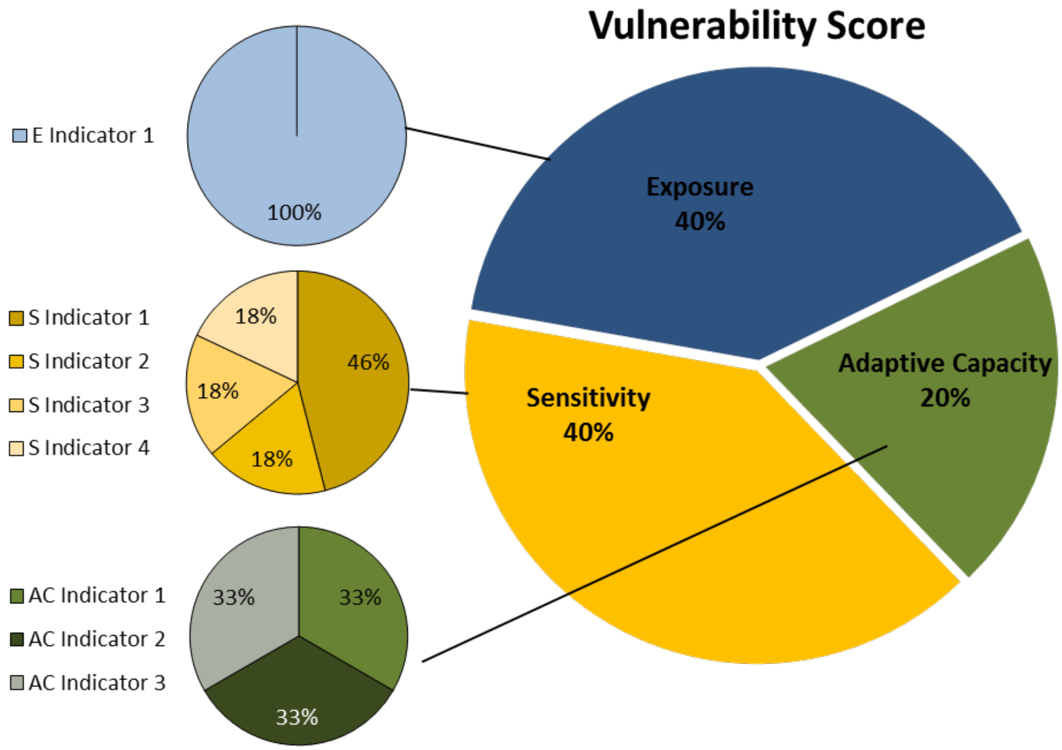
### 3.5.1 Introduction to the Indicator-Based Vulnerability Assessment

Exposure, sensitivity, and adaptive capacity are abstract concepts. While there are some formulas that can calculate how individual assets are specifically damaged by certain weather conditions (for example, as used in HAZUS), these types of formulas are not practical for large-scale assessments given resource and time limitations. Therefore, while we have projections on how the climate may change, and a general understanding of how the transportation system may or may not be sensitive to those changes, it can be challenging to overlay those pieces of information to pinpoint specific assets that are particularly vulnerable to climate change.

The research team therefore used an "indicators" approach to evaluate exposure, sensitivity, adaptive capacity, and, ultimately, vulnerability. An indicator is a representative data element that can be used as a proxy measurement of the overall exposure, sensitivity, and adaptive capacity of specific assets. For example, paving materials vary in their sensitivity to temperature, so looking at the types of paving materials used for highways or runways can provide an indication of how sensitive specific assets might be to high temperatures.

Appropriate indicators, and a numerical scoring system for each indicator, were developed through consultation with modal experts, local stakeholders, and other sources. Indicators were used to develop an overall exposure, sensitivity, and adaptive score for each asset, which were then rolled up into an ultimate vulnerability score for each asset, as shown in Figure **25**. Assets were then deemed to have High, Moderate, or Low vulnerability to a certain climate stressor based on their vulnerability score. Assets were also ranked relative to one another to determine which assets are likely to be more vulnerable than others.

Figure 25: Diagram Illustrating Use of Weighted Indicators to Develop an Asset-Specific Vulnerability Score




The indicators approach provides a relatively low-cost way to screen transportation assets for vulnerability by relying on readily available data. The results of the data-driven vulnerability screen provide transportation managers with a starting point for understanding their system's vulnerabilities and making decisions on how to best manage those vulnerabilities. Similar approaches have been tested in other settings, such as to evaluate society-level vulnerability to broadly-defined external stressors,[16] social and ecosystem vulnerability to climate change,[17] and national-level vulnerability to climate change.[18]

### 3.5.2 Selecting Indicators

Over the course of this assessment, the project team developed sensitivity, exposure, and adaptive capacity indicators for all modes and climate impacts. These indicators were selected based on data availability, stakeholder input, and expert judgment. The full list of indicators used in this report can be found in Appendices B through D.

Useful indicators have several important characteristics. First, indicators are most useful when they are able to help the user distinguish among assets. For example, if an agency is conducting a

[16] Yohe and Tol, 2002
[17] Wongbusarakum, S. and C. Loper, 2011
[18] Brooks et al., 2005; Füssel, 2010; and Harley et al., 2008

storm surge vulnerability assessment of ten coastal bridges that are all the same structure type, structure type will not distinguish any particular bridge as being more or less sensitive to storm surge. However, if some are movable bridges, which are more sensitive to storm surge, structure type could be a useful indicator. Similarly, if the bridges are all at different elevations above the water surface, then that elevation could be a useful indicator to distinguish vulnerability among bridges.

Second, indicators with complete or nearly complete data are more useful than indicators with little data availability. Complete datasets allow for fair comparisons across assets. The vulnerability assessment presented in this report includes a "data completeness score" that alerts the user to vulnerability scores reliant on a relatively low number of datasets.

Third, effective indictors are transparent, allowing stakeholders to quickly grasp the meaning of the indicator in the broader context of vulnerability.

### 3.5.3 Sources of Data to Evaluate Indicators

Information about indicators can be collected and scored using several sources, including asset management systems and other databases, spatial analysis (especially for exposure indicators), and input from stakeholders.

#### Asset Management Systems and Databases

Asset management systems can be valuable sources of vulnerability indicator data. National level databases can be particularly useful because they are consistently available across a wide range of assets. Because data about the study assets were not available from an asset management system, this vulnerability assessment relied heavily on the National Bridge Inventory (NBI) information about bridge attributes. NBI is spatially referenced, allowing for the exposure analyses described in more detail below. In addition, the database contains information on the scour criticality, navigational clearance, condition, detour length, and replacement value of bridges and large culverts. The project team developed indicators based on these data elements in order to score the sensitivity and adaptive capacity of bridges.

#### Spatial Analysis

Evaluating the exposure of transportation assets often requires spatially overlying asset locations with information on the extent of projected climate impacts. For example, if an asset is far inland it will not experience, or be exposed to, storm surge. Exposure is a prerequisite for vulnerability—if an asset is not exposed to a hazard, it cannot be vulnerable to that hazard. This vulnerability assessment relied on several spatial analyses to understand the exposure of assets to sea level rise, storm surge, and wind speeds. See Appendix B for more information.

Additionally, spatial analyses were used to evaluate sensitivity indicators related to whether an asset is likely to experience flooding. Spatial analyses evaluated whether assets were located in

FEMA flood zones, were at lower elevation that the areas immediately surrounding them, or in areas with limited permeable surfaces. See Appendix C for more information).

#### Local Expertise and Stakeholders

Successful vulnerability assessments integrate stakeholder involvement at nearly every step, including indicator selection. Not only are local experts often deeply familiar with datasets and able to offer recommendations on indicators, but they know their transportation systems intimately. The institutional knowledge of hydraulics engineers, maintenance and operations staff, and assets managers is an invaluable source of information on existing asset vulnerabilities. Over the course of this vulnerability assessment, the project team interviewed over 25 local transportation experts and solicited additional input from the Climate Change Working Group. We integrated this input into the selection of indicators, the weighting of indicators, and the information contained in the "historical performance" indicator.

### 3.5.4 Calculating Vulnerability Scores

This section provides a brief overview of the way indicators were scored, weighted, and assessed for data completeness. For more detailed information on the methodologies, please see Section 4 and Appendices B through D.

#### Scoring Indicators

Each sensitivity, adaptive capacity, and exposure score is essentially an index comprised of a set of indicators. The vulnerability assessment bins each indicator dataset into 4 categories and scores each asset according to these bins. Scores of "1" represent low exposure, low sensitivity, and high adaptive capacity, whereas scores of "4" represent high exposure, high sensitivity, and low adaptive capacity. The vulnerability assessment next takes the weighted average of these individual indicator scores to develop the sensitivity, adaptive capacity, and exposure scores, which are indices. Finally, the assessment weights these three numbers to develop a final vulnerability score.

The project team used the final vulnerability scores to identify which assets were considered to have vulnerability of High (vulnerability scores between 3 and 4), Medium (scores between 2 and 2.9), and Low (scores between 1 and 1.9). This scoring system allowed for the identification of certain areas that appear particularly vulnerable to particular climate stressors and evaluation of which climate stressors appear to be particularly problematic for certain modes. In addition, the scores allowed for a relative ranking of the assets, to determine which assets appear to be the most vulnerable and which ones are less vulnerable.

#### Weighting Indicators

Not all indicators are created equal and it is likely that transportation practitioners will have more faith in some indicators than in others. For example, the sensitivity score as shown in Figure **25** is influenced more heavily by the score for Exposure Indicator 1 than it is by the other indicators.

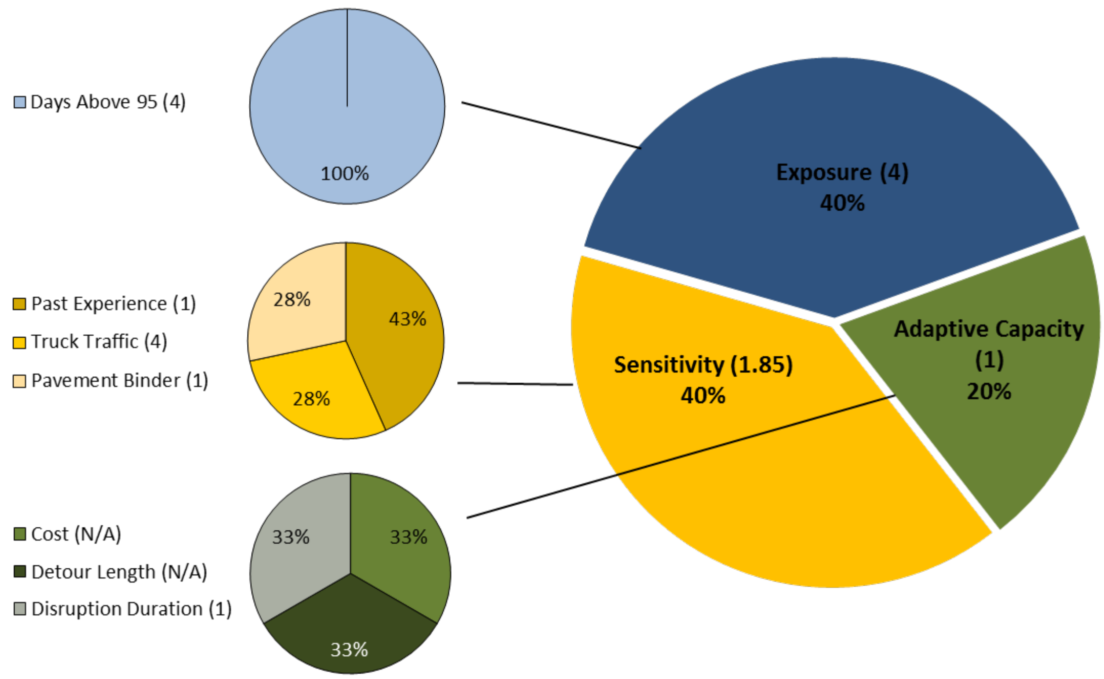
This situation may arise if stakeholders feel more confidence in the accuracy or completeness of one indicator dataset over the others. For example, in this study, Mobile stakeholders chose to weight “historical performance” 15 percent higher than any other indicator when developing exposure, sensitivity, and adaptive capacity indices. They also chose to weight exposure and sensitivity more highly than adaptive capacity, since they felt that these components contributed more to overall vulnerability of assets.

In other cases, there can be multiple indicators that represent similar characteristics. For example, location in the 100-year and the 500-year flood zones may be two separate indicators that both represent the location of an asset in an area thought to be prone to flooding. In order to not overstate “location” relative to other characteristics that may indicate sensitivity to precipitation, these two indicators can individually be weighted less, so that their combined weight is on par with other precipitation indicators.

For these reasons, it was important that the scoring methodology allow for some indicators to be weighted more heavily than others when calculated the exposure, sensitivity and adaptive capacity scores. During the scoring process, each indicator was assigned a weighting so that the total weight of all indicators added up to 100%. For similar reasons, the scoring methodology allowed for exposure, sensitivity, and adaptive capacity to be weighted differently when calculating the overall vulnerability scores.

Figure 26 provides a diagram of how the vulnerability scoring process works, using the Wallace Tunnel (R1) as an example. The figure shows how the temperature vulnerability score was calculated for that asset, where data were first collected for each indicator, assigned a score, and then weighted into component score that were, in turn, weighted to calculate a vulnerability score.

**Figure 26: Example of Vulnerability Score Calculations for a Single Asset (R1) to High Temperatures Projected under the Hotter Narrative by the End of the Century**




| Component | Indicator | Value | Score | Weight | Component Score | Weight | Vulnerability Score |
|---|---|---|---|---|---|---|---|
| Exposure | Days above 95 | 105 | 4 | 100% | 4 | 40% | 2.54 |
| Sensitivity | Past Experience | No | 1 | 43% | 1.85 | 40% | |
| | Truck Traffic | 4875 | 4 | 28% | | | |
| | Pavement Binder | PG 67-22 | 1 | 28% | | | |
| Adaptive Capacity | Cost | No data | n/a | n/a | 1 | 20% | |
| | Detour Length | No data | n/a | n/a | | | |
| | Disruption Duration | hours | 1 | 100% | | | |

## Data Availability

It is important to note that as a result of this approach, the results are influenced by data availability—which assets and indicators the study team was able to collect data for. For example, the National Bridge Inventory contains information about several bridge attributes that can serve as indicators of their vulnerability to climate change. As a result, the assessment included data for many bridge assets that was not available for roads, and could result in different vulnerabilities for highway segments with and without bridges. This study also assigned a "data availability score" to each result so that decision-makers can know where incomplete data may have influenced the results.

Finally, it is difficult to make an apples-to-apples comparison of the different climate stressors. The analysis provides a general look at which stressors may be particularly problematic for Mobile and for specific assets, and for which stressors there may be less vulnerability. However, it is important to remember that different indicators were used for each stressor, so vulnerability scores for two stressors cannot be compared explicitly.

# 4. Methodology for Evaluating Vulnerability

As discussed in Section 3.5, this analysis evaluated the vulnerability of transportation assets using an indicators approach. Indicators were developed for each of the three components of vulnerability (exposure, sensitivity, and adaptive capacity), and assets were scored against these indicators.

For each asset and climate stressor, overall exposure, sensitivity, and adaptive capacity scores were developed, and each asset was evaluated against these indicators using a variety of data sources. See Appendices B through D for detailed information on the scoring and weighting systems used for each indicator. Then, an overall vulnerability score for the asset to the climate stressor was developed by weighting and combining the exposure, sensitivity, and adaptive capacity scores (see box below).

Scores were used to identify which assets were considered to have vulnerability of High (vulnerability scores between 3 and 4), Medium (scores between 2 and 2.9), and Low (scores between 1 and 1.9). This scoring system allowed for the identification of certain areas that appear particularly vulnerable to particular climate stressors and evaluation of which climate stressors appear to be particularly problematic for certain modes. In addition, the scores allowed for a relative ranking of the assets, to determine which assets appear to be the most vulnerable and which ones are less vulnerable.

### Weighting of Exposure, Sensitivity, and Adaptive Capacity

For all climate stressors *except* sea level rise, exposure and sensitivity were given twice the weight as adaptive capacity (40% each vs. 20%). While adaptive capacity is an important component of vulnerability, discussions with stakeholders indicated that, from their perspective, exposure and sensitivity were key determinants of vulnerability, and that adaptive capacity played a more minor role in overall vulnerability. Additionally, the concept of adaptive capacity was more difficult to convey in terms that could be represented by quantitative or qualitative indictors; conversely, the exposure and sensitivity indicators were more easily defined and agreed upon among members of the project team, stakeholders, and modal experts consulted. Therefore, confidence in the ability of adaptive capacity indicators to represent true adaptive capacity is somewhat lower than confidence in the indictors for exposure and sensitivity. Overall vulnerability scores were calculated using the following equation:

*Vulnerability Score = (40% x Exposure Score) + (40% x Sensitivity Score) x (20% x Adaptive Capacity Score)*

This assessment did not score asset exposure to sea level rise, but assumed that only the exposed assets would be vulnerable to this impact. In other words, if an asset *is* exposed to sea level rise, the sensitivity and adaptive capacity scores were weighted and then combined. If an asset is not exposed, the vulnerability is assumed to be very low. It is worth noting that sea level rise can increase tailwater (water downstream from a hydraulic structure), which decreases the performance of drainage structures during heavy rainfall. Therefore, sea level rise can increase the vulnerability of non-exposed assets to precipitation. This analysis did not take this impact into consideration. As the equation below illustrates, vulnerability to sea level rise was calculated by weighting the sensitivity score twice as heavily as the adaptive capacity score:

*Vulnerability Score = (67% x Sensitivity Score) x (33% x Adaptive Capacity Score)*

The remainder of this section discusses the indicators used to evaluate exposure, sensitivity, and adaptive capacity for each transportation mode and climate stressor. The results of the analysis are provided in Section 5.

Because incomplete data sets were available for each indicator, the project team calculated a data availability score (out of 100%), to illustrate how complete the datasets were for each asset. Data availability scores are shown alongside the vulnerability scores in Section 5. For detailed information on how these scores were calculated, please see Appendix E. The project team also conducted an analysis to identify whether any particular indicator was driving the results for a given mode or climate stressor—that is, to assess the robustness of the results to changes in indicator assumptions. More information on this analysis is provided in Appendix F, and the robustness of the results is discussed in the results sections for each mode within Section 5. Together, the data availability scores and the evaluation of robustness help illustrate where final scores may be more robust, and where final scores or rankings may potentially be influenced by incomplete data or scoring and weighting assumptions.

## 4.1 Evaluating Exposure

Exposure is a component of vulnerability that refers to whether an asset will experience a given condition. For example, if an asset is far inland it will not experience, or *be exposed to*, storm surge. Exposure is a prerequisite for vulnerability—if an asset is not exposed to a hazard, it cannot be vulnerable to that hazard.

This study assesses exposure for all assets to the five climate stressors considered throughout the study: temperature, precipitation, sea level rise, storm surge, and wind. **The exposure methodology is the same for all modes of transportation: highways, ports, airports, rail, and transit.**[19]

For each stressor, the study used a single indicator of exposure (see Table 9), derived from climate projections generated in an earlier stage in the Gulf Coast Study, Phase 2.[20] Each asset received an exposure score (on a scale of 1 to 4) for each climate stressor based the value of each indicator.[21] All assets were scored uniformly for temperature and precipitation. Appendix B provides detailed information about the methodology used to generate exposure scores for each stressor and asset.

19 The assessment made a small modification to the sea level rise and storm surge exposure calculations for one of the transit assets, the bus fleet and service (T3). Sea level rise and storm surge exposure for the bus fleet and service asset is based on percent of bus stops exposed to inundation. See Appendix C for more information.

20 U.S. DOT, 2012b

21 Sea level rise was exposure was not scored on a scale of 1-4 because of its binary nature. All assets were marked as either Exposed or Not Exposed and the vulnerability scores for exposed assets were calculated based on only sensitivity and adaptive capacity scores.

Table 9: Indicators Used to Evaluate Exposure to Climate Stressors

| Stressor | Indicator | Rationale | Data Source |
|---|---|---|---|
| **Temperature** | Projected percent change in number of days per year above 95°F | Stakeholders indicated that temperatures exceeding 95°F (35°C) affect service, operations, and workforce conditions in Mobile. In addition, the number of days above 95°F is a transparent and easy to communicate variable that stakeholders intuitively understand. | Climate model projections developed under Task 2 (U.S. DOT, 2012b; U.S. DOT, 2012c) |
| **Precipitation** | Projected percent change in amount of rain that falls in 24 hours in the 100-year storm | Stakeholders and research revealed that infrastructure is more sensitive to the short-term, extreme precipitation events, rather than incremental changes in the mean. The 24-hour storm was shortest period for which projected return intervals were available. Within the multiple projections representing short-term extreme events, all exhibited similar changes over time so a single precipitation variable was selected to represent exposure. In addition, the variable is transparent and easy to communicate. | Climate model projections developed under Task 2 (U.S. DOT, 2012b; U.S. DOT, 2012c) |
| **Sea Level Rise** | Inundation (Yes or No) under SLR narratives | An asset is exposed to sea level rise if it is inundated under projected sea level rise narratives. | Spatial sea level rise modeling conducted under Task 2 (U.S. DOT, 2012b) |
| **Storm Surge** | Depth of storm surge inundation | The more deeply an asset is inundated, the more it is exposed to storm surge. | Advanced CIRCulation (ADCIRC) and STeady State spectral WAVE (STWAVE) modeling conducted under Task 2 (U.S. DOT, 2012b) |
| **Wind** | Highest modeled wind speed at asset location, relative to design wind speed | If an asset experiences wind speeds greater than the speeds it was designed to withstand, then the asset is exposed to wind. | *Projected wind speeds*: ADCIRC modeling conducted under Task 2 (U.S. DOT, 2012b)<br>*Design wind speeds*: Personal communication with ALDOT (Powell, 2012) |

This approach resulted in the following exposure:

- **Notable increases in exposure to high temperatures, with significant increases by the end-of-century.** Under the warmer narrative, the number of days above 95°F is expected to increase 25% in the near term and 96% by the end-of the century, representing relatively low exposure. Under the hotter narrative, exposure to of days above 95°F is projected to increase over time, eventually increasing by over ten-fold by end-of-century.
- **Low exposure to precipitation under the drier narrative, but high exposure under the wetter narrative, all time periods.** Under the drier narrative, the amount of rainfall

associated with the 100-year 24-hour storm is projected to decrease or stay about the same as under current conditions, indicating low exposure to these extreme events. However, under the wetter narrative, the amount of rainfall is projected to increase between 72% and 89% in the near-term, mid-century, and end-of-century. All assets as considered highly exposed to extreme precipitation events under the wetter narrative, regardless of time period.

- **Widespread exposure to sea level rise under all three narratives for highways, ports, and rail.** Under the lowest sea level rise narrative of 30 centimeters, 63% of all representative highway segments would be inundated. This represents 97% of coastal highway segments. The exposure statistics stay about the same under the higher narratives of 75 cm and 200 cm sea level rise. Under these narratives, 65% and 68% of segments would be inundated, representing 97% and 98% of coastal assets, respectively. Ports are similarly exposed under all scenarios. About half of the ports are exposed to 30 cm of sea level rise, increasing to 92% under the 200 cm narrative. The rail representative segments, which are concentrated around the Mobile River and ports, are also highly exposed, ranging from two thirds to three quarters of segments inundated under the sea level rise narratives. Airport and transit assets studied are not exposed to sea level rise of up to 200 cm.
- **High exposure to storm surge under all storm narratives.** Under the least extreme storm narrative (a replication of Hurricane Katrina on its historical path), over three quarters of all assets studied—59% of representative highway segments, 92% of critical ports, 75% of representative rail assets, and 50% of transit facilities— in Mobile would be inundated, under an average of about 12.6 feet of storm surge. Under the two higher storm surge narratives (direct hits from a storm like Katrina and a storm stronger than Katrina), 85 and 89% of all assets studied would be under storm surge depths of about 20 and 24 feet, respectively. Port and rail assets experience the greatest depth and furthest extent of storm surge, followed by highway assets.
- **Low exposure to wind under least extreme storm narrative, and moderate exposure under more extreme storms.** Under the lowest storm narrative, modeled wind speeds range from 72 to 84 mph. This would exceed the design thresholds for 19% of Mobile's highway assets and the bus and fleet service, but no other assets. Under the two more extreme storm narratives, peak winds range from 101 to 120 mph, which exceed the design or operations thresholds for 65% of highway assets, 100% of rail assets, and bus and fleet service.

## Potential Alternate Exposure Indicators

### Temperature

In different climates, other temperature indicators may be more relevant. For example, in colder climates the relevant temperature threshold (where service, operations, and labor are affected) may be lower than 95°F. Exposure could also be indicated by the longest number of consecutive days per year above a certain temperature if duration, as opposed to severity, of heat waves is more problematic in an area. In climates where ports are more sensitive to cold temperatures, the annual number of days below freezing (or another temperature threshold) could be used.

In cold climates, agencies may wish to assess the vulnerability of transportation facilities to changes in the freeze-thaw cycle and/or permafrost conditions. For example, in places where the biggest temperature-related cause of damage to infrastructure is changes to freeze-thaw regimes, the appropriate indicator may not be temperatures on either extreme, as discussed above, but how often the temperatures vary between above and below freezing.

Temperature can also influence the frequency and intensity of wildfires and dust storms, as well as the amount and types of vegetative cover, and number of pests. These secondary impacts can affect the generation of runoff from precipitation through changes in soil moisture and vegetative cover.

### Precipitation

Different types of infrastructure are designed to handle different aspects of heavy rain events. Peak flow, velocity, soil moisture, and discharge volume calculations inform the design of transportation and stormwater management design. For example, culverts are designed based on the peak discharge associated with a flooding event of a given return period. However, storm sewer inlets and storm sewers take volume and velocity into consideration. For wetland mitigation projects, seasonal precipitation may be an important design consideration. The correct choice of indicator(s) depends on the nature of the assets being analyzed. Potential options include an extreme heavy downpour like the 100-year 24-hour storm, as used in this project, or the number of consecutive days with precipitation, multi-day precipitation totals, total seasonal precipitation, hourly rainfall totals, or others. Existing flood zones could also serve as exposure indicators for precipitation-driven flooding if model results are not available.

Snow and ice may also be a consideration, as disruption due to heavy snows and use of chlorides for snow removal can degrade roads and cause water quality issues. While overall temperatures are increasing, there is the potential for more variability in snowstorm intensity, which can cause operations and maintenance issues as well as structural issues.

### Sea Level Rise

An alternate approach would be to calculate a sea level rise exposure score based on depth of inundation for each asset, as is done for the other stressors in this project. This could be accomplished either by a more detailed inundation mapping that provides inundation depths for each asset (more precise than the approach used) or by using elevation data as a proxy for sea level rise exposure (less precise than the approach used). Using either of these approaches, one could devise scoring bins for certain inundation depths or elevations to assign sea level rise exposure scores to assets.

If sea level rise modeling cannot be completed, other characteristics might indicate potential exposure to sea level rise. For instance, areas known to flood due to tidal events could be identified as areas likely to be exposed to sea level rise.

### Storm Surge

If resources are not available for detailed storm surge modeling, alternative data could serve as proxy indicators for storm surge exposure. For example, a combination of proximity to coastline and elevation could serve as a measure of relative storm surge exposure. Storm surge exposure could also be estimated using results from NOAA's Sea, Lake and Overland Surges from Hurricanes (SLOSH) model; the USGS' Coastal Vulnerability Index; FEMA coastal flood zone maps; and/or the presence or absence of physical buffers like barrier islands, dunes, shoreline vegetation, and wide beaches.

### Wind

If resources are not available for detailed storm modeling, alternative data could serve as proxy indicators for wind exposure. For example, instead of modeling specific storms, one could assess exposure to certain storm levels and use estimates of their wind speeds (for example, each category of tropical storms has a designated minimum wind speed). Further, one could use wind speeds alone, regardless of asset design thresholds, to assess relative exposure for assets. In areas not prone to tropical storms, lower wind speeds associated with the types of storm events common for the area could be used, in which case storm modeling may not be necessary.

## 4.2 Evaluating Sensitivity

While exposure captures the asset's location relative to a climate stressor, sensitivity captures the asset's response to, or how it is affected by, that exposure. A highly sensitive asset 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.

Sensitivity is a component of vulnerability that can be difficult to define and assess because it depends on site-specific factors, such as asset design and condition. In order to assess sensitivity, the project team developed a list of indicators from publicly available sources and interviews with stakeholders. The assessment scored and weighted these indicators to generate sensitivity scores for all assets under each of the five climate stressors considered. The sensitivity indicators chosen for each stressor are specific to the asset type and the stressor. In other words, each transportation mode uses a different set of sensitivity indicators for each climate stressor.

### 4.2.1 Highways Sensitivity Indicators

For the purpose of this assessment, the project team defined the highway assets as containing two types of sub-segments: bridges[22] and roads. Bridges and roads have very different engineering characteristics and available data sources; therefore, different indicators were used to evaluate the sensitivity and adaptive capacity of these two highway elements.

The indicators used for each climate stressors are discussed in the subsections that follow. Using these indicators, the analysis found the following:

- **Relatively low sensitivity to temperature**. According to ALDOT, the representative segments studied are constructed using an asphalt binder that is highly resistant to heat, which means that the projected temperatures are not likely to damage the pavement. Further, no segments have been damaged in the past due to heat events.
- **Relatively moderate sensitivity to precipitation**. The vast majority of assets were scored as moderately sensitive to precipitation, because high sensitivity according to some indicators (such as flood zone) is balanced out by low sensitivity according to others (such as age or previous flooding). A handful of assets show high sensitivity, all of which are bridges on the Causeway (R10) with low approach heights and that have been flooded in the past from heavy rain events.
- **Relatively low sensitivity to sea level rise for bridges and moderate sensitivity for roadways.** The majority of bridges in the study area do not cross water, so are not sensitive to sea level rise. Most coastal bridges and roadways are moderately sensitive, because features indicating high sensitivity (such as low approach height) balance with features indicating low sensitivity (such high deck height). The most sensitive assets are the ones that have proven to have historical flooding problems.

[22] Bridges also included very large culverts.

- **Relatively high sensitivity to storm surge.** Coastal bridges and roadways are sensitive as determined by their previous damage from storm surge and low approach and embankment heights (for bridges). Their sensitivity is tempered by good condition ratings, but average sensitivity to storm surge is higher than for all other stressors.
- **Relatively low sensitivity to wind.** Roadway signal density was the only wind sensitivity indicator. Most of the representative highway assets (both bridges and roads) had low signal density, indicating low sensitivity. One asset (US-90, Section East of Broad Street) had a high density, probably because it is located closer to Mobile's downtown, and thus is considered sensitive to wind damage.

### Temperature

Temperature can affect highways by causing pavement rutting or shoving, or structurally weakening other components of bridges or roads.[23] Therefore, the project team looked for characteristics of bridges and roads that would indicate they may be sensitive to pavement damage from temperature. The resulting sensitivity indicators considered characteristics such as truck traffic, pavement design, and the historical performance of the bridge or road. The assessment captured these elements of sensitivity by relying on two different, but overlapping sets of indicators for bridges and roads. Table 10 describes the data sources and rationale for each of these indicators.

[23] Increased temperatures could affect air quality, which could indirectly affect transportation planning if a community is subsequently deemed to be in non-attainment of National Ambient Air Quality Standards, a designation that would require a community to develop a plan to meet those standards. The Gulf Coast study focuses on the more direct impacts on transportation assets and services, and does not consider effect on air quality.

**Table 10: Indicators Used to Assess the Sensitivity of Highways to Temperature**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Pavement rutting, shoving, or other compromised integrity | Whether pavement has rutted (or shown other signs of damage) in the past due to high temperatures | Road segments that already experience rutting may experience worsening problems as the temperature increases. | **Yes/No Record of Previous Damage from Temperature**—Stakeholder interviews | Roads and bridges |
| | High volumes of truck traffic | Pavement experiences greater stress from heavy vehicle traffic. As temperatures increase, rutting may occur on segments of road with high volumes of truck traffic. | **External Truck Trip Productions** (for roads)—Mobile MPO Long Range Transportation Plan Model Documentation and Appendices, Table 11<br>**Average Daily Truck Traffic** (for bridges)—National Bridge Inventory Item 109 and Item 29 | Roads and bridges |
| | Pavement binder type relative to projected temperatures | Pavement binders are designed to withstand specific temperature thresholds. Asphalt may experience rutting if pavement temperatures exceed the high temperature thresholds. | **Pavement Binder Used**—Watson 2010; Powell and Reach 2012 | Roads and bridges |

Since sensitivity of roads and bridges to temperature is very low, this assessment did not identify segments that were significantly more or less sensitive than others. For the full scoring methodology, including information about how the indicator weightings changed in the absence of perfect data, see Appendix C.

### Alternate Temperature Sensitivity Indicators for Highways

Asphalt and concrete paving types have different sensitivities to temperature. For example, concrete expands and contracts as the temperature changes. Recent research has found that stone volume, aggregate type, and sand type present in the concrete mix significantly affect the thermal expansion properties of the concrete.[24] In jointed, plain concrete pavement, the traverse contraction joints allow for load transfer without damage to the pavement, as long as the joints are functioning properly. This analysis did not consider concrete paving, since nearly all of the paving in Mobile is asphalt. However, relevant indicators might include the thermal expansion coefficient of the concrete and condition of the joints. At a more simple level, indicators could also consider whether asphalt or concrete is used as the paving material.

The Performance Graded (PG) system has been developed to improve the performance of asphalt pavement given a set of environmental and reliability assumptions. Special PG recommendations are sometimes made for roadways with high truck or bus traffic, truck and bus stopping areas, and truck and bus stop and go areas. In addition, some states may recommend the use of polymer-modified binders in areas where extra performance and durability are needed. Therefore, alternate indicators of temperature sensitivity for asphalt paving include the presence of bus routes and use of polymer-modified binders. Shoving is also more common in areas where traffic must come to a quick stop, so whether an asset includes a factor that would make it more prone to shoving could be another pavement-related temperature sensitivity indicator.

## Precipitation

Precipitation events can cause temporary flooding, erosion and scour, and associated impacts on highways. Therefore, the project team looked for characteristics that would indicate an asset is more likely to flood during a rain event, and is more likely to experience damage due to flooding or increased run-off. The resulting sensitivity indicators considered characteristics such as historical performance, aspects of condition, and the flooding potential of each asset's specific site. The assessment captured these elements of sensitivity by relying on two different, but overlapping sets of indicators for bridges and roads. The main reason for this distinction is that the National Bridge Inventory (NBI) provided an important source of data for bridges, but not for roads. Table 11 describes the indicators used to assess the sensitivity of roads and bridges to precipitation.

24 Kim and Jeong, 2013

**Table 11: Indicators Used to Assess the Sensitivity of Highways to Precipitation**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Flooding | Whether an asset has flooded in the past due to heavy rain | Roads and bridges that have experienced damage during past heavy rain events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Flooding from Rainfall**—Stakeholder interviews | Roads and bridges |
| | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | Roads and bridges |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs | Roads and bridges |
| | Asset's elevation relative to surrounding areas | If an asset is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events. | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the road (elevation data from 3 ft. x 3 ft. LiDAR) | Roads |
| | Amount of impervious surface surrounding an asset | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation. | **Percent of Area Surrounding Asset with Above Average Impermeability**—USGS National Land Cover Database 2006 Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) | Roads |
| | Elevation of the approach to a bridge | Bridge approaches are often the most affected part of the bridge. Approaches that are closer to the water surface are more sensitive to flooding from sea level rise, storm surge, or heavy rain. | **Minimum Height of Bridge Approach above Water Surface**—Project team analysis of LiDAR data | Bridges |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| | Age of an asset | Older bridges may have been built to older design standards, deteriorated bridge deck drainage systems, clogged inlets, or experienced more extreme damaging scour events, rendering them more sensitive to precipitation events than bridges designed more recently. | **Year Built**—National Bridge Inventory, Item 27 | Bridges |
| | Whether a bridge is "scour critical" | Bridges that have already been identified as having problems with scour are more likely to be damaged during precipitation events. | **Scour Critical Bridges**—National Bridge Inventory, Item 113 | Bridges |
| Scour, washout, overtopping, or other structural damage | Conditions associated with water flow through a bridge | This item describes the physical conditions associated with the flow of water through the bridge such as stream stability and the condition of the channel, riprap, slope protection, or stream control devices including spur dikes. Bridges with erosion or bank failure will be more sensitive to flooding and high stream flows. | **Channel Condition Rating**—National Bridge Inventory, Item 61 | Bridges |
| | Condition of culverts | This item evaluates the alignment, settlement, joints, structural condition, scour, and other items associated with culverts. Bridges with deterioration in culvert conditions may be more sensitive to damage from flooding. | **Culvert Condition Rating**—National Bridge Inventory, Item 62 | Bridges |
| | Frequency that water overtops a bridge | This item appraises the waterway opening with respect to passage of flow through the bridge. Bridges that are subject to more frequent overtopping may be sensitive to damage from flooding impacts. | **Waterway Adequacy**—National Bridge Inventory, Item 71 | Bridges |

For the full scoring methodology, including information about how the weights changed in the absence of perfect data, please see Appendix C.

Among the bridges, five bridges on the Causeway emerged as most sensitive to precipitation. These five bridges have approaches that are roughly equal in elevation to the water surface, indicating that any increase in Mobile Bay due to precipitation would flood the Causeway. In addition, according to stakeholder interviews, parts of the Causeway already flood during heavy rain events. Among the roads, the half-mile segment on Bellingrath Road crossing the stream north of Plantation Woods Drive (R25) emerged as the road sub-segment most sensitive to precipitation. One important driver for this high sensitivity is that the road has a history of overtopping during heavy rain events. In addition, almost half of R25 is located in a non-coastal, 100-year flood zone and an additional 40% is located in the part of the 500-year flood zone that extends beyond the 100-year flood zone.

### Alternate Precipitation Sensitivity Indicators for Highways

Propensity to pond, impermeability, and location relative to flood zones are all indictors intended to help understand the local flood risk of specific roads and bridges. Further work is needed in order to better understand how well these simple analyses can capture complex watershed dynamics. For example, it may be preferable to examine impermeability at an upstream location to an asset instead of at the asset's location. Given these uncertainties, the project team chose to weight the historical performance of road segments higher than the other sensitivity indicators. The knowledge of maintenance and emergency management staff can help to pinpoint sensitive areas without a requiring a deep understanding of complex watershed dynamics.

During the research phase of this project, the project team attempted to find spatial data on the 10- and 25-year floodplains. While these data exist in the Flood Insurance Studies, spatial data on these floodplains were not readily accessible. However, these flood zones might provide more refined indicators of exposure to flooding because they capture the lower magnitude, higher frequency events.

The project team also researched the possibility of using HEC modeling to calculate the impact that the Wetter and Drier precipitation narratives would have on local flooding patterns. Unfortunately, HEC models were not available for Mobile in a format that could be used for this study. Other locations may have water models that could be more easily updated using projected precipitation information.

Information on drainage system capacity was not available in a useable format for this study, but this characteristic warrants further consideration in the future. Stakeholders noted that Mobile's drainage system is simply not sufficient for today's urbanized area. In some cases, simply increasing the size of a culvert or drain would not solve the problem, since the entire drainage system is interconnected, and local flooding is affected by the limits of the system as a whole. Further thought could be given to how to represent where systemic drainage issues are most likely to manifest. For example, proximity to the coast (to where the drainage flows) could be a potential indicator in some areas, under the assumption that the coastal areas would back up sooner than the inland areas.

## Sea Level Rise

Sea level rise can permanently or temporarily inundate roads, saturate and degrade roadbeds, cause wetland migration, and exacerbate precipitation-related flooding. The project team therefore looked for characteristics that suggest a road or bridge may be sensitive to these impacts of sea level rise. The resulting sensitivity indicators considered characteristics such as historical performance during high tide events, the height of bridge approach and deck above water, and the presence of shoreline protection. Table 12 describes the data sources and rationale for each of these indicators.

**Table 12: Indicators Used to Assess the Sensitivity of Highways to Sea Level Rise**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Flooding | Whether an asset has flooded in the past due to tidal events | Roads and bridges that have experienced flooding during extreme high tide events in the past are likely to be some of the first roads impacted by sea level rise. | **Yes/No Record of Previous Flooding from Tides**—Stakeholder interviews | Roads and bridges |
| | Whether an asset is protected from flooding | Roads protected by a dike, sea wall, or other structure are less likely to be affected by sea level rise. | **Yes/No Indication of Protection**—Stakeholder interviews | Roads |
| | Elevation of the approach to a bridge | Bridge approaches are often the most affected part of the bridge. Approaches that are at an elevation similar to the water surface are more sensitive to flooding from sea level rise, storm surge, or heavy rain. | **Minimum Height of Bridge Approach above Water Surface**—Project team analysis of LiDAR data | Bridges |
| Limitations on vessel size that can clear the bridge, or potential for bridge to be overtopped | Navigational clearance of a bridge | Bridges with less clearance above the waterway are more likely to be affected by sea level rise; operational changes be needed if certain sized vessels no longer have sufficient clearance as sea level rises. | **Navigation Vertical Clearance**—National Bridge Inventory, Item 39 | Bridges |
| | Bridge height | Bridges with less clearance above the waterway are more likely to be at risk of waters reaching and deteriorating the bridge deck during high tides or storms; further, operational changes may be needed if certain sized vessels no longer have sufficient clearance. | **Height of Bridge Embankment Relative to Water Surface**—Project team analysis of LiDAR data | Bridges |

The study generated a composite sensitivity score for each segment based on a weighted average of its indicator scores. For the full scoring methodology, including information about how the weights changed in the absence of perfect data, see Appendix C.

Overall, two bridges on the Causeway (R10) and one bridge on Dauphin Island Parkway (R22) emerged as most sensitive to sea level rise. The very low deck and approach heights of these bridges indicate that they may be impacted by sea level rise. In addition, the Causeway has a history of flooding during certain high tide events. The assessment scored the Causeway and Dauphin Island Parkway (from Island Road to Terrell Road—R14) as the road segments most sensitive to sea level rise. This result is based on historical performance and shoreline protection information provided by stakeholders. Both of these segments are known to flood during a strong southeast wind and high tide conditions.

### Alternate Sea Level Rise Sensitivity Indicators for Highways

Soil type is an important indicator of sensitivity to sea level rise that was not included in this analysis. The susceptibility of soils to erosion, as well as their drainage characteristics and porosity can impact the sensitivity of shoreline infrastructure to sea level rise. It is important to note that physical protection structures like levees or sea walls may not protect against encroaching waters in all instances. In areas where soil is particularly porous, water can actually seep up from the ground. Therefore, soil type may be an important indicator in some areas.

Furthermore, if inundation occurs in adjacent geographical areas, then a "protected" structure may still be inundated as waters come in from other directions. A sensitivity indicator may therefore try to capture whether an asset is adjacent to other areas expected to be exposed to sea level rise. Similarly, an indicator may consider whether the protective riprap surrounding bridge approaches may be inundated. This analysis considered the elevation of bridge approach, but some analyses may prefer to consider the elevation of bridge approach slope protection. This is because if the protection is inundated long-term, the bridge would be more sensitive to flooding, even if the approach itself is not inundated by sea level rise.

Pavement substructure could be used as an additional indicator of sensitivity to sea level rise. Certain pavements may have more resistant subgrades than others and may be less sensitive to saltwater intrusion associated with sea level rise than other subgrades. However, if saturation conditions reach intolerable levels, then all pavements may be equally sensitive.

## Storm Surge

Storm surge can temporarily inundate roads and bridges, making them temporarily impassable and damaging their structure. Storm surge can also contribute to erosion and scour. The project team therefore developed sensitivity indicators that considered characteristics such as historical performance during storm events, elements of bridge height and design, condition, and the presence of shoreline protection. Table 13 describes the data sources and rationale for each of these indicators.

**Table 13: Indicators Used to Assess the Sensitivity of Highways to Storm Surge**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Structural damage to roads and bridges from storm surge | Whether an asset has been damaged in the past due to storm surge | Roads and bridges that have experienced damage during past storm events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews | Roads and Bridges |
| | Whether an asset is protected from storm surge | Roads protected by a dike, sea wall, vegetation, or other structure are less likely to be affected by storm surge. | **Yes/No Indication of Protection**—Stakeholder interviews | Roads |
| | Bridge height | Bridges with less clearance above the waterway are more likely to experience storm surge heights that reach their deck.* | **Bridge Embankment Elevation Relative to Current Water Surface**—Project team analysis of LiDAR data, | Bridges |
| | Distance between water and bridge deck | Bridges with less clearance above the waterway are more likely to experience storm surge heights that reach their deck. | **Navigation Vertical Clearance**—National Bridge Inventory, Item 39 | Bridges |
| | Whether a bridge is "scour critical" | Bridges that have already been identified as having problems with scour are more likely to be damaged during storm surge events. | **Scour Critical Bridges**—National Bridge Inventory, Item 113 | Bridges |
| | Condition of bridge substructure | Bridges that are in poor condition are more likely to be damaged during storm surge events. | **Substructure Condition Rating**—National Bridge Inventory, Item 60 | Bridges |
| | Condition of bridge superstructure | Bridges that are in poor condition are more likely to be damaged during storm surge events. | **Superstructure Condition Rating**—National Bridge Inventory, Item 59 | Bridges |
| | Condition of bridge deck | Bridges that are in poor condition are more likely to be damaged during storm surge events. | **Deck Condition Rating**—National Bridge Inventory, Item 58 | Bridges |
| | Whether bridge is movable | Movable bridges can be more susceptible to damage during storm surge events because they have electrical components. | **Structure Type**—National Bridge Inventory, Item 43b | Bridges |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| | Age of an asset | Older bridges may have been built to older design standards, have deteriorated structures, or have experienced more extreme damaging storm surge events, rendering them more sensitive to storm surge events than bridges designed more recently. In addition, changes in sea level and the accumulation of more historical extreme storm events could greatly change the value of the water surface level (e.g., the Q100 water surface level) that an older bridge was originally designed for. | **Year Built**—National Bridge Inventory, Item 27 | Bridges |
| Flooding | Elevation of the approach to a bridge | Bridge approaches are often the most affected part of the bridge. Approaches that are not much higher than the water surface are more sensitive to flooding from sea level rise, storm surge, or heavy rain. In addition, the velocity vectors associated with contraction and expansion of flow through the bridge opening are higher near the approach than in the middle of the bridge opening. | **Minimum Height of Bridge Approach above Water Surface**—Project team analysis of LiDAR data | Bridges |

*There may not always be a direct, inverse relationship between bridge height and sensitivity to storm surge. Very low bridges may be completely inundated from storm surge and experience less wave action on the underside of decks than higher bridges. This can be incorporated in how bridge heights are scored—if storm surge and wave heights for each bridge are known, scoring can be adjusted so that the bridges that meet the wave heights are scored as more sensitive than bridges that may be completely inundated and thus subject to less stress from waves.

For the full scoring methodology, including information about how the weights changed in the absence of perfect data, see Appendix C.

All of the bridges on the Causeway emerge as having higher sensitivity scores than the rest of the bridge sub-segments. These high sensitivity scores result from low approach and embankment heights as well as historical performance. The I-10 tunnel (R1), Telegraph Road from downtown to Bay Bridge Road (R6), the Causeway (R10), and Dauphin Island Parkway from Island Road to Terrell Road (R14) are the road segments that emerge as highly sensitive to storm surge. Since road sensitivity was calculated based on only two indicators, these scores are driven largely by historical performance.

The sensitivity of road segments was based solely on historical performance and shoreline protection, both of which were gleaned from interviews with ALDOT, Mobile County, and the City of Mobile. For example, stakeholders indicated that the segment of Old Spanish Trail between the Cochrane Bridge and the tunnels (R32) floods during storms, despite the protection of a nearby dam.[25] The Dauphin Island Bridge (R26) also repeatedly closes during storm events.

### Alternate Storm Surge Sensitivity Indicators for Highways

Analyzing emergency response records from Federal Emergency Management Agency (FEMA)'s public assistance program might be an additional method for identifying assets that have been repeatedly damaged in the past. This data source might provide another approach, to complement stakeholder input, of obtaining comprehensive information regarding existing vulnerabilities.

Other indicators of bridge sensitivity to storm surge include the weight of the bridge deck, whether the bridge deck is supported or an integral part of the bridge structure, and whether the bridge has longitudinal girders underneath the deck (which could act as air-trapping pockets, increasing wave action against the deck and increasing the likelihood of damage from storm surge).

Land elevation on which the asset sits, or height of the actual asset, could be used even if the storm surge depths are not known. That is, the higher the asset is, the less likely it would be inundated. This indicator might provide a reasonable (if imperfect) indicator if more detailed comparisons cannot be made to the surge depths.

Finally, the most sophisticated way to estimate bridge sensitivity to storm surge would be to use two-dimensional computer models of storm surge and wave action to identify the bridges most subject to damaging wave action. This is influenced by factors such as the topography/bathymetry coast and the reflection and amplification of waves interacting with the coast. Without such modeling, the indicators used in this study and listed in this text box attempt to determine which bridges will be most sensitive to damage from storm surge.

## Wind

Wind can affect highways by damaging the signals and signs that are important for use of the highways and by causing debris (from tree limbs to downed power lines to other sources of debris) to create roadblocks or driving hazards. It is very difficult to predict where wind damage will occur, particularly where debris might occur since debris can come from many different sources. However, highway stakeholders concurred that damage to roadway signs from wind is common during storms. Therefore, the project team looked for characteristics that would indicate that particular segments would be more likely to experience damage to signals and signs. In this case, only one sensitivity indicator was identified: the density of roadway signals on the road segment. Table 14 describes the data sources and rationale for this indicator.

[25] ALDOT, 2012

**Table 14: Indicators Used to Assess the Sensitivity of Highways to Wind**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Debris on roadways and damage to roadway signals and signs | Density of roadway signals | Wind damage to roadway signals and signs can delay traffic significantly and disrupt evacuation and recovery; roads and bridges with a higher density of road way signs and signal lights may be more prone to this type of damage. | **Traffic Signals Per Mile of Roadway**—City of Mobile GIS data | Roads and bridges |

Most of the representative highway assets (both bridges and roads) had low signal density. However, the US-90 segment east of Broad Street (R9) had a high density, probably because it is located closer to Mobile's downtown.

**Alternate Wind Sensitivity Indicators for Highways**

Due to a lack of data, this study relied on the density of traffic signals to estimate the sensitivity of roads to wind. However, since debris is often the major cause of wind-related damage, it would be appropriate to consider the proximity of trees to power lines and the efficacy of tree trimming maintenance as alternate indicators. However, debris can come from non-vegetative sources too, such as buildings, so building density is another potential indicator for wind debris, as would be presence of overhead utility lines, for example. Some communities may know that they generally experience wind-related debris from specific sources, which may provide insights into appropriate wind indicators.

Wind design thresholds, used in this analysis to evaluate exposure, could be used instead as a sensitivity indicator. In addition, future projects may consider sign support strength, height and size of the signs, and length of support arms as indicators. Finally, the percentage of fixed vs. cabled signals and the ratio of underground power and utilities to overhead utilities might also serve as useful alternate indicators. All of these indicators get at the quantity of different materials that have debris-causing potential for roads.

### 4.2.2 Ports Sensitivity Indicators

The project team identified several indicators to determine how Mobile's ports' infrastructure and operations might be sensitive to disruptions from high temperatures, heavy precipitation, sea level rise, storm surge, and high winds.

The indicators used for each climate stressors are discussed in the subsections that follow. Using these indicators, the analysis found the following:

- **Relatively low sensitivity to temperature**. The majority of port facilities were scored as having a low or moderate sensitivity to temperature. Port facilities and operations have not historically experienced any problems during heat events. In addition, only a few of the freight materials traveling through Mobile require refrigeration and/or are sensitive to heat exposure. Sensitive assets included those with a high reliance on electrical power and/or a large asphalt loading area, which could experience rutting during extremely hot days.

- **Varied sensitivity to precipitation**. Sensitivity of port facilities to precipitation varied from low to high. The few highly sensitive assets are located entirely in the 100-year flood zone and have experienced flooding during heavy rain in the past. Assets with low sensitivity are located outside of the 100-year flood zone and have no history of flooding.
- **Relatively low sensitivity to sea level rise.** Most critical port facilities have shoreline protection, which may limit vulnerability to sea level rise. In addition, very few facilities have experienced coastal flooding historically.
- **Varied sensitivity to storm surge.** Sensitivity of port facilities to storm surge ranged from low to high, depending on the characteristics of the asset. Highly sensitive facilities are generally older, with a high reliance on electricity, and operations that are easily disrupted by storm surge. Facilities lacking shoreline protection and/or in poor condition are also highly sensitive.
- **Varied sensitivity to wind.** Sensitivity of port facilities to wind varied from low to high. Highly sensitive assets are those handling floating equipment, passengers, or other materials that are susceptible to wind damage. Older facilities with a high reliance on electricity and a history of wind damage are also considered more sensitive.

### Temperature

Temperature can affect ports by damaging paved areas and/or disrupting operations by increasingly the likelihood of power outages and labor slowdowns due to safety measures. In order to capture these potential causes of damage, this analysis considered characteristics such as materials handled, reliance on electrical power, size of paved asphalt areas, and the historical performance of the port. Table 15 describes the data sources and rationale for each of these indicators.

**Table 15: Indicators Used to Assess the Sensitivity of Ports to Temperature**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Pavement rutting, shoving, or other compromised integrity | Whether pavement has rutted (or shown other signs of damage) in the past due to high temperatures | Ports that have experienced damage during past heat events are more likely to be damaged if exposed in the future. | **Yes/No record of Previous Damage from Temperature**—Stakeholder interviews |
| | Size of paved areas | Pavement can buckle or sink in high temperatures. The extent of paved asphalt areas is therefore an indicator of sensitivity to heat. | **Size of Paved Asphalt Areas—**Visual inspection of satellite imagery |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Heat damage to perishable freight | Materials handled | If materials stored or handled at the facility are perishable or otherwise possibly damaged by high temperatures, they will be more sensitive to temperature changes. | **Materials Handled**—Alabama State Port Authority (2013), stakeholder interviews |
| Disruption to operations | Reliance on electrical power | Ports and port facilities that are highly reliant on electrical power to operate will be more sensitive to electricity losses due to widespread power outages, including those caused by stress on the grid from high temperatures (e.g. brownouts). | **Reliance on Electrical Power**—Stakeholder interviews and survey responses |

While the sensitivity of ports to climate impacts varied according to the stressor, the Alabama State Docks Facility, Atlantic Marine, and Standard Concrete Products were sensitive across multiple stressors due to age, condition, and reliance on electrical power. The McDuffie coal terminal exhibited high sensitivity for storm surge and wind, partially because it handles coal that is exposed to the elements. For the full scoring methodology, including information about how the indicator weightings changed in the absence of perfect data, see Appendix C.

### Alternate Temperature Sensitivity Indicators for Ports

While sensitivity of port infrastructure to heat is low, there are likely to be operations and safety impacts at a certain threshold when labor restrictions are put into place. For example, safety regulations might require personnel to take more frequent breaks or work different shifts. Our analysis does not address these labor slowdown impacts, since Mobile ports are used to implementing these safety measures and it was not clear the extent to which additional days requiring more breaks or schedule shifts would slow down productivity. However, in locations where heat impacts on worker schedules are currently not the norm, sensitivity indicators could address the reliance of port operations on outside labor. Another sensitivity indicator might include consideration of the threshold for safety regulations as compared to the projected changes in temperature.

## Precipitation

Heavy rainfall can flood port facilities, particularly in low-lying areas where drainage is poor (a condition that sea level rise will likely exacerbate). Therefore, the project team identified characteristics that would indicate how likely an asset is to flood during a rain event and/or experience damage due to flooding or increased run-off. The resulting sensitivity indicators considered characteristics such as historical performance, age of structures, and the flooding and ponding potential of each asset's specific site. Table 16 describes the indicators used to assess the sensitivity of ports to precipitation.

**Table 16: Indicators Used to Assess the Sensitivity of Ports to Precipitation**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Flooding on port property | Whether an asset has flooded in the past due to heavy rain | Ports that have experienced damage during past heavy rain events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Flooding from Rainfall**—stakeholder interviews |
| | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs |
| | Susceptibility of an asset to ponding | If an asset is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events. | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the road (elevation data from 3 ft. x 3 ft. LiDAR) |
| | Amount of impervious surface at asset | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation. | **Percent of Asset with Above Average Impermeability—** USGS National Land Cover Database (NLCD) 2006 Impervious Surfaces |
| Damage of structures or cargo due to flooding | Materials handled | If materials stored or handled at the facility are perishable or otherwise damaged by water, they will be more sensitive to flooding. | **Materials Handled**—ASPA (2013) and stakeholder interviews |
| | Age of wharves, structures | Older wharves and structures may have been built to lower standards and/or be in poorer condition compared to newer structures, and therefore more susceptible to damage. | **Year in which Facility was Built—**ASPA (2013), stakeholder surveys and interviews |

For the full scoring methodology, including information about how the weights changed in the absence of perfect data, see Appendix C.

The Atlantic Marine facility, Oil Recovery Co., Shell Chemical Co., and U.S. Coast Guard Pier are the four ports most sensitivity to precipitation. These ports are located entirely in the 100-year flood zone and handle materials that could be damaged during flooding. For example, the Atlantic Marine port is one of the oldest port facilities in Mobile and has experienced flooding in the past.

### Alternate Precipitation Sensitivity Indicators for Ports

Propensity to pond, impermeability, and location relative to flood zones are all indictors intended to help understand the local flood risk of specific ports. Further work is needed in order to better understand how well these simple analyses can capture complex watershed dynamics. Other indicators or modeling efforts may be able to capture these complex dynamics more fully.

For example, during the research phase of this project, the project team attempted to find spatial data on the 10- and 25-year floodplains. While these data exist in the Flood Insurance Studies, spatial data on these floodplains were not readily accessible. However, these flood zones might provide more refined indicators of exposure to flooding because they capture the lower magnitude, higher frequency events.

The project team also researched the possibility of using HEC modeling to calculate the impact that the Wetter and Drier precipitation narratives would have on local flooding patterns. Unfortunately, HEC models were not available for Mobile in a format that could be used for this study. Other locations may have water models that could be more easily updated using projected precipitation information.

Drainage systems play a major role in whether an area floods during a precipitation event. Alternate indicators could evaluate whether the current drainage system is considered sufficient, or whether key infrastructure at a port are located in the areas most likely to flood if the system backs up.

Dredging needs typically increase during periods of heavy rain, since the rain causes erosion and runoff that can build up in the waterways. An alternate sensitivity indicator could evaluate how prone a port’s waterway is to sediment build-up.

Finally, in colder climates, winter precipitation could cause damage from freezing. Indicators could evaluate the use of materials or equipment that may be particularly sensitive to freezing conditions.

## Sea Level Rise

Sea level rise can permanently or temporarily inundate ports and exacerbate precipitation-related flooding. The project team therefore looked for characteristics that suggest a port may be sensitive to these impacts of sea level rise. The resulting sensitivity indicators considered characteristics such as historical performance during high tide events, age of the asset, and the presence of shoreline protection. Table 17 describes the data sources and rationale for each of these indicators.

**Table 17: Indicators Used to Assess the Sensitivity of Ports to Sea Level Rise**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Temporary inundation from high tides or permanent inundation | Whether an asset has flooded in the past due to tidal events | Ports that have experienced previous issues with tidal variation are more likely to be sensitive to sea level rise. | **Yes/No Record of Previous Flooding from Tides**—stakeholder interviews |
| Damage to structures from higher water levels | Shoreline protection | Ports with shoreline protection such as bulkheads or riprap are less sensitive to sea level rise than those without. | **Yes/No Indication of Protection** –visual inspection of satellite imagery |
| | Age of facility | Older wharves and structures may have been built to lower standards and/or be in poorer condition compared to newer structures, and therefore more susceptible to damage. | **Year in which Wharf or Structure was Built—** ASPA (2013), Stakeholder surveys and interviews |

For the full scoring methodology, including information about how the weights changed in the absence of perfect data, see Appendix C.

Overall, Standard Concrete Products and Alabama State Docks Main Complex emerged as highly sensitive to sea level rise. These older facilities had little shoreline protection, which resulted in a high sensitivity score. The remainder of the critical ports had low to moderate sensitivity. Based on stakeholder interviews, Mobile's ports have not experienced flooding during high tide events. In addition, many ports are elevated and protected by from sea level rise by sea walls, berms, and riprap.

### Alternate Sea Level Rise Sensitivity Indicators for Ports

Height of docks and other key port infrastructure, relative to the current sea level, could be evaluated. If all of the key infrastructure is currently significantly above high tides, then a certain amount of sea level could occur without causing problems for the ports.

Similarly, the height of drainage outlets above the sea level could be evaluated. Even if sea level rise is not sufficient to inundate a port, if it blocks a drainage outlet, then the port may flood during precipitation events.

Finally, whether docks are floating or are fixed, and the type of operations occurring at the port, could be indicators. At least one interviewed port in Mobile noted that their docks are floating and therefore would not be affected by sea level rise; furthermore, deeper waters would actually make it easier for them to access and work on larger vessels.

## Storm Surge

Storm surge can temporarily inundate ports, disrupting operations and damaging their structure. The project team therefore developed sensitivity indicators that considered characteristics such as historical performance during storm events, elements of port condition, height of infrastructure above sea level, and the presence of shoreline protection. Table 18 describes the data sources and rationale for each of these indicators.

**Table 18: Indicators Used to Assess the Sensitivity of Ports to Storm Surge**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Structural damage to ports from storm surge | Whether an asset has been damaged in the past due to storm surge | Ports that have experienced damage during past storm events are more likely to be damaged if exposed in the future. Note that mitigating actions taken since previous storms may not be fully accounted for under this indicator. | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews |
| | Shoreline protection | Ports with protection features such as bulkheads or riprap are less likely to be affected by storm surge. | **Yes/No Indication of Protection**—visual inspection of satellite imagery, stakeholder interviews |
| | Height of key infrastructure above sea level | Ports with docks and other infrastructure closer to sea level are more likely to experience damage from storm surges. | **Height of Key Infrastructure Relative to Current Water Surface—** stakeholder survey responses and interviews |
| | Age of wharves and structures | Older wharves and structures may have been built to lower standards and/or be in poorer condition compared to newer structures, and therefore more susceptible to damage. | **Year in which Facility was Built—**SPA (2013), Stakeholder survey responses |
| | Condition of facility | Current condition (ranging from Good to Poor) can be an indicator of how likely an asset is to be damaged by future impacts. | **Condition Rating**—Stakeholder interviews and surveys, Maritime Strategic Development Study Phase III: Inventory of Existing Port Maritime Facilities |
| Disruption of port operations due to power outages | Reliance on electrical power | Ports and port facilities that rely on electrical power to operate will be more sensitive to electricity losses due to widespread weather-related outages or submersion of electrical equipment. | **Reliance on Electricity—** stakeholder interviews and surveys |
| Likelihood of damage due to exposure to storm surge | Materials handled | If materials handled or stored at the facility are damaged by water or are perishable, they will experience greater negative effects from storm surges. | **Materials Handled**—ASPA (2013), stakeholder interviews |

For the full scoring methodology, including information about how the weights changed in the absence of perfect data, see Appendix C.

Alabama State Docks Complex, McDuffie Terminal, and Atlantic Marine are the three port facilities most sensitive to storm surge. All three of these facilities are older, highly reliant on electricity, and have been damaged in past storm events.

### Alternate Storm Surge Sensitivity Indicators for Ports

Indicators could also consider the types of key infrastructure upon which port operations rely. Some ports interviewed indicated that most of their low-lying infrastructure consisted of parking lots or metal buildings; storm surge would bring in debris and dirt that would need to be cleaned up, but the infrastructures are unlikely to be significantly damaged. Other ports had infrastructure or equipment that would be more likely to be damaged to storm surge. Similarly, indicators could also consider the extent to which key equipment is kept in low-lying areas of the ports, or whether it is more elevated.

## Wind

Wind can affect ports through structural damage or power outages that disrupt operations. The indicators considered characteristics that would make ports more likely to experience negative effects from high winds, such as historical performance, age of the facility, and reliance on electrical power. Table 19 describes the data sources and rationale for these indicators.

**Table 19: Indicators Used to Assess the Sensitivity of Ports to Wind**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Structural damage to ports from high winds | Whether or not an asset has experience damage during past high winds | Ports that have experienced damage during past high winds are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Wind—**stakeholder interviews |
| | Age of wharves and structures | Older wharves and structures may have been built to lower standards and/or be in poorer condition compared to newer structures, and therefore more susceptible to damage. | **Year in which Facility was Built**—ASPA (2013), Stakeholder survey responses |
| Damage of cargo due to high winds | Materials handled | If materials handled or stored at the facility are easily damaged by high winds, they will experience greater negative effects from storm-force winds. | **Materials Handled**—ASPA (2013), stakeholder interviews) |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Disruption of port operations due to power outages from downed power lines | Reliance on electrical power | Ports and port facilities that rely on electrical power to operate will be more sensitive to electricity losses due to widespread weather-related outages including those caused by stress on the grid from high winds. | **Reliance on Electricity—**stakeholder interviews and surveys |

Age and materials handled were two influential indicators of sensitivity to wind. Since the availability of data on these sensitivity indicators was inconsistent, but all ports had data on materials handled, the materials handled indicator was particularly influential for certain ports. For example, the analysis found that the most sensitive port was U.S. Coast Guard Pier. This facility had low data availability and the assessment was based solely on the fact that the Pier handles floating materials, which are particularly sensitive to wind damage. In addition to the Pier, the three most sensitive ports were Atlantic Marine, ASPA's McDuffie Terminal, and Shell Chemical Co. These ports handle materials that are sensitive to wind and have a high reliance on electricity. In addition to these two factors, Atlantic Marine is an older facility that has experienced damage due to wind in the past. For the full scoring methodology, including information about how the weights changed in the absence of perfect data, see Appendix C.

**Alternate Wind Sensitivity Indicators for Ports**

Wind design thresholds, used in this analysis to evaluate exposure, could be used instead as a sensitivity indicator.

Since debris is often the major cause of wind-related damage, it would also be appropriate to consider the extent to which boats, docks, cranes, and other equipment at the port are sufficiently secured during high wind events. Similarly, attempts could be made to identify nearby objects that could potentially cause debris hazards. For example, if there is a lot of at-risk infrastructure nearby, there may be of a chance that some of that infrastructure could come lose and create debris hazards.

### 4.2.3 Airports Sensitivity Indicators

The project team identified several indicators to determine how Mobile's two critical airports' infrastructure and operations might be sensitive to disruptions from high temperatures, heavy precipitation, sea level rise, storm surge, and high winds.

The indicators used for each climate stressors are discussed in the subsections that follow. Using these indicators, the analysis found the following:

- **Relatively high sensitivity to temperature**. The two critical airports have demonstrated issues in the past due to high temperatures, particularly when runways experience pavement damage.
- **Relatively low sensitivity to precipitation**. Though both airports studied have old drainage systems, features at the airports such as lighting and instrumentation systems are configured to allow operations to continue despite rainfall.
- **Relatively low sensitivity to sea level rise.** Both airports have not experienced tidal issues in the past, and they have drainage systems that drain at relatively high elevations, indicating low sensitivity to drainage problems from sea level rise.
- **Relatively moderate sensitivity to storm surge.** Mobile's airports' past experience with storms has demonstrated a low sensitivity to storm surge, despite limitations to drainage systems. Operations would shut down during the surge, and the infrastructure overall is not particularly sensitive.
- **Relatively high sensitivity to wind.** High winds can affect airport infrastructure as well as operations. Taller buildings (such as air traffic control towers) and those with flat roofs may be more likely to be damaged by high winds associated with hurricanes.

### Temperature

Temperature can affect airports assets by causing pavement damage on runways, and changing air density and the runway lengths required for planes to take off. Therefore, the project team looked for characteristics of airport runways that would indicate they may be sensitive to either pavement damage from temperature or flight restrictions due to runway length. The resulting sensitivity indicators considered characteristics such as runway surface type, runway condition, historical performance of runways, and runway length. Table 20 describes the data sources and rationale for each of these indicators.

**Table 20: Indicators Used to Assess the Sensitivity of Airports to Temperature**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Pavement rutting, shoving, or other compromised integrity | Whether runways have experienced damage in the past associated with high temperatures (e.g., expansion/contraction, discoloration) | Runways that already experience damage from temperature may experience worsening problems as the temperature increases. | **Yes/No Record of Previous Damage from Temperature**—Stakeholder interviews, Mobile Airport Authority |
| | Runway surface type | Runway surface material can impact how sensitive the runways are to heat-related issues such as expansion/contraction, discoloration, degradation, etc. According to Mobile stakeholders, asphalt is overall more susceptible to heat-related problems than concrete, as long as there is adequate space for expansion/contraction (Hughes 2012). | **Runway Surface Type**—Stakeholder interviews, Mobile Airport Authority |
| | Runway condition | Assets in already poor condition may be more sensitive to weather-related damage. | **Runway Condition Rating**—FAA Airport Master Record Forms 5010-1 & 5010-2 |
| Flight restrictions due to insufficient runway length | Runway length | As temperatures increase, air density decreases, meaning aircraft need longer runways or reduced payloads or engines with sufficient power in order to take off. Runways exceeding current take-off requirement lengths are less likely to become unusable in high temperatures. | **Runway Length** —FAA Airport Master Record Forms 5010-1 & 5010-2 |

Mobile Regional Airport is slightly more sensitive to temperature than Mobile Downtown, because the Regional Airport's runways are partly concrete, which is less sensitive to temperature than asphalt. For the full scoring methodology, including information about how the indicators were weighted and how those weights changed in the absence of perfect data, see Appendix C.

### Alternate Temperature Sensitivity Indicators for Airports

Asphalt and concrete paving types have different sensitivities to temperature and so this analysis used the simple indicator of whether the runway surface was asphalt or concrete. More refined indicators could reflect that concrete expands and contracts as the temperature changes. Recent research has found that stone volume, aggregate type, and sand type present in the concrete mix significantly affect the thermal expansion properties of the concrete.[26] For areas with common concrete runways, relevant indicators might include the thermal expansion coefficient of the concrete and condition of the joints. Alternate indicators of temperature sensitivity for asphalt paving include the pavement binder used and whether polymer-modified binder was used. Airports are beginning to experiment with lower embodied-energy warm-mix asphalts that may also have differing operational thermal performance than conventional mixes. Warm-mix asphalt may have different heat susceptibility than the existing airport pavement materials.

In addition, elevation influences the relationship between temperature and air density. Therefore, airport elevation could be considered another indicator in determining whether runway lengths would be sufficient under future temperature conditions.

## Precipitation

Precipitation events can cause temporary flooding and disrupt airport operations, causing flight delays. Therefore, the project team looked for characteristics that would indicate an airport is more likely to flood during a rain event, and is more likely to experience delays due precipitation. The resulting sensitivity indicators considered characteristics such as historical performance, qualities of the drainage system, and presence of features (such as runway lights and navigational aids) that functionally enable operations when it rains. Table 21 describes the indicators used to assess the sensitivity of airports to precipitation.

[26] Kim and Jeong, 2013

**Table 21: Indicators Used to Assess the Sensitivity of Airports to Precipitation**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Flooding | Whether the drainage system is already experiencing "blowouts" | Blowouts indicate that joints are failing and/or pipes are collapsing. A higher number of blowouts would therefore indicate a higher sensitivity to future precipitation levels. Blowouts occur when a leak, failure, or collapse in the drainage pipe begins to suck in sediment and creates a depression in the field. | **Number of Areas with Evidence of Blowouts**—Stakeholder interviews, Mobile Airport Authority |
| | Age of drainage system | In older drainage systems, joints will degrade over time. The older the drainage system, the more likely it is to fail during a heavy rain event. | **Year Drainage System Built—**Stakeholder interviews, Mobile Airport Authority |
| | Drainage system pipe material | Stakeholders in Mobile indicated that they have experienced more drainage problems with pipes that are made of certain materials. For example, Mobile stakeholders noted more problems with metal corrugated pipes relative to newer plastic or concrete pipes. This difference in performance may be related to age, condition, or maintenance more so than the actual materials used; however, in Mobile at least, identifying material type appears to be a good proxy for identifying drainage areas that may experience problems. | **Drainage System Pipe Material—**Stakeholder interviews, Mobile Airport Authority |
| | Whether the airport is located in the FEMA 100-year flood zone | If an airport is located within the 100-year floodplain, it is more likely to be susceptible to flooding caused by precipitation. | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) |
| | Whether the airport is located in the FEMA 500-year flood zone | If an airport is located within the 500-year floodplain, it is more likely to be susceptible to flooding caused by precipitation. | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| | Airport's elevation relative to surrounding areas | If an airport is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events. | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the road (elevation data from 3 ft. x 3 ft. LiDAR) |
| | Amount of impervious surface at the airport | Airports with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation. | **Percent of Airport with Above Average Impermeability**—USGS National Land Cover Database 2006 Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) |
| Damage to runways from flooding | Runway condition | Assets in already poor condition may be more sensitive to weather-related damage. | **Runway Condition Rating**—FAA Airport Master Record Forms 5010-1 & 5010-2 |
| | Soil type | Some soil types may be more susceptible to movement or sliding (e.g., mud or fill is more susceptible to movement than sand"). Therefore, infrastructure built on these more susceptible soil types are more likely to be damaged during rain events. | **Soil Type**—Stakeholder interviews, Mobile Airport Authority |
| Inability to operate flights during rain events | Whether approach lights can function under water | LED lights can operate while underwater, but older incandescent lights cannot and would be more sensitive to precipitation changes.<br>Note: LEDs have not been approved for runways by FAA, but can be used on taxiways. | **Lighting Used**—Stakeholder interviews, Mobile Airport Authority |
| | Type of instrumentation landing system | Some types of instrument landing systems allow for landings in low visibility and poor weather conditions, which reduces the sensitivity of airport operations to bad weather. | **Instrumentation**—FAA Airport Master Record Forms 5010-1 & 5010-2 |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| | Whether runway surface is treated | Runways with groove treatments are better able to handle surface water and precipitation than runways without a surface treatment. | **Runway Surface Treatment**—FAA Airport Master Record Forms 5010-1 & 5010-2 |
| | Airport traffic levels | This indicator relates to the operational sensitivity of airports. Airports with higher levels of traffic would experience greater operational impacts (more passengers affected and cause larger "network" effects) if precipitation changes cause increases in weather-related delays. | **Total Operations**—FAA Airport Master Record Forms 5010-1 & 5010-2 |

For the full scoring methodology, see Appendix C.

Mobile Downtown Airport emerged as slightly more sensitive to precipitation than Mobile Regional Airport, primarily because it is already experiencing blowouts of its drainage system. In addition, portions of the downtown airport are located in the 100 and 500-year flood zones, while the Regional airport is not located in a flood zone.

### Alternate Precipitation Sensitivity Indicators for Airports

Propensity to pond, impermeability, and location relative to flood zones are all indictors intended to help understand the local flood risk at airports. Further work is needed in order to better understand how well these simple analyses can capture complex watershed dynamics.

Additional information on airport drainage systems could serve as indicators of precipitation sensitivity. For example, how much elevation head exists from the runways to the drainage system outfall point could provide information on how likely the drainage system is to back up during heavy precipitation events.

During the research phase of this project, the project team attempted to find spatial data on the 10- and 25-year floodplains. While these data exist in the Flood Insurance Studies, spatial data on these floodplains were not readily accessible. However, these lower threshold flood zones might provide more refined indicators of exposure to flooding because they capture the lower magnitude, higher frequency events.

The project team also researched the possibility of using HEC modeling to calculate the impact that the Wetter and Drier precipitation narratives would have on local flooding patterns. Unfortunately, HEC models were not available for Mobile in a format that could be used for this study. Other locations may have water models that could be more easily updated using projected precipitation information.

## Sea Level Rise

Sea level rise can permanently or temporarily inundate airports and exacerbate precipitation-related flooding. The project team therefore looked for characteristics that suggest an airport may be sensitive to these impacts of sea level rise. The resulting sensitivity indicators considered characteristics such as historical performance during high tide events, the height of drainage system discharge points, and the quality of the airports' drainage systems. Table 22 describes the data sources and rationale for each of these indicators.

**Table 22: Indicators Used to Assess the Sensitivity of Airports to Sea Level Rise**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Flooding | Whether an asset has flooded in the past due to tidal events | Airports that have experienced flooding during extreme high tide events in the past are likely to be some of the first roads impacted by sea level rise | **Yes/No Record of Previous Flooding from Tides**—Stakeholder interviews, Mobile Airport Authority |
| | Height of drainage system discharge point above sea level | If drainage system discharge point is below projected sea level rise, airport would be affected. | **Drainage System Discharge Elevation**—Stakeholder interviews, Mobile Airport Authority |
| | Whether the drainage system is already experiencing "blowouts" | Blowouts indicate that joints are failing and/or pipes are collapsing. A higher number of blowouts would therefore indicate a higher sensitivity to future precipitation levels, exacerbated by sea level rise. Blowouts occur when a leak, failure, or collapse in the drainage pipe begins to suck in sediment and creates a depression in the field. | **Number of Areas with Evidence of Blowouts**—Stakeholder interviews, Mobile Airport Authority |
| | Age of drainage system | In older drainage systems, joints can fall apart over time. The older the drainage system, the more likely it is to fail during a flooding event. | **Year Drainage System Built—**Stakeholder interviews, Mobile Airport Authority |
| | Drainage system pipe material | Stakeholders in Mobile indicated that they have experienced more drainage problems with pipes that are made of certain materials. For example, Mobile stakeholders noted more problems with metal corrugated pipes relative to newer plastic or concrete pipes. This difference in performance may be related to age, condition, or maintenance more so than the actual materials used; however, in Mobile at least, identifying material type appears to be a good proxy for identifying drainage areas that may experience problems. | **Drainage System Pipe Material—**Stakeholder interviews, Mobile Airport Authority |

The study generated a composite sensitivity score for each segment based on a weighted average of its indicator scores. For the full scoring methodology, including information about how the indicators were scored and weighted, see Appendix C.

Neither of the critical airports in Mobile is sensitive to sea level rise, since both have not experienced issues in the past and have high elevation drainage discharge points. These traits overcome sensitivities that may arise due to old and declining drainage systems.

### Alternate Sea Level Rise Sensitivity Indicators for Airports

If inundation occurs in adjacent geographical areas, then even protected structures may still be inundated as waters come in from other directions. A sensitivity indicator may therefore try to capture whether an airport is adjacent to other areas expected to be exposed to sea level rise.

Furthermore, an airport itself may not be vulnerable to sea level rise, but the roads that access it could be. An alternate indicator could consider whether the airport is serviced by roads vulnerable to sea level rise.

Another indirect way sea level rise could affect airports is by affecting the locations of wetlands, which are habitats for shorebirds and other wildlife. The presence of new wetlands could affect airport operations. Whether nearby land is likely to become new wetland habitat could potentially serve as an indicator of airport sensitivity to sea level rise.

## Storm Surge

Storm surge can temporarily inundate airports, causing structural damage and making them temporarily unusable. The project team therefore developed sensitivity indicators that considered characteristics such as historical performance during storm events, soil type, building foundation type, drainage system quality, and whether lighting elements are water-resistant. Table 23 describes the data sources and rationale for each of these indicators.

**Table 23: Indicators Used to Assess the Sensitivity of Airports to Storm Surge**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Structural damage due to storm surge | Whether an asset has been damaged in the past due to storm surge | Airports that have experienced damage during past storm events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews, Mobile Airport Authority |
| | Building foundation type | Some foundation types are more likely to withstand storm surge than others. For example, pilings are the strongest foundation type while footers are less strong. | **Foundation Type**—Stakeholder interviews, Mobile Airport Authority |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| | Soil type | Some soil types may be more susceptible to movement or sliding (e.g., mud or fill is more susceptible to movement than sand"). Therefore, infrastructure built on these more susceptible soil types are more likely to be damaged during storm surge. | **Soil Type**—Stakeholder interviews, Mobile Airport Authority |
| | Whether approach lights can function under water | Watertight electrical wiring conduit is necessary to resist saltwater intrusion damage.<br>LED lights can operate while underwater, but older incandescent lights cannot and would be more sensitive to precipitation changes.<br>Note: LEDs have not been approved for runways by FAA, but can be used on taxiways. | **Lighting Used**—Stakeholder interviews, Mobile Airport Authority |
| Flooding | Whether the drainage system is already experiencing "blowouts" | Blowouts indicate that joints are failing and/or pipes are collapsing. A higher number of blowouts would therefore indicate a higher sensitivity to flooding. Blowouts occur when a leak, failure, or collapse in the drainage pipe begins to suck in sediment and creates a depression in the field. | **Number of Areas with Evidence of Blowouts**—Stakeholder interviews, Mobile Airport Authority |
| | Age of drainage system | In older drainage systems, joints can fall apart over time. The older the drainage system, the more likely it is to fail during a flooding event. | **Year Drainage System Built—**Stakeholder interviews, Mobile Airport Authority |
| | Drainage system pipe material | Stakeholders in Mobile indicated that they have experienced more drainage problems with pipes that are made of certain materials. For example, Mobile stakeholders noted more problems with metal corrugated pipes relative to newer plastic or concrete pipes. This difference in performance may be related to age, condition, or maintenance more so than the actual materials used; however, in Mobile at least, identifying material type appears to be a good proxy for identifying drainage areas that may experience problems. | **Drainage System Pipe Material—**Stakeholder interviews, Mobile Airport Authority |

The study generated a composite sensitivity score for each segment based on a weighted average of its indicator scores. For the full scoring methodology, including information about how the indicators were scored and weighted, see Appendix C.

Neither airport is highly sensitive to storm surge.

### Alternate Storm Surge Sensitivity Indicators for Airports

Analyzing emergency response records from Federal Emergency Management Agency (FEMA)'s public assistance program might be an additional method for identifying airports or portions or airports that have been repeatedly damaged in the past. This data source might provide another approach, to complement stakeholder input, of obtaining comprehensive information regarding existing vulnerabilities.

## Wind

Wind can affect airports by damaging airport facilities such as terminals, hangars, and air traffic control towers. Severe winds such as those associated with hurricanes also disrupt operations, and aircraft are grounded during these storms. Because airport operations are uniformly disrupted during hurricanes, the project team focused on indicators that would indicate which airports would be more likely to experience structural damage as a result of the high winds. These characteristics included previous experience with wind damage, the type of building material used, building height, building age (as a proxy for design standards), and whether airport facilities are sheltered from winds. Table 24 describes the data sources and rationale for these indicators.

**Table 24: Indicators Used to Assess the Sensitivity of Airports to Wind**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Structural damage to airport buildings due to high winds | Whether an asset has been damaged in the past due to high winds | Airports that have experienced wind damage during past hurricanes are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Wind**—Stakeholder interviews, Mobile Airport Authority |
| | Age of buildings | Older buildings are more likely to be built to lower design standards than newer buildings, and therefore more sensitive to damage from wind and other weather. | **Year Built**—Stakeholder interviews, Mobile Airport Authority |
| | Building material | Some building materials may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that metal and wood buildings are more sensitive to wind than masonry. | **Building Material**—Stakeholder interviews, Mobile Airport Authority |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| | Roof type | Some roof types may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that flat roofs are more sensitive to wind than pitched roofs. | **Roof Type**—Stakeholder interviews, Mobile Airport Authority |
| | Height of buildings | Taller buildings are more sensitive to high winds than shorter ones. | **Height of Air Traffic Control Tower**<br>**Height of Hangars**<br>**Height of Terminals**<br>—Stakeholder interviews, Mobile Airport Authority |
| | Whether airport is sheltered from wind | Buildings that are sheltered (e.g., by surrounding structures or terrain) may be less sensitive to wind. | **Yes/No Indication of Shelter**—Stakeholder interviews, Mobile Airport Authority |

Mobile Downtown Airport emerged as more sensitive to wind than Mobile Regional Airport, although both emerged as having moderate-high sensitivity to wind damage. The downtown airport's sensitivity is driven primarily by its age—the buildings were constructed in 1957—which the study assumed meant the buildings may have been built to a lower design standard for wind. Both airports emerged as sensitive because they have flat roofs, metal was used in constructing the buildings, and have been damaged by wind in the past. For the full scoring methodology, including information about how the indicators were weighted and how those weights changed in the absence of perfect data, see Appendix C.

**Alternate Wind Sensitivity Indicators for Airports**

Wind design speeds of airport buildings and other engineering traits could also serve as indicators of whether they would be damaged by severe winds. Other studies could also consider indicators of whether winds would affect operations, such as runway orientation (as relates to prevailing wind speeds) or other factors.

Another potential indicator is the airport proximity to areas with potential projectile materials (e.g. adjacent properties with commercial building roof ballast).

### 4.2.4 Rail Sensitivity Indicators

The project team identified several indicators to determine how Mobile's critical rail infrastructure and operations might be sensitive to disruptions from high temperatures, heavy precipitation, sea level rise, storm surge, and high winds.

The indicators used for each climate stressors are discussed in the subsections that follow. Using these indicators, the analysis found the following for the TASD assets:

- **Relatively low sensitivity to temperature**. Some critical rail segments have demonstrated sensitivity to high temperatures in the past in the form of buckling. However, none of the TASD assets have continuously welded rail, which is the most sensitive type of rail to heat-related buckling.
- **Relatively low sensitivity to precipitation**. Mobile's rail assets are largely located within the 100-year flood zone, in areas with high amounts of impervious surface, and on ballast that is prone to washouts, which contributes to sensitivity to precipitation. However, low likelihood of runoff issues and lack of historical drainage problems indicate lower sensitivity to heavy rainfall.
- **Relatively high sensitivity to sea level rise.** Though there is little available information about how Mobile's critical rail assets may be sensitive to sea level rise, what information is available—such as drainage system performance and whether tracks are elevated—indicates that the assets may be sensitive to damage from sea level rise.
- **Relatively moderate sensitivity to storm surge.** Rail assets could be damaged by storm surge through flooding and track washouts. Mobile's rail assets' elevation and ballast may make them sensitive to damage from storm surge, though this may be balanced by drainage systems and other factors.
- **Relatively high sensitivity to wind.** High winds can damage hanging signals and signs and blow coal dust, affecting rail operations. Mobile's rail assets may be sensitive to damage from heavy winds, such as those from tropical storms and hurricanes.

As noted previously, the study team had difficulty collecting information about the privately-owned critical rail assets in Mobile. Information about indicators was available only for the four Terminal Railway Alabama State Docks (TASD) assets in the analysis—the TASD rail yards, the segment near ports on Tensaw River, and the segments on the eastern and western side of McDuffie Island. Results are therefore discussed primarily in the context of the TASD assets, except where explicitly noted.

## Temperature

Extreme heat can result in rail kinks (sun kinks) or buckling, requiring trains to slow down to avoid derailment and requiring replacement of the tracks.[27] The project team identified three characteristics that may indicate sensitivity to temperature: whether the asset had experienced heat-related issues in the past, how frequently the asset is maintained, and whether the asset is continuously-welded rail. Table 25 describes the data sources and rationale for each of these indicators.

[27] FTA, 2011

**Table 25: Indicators Used to Assess the Sensitivity of Rail to Temperature**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Rail kinking or buckling | Whether asset has experienced damage in the past associated with high temperatures | Rail assets that have experienced damage during extreme temperatures in the past may be sensitive to higher or more frequent periods of extreme temperatures in the future. | **Yes/No Record of Previous Damage from Temperature** –Interviews with Mobile rail owners and operators |
| | Type of rail design | Some types of rail, such as continuously-welded rail, are more prone to buckling. | **Rail Design** –Interviews with Mobile rail owners and operators |
| | Maintenance frequency | Tracks that are frequently monitored and maintained by running tampers along the lines are more likely to have stable ballast that is less sensitive to buckling during periods of extreme temperatures. | **Maintenance Frequency** – Interviews with Mobile rail owners and operators |

Two TASD assets (the McDuffie Island rail segments) have experienced heat-related buckling in the past, and are the most sensitive assets to temperature. The other assets have not experienced buckling and have jointed rails, and are therefore not considered sensitive to increases in temperature. No information on maintenance frequency was available for the TASD assets. For the full scoring methodology, including information about how indicators were scored and weighted, see Appendix C.

### Alternate Temperature Sensitivity Indicators for Rail

The likelihood of a rail to buckle in extreme heat is determined by a number of factors, all of which could be used as indicators of temperature sensitivity if data were available. For example, tracks with rock ballast are more sensitive than tracks on concrete slab, since the concrete provides more support for the rail (FTA, 2011). Whether or not track is shaded could also be an indicator of temperature sensitivity, since areas exposed to direct sunlight are more likely to buckle. Finally, the rail-neutral temperature of the rail, which is a temperature threshold before rails start to compress and buckle, could be an indicator of temperature sensitivity. The lower the rail-neutral temperature, the more likely a rail segment may be to buckle during extreme heat.

For areas where cold temperatures or changes in freeze-thaw cycles are problematic, different indicators might be applicable, such as whether the rail is built over permafrost.

## Precipitation

Precipitation events can cause temporary rail flooding and cause electric signal failure and track bed washouts. Therefore, the project team looked for characteristics that would make an asset more likely to flood during a rain event and more likely to experience damage due to flooding or increased run-off. The resulting sensitivity indicators considered characteristics such as drainage system performance, ballast type, and the flooding potential of each asset's specific site. Table 26 describes the indicators used to assess the sensitivity of rail to precipitation.

**Table 26: Indicators Used to Assess the Sensitivity of Rail to Precipitation**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Flooding | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs |
| | Asset's elevation relative to surrounding areas | If an asset is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the rail (elevation data from 3 ft. x 3 ft. LiDAR) |
| | Amount of impervious surface surrounding an asset | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation | **Percent of Area Surrounding Asset with Above Average Impermeability**—USGS National Land Cover Database 2006 Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) |
| | Whether track is undercut | Track that crosses underneath major overpasses may have been undercut in order to accommodate larger, double-stacked trains. These areas may be more sensitive to impacts from flooding. | **Yes/No Indication of Whether Track Passes Below Overpass**—Project team analysis of satellite imagery |
| | Whether drainage system has experienced issues in the past | Rail assets that have experienced drainage system performance issues are more likely to experience flooding or drainage issues from heavy rainfall events. | **Yes/No Record of Previous Drainage Issues**—Interviews with Mobile rail owners and operators |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Track washouts | Ballast type | Certain types of ballast anchor the track more firmly than others and may be less sensitive to washouts from heavy rainfall. | **Ballast Type Used**—Interviews with Mobile rail owners and operators |
| | Maintenance frequency | Tracks that are frequently monitored and maintained by running tampers along the lines are more likely to have stable ballast that can withstand impacts from flooding. | **Maintenance Frequency** – Interviews with Mobile rail owners and operators |
| | Soil type | Rail that is on soil that is susceptible to erosion or flooding (e.g., in low-lying, marsh areas or areas with fill) may be more sensitive to washouts. | **Soil Type** –Interviews with Mobile rail owners and operators |
| Signal failure | Whether rail asset has electric signals | Electric signals may be damaged by exposure to water from flooding during heavy rainfalls. | **Yes/No Record of Electric Signals**—Interviews with Mobile rail owners and operators |

The most sensitive asset to heavy precipitation is the TASD rail yard. The entire yard is located in the 100-year flood zone, and the rail yard uses limestone ballast, which is relatively susceptible to washouts. Among the non-TASD assets, the most sensitive are the CSX segments, because they are located in the 100-year and 500-year flood zones. For the full scoring methodology, including information about how indicators were scored and weighted, see Appendix C.

### Alternate Precipitation Sensitivity Indicators for Rail

An alternate indicator could consider the type of cargo handled. Some cargo is shipped via open top cars, and although these types of cargo tend to be less sensitive to precipitation, significant increases in precipitation could have some impacts.

Propensity to pond, impermeability, and location relative to flood zones are all indictors intended to help understand the local flood risk of specific rail assets. Further work is needed in order to better understand how well these simple analyses can capture complex watershed dynamics.

In searching for information on potential indicators, the project team attempted to find spatial data on the 10- and 25-year floodplains. While these data exist in the Flood Insurance Studies, spatial data on these floodplains were not readily accessible. However, these flood zones might provide more refined indicators of exposure to flooding because they capture the lower magnitude, higher frequency events.

The project team also researched the possibility of using HEC modeling to calculate the impact that the Wetter and Drier precipitation narratives would have on local flooding patterns. Unfortunately, HEC models were not available for Mobile in a format that could be used for this study. Other locations may have water models that could be more easily updated using projected precipitation information.

Additional information about the drainage system besides its historical performance would also be useful indicators of precipitation sensitivity. For example, the drainage system's age or design capacity could be useful indicators.

## Sea Level Rise

Sea level rise can cause portions of rail assets to be permanently inundated or to be temporarily inundated at high tide. Higher sea levels can also exacerbate flood risks from heavy rain. The project team identified indicators that would suggest whether rail assets were likely to experience problems associated with sea level rise, such as whether assets flood under existing high tides, the quality of the drainage system associated with the asset, and whether the asset is elevated. Table 27 describes the indicators used to assess the sensitivity of rail to sea level rise.

**Table 27: Indicators Used to Assess the Sensitivity of Rail to Sea Level Rise**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Flooding | Whether an asset has flooded in the past due to tidal events | Rail assets that have experienced flooding during extreme high tide events in the past are likely to be some of the first rail assets impacted by sea level rise | **Yes/No Record of Previous Flooding from Tides**—Interviews with Mobile rail owners and operators |
| | Whether drainage system has experienced issues in the past | Rail assets that have experienced drainage system performance issues are more likely to experience flooding or drainage issues from sea level rise. | **Yes/No Record of Previous Drainage Issues**—Interviews with Mobile rail owners and operators |
| | Whether rail is elevated | Assets that are elevated above ground level may be shielded from exposure to storm surge. | **Yes/No Record of Asset Elevation**—Interviews with Mobile rail owners and operators |

The most sensitive asset to sea level rise is the TASD rail yard. The yard has been flooded in the past during high tides, has experienced issues with drainage system performance, and has low elevation, all contributing to high sensitivity. For the full scoring methodology, including how indicators were scored and weighted, see Appendix C.

### Alternate Sea Level Rise Sensitivity Indicators for Rail

Whether rail assets are sensitive to sea level rise may also depend on the type of soil and substrate of the rail. More porous soils may allow water to more easily infiltrate and destabilize the rail bed, while more compact soils may divert rising waters elsewhere. Sensitivity thus could depend not only on soil type at the asset's location, but in nearby locations as well.

Whether a rail asset is protected from sea level rise, other physical or man-made barriers could also be a sensitivity indicator.

Finally, multimodal access to rail could also be an indicator. A rail line itself may not be sensitive to sea level rise, but if key roads or ports that it serves are vulnerable, then operations could be compromised.

## Storm Surge

Storm surge can flood rail lines and rail yards, cause electric signal failure, and create track bed washouts. The project team looked for characteristics that would make an asset more likely to flood from storm surge and more likely to experience damage from the flooding. The resulting sensitivity indicators are similar to the ones used to evaluate sensitivity to precipitation-driven flooding, and include characteristics such as drainage system performance, ballast type, and the flooding potential of each asset's specific site. Table 28 describes the indicators used to assess the sensitivity of rail to precipitation.

**Table 28: Indicators Used to Assess the Sensitivity of Rail to Storm Surge**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Flooding | Whether an asset has flooded in the past due to storm surge | Rail assets that have experienced flooding during storm events in the past are likely to flooded during future storm events | **Yes/No Record of Previous Flooding from Storm Surge**—Interviews with Mobile rail owners and operators |
| | Whether asset is protected or elevated from storm surge | Assets that are protected by seawalls, dikes, or that are otherwise elevated above ground level may be shielded from exposure to storm surge | **Yes/No Record of Protection—** Interviews with Mobile rail owners and operators |
| | Whether track is undercut | Track that crosses underneath major overpasses may have been undercut in order to accommodate larger, double-stacked trains. These areas may be more sensitive to impacts from flooding. | **Yes/No Indication of Whether Track is Undercut**—Project team analysis of satellite imagery |
| | Whether drainage system has experienced issues in the past | Rail assets that have experienced drainage system performance issues are more likely to experience flooding or drainage issues from heavy rainfall events. | **Yes/No Record of Previous Drainage Issues**—Interviews with Mobile rail owners and operators |
| Track washouts | Ballast type | Certain types of ballast anchor the track more firmly than others and may be less sensitive to washouts from storm surge. | **Ballast Type Used**—Interviews with Mobile rail owners and operators |
| | Soil type | Rail that is on soil that is susceptible to erosion or flooding (e.g., in low-lying, marsh areas or areas with fill) may be more sensitive to washouts. | **Soil Type** –Interviews with Mobile rail owners and operators |
| Signal failure | Whether rail asset has electric signals | Electric signals may be damaged by exposure to water from flooding during storm surge. | **Yes/No Record of Electric Signals**—Interviews with Mobile rail owners and operators |

The most sensitive asset to storm surge is the TASD rail yard. The yard has been flooded in the past during storm surge, has experienced issues with drainage system performance, has limestone ballast, and is not protected or elevated from storm surge, all contributing to high sensitivity. For the full scoring methodology, including how indicators were scored and weighted, see Appendix C.

### Alternate Storm Surge Sensitivity Indicators for Rail

Land elevation on which the rail sits could be used as a storm surge sensitivity indicator even if the storm surge depths are not known. That is, the higher the asset is, the less likely it would be inundated. This indicator might provide a reasonable (if imperfect) indicator if more detailed comparisons cannot be made to the surge depths.

Additional information about the drainage system besides its historical performance would also be useful indicators of storm surge sensitivity. For example, the drainage system's age or design capacity could be useful indicators.

## Wind

Wind can affect railways by damaging aerial signals, damaging crossing gates, depositing debris on rail, and even by affecting freight contents. For example, winds can stir up coal dust, limiting operations. It is very difficult to predict where wind damage will occur, particularly where debris might occur since debris can come from many different sources. However, stakeholders concurred that signs and signals are most frequently damaged during high winds. Therefore, the project team looked for characteristics that would indicate that particular assets would be more likely to experience damage to signals and signs, such as the number of major crossings and whether segments had aerial signal lines. Table 29 describes the indicators used to assess the sensitivity of rail to wind.

**Table 29: Indicators Used to Assess the Sensitivity of Rail to Storm Surge**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Damage to signals, signs, and other infrastructure | Whether an asset has been damaged in the past due to wind | Rail assets that have experienced damage during storm events in the past may be more prone to damage in the future. | **Yes/No Record of Previous Damage from Wind**—Interviews with Mobile rail owners and operators |
| | Number of major crossings | Rail assets with a number of major crossings are more likely to have signs and signals that could be damaged by wind. | **Number of Major Crossings—** Project team analysis of satellite imagery |
| | Whether asset has aerial signal lines | Aerial signals and lines are sensitive to wind impacts and could be damaged during storms. This, in turn, could cause delays or damage to rail assets. | **Yes/No Indication of Aerial Signal Lines**—Project team analysis of satellite imagery |

The most sensitive asset to wind is the TASD segment near ports on Tensaw River (between Hardwood Lane and Travis Drive). This segment has three major crossings and has aerial signal lines, indicating a potentially high number of signals that could be damaged from wind. For the full scoring methodology, how indicators were scored and weighted, see Appendix C.

**Alternate Wind Sensitivity Indicators for Rail**

Based on available data, this study relied on information about the presence of signals to estimate the sensitivity of railways to wind. However, since debris is often the major cause of wind-related damage, it would be appropriate to consider the proximity of trees to power lines and the efficacy of tree trimming maintenance as alternate indicators. However, debris can come from non-vegetative sources too, such as buildings, so building density is another potential indicator for wind debris, as would be presence of overhead utility lines, for example. Some communities may know that they generally experience wind-related debris from specific sources, which may provide insights into appropriate wind indicators.

In addition, future projects may consider sign support strength, height and size of the signs, and length of support arms as indicators. Finally, the percentage of fixed vs. cabled signals and the ratio of underground power and utilities to overhead utilities might also serve as useful alternate indicators. All of these indicators get at the quantity of different materials that have debris-causing potential for rail. Wind design thresholds, used in this analysis to evaluate exposure, could be used instead as a sensitivity indicator.

### 4.2.5 Transit Sensitivity Indicators

The project team identified several indicators to evaluate the sensitivity of Mobile's transit infrastructure and operations to disruptions from high temperatures, heavy precipitation, sea level rise, storm surge, and strong winds.

The indicators used for each climate stressors are discussed in the subsections that follow. Using these indicators, the analysis found the following:

- **Very low sensitivity to temperature**. Mobile's transit facilities have never experienced disruption or damage during extreme heat events. In addition, the cooling systems in the bus fleet are adequate for hotter temperatures.
- **Relatively low sensitivity to precipitation**. While the Beltline O&M facility has very low sensitivity to precipitation, both the GM&O Terminal and the bus fleet and service are moderately sensitive. These sensitivities stem from the fact that the bus fleet has experienced operational delays due to heavy rains in the past and the GM&O Terminal is located in the 100-year flood zone.
- **Moderate sensitivity to sea level rise.** While none of the transit assets has experienced coastal flooding historically, they are not elevated or otherwise protected from flooding. In addition, both the GM&O Terminal and the bus fleet could be disrupted due to coastal flooding in nearby flood-prone areas.
- **Varied sensitivity to storm surge.** Sensitivity to storm surge varies significantly among the three critical assets. The GM&O Terminal has extremely high sensitivity due to historical problems, lack of elevation, and impaired access during storms. The Beltline O&M Facility and the bus fleet have low-to-moderate sensitivity.

- **Varied sensitivity to wind.** Poor building design and a past history of wind damage drive the high wind sensitivity of the Beltline O&M facility. However, GM&O Terminal and the bus fleet have low-moderate sensitivity.

### Temperature

Heat events can disrupt transit operations by stressing the cooling systems of bus fleets or causing other impacts to service and operations. The project team selected historical experience with high temperatures and age of buses as indicators of sensitivity to temperature. Table 30 describes the data sources and rationale for each of these indicators.

**Table 30: Indicators Used to Assess the Sensitivity of Transit to Temperature**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Disruption to transit service and/or structural damage to facilities | Whether asset has experienced damage or disruption in the past during heat events | Transit assets that already experience damage during heat events may experience worsening problems as the temperature increases. | **Yes/No Record of Previous Damage from Temperature**—Stakeholder interviews | All assets |
| Maintenance problems for vehicles | Age of buses | High temperatures can cause cooling system breakdowns on buses. Newer buses may be better suited to handling higher temperatures. | **Age of Buses** —Stakeholder interviews, Downtown Mobile Alliance | Bus fleet only |

All three assets had low sensitivity to temperature. For the full scoring methodology, including information about how the indicators were weighted and how those weights changed in the absence of perfect data, see Appendix C.

#### Alternate Temperature Sensitivity Indicators for Transit

Since Mobile does not have a fixed rail transit system, this analysis did not analyze the sensitivity of transit rail to temperature. Some indicators used to evaluate sensitivity of rail may be applicable to fixed rail transit, particularly fixed rail transit that operates above ground.

In addition, this analysis did not consider the pavement condition and binder choice of the bus routes since the roadway conditions were evaluated under highways. However, in cases where only transit is being evaluated for vulnerability, the sensitivity indicators for highways should be considered.

### Precipitation

Precipitation events can cause temporary flooding, disrupting bus service, damaging facilities, and impeding access to transit services. Therefore, the project team looked for characteristics that would indicate an asset is more likely to experience flooding during a precipitation event, or that access to the transit asset would be impaired by heavy rain. The resulting sensitivity indicators considered characteristics such as historical performance, proximity to flood zones, and access to the transit service. Table 31 describes the indicators used to assess the sensitivity of transit assets to precipitation.

**Table 31: Indicators Used to Assess the Sensitivity of Transit to Precipitation**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Flooding | Whether asset has experienced damage in the past associated with heavy rainfall | Assets that have experienced damage in the past from precipitation events are more likely to be damaged if exposed in the future | **Yes/No Record of Previous Damage from Precipitation** -- Stakeholder interviews | All assets |
| | Whether the asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | All assets |
| | Whether the asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs | All assets |
| | Asset's elevation relative to surrounding areas | If an asset is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the road (elevation data from 3 ft. x 3 ft. LiDAR) | All assets |
| | Amount of impervious surface surrounding an asset | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation | **Percent of Area Around Asset with Above Average Impermeability**—USGS National Land Cover Database 2006 Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) | All assets |
| Inability to access facilities | Access to transit asset during heavy precipitation events | Even if the asset itself is unaffected, if structures near the asset are flooded, the ability to access and operate a facility or bus service may be impeded | **Yes/No on Potential for Nearby Assets to Flood**—Stakeholder interviews | All assets |

For the full scoring methodology, see Appendix C.

Due to difficulties accessing and operating the bus service during heavy rain events, the bus fleet was rated as the most sensitive transit asset to precipitation. The GM&O Terminal, which is located in the 100-year and 500-year flood zones, also scored in the moderate sensitivity range. The Beltline O&M Facility has very low sensitivity to precipitation, resulting from its low likelihood of flooding, accessibility during extreme climate events, and historical capacity to cope with heavy rainfall.

### Alternate Precipitation Sensitivity Indicators for Transit

In areas where underground transit systems are present, water can enter through ventilation systems, tunnel openings, or seep through other openings to the underground system. For underground transit, sensitivity indicators might consider whether ventilation openings or tunnel openings are located in areas prone to flooding, and whether there are any protective features in place to prevent water from entering the system.

This analysis did not consider the sensitivities of the roads on which transit buses run, since those roads were evaluated under highways. However, in cases where only transit is being evaluated for vulnerability, the sensitivity indicators for highways should be considered.

## Sea Level Rise

Sea level rise can permanently or temporarily inundate transit assets and exacerbate precipitation-related flooding. The project team identified characteristics that suggest an asset may be sensitive to these impacts of sea level rise. The resulting sensitivity indicators considered characteristics such as historical performance during high tide events, the asset's elevation or protection, and ease of access during inundations. Table 32 describes the data sources and rationale for each of these indicators.

**Table 32: Indicators Used to Assess the Sensitivity of Transit to Sea Level Rise**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Flooding | Whether an asset has flooded in the past due to tidal events | Assets that have experienced flooding during extreme high tide events in the past are more likely to experience disruption again in the future | **Yes/No Record of Previous Flooding from Tides**—Stakeholder interviews | All assets |
| | Elevation or protection of asset | Assets that are elevated or well protected are less likely to be affected during sea level rise events | **Yes/No on Elevation or Protection**—Stakeholder interviews, confirmed by satellite imagery | All assets |
| Inability to access facilities | Access to asset during inundation event | Even if the asset itself is unaffected, if structures near the asset are flooded, the ability to access and operate a facility or bus service may be impeded | **Yes/No on Potential for Nearby Assets to Flood**—Stakeholder interviews | All assets |

For the full scoring methodology, including information about how the indicators were scored and weighted, see Appendix C.

All three transit assets in Mobile have low or moderate sensitivity to sea level rise. While none of the assets has experienced difficulties in the past due to high tide events, they are also not elevated or otherwise protected from sea level rise. However, because GM&O Terminal and the bus fleet could be affected by disruptions to nearby, flood-prone areas, they are moderately sensitive to sea level rise. The Beltline O&M Facility is the least sensitive of the three facilities.

### Alternate Sea Level Rise Sensitivity Indicators for Transit

For underground transit, indicators may include the extent to which ventilation or tunnel openings are located in areas thought to be exposed to sea level rise.

This analysis did not consider the sensitivities of the roads on which transit buses run, since those roads were evaluated under Highways. However, in cases where only transit is being evaluated for vulnerability, the sensitivity indicators for Highways should be considered.

## Storm Surge

Storm surge can temporarily inundate transit assets, causing structural damage and obstructing access to and operation of transit services. The project team therefore developed sensitivity indicators that considered characteristics such as historical performance during storm events, building foundation, elevation or protection of the asset, and accessibility during storm surge. Table 33 describes the data sources and rationale for each of these indicators.

**Table 33: Indicators Used to Assess the Sensitivity of Transit to Storm Surge**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Structural damage due to storm surge | Whether an asset has been damaged in the past due to storm surge | Assets that have experienced damage during past storm events are more likely to be damaged if exposed in the future | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews | All assets |
| | Elevation or protection of asset | Assets that are elevated or well protected are less likely to be affected during storm surge events | **Yes/No on Elevation or Protection**—Stakeholder interviews, confirmed by satellite imagery | All assets |
| | Building foundation | Certain foundation designs may be more vulnerable to structural damage than others | **Building Foundation Type** – Stakeholder interviews | Facilities only |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Inability to access facilities | Access to asset during inundation event | Even if the asset itself is unaffected, if structures near the asset are flooded, the ability to access and operate a facility or bus service may be impeded | **Yes/No on Potential for Nearby Assets to Flood**—Stakeholder interviews | All assets |

For the full scoring methodology, including information about how the indicators were scored and weighted, see Appendix C.

Mobile's transit assets displayed varied sensitivity to storm surge. The GM&O Terminal is highly sensitive because it has been damaged by storm surge in the past, is neither protected nor elevated, and is located near flood-prone access routes. In contrast, neither Beltline O&M Facility nor the bus fleet has a history of storm surge damage.

**Alternate Storm Surge Sensitivity Indicators for Transit**

For underground transit, indicators may include the extent to which ventilation or tunnel openings are located in areas thought to be exposed to storm surge.

This analysis did not consider the sensitivities of the roads on which transit buses run, since those roads were evaluated under Highways. However, in cases where only transit is being evaluated for vulnerability, the sensitivity indicators for Highways should be considered.

## Wind

Strong winds are an important cause of structural damage during storms. Therefore, the project team focused on indicators that predict assets likely to experience structural damage due to wind. These characteristics included history of wind damage, building material type, building height, roof type, wind rating of assets, and whether the asset is sheltered by surrounding structures. Table 34 describes the data sources and rationale for these indicators.

**Table 34: Indicators Used to Assess the Sensitivity of Transit to Wind**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Structural damage to transit assets due to high winds | Whether an asset has been damaged in the past due to high winds | Transit assets that have experienced wind damage during past hurricanes are more likely to be damaged if exposed in the future | **Yes/No Record of Previous Damage from Wind**—Stakeholder interviews | All assets |
| | Age of buildings or fleet | Older buildings or buses are more likely to be built to lower design standards than newer ones, and therefore more sensitive to damage from wind and other weather | **Year Built**—Stakeholder interviews | All assets |
| | Building material | Some building materials may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that metal and wood buildings are more sensitive to wind than masonry. | **Building Material**—Stakeholder interviews | Facilities only |
| | Roof type | Some roof types may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that flat roofs are more sensitive to wind than pitched roofs. | **Roof Type**—Stakeholder interviews | Facilities only |
| | Height of buildings | Taller buildings are more sensitive to high winds than shorter ones. | **Building Height** —Stakeholder interviews | Facilities only |
| | Whether asset is sheltered from wind | Assets that are sheltered (e.g., by surrounding structures or terrain) may be less sensitive to wind. | **Yes/No Indication of Shelter**—Stakeholder interviews | All assets |

The sensitivity of Mobile's transit assets to wind varied greatly. The Beltline O&M facility was rated most sensitive to wind, followed by the bus fleet and the GM&O Terminal. The Beltline facility's high rating is largely due to its metal and concrete construction, flat roof, and lack of shelter. On the other hand, GM&O Terminal's low sensitivity arises primarily from its masonry construction and pitched roof, which are better suited to withstanding high winds. The bus fleet has been damaged from debris in the past, but buses are sheltered during high wind events, leading to a moderate overall sensitivity. For the full scoring methodology, including information about how the indicators were scored and weighted, see Appendix C.

**Alternate Wind Sensitivity Indicators for Transit**

Wind design thresholds, used in this analysis to evaluate exposure, could be used instead as a sensitivity indicator. Further, since debris is often the major cause of wind-related damage, it would be appropriate to consider any factors that might contribute to the likelihood of debris formation. However, it is very difficult to predict damage due to debris.

This analysis did not consider the sensitivities of the roads on which transit buses run, since those roads were evaluated under Highways. However, in cases where only transit is being evaluated for vulnerability, the sensitivity indicators for Highways should be considered.

## 4.3 Evaluating Adaptive Capacity

Adaptive capacity refers to the ability of a transportation system or asset to adjust, repair, or flexibly respond to damage. An asset or system could be highly exposed and highly sensitive, but if it also has the capacity to adjust to an impact, its overall vulnerability is lower. For example, a particular bridge may frequently be flooded and impassable during rain events, but if there are many other routes to get to the same place, the overall disruption to traffic may be low.

Adaptive capacity is a difficult concept to quantify and evaluate since there are many internal and external factors that affect it. It is also a less intuitive concept than exposure and sensitivity. Articulating adaptive capacity indicators was more difficult than for exposure and sensitivity, and there was somewhat less agreement among the technical experts and stakeholders on which indicators best represented adaptive capacity. Still, it is an important component of vulnerability, and few common indicator themes emerged:

- **Ability to quickly repair damage** is one measurement of adaptive capacity. The measurement of this factor varies by mode. Replacement or upgrade cost of an asset is a reasonable (if imperfect) proxy for the general complexity and cost of an asset; more complex and expensive assets may take longer to repair or replace when needed. For some modes, facilities may have a special designation as a critical facility in the area, meaning it received priority for resources to repair damage after a major weather event.
- **Redundancy** is another key factor, and it also is measured in different ways for each mode. As mentioned in the example above, alternative routes to get from Point A to Point B can lessen the disruption of temporarily losing access to one highway asset. For other modes, redundancy manifests itself in the ability to shift operations from one facility to another (external redundancy) or the presence of multiple similar facility features, such as multiple runways, terminals, piers, etc. (internal redundancy).
- **Duration of operational disruption** is also important to capture. Precipitation-related flooding often lasts only a few hours, whereas inundation from sea level rise could be permanent. A transportation asset and system can more easily adjust to short-term flooding than it can to permanent flooding. Therefore, the project team developed disruption duration scores for temperature, precipitation, sea level rise, storm surge, and wind. The same scores were used for all transportation assets.

While these themes are common across the mode-specific adaptive capacity indicators, the actual indicators used for each mode vary, in order to account for the uniqueness of each mode and for differences in data availability. Within a given mode, the same factors were used to evaluate adaptive capacity, as discussed in the sections that follow.

As mentioned, the adaptive capacity indicators were more difficult to articulate, evaluate, and quantify than exposure and sensitivity. Within the three indicator themes discussed above, the indicators used to evaluate the themes were not perfect. For example, all disruption duration scores were the same for all assets for each climate stressor. In reality, the actual duration of any disruption could be quite site- and event-specific, so this indicator provides only a rough proxy of the length of time of operational disruption. As another example, the cost information available for most modes was limited in terms of the costs represented, and may not represent the actual repair costs associated with a specific climate event. Further, the adaptive capacity indicators address the capacity to respond to damage in a discrete event. The adaptive capacity of assets and transportation systems may change if exposed to repeated damage over time, but that is not explicitly considered in the selected indicators.

### 4.3.1 Highways Adaptive Capacity Indicators

Across all climate stressors, the same indicators were used to evaluate adaptive capacity for highways. These indicators are shown in Table 35. Overall, this approach resulted in the following:

- **Relatively high adaptive capacity to temperature**. These findings are consistent with information from stakeholders, who indicated that disruptions associated with temperature are very minor and virtually non-existent beyond the disruptions caused by pavement repair. The five assets with the lowest adaptive capacity scores are all bridges with long detour lengths indicating low redundancy.
- **Relatively high adaptive capacity to precipitation**. Stakeholders noted that precipitation-driven flooding generally affects roads for a matter of hours before it clears. The five assets with the lowest adaptive capacity are all bridges with long detour lengths indicating low redundancy.
- **Relatively low adaptive capacity to sea level rise**. One quarter of all assets scored a 4 for adaptive capacity, which includes all roadways (whose scores are driven solely by the disruption duration score) and five bridges with high costs and detour lengths. Stakeholders noted that permanent inundation of assets would require major modifications or protections to restore the asset, if restoration were even possible.
- **Relatively low adaptive capacity to storm surge**. One quarter of all assets scored a 4 for adaptive capacity, which includes all roadways (whose scores are driven solely by the disruption duration score) and five bridges with high costs and detour lengths. Stakeholders noted that assets damaged by storm surge can take months to fully repair or replace, and repairs can be expensive.
- **Relatively high adaptive capacity to wind** (though lower than adaptive capacity to temperature). Stakeholders noted that debris from wind can be cleared easily, as can lights and signs that have been displaced, but clean-up may take more than one day after a major

storm. Five bridges however, had relatively low adaptive capacity, driven by their high costs and long detour lengths.

**Table 35: Indicators Used to Assess the Adaptive Capacity of Highways**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Ability to quickly repair damage | Cost to replace an asset | Replacement costs for each asset are used as a rough proxy for the ease in which assets could be repaired or replaced. Resources are assumed to be more easily mobilized for lower cost repairs, and replacement costs may indicate overall complexity, size, and expense of the asset itself. | **Total Project Cost**—National Bridge Inventory, Item 96 | Bridges |
| Redundancy | Length of detour around a damaged asset | Detour length is used as an indicator of redundancy in the system. Segments with longer detour lengths assumed to have less adaptive capacity than segments with shorter detours. | **Bypass, Detour Length—**National Bridge Inventory, Item 19 | Bridges |
| Duration of operational disruption | Length of time an asset is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)** – Stakeholder interviews | Roads and bridges |

Note: Cost and detour indicators are specific to each asset; scores for these indicators will vary by asset but will not vary by climate stressor. Disruption duration is specific to each climate stressor; scores for this indicator will vary by stressor, but not by asset.

Note: Data needed to evaluate the first two indicators were available only for bridges and culverts. Therefore, the adaptive capacity of roads was evaluated solely based on the duration of disruptions.

The study generated a composite adaptive capacity score for each asset based on a weighted average of its scores for the three indicators. For the full scoring methodology, including information about how the weights changed in the absence of full data, see Appendix D.

### Alternate Adaptive Capacity Indicators for Highways

Replacement cost is not a perfect proxy for repair or maintenance costs, and so is limited as an indicator, particularly for climate hazards that are not likely to result in full-scale replacement of an asset. Alternative or supplemental indicators may include those that capture relative repair or maintenance costs. For this project, data sources for historical repair costs were pursued, but appropriate databases could not be identified. In locations where historical repair costs for specific assets are available, this information might prove to be a more accurate indicator, particularly if those costs could be associated with specific weather events. In addition, many communities and government agencies produce post-event damage reports that detail disruption delays, damage costs, and alternate routes used. These reports can serve as sources of information for evaluating adaptive capacity.

In general, indicators of adaptive capacity should capture the impact of damage to an asset on the larger transportation system. This analysis uses replacement cost, detour length, and length of disruptions, but additional indicators may include traffic/use statistics. In addition to detour length, other redundancy factors could be used, such as whether assets provide the only access to critical areas. In this study, assets were already screened for criticality under an earlier stage of the project, so all assets evaluated for vulnerability were already deemed to be highly critical, and additional criticality indicators were therefore not developed.

Evaluation of “damage” due to disrupted use of an asset could take many forms. There are purely economic measures of damage, which could relate to actual repair costs, costs associated with disrupted or increased shipping routes, or costs of employees not being able to get to work or tourists not being able to get to attraction sites. Other measures of damage could include the quality-of-life implications of increased traffic, long detours, or difficulty in accessing certain medical or entertainment centers, just to name a few.

More asset-specific or situation-specific indicators regarding the length of disruption time could be considered. The approached employed in this methodology applies the same disruption duration score to all assets under a given stressor. In reality, certain assets might experience differing lengths of duration disruption. Duration may also be tied to specifics about the nature of the event. For example, minor flooding could be assumed to cause very short-term disruptions, but more major flooding could be assumed to cause longer-term disruptions.

### 4.3.2 Ports Adaptive Capacity Indicators

The indicators in Table 36 were used to evaluate adaptive capacity in ports across all climate stressors. These indicators consider redundancies within and across ports as well as operational disruption estimates. This approach yielded the following results:

- **Relatively high adaptive capacity to temperature**. These findings are consistent with information from stakeholders, who indicated that disruptions associated with temperature are very minor when they do occur. Ports with very low operational redundancy exhibit lower adaptive capacity, under the assumption that it is difficult or impossible to shift operations in the event of an extreme heat event.
- **Relatively high adaptive capacity to precipitation**. Stakeholders noted that precipitation-driven flooding generally affects roads for a matter of hours before it clears. Ports with very low operational redundancy exhibit lower adaptive capacity, under the assumption that it is difficult or impossible to shift operations in the event of a serious flooding event.
- **Relatively low adaptive capacity to sea level rise**. Over sixty percent of all ports scored a 4 for adaptive capacity, indicating a low ability to adapt to sea level rise inundation.

Stakeholders noted that permanent inundation of assets would require major modifications or protections to restore the asset, if restoration were even possible.

- **Moderate adaptive capacity to storm surge**. Most ports have a moderate capacity to adapt to storm surge damage. Stakeholders noted that assets damaged by storm surge can take months to fully repair or replace, and repairs can be expensive. Ports with very low operational redundancy exhibit lower adaptive capacity, under the assumption that it is difficult or impossible to shift operations in the event of an emergency.
- **Relatively high adaptive capacity to wind** (though lower than adaptive capacity to temperature). Wind damage due to debris can usually be fixed relatively quickly following a storm.

**Table 36: Indicators Used to Assess the Adaptive Capacity of Ports**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Redundancy | Redundancy within the facility: whether operations can be shifted to another part of the same port | Operational disruptions are less likely to occur if other parts of the same facility can be substituted in the event of minor damage. | **Ability to Shift Operations Internally** –Stakeholder surveys, interviews, and emails |
| | Redundancy across facilities: whether operations can be shifted to a different facility | Serious operation disruptions are less likely to occur if other facilities can be substituted in the event of major damage. | **Ability to Shift Operations Externally** –Stakeholder surveys, interviews, and emails |
| Duration of operational disruption | Length of time an asset is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**—Stakeholder interviews |

The study generated a composite adaptive capacity score for each asset based on a weighted average of its scores for the three indicators. For the full scoring methodology, including how indicators were scored and weighted, see Appendix D.

**Alternate Adaptive Capacity Indicators for Ports**

The extent to which supplies and repair equipment are stockpiled could be an indicator of how quickly ports would be able to recover from damage. Similarly, agreements with other ports or agencies to share equipment or facilities to maintain operations after a major event could be indicators of adaptive capacity.

If data were available, several other attributes of ports could serve as indicators of their adaptive capacity. For example, the replacement cost of specific buildings could be a proxy for the ease of repair and/or cost of replacement. In locations where historical repair costs for specific assets are available, this information might prove to be a more accurate indicator, particularly if those costs could be associated with specific weather events. In addition, many communities and government agencies produce post-event damage reports that detail disruption delays, damage costs, and alternate facilities used. These reports can serve as sources of information for evaluating adaptive capacity.

In general, indicators of adaptive capacity should capture the impact of damage to an asset on the larger transportation system. In addition to the internal and regional system redundancy factors used, others could include whether assets provide the only access to critical areas or usage statistics such as operations, passenger-miles, or cargo volumes. In this study, assets were already screened for criticality under an earlier stage of the project, so all assets evaluated for vulnerability were already deemed to be highly critical, and additional criticality indicators were therefore not developed.

Evaluation of “damage” due to disrupted use of an asset could take many forms, including: actual repair costs, costs associated with disrupted or increased shipping routes, or costs of tourists not being able to visit.

### 4.3.3 Airports Adaptive Capacity Indicators

The same indicators were used to evaluate adaptive capacity for airports across all climate stressors. These indicators are shown in Table 37 and incorporate redundancy (within the airport and across neighboring airports) and estimated duration of operational disruption.

Overall, this approach resulted in the following:

- Low adaptive capacity to sea level rise for both airports, due to the permanent nature of such inundation and the challenges of armoring an airport against that inundation.
- Moderate adaptive capacity for both airports across all other stressors. Indicators representing low adaptive capacity (such as that both airports are small, lacking internal redundancy, and far from other airports) are balanced by indicators representing high adaptive capacity, such as that both airports have special designations for emergency response and experience relatively brief disruptions for most climate impacts.
- Lower adaptive capacity for Mobile Downtown airport for all stressors, because of very low redundancy both within the airport (it is a small airport with little capacity to cope with damage) and in the region, with few general aviation and cargo airports nearby.

**Table 37: Indicators Used to Assess the Adaptive Capacity of Airports**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source |
|---|---|---|---|
| Ability to quickly repair damage | Whether the airport is likely to be prioritized for repair | If airports are specifically designated as important for emergency response, national security, defense, or support to health facilities, they are more likely to be re-opened quickly after damage. | **Yes/No Indication of Special Designation**—Stakeholder interviews, Mobile Airport Authority |
| Redundancy | Number of terminals at the airport | The number of terminals at an airport is an indicator of internal redundancy within the airport. Airports with multiple terminals may be able to shift operations to other portions of the airport if a specific terminal or area is damaged. | **Number of Terminals** – Stakeholder interviews, Mobile Airport Authority |
| | Number of runway headings at the airport | A runway heading refers to the direction the runway is facing (relative to north). The number of runway headings at an airport is an indicator of internal redundancy within the airport, since the more directions that planes can take off from an airport, the more resilient that airport is to weather-related disruptions. If airport has more than one runway facing in direction of prevailing winds, this reduces the chances that planes will have to take off and land in cross winds, reducing delays. | **Number of Runway Headings** –FAA Airport Master Record Forms 5010-1 and 5010-2 |
| | Distance to nearest "substitute"* airport | The distance to an airport that has similar characteristics to the given airport is a measure of air service system redundancy. | **Distance to Nearest "Substitute" Airport**—FAA National Plan of Integrated Airport Systems (NPIAS) |
| | Number of "substitute" airports within reasonable driving distance | The number of airports that could act as substitutes for the given airport and that are within a 2 hour drive is a measure of system redundancy. | **Number of "Substitute" Airports within 120 Miles**—FAA National Plan of Integrated Airport Systems (NPIAS) |
| Duration of operational disruption | Length of time the airport is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**—Stakeholder interviews |

*A "substitute" airport was defined in this study as an airport sharing similar key characteristics as the airport in question. For Mobile Downtown, a "substitute" airport meets the following three criteria: Service Level: General Aviation or Primary; qualifying cargo airport, and ARC: D-V. For Mobile Regional, a "substitute" airport meets the following three criteria: Service Level—Primary; Hub Type-Non-hub or small; ARC: D-V.

The study generated a composite adaptive capacity score for each asset based on a weighted average of its scores for the six indicators. For the full scoring methodology, including how indicators were scored and weighted, see Appendix D.

**Alternate Adaptive Capacity Indicators for Airports**

If data were available, several other attributes of airports could serve as indicators of their adaptive capacity. For example, replacement cost of specific buildings or runways could be a proxy for how easy they would be to repair or replace. In locations where historical repair costs for specific assets are available, this information might prove to be a more accurate indicator, particularly if those costs could be associated with specific weather events. In addition, many communities and government agencies produce post-event damage reports that detail disruption delays, damage costs, and alternate facilities used. These reports can serve as sources of information for evaluating adaptive capacity.

In general, indicators of adaptive capacity should capture the impact of damage to an asset on the larger transportation system. In addition to the internal and regional system redundancy factors used, others could include whether assets provide the only access to critical areas or usage statistics such as operations, passenger-miles, or cargo volumes. In this study, assets were already screened for criticality under an earlier stage of the project, so all assets evaluated for vulnerability were already deemed to be highly critical, and additional criticality indicators were therefore not developed.

Evaluation of "damage" due to disrupted use of an asset could take many forms. There are purely economic measures of damage, which could relate to actual repair costs, costs associated with disrupted or increased shipping routes, or costs of tourists not being able to visit.

Another indicator could be redundancy in power systems. Airports relay on continuous energy to provide navigation safety for air traffic. Protection of back up engine generators, capacity of their fuel tanks to power critical infrastructure and presence of alternatives such as battery banks would enable airports to function when grid power is unavailable.

### 4.3.4 Rail Adaptive Capacity Indicators

The same indicators were used to evaluate adaptive capacity for rail assets across all climate stressors. These indicators are shown in Table 38 and incorporate system flexibility, relative speed and ease of repair, and estimated duration of operational disruption. Some indicators applied only to rail yards or rail lines, as noted in the far right column of Table 38.

Overall, this approach resulted in the following:

- Low adaptive capacity to sea level rise for all assets, largely due to the permanent nature of such inundation.
- Moderate adaptive capacity for all assets to all other climate stressors. Indicators representing low adaptive capacity (and thus high vulnerability) such as the presence of expensive components or status within disaster recovery plans are balanced by indicators representing high adaptive capacity, such as the presence of self-administered evacuation plans.
- Lowest adaptive capacity for the TASD segment near ports on Tensaw River, because it includes bridges (which can be difficult to repair) and may not be a priority for repair since it is not a part of the local disaster recovery relief plan.

**Table 38: Indicators Used to Assess the Adaptive Capacity of Rail**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Ability to quickly repair damage | Presence of bridges along segment | Bridges are generally more expensive to replace than rail; the speed to recover from damage to bridges along a segment of rail may therefore be longer than segments without bridges. | **Yes/No on Presence of Bridges—**Visual inspection of segments | Rail yards and segments |
| | Whether track is signaled | Signaling can be expensive and time-intensive to replace. | **Yes/No on Signaling—** Interviews with Mobile rail owners and operators | Rail yards and segments |
| | Self-administered evacuation plans | Rail companies with a plan in place are expected to suffer less damage and recover more quickly from storms. | **Yes/No on Existence of Evacuation Plans—**Task 1 Criticality Report (U.S. DOT, 2011) | Rail yards and segments |
| | Part of disaster relief recovery plan | Emphasis to restore operations may be placed on rails that are part of disaster relief recovery plans. | **Yes/No on Involvement in Plan—**Task 1 Criticality Report (U.S. DOT, 2011) | Rail yards and segments |
| Redundancy | Ability of system to reroute around obstacles or closed routes | Systems and segments that can flexibly reroute will be more resilient to damage, track obstructions, and outages. | **Yes/No on Ability to Reroute**—Interviews with Mobile rail owners and operators | Rail segments |
| | Interchange utility | This is a yard-specific measure of the interchange between carriers, which is of importance in the ability to transfer all cars within yards. | **Qualitative Rating of Low/Med/High**—On-site observation, Task 1 Criticality Report (U.S. DOT, 2011) | Rail yards |
| Duration of operational disruption | Disruption duration | Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**—<br>Interviews with Mobile rail owners and operators | Rail yards and segments |

For the full scoring methodology, including how indicators were scored and weighted, see Appendix D.

**Alternate Adaptive Capacity Indicators for Rail**

The extent to which supplies and repair equipment are stockpiled could be an indicator of how quickly rail would be able to recover from damage. Similarly, agreements with other rail companies to share equipment or facilities to maintain operations after a major event could be indicators of adaptive capacity. For example, some rail companies have agreements that allow them to use each other's rail systems in the situation where one company's rail lines are heavily damaged during a climate event.

If data were available, several other attributes of rail could serve as indicators of their adaptive capacity. For example, specific replacement cost of assets or specific sub-components could serve as a proxy for how easy that asset would be to repair or replace if damaged.

Indicators of adaptive capacity could capture the impact of damage to an asset on the larger transportation system. Indicators of redundancy such as number of rail lines serving a specific location may be appropriate. In addition, other indicators could include usage statistics such as freight volumes or values. In this study, assets were already screened for criticality under an earlier stage of the project, so all assets evaluated for vulnerability were already deemed to be highly critical, and additional criticality indicators were therefore not developed.

Evaluation of "damage" due to disrupted use of an asset could take many forms, including actual repair costs or costs associated with disrupted or increased shipping routes, as well as temporal length of damage or an indication of the proportion of the system ( track length or freight values or similar metric) damaged.

### 4.3.5 Transit Adaptive Capacity Indicators

The same indicators were used to evaluate adaptive capacity for transit assets across all climate stressors. These indicators are shown in Table 39 and incorporate how quickly a facility or service can recover from a disruption and whether the broader system can cope with the shutdown of the single asset.

Overall, this approach resulted in low to high adaptive capacity across all stressors. On average, Mobile's transit facilities had the least adaptive capacity to storm surge as a result of long disruption durations. Because it is both impossible to move and difficult to replace, the Beltline O&M Facility scored lowest on adaptive capacity across all stressors; long term adaptation strategies would need to consider moving operations out of this particular building. The bus fleet, however, has higher adaptive capacity because of its redundant nature (many buses available) and because of the mobile nature of the bus fleet and routes. In fact, the bus fleet is unique among assets across all modes in that the buses and their routes can be easily moved at low cost to avoid or adjust to climate-related hazards; most other assets considered in this study have more permanent infrastructure that would require more significant time and resources to relocate.

**Table 39: Indicators Used to Assess the Adaptive Capacity of Transit Assets**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Applied To |
|---|---|---|---|---|
| Ability to quickly repair damage | Whether the asset is likely to be prioritized for repair | If a transit asset is designated with USACE priority for assistance after a major weather event, it is more likely to be re-opened quickly after damage. | **Yes/No Indication of Special Designation**—Gulf Coast Phase 2, Task 1 Criticality Report | All assets |
| Redundancy | Function of facility or asset | Assets that are difficult to replace or move have lower adaptive capacity than assets that are replaceable or movable. | **Qualitative Assessment** –Wave Transit | All assets |
| | Ability of system to reroute around obstacles or closed routes | Assets that are able to reroute or detour easily are more capable of adapting to extreme weather events. | **Qualitative Assessment** – Stakeholder interviews | Bus fleet only |
| Duration of disruption | Length of time the asset is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**—Stakeholder interviews | All assets |

The study generated a composite adaptive capacity score for each asset. For the full scoring methodology, including how indicators were scored and weighted, see Appendix D.

### Alternate Adaptive Capacity Indicators for Transit

For transit that runs on fixed lines (such as subways), alternate indicators could consider whether alternative routes and modes can be employed if one line is disrupted. That is, to what extent would buses be able to be quickly deployed to sufficiently fill the gap created if a subway or light rail line became inoperable? Another indicator could consider how easily transit could be rerouted around problem areas. That is, if a single station or a single point on the rail is damaged, does the entire line shut down, or can trains be routed around the problem areas?

If data were available, several other attributes of transit facilities could serve as indicators of their adaptive capacity. For example, replacement cost of buildings could be a proxy for how easy they would be to repair or replace. In locations where historical repair costs for specific assets are available, this information might prove to be a more accurate indicator, particularly if those costs could be associated with specific weather events. In addition, many communities and government agencies produce post-event damage reports that detail disruption delays, damage costs, and alternate facilities used. These reports can serve as sources of information for evaluating adaptive capacity.

The importance, or "criticality," of an asset can also be a good indicator of adaptive capacity if not already included in asset selection. The assets considered in this study were already identified as "critical" using several criticality indicators (e.g., usage, evacuation route, provides access to health facilities). These could all be good indicators of how well the transportation system could cope with damage to these assets relative to other, less critical assets (i.e., its adaptive capacity).

# 5. Detailed Vulnerability Results

This section provides detail on the vulnerability results discussed in Section 1.3, "Key Findings in Mobile." Recall the key caveat to that discussion, which is that different methodologies are used for each mode and climate stressor. Therefore, direct comparisons cannot be made between scores across modes or stressors. However, the "High"/"Medium"/"Low" results and relative rankings, along with local context, can provide a sense of the key transportation system vulnerabilities in Mobile.

## 5.1 Highways Results

As noted previously, the vulnerability assessment applied slightly different sensitivity and adaptive capacity indicators to roads and bridges. For example, for temperature, the assessment of bridges included truck traffic, detour length, and replacement cost as indicators of sensitivity and adaptive capacity. Fewer indicators were used to evaluate roads, and the truck traffic indicator for roads was based on data from the LRTP, rather than the NBI. Due to these differences in methodology, this section first discusses the results for bridges and roads separately when discussing the vulnerability results for each climate stressor.

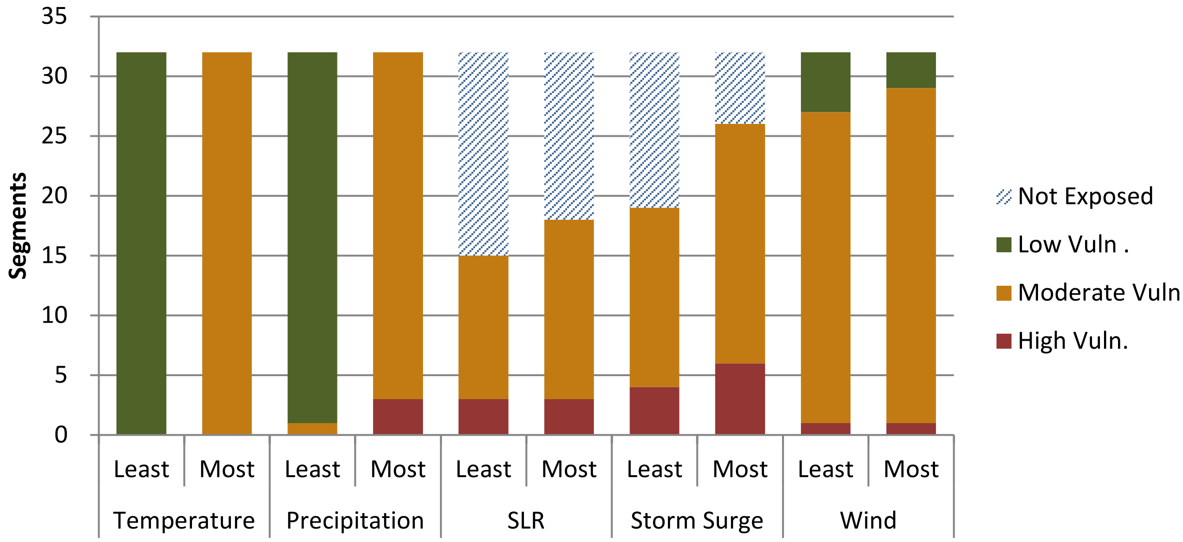
While assessment scored bridges and roads separately, it is more intuitive to consider the integrated vulnerability of the entire highway segment. In practice, the vulnerability of roads and bridges within a given segment need to be considered together; one vulnerable part of a segment means the entire segment may be vulnerable. To accomplish this goal, the assessment also generated asset-scale vulnerability scores based on the maximum score of the bridge and road sub-segments comprising each highway asset.[28] The overall results (which take a broader look across stressors) present findings only at the highway segment level (and not for individual roads or bridges).

### 5.1.1 Overall Results

The range of highway vulnerabilities for each stressor is summarized in Figure 27. Overall, highways are less vulnerable to projected changes in temperature and precipitation, slightly more vulnerable to wind, and most vulnerable to storm surge and sea level rise.

[28] It is important to note that since bridges tended to score slightly higher than roads (due to the differences in indicators and data sources), the highway segments with bridges and culverts tended to score more highly than segments without bridges. Therefore, the combined highway results should be viewed with the understanding that they are slightly skewed toward bridge/culvert-containing segments. Due to the differences in the indicators, it is not accurate to conclude that bridges are in fact more sensitive to temperature than roads.

**Figure 27: Number of Highway Assets that are Not Exposed or have Low, Moderate, or High Vulnerability, By Climate Stressor***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Segment vulnerability is calculated using the maximum vulnerability score across sub-segments.
Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. Assets that are not exposed are considered not vulnerable.

Vulnerabilities are not necessarily uniform across geography. The coastal areas of Mobile are, unsurprisingly, most vulnerable to sea level rise and storm surge, particularly in the areas closest to Downtown as well as the southern tip of Mobile, near Dauphin Island. Precipitation vulnerability tended to be higher near the coast, which is where the land elevation is lower and where more water features are found. Wind vulnerabilities were higher in more developed areas, as the number of intersections, traffic lights, and signage increases. Temperature was one stressor with no clear geographic themes.

It is worth noting that there are substantial similarities between asset vulnerability to sea level rise and asset vulnerability to storm surge. Although the exact vulnerability scores differ, many of the same assets appear in the "top ten" ranked lists for both stressors. This similarity is unsurprising given some overlap in patterns of exposure and shared sensitivity indicators. However, there are additional assets that score as highly vulnerable to storm surge, but did not necessarily score as highly vulnerable to sea level rise, due in part to the fact that more assets are exposed to storm surge than to sea level rise.

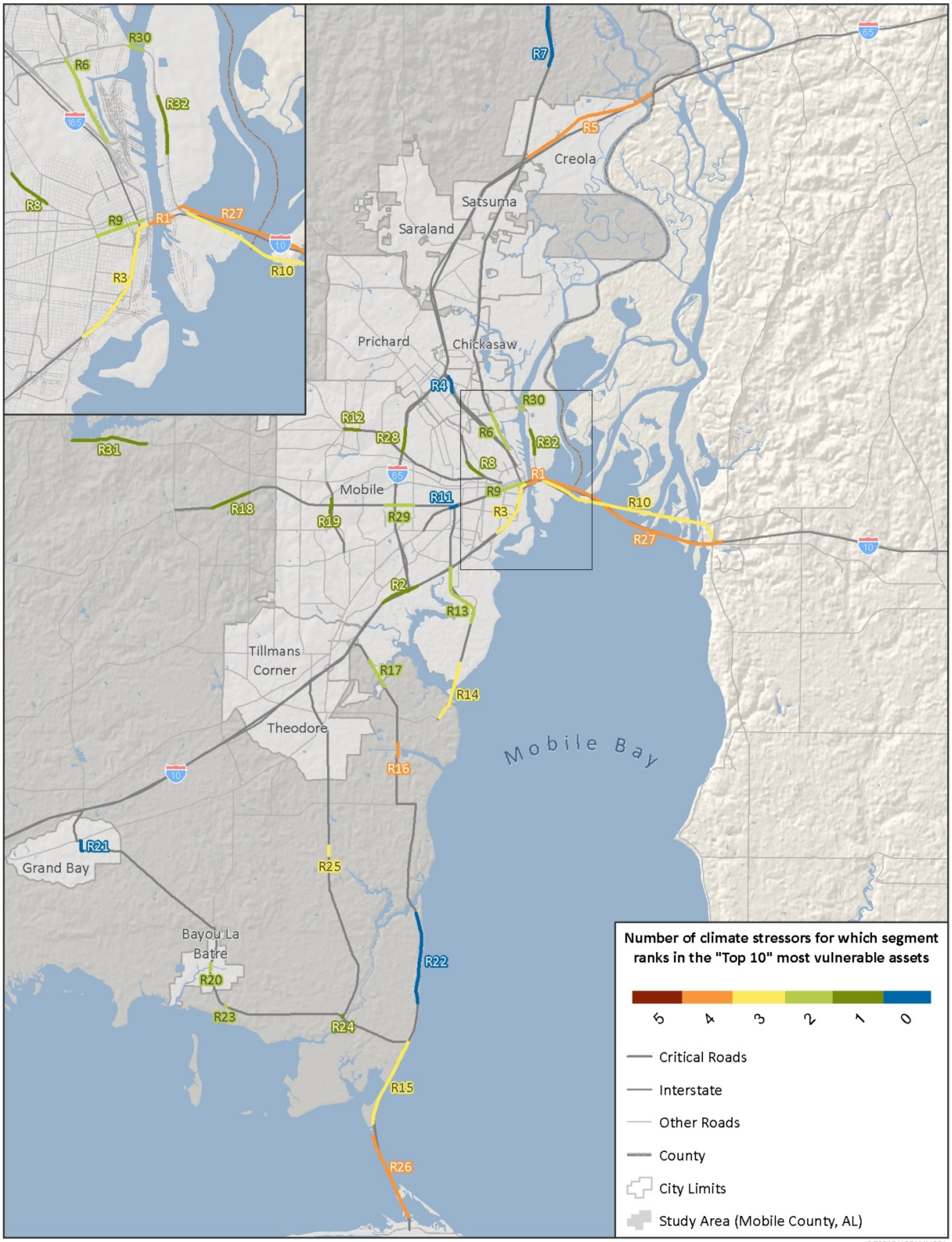
Vulnerabilities to the different stressors differ significantly in terms of the potential cost and nature of damage, the duration of operational disruption, and potential adaptation measures. However, certain assets repeatedly appeared in the "Top 10" most vulnerable assets across all of the climate stressors, as shown in Table 40 and Figure 28.

**Table 40: Highway Segments Most Frequently within the "Top 10" Most Vulnerable Assets across Climate Stressors**

| Least Extreme Narrative* | Most Extreme Narrative* |
|---|---|
| • Wallace Tunnel (R1)<br>• SR-193 (Range Line Road), running about 0.5 mile on either side of Theodore Industrial Canal (R16)<br>• I-10 Bridge across Mobile Bay (R27) | • Wallace Tunnel (R1)<br>• I-65, between US-43 and the County boundary (R5)<br>• SR-193 (Range Line Road), running about 0.5 mile on either side of Theodore Industrial Canal (R16)<br>• Dauphin Island Bridge (R26)<br>• I-10 Bridge across Mobile Bay (R27) |

*In the Least Extreme Narrative, three highway segments scored within the top 10 most vulnerable segments for *all five* of the climate stressors. In the Most Extreme Narrative, no highway segments scored within the top 10 of all stressors, but five scored within the top 10 for four of the climate stressors.

**Figure 28: Number of Climate Stressors for which a Highway Segment Ranks in the "Top 10" Most Vulnerable Segments (most extreme narrative)**



Bridges and highways are analyzed separately and then aggregated. Since the bridge analysis relies on indicators selected from the National Bridge Inventory, the sensitivity and adaptive capacity scores for bridges are usually more robust (relying on a greater number of indicators) than the scores for road segments without bridges. This data availability gap can propel certain road segments without bridges to the top of vulnerability lists (i.e., the vulnerability of the Wallace Tunnel to storm surge and sea level rise). Meanwhile, the use of slightly different indicators for roads and bridges means that the road and bridge scores are not directly comparable. For some climate stressors, bridges tended to have slightly higher scores than roads, but this discrepancy is in some cases due to differences in indicators rather than the fact that bridges are necessarily more vulnerable to roads. Since the overall segment scores were estimated using the maximum score of the sub-segments, segments with bridges might have slightly higher scores than the few road-only segments.

The remainder of this section discusses the climate stressor-specific findings of vulnerability for temperature, precipitation, sea level rise, storm surge, and wind. Each subsection also contains discussions on the completeness of the datasets for the analyses, and the extent to which specific indicators might have a disproportionate impact on the results.

### 5.1.2 Temperature

#### Findings

This vulnerability assessment found that highways are not very sensitive to temperature. All highway segments are rated as having low vulnerability in the least extreme narrative. In the more extreme narrative, when temperature exposure increases significantly, all assets are considered to have moderate vulnerability. This finding is in line with interviews with Mobile stakeholders, which indicated very low sensitivity to temperature. Even though exposure scores were high under the end-of-century hotter narrative, the sensitivity and adaptive capacity scores were low enough that the overall vulnerability is moderate for all segments.

The assessment found that most segments exhibit approximately the same vulnerability to temperature. In other words, distinctions between the most vulnerable and least vulnerable segment in a given narrative are minimal. For example, under the Hotter narrative, the highest score (2.7) was only 0.5 points higher than the lowest score (2.2). Segments with more truck traffic are more sensitive to temperature. However, based on stakeholder input from ALDOT, most critical Mobile routes are constructed using an asphalt binder that is highly resistant to heat,[29] meaning that sensitivity of highways to temperature is fairly low. Furthermore, adaptive capacity is high[30] because disruptions due to heat events (e.g., construction worker safety restrictions, asphalt rutting) are relatively minor and inexpensive to repair. Table 41 shows the

[29] The one location known to experience rutting problems currently (Exit 4 off of I-10) is not captured within our representative segments.

[30] Because high adaptive capacity *decreases* vulnerability, assets with high adaptive capacity have a low score (on a scale of 1 to 4) in the vulnerability screen. Conversely, lack of adaptive capacity would correspond to a high adaptive capacity score.

highway segments most vulnerable to temperature, according to the screen. When the bridge and road segments are considered together, the I-10 intersection with I-65 (R2) and the segment of I-10 between the Tunnel to S Broad Street (R3) emerge as the segments most vulnerable to extreme heat. Both segments have high volumes of truck traffic, which increased their sensitivity to temperature. In addition, they each contain relatively expensive bridge segments, which decreased their adaptive capacity scores.[31]

**Table 41: Highway Segments Most Vulnerable to Temperature in the Least Extreme and Most Extreme Narratives**

| Segment ID | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| R2 | I-10, intersection with I-65 | 1.9 | 2.7 | 97% |
| R3 | I-10, from Wallace Tunnel to S Broad Street | 1.9 | 2.7 | 96% |
| R16 | SR-193 (Range Line Road), running about 0.5 mile on either side of Theodore Industrial Canal | 1.8 | 2.6 | 93% |
| R26 | Dauphin Island Bridge | 1.8 | 2.6 | 100% |
| R27 | I-10 Bridge across Mobile Bay | 1.8 | 2.6 | 96% |
| R30 | Cochrane Bridge (Bay Bridge Road) | 1.8 | 2.6 | 100% |
| R28 | I-165, near intersection with Route 98 | 1.8 | 2.6 | 96% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the highway segments (see page 143 for more information on data availability).

Note: The segment scores shown represent the maximum score of all sub-segments within a given segment.

For full vulnerability scores of all assets (including highway segments and sub-segments), see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

[31] The underlying assumption is that more expensive bridges will be more difficult and expensive to repair and maintain. However, this assumption might be less valid for temperature than for other climate stressors since temperature tends to cause minor pavement damage, which is unrelated to the overall replacement value of the structure.

### Stakeholder Input on Highway Temperature Vulnerability

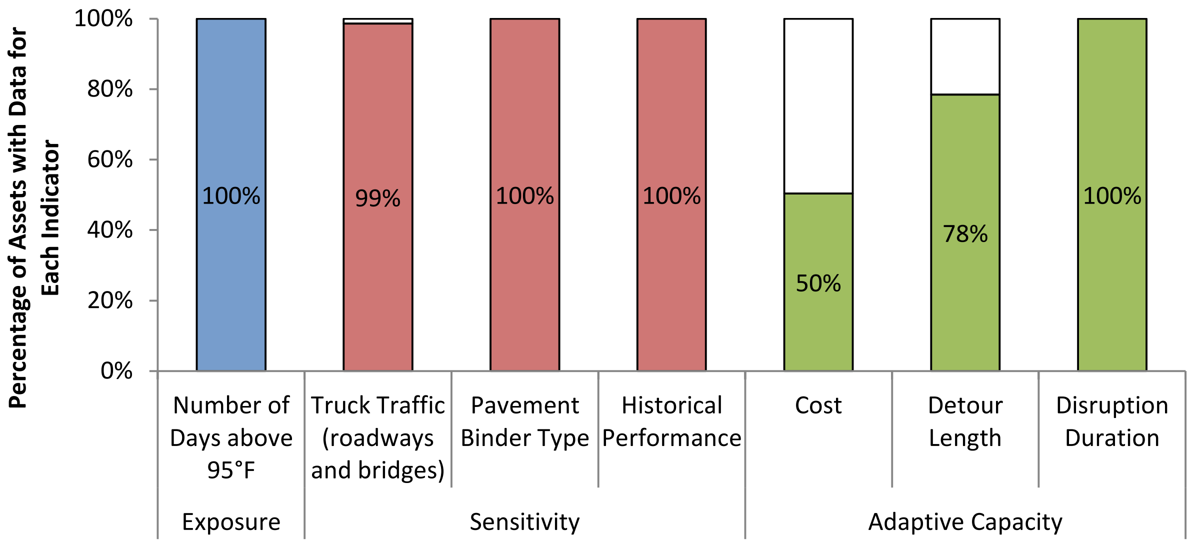
ALDOT, Mobile County, and the City of Mobile agreed that Mobile's highway system is not very vulnerable to high temperatures. They emphasized that infrastructure in Mobile is already designed to withstand extreme heat. While the labor force has some sensitivity to temperature, the County noted that it is not common to limit hours or worker schedules during heat events.[32] ALDOT does adjust worker schedules by one hour in the summer to shift more work to cooler parts of the day.[33]

Stakeholders agreed that while heat may contribute to pavement rutting, most rutting is due to high volumes of truck traffic; since trucks are heavy, they are more likely than cars to rut pavement that has been softened by heat. Currently, rutting is a problem only in a very limited number of locations in Mobile, such as at the bottom of the I-10 Exit 4 Eastbound off-ramp, where many trucks exit the highway and then wait at a traffic light.[34]

## Data Availability

Overall, highways have very complete data availability for temperature indicators, looking across exposure, sensitivity, and adaptive capacity. Approximately one-half of assets have data for all indicators, and the lowest data availability score is 75% (there are four assets with that score). Figure 29 shows how many assets have data for each vulnerability indicator.

Figure 29: Percentage of Assets with Data Available for each Highways Temperature Indicator




Please see Appendix E for information on how data availability scores were calculated.

## Robustness of Results

Missing data or weighting/scoring assumptions for certain indicators could affect final scores or relative rankings somewhat, as discussed below. *However, it is important to remember that there*

[32] Mitchell and Sanchez, 2012
[33] Powell and Reach, 2012
[34] Powell and Reach, 2012

*is a relatively small range of temperature vulnerability scores to begin with.* Therefore, if there is data missing for any given segment, the segment's relative ranking may be affected somewhat, but its overall classification of high, medium, or low vulnerability is likely not impacted significantly.

The analysis showed that of all vulnerability indicators, the sensitivity indicators average daily truck traffic and historical performance have the largest impact on temperature vulnerability scores and relative rankings. Removing either indicator causes vulnerability scores to change, on average, by just two percent (scores decrease without average daily truck traffic and increase without historical performance). These two indicators also affect relative rankings. Disruption duration, an adaptive capacity indicator, also has an impact on results because it is the only adaptive capacity indicator for segments without bridges. Without disruption duration, the vulnerability scores for road-only segments drop and are lower than segments with bridges.

For temperature, the highest-ranked assets are not greatly affected by changes in the indicators used to assess infrastructure sensitivity and adaptive capacity. Without average daily truck traffic, I-10 from the Wallace Tunnel to S Broad Street segment (R3), which is one of the most vulnerable assets according to the methodology, becomes less vulnerable relative to other assets. Beyond that segment, however, those assets in the top 10 ranked assets tend to remain in the top 10, or within a few places of their current ranking. The relative rankings of assets generally moved about 7 spots or less when any one indicator was removed. The assets that appear most affected by changes to the indicators are R4 (I-165, 1 mile before intersection with I-65), R10 (The Causeway), and R13 (a segment of the Dauphin Island Parkway).

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.1.3 Precipitation

#### Findings

Assets showed a greater range of vulnerabilities to projected changes in precipitation, depending on asset locations and characteristics, as well as assumptions about exposure. Under the Drier narrative, the vulnerability of all highway segments is low to moderate across all time frames. However, vulnerability increases to moderate or high under the Wetter narrative, even in the near term, due to the substantial increase in precipitation under the Wetter narrative. Vulnerability scores tended to be slightly higher for bridges/culverts than for roads, so the assets with bridges or culverts tended to score more highly than road-only segments.

Table 42 and Figure 8 show the highway assets that emerged as the most vulnerable according to the screen. The finding that the Causeway (R10) and Bellingrath Road (R25) are the most vulnerable to precipitation is not surprising. Parts of the Causeway are low-lying and known to flood under the right weather conditions; further, several of the Causeway bridges have very low approach heights, and are located in the 100-yr and 500-yr flood zones. The section of

Bellingrath Road near Plantation Woods Drive (R25) is also largely in the 100-yr and 500-yr flood zones, and a bridge there has a low approach that is prone to flood. The segment of the Dauphin Island Parkway (R15) emerged as vulnerable because of its low approach elevation, scour critical condition, and long detour length. However, some results were unexpected. For example, The I-10 Bridge (R27) and Dauphin Island Bridge (R26) also emerge as among the most vulnerable highway assets to precipitation, but they are both large coastal bridges that at first would not seem likely to be flooded from heavy rainfall. Their high vulnerability scores arose from their low adaptive capacity as indicated by high cost and low redundancy. These surprising results raise several points of consideration about the analysis, discussed in the text box below ("Note on Unexpected Findings…") and in the "Key Findings in Methodology" in Section 1.2.

**Table 42: Highway Assets Most Vulnerable to Precipitation in the Least Extreme and Most Extreme Narratives**

| Segment ID | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| R10 | The Causeway (Battleship Parkway) | 2.2 | 3.4 | 90% |
| R25 | CR-59 (Bellingrath Road), 0.5 mile on either side of large stream crossing north of Plantation Woods Drive | 1.8 | 3.0 | 93% |
| R15 | SR-193 (Dauphin Island Parkway), from Dauphin Island Bridge to CR-188 | 1.8 | 3.0 | 83% |
| R27 | I-10 Bridge across Mobile Bay | 1.8 | 3.0 | 84% |
| R26 | Dauphin Island Bridge | 1.7 | 2.9 | 92% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the highway segments (see page 147 for more information on data availability).

Note: The segment scores shown represent the maximum score of all sub-segments within a given segment.

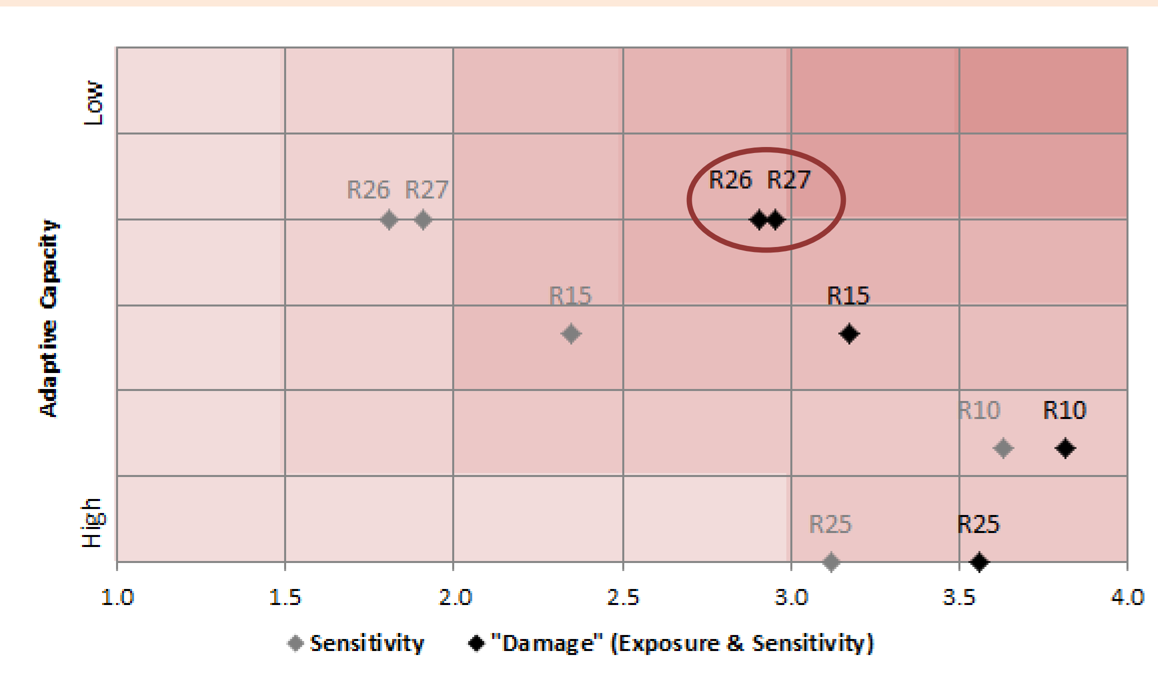
For full vulnerability scores of all assets (including highway segments and sub-segments), see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

### Note on Unexpected Findings in Precipitation Analysis

The results of the analysis show two major coastal bridges, the I-10 Bridge across Mobile Bay (R27) and the Dauphin Island Bridge (R26) as among the most vulnerable highway assets to heavy precipitation in Mobile. They received relatively high vulnerability scores, which are mostly reflective of their relatively low adaptive capacity—despite not being particularly sensitive to damage from heavy precipitation. This finding raises two key issues:

- **Results based on indicators require a "gut check" before being applied**—The indicator-based vulnerability screening approach offers a systematic, transparent approach. However, this type of approach will never perfectly capture local circumstances or asset-specific idiosyncrasies. Instead, this approach provides a starting point for understanding *relative* vulnerability. From the initial screening results, decision-makers may tweak and/or adjust weighting and selection of indicators to reflect local circumstances. Further analyses can be undertaken to understand case-by-case vulnerabilities for assets of concern.
- **The need to evaluate each vulnerability component separately and as part of a whole**—The composite vulnerability scores presented in this study represent a combination of each asset's exposure, sensitivity, and adaptive capacity scores. Nuances of each component are also instructive and should be considered as well. For the I-10 Bridge and the Dauphin Island Bridge, for example, the screen indicates that they are not likely to be damaged by heavy precipitation. This finding implies that adaptive capacity may be unimportant. However, given criticality of these bridges to the community, it is important to capture their low adaptive capacity; these make the point that even small disruptions could have widespread ramifications.

  This distinction can be illustrated graphically. Consider vulnerability as a relationship between likelihood of damage (a combination of exposure and sensitivity) and adaptive capacity. When scores are plotted for the top five most vulnerable highway segments to precipitation, you see that all assets are highly exposed, so all have relatively high "Damage" scores, but assets have different capacities to respond to that damage. A plot like this provides an additional dimension to vulnerability assessments, allowing decision-makers to decide how to incorporate adaptive capacity.



### Stakeholder Input on Highway Precipitation Vulnerability

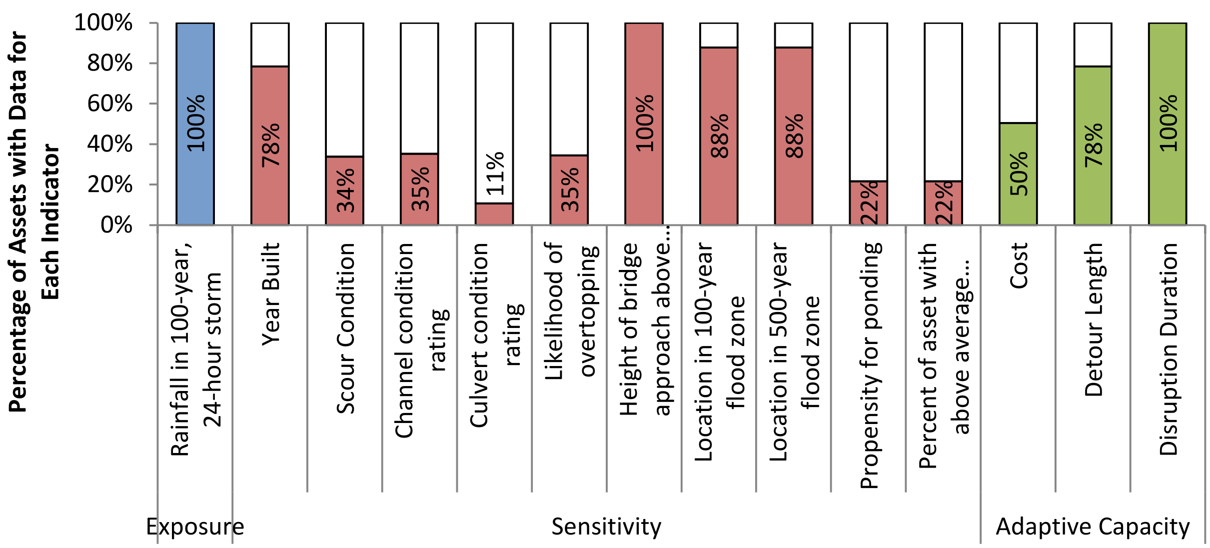
Mobile's flat topography, high rainfall, ongoing development, and older drainage system make it susceptible to flooding during heavy rain. During interviews, ALDOT, the City of Mobile, and Mobile County each identified areas of the system that flood frequently. For example, the County noted that the intersection of SR 188 and CR 59 (Bellingrath Road) near Fowl River (R24) overtops during heavy rain events. ALDOT identified Government Street, particularly the downtown sections, as being prone to flooding during heavy rain.

However, for the most part, roads re-open to traffic within hours of a flooding incident. ALDOT and Mobile County actively maintain and monitor the drainage systems surrounding segments that they know are at risk in order to minimize the likelihood of extreme floods. There is usually little long-term damage from the floods. In a more extreme example, in March and December of 2009, parts of Highway 90 washed out due to extreme flooding. As a result of this experience, ALDOT resized the culvert in order to add in an additional safety factor. They noted that the consequence of the flooding was mitigated by the fact that a good detour exists for that route, so traffic was able to avoid the flooded section of road.

## Data Availability

Of all stressors, data availability for highways was lowest for precipitation. No assets have data for all indicators. Culverts have the highest data availability, with data for 80% of the indicators (weighted).[35] Bridges have data availability ranging between 63% and 78%, and the majority of roadways have data availability of 67%. Five road-only assets have the lowest data availability score for precipitation of 61% of indicators (weighted). Most of the gaps in data availability stem from the sensitivity indicators. Figure 30 shows how many assets have data for each vulnerability indicator.

Figure 30: Percentage of Assets with Data Available for each Highways Precipitation Indicator




35 The data availability percentage is the percentage of the score weight with available data. For each indicator where data is missing, the weight of that indicator is deducted from 100%.

In the final results, the assets with the lowest precipitation vulnerability scores are also those with the lowest data availability, and are predominately roads. Assets in the top two-thirds of vulnerability scores vary in their data availability. It is therefore possible that the results favor showing assets with bridges or culverts as more vulnerable.

Please see Appendix E for information on how data availability scores were calculated.

#### Robustness of Results

Historical performance is the only indicator that, when removed, affects relative vulnerability results for highways. Removing any other indicator leaves largely the same 10 assets as the most vulnerable. The historical performance indicator, which is weighted higher than all other indicators, is responsible for lowering the vulnerability scores of the Wallace Tunnel (R1), the I-10 Bridge across Mobile Bay (R27), and all sub-segments of Range Line Road (R14). Without the historical performance indicator, these assets are among the most vulnerable according to all other indicators, but receive a somewhat lower overall vulnerability score due to the inclusion of historical performance.

Removing any indicator has localized effects on results. For example, for the Wallace Tunnel (R1), all of its sensitivity indicators score a 4, the highest sensitivity, except for the historical performance indicator, which scores a 1. Removing historical performance changes its sensitivity score from a 2.7 to a 4 and brings it from the 13$^{th}$ most vulnerable asset to the 1$^{st}$. Similar individual asset fluctuations occur for the I-10 Bridge across Mobile Bay (R27) with disruption duration and Range Line Road (R16) with detour length. Overall, however, historical performance is the only indicator with an outsized effect on the precipitation vulnerability results, which was an intentional effect per stakeholder feedback.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.1.4 Sea Level Rise

#### Findings

Mobile's coastal highways and bridges are highly vulnerable to sea level rise. Since exposure was scored as a "Yes/No", vulnerability scores for this climate stressor are solely based on sensitivity and adaptive capacity. In particular, sensitivity accounted for two-thirds of the overall score weighting and was the underlying driver for the vulnerability assessment results. Historical performance was a strong determinant of vulnerability because it was weighted higher than the other sensitivity indicators. Therefore, many of the road segments scored as "high" in this screen are known to have experienced flooding problems in the past. For example, the Causeway (R10), Dauphin Island Parkway from Island Road to Terrell Road (R14), and Telegraph Road from downtown to the Bay Bridge Road (R6) have all experienced coastal flooding in the past.

Many of Mobile's highways are too far inland to be exposed to the sea level rise narratives, and are therefore not considered to be vulnerable to sea level rise.

As shown in Table 43, the low-lying coastal segments of the Causeway and Dauphin Island Parkway emerge as the most vulnerable highway assets to sea level rise. The low-lying nature of these segments (or the approaches of the bridges), is a significant factor in their vulnerability. Historical performance is another important driver for the Causeway, since the Causeway is already known to flood in some areas due to high tides and high winds, and this flooding may become more frequent and severe as sea levels rise. Finally, several assets had low adaptive capacity due to lack of alternative routes, high cost of the bridges, and the potential for long-term disruptions due to permanent inundation from sea level rise.

**Table 43: Highway Assets Most Vulnerable to Sea Level Rise in the Least Extreme and Most Extreme Narratives**

| Segment ID | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| R10 | The Causeway (Battleship Parkway) | 4.0 | 4.0 | 86% |
| R14 | SR-163 (Dauphin Island Parkway), from Island Road to Terrell Road | 4.0 | 4.0 | 79% |
| R26 | Dauphin Island Bridge | 3.3 | 3.3 | 100% |
| R1 | I-10 Tunnel (Wallace Tunnel) | 2.8 | 2.8 | 78% |
| R9 | US-90 (SR-16), section east of Broad Street | 2.8 | 2.8 | 78% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of highway and road segments (see page 150 for more information on data availability).

Note: The segment scores shown represent the maximum score of all sub-segments within a given segment.

For full vulnerability scores of all assets (including highway segments and sub-segments), see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

### Stakeholder Input on Highway Sea Level Rise Vulnerability

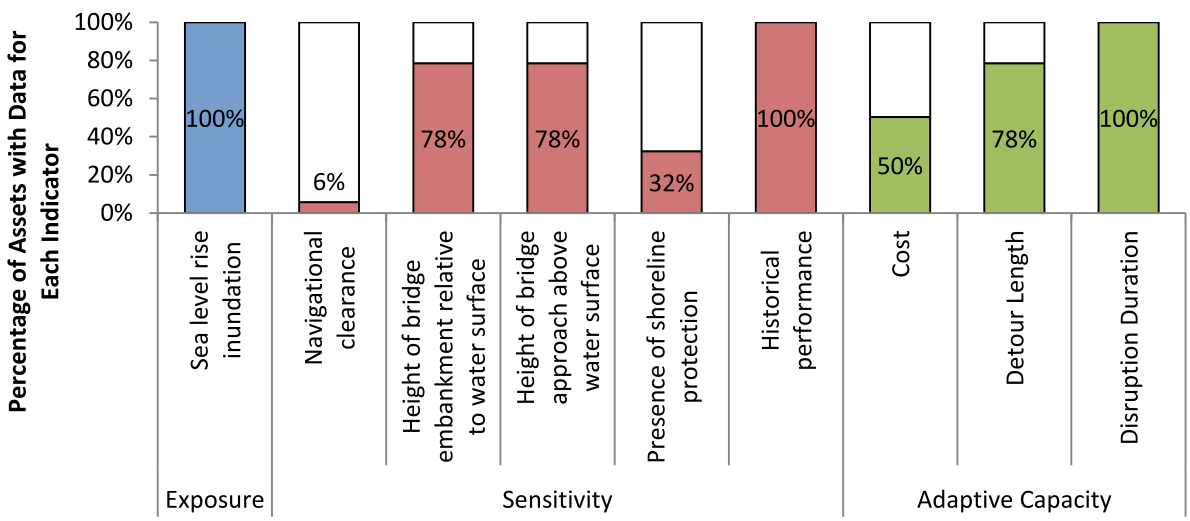
Significant portions of Mobile's road and highway system are low-lying and coastal, which indicates exposure to future sea level rise. While many of the critical roads are protected by some degree of coastal hardening (often riprap), coastal flooding and erosion already pose problems for certain areas. For example, sections of the Causeway and Dauphin Island Parkway flood during the certain wind and tide conditions. As sea levels rise, this flooding could become more common. For this reason, stakeholders suggested that historical performance be given more weight in the vulnerability screen. Some of Mobile's coastal transportation infrastructure is protected from erosion by seawalls and riprap. For example, the Causeway has a barrier rail that protects it from routine flooding. ALDOT noted that without this barrier, the Causeway would flood much more frequently. The causeway to Dauphin Island also has a seawall.[36]

## Data Availability

Data availability for sea level rise was reasonably good overall. On average, the assets studied have data for 76% of the sea level rise vulnerability indicators (weighted).[37] All assets have data for exposure. For sensitivity, all road sub-segments have 100% data availability, and all bridges/culverts have data for at least two of the three bridge sensitivity indicators. For adaptive capacity, about half of the assets did not have data for replacement cost and about a fifth did not have data for detour length. Figure 31 shows the percentage of assets with data for each sea level rise indicator. Overall, data availability does not appear to have an effect on sea level rise vulnerability results, showing no correlation with either asset rank or vulnerability score.

Please see Appendix E for information on how data availability scores were calculated.

Figure 31: Percentage of Assets with Data Available for each Highways Sea Level Rise Indicator




36 Powell and Reach, 2012

37 The data availability percentage is the percentage of the score weight with available data. For each indicator where data is missing, the weight of that indicator is deducted from 100%.

### Robustness of Results

For sea level rise vulnerability, the historical performance sensitivity indicator and the disruption duration adaptive capacity indicator appear to be the largest drivers of the results. Historical performance is a dominant indicator, particularly for road assets, because it is one of only two sensitivity indicators and, further, is more heavily weighted than shoreline protection. If the two indicators have different scores from an asset, removing one can drastically change the asset's score. For example, twelve assets, all roads, jump from scores of 2.8 to 4.0 when historical performance is removed, and they become the most vulnerable of all highway assets. Disruption duration, as for all stressors, is another important driver of sea level rise results. Because disruption duration is the only adaptive capacity indicator for all 30 road assets, it contributes directly to a third of the overall vulnerability score.

For sea level, no one indicator has a disproportionate effect on results, though removing any indicator affected how vulnerable some assets were in relation to others. Detour length above water had the biggest effect on asset rankings, and, on average, caused an asset to move 8 spots in the relative rankings of asset vulnerability. Detour length did not affect rankings among the most or least vulnerable assets, but shifted rankings for assets in the middle. Historical performance and approach height were the only indicators that influenced results among the *most vulnerable* assets. Removing historical performance would cause several road assets to score as highly vulnerable and removing approach height causes several sub-segments of the Causeway (R10) to become less vulnerable.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.1.5 Storm Surge

### Findings

Highways in Mobile have moderate to high vulnerability to storm surge *when exposed*. About a fifth of exposed representative assets are highly vulnerable and none have low vulnerability. The likelihood and extent of damage from storm surge drives these vulnerabilities. In other words, the most vulnerable assets are those likely to be damaged by the surge, and also to be more difficult to repair. The assets with the highest storm surge vulnerability are those close to the downtown area of Mobile, close to the Mobile Bay, or near Dauphin Island Bridge in the south.

Table 44 and Figure 13 show the highway assets that emerged as the most vulnerable according to the screen. The most important driver of their vulnerability is that they have demonstrated vulnerability in the past during hurricanes like Katrina and Gustav. With the exception of the I-10 Bridge (R27), all have experienced flooding and damage from hurricanes in the past, demonstrating vulnerability to storm surge. Furthermore, these assets contain bridges or approaches that are both relatively low-lying and also projected to be exposed to significant storm surges under the modeled scenarios. For example, even under the less severe Katrina narrative, the Causeway (R10) is predicted to be exposed to storm depths of over 17 feet (including wave height). In the most severe Katrina narrative, predicted storm surge depths at the Causeway is over 29 feet. In addition, several of these bridges have low approach and embankment heights, which make them more likely to be flooded.

**Table 44: Highway Assets Most Vulnerable to Storm Surge in the Least Extreme and Most Extreme Narratives**

| Segment ID | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| R6 | Telegraph Road, from Downtown to Baybridge Road | 3.2 | 4.0 | 92% |
| R10 | The Causeway (Battleship Parkway) | 3.2 | 4.0 | 91% |
| R1 | I-10 Tunnel (Wallace Tunnel) | 3.2 | 3.6 | 87% |
| R14 | SR-163 (Dauphin Island Parkway), from Island Road to Terrell Road | 3.2 | 3.6 | 81% |
| R27 | I-10 Bridge across Mobile Bay | 2.5 | 3.3 | 86% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of highway and road segments (see page 152 for more information on data availability).

Note: The segment scores shown represent the maximum score of all sub-segments within a given segment.

For full vulnerability scores of all assets (including highway segments and sub-segments), see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Highway Storm Surge Vulnerability**

The City of Mobile, Mobile County, and ALDOT agreed that storms are the biggest vulnerability of Mobile's highway system. Due to the low elevation of the area, even an 8-10 foot (2.4 to 3.0 meter) storm surge will inundate Dauphin Island and flood much of the coast. ALDOT noted that the Bankhead Tunnel has floodgates on the east end since it is lower and less protected than the west end. The agency closes the tunnel in the event of a tropical storm. The Wallace Tunnel does not have floodgates, and it flooded during Katrina.[38] The stakeholders concurred that infrastructure that has been damaged during past storms is more likely to be damaged in the future.

### Data Availability

Overall, data availability for storm surge is reasonably good. No asset has data availability lower than 78%. Seven highway assets have complete datasets for all storm surge exposure, sensitivity,

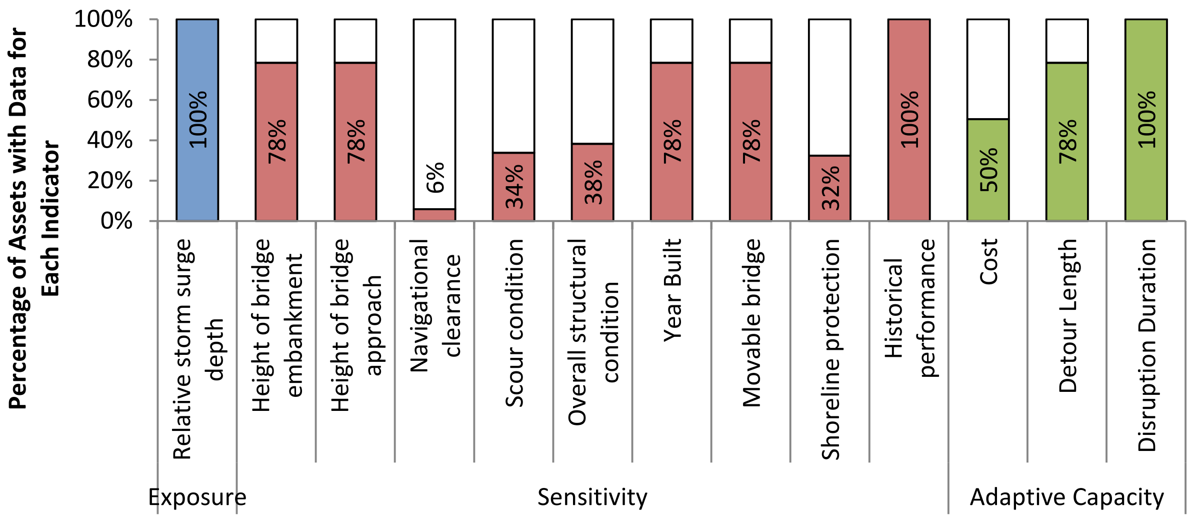
[38] Powell and Reach, 2012

and adaptive capacity indicators. On average, highways assets have data available for 88% of storm surge indicators (weighted).[39]

All road sub-segments have data available for 87% of storm surge vulnerability indicators: they have full data for exposure, both sensitivity indicators, and have data only for disruption duration under adaptive capacity. Data availability for bridge/culvert sub-segments is more varied. Many bridges/culverts are missing data for the sensitivity indicators of navigation vertical clearance, scour condition, or the bridge condition ratings and the adaptive capacity indicator of replacement cost. Figure 32 shows the percentage of assets with data for each storm surge indicator.

Please see Appendix E for information on how data availability scores were calculated.

Figure 32: Percentage of Assets with Data Available for each Highways Storm Surge Indicator




## Robustness of Results

It does not appear than any one indicator is disproportionately affecting the storm surge results. The storm surge vulnerability results hold even if certain indicators are not included. Even removing the indicator with the largest weight—historical performance—does not affect relative results because that indicator is in agreement with the other indicators. Removing any storm surge sensitivity or adaptive capacity indicator leaves the same five assets as most vulnerable. Removing indicators shifts the relative scores in the middle range of assets, but overall does not affect the results.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

[39] The data availability percentage is the percentage of the score weight with available data. For each indicator where data is missing, the weight of that indicator is deducted from 100%.

### 5.1.6 Wind

#### Findings

This vulnerability assessment found that highway segments can become vulnerable to wind once the wind speed exceeds a given threshold. Most bridges are designed to withstand wind speeds of 100 to 150 mph for inland and coastal bridges,[40] respectively, and the predicted wind speeds associated with the Katrina storm narratives varied from 71 to 120 mph. In many cases, the assets' design thresholds were not exceeded by the modeled wind speeds (particularly in the case of bridges), reducing the vulnerability of highway segments to wind. However, wind speeds negatively impact signs, power lines, and service at lower thresholds, generally starting at around 74 mph.[41] Thus, under less extreme storm narratives, the vulnerabilities of the highways to wind stem not from significant vulnerability to structural damage to a bridge or roadway itself, but to the signs or signals that are important components of smooth operation of the highway, as well as the potential for traffic to be disrupted due to high winds. Under more extreme storm narratives, the thresholds of certain inland bridges are exceeded, indicated an increased possibility for structural damage to bridges.

The highway segments with a high density of traffic signals tend to be the most vulnerable.[42] These results rely on the assumption that the more traffic signals there are, the more likely it is that at least one of them could sustain damage. The other key driver of vulnerability are where the wind speed exposure exceeds the wind speed design threshold of the roadway operation or bridge, which occurs mainly on roadways, and also on inland bridges under the most extreme narratives.

As shown in Figure 11 and Table 45, downtown road segments and highways with inland bridges emerge as the most vulnerable highway assets to wind.

**Table 45: Highway Assets Most Vulnerable to Wind in the Least Extreme and Most Extreme Narratives**

| Segment ID | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| R9 | US-90 (SR-16), section east of Broad Street | 3.6 | 3.6 | 87% |
| R8 | US-45 (St. Stephens Road), between Rylands Street and Simington Drive | 2.8 | 2.8 | 93% |
| R12 | Route 98 near the Stickney Filtration Plant | 2.8 | 2.8 | 93% |

40 Powell, 2012, citing AASHTO, 1983 and AASHTO, 2008

41 OFCM, 2002

42 It is important to note that debris on the road is a common source of traffic disruption from high wind events. However, debris can come from a variety of sources, including trees and other vegetation, buildings, etc. A good indicator for areas prone to debris was not identified in this analysis, and the potential for debris is therefore not captured in these results.

| Segment ID | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| R18 | Airport Blvd, between CR-31 (Schillinger Road) and airport | 2.8 | 2.8 | 87% |
| R19 | South University Blvd, 0.5 mile segment either side of CR-56 (Airport Blvd) | 2.8 | 2.8 | 87% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of highway and road segments (see page 155 for more information on data availability).

Note: The segment scores shown represent the maximum score of all sub-segments within a given segment.

For full vulnerability scores of all assets (including highway segments and sub-segments), see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

### Stakeholder Input on Highway Wind Vulnerability

ALDOT, the City of Mobile, and Mobile County agreed that it is very difficult to predict where damage from wind will occur. Wind damage is often due to debris, which can happen anywhere. Historically, ALDOT has experienced trouble with traffic signals and (to a lesser extent) with traffic signs. ALDOT is currently doing signal runs and changing to mast-arms to save on maintenance money. They noted that many of their highway decisions are driven by maintenance costs. The highway stakeholders recommended consulting the ASCE design standards to determine the sensitivity of highways to wind. While road structures are not sensitive to wind, bridges, traffic signals, and road signs are sensitive. ALDOT builds bridges to the ASCE-17 design standards, which specifies 150 mph for coastal bridges and 100 mph for inland bridges.

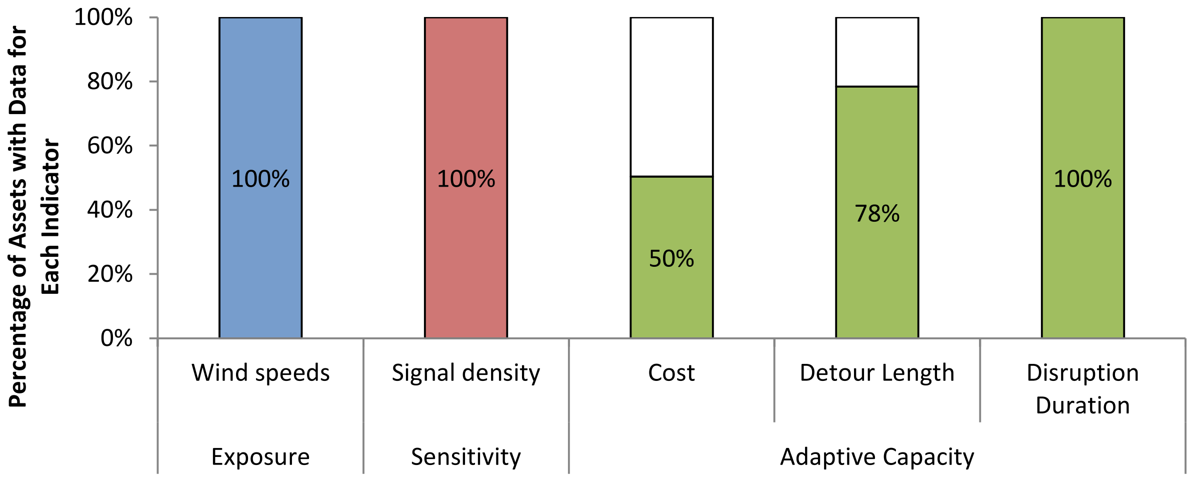
## Data Availability

Highway assets have high data availability for wind vulnerability indicators. About half of assets have data available for 100% of indicators, 28% of assets have data for 93% of indicators (weighted).[43] The remaining assets have data for 87% of the weighted vulnerability score. All data gaps are in the adaptive capacity indicators of replacement cost and detour length (see Figure 33).

Please see Appendix E for information on how data availability scores were calculated.

[43] The data availability percentage is the percentage of the score weight with available data. For each indicator where data is missing, the weight of that indicator is deducted from 100%.

**Figure 33: Percentage of Assets with Data Available for each Highways Wind Indicator**




### Robustness of Results

Because there is only one sensitivity indicator for wind, the scores for that indicator (roadway sign/signal density) are a primary driver of the vulnerability results. Fortunately, all assets had data available for this indicator. The other primary driver is disruption duration, which is the sole indicator with data for the adaptive capacity component for all road sub-segments. Because of the limited number of indicators for wind, changes or data gaps in any of them, particularly roadway signal density and disruption duration, affect the ultimate results. Removing disruption duration, for example, lowers vulnerability scores for roads relative to bridges, and therefore drops sub-segments like US-45 (R8), Route 98 (R12), Dauphin Island Parkway (R13), CR-56 (R18 and R29), and South University Boulevard (R19) out of the top most vulnerable assets.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.2 Ports Results

### 5.2.1 Overall Results

The port and marine waterway system in Mobile is highly vulnerable to storm surge and moderately vulnerable to sea level rise and increases in precipitation. The Alabama State Port Authority (ASPA) State Docks facility is the most vulnerable port across stressors with particularly high vulnerability to storm surge and sea level rise. This older facility has a lower elevation, little shoreline protection, and is in worse condition compared to other ports. Figure 34 summarizes the vulnerabilities of critical port facilities.

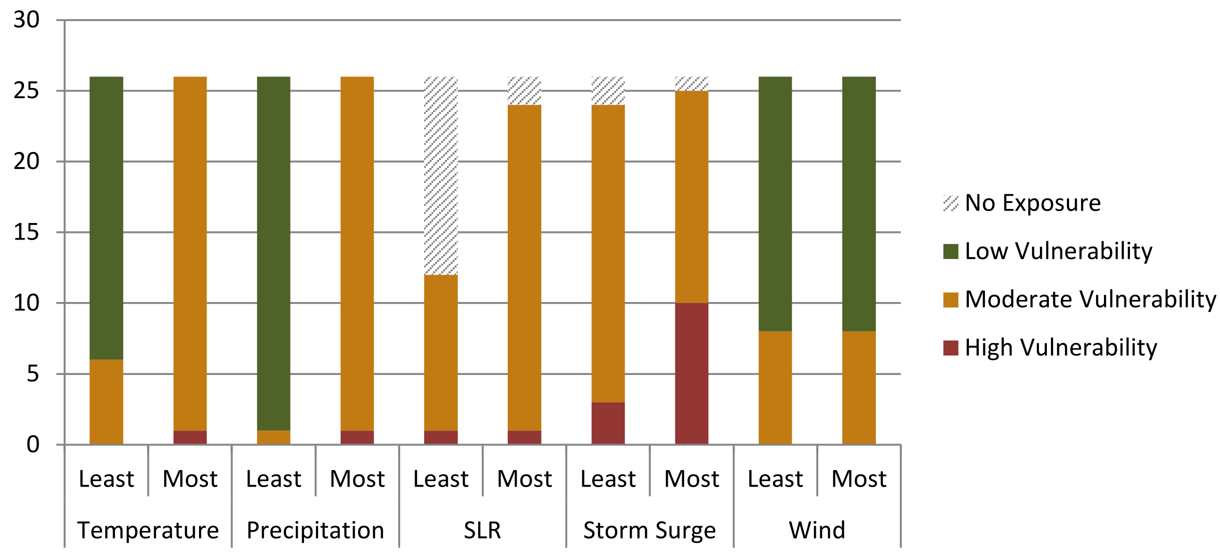
Overall, highly vulnerable ports tend to share the following characteristics:

- Low elevation
- Advanced age or sub-optimal condition

- Reliance on electricity
- History of damage due to flooding or storm surge
- Inability to shift operations to other facilities or within the same facility

Furthermore, vulnerability tends to be greater from climate stressors that may take a long time to recover from (such as storm surge) compared to other stressors that may cause less dramatic service disruption or cost of repairs (like temperature).

**Figure 34: Number of Ports that are Not Exposed or have Low, Moderate, or High Vulnerability, by Climate Stressor***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.
Low = vulnerability score from 1.0 to 1.9; Moderate = score from 2.0 to 2.9; High = score from 3.0 to 4.0. Assets that are not exposed are considered not vulnerable.

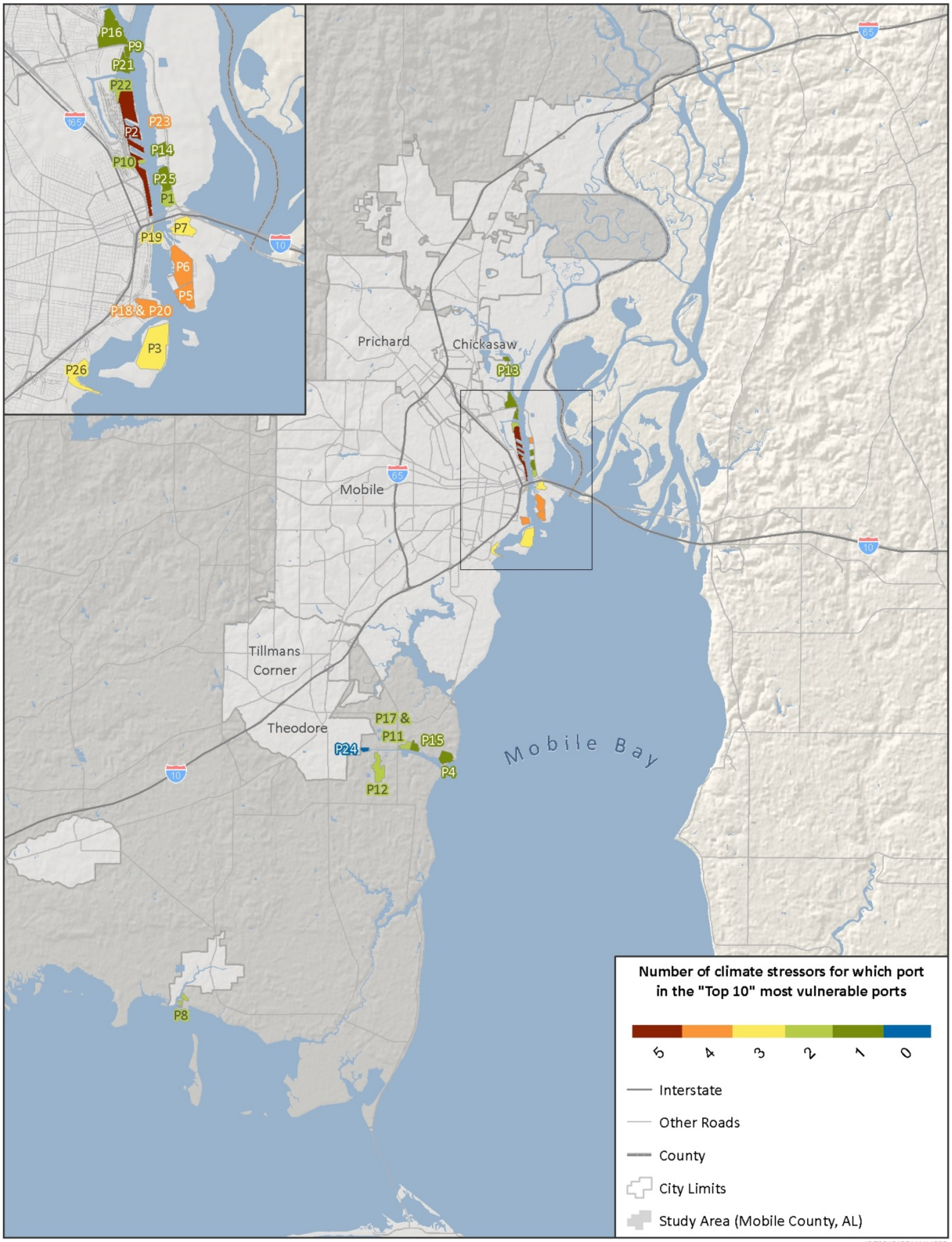
Certain ports repeatedly appeared in the "Top 10" most vulnerable ports across all of the climate stressors, as shown in Table 46 and Figure 35.

**Table 46: Ports Most Frequently within the "Top 10" Most Vulnerable Assets across Climate Stressors**

| Least Extreme Narrative* | Most Extreme Narrative* |
|---|---|
| • Alabama State Port Authority (ASPA)—Alabama State Docks Main Complex (P2)<br>• Atlantic Marine (BAE Systems Southeast Shipyards) (P6)<br>• Mobile Container Terminal (P18)<br>• Shell Chemical Co. (P23)<br>• U.S. Coast Guard Pier (P26) | • Alabama State Port Authority (ASPA)—Alabama State Docks Main Complex (P2)<br>• Atlantic Marine (BAE Systems Southeast Shipyards) (P6)<br>• Mobile Container Terminal (P18)<br>• Shell Chemical Co. (P23)<br>• Alabama State Port Authority (ASPA)—Pinto Island (P5) |

*In both the Least and Most Extreme Narratives, only Alabama State Docks Main Complex scored in the top 10 for all five climate stressors; the others scored in the top 10 for four of five stressors.

Figure 35: Number of Climate Stressors for which a Port Ranks in the "Top 10" Most Vulnerable Ports (most extreme narrative)



The remainder of this section discusses the climate stressor-specific findings of vulnerability for temperature, precipitation, sea level rise, storm surge, and wind. Each subsection also contains discussions on the completeness of the datasets for the analyses, and the extent to which specific indicators might have a disproportionate impact on the results.

### 5.2.2 Temperature

#### Findings

Even under the most extreme scenario, Mobile's port system exhibits a low to moderate vulnerability to projected temperature increases. Sensitivity of ports to temperature is low, partially because ports have not historically experienced noticeable impacts during heat events. In addition, the ability of ports to recovery from and adapt to increased temperatures is high. ASPA's Pinto Island facility is the only asset that exhibits high vulnerability under the most extreme temperature narrative. The facility's lack of operational redundancy and high reliance on electricity drive its vulnerability. For additional information on the vulnerability of ports to temperature, see Table 47.

Within each climate narrative and timeframe, the analysis identifies certain ports (e.g., Pinto Island) to be more vulnerable than others (e.g., Gulf Coast Asphalt) due to port-specific sensitivities and adaptive capacity factors such as material handled, reliance on electricity, and operational redundancy. However, the choice of exposure narrative drives significant differences in scores between the warmer and hotter narratives and the three time frames. As shown in Figure 7, the vulnerability scores of most ports increase from low to moderate from the less extreme (warmer, near-term) to most extreme (hotter, end-of-century) narratives due to the projected increases in temperature.

**Table 47: Ports Most Vulnerable to Temperature in the Least Extreme and Most Extreme Narratives**

| ID | Port Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| P5 | Alabama State Port Authority (ASPA)—Pinto Island | 2.4 | 3.0 | 100% |
| P7 | Austal | 2.2 | 2.9 | 100% |
| P23 | Shell Chemical Co. | 2.2 | 2.8 | 100% |
| P2 | Alabama State Port Authority (ASPA)—Alabama State Docks Main Complex | 2.1 | 2.8 | 100% |
| P18 | Mobile Container Terminal | 2.1 | 2.8 | 100% |
| P3 | Alabama State Port Authority (ASPA)—McDuffie Terminal | 2.1 | 2.7 | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each port (see page 161 for more information on data availability).

For full vulnerability scores, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

### Stakeholder Input on Ports Temperature Vulnerability

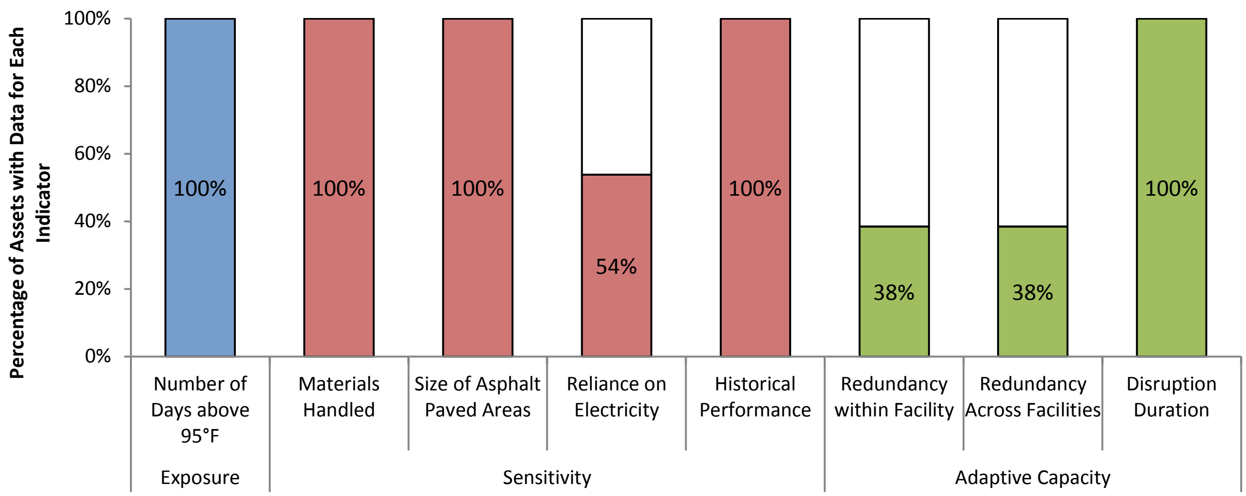
Stakeholders agreed that Mobile's port system exhibits very low vulnerable to high temperatures. They emphasized that infrastructure in Mobile is already designed to withstand extreme heat. While high temperatures could potentially exacerbate low water levels and increase dredging needs during a drought, the region has never had to dredge waterways due to heat events. The ports do not experience safety or labor force issues during periods of extreme heat.

## Data Availability

Overall, ports have incomplete data availability for three of the eight temperature indicators used across exposure, sensitivity, and adaptive capacity. Nearly forty percent of assets have data for all indicators, but there are 12 ports with the lowest data availability score of 71%. Figure 36 shows how many assets have data for each vulnerability indicator. The top 10 most vulnerable ports were all ports with 100% data availability.

Please see Appendix E for information on how data availability scores were calculated.

Figure 36: Percentage of Assets with Data Available for each Ports Temperature Indicator




## Robustness of Results

Patterns in data availability and indicator weighting and scoring assumptions moderately affect the temperature vulnerability scores and rankings. Removing the historical performance, size of paved asphalt areas, or disruption duration indicators alters the vulnerability scores by between 4 and 6 percent on average. For example, removing the historical performance indicator causes scores to increase by an average of 6 percent. This result occurs because data availability for historical performance is 100% and not a single port has experienced disruptions due to extreme heat in the past.

The relative vulnerability ranking of ports is moderately affected by changes in indicators. While the ASPA Pinto Island and Austal facilities remain the two most vulnerable ports across all indicator scenarios, removing indicators impacts the relative ranking of other vulnerable ports such as Shell Chemical Co and the Alabama State Docks Main Complex. For example, Shell Chemical Co is ranked as the third most vulnerable asset in the vulnerability screen. However, it ranges from second most vulnerable (when the size of paved asphalt indicator is removed) to fifth most vulnerable (when either the reliance on electrical power or redundancy across facilities indicator is removed).

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.2.3 Precipitation

#### Findings

The port system's vulnerability to changes in precipitation events depends greatly on whether today's extreme rain events become more frequent and severe, or not. If they do, as projected under the "wetter" narrative in this study, then portions of Mobile's port system are vulnerable to these changes. Two important drivers of vulnerability to increases in heavy precipitation are whether the port has historically flooded during heavy rain events and the location of the port in the 100-year flood zone. Differences in the adaptive capacity of ports also drive vulnerability results. For example, the only asset analyzed as highly vulnerable to precipitation events is Shell Chemical Co. This facility has unusually low adaptive capacity because it is reliant on import of feedstocks and export of products via marine movements. In the event of a power outage, the facility would be unable to operate after the limited amount of crude oil in inventory was consumed. For more information on the vulnerability of port facilities to precipitation, please see Table 48.

**Table 48: Ports Most Vulnerable to Precipitation in the Least Extreme and Most Extreme Narratives**

| Segment | Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| P23 | Shell Chemical Co. | 2.2 | 3.2 | 100% |
| P10 | Crescent Towing and Salvage Co A Wharf | 1.9 | 2.9 | 67% |
| P11 | Environmental Treatment Team Wharf | 1.9 | 2.9 | 61% |
| P6 | Atlantic Marine (BAE Systems Southeast Shipyards) | 1.8 | 2.8 | 100% |

| Segment | Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| P18 | Mobile Container Terminal | 1.7 | 2.7 | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the ports (see page 163 for more information on data availability).

For full vulnerability scores, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Port Precipitation Vulnerability**

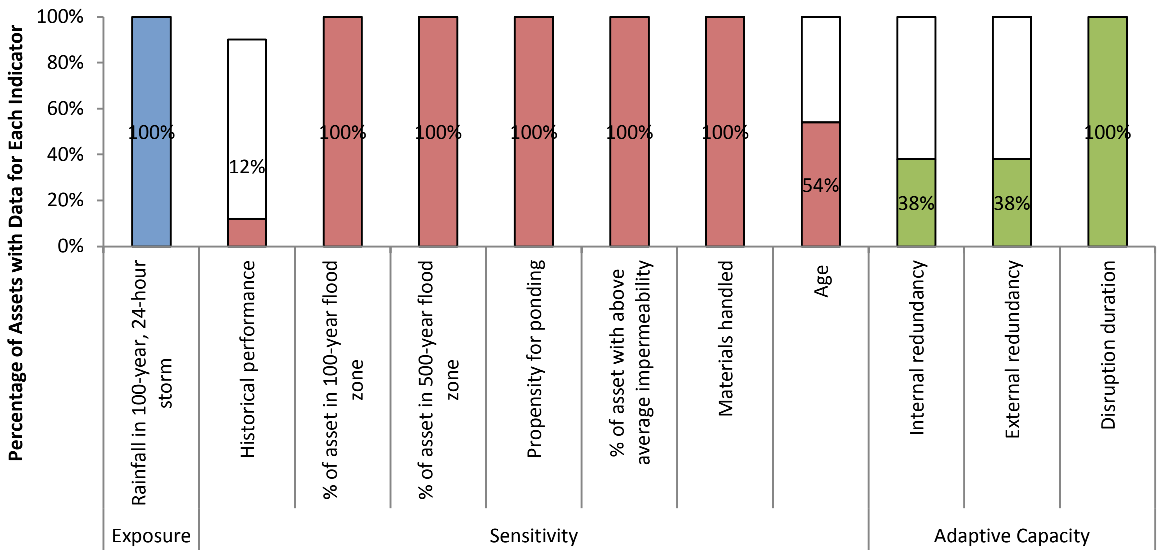
Mobile's flat topography, high rainfall, ongoing development, and older drainage system make it susceptible to flooding during heavy rain. Stakeholders mentioned that some of the ports, particularly in Mobile Bay, have problems draining during heavy rain. However, these issues are not generally disruptive to port activities. Stakeholder also indicated that precipitation increases runoff and erosion, which increases dredging requirements. However, dredging frequency is driven by a number of other factors (including budget availability), so it is difficult to connect the amount of dredging in any given year to the amount or type of rainfall events of that year.

## Data Availability

Overall, ports have fairly low data availability for precipitation indicators, looking across exposure, sensitivity, and adaptive capacity. Only twenty percent of assets have data for all indicators, and the lowest data availability score is 61% (there are twelve assets with that score). Figure 37 shows how many assets have data for each vulnerability indicator.

Please see Appendix E for information on how data availability scores were calculated.

**Figure 37: Percentage of Assets with Data Available for each Ports Precipitation Indicator**




### Robustness of Results

The precipitation vulnerability scores of port assets remain fairly consistent when individual indicators are removed from the analysis. Removing either the disruption duration or materials handled indicator changes the overall scores by an average of plus or minus two percent respectively.

For precipitation, the highest-ranked assets are somewhat affected by changes in the indicators used to assess infrastructure sensitivity and adaptive capacity. Shell Chemical Co and Crescent Towing & Salvage Co., River A Wharf rank consistently as the two most vulnerable assets across nearly all of the indicator scenarios. Other highly vulnerable assets, such as the Environmental Treatment Team Wharf and Atlantic Marine (BAE Systems Southeast Shipyards) vary across the indicator scenarios, but remain in the list of top ten ports most vulnerable to precipitation. The Environmental Treatment Team's ranking drops from 3$^{rd}$ to 7$^{th}$ place when the materials handled indicator is removed, whereas the Atlantic Marine facility rises from 4$^{th}$ place to 2$^{nd}$ place in that same scenario. These adjustments reflect the strong influence of the materials handled indicator.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.2.4 Sea Level Rise

### Findings

Mobile's ports are moderately vulnerable to sea level rise. Under the 30 cm scenario, just under half of the critical port facilities are projected to be inundated. However, despite relatively high exposure, port sensitivity to sea level rise tends to be low, due to a high degree of shoreline protection. Interviews with stakeholders indicated that port facilities do not currently experience flooding during high tide events. The more vulnerable assets tend to be older facilities with less shoreline protection and little ability to shift operations to another facility or area. The three most vulnerable assets are the ASPA State Docks Complex and the North and South Terminals of Plains Marketing. The North Terminal only emerges as inundated (and vulnerable) in the 200cm sea level rise scenario. For more information on the vulnerability of port facilities to sea level rise, please see Table 49 and Figure 9.

### Stakeholder Input on Port Sea Level Rise Vulnerability

Mobile's port system is low-lying and coastal, which indicates exposure to future sea level rise. However, most of the critical ports are either elevated or protected by some degree of coastal hardening (often riprap). Stakeholder indicated that coastal flooding during extreme high tides is not currently a problem for ports. However, as sea levels rise, flooding and erosion could become more common.

Also, sea level rise is not necessarily problematic for certain ports that contain floating docks or that need minimum levels of water to accommodate large vessels. As long as the main port areas are at a high enough elevation to not be inundated, they can easily accommodate a certain degree of sea level rise, as their docks will float. A representative at Austal noted that sea level rise could actually help them accommodate larger vessels and the equipment needed to work on them (Kujala 2012).

**Table 49: Ports Most Vulnerable to Sea Level Rise in the Least Extreme and Most Extreme Narratives**

| Sub-segment | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| P2 | Alabama State Port Authority (ASPA)—Alabama State Docks Main Complex | 3.7 | 3.7 | 78% |
| P22 | Plains Marketing—South Terminal | 2.8 | 2.8 | 45% |
| P21 | Plains Marketing—North Terminal | Not Exposed | 2.8 | 45% |
| P5 | Alabama State Port Authority (ASPA) - Pinto Island | 2.5 | 2.5 | 78% |
| P8 | Bayou La Batre | 2.5 | 2.5 | 31% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the ports (see page 166 for more information on data availability).

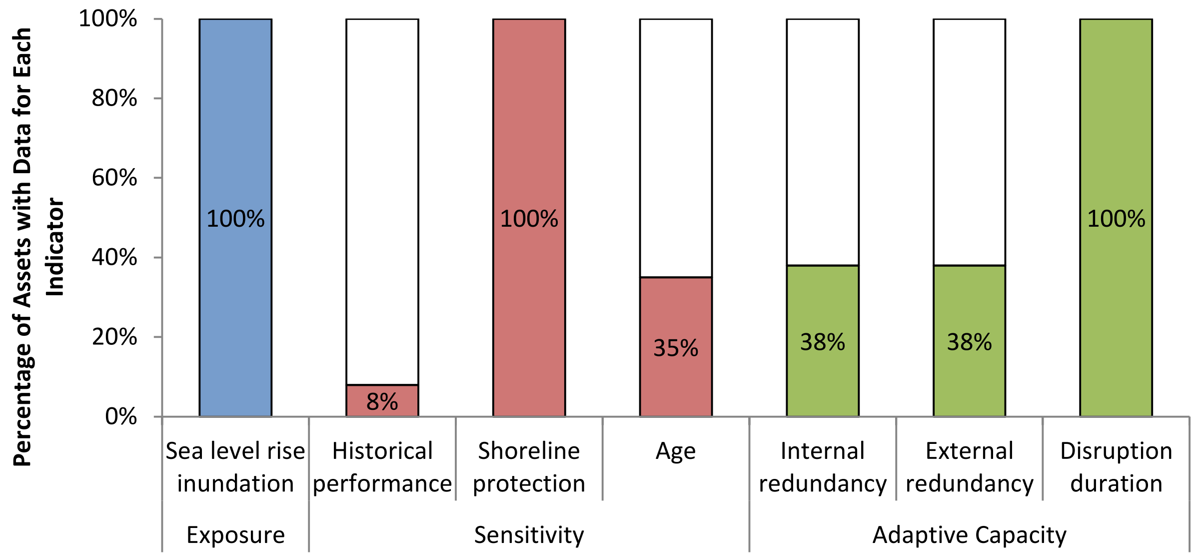
For full vulnerability scores of all ports, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

### Data Availability

Overall, ports have fairly low data availability for sea level rise indicators, looking across exposure, sensitivity, and adaptive capacity. Only twelve percent of assets have data for all indicators, and the lowest data availability score is 31% (there are twelve assets with that score). Figure 38 charts the percentage of assets with data for each sea level rise indicator. Only three of the indicators (exposure, shoreline protection, and disruption duration) are available for all assets. The remaining four indicators are only available for between eight and thirty-eight percent of assets.

Please see Appendix E for information on how data availability scores were calculated.

Figure 38: Percentage of Assets with Data Available for each Ports Sea Level Rise Indicator




### Robustness of Results

For sea level rise vulnerability, the shoreline protection score is the strongest driver of the results. This finding occurs because shoreline protection is one of only three sensitivity indicators and has the highest data availability of the three. Since sensitivity and exposure are weighted more heavily than adaptive capacity, the shoreline protection score ends up driving the final vulnerability score. Removing the shoreline protection indicator caused port vulnerability scores to decrease by an average of 7 percent.

Despite the influence of the shoreline protection score, the Alabama State Docks Main Complex and the North and South Terminals of the Plains Marketing port are consistently ranked as the three most vulnerable facilities, even when the shoreline protection indicator is removed from the analysis. However, most of the other port facilities experience significant changes in rank when different indicators are removed.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.2.5 Storm Surge

#### Findings

Mobile's port system is largely coastal and vulnerability of facilities to storm surge is very high. Even in the less extreme storm surge scenario, nearly all critical facilities experience at least some degree of inundation, with average surge depths of over 12 feet (4 meters). Under the most extreme storm scenario, average projected flooding depths at the critical ports are nearly 25 feet (8 meters), including wave height. This high exposure results in high vulnerability for those exposed facilities that are also sensitive and have a low capacity to adapt. For example, the Alabama State Docks Main Complex (P2), McDuffie Terminal (P3), and Austal (P7) score as highly vulnerable because of their location, lack of redundancy, history of flooding, and reliance on electricity. For more information on the vulnerability of port facilities to storm surge, please see Table 50 and Figure 10 in this report. Detailed maps of results are also available in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/, and full vulnerability scores are available in the result summary spreadsheet accompanying this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3.

**Stakeholder Input on Port Storm Surge Vulnerability**

Port stakeholders agreed that storm surge is the extreme weather impact of greatest concern. However, they felt that ports were able to effectively evacuate, secure equipment, and otherwise prepare for storms.

**Table 50: Ports Most Vulnerable to Storm Surge in the Least Extreme and Most Extreme Narratives**

| ID | Port Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| P2 | Alabama State Port Authority (ASPA) - Alabama State Docks Main Complex | 2.8 | 3.5 | 100% |
| P8 | Bayou La Batre | 2.6 | 3.2 | 57% |
| P5 | Alabama State Port Authority (ASPA) - Pinto Island | 2.4 | 3.1 | 87% |
| P23 | Shell Chemical Co. | 2.7 | 3.0 | 100% |
| P7 | Austal | 2.7 | 3.0 | 96% |
| P3 | Alabama State Port Authority (ASPA) - McDuffie Terminal | 2.7 | 3.0 | 96% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the ports (see page 168 for more information on data availability).

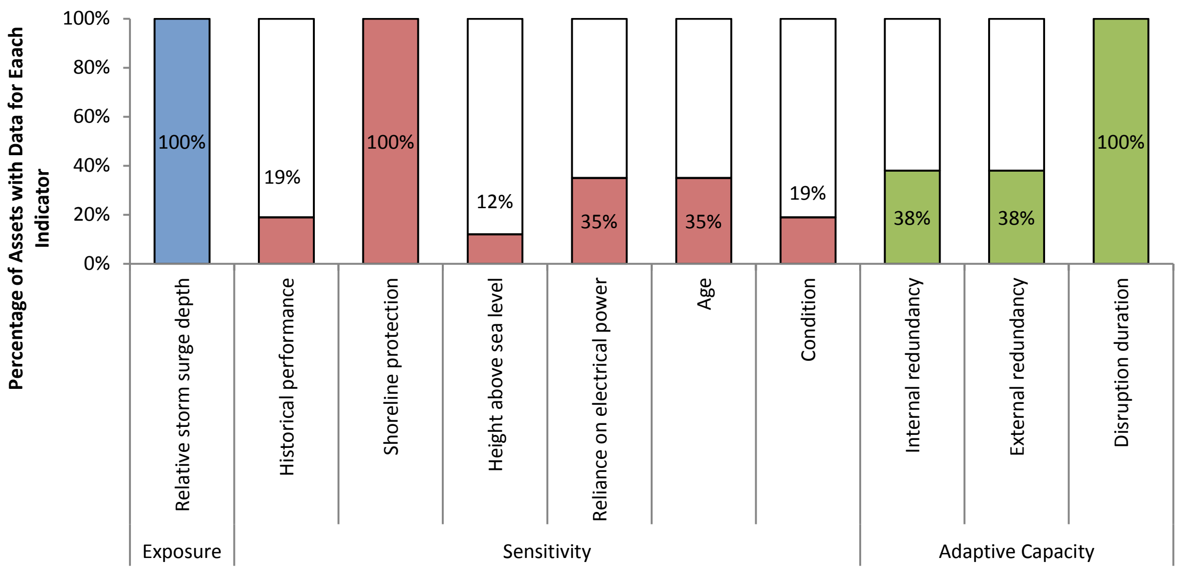
For full vulnerability scores of all ports, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

## Data Availability

Overall, ports have fairly low data availability for storm surge indicators, looking across exposure, sensitivity, and adaptive capacity. Only fifteen percent of assets have data for all indicators, and the lowest data availability score is 53% (there are eleven assets with that score). Figure 39 charts the percentage of assets with data for each storm surge indicator. Only three of the indicators (exposure, shoreline protection, and disruption duration) are available for all assets. The remaining four indicators are only available for between twelve and thirty-eight percent of assets.

Please see Appendix E for information on how data availability scores were calculated.

**Figure 39: Percentage of Assets with Data Available for each Ports Storm Surge Indicator**




## Robustness of Results

For storm surge vulnerability, the shoreline protection score is the strongest driver of the results. This finding occurs because shoreline protection has much higher data availability than the other five sensitivity indicators. Removing the shoreline protection indicator caused port vulnerability scores to increase by an average of 6 percent.

However, despite the influence of the shoreline protection score, the relative rankings of the ports remain fairly consistent across the indicator scenarios tested. The Alabama State Docks Main Complex is rated as the most vulnerable asset to storm surge in all scenarios except when the shoreline protection indicator is removed. Without that indicator, the asset drops to 3rd place in the vulnerability rankings and the Environmental Treatment Team Wharf becomes most vulnerable. The top three most vulnerable assets, which include the Atlantic Marine (BAE Systems Southeast Shipyards) and the Environmental Treatment Team Wharf in addition to the Main Docks Complex, remain as the top three most vulnerable assets across indicator scenarios.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.2.6 Wind

#### Findings

Mobile's port system exhibits a low vulnerability to extreme winds from hurricanes that may affect the area. Most coastal buildings, including port facilities, in Mobile are designed to withstand wind speeds of 130 to 150 mph. The projected wind speeds associated with the most extreme storm scenarios used in this study ranged from 108 to 120 mph. Therefore, ports in Mobile are considered to have low vulnerability to wind from a structural standpoint. The assets most vulnerable to wind tended to have a high reliance on electricity, a history of wind damage, and a lack of operational redundancy. For example, Shell Chemical Co. has a very low adaptive capacity because it is reliant on import of feedstocks and export of products via marine movements. In the event of a power outage, the facility would be unable to operate after the limited amount of crude oil in inventory was consumed. For more information on the vulnerability of port facilities to wind, please see Table 51.

**Table 51: Ports Most Vulnerable to Wind in the Least Extreme and Most Extreme Narratives**

| Sub-segment | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| P23 | Shell Chemical Co. | 2.4 | 2.4 | 100% |
| P3 | ASPA McDuffie Terminal | 2.3 | 2.3 | 88% |
| P26 | U.S. Coast Guard Pier | 2.3 | 2.3 | 52% |
| P6 | Atlantic Marine (BAE Systems Southeast Shipyards) | 2.3 | 2.3 | 100% |
| P2 | Alabama State Port Authority (ASPA) - Alabama State Docks Main Complex | 2.2 | 2.2 | 88% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the ports (see page 170 for more information on data availability).

For full vulnerability scores of all ports, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adap tation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

### Stakeholder Input on Port Wind Vulnerability

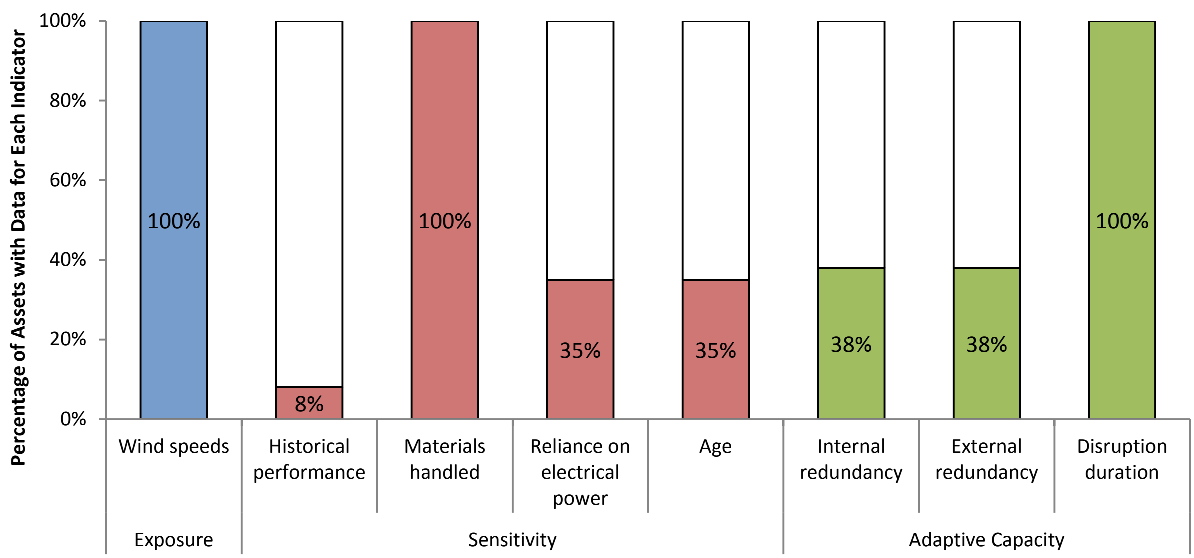
Port stakeholders agreed that wind damage due to debris can often be the most damaging impact from a storm. There are multiple examples of how debris has caused a great deal of damage during post storms in Mobile. However, it is extremely difficult to predict the damage resulting from wind debris impacts.

## Data Availability

Overall, ports have fairly low data availability for wind indicators, looking across exposure, sensitivity, and adaptive capacity. Only twelve percent of assets have data for all indicators, and the lowest data availability score is 52% (there are eleven assets with that score). Figure 40 charts the percentage of assets with data for each wind indicator. Only three of the indicators (exposure, materials handled, and disruption duration) are available for all assets. The remaining five indicators are only available for between eight and thirty-eight percent of assets.

Please see Appendix E for information on how data availability scores were calculated.

**Figure 40: Percentage of Assets with Data Available for each Ports Wind Indicator**




## Robustness of Results

For wind vulnerability, the materials handled score strongly influences the vulnerability results. This finding occurs because the materials handled indicator has much higher data availability than the other three sensitivity indicators. Removing this indicator caused port vulnerability scores to decrease by an average of 15 percent.

Due to the influence of the materials handled score, the relative ranking of the most vulnerable ports varies across the indicator scenarios tested. The top three most vulnerable ports consistently score in the top five most vulnerable ports, with the exception of the U.S. Coast Guard Pier, which drops to 16th place when the materials handled indicator is removed.

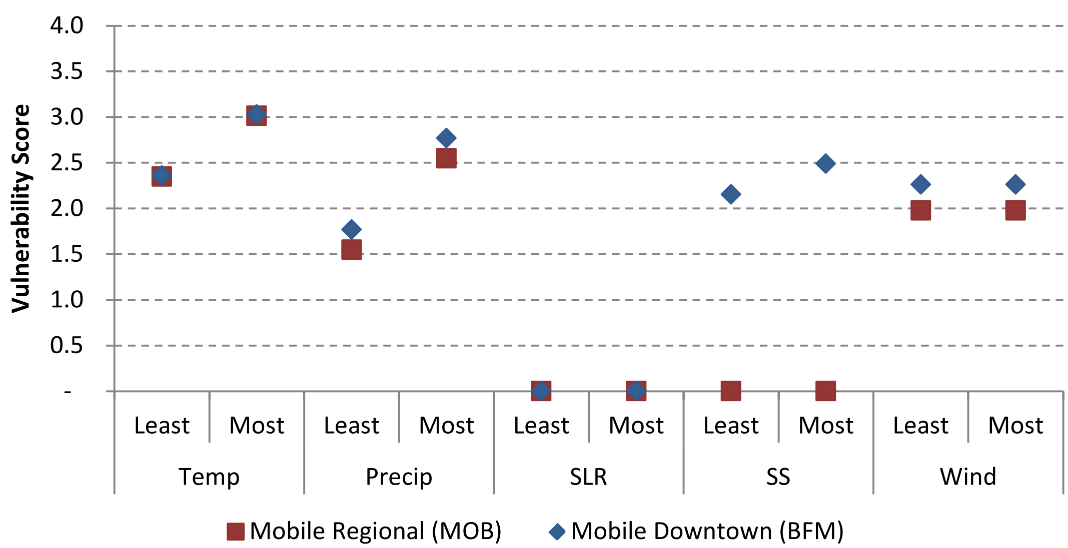
Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.3 Airports Results

### 5.3.1 Overall Results

The results show that Mobile Downtown airport is more vulnerable than Mobile Regional airport to all climate stressors. Across stressors, Mobile's airports are most vulnerable to increases in temperature, strong winds, and increases in heavy precipitation. Mobile Regional airport is not coastal, and therefore not exposed or vulnerable to storm surge and sea level rise. A small area of Mobile Downtown airport is inundated under each storm surge narrative, but is otherwise not vulnerable to storm surge or sea level rise. The vulnerabilities are summarized in Figure 41.

**Figure 41: Airport Vulnerability Scores by Climate Stressor, under Least and Most Extreme Narratives***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.

### 5.3.2 Temperature

#### Findings

Mobile's airports are most vulnerable to increases in high temperatures, but temperature vulnerability is relatively low except under the most extreme narrative. The airports are considered vulnerable largely because the airports are sensitive to temperature increases. That is, temperature increases can detrimentally affect infrastructure and operations at Mobile's airports. Runway pavement degradation—including expansion and contraction and discoloration (affecting visual aids for pilots)—is already occurring in today's climate. Although higher temperatures can necessitate longer take-off distances, Mobile's airports already have greater-than-sufficient runway lengths.[44] Both of Mobile's airports have approximately the same vulnerability to temperature under all exposure levels. See results in Table 52.

**Table 52: Airports Vulnerability to Temperature in the Least Extreme and Most Extreme Narratives**

| ID | Airport | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| BFM | Mobile Downtown Airport (Brookley Field) | 2.4 | 3.0 | 100% |
| MOB | Mobile Regional Airport | 2.3 | 3.0 | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the airports (see page 172 for more information on data availability).

For full vulnerability, exposure, sensitivity, and adaptive capacity scores, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Airports Temperature Vulnerability**

The Mobile Airport Authority shared that most temperature vulnerabilities are related to pavement materials. Stakeholders emphasized that expansion and contraction of pavement materials have affected alignment of ramps and that paint on the runways, used to guide planes, fades quickly in Mobile's hot temperatures. Stakeholders indicated that asphalt runways are more problematic than concrete ones when it comes to temperature issues, so long as concrete has adequate space for expansion and contraction.

Stakeholders also provided input on the relationship between temperatures and payload in Mobile. Stakeholders said that while high temperatures require extra runway lengths, the runways at Mobile's airports have sufficient buffer in their length to function in temperatures higher than those projected for Mobile.

[44] Hughes, 2012

### Data Availability

Data were available for all indicators for both airports.

### Robustness of Results

The airports temperature vulnerability results are robust, regardless of whether any indicators are removed. Vulnerability scores for the two airports consistently fall between 2.8 and 3.2 and show very low volatility if any sensitivity or adaptive capacity indicators are removed from the analysis.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.3.3 Precipitation

### Findings

The results show that Mobile's airports are only moderately vulnerable to increases in heavy precipitation. Their vulnerability is driven primarily by exposure (under the wetter narrative), and moderate adaptive capacity. The airports' adaptive capacity is neutral, balanced between low redundancy and high criticality and minimal length of disruptions. Mobile Downtown airport is slightly more vulnerable to precipitation changes under all exposure levels because it has an old and degrading drainage system that is already experiencing blowouts under current conditions. See results in Table 53.

**Table 53: Airports Vulnerability to Precipitation in the Least Extreme and Most Extreme Narratives**

| ID | Airport | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| BFM | Mobile Downtown Airport (Brookley Field) | 1.8 | 2.8 | 100% |
| MOB | Mobile Regional Airport | 1.5 | 2.5 | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the airports (see page 174 for more information on data availability).

For full vulnerability, exposure, sensitivity, and adaptive capacity scores, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Airports Precipitation Vulnerability**

Stakeholders said that Mobile's airports are not very vulnerable to heavy precipitation. Although the airports experience flight delays when it rains, the issues are normally resolved relatively quickly. Stakeholders noted that weather affecting nearby large hubs (such as Atlanta) tends to have a bigger effect on the Mobile airport system than local weather conditions.

#### Data Availability

Data were available for all indicators for both airports.

#### Robustness of Results

The airports precipitation vulnerability results are robust, regardless of whether any indicators are removed. Vulnerability scores for each airport fluctuate by no more than two tenths of a point if any sensitivity or adaptive capacity indicators are removed from the analysis.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.3.4 Sea Level Rise

#### Findings

Mobile's airports are not exposed to, and therefore not vulnerable to, the sea level rise narratives investigated for this analysis.

**Stakeholder Input on Airports Sea Level Rise Vulnerability**

Stakeholders indicated that tidal variation has not been a problem historically for Mobile's airports. They noted that although the Downtown airport is directly adjacent to the Bay, the airport grounds are fairly elevated. Stakeholders suggested that the height of drainage discharge, age of drainage system, and drainage pipe materials could be indicators of which areas may experience problems as sea levels rise.

#### Data Availability

Data were available for all indicators for both airports.

#### Robustness of Results

The airports sea level rise vulnerability results are robust, regardless of whether any indicators are removed. This is because exposure is a prerequisite for vulnerability, so if the airports are not exposed, they are not vulnerable, regardless of which sensitivity or adaptive capacity indicators are used.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.3.5 Storm Surge

#### Findings

The Mobile Regional airport is an inland airport and not exposed to, and therefore not vulnerable to, storm surge. Mobile Downtown airport is exposed to storm surge under all storm narratives. The inundation depths range from 12.4 to 25.4 feet from the least to most extreme narratives, but apply to a small portion of the airport in its southeastern-most corner. The moderate vulnerability score is driven by the high storm surge depths, but mitigated by low sensitivity (evidenced by no past issues with storm surge damage) and middling adaptive capacity, influenced in turn by low redundancy but low disruption duration. See results in Table 54.

**Table 54: Airports Vulnerability to Storm Surge in the Least Extreme and Most Extreme Narratives**

| ID | Airport | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| BFM | Mobile Downtown Airport (Brookley Field) | 2.2 | 2.5 | 100% |
| MOB | Mobile Regional Airport | not exposed | not exposed | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the airports (see page 175 for more information on data availability).

For full vulnerability, exposure, sensitivity, and adaptive capacity scores, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Airports Storm Surge Vulnerability**

Stakeholders indicated runways and taxiways at Mobile Downtown have been inundated due to storm surge in the past, but that the surge does not affect buildings and ramps, which are farther away from the water. If the water is able to drain away relatively quickly, the runways experience little damage. However, the longer the water sits on the runways and taxiways, the more likely damage is to pavement and navigational lights.

#### Data Availability

Data were available for all indicators for both airports.

#### Robustness of Results

The airports storm surge vulnerability results are robust, regardless of whether any indicators are removed. This is because exposure is a prerequisite for vulnerability, so if the airports are not exposed, they are not vulnerable, regardless of which sensitivity or adaptive capacity indicators are used. Even under a narrative with exposure, the vulnerability scores for Mobile Downtown airport vary by at most two tenths of a point when sensitivity or adaptive capacity indicators are removed.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.3.6 Wind

#### Findings

Mobile's airports are relatively vulnerable to high winds, even without considering operational vulnerabilities. Mobile Downtown airport is more vulnerable than Mobile Regional, because the age of its buildings indicates that it is more sensitive to wind damage. Both airports are sensitive to damage from wind because they have flat roofs, metal used in constructing the buildings, and because they have been damaged by wind in the past. See results in Table 55.

**Table 55: Airports Vulnerability to Wind in the Least Extreme and Most Extreme Narratives**

| ID | Airport | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| BFM | Mobile Downtown Airport (Brookley Field) | 2.3 | 2.3 | 100% |
| MOB | Mobile Regional Airport | 2.0 | 2.0 | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the airports (see page 176 for more information on data availability).

For full vulnerability, exposure, sensitivity, and adaptive capacity scores, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Airports Wind Vulnerability**

Stakeholders indicated that wind design ratings are an important factor in airport facility's vulnerability to wind. They also noted that certain construction features—foundation, roof type, construction material, and height—all influence whether a building is more or less likely to be damaged by wind.

According to stakeholders, a piling system is the strongest foundation, while a slab with footers is more sensitive. In addition, flat roofs are more sensitive to damage than pitched roofs and buildings built with masonry are more resistant to wind than those built with metals or wood. Taller buildings are also more sensitive to damage from wind.

Mobile's airports suffered roof damage in 2005 because of the winds associated with Hurricane Katrina. The roofs were replaced to be more resistant to hurricane damage.

#### Data Availability

Data were available for all indicators for both airports.

#### Robustness of Results

The airports wind vulnerability results are robust, regardless of whether any indicators are removed. Vulnerability scores for each airport fluctuate by no more than one tenths of a point if any sensitivity or adaptive capacity indicators are removed from the analysis.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

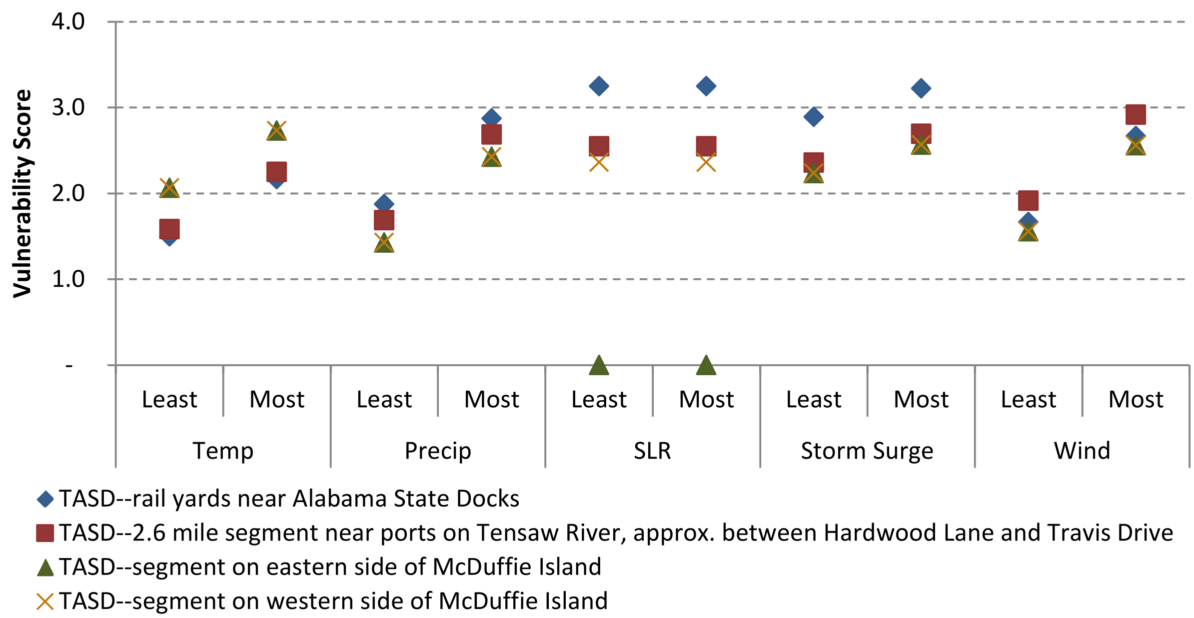
## 5.4 Rail Results

Recall that the rail results must be taken with the caveat that they represent only four of the twelve critical rail assets, because reliable information was not available about the privately-owned rail lines. The results are therefore showing a relatively small sample size, which is concentrated around the ASPA ports along the Mobile River. It is thus difficult to draw broad conclusions about the overall rail system's vulnerability, including inland rail lines. The vulnerability results discussed here are more reflective of coastal rail assets.

### 5.4.1 Overall Results

Overall, the results show that Mobile's TASD rail assets have moderate-to-high vulnerability to storm surge and sea level rise, followed by low-to-moderate vulnerability to increases in temperature, precipitation, and wind speed. The TASD rail yards are particularly vulnerable to flooding from precipitation, sea level rise and storm surge, while the eastern and western segments on McDuffie Island display moderate vulnerability to all five climate stressors. The vulnerabilities are summarized in Figure 42.

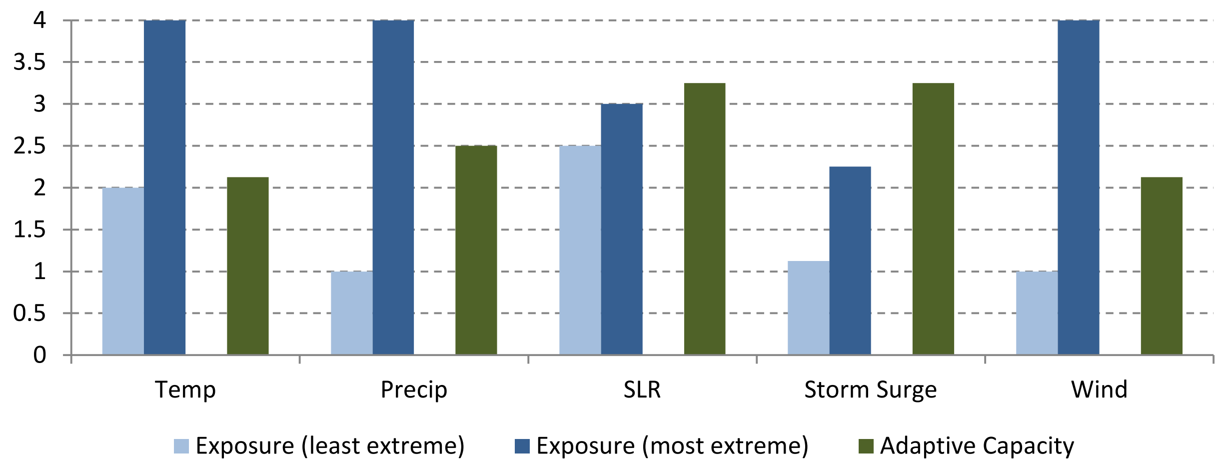
**Figure 42: Rail Vulnerability Scores by Climate Stressor, under Least and Most Extreme Narratives***




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.

The study team was unable to collect information about sensitivity indicators for Mobile's privately-owned critical rail assets. However, complete information was available on those assets' exposure, and partial information was available about their adaptive capacity (presence of bridges and railroad class were unknown). The vulnerability assessment for these assets is incomplete because of lack of data about their sensitivity, and so their vulnerability is excluded from the discussion of results. What information is known about their exposure and adaptive capacity is shown in Figure 43; there was very little fluctuation in scores between assets, so the average scores are shown. The available data indicates that Mobile's privately-owned rail assets are exposed to climate stressors (particularly under the most extreme narratives), and also have relatively low adaptive capacity; they are thus likely to be vulnerable to projected changes in climate.

**Figure 43: Average Exposure and Adaptive Capacity Scores for Privately-Owned Rail Assets**




## 5.4.2 Temperature

### Findings

Mobile's public critical rail assets have low-to-moderate vulnerability to increased high temperatures. The eastern and western rail lines on McDuffie Island have higher vulnerability primarily due to historical performance; both have experienced track buckling in the past, which indicates higher sensitivity. All four assets have jointed design (which is less susceptible to buckling than continuously-welded rail) and moderate adaptive capacity with respect to high temperatures. Vulnerability increases from low (between 1.5 and 2.1) in the least extreme narrative to moderate (between 2.2 and 2.7) in the most extreme narrative. See results in Table 56.

**Table 56: Rail Vulnerability to Temperature in the Least Extreme and Most Extreme Narratives**

| ID | Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| RR7 | TASD--segment on eastern side of McDuffie Island | 2.1 | 2.7 | 79% |
| RR8 | TASD--segment on western side of McDuffie Island | 2.1 | 2.7 | 79% |
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive | 1.6 | 2.3 | 79% |
| RR1 | TASD--rail yards near Alabama State Docks | 1.5 | 2.2 | 91% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the rail assets (see page 180 for more information on data availability).

For full vulnerability scores of all TASD rail assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/

adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Rail Temperature Vulnerability**

Stakeholders indicated that rail buckling can be a problem in Mobile when temperatures get very hot. Continuously-welded rail is more prone to this buckling, but stakeholders pointed out that none of the State of Alabama terminal rails are continuously-welded. They said that buckling in Mobile is more likely due to rail curvature—the tighter the curve on a portion of rail, the more likely it is to buckle, especially at fixed points like road crossings. Stakeholders also noted that salt air can cause rail corrosion, which in turn weakens rail and makes it more vulnerable to kinks. However, stakeholders added that even during extreme heat events, operational impacts are minimal and short-lived.

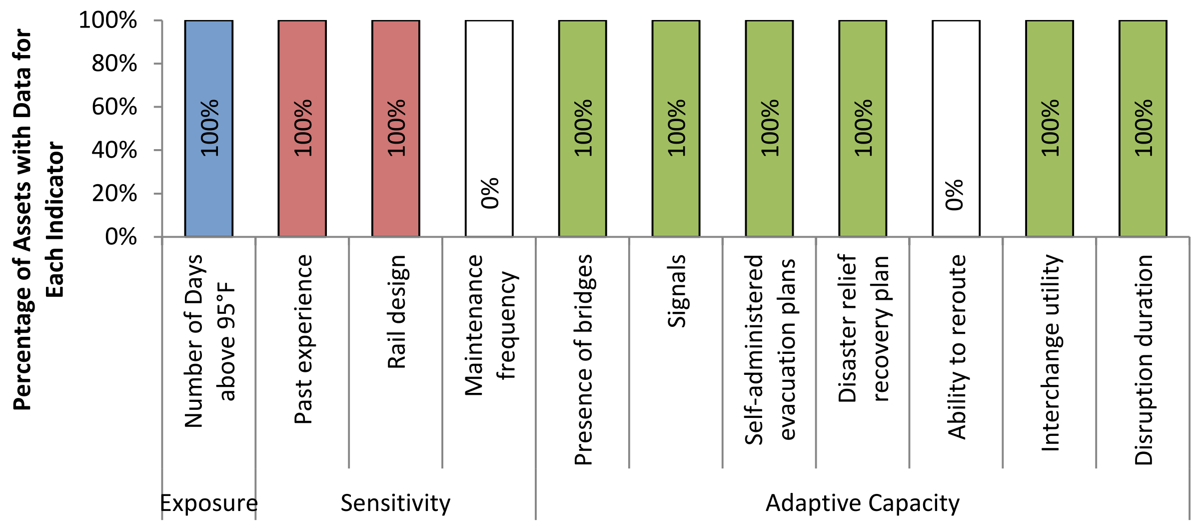
### Data Availability

As noted earlier, limited data were available for Mobile's rail assets, and no information was available about sensitivity for the eight non-TASD rail assets. For the TASD assets, no information was available about maintenance frequency (a sensitivity indicator) or ability to reroute around obstacles (an adaptive capacity indicator).

Adaptive capacity data availability is the same across all stressors. All assets lack data on ability to reroute around obstacles, which would have contributed a third of the adaptive capacity score for the rail line assets. This indicator is not applicable for the rail yards, so the rail yards have full data availability for adaptive capacity.

Because ability to reroute is not applicable to the rail yards, this resulted in 91% temperature data availability for the rail yards and 79% data availability for the other three assets. Additional information on how data availability scores were calculated is available in Appendix E. Figure 44 summarizes the data availability for rail temperature indicators, showing that data are available for all applicable assets for all indicators except for maintenance frequency and ability to reroute.

**Figure 44: Percentage of Assets with Data Available for each Rail Temperature Indicator**




### Robustness of Results

The rail temperature vulnerability results are robust, regardless of whether any indicators are removed. The rail design sensitivity indicator has the largest influence on absolute vulnerability scores, but does not affect asset rankings and only causes asset scores to fluctuate by about 0.6 points if it is removed.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.4.3 Precipitation

### Findings

All four TASD rail assets display similar vulnerability to projected changes in precipitation. Of the four, rail yards are the most vulnerable to increases in heavy precipitation. The rail yards evaluated have had drainage issues in the past and are located entirely within the 100-year flood zone, increasing sensitivity to flooding as a result of heavy rain. However, given that there were a limited number of rail segments with sufficiently complete information, it cannot be concluded that rail yards are inherently more vulnerable. All assets have moderate adaptive capacity, though the rail segment near ports on Tensaw River scores slightly lower due to the presence of bridges. The average vulnerability score rises from 1.6 in the least extreme narrative to 2.6 in the most extreme narrative, which significantly shifts how precipitation vulnerability compares to the other climate stressors. In the least extreme narrative, precipitation (on average) poses the least threat, while it is tied for the highest average vulnerability in the most extreme narrative. See results in Table 57.

**Table 57: Rail Vulnerability to Precipitation in the Least Extreme and Most Extreme Narratives**

| ID | Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| RR1 | TASD--rail yards near Alabama State Docks | 1.9 | 2.9 | 93% |
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive | 1.7 | 2.7 | 82% |
| RR7 | TASD--segment on eastern side of McDuffie Island | 1.4 | 2.4 | 82% |
| RR8 | TASD--segment on western side of McDuffie Island | 1.4 | 2.4 | 82% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the rail assets (see page 182 for more information on data availability).

For full vulnerability scores of all TASD rail assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

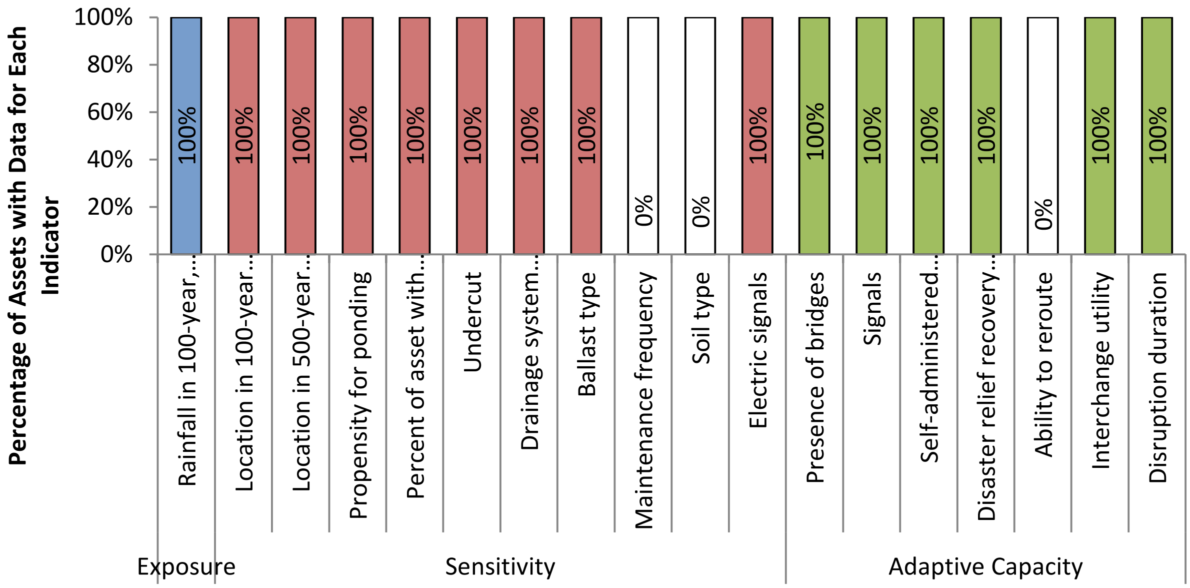
### Stakeholder Input on Rail Precipitation Vulnerability

Stakeholders contributed information on any past difficulties that precipitation has caused for certain rail assets and estimate that disruptions from precipitation could range from hours to days. They noted that the main concern with flooding is ballast stability, because ballast can be washed out from heavy precipitation. In addition, stakeholders provided input on contingency plans to avoid damage from heavy rainfall. For example, trains are moved to an area 15 feet above sea level at McDuffie Terminal.

## Data Availability

Within the TASD assets, data were available for all but three indicators: maintenance frequency, soil type (both sensitivity indicators), and ability to reroute (an adaptive capacity indicator). Because ability to reroute is not applicable to the rail yards, this resulted in 93% precipitation data availability for the rail yards and 82% data availability for the other three assets. Additional information on how data availability scores were calculated is available in Appendix E. Figure 45 summarizes the data availability for rail precipitation indicators, showing that data are available for all applicable assets for all indicators except for maintenance frequency, soil type, and ability to reroute.

**Figure 45: Percentage of Assets with Data Available for each Rail Precipitation Indicator**




### Robustness of Results

The rail precipitation vulnerability results are robust, regardless of whether any indicators are removed. Vulnerability scores for each asset fluctuate by no more than two tenths of a point if any sensitivity or adaptive capacity indicators are removed from the analysis, and rankings are not affected.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.4.4 Sea Level Rise

### Findings

Across all the climate stressors, sea level rise poses the greatest risk to Mobile's rail system. Rail yards are highly vulnerable under both the least and most extreme narratives, while two of the rail segments are moderately vulnerable. The segment on the eastern side of McDuffie Island is not exposed to sea level rise under any narrative, and therefore is not vulnerable. The vulnerability of the rail yards results from past difficulties with drainage and a lack of elevation or protective structures. In addition, adaptive capacity is low for all four assets because the disruption duration caused by sea level rise is so severe (months, rather than a few hours or days). Vulnerability is the same for both the least and most extreme narrative because exposure is constant: the segment on the eastern side of McDuffie Island is not exposed under either narrative, while the other three assets are exposed in both narratives. See results in Table 58.

**Table 58: Rail Vulnerability to Sea Level Rise in the Least Extreme and Most Extreme Narratives**

| ID | Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| RR1 | TASD--rail yards near Alabama State Docks | 3.3 | 3.3 | 100% |
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive | 2.6 | 2.6 | 83% |
| RR8 | TASD--segment on western side of McDuffie Island | 2.4 | 2.4 | 83% |
| RR7 | TASD--segment on eastern side of McDuffie Island | not exposed | not exposed | 83% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the rail assets (see page 184 for more information on data availability).

For full vulnerability scores of all TASD rail assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

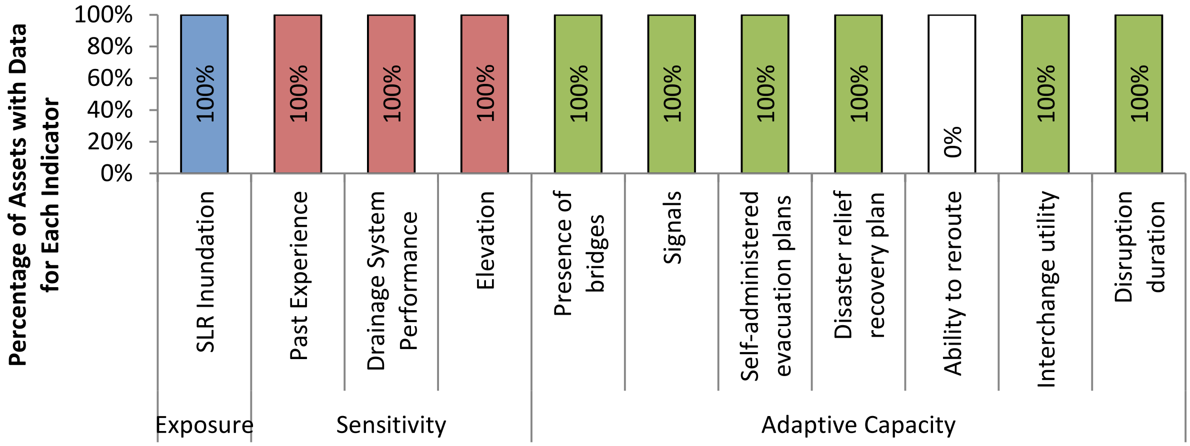
### Stakeholder Input on Rail Sea Level Rise Vulnerability

Stakeholders said that rail assets in Mobile do not currently experience issues with high tides. They suggested that most rail vulnerabilities from sea level rise would be indirect, due to exacerbated storm surge or flooding associated with heavy precipitation. However, they suggested that track beds may need to be raised by adding ballast because if sea level were to rise to the level of the tracks, delays would be very severe (months); however, rail segments would likely be relocated before being inundated.

## Data Availability

Data were available for all TASD assets for all three sea level rise sensitivity indicators. No data were available for a rail's ability to reroute, an adaptive capacity indicator that would have accounted for a third of the adaptive capacity score, so all rail line assets have data availability scores of 83%. Ability to reroute is not an indicator for the rail yards, so the rail yards have full data availability for sea level rise. Figure 46 shows the data availability for rail sea level rise indicators, including full data availability for the sensitivity indicators. Additional information on how data availability scores were calculated is available in Appendix E.

Figure 46: Percentage of Assets with Data Available for each Rail Sea Level Rise Indicator




### Robustness of Results

Exposure is the most important driver of sea level rise vulnerability, so the rail sea level rise results are robust against changes to the sensitivity or adaptive capacity indicators. Eliminating disruption duration has the largest effect on scores (reducing them by an average of 0.3 points), but rankings are not affected.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.4.5 Storm Surge

### Findings

Mobile's rail system has moderate vulnerability to storm surge. The rail yards (RR1) have the highest vulnerability due to high exposure, experiencing the highest modeled storm surge depth across all modes. They also have high sensitivity, and are also the only asset to have a history of flooding due to storm surge. The three rail segments have similar exposure and sensitivity, but the segment near the Tensaw River ports has lower adaptive capacity. See results in Table 59.

**Table 59: Rail Vulnerability to Storm Surge in the Least Extreme and Most Extreme Narratives**

| ID | Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| RR1 | TASD--rail yards near Alabama State Docks | 2.9 | 3.2 | 96% |
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive | 2.4 | 2.7 | 85% |
| RR7 | TASD--segment on eastern side of McDuffie Island | 2.2 | 2.6 | 85% |
| RR8 | TASD--segment on western side of McDuffie Island | 2.2 | 2.6 | 85% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the rail assets (see page 186 for more information on data availability).

For full vulnerability scores of all TASD rail assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

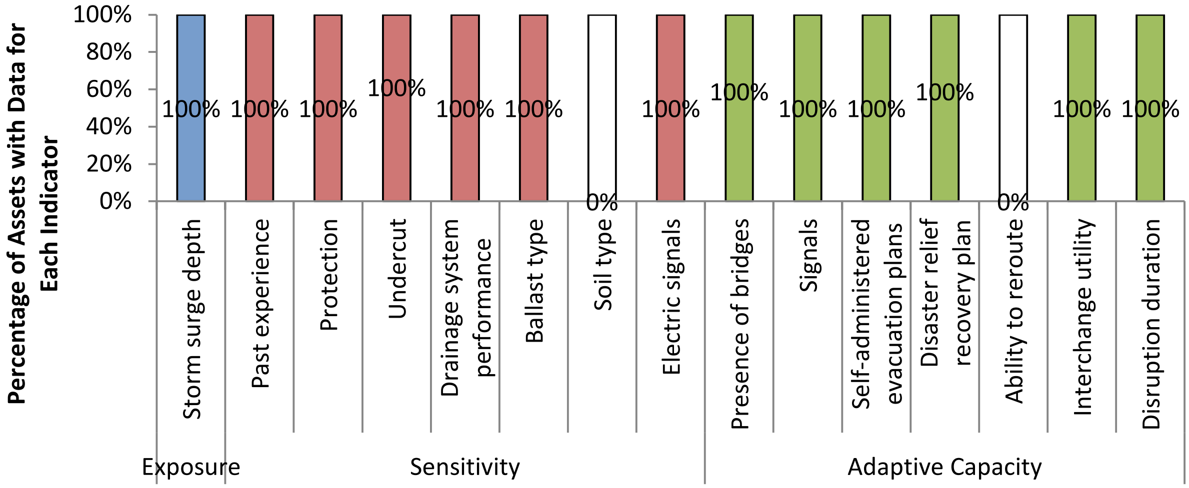
### Stakeholder Input on Rail Storm Surge Vulnerability

Stakeholders said that vulnerability of the rail system is to storm surge depends on the specifics of a given storm, but that flooding, washouts, and debris are the common types of damage. The rail yards are particularly susceptible to storm surge-related flooding and can be difficult to drain. Stakeholders also noted that temporary damage to operations infrastructure (e.g., signals, rail bridges) is not problematic, since trains do not operate during severe storm conditions. If those issues can be resolved by the time the weather clears, then the system does not suffer overall, especially relative to other kinds of damage.

## Data Availability

Within the TASD assets, data were available for all storm surge indicators except soil type (a sensitivity indicator) and ability to reroute (an adaptive capacity indicator). Because ability to reroute is not applicable to the rail yards, this resulted in 96% storm surge data availability for the rail yards and 85% data availability for the other three assets. Figure 47 summarizes the data availability for rail storm surge indicators, showing that data are available for all applicable assets for all indicators except for maintenance frequency, soil type, and ability to reroute. Additional information on how data availability scores were calculated is available in Appendix E.

**Figure 47: Percentage of Assets with Data Available for each Rail Storm Surge Indicator**




### Robustness of Results

Exposure is the most important driver of storm surge vulnerability, so the rail storm surge results are robust against changes to the sensitivity or adaptive capacity indicators. Eliminating disruption duration has the largest effect on storm surge vulnerability scores (reducing them by an average of 0.3 points), but rankings are not affected.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.4.6 Wind

### Findings

Overall, Mobile's rail assets have low-to-moderate vulnerability to high wind speeds. Of the four assets, the rail segment near the ports on Tensaw River has the highest vulnerability due to the greatest sensitivity and the least adaptive capacity. The signals and aerial lines on this rail segment are particularly prone to wind damage. Rail yards have the next highest vulnerability primarily because of historical experience with flooding from strong winds. In the most extreme narrative, high exposure raises the vulnerability scores from low to moderate. See results in Table 60.

**Table 60: Rail Vulnerability to Wind in the Least Extreme and Most Extreme Narratives**

| ID | Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive | 1.9 | 2.9 | 74% |
| RR1 | TASD--rail yards near Alabama State Docks | 1.7 | 2.7 | 86% |
| RR7 | TASD--segment on eastern side of McDuffie Island | 1.6 | 2.6 | 89% |
| RR8 | TASD--segment on western side of McDuffie Island | 1.6 | 2.6 | 89% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the rail assets (see page 188 for more information on data availability).

For full vulnerability scores of all TASD rail assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

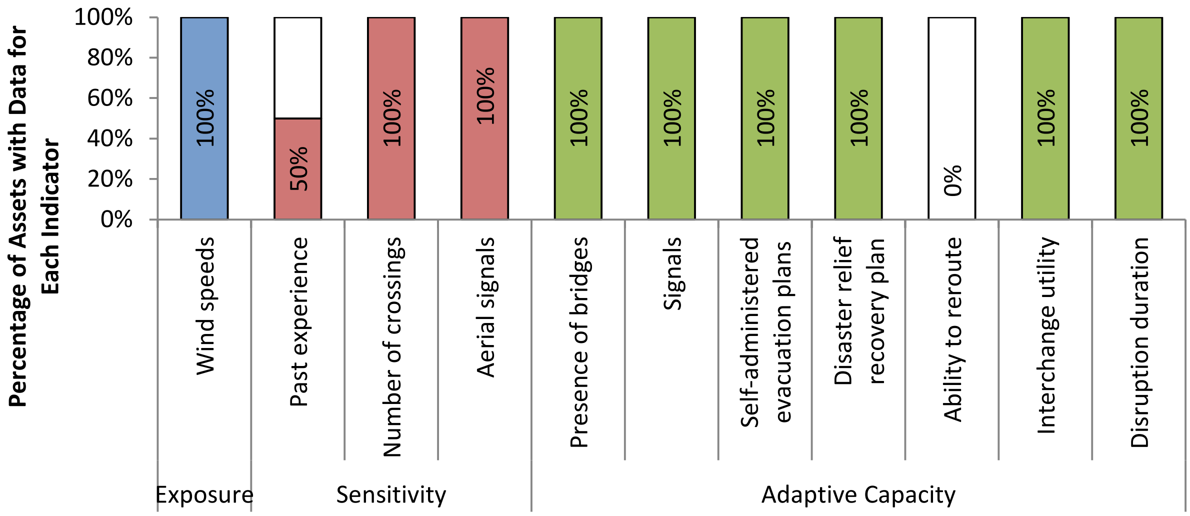
### Stakeholder Input on Rail Wind Vulnerability

Stakeholders provided information on how high winds have affected the rail system in the past. The combination of high tides and strong winds has caused flooding at rail yards, and the rail lines on McDuffie Island have experienced issues with coal dust as a result of high winds. Overall, stakeholders reported that disruptions from high winds are minor because repairs can be done quickly and dispatchers can be used in place of downed signals.

## Data Availability

No data on historical performance (a sensitivity indicator) were available for two of the TASD assets: the TASD rail yards and the segment near ports on Tensaw River. In addition, no information was available for any assets on railroad class, an adaptive capacity indicator. The result was 89% data availability for the two McDuffie Island rail lines, 86% data availability for the rail yards, and 74% data availability for the TASD rail segment near the ports on Tensaw River. Figure 48 shows the percentage of assets with data available for each rail wind indicator, showing that only half of assets have data for past experience and no assets have data for ability to reroute. Additional information on how data availability scores were calculated is available in Appendix E.

**Figure 48: Percentage of Assets with Data Available for each Rail Wind Indicator**




### Robustness of Results

The limited data availability behind the wind vulnerability scores means that the scores fluctuate more than for other stressors if individual sensitivity or adaptive capacity indicators are removed. Removing either of the two sensitivity indicators cause scores to fluctuate by about 0.4 points; however; relative vulnerability rankings are not affected.

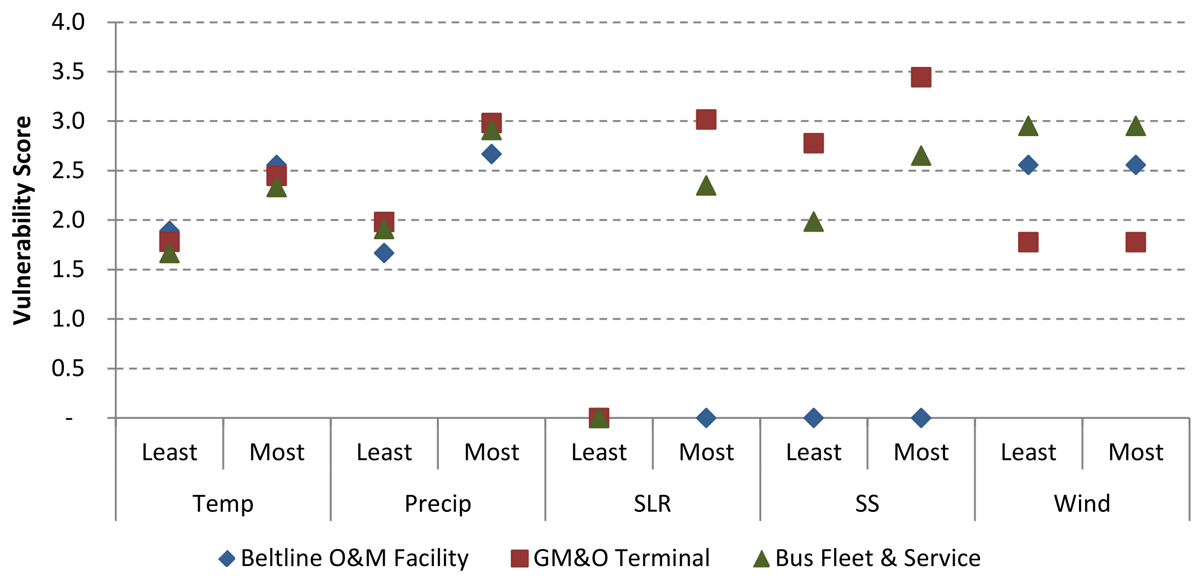
Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.5 Transit Results

### 5.5.1 Overall Results

The three transit assets exhibit a low to moderate vulnerability for most climate stressors and narratives. However, the specific vulnerabilities of the three assets are different. For example, the GM&O Terminal is highly vulnerable to storm surge but has a low vulnerability to wind. On the other hand, the Beltline O&M Facility is not vulnerable to storm surge, but has moderate vulnerability to wind, and changes in precipitation and temperature. The bus fleet exhibits low to moderate vulnerability for all climate stressors, but is most vulnerable to wind. The range of transit asset vulnerabilities for each stressor is summarized in Figure 49.

**Figure 49: Transit Asset Vulnerability Scores by Climate Stressor, under Least and Most Extreme Narratives**




*"Least" and "Most" refer to the Least Extreme and Most Extreme narratives/timeframes as described in Section 3.2.

## 5.5.2 Temperature

### Findings

This vulnerability assessment found that transit assets are not very sensitive to projected changes in temperature. All assets are rated as having low vulnerability in the least extreme narrative. In the more extreme narrative, when temperature exposure increases significantly, all assets are considered to have moderate vulnerability. This finding is in line with interviews with Mobile stakeholders, which indicated very low sensitivity to temperature. Even though exposure scores were high under the end-of-century hotter narrative, the sensitivity and adaptive capacity scores were low enough that the overall vulnerability is moderate for all segments.

The assessment found that most assets exhibit approximately the same vulnerability to temperature. In other words, distinctions between the most vulnerable and least vulnerable segment in a given narrative are minimal. For example, under the Hotter narrative, the highest score (2.6) was only 0.3 points higher than the lowest score (2.3). This finding arises because the assets have identical sensitivity and exposure ratings.

Table 61 and shows the transit assets most vulnerable to projected changes in temperature, according to the screen. The Beltline O&M Facility is consistently ranked as the asset most vulnerable to heat events because it is difficult to replace. The bus fleet's preparedness for heat waves and ability to adapt make it the least vulnerable to extreme heat events.

**Table 61: Transit Vulnerability to Temperature in the Least Extreme and Most Extreme Narratives**

| Segment | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| T1 | Beltline O&M Facility | 1.9 | 2.6 | 100% |
| T2 | GM&O Terminal | 1.8 | 2.4 | 100% |
| T3 | Bus Fleet & Service | 1.7 | 2.3 | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the transit assets (see page 191 for more information on data availability).

For full vulnerability scores of all assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Transit Assets' Temperature Vulnerability**

Interviews with WAVE representatives provided much of the data for the sensitivity analysis of these transit assets. Stakeholders provided input on both the age of the bus fleet, noting that bus air conditioning systems are sized to withstand Mobile heat waves. They also added that bus life is ten years, so adjustments could be made if necessary. Interviewees also shared that none of these assets had experienced heat-related issues in the past.

## Data Availability

Data availability for all three transit facilities was 100%, meaning that all indicator datasets were available for all facilities.

## Robustness of Results

The analysis showed that of all vulnerability indicators, historical performance, speed of asset recovery, and disruption duration had the largest impact on temperature vulnerability scores. Removing these indicators causes vulnerability scores to change, on average, by between 9 and 11 percent. For example, removing the speed of asset recovery asset causes the transit vulnerability scores to drop by 11% on average. However, removing either the speed of asset recovery or disruption duration indicator does not influence the relative ranking of the transit facilities. On the other hand, removing the historical performance indicator causes the bus fleet and service to become the most vulnerable asset, rather than the Beltline O&M facility.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.5.3 Precipitation

#### Findings

The assessment found that most segments exhibit approximately the same moderate vulnerability to projected changes in precipitation. In other words, distinctions between the most vulnerable and least vulnerable segment in a given narrative are minimal. For example, under the Wetter narrative, the highest score (3.0) was only 0.3 points higher than the lowest score (2.7). This finding arises because the sensitivity and adaptive capacity of the assets cancel each other out, resulting in moderate scores across the assets.

Though the three vulnerability scores are relatively similar overall, the sensitivity and adaptive capacity of the assets vary greatly. The Beltline O&M Facility has a very low sensitivity to precipitation because it is located outside of the flood zones, while GM&O Terminal is located in the 100-year flood zone and therefore has higher sensitivity. The bus fleet has struggled with heavy rainfall in the past, but is also very adaptable and can cope well with localized flooding.

Table 62 shows the transit facilities most vulnerable to projected changes in precipitation, according to the screen. The GM&O Terminal is consistently ranked as the asset most vulnerable to precipitation due to a low adaptive capacity and location in a 100-year flood zone. While the bus fleet has a history of disruption during heavy rainfall, it also has a high adaptive capacity, which lowers its overall vulnerability.

**Table 62: Transit Vulnerability to Precipitation in the Least Extreme and Most Extreme Narratives**

| Segment | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| T2 | GM&O Terminal | 2.0 | 3.0 | 100% |
| T3 | Bus Fleet & Service | 1.9 | 2.9 | 100% |
| T1 | Beltline O&M Facility | 1.7 | 2.7 | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the transit assets (see page 193 for more information on data availability).

For full vulnerability scores of all assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Transit Assets' Precipitation Vulnerability**

WAVE representatives shared information on past experiences with heavy rainfall events in Mobile. They noted that the downtown location of GM&O Terminal is particularly prone to flooding, while Beltline O&M Facility is sited further inland on higher ground. Stakeholders also said that heavy rainfall disrupts both access to buses and operations, but the ability to reroute keeps service delays fairly short (a few hours at most).

#### Data Availability

Data availability for all three transit facilities was 100%, meaning that all precipitation vulnerability indicator datasets were available for all facilities.

#### Robustness of Results

The analysis showed that of all vulnerability indicators, historical performance, speed of asset recovery, disruption duration, and impaired access during weather events had the largest impact on precipitation vulnerability scores. Removing these indicators causes vulnerability scores to change, on average, by between 3 and 8 percent. For example, removing the speed of asset recovery indicator causes the transit vulnerability scores to drop by 8% on average. However, removing most of these indicators does not influence the relative ranking of the transit facilities. On the other hand, removing the historical performance indicator causes the bus fleet and service and the Beltline O&M facility to become tied as the second most vulnerable assets behind the GM&O Terminal. In the original analysis, the bus fleet and service asset is slightly more vulnerable than the Beltline O&M facility.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

### 5.5.4 Sea Level Rise

#### Findings

None of the critical transit assets in Mobile is exposed to sea level rise under the least extreme narrative, and only the bus fleet and GM&O Terminal are exposed under the most extreme narrative. The Beltline O&M facility's inland location shields it from sea level rise impacts. In the most extreme scenario, the GM&O Terminal ranks as highly vulnerable principally because of its lengthy disruption duration—in the event of sea level inundation, the entire facility would need to be moved. The bus fleet is much more mobile, and therefore has moderate vulnerability to sea level rise.

Table 63 shows the transit facilities most vulnerable to sea level rise, according to the screen. Under the most extreme narrative, the GM&O Terminal ranks as the asset most vulnerable to sea level rise due to a low adaptive capacity, lack of shoreline protection, and proximity to flood-prone access routes. While the bus fleet shares similar sensitivity characteristics, it also has a high adaptive capacity, which lowers its overall vulnerability. The Beltline O&M Facility is not exposed to projected sea level rise, even under the most extreme narrative.

**Table 63: Transit Vulnerability to Sea Level Rise in the Least Extreme and Most Extreme Narratives**

| Segment | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| T2 | GM&O Terminal | Not exposed | 3.0 | 100% |
| T3 | Bus Fleet & Service | Not exposed | 2.4 | 100% |
| T1 | Beltline O&M Facility | Not exposed | Not exposed | 100% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the transit assets (see page 194 for more information on data availability).

For full vulnerability scores of all assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Transit Assets' Sea Level Rise Vulnerability**

Representatives of WAVE shared that none of the assets had experienced any historical issues with sea level rise or high tides. However, they also noted that none of the assets are protected or elevated, and that if inundation were to threaten the facilities, they would have to be relocated entirely. On the other hand, the bus fleet would be able to adjust and would be relatively undamaged.

### Data Availability

Data availability for all three transit facilities was 100%, meaning that all sea level rise vulnerability indicator datasets were available for all facilities.

### Robustness of Results

The analysis showed that removing the historical performance indicator had a large impact on vulnerability scores (24%), but no impact on relative vulnerability rankings. Similarly, removing the shoreline protection, proximity to flood-prone routes, and asset recovery speed indicators altered overall vulnerability scores by between 8 and 12 percent. However, these changes did not affect the relative rankings of the three transit assets.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.5.5 Storm Surge

### Findings

Mobile's transit facilities exhibit high vulnerability to storm surge if they are exposed to the inundation. Due to its inland location, the Beltline O&M Facility is not exposed to storm surge under any narrative. However, the GM&O Terminal is considered highly vulnerable to storm surge because it has been damaged during past storm events, relies on access from flood-prone streets, and is neither protected nor elevated. While over 50% of Mobile's bus stops are located in the inundation zone of the most extreme storm event, the bus fleet and service asset is only moderately vulnerable to storm surge due to its high adaptive capacity.

Table 64 shows the transit assets most vulnerable to storm surge, according to the screen. The GM&O Terminal is consistently ranked as the asset most vulnerable to sea level rise due to its history of flooding during storm events, lack of shoreline protection, and proximity to flood-prone access routes. While the bus fleet shares similar sensitivity characteristics, it also has a high adaptive capacity, which lowers its overall vulnerability. The Beltline O&M Facility is not exposed to storm surge, even under the most extreme narrative.

**Table 64: Transit Vulnerability to Storm Surge in the Least Extreme and Most Extreme Narratives**

| Segment | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| T2 | GM&O Terminal | 2.8 | 3.4 | 93% |
| T3 | Bus Fleet & Service | 2.0 | 2.7 | 100% |
| T1 | Beltline O&M Facility | Not exposed | Not exposed | 93% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the transit assets (see page 195 for more information on data availability).

For full vulnerability scores of all assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

**Stakeholder Input on Transit Assets' Storm Surge Vulnerability**

Stakeholders provided useful input on how transit assets typically cope with storm surge events. It was noted that buses are delayed in exposed coastal areas, and that buses do not run for 1-2 days after storms in order to make way for emergency crews. Stakeholders also shared that GM&O Terminal flooded during Hurricane Katrina, and that disruptions due to storm surge can last up to several months.

### Data Availability

For the transit facilities (T1 and T2), no information was available on building foundation type, one of the storm surge sensitivity indicators. Data were available for all facilities for all other storm surge vulnerability indicators.

### Robustness of Results

Historical performance was the strongest driver of vulnerability scores and rankings. Removing this indicator increased transit vulnerability scores by 8 percent on average and shifted the bus fleet and service asset to the top of the vulnerability rankings. Removing the disruption duration indicator caused scores to drop by 6 percent on average, but did not result in any changes to the vulnerability rankings. Removing any of the other indicators resulted in a very minor (less than 3 percent) change to vulnerability scores and no change to vulnerability rankings.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

## 5.5.6 Wind

### Findings

The bus fleet displays relatively high vulnerability to wind, followed by Beltline O&M Facility with moderate vulnerability and GM&O Terminal with low vulnerability. The bus fleet is by far the most exposed asset and is more vulnerable to wind than any other climate stressor. Neither facility is particularly exposed to high winds, but Beltline O&M Facility has much higher sensitivity due to building design and is more difficult to replace. Exposure scores are constant in all narratives, so vulnerability scores remain the same. Table 65 shows the vulnerability scores.

**Table 65: Transit Vulnerability to Wind in the Least Extreme and Most Extreme Narratives**

| Segment | Segment Name | Vulnerability Score (Least Extreme) | Vulnerability Score (Most Extreme) | Data Availability* |
|---|---|---|---|---|
| T3 | Bus Fleet & Service | 3.0 | 3.0 | 100% |
| T2 | GM&O Terminal | 2.6 | 2.6 | 95% |
| T1 | Beltline O&M Facility | 1.8 | 1.8 | 95% |

*The data availability percentages listed in this column indicate how complete the indicator set was for each of the transit assets (see page 197 for more information on data availability).

For full vulnerability scores of all assets, see the results summary table spreadsheet that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3. Results are also provided in maps in the web viewer that accompanies this report, available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/geospatial/.

### Stakeholder Input on Transit Assets' Wind Vulnerability

Interviews with WAVE representatives provided data on building design, whether wind has caused any structural or operational damage in the past, and how long it takes to recover from wind-induced damages. Stakeholders noted that neither facility is well protected from winds due to relatively isolated locations, but that buses are stored and sheltered during high wind events. For all assets, disruption duration was estimated at a few days.

## Data Availability

For the transit facilities (T1 and T2), no information was available on facility age, one of the storm surge sensitivity indicators. Data were available for all facilities for all other wind vulnerability indicators.

## Robustness of Results

Historical performance was the strongest driver of vulnerability scores and rankings. Removing this indicator decreased transit vulnerability scores by 8 percent on average and shifted the Beltline O&M facility to the top of the vulnerability rankings. Removing the speed of asset recovery indicator caused scores to drop by 9 percent on average, but did not result in any changes to the vulnerability rankings. Removing any of the other indicators resulted in a very minor (less than 4 percent) change to vulnerability scores and no change to vulnerability rankings.

Please see Appendix F for a detailed explanation of how the robustness of results was evaluated.

# 6. Evaluating Vulnerability of Pipelines

## 6.1 Method and Limitations

Unlike other modes, the research team was not able to complete a vulnerability screen for pipelines. However, the team completed several interviews with pipeline companies, and obtained valuable information regarding climate-related vulnerabilities of pipelines in general. The findings of these interviews and a review of existing literature on climate change impacts on pipelines form the basis of a qualitative discussion in this section regarding the exposure, sensitivity, adaptive capacity, and overall vulnerability of a representative set of oil and gas pipeline infrastructure to climate change impacts in Mobile County. The research conducted in this analysis focused on representative pipeline segments (see Section 6.1.1); however, much of the information gathered was not segment-specific and thus applies equally to all critical pipelines.

The research team was unable to complete a vulnerability screen for pipelines for the following reasons:

- First, there is less publicly-available information on pipeline operations and vulnerability because pipelines are privately-operated by oil and gas transmission and distribution companies. To address this issue, a number of publicly-available data sources were considered, which are described in Table 66. However, each source was subject to limitations that either prevented use of the source, or did not provide information that was suitably specific to the operation of specific pipeline assets in the Mobile County area. These resources may still be useful for municipalities, regions, or private operators who are considering resources to supplement their own vulnerability assessments in other jurisdictions.
- Second, based on the study scope determined at the beginning of this study and the critical oil and gas pipelines assets identified during the criticality assessment, this assessment focuses on onshore transmission pipeline infrastructure. However, most of what is known about severe weather- and climate-related vulnerabilities of pipelines is applicable to offshore infrastructure only. Onshore pipeline assets in Mobile County, meanwhile, have historically demonstrated a relatively low level of overall vulnerability to weather-related impacts. Onshore pipelines are buried underground, except at valves, metering stations, or compressor or gas processing facilities; they travel along Right of Ways (ROWs) that are typically cleared of debris, maintained to limit erosion and washouts, and carefully monitored. Consequently, these assets generally have a low level of exposure and sensitivity to severe weather such as storm surge, flooding, and high winds, thereby making it difficult to identify and assess the underlying relationships between specific pipeline infrastructure and climate stressors that could affect assets in the future.

The assessment of onshore oil and gas transmission pipelines in this section relies on qualitative information from existing literature on pipeline infrastructure sensitivities and adaptive capacity[45] and interviews with local experts in Mobile County to evaluate overall vulnerability. The exposure, sensitivity, and adaptive capacity of onshore oil and gas transmission pipelines are discussed in the following three sections. Section 6.1.2 provides important background information on pipelines in Mobile. Section 6.2 explores the sensitivity of these assets, and Section 6.3 examines the adaptive capacity of pipeline operations to climate indicators. Where possible, this chapter discusses potential indicators of sensitivity and adaptive capacity, even though sufficient data for evaluating these indicators were not available for this study. Each section considers the impacts of temperature, precipitation, sea level rise, storm surge, and wind. Findings of the overall vulnerability to pipelines are summarized in Section 6.4. In this report, references to "critical" pipeline segments and infrastructure refer to assets that were identified as critical in the Task 1 report of the Gulf Coast Study.[46]

### 6.1.1 Identifying Representative Pipeline Segments

As for highways and rail assets, the study team narrowed the set of critical pipelines to a representative group. The assessment identified 426 miles of pipeline in the study region as being highly critical. Representative pipeline segments were selected from these critical assets.

The project team was careful to identify segments that, taken as a whole, represented the full geographic diversity of pipelines within Mobile County. While rail and highways tend to concentrate near the general downtown area, and then radiate outward, pipelines tend to run inland and along the outer edges of the county. Within those specifications, the project team selected for assets with the following characteristics:

- Location in the southernmost part of the County. Some of these pipelines run outside of the County into the ocean and across the Bay, and could be of particular interest during the exposure assessment.
- Aboveground segments that may be more exposed to weather events. Pipelines are mostly underground, but do come aboveground at storage and other facilities and sometimes are aboveground across rivers. While the project team was unable to identify the exact locations of where pipelines surface, the team identified facilities and river crossings[47] where they would be more likely to be aboveground.
- Proximity to the industrial part of the Hwy-43 industrial corridor.
- Convergence of multiple pipelines, allowing the project team to evaluate multiple critical pipelines as one segment.

After applying these criteria, the project team identified a total of 8 representative pipeline segments with an approximate mileage of 34 miles.

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[45] U.S. DOT, 2012a; Rowan et al., 2013

[46] U.S. DOT, 2011

[47] The study team subsequently determined that all representative pipeline segments are underground pipelines with submerged or underground river crossings.

**Table 66: Data Sources Considered for Vulnerability Assessment of Oil and Gas Pipeline Infrastructure in Mobile County**

| Name | Organization | Description | Data Availability | Limitations |
|---|---|---|---|---|
| National Pipeline Mapping System | Pipeline and Hazardous Materials Safety Administration (PHMSA) | A geographic information system (GIS) containing geospatial data, attribute data, public contact information, and other data on inter- and intrastate hazardous liquid and gas transmission lines, liquefied natural gas (LNG) plants, and hazardous liquid break-out tanks within PHMSA's jurisdiction. | GIS-based system that provides information on pipeline locations, operator, pipeline system, commodity, interstate designation, status, contact information. | Does not provide information on design, materials of construction, condition, performance, or operation of specific pipelines.<br>Does not include facilities outside of PHMSA's jurisdiction. These include gas distribution systems, storage tanks, compressor and pumping stations. |
| Pipeline Incidents and Mileage Reports | PHMSA | An online database that provides information on national and state-specific trends related to pipeline incidents over the past 20 years. | Detailed information on the incident, location, operator, facilities and assets involved, operating information, and a description of the apparent cause. | Reports are generated only for incidents that meet PHMSA reporting criteria[48] and not all are related to weather impacts.<br>The total number of historical incidents in Mobile County is too small to inform reliable indicators of sensitivity to climate-related impacts.<br>Does not include facilities outside of PHMSA's jurisdiction. |

[48] PHMSA, 2011d

| Name | Organization | Description | Data Availability | Limitations |
|---|---|---|---|---|
| Risk Ranking Index Model (RRIM) | PHMSA | Identifies pipeline systems in greatest need of inspection by assigning risk values based on factors, including number of pipeline-related injuries, fatalities, and enforcement actions. | Data used by RRIM includes pipeline age, construction material, enforcement actions, injuries and fatalities, population numbers, and environmental factors. | Information is not available at the level of detail required; assets are categorized in units defined as a collection of assets that could be inspected over a three-year time span; the units can be broad and include a collection of different facilities.[49]<br>Does not include facilities outside of PHMSA's jurisdiction. |
| Company annual reports and operations and maintenance plans | Pipeline operators; federal and state regulators | Reports that are developed by pipeline operators and submitted to state and federal regulators for reporting on jurisdictional pipeline assets, operations, and maintenance activities. | Operations and maintenance plans including information on normal O&M activities, leak surveys, atmospheric corrosion records, pipeline markers, valve and regulator checks, and emergency issues and response plans.<br>Annual reports contain information on pipeline mileage, approximate year of manufacture (if known). | Considered confidential or proprietary information. |

[49] Little, 2012

### 6.1.2 Setting the Stage

Oil and gas pipeline systems include the following assets, equipment, and systems that are relevant to assessing the vulnerability of these systems to climate impacts:

- **Pipelines** transport oil, natural gas, and petroleum products to industries and consumers. They include: (i) gathering pipelines that collect products from oil fields, gas wells, or shipping points, (ii) transmission pipelines that transport large quantities of products over longer distances, and (iii) distribution pipelines that deliver natural gas to industrial, commercial, and residential customers. Offshore pipelines in the Mobile area include oil and gas gathering systems from offshore production wells, and offshore transmission pipelines. Onshore pipelines include both oil and natural gas pipelines, typically buried about three feet (0.9 meters) underground. They come above ground at metering stations, valve stations, gas processing facilities, and compressor facilities.
- **Compressor and pump stations** are facilities that serve to move oil, petroleum products, and natural gas through pipelines. Compressor stations pressurize natural gas so it can be transported through pipelines.[50] Pump stations facilitate the transportation of oil through pipelines by keeping the oil in motion using pumps.
- **Metering and valve stations** are used to measure and control the flow of products in pipelines, respectively. Underground pipelines come above ground at metering and valve stations to provide access to these devices.
- **Rights-of-way** (ROWs) are strips of land covering and running along pipelines, usually extending about 25 feet (7.6 meters) from each side of the pipeline. Some of the property owner's legal rights are granted to a pipeline company under an agreement called an easement, which allows the pipeline company to conduct daily operations on property owned by others.[51]
- **Cathodic protection systems** prevent corrosion by connecting the pipeline metal to a sacrificial anode metal, or anode, that corrodes more readily than the pipeline material. There are two types of anodes: (i) galvanic, where the anode is attached to the metal surface that is to be protected and the system is driven by the difference in electrochemical chemical potential between the metal surface and the anode, or (ii) impressed current, where the anode is connected to an external power source that helps drives the electrochemical reaction. An impressed current cathodic protection system transmits a direct current onto the buried pipeline, with the sacrificial anode chemically interacting with its surroundings (i.e., corroding) instead of the pipeline.[52]
- **Natural gas processing plants** are facilities that prepare natural gas collected from production wells for transmission and delivery to customers. Processing facilities remove water (condensate), other natural gas liquids, and other impurities from the gas to produce "pipeline quality" gas that is almost entirely pure methane.[53]

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50 PHMSA, 2013
51 PHMSA, 2012a
52 PHMSA, 2011a; PHSMA, 2012a
53 PHMSA, 2011b

Table 67 provides a summary of the pipeline operations at each of the representative segments in Mobile. Several natural gas transmission pipelines operate in the area, including the Gulf South Natural Gas Pipeline System, operated by Gulf South, a wholly-owned subsidiary of Boardwalk Pipeline Partners; the Gulfstream Natural Gas System, operated by Williams in partnership with Spectra Energy; the Transco Pipeline, operated by Williams, and Florida Gas Transmission's natural gas pipeline. There are several natural gas processing facilities that treat gas gathered from offshore production fields for supply to onshore transmission and distribution networks. These facilities are located near Coden, Alabama and include the Williams Mobile Bay Gas Processing Plant, the DCP Midstream Gas Processing Plant, and the W&T Yellowhammer Plant (formerly owned by Shell).

**Table 67: Pipelines Operating at Representative Segments in the Mobile Area**[54]

| Location | Operator | Pipeline System | Commodity |
|---|---|---|---|
| 1 | Shell Chemical Company | Mobile Site/Blakely Island Terminal | Gasoline and Distillates |
| | Plains Marketing, L.P. | Mississippi, Alabama | Crude Oil |
| 2 | Bay Gas Storage Company, Ltd. | Bay Gas Storage | Natural Gas |
| | Gulf South Pipeline Company, LP | Gulf South Pipeline | Natural Gas |
| | Mobile Gas Service Corporation | Mobile Gas Service Corporation | Natural Gas |
| 3 | Gulf South Pipeline Company | Gulf South Pipeline | Natural Gas |
| 4 | Gulfstream Natural Gas System, LLC | Gulfstream | Natural Gas |
| | DCP Midstream | — | Natural Gas |
| | William Gas Pipeline Transco | Transco | Natural Gas |
| | Dauphin Island Gathering Partners | Dauphin Island Gathering System | Natural Gas |
| | Chevron Pipeline | Chandeleur Pipeline | Natural Gas |
| 5 | Gulf South Pipeline Company, LP | Gulf South Pipeline | Natural Gas |
| | Southeast Supply Header, LLC | — | Natural Gas |
| | Florida Gas Transmission Co. | — | Natural Gas |
| | William Gas Pipeline | Transco | Natural Gas |
| 6 | Florida Gas Transmission Co. | — | Natural Gas |
| 7 | Gulf South Pipeline Company, LP | Gulf South Pipeline | Natural Gas |
| | Williams Gas Pipeline | Transco | Natural Gas |
| | Mobile Gas Service Corporation | Mobile Gas Service Corporation | Natural Gas |
| 8 | Bay Gas Storage Company, Ltd. | Bay Gas Storage | Natural Gas |

[54] PHMSA, 2012b

## 6.2 Qualitative Sensitivity Findings

This section discusses the sensitivity of onshore oil and gas transmission pipelines to weather-related impacts, and identifies potential indicators for assessing the sensitivity of assets to future changes in climate. Sensitivities to changes in temperature, precipitation, sea level rise, storm surge, and wind are discussed in the following subsections.

Although they were not included within the scope of critical assets evaluated in Mobile County, offshore oil and gas pipelines and gas distribution pipelines may exhibit higher sensitivities to extreme events than onshore transmission infrastructure for the following reasons:

- Offshore pipelines have a much greater level of exposure and sensitivity to extreme events, particularly storm surge from hurricanes. Historically, damage has greatly increased as hurricanes reach Category 4 status or greater, with storm surges of 13 to 18 feet (4.0 to 5.5 meters) and wind of 130 to 155 miles per hour (209.2 to 249.4 kilometers per hour). Often, damage occurs to offshore platforms and pipeline risers at platform interfaces. Wave action can also cause loss of cover and movement of pipelines, particularly at smaller diameter pipelines (i.e. 2 to 6 inches, or 5.1 to 15.2 centimeters) in less than 100 feet (30.5 meters) of water.
- Compared to natural gas transmission pipelines, local gas distribution infrastructure in Mobile may have a higher sensitivity to weather impacts than gas transmission pipelines. During storms with high winds and hurricanes, distribution pipelines can be disrupted by uprooted trees. In flooded areas, water can enter low-pressure gas distribution lines, increasing the gas pressure needed to overcome the resulting water pressure. Regulator stations, which limit the pressure that gas is distributed to downstream residential and commercial customers, are sensitive to flooding and storm surge impacts and may need to be taken out of service to avoid dangerous pressures in downstream gas distribution lines.[55]

### 6.2.1 Temperature

Temperature poses limited impacts on pipeline operations, with the most significant impacts likely to occur during periods of extreme heat. Pipeline sensitivities to temperature include the following:

- Increased temperatures may increase space cooling requirements in buildings housing compressors at pipeline compressor stations.[56]
- On the other hand, increases in temperature may reduce heating requirements for heaters installed on metering stations for cold weather.[57]

> The average mean temperature in the Mobile area is projected to increase by 1 to 5 degrees F by mid-century.
>
> *The number of days where temperatures exceed 95 degrees F is projected to increase from 10 days currently to between 17 and 53 days by mid-century.*
>
> *Source: U.S. DOT, 2012b*

[55] ConEdison, 2010
[56] Wardrop, 2012
[57] Keegan, 2012

- Workers operating outside may require additional breaks in order to cool off and stay hydrated.[58] However, since Mobile already experiences frequent periods of extreme heat, operators are generally used to dealing with these impacts.
- Warmer temperatures lower the density of natural gas, which reduces the amount of energy per cubic foot of gas delivered to consumers and increases the capacity required to deliver sufficient volumes of gas to meet customers' needs. This effect, however, has not had a large impact in the Mobile area historically.[59]
- Increased temperatures may affect the demand for heat and power from industrial and residential consumers in the Mobile area, which in turn may influence demand for natural gas. This could be a contributing factor in the need for pipeline and service expansion. One of the largest customers in the Mobile area is Alabama Power, which operates the Theodore Cogen Facility, a natural gas-powered cogeneration plant in Mobile County.[60,61] Consequently, an increase in demand for electricity for space cooling from customers supplied by the facility would result in increased demand for natural gas.

These impacts are associated with increased operational costs and changes in revenue from natural gas sales to customers.

### Summary Indicator of Sensitivity to Temperature

The key indicator the research team identified for assessing the sensitivity of pipelines to temperature impacts is historical performance. Most operators indicated that the sensitivity of pipeline infrastructure to temperature is generally low in the Mobile area, even during past extreme heat events. This impact is summarized in Table 68.

**Table 68: Indicators of Pipelines Sensitivity to Temperature Impacts**

| Category | Indicator | Indicator Description |
|---|---|---|
| Condition and Performance | Historical performance | Increased temperatures may reduce operational efficiency due to breaks in shifts for workers to cool off or remain hydrated. Energy consumption and consequently energy costs at air-conditioned facilities may also increase under warmer temperatures. |

58 Wardrop, 2012
59 Keegan, 2012
60 Keegan, 2012
61 Alabama Power, 2012

### 6.2.2 Precipitation

Pipelines are relatively sensitive to changes in precipitation compared to other climate stressors, particularly from run-off and flooding from extreme precipitation events. Pipeline sensitivities to precipitation and drought include the following:

> Projected changes in precipitation are uncertain, but annual precipitation in the Mobile area may increase by 22% in a wetter climate or decrease by 5% in a drier climate.
>
> *The frequency of heavy precipitation is projected to increase. By mid-century, the probability of a 1-in-20 year downpour could increase by 4% to 32%.*
>
> *Source: U.S. DOT, 2012b*

- Weakened soil structure and erosion, which can expose underground pipelines.
- Reduced access to pipeline Right of Ways (ROWs).
- The possibility of changes in the operation and effectiveness of pipeline corrosion protection systems, although impacts on these systems are likely to be minor.
- Disruption to communication, monitoring, and electronic systems during storms and severe weather.

Each of these impacts is discussed in greater detail in the following sub-sections.

#### Erosion

Erosion can uncover and expose pipelines. Some washout has occurred after particularly intense storms that exceed between two and five inches (5 to 12 centimeters) of rain over a window of six to seven hours. One operator reported that pipelines and operations had no problems during a recent storm that shed over three inches (8 centimeters) of rain, although he acknowledged that exceptional rainfall of more than five inches (13 centimeters) could move or erode berms, or mounds of earth that are used to protect against flooding.[62]

> *Washouts are more likely to occur after 2-5 inches (5 to 12 cm) of rain fall over 6-7 hours.*
>
> *Source: Jackson, 2012*

Areas most vulnerable to erosion for underground pipelines are generally near creeks, rivers, and any apparatus that funnels water away from facilities and the surrounding area.[63] Erosion has also been observed to occur on hillsides or very low points, though these instances have not been severe enough to create safety issues.[64] Inshore drainage ditches and creeks erode over time, and flooding from precipitation thus can contribute to scouring at creek crossings, potentially uncovering and exposing pipelines.[65] Soil type may also influence erosion; particularly dry or

62 Jackson, 2012
63 Falkenhagen, 2012
64 Wardrop, 2012
65 Falkenhagen, 2012

sandy soils loosen vegetation, becoming more susceptible to erosion. Soil stability can be an issue for pipelines, and is examined during inspections.[66]

If exposed by soil erosion, pipelines may be more vulnerable to damage from scouring or washouts, flotation from flooding, or damage from collisions with objects such as debris, vehicles, or boats. Pipeline operators frequently monitor and maintain pipeline ROWs to keep pipelines at least three feet underground; as a result, increased precipitation during extreme events that cause scour and washouts may lead to additional maintenance and monitoring costs.[67]

### Access to ROWs and Aboveground Pipeline Infrastructure

Heavy precipitation and flooding may cause standing water or wet soils that limit access by ground service crews along pipeline ROWs. Pipeline operators typically conduct fly-over inspections of pipeline ROWs following extreme weather events to assess the condition of pipeline cover;[68] see Section 6.3 for details.

During springtime rains and during heavy rainfall from storms and hurricanes, the Mobile River backs water up towards Mount Vernon, Alabama. In past events, operators have observed flooding over a 12-mile (19-kilometer) area out to the east of the Mobile River, where elevation is lower.[69] Flooding in this area led one operator to relocate a valve station to a higher elevation; secondary valves can also be used to shut-in gas if a given valve is inaccessible due to flooding.[70] As long as valves are sufficiently accessible and monitoring is available to ensure there are no impacts, buried pipelines are not sensitive to standing water from flooding.

### Corrosion

Varying levels of precipitation can have an effect on the speed of corrosion of pipelines and the effectiveness of cathodic protection systems that are used to protect pipelines from corrosion. Because cathodic protection systems rely on soil conductivity, drier soils and sandy soils require a higher electrical current to be used in impressed current systems. While drier soils do not impact the effectiveness of the system, they do increase the cost. Cathodic protection systems work better in wetter soils.[71] However, wetter soil causes the sacrificial anode to corrode more quickly in both galvanic and impressed current systems. Pipeline operators were uncertain about how significant this effect might be, but did not see it as having a large impact on pipeline corrosion systems since anodes are monitored and replaced as they degrade. One operator noted that their cathodic protection systems are surveyed annually.[72]

[66] Barlow, 2012
[67] Wardrop, 2012
[68] Jackson, 2012
[69] Jackson, 2012
[70] Jackson, 2012
[71] Wardrop, 2012; Falkenhagen, 2012; Keegan, 2012
[72] Falkenhagen, 2012

## Impacts to Communications and Monitoring During Storms

Operators in the Mobile area communicate and relay data collected on pipeline operations using satellite, cellular, and wire systems, which may be affected by severe weather events.[73] One operator noted that its satellite and wire communication systems serve as a back-up for each other in case one fails. In the event that remote monitoring or communication systems fail, responders are dispatched as soon as it is safe to monitor facilities (for more details, see section 1.1.5 on Adaptive Capacity).[74]

Lightning is one of the most prominent weather-related issues due it its effect on electronics systems. Because pipelines are highly conductive, electronics can be impacted miles away from where the pipeline was initially struck. This can cause electrical shorts and electronic malfunctions at assets along the pipelines that rely on electronics for stability.[75]

## Summary Indicators of Sensitivity to Precipitation

Table 69 provides a summary of several indicators to assess the sensitivity of pipelines to precipitation impacts.

**Table 69: Indicators of Pipelines Sensitivity to Precipitation Impacts**

| Category | Indicator | Indicator Description |
|---|---|---|
| Condition and Performance | Cathodic protection performance | The performance of cathodic protection systems may degrade when exposed to drier conditions. Wetter conditions improve performance but also increase the rate of sacrificial anode corrosion. |
| | Historical performance | Historical weather-related issues with erosion, corrosion, or disruption in communications and monitoring may indicate sensitivities to future climate changes. |
| Design | Pipe Coating | Coal-tar enamel coatings are not as durable as newer, epoxy coatings; may result in gaps that are susceptible to corrosion. |
| | Age of pipeline | Older pipelines are more likely to have been designed to outdated standards. Age itself is not a reliable indicator of performance, however, because older pipelines can still be maintained and managed to perform well. |
| Location | Access | Inaccessible areas during or following precipitation events may disrupt monitoring and maintenance activities, even if pipelines or related infrastructure are not directly damaged or otherwise affected. |
| | Flood zone | Pipelines located in flood zones may be more sensitive to flooding during heavy precipitation events. |
| | Ponding | Pipelines located in low-lying areas where water flows to may be more sensitive to impacts from erosion and water ponding during precipitation. |
| | Permeability | Pipelines located in areas where surfaces are impermeable (e.g., concrete) may experience higher levels of run off and water flows during precipitation events. |

[73] Jackson, 2012
[74] Jackson, 2012
[75] Wardrop, 2012

| Category | Indicator | Indicator Description |
|---|---|---|
| | Soil type | Sandy and dry soils are more susceptible to erosion than other soil types. Pipelines located in these soils may have a higher sensitivity to erosion impacts during precipitation events. |

### 6.2.3 Sea Level Rise

*Sea level rises of 1 to 6.5 feet (30 to 200 cm) are plausible in the Mobile area.*

*Source: U.S. DOT, 2012b*

Critical onshore pipeline assets have a low sensitivity to sea level rise in the Mobile area. Operators with pipelines in coastal areas that are threatened by erosion or loss of protective wetlands may face reduced access to pipelines for operations and maintenance activities. Pipelines may also be sensitive to changes in water tables, soil stability, and intrusion of saltwater due to sea level rise.[76]

Pipelines and related infrastructure in the Mobile area, however, are largely protected or not likely to be exposed to these impacts. Pipelines and oil and gas infrastructure such as compressor stations, natural gas plants, and metering and valve stations in Mobile are located outside of the sea level rise exposure zones modeled in the Criticality Assessment (see Section 1.1.2).[77,78]

Pipeline sensitivities to sea level rise are discussed in further detail below.

#### Erosion and Restricted Access to Shut-in Valves and Pipeline Equipment

Rising sea levels could restrict access to pipelines and shut-in valves for operations and maintenance activities. These impacts will likely be particularly acute in areas already experiencing coastal erosion, land subsidence, and coastal inundation during storms. In areas of Louisiana west of Mobile, lands surrounding some pipelines have degraded from solid earth to marsh, causing significant access issues. In some areas once accessible by vehicle or foot, boats are now needed for accessing valves to shut-in pipelines and for performing maintenance on pipelines, such as recoating.[79] Additionally, if the land surrounding pipelines in coastal areas continues to erode, pipelines could be exposed to open-water vulnerabilities, including boats, waves, and storms.[80]

#### Changes in Sea Level at Onshore Pipeline Approaches

Salt water is corrosive to pipelines.[81] Higher sea levels could increase the risk of saltwater intrusion into low-lying or coastal areas. As sea levels rise, assets not originally built to

76 U.S. DOT, 2012a, citing CCSP, 2008
77 Falkenhagen, 2012
78 U.S. DOT, 2011
79 Falkenhagen, 2012
80 Dell'Amore, 2012
81 Barlow, 2012

withstand the added stress of salt water may be affected. Pipeline manufacturers and operators, however, protect against corrosion using pipeline coatings and cathodic protection systems. Onshore pipelines are typically protected using fusion-bonded epoxy coatings, which provide good corrosion protection and can withstand high temperatures and stress.[82] Cathodic protection systems (see Precipitation) are used alongside coatings to enhance protection.[83] Older pipelines may still use coal-tar coatings that are less effective.[84,85] One operator indicated that their offshore pipelines have cement coatings to protect against corrosion and reduce the buoyancy of pipelines, making them less sensitive to movement from wave action and flooding.[86]

In the Mobile area, critical onshore pipeline assets are not located in areas that are exposed to sea level rise in modeled scenarios of future sea level. Offshore pipelines from the Gulf of Mexico come ashore in Mobile County in two specific corridors. One corridor is at Portersville Bay south of Coden, Alabama. The second corridor is east of the W&T Yellowhammer gas processing plant near the Dauphin Island Parkway. When they transition offshore, pipelines are directionally drilled (meaning they are drilled at an angle or horizontally) approximately 40 feet (12 meters) deep for 100 feet (30 meters) on either side of the coast line.[87] This provides a large buffer around the coastal area. Onshore pipelines and related oil and gas infrastructure are located in areas that are sufficiently elevated and far enough inland that they are not likely to be exposed to sea level rise changes (see Exposure section).

## Summary Indicators of Sensitivity to Sea Level Rise

Table 2 provides a summary of several indicators identified to assess the sensitivity of pipelines to sea level rise impacts.

**Table 70: Indicators of Pipelines Sensitivity to Sea Level Rise Impacts**

| Category | Indicator | Indicator Description |
|---|---|---|
| Condition and performance | Historical performance | Historical weather-related issues with erosion, corrosion, or restricted access from coastal inundation may indicate pipelines that are particularly sensitive to impacts from sea level rise. |
| Design | Age of pipeline | Older pipelines are more likely to have been designed to outdated standards or use older coatings that are more susceptible to corrosion from saltwater intrusion than newer pipelines. Age itself is not a reliable indicator of performance, however, because older pipelines can still be maintained and managed to perform well. |
| | Pipe coating | Coal-tar enamel coatings are not as durable as newer, epoxy coatings; may result in gaps that are susceptible to corrosion from saltwater intrusion. |

82 PHMSA, 2011c
83 PHMSA, 2011c
84 Falkenhagen, 2012
85 PHMSA, 2011a
86 Wardrop, 2012
87 Falkenhagen, 2012

| Category | Indicator | Indicator Description |
|---|---|---|
| Location | Elevation | Pipelines located in shifting flood zones may be more sensitive to flooding due to sea level rise. |
| | Access | Pipelines located in coastal areas where access is restricted by erosion and flooding from storm surge may be more sensitive to impacts from erosion and water ponding from sea level rise. |
| | Soil type | Sandy and dry soils are more susceptible to erosion than other soil types. Pipelines located in these soils may have a higher sensitivity to erosion impacts from sea level rise. |

## 6.2.4 Storm Surge

Storm surge depths (including wave heights) of up to 37.7 feet (11.5 meters) were modeled for the transportation assets under this project. *Source: U.S. DOT, 2012b*

Pipelines are moderately sensitive to storm surge. In general, buried onshore pipelines are protected from the destructive force of storm surge and from collisions with debris during storm events. Storm surge affects only some of the critical pipeline segments in the Mobile, Alabama area. However, eroding soil and marshes as well as the loose debris can pose significant impacts to pipelines if hit by a storm surge. Pipeline sensitivities to storm surge include the following:

- Storm surge can contribute to scour and erosion that exposes buried pipelines, particularly in coastal areas where erosion is already an issue and protective marshes are degraded.
- Exposed or aboveground pipeline sections can be damaged by collisions with debris carried by storm surge.
- Inundation from storm surge can restrict access to valves and pipelines for operations and maintenance following hurricanes and storms.
- Facilities, communications, and monitoring systems are sensitive to damage from debris and the storm surge itself.

Each of these impacts is discussed in greater detail in the following sub-sections.

### Erosion, Removal of Cover, and Movement of Pipelines

The stability of soil surrounding pipelines can be affected by storm surge.[88] Pipelines are typically buried at least three feet underground. As long as they are buried underground, the effects from storm surge on pipelines are minimal. Pipeline operators therefore take steps to monitor and maintain the depth of cover of pipelines through visual inspections, maintenance of ROWs, and depth of cover surveys. One operator reported that they immediately fly their pipelines after intense storms to identify any areas of exposed pipeline where water has unearthed or undercut pipelines.[89] Where high rates of scour during storms may have disturbed

88 Barlow, 2012; CCSP, 2008
89 Jackson, 2012

pipelines underneath riverbeds, operators can conduct depth of cover surveys to compare any change in cover from before the storm. For example, one operator described a depth of cover survey that was conducted across the Bay of St. Louis in Mississippi following Hurricane Katrina.[90]

Storm surge from hurricanes, however can expose pipelines from soil removal and erosion. Exposure of underground pipelines does not itself cause damage or impact performance of pipelines, but it does increase the risk of damage. Once exposed, pipes are more susceptible to movement from wave action or buoyancy in water, or to damage from collisions with debris during storms.

These sensitivities are greater in areas with high rates of coastal erosion and degradation of marshes. As coastal areas erode, pipelines lose their natural storm protection and become increasingly exposed to outside elements, and construction and maintenance activities become more challenging.[91,92] For example, in Louisiana, west of Mobile, pipelines running through marshes have become increasingly exposed to damage to storm surges as a result of the erosion of protective coastal marshes.[93,94]

### Access to ROWs and Shut-in Valves

Inundation from storm surge in low-lying areas can restrict access to pipeline ROWs and shut-in valves, impeding maintenance and operation activities following storm events. Above-ground sections of pipelines, such as metering and valve stations are vulnerable to damage from debris from storm surges.[95]

### Physical Damage to Facilities and to Monitoring and Communications Infrastructure

Aboveground facilities, such as buildings, compressor stations, and metering stations can be damaged by the force of a storm surge or by debris. In the Mobile area, aboveground assets are located outside of areas that have been historically exposed to storm surge. Most of the damage from surges occurs at the interface between the edge of the storm surge and land, which is where the force of the surge is directed. Assets that are inundated by storm surge, but which are not located at this interface may not experience as much damage as assets that are exposed to the full force of the surge.[96]

Hurricanes, storm surge, and high winds can interrupt remote data acquisition and communications infrastructure. Communication and data collection equipment are at points of

90 Wardrop, 2012
91 Dell'Amore, 2012
92 Falkenhagen, 2012
93 Dell'Amore, 2012
94 Falkenhagen, 2012
95 Falkenhagen, 2012
96 Falkenhagen, 2012

service, such as delivery and control plants, compressor stations, and large delivery points. The loss of monitoring and data acquisition at these points requires operators to dispatch ground personnel to monitor operations until communications are restored. This is the case, for example, at the natural gas compressor station located at Airport Boulevard in western Mobile County. One operator noted that interruptions in communication and data acquisition infrastructure can be more important than power outages because it is difficult to reliably back-up, or ensure redundancy in, communication systems.[97] In response, the operator has relocated cell phone towers away from areas vulnerable to severe weather and disruption.[98]

### Summary Indicators of Sensitivity to Storm Surge

Table 71 is based on the above discussion and provides a summary of several indicators identified to assess the sensitivity of pipelines to precipitation impacts.

**Table 71: Indicators of Pipelines Sensitivity to Storm Surge Impacts**

| Category | Indicator | Indicator Description |
|---|---|---|
| Condition and performance | Historical performance | Historical weather-related issues with erosion, removal of cover, or disruption in communications and monitoring may indicate sensitivities to storm surge impacts. |
| Design | Age of pipeline | Older pipelines are more likely to have been designed to outdated standards. Age itself is not a reliable indicator of performance, however, because older pipelines can still be maintained and managed to perform well. |
| Location | Elevation | Pipelines located in flood zones and low-lying areas may be more sensitive to flooding and physical damage from debris and the force of a storm surge. |
| | Access | Pipelines and facilities located in low-lying areas where water flows to may be more sensitive to impacts from erosion and water ponding during storm surges. |
| | Soil type | Sandy and dry soils are more susceptible to erosion than other soil types. Pipelines located in these soils may have a higher sensitivity to erosion impacts from the force of storm surge. |

## 6.2.5 Wind

While pipelines buried underground are not vulnerable to wind impacts, other aboveground assets, such as buildings, are vulnerable, particularly from damage due to debris. The sensitivities of pipeline infrastructure to wind include the following:

> Modeling of hurricane scenarios showed that Wind speeds can reach up to 155 mph (250 km/hour) during storms or higher in coastal areas.
>
> *Source: U.S. DOT, 2012b*

- Aboveground assets, such as buildings, compressor stations, valve and metering stations, and pipeline ROWs can be damaged or blocked by wind-blown debris during storms.

97 Wardrop, 2012
98 Wardrop, 2012

- Buildings are sensitive to category 4 and 5 winds, particularly those built from wood or metal.
- High winds can cause damage to power lines during storms, disrupting delivery of electricity to oil and gas facilities and infrastructure.
- Communication and remote data acquisition systems can be disrupted by high winds.

Each of these impacts is discussed in greater detail in the following sub-sections.

### Damage to Pipeline Infrastructure from Wind-Blown Debris

Aboveground pipeline infrastructure is sensitive to damage from wind-blown debris. One operator mentioned that damage may occur at metering stations in category 4 or 5 storms due to debris and tree falls.[99]

> Damage may occur at metering stations in category 4 or 5 storms due to debris and tree falls.
>
> *Source: Wardrop, 2012*

A key factor of sensitivity is what is surrounding an asset. One operator mentioned that they will remove trees around their facilities and along ROWs to avoid damage caused by wind-blown debris.[100] Another operator, however, noted that structures and natural vegetation surrounding assets may also act as a buffer to provide protection from high winds.[101]

### Damage to Pipeline Infrastructure from High Winds

> Buildings along the Gulf coastline are rated to withstand winds of up to 155 mph (250 km/hour).
>
> *Source: U.S. DOT, 2012b*

High winds themselves can cause damage to buildings and other aboveground structures. Buildings along the Gulf coastline are rated for winds of up to 155 mph (250 km per hour), though they still may exhibit sensitivity to wind impacts. During Hurricane Katrina, roofs of buildings lost shingles and sustained other damage as well.[102] One of the drivers of this sensitivity is the type of construction of buildings. For example, those built with wood and steel are more sensitive to high winds. Generally, pipeline facilities like processing plants are built at one to two stories at ground level with metal sides. Control rooms, built with cinderblocks, are sturdier structures.[103]

Damage to power lines during storms is common, forcing many facilities to have gas generators on reserve to produce their own electricity for electrical compressors and other machinery. Communications can also be sensitive. Operators use a wide variety of communication systems, including satellite, microwave, and radio, and these systems can also be affected by high winds.[104]

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99 Wardrop, 2012
100 Jackson, 2012
101 Falkenhagen, 2012
102 Wardrop, 2012
103 Falkenhagen, 2012
104 Falkenhagen, 2012

If certain systems are impacted, operators must be prepared to adapt communication connections in order to maintain proper communication. Both issues can pose added costs to operators.

#### Summary Indicators of Sensitivity to Wind

Table 72 is based on the above discussion and provides a summary of several indicators identified to assess the sensitivity of pipelines to wind impacts.

**Table 72: Indicators of Pipelines Sensitivity to Wind Impacts**

| Category | Indicator | Indicator Description |
|---|---|---|
| Condition and Performance | Historical performance | Historical weather-related issues with damage to building structures from debris and the force of wind—as well as disruption in communications and monitoring—may indicate sensitivities to wind impacts. |
| Design | Wind ratings | Wind velocities that exceed a building's wind rating are more likely to cause more damage to the structure. |
| | Height and placement of building | Taller buildings and those unprotected by buildings of similar size are more susceptible to become damaged by debris and high winds. |
| | Building materials and construction | According to Mobile stakeholders, buildings and roofs made from wood and metal are more likely to be impacted by high winds, whereas buildings constructed with brick or cinderblock are more wind resistant. |
| Location | Proximity to trees/ vegetation | Assets located in areas protected by vegetation may be "sheltered" from high winds, but also could be susceptible to debris issues. |

## 6.3 Adaptive Capacity Findings

This section evaluates the adaptive capacity of pipelines that face weather-related impacts according to three categories: (i) existing practices that enable pipeline operators to recover quickly from impacts (i.e., "speed to recovery"), (ii) redundancy that exists within pipeline assets to minimize disruptions from weather-related impacts, and (iii) a qualitative assessment of the approximate length of disruption possible from weather impacts, if a disruption occurs to the operation of pipeline assets.

### 6.3.1 Speed to Recovery if Affected

Pipeline operators have existing practices to maintain pipeline assets, prepare for extreme events, and respond to impacts that increase the speed with which assets impacted by weather-related events can recover.

ROW maintenance and pipeline inspections are important maintenance practices the increase the resiliency of pipelines to weather-related impacts. Operators will plant grass over pipelines in order to prevent erosion and build berms to redirect the flow of water. For new pipelines, ROWs will be cleared from any obstructions and covered with grass as quickly as possible. Washouts can occur frequently until grass is planted and growing and berms are in place.[105] To avoid damage from debris and trees in storms, operators remove trees and other objects that could obstruct equipment around metering stations, compressor stations, valve stations, and along ROWs.[106]

Operators inspect pipelines throughout the year at different frequencies depending on the proximity of pipelines to inhabited areas, as shown in Table 73. Inspections allow operators to monitor conditions such as corrosion, erosion, and drainage issues that may increase the sensitivity of pipelines to weather-related impacts from flooding and storm surge in coastal areas.

**Table 73: Degree of Pipeline Inspection[107]**

| Category | Location | Level of Inspection |
|---|---|---|
| Category 1 | Neighborhood, near larger populations | Visually inspected at least twice per year |
| Category 2 | Located in town, but not highly urban | Visually inspected once per year |
| Category 3 | Remote areas, or contains safer materials or a lower pressure | Inspected once per year, but can be inspected with a fly-over |

Operators also prepare in advance for hurricanes. These preparations include developing pre- and post-disaster operations plans, downloading data from monitoring equipment in case electronics are damaged, obtaining emergency fuel supplies, and recording alternative contacts for employees. Other aspects of storms are taken into account, as well. Because lightning can cause electrical shorts or electrical equipment to malfunction, lighting protection systems are installed, though these systems are not always effective.[108]

Following extreme events, such as hurricanes or floods, operators will inspect ROWs for exposed pipeline and depth of cover. One operator noted that they will immediately fly over the pipeline after events, looking for areas where water has moved soil or undercut the pipeline.[109] If necessary, operators may also conduct a depth of cover survey across bays or river crossings to compare the change in cover of pipelines after a storm. For example, a depth of cover survey was conducted in the Bay of St. Louis following Hurricane Katrina.[110]

The availability of replacement equipment and repair materials affects recovery speed as well. After an event where the operations of multiple pipeline companies are impacted, operators often may seek similar equipment for repair or maintenance, making them difficult to obtain. It is

105 Jackson, 2012
106 Jackson, 2012
107 Barlow, 2012
108 Wardrop, 2012
109 Jackson, 2012
110 Wardrop, 2012

possible to avoid this issue by stockpiling enough parts prior to an event in order to continue to operations afterwards.[111]

### 6.3.2 Redundancy

Pipeline operators often rely on redundancy in pipeline shut-in valves, communications and data acquisition systems, and power systems to avoid disruptions from flooding and access issues, wind and storm impacts, and loss of power at key facilities.

Access to valves can be impaired during flooding from precipitation or storm surge. The use of secondary valves further away from flooding areas enables operators to alleviate access issues.[112]

Communications and data acquisition systems also include redundancy. One operator in the Mobile area explained that they use two systems to continuously monitor pipelines: a satellite monitoring system and another by wire, via a T1 circuit at Mount Vernon. If one system fails, the other serves as a back-up. A failure of both systems would require a responder located several miles away to go to the facility as soon as conditions are safe.[113] Operators also use cellular phones to communicate after storms, since mobile devices are perceived to be less affected by power outages than other communication systems. One operator reported that texting generally works well after storms and is used often during power outages.[114]

In the case that compressor stations are disconnected from a power source, operators keep generators on site for back-up power.[115] One operator in the Mobile area reported that their back-up generators prevented disruptions from power outages during Hurricane Katrina.[116]

### 6.3.3 Disruption Duration

Using qualitative information on the potential weather-related impacts to pipelines, Table 74 assesses the potential duration of disruptions to pipeline assets by climate stressor. This provides an indication of how long pipeline assets in general may be affected by weather-related impacts. In general, disruptions from temperature or precipitation impacts are negligible or relatively short; damage from storm surge and hurricanes causes longer disruptions.

111 Wardrop, 2012
112 Jackson, 2012
113 Jackson, 2012
114 Falkenhagen, 2012
115 Jackson, 2012
116 Wardrop, 2012

**Table 74: Disruption Duration of Pipeline Assets[117,118,119]**

| Climate Stressor | Disruption Duration | Explanation |
|---|---|---|
| Temperature | None or a few hours | Temperature impacts are generally minor, though some impacts on space cooling requirements and staff health and safety during extreme heat events exist. |
| Precipitation and heavy rainfall events | A few days | Flooding may cause erosion, scour, and access issues. Impacts are not severe and do not affect the actual transmission of oil and gas. After water subsides, maintenance can be performed. |
| Hurricanes and storm surge | A few days | Storm surge can cause damage to pipelines and also cause access issues, although aboveground pipelines are generally sheltered from the most severe effects.<br>Power outages may affect the operation of oil and gas pipelines, though some systems are equipped with back-up power. Communications may be disrupted.<br>During extreme weather, gas flowing through pipelines is very low, so most services are shut down anyways. The presence of staff would therefore not be necessary in the case of a power outage, though staff is dispatched to monitor the operation of equipment once conditions are safe. |

## 6.4 Overall Qualitative Assessment of Vulnerability

In general, onshore oil and gas transmission pipelines have demonstrated a relatively low vulnerability to weather-related impacts in the Mobile area. These assets generally have a low level of both exposure and sensitivity because they are mainly buried underground where they are protected from impacts and located in areas that are not exposure to extreme events such as storm surge, flooding, and high winds.

Relative to other climate stressors (e.g., temperature, precipitation, sea level rise, and wind), pipelines are most vulnerable to impacts from storm surge, flooding from heavy precipitation, and high winds. Storm surge and flooding events can erode ROWs, unearth buried pipelines, move exposed pipelines, damage facilities and related equipment, and limit access to pipeline assets. Aboveground facilities, such as buildings, compressor stations, valve and metering stations, communications and power lines, and ROWs are sensitive to wind-blown debris and damage from high winds.

Pipelines exhibit lower vulnerabilities to temperature impacts and sea level rise in Mobile. Although the exposure of pipeline assets, facilities, and personnel to extreme heat events is projected to greatly increase, the sensitivity of pipelines to temperature impacts is generally low,

117 Wardrop, 2012
118 Jackson, 2012
119 Falkenhagen, 2012

even during extreme heat events. Onshore pipelines in the Mobile are not projected to be exposed to sea level rise impacts.

From an operations perspective, power and communications systems are likely to exhibit some of the highest system-wide vulnerabilities to climate impacts because they are important, exposed, sensitive, and hard to restore or make completely redundant. These systems are sensitive to storm surge, flooding from heavy precipitation, and high winds—particularly during hurricane or storm events.

To mitigate these vulnerabilities, pipeline operators have implemented strategies to reduce the vulnerability of their assets to weather impacts in Mobile. Maintenance of ROWs, inspections, planning for extreme events, and redundancy in pipeline operations, communications, and power systems help limit the effects of disruptions.

# 7. References

Alabama Department of Transportation (ALDOT). 2012. Personal communication between ALDOT and ICF International. July 9, 2012.

Alabama Power. 2012. Generating Plants. Web, Accessed January 2013, http://www.alabamapower.com/about-us/plants/home.asp.

Alabama State Port Authority (ASPA). 2013. Facilities. Web, Accessed October 10, 2012, http://www.asdd.com/facilities.html.

Alfred, G. and G. Bryant. 2012. Interviews with Gerald Alfred and George Bryant of WAVE Transit, March 12, 2012 and October 2, 2012.

Amberger, N. 2012. Interviews with Nick Amberger, City of Mobile. August 9, 2012 and September 20, 2012.

American Association of State Highway and Transportation Officials (AASHTO). 1983. Standard Specifications for Highway Bridges. 13th ed. American Association of State Highway and Transportation Officials, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). 2008. Guide Specifications for Bridges Vulnerable to Coastal Storms. American Association of State Highway and Transportation Officials, Washington, DC.

Applied Technology Council (ATC). 2012. Windspeed by location. Applied Technology Council. Web, Accessed November 14, 2012, http://www.atcouncil.org/windspeed/index.php.

Bailey, C. 2012. Interview with Charles Bailey of CSX Rail. October 2, 2012.

Barlow, M. 2012. Interviews with Mark Barlow, March 20, 2012 and September 21, 2012.

Brooks, N., W. N. Adger, and P. M. Kelly. 2005. The Determinants of Vulnerability and Adaptive Capacity at the National Level and the Implications for Adaptation. *Global Environmental Change* 15(2):151–163.

Bush, H. and D. Harris. 2012. Interview with Helen Bush and Dave Harris, Evonik. August 13, 2012.

Climate Change Science Program (CCSP). 2008. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I, U.S. Climate Change Science Program Synthesis and Assessment Product 4.7. U.S. Climate Change Science Program. Available at: http://www.climatescience.gov/Library/sap/sap4-7/final-report/.

ConEdison. 2010. Gas Long Range Plan: 2010 to 2030. Web, Accessed January 14, 2013, http://www.coned.com/PublicIssues/PDF/GLRP1210c.pdf.

Dell'Amore, C. 2010. Coast Pipelines Face Damage as Gulf Oil Eats Marshes? National Geographic News. Web, Accessed January 3, 2012, http://news.nationalgeographic.com/news/2010/05/100525-gulf-oil-spill-pipelines-science-environment.

Dyess, C. 2012. Interview with Carl Dyess, U.S. Army Corp of Engineers. July 20, 2012.

ESRI. 2012. ArcGIS Help 10.1 Resource Center: Flow Direction (Spatial Analyst). Web, Accessed February 11, 2013, http://resources.arcgis.com/en/help/main/10.1/index.html#//009z00000052000000.

Falkenhagen, M. Interview with Mark Falkenhagen, Spectra Gases, Inc. September 21, 2012.

Federal Emergency Management Agency (FEMA). 2010. Digital Flood Insurance Rate Map (DFIRM) Database for Mobile County, AL, Community No.01097C. https://msc.fema.gov.

Federal Emergency Management Agency (FEMA). 2012. Flood Zones NFIP Policy Index. Web, Accessed February 11, 2013, http://www.fema.gov/national-flood-insurance-program-2/flood-zones.

Federal Highway Administration (FHWA). 1995. Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. U.S. Department of Transportation, Federal Highway Administration, Office of Engineering Bridge Division. FHWA-PD-96-001.

Federal Highway Adminstration (FHWA). 2008. Highways in the Coastal Environment – 2$^{nd}$ edition. U.S. Department of Transportation, Federal Highway Administration. NHI-07-096.

Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation. U.S. Department of Transportation, Federal Transit Administration. FTA Report No. 0001.

Fry, J., G. Xian, S. Jin, J. Dewitz, C. Homer, L. Yang, C. Barnes, N. Herold, and J. Wickham. 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering & Remote Sensing*, Vol. 77(9):858–864.

Füssel, H. M. 2010. Review and Quantitative Analysis of Indices of Climate Change Exposure, Adaptive Capacity, Sensitivity, and Impacts. The World Bank, World Development Report.

Governor of New York State. 2012. Governor Cuomo Announces 2PM Closure Of Holland and Hugh Carey Tunnels. Governor of New York State, Governor's Press Office. Web, Accessed January 14, 2013, http://www.governor.ny.gov/press/10292012-holland-hugh-carey-tunnelclosings.

Harley, M., L. Horrocks, N. Hodgson, and J. van Minnen. 2008. Climate Change Vulnerability and Adaptation Indicators. European Topic Centre on Air and Climate Change, EET/ACC Technical Paper 2008/9.

Harris, B. 2012. Interviews with Bob Harris of Alabama State Port Authority. July 11, 2012, March 12, 2012, and September 21, 2012.

Hill, L. 2012. Interview with Larry Hill of Shell Chemical. August 13, 2012.

Hughes, T., P. Faggard, and A. Pabst. 2012. Interviews with Thomas Hughes, Paul Faggard, and Andrew Pabst, Mobile Airport Authority. March 13, 2012.

Hughes, T. 2012. Personal communication between Thomas Hughes of Mobile Airport Authority and ICF International. September 20, 2012.

Jackson, R. 2012. Interview with Riley Jackson, Southern Union Gas Co. July 5, 2012.

Keegan, P. 2012. Interview with Peter Keegan, Mobile Gas. July 17, 2012.

Kim, S. and J. Jeong. 2013. Measurement and Prediction of Coefficient of Thermal Expansion for Concrete Pavement Design in Georgia. Transportation Research Board 92nd Annual Meeting Compendium of Papers. Available at: http://trid.trb.org/view.aspx?id=1241634.

Kujala, K. 2012. Interview with Ken Kujala, Austal. July 26, 2012.

Little, R. 2012. Interview with Roger Little, Pipeline & Hazardous Materials Safety Administration. September 4, 2012.

Meigs, W. 2012. Interview with Walter Meigs, BAE Systems. August 2, 2012.

Mitchell, R. and T. Sanchez. 2012. Interviews with Ricky Mitchell and Tina Sanchez, Mobile County. March 12, 2012 and September 20, 2012.

Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM). 2002. Weather Information for Surface Transportation: National Needs Assessment Report. U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), FCM-R18-2002. Available at: http://www.ofcm.gov/wist_report/pdf/01-opening.pdf.

Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson (eds). 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Pipeline & Hazardous Materials Safety Administration (PHMSA). 2011a. Fact Sheet: Cathodic Protection. Web, Accessed January 3, 2013, http://primis.phmsa.dot.gov/comm/FactSheets/FSCathodicProtection.htm.

Pipeline & Hazardous Materials Safety Administration (PHMSA). 2011b. Fact Sheet: Natural Gas Processing Plants. Web, Accessed April 24 2013, http://primis.phmsa.dot.gov/comm/factsheets/fsnaturalgasprocessingplants.htm.

Pipeline & Hazardous Materials Safety Administration (PHMSA). 2011c. Fact Sheet: Pipe Coatings. Web, Accessed January 8, 2013, http://primis.phmsa.dot.gov/comm/FactSheets/FSPipeCoatings.htm.

Pipeline & Hazardous Materials Safety Administration (PHMSA). 2011d. Reporting Criteria Changes—1990-Current. Web, Accessed February 12, 2013, http://primis.phmsa.dot.gov/comm/reports/safety/docs/IncidentReportingCriteriaHistory1990-2011.pdf.

Pipeline & Hazardous Materials Safety Administration (PHMSA). 2012a. Glossary. Web, Accessed January 3, 2013, http://www.phmsa.dot.gov/resources/glossary.

Pipeline & Hazardous Materials Safety Administration (PHMSA). 2012b. National Pipeline Mapping System. Web, Accessed June 22, 2012, https://www.npms.phmsa.dot.gov/default.htm.

Pipeline & Hazardous Materials Safety Administration (PHMSA). 2013. General Pipeline FAQs. Web, Accessed April 24, 2013, http://www.phmsa.dot.gov/portal/site/PHMSA/menuitem.ebdc7a8a7e39f2e55cf2031050248a0c/?vgnextoid=a62924cc45ea4110VgnVCM1000009ed07898RCRD&vgnextchannel=f7280665b91ac010VgnVCM1000008049a8c0RCRD.

Powell, D. and L. Reach. 2012. Interview with Don Powell and Lee Reach, Alabama State Department of Transportation, Ninth Division. March 12, 2012.

Powell, D. 2012. Personal communication between Don Powell of ALDOT and ICF International. July 11, 2012.

Rowan, E., C. Evans, M. Riley-Gilbert, R. Hyman, R. Kafalenos, B. Beucler, B. Rodehorst, and A. Choate. 2013. Assessing the Sensitivity of Transportation Assets to Extreme Weather Events and Climate Change. *Transportation Research Record: The Journal of the Transportation Research Board* 2326:16–23.

South Alabama Regional Planning Commission (SARPC). 2010. Mobile Area Transportation Study (MATS) Metropolitan Planning Organization (MPO) Long Range Transportation Plan (LRTP) Model Documentation and Appendices. Prepared for the MATS MPO by the South Alabama Regional Planning Commission.

Terminal Rail at Alabama State Docks (TASD). 2012. Personal communication between Mike Russell at Alabama State Port Authority and ICF International. September 21, 2012.

U.S. DOT. 2011. Assessing Infrastructure for Criticality in Mobile, Alabama: Final Technical Memo, Task 1. Prepared by ICF International and PB Americas for the U.S. Department of Transportation Center for Climate Change and Environmental Forecasting. Report No. FHWA-HEP-11-029. Available at: http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task1/index.cfm.

U.S. DOT. 2012a. Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama. The Gulf Coast Study, Phase 2, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure. Prepared by ICF International for the U.S. Department of Transportation Center for Climate Change and Environmental Forecasting, FHWA-HEP-12-054. Available at: http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task2/sensitivity_report/index.cfm.

U.S. DOT. 2012b. Climate Variability and Change in Mobile, Alabama. The Gulf Coast Study, Phase 2, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure. Prepared by ICF International for the U.S. Department of Transportation Center for Climate Change and Environmental Forecasting, FHWA-HEP-12-053. Available at: http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task2/mobile_variability/

U.S. DOT. 2012c. Temperature and Precipitation Projections for the Mobile Bay Region. The Gulf Coast Study, Phase 2, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure. Prepared by Katharine Hayhoe and Anne Stoner of Texas Tech University Climate Science Center for the U.S. DOT Center for Climate Change and Environmental Forecasting, FHWA-HEP-12-055. Available at: http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task2/mobile_infrastructure.

Wardrop, F. 2012. Interviews with Forrest Wardrop, Boardwalk Pipeline Partners. July 5, 2012 and September 21, 2012.

Watson, D. 2010. Personal communication between Emily Rowan, ICF International and Donald Watson, National Center for Asphalt Technology, Auburn University, Auburn, Alabama. June 8, 2010.

Wongbusarakum, S. and C. Loper. 2011. Indicators to Assess Community-Level Social Vulnerability to Climate Change—An Addendum to SocMon and SEM-Pasifika Regional Socioeconomic Monitoring Guidelines. Pacific Environment Programme, The Nature Conservancy, National Oceanic and Atmospheric Association (NOAA) Coral Reef Conservation Program.

Yohe, G. and R. S. J. Tol. 2002. Indicators for Social and Economic Coping Capacity—Moving Toward a Working Definition of Adaptive Capacity. *Global Environmental Change* 12(1):25–40.

# APPENDICES

# A. Current Efforts in Mobile to Mitigate Transportation Impacts of Severe Climate

Vulnerability assessments are often done as a first step of a wider effort to prepare for climate change. Once vulnerabilities are identified, attention can be paid to how to reduce those vulnerabilities, or *adapt* to climate change.

A comprehensive evaluation of potential adaptation options for Mobile's transportation system is beyond the scope of the Gulf Coast Study (although some potential adaptation measures for a sampling of specific assets *are* investigated under Task 3.2 of this study). However, the stakeholder interviews conducted for the vulnerability assessment uncovered examples of adaptation measures that can be employed by transportation officials.

Mobile already experiences severe weather—including high temperatures, intense rainfall, and tropical storms—and has implemented strategies to mitigate the impacts on their transportation system. These strategies were not implemented with *climate change* in mind; rather they are necessary steps in order to maintain the transportation system's assets and services. Nonetheless, these efforts make Mobile more resilient to severe climate events. Mobile's current actions can be informative to areas that may not yet experience similar climate to Mobile but that wish to prepare for similar conditions in the future. These efforts are detailed below.[120]

## A.1. General Adaptation Measures

There are three key types of efforts that provide climate-related resilience across climate stressors. These efforts are employed across modes.

First, all transportation agencies and operators are required to have a series of emergency management plans in place. They all have hurricane plans, and specific modes or operators will also have plans that cover emergencies ranging from terrorist threats to other natural hazards. These plans lay out the specific steps that must be taken when a climate or other threat arises. For example, one port operator noted that their hurricane plan is put in place starting at least 96 hours before a hurricane is expected to hit. The checklists in the plan include directions on which equipment gets tied down, what gets moved, how operations are adjusted, when evacuations must occur, etc. These plans are developed in advance, allowing for efficient and effective measures to be taken ahead of time in order to minimize damage. These plans will also include contingency measures for minimizing disruptions if damage does occur: how cargo could be rerouted, which specific locations or assets are considered highest priority for repair, how the system could be operated if signal systems are lost, etc.

[120] All information provided in this section is drawn from interviews from Alfred and Bryant, 2012; Amberger, 2012; Bailey, 2012; Barlow, 2012; Bush and Harris, 2012; Dyess, 2012; Harris, 2012; Hill, 2012; Hughes, Faggard, and Pabst, 2012; Jackson, 2012; Kujala, 2012; Meigs, 2012; Mitchell and Sanchez, 2012; Powell and Reach, 2012; TASD, 2012; and Wardrop, 2012.

Across modes, stakeholders noted the importance in redundancy of their communications systems. Phone lines, satellite systems, microwave systems—there are multiple ways for communications to occur among staff and with equipment, and transportation officials are careful to not rely exclusively on one type of system. Close coordination and communication is important in both preparing for severe events (like hurricanes) and in re-establishing operations after an event occurs.

Finally, some modes subscribe to specific weather alert services or otherwise monitor climate and weather information. Some ports mentioned that they subscribe to sophisticated weather monitoring systems that help alert them to upcoming high heat-index days or other severe weather events. Doing so allows them to adequately prepare their workforce and operations in advance of the event. Highway managers also pay attention to NOAA efforts to monitor water levels. There are water monitors near many bridges, allowing highway managers to be alerted to both short-term and long-term changes in the water levels.

## A.2. Temperature Adaptation Measures

High temperatures are common events in summer in Mobile, most commonly affecting worker schedules across modes. Workers repairing or maintaining infrastructure and workers running dock operations, for example, work outside and are inevitably exposed to extreme heat.

ALDOT noted that in the summer, they shift worker schedules to 6 am to 2 pm, an hour earlier than the normal work schedule. This simple adaptation measure does not incur any costs or savings. Similarly, several ports noted that the Occupational Safety and Health Administration (OSHA) requires certain worker protection measures on high heat-index days (which take into account both temperature and humidity). These measures include supplying water and taking 10-15 minute breaks every hour or attempting to schedule worker activities so that they are spending equal amounts of time indoors and outdoors. These measures result in some slight costs to the ports, as some productivity is lost, but the ports seem to consider the costs and schedule disruptions minor and something that they anticipate.

The Mobile Airport Authority noted another operational adaptation measure: planes will take on less weight during hot weather, since they will need to generate extra lift to take off. This action is particularly noted at the Downtown Airport, which is used heavily by cargo planes.

Several adaptation activities related to infrastructure were noted by highways and rail. ALDOT noted that they repair rutting issues as they arise, since rutting can cause cars to hydroplane during rain events. Rail tracks are laid with high rail neutral temperatures—heat expansion is built into the tracks to mitigate risk of buckling. Where appropriate, continuous welded rail (CWR) is avoided, so that the gaps in between rail segments allow for more expansion. The rails are also frequently inspected during periods of extreme heat, so potential weaknesses in the track can be addressed immediately.

## A.3. Precipitation Adaptation Measures

Proper drainage is already a problem in Mobile, and stakeholders across the transportation modes highlighted their efforts to maintain and improve drainage around their assets. Several stakeholders noted key maintenance efforts to ensure resiliency against climate stressors. For example, the airports mentioned that they run cameras through the drainage pipes on a regular basis to identify potential blockages before they become severe. ALDOT also noted that they frequently clean drains in areas that tend to flood. Pipeline companies make strong efforts to maintain the pipeline right-of-ways (ROWs), including planting vegetation or hardening the ROWs to fortify the banks against erosion caused by heavy precipitation. Ports and the U.S. Army Corps of Engineers will dredge the Mobile River and other area key areas more frequently after higher-than-normal periods of rains.

Interviewees also noted instances in which they take advantage of repair/replacement opportunities to improve drainage. Waiting to make upgrades until repair/replacement is needed anyway is one way to reduce costs. For example, airports noted that whenever they put a new ramp into the airfield, they replace the existing drainage with newer, improved systems. For example, they may replace metal or terracotta systems with plastic. The airports are also gradually shifting to LED lighting systems, which are more resilient against water and floods. ALDOT noted similar “opportunistic adaptation” activities. For example, when part of Highway 90 washed out after the intense rain season of 2009, they resized the culvert to add in additional margin of safety. Similarly, when they needed to resurface a flood-prone area in Bay Minette, they leveled the roadway to make it less likely to flood.

Some infrastructure improvements are made specifically to address drainage and flooding problems. TASD noted one particularly flood-prone area where they had to rebuild the ground and overhaul the drainage system. One pipeline company mentioned that they have previously had to relocate valves; for example, the company had trouble accessing a valve located in the Mount Vernon area during major flood events, and had to relocate it. Redundancy in pipeline valves also helps mitigate problems associated with being unable to access a specific valve.

Finally, anticipating flooding strains affects the design of some infrastructure. Pipeline companies often use a cement coating on the pipelines to make them heavier, thus preventing them from floating during flood events, which could cause significant damage. Pipeline operators also add fill to flood-prone areas, build “breakers” or levees to direct water away from pipeline ROW and equipment. Finally, ports often use semi-porous pavement construction to help facilitate drainage.

Most transportation stakeholders, however, noted that there are larger challenges associated with flooding in Mobile. Mainly, the overall drainage system was not designed for the capacity that Mobile’s growth now demands. So, while culverts and site-specific drainage features can be maintained and improved, the overall drainage system in Mobile is sometimes stretched past capacity, making it difficult to completely avoid flooding in some areas. More attention is now being paid in Mobile regarding where new development can occur, particularly in relation to flood plains.

## A.4. Sea Level Rise and Storm Surge Adaptation Measures

Given Mobile's past experience with severe storms, Mobile stakeholders are conscious of the need to protect transportation assets against future storm surges. Many of these activities will also make the assets more resilience against sea level rise.

Structural measures include use of rip rap and seawalls to protect coastal assets against erosion and storm surge. For instance, the Causeway has a simple concrete barrier rail that already provides protection against some floods. These protective measures are used across modes (particularly highways, ports, and airports) in areas where assets abut the Bay or ocean. The ports place electrical transformers higher than normal to keep them out of the reach of floodwaters. Some structural measures are instituted gradually. For example, ports are not tearing down and rebuilding piers while the piers still have useful life, but new piers are built several feet higher (14 or 15 feet) than older piers (11 or 12 feet) to make them more resilient to surges and flooding. Floodgates are used on the east end of the Bankhead tunnel (the west end is higher and more protected, making floodgates less necessary). Sandbags are used to protect the Wallace tunnel and the west end of the Bankhead tunnel if needed.

Before, during, and after hurricanes, there are important operational and planning measures that help reduce service disruptions. Several modes noted that they do not station all equipment and supplies in one location; rather they ensure equipment and supplies (such as backhoes, chainsaws, etc.) are stationed in multiple easy-to-access locations, generally in areas more protected from storm surges. Doing so helps avoid the risk that a storm would prevent them from accessing all equipment and supplies at once; the geographical diversity of supplies also allows them to reach the areas where they are needed more quickly. Pipeline operators noted that, after a storm, there can be supply shortages of key equipment or construction supplies, so they also ensure they have a reasonable stockpile of essential supplies on hand at all times.

Transportation managers also ensure that operational controls can be run from multiple or more resilient locations. One pipeline company noted that some gas control operations were relocated from a more vulnerable area in Texas to a less vulnerable area in Kentucky. The Wave transit has established flexibility where their fleet can refuel, so that they could refuel at stations run by the City of Mobile if the Beltline facility gets damaged.

Prior to a hurricane, transportation managers will locate moveable equipment, rail cars, buses, and ships to higher elevation or less vulnerable locations, or raise them up higher in their current locations. Other equipment—like non-relocatable port equipment, movable bridges, or planes that could not be flown out—will be tied down. Ports and rail will begin delaying and rerouting shipments to help minimize the cargo that could be exposed to storm surge.

During a storm, cameras are sometimes used to monitor where damage is occurring. Immediately after a storm, flyovers may be used to quickly identify damaged locations. Combined, these efforts help transportation managers quickly deploy resources to the areas that need it most.

Stakeholders also mentioned the immense amount of communication and coordination that occurs following major storms. Rail companies will often carry cargo for each other to help minimize downtime after a storm. Similar cooperative efforts can occur among airports and ports, although the specialized equipment required to move specific cargo types can sometimes limit the ability to shift operations of one port/airport to another.

## A.5. Wind Adaptation Measures

Many transportation modes experienced significant wind damage during Hurricane Katrina in 2005. Therefore, new structures built since 2005 are generally built to higher wind rating standards. Roofs, buildings, and signal systems are increasingly being built to withstand winds of 130-160 miles per hour, which exceed the maximum wind speeds modeled in this project. ALDOT is also using hardened traffic lights and signals with mast arms, instead of wires, in coastal areas more exposed to high winds.

The Wave noted that buses are able to operate in wind speeds up to 45 miles per hour, and that they build in a time buffer so that operations cease one hour before wind speeds are projected to reach that threshold. Buses are moved to the bus yard at the Beltline facility and parked very close together, so that they protect each other from severe winds.

Rail and highways both noted that they have capability of operating (albeit in a more limited or slower manner) without their signal systems. They have existing plans in place for how to prioritize and operationalize their systems when signal systems are offline.

# B. Detailed Methodology for Evaluating Exposure

This study assesses exposure for all assets to the five climate stressors considered throughout the study: temperature, precipitation, sea level rise, storm surge, and wind. The exposure methodology is the same for all modes of transportation: highways, ports, airports, rail, and transit.

For all stressors (except sea level rise), each asset is assigned an exposure score on a scale of 1 through 4. Sea level rise is scored as either "exposed" or "not exposed." This appendix documents the methodology used to assign exposure scores to each asset.

Downscaled temperature and precipitation projection data, as well as modeled sea level rise, storm surge, and wind data, were developed under an earlier stage in this study.[121]

## B.1. Temperature

### Exposure Indicator: Number of Days above 95°F

Exposure to temperature was calculated uniformly for all assets in the study area using the projected percent change in the number of days per year above 95°F.

Transportation assets in Mobile (and elsewhere) are more sensitive to short-term, extreme events than changes in seasonal or annual means, and the selected exposure indicator therefore needed to reflect projected short-term heat events. There were several short-term temperature variables that could have been selected for the exposure indicator, including average maximum temperature or maximum number of consecutive days (i.e. length of a heat wave) above 95°F. However, the other variables representing short-term extreme events exhibited similar changes over time, so only one of the variables was selected.

The number of days above 95°F was selected because stakeholders indicated that temperatures exceeding 95°F (35°C) affect service, operations, and workforce conditions in Mobile. In addition, the number of days above 95°F is a transparent and easy to communicate variable that stakeholders intuitively understand.

In order to assess exposure, the study assigned an exposure score of 1 through 4 to indicate the extent to which the variable is projected to change into the future, relative to the baseline. Scores were assigned for six time periods: near-term, mid-term, and end-of-century for both the Warmer and Hotter temperature narratives (please see Section 3.2). The exposure scores were determined by calculating the maximum change in number of days above 95°F (looking across all timeframes and climate narratives), and then dividing that maximum change into equal intervals. Each interval was assigned an exposure score of 1 through 4.

[121] U.S. DOT, 2012b

Historically, Mobile has experienced an average of 9.6 days above 95°F. The projected change in the number of days above 95°F range from an increase of 2.4 days (near term, Warmer scenario) to 94.7 days (end-of-century, Hotter narrative). The most extreme value is equal to 1,087% of the historic average of 9.6 days (or an increase of 987%). Any value that is 100% or less of the baseline (meaning that the number of days above 95°F is projected to stay the same or decrease) equated to a score of 1, or very low exposure. Other scores were assigned based on even intervals between 100% and 1,087% of the baseline, as shown in Table 75.

**Table 75: Temperature Exposure Scoring Methodology, All Modes**

| Future Number of Days above 95°F | Exposure Score |
|---|---|
| Equal to 100% of baseline or lower | 1 |
| Greater than 100% and up to 430% of the baseline | 2 |
| Greater than 430% and up to 760% of the baseline | 3 |
| Greater than 760% of the baseline | 4 |
| **Max exposure** | **1,087% of baseline** |
| **Interval size** | **330%** |

## B.2. Precipitation

### Exposure Indicator: 1 in 100 year 24-hour Precipitation Event

Exposure to precipitation was calculated uniformly for all assets in the study area using the projected percent change in the amount of rain that falls in 24-hours during a 100-year (i.e., 1% annual likelihood) storm event.

Interviews with stakeholders and other research revealed that infrastructure is more sensitive to the short-term, extreme precipitation events, rather than incremental changes in seasonal or annual means. While there were other short-term precipitation variables that could have been selected, all of the variables representing short-term extreme events exhibited similar changes over time; therefore, only one of these short-term variables was selected to represent exposure.

The 100-year 24-hour precipitation event was selected because it represents the shortest time period for which projection data were available from the climate model analysis.[122] While infrastructure design standards often require shorter period data (such as 6-hour events), climate models, because they are not weather models, are not designed to produce outputs at this temporal scale. In addition, the variable is transparent and easy to communicate.

[122] U.S. DOT, 2012b; U.S. DOT, 2012c

In order to assess exposure, the study assigned an exposure score to indicate the extent to which the variable is projected to change into the future, relative to the baseline. Scores were assigned for six time periods: near-term, mid-term, and end-of-century for both the Wetter and Drier precipitation narratives (please see Section 3.2). The exposure scores were determined by calculating the maximum change in 1 in 100 year 24-hour precipitation events (looking across all timeframes and climate narratives), and then dividing that maximum change into equal intervals. Each interval was assigned an exposure score of 1 through 4.

Historically, the 100-year storm in Mobile has released 13 inches of rain in 24 hours. The projected change in the amount of rainfall associated with the 100-year 24-hour precipitation event range from a decrease of 2 inches (near-term, Drier narrative) to an increase of 12 inches (end-of-century, Wetter narrative). The most extreme value equals 189% of the historical average (or an increase of 89%). Any value of 100% or less (meaning that the 100-year storm rainfall amount is projected to stay the same or decrease) equated to a score of 1, or very low exposure. Other scores were assigned based on even intervals 100% and the 189% maximum increase in rainfall, as shown in Table 76.

**Table 76: Precipitation Exposure Methodology, All Modes**

| Future Rainfall Associated with 1 in 100 year 24-hour Precipitation Event | Exposure Score |
|---|---|
| Equal to 100% of baseline or lower | 1 |
| Greater than 100% and up to 130% of the baseline | 2 |
| Greater than 130% and up to 160% of the baseline | 3 |
| Greater than 160% of the baseline | 4 |
| **Max exposure** | **189% of baseline** |
| **Interval size** | **30%** |

## B.3. Sea Level Rise

### Exposure Indicator: Sea Level Rise Inundation

Sea level rise exposure for all assets was based on sea level rise inundation mapping for three scenarios: 0.3 meters (1.0 foot), 0.75 meters (2.5 feet), or 2.0 meters (6.6 feet). Information on depth of inundation was not available, so exposure for most assets was scored as either “yes” (exposed) or “no” (not exposed) for each of those modeled scenarios. Because of the binary nature of the sea level rise exposure assessment, exposure scores were not calculated. Rather, vulnerability scores for exposed assets were determined by the sensitivity and adaptive capacity scores. Assets deemed to not be exposed to sea level rise were not further evaluated for vulnerability.

The project team analyzed one of the transit assets, bus fleet and service (T3), slightly differently. In this case, the assessment calculated the percent of bus stops inundated under each sea level rise scenario. For bus and fleet service, exposure scores were evaluated based on the share of total bus stops exposed to sea level rise across all scenarios. The exposure scores were assigned to intervals of equal size between 25% and 100% of bus stops exposed to storm surge. See Table 78 for more information on the scoring methodology.

**Table 77: Sea Level Rise Exposure Methodology, All Modes and Assets except Transit Bus Fleet and Service (T3)**

| Asset Exposure to Sea Level Rise Narratives | Exposure Designation |
|---|---|
| Asset falls within boundaries of sea level rise inundation zone | Yes |
| Asset does not fall within boundaries of sea level rise inundation zone | No |

**Table 78: Sea Level Rise Exposure Methodology, Transit Bus Fleet and Service (T3)**

| Asset Exposure to Sea Level Rise Narratives | Exposure Score |
|---|---|
| Up to 25% of assets exposed | 1 |
| Greater than 25% and up to 50% of assets exposed | 2 |
| Greater than 50% and up to 75% of assets exposed | 3 |
| Greater than 75% of assets exposed | 4 |

## B.4. Storm Surge

### Exposure Indicator: Relative Depth of Storm Surge

Exposure scores for each asset were calculated based on the relative depth of the storm surge across all assets, modes, and storm scenarios. Storm surge depth for each asset was modeled surge using the ADvanced CIRCulation model (ADCIRC) and the STeady State spectral WAVE (STWAVE) model under three storm scenarios: Katrina Base, Katrina Shifted, and Katrina Shifted with reduced pressure and 0.75 meters (2.5 feet) of sea level rise.[123] The final storm surge depths used to calculate exposure scores and the methodology used to arrive at them are presented in Appendix H.

Each asset was assigned an exposure score based on how its storm surge depth compared to the maximum storm surge depth across all scenarios and transportation assets. The largest modeled storm surge depth was 37.7 feet (11.5 meters), at the Terminal Rail at Alabama State Docks

[123] U.S. DOT, 2012b

(TASD) Rail Yards (RR1) under the most extreme storm scenario. Table 79 shows how the storm surge exposure scores were assigned to assets under each storm scenario.

The project team analyzed one of the transit assets, bus fleet and service (T3), slightly differently. For this asset, exposure scores were calculated based on the percentage of bus stops inundated under each storm surge scenario. The exposure scores were assigned to intervals of equal size between 25% and 100% of bus stops exposed to storm surge. See Table 80 for more information on the scoring methodology for this asset.

**Table 79: Storm Surge Exposure Methodology, All Modes and Assets except Transit Bus Fleet and Service (T3)**

| Depth of Storm Surge at Asset Location Compared to Maximum Modeled Depth across All Assets and Scenarios | Exposure Score |
|---|---|
| Up to 25% of max. depth or lower | 1 |
| Greater than 25% and up to 50% of max. depth | 2 |
| Greater than 50% and up to 75% of max. depth | 3 |
| Greater than 75% of max. depth | 4 |
| **Max depth (feet)** | **37.7** |
| **Interval size** | **25%** |

**Table 80: Storm Surge Exposure Methodology, Transit Bus Fleet and Service (T3)**

| Asset Exposure to Sea Level Rise Narratives | Exposure Score |
|---|---|
| Up to 25% of assets exposed | 1 |
| Greater than 25% and up to 50% of assets exposed | 2 |
| Greater than 50% and up to 75% of assets exposed | 3 |
| Greater than 75% of assets exposed | 4 |

## B.5. Wind

### Exposure Indicator: Wind Speed Relative to Design Standard

Wind exposure scores for each asset were calculated based on how the maximum wind speed at that asset's location compared to the wind speed the asset was designed to withstand. Wind speeds were modeled under the same three storm scenarios used to evaluate storm surge exposure. As shown in Table 81, if the maximum wind speed exceeded the design wind speed for an asset, that asset scored a 4 for wind exposure. If not, then the asset scored a 1.

**Table 81: Wind Exposure Methodology, All Modes**

| Description | % of Threshold Value | Exposure Score |
|---|---|---|
| Wind speed is below the threshold value at which impacts may occur | 0% | 1 |
| Wind speed is above the threshold value at which impacts may occur | 100% | 4 |

Information on the wind speed design threshold for different assets came from different sources for each mode, as shown in Table 82.

**Table 82: Data Sources and Ranges for Wind Design Thresholds of Assets in Mobile**

| Mode | Wind Design Threshold Data Source | Range of Design Thresholds* |
|---|---|---|
| Highways | Interviews with ALDOT[124] | 74—150 mph |
| Ports | Applied Technology Council (ATC)'s Windspeed by Location calculator to determine ASCE 7-05 wind speed design standards (3-second peak gusts) for each port using its coordinates[125] | 130—150 mph |
| Airports | Interviews with Mobile Airport Authority stated that buildings were compliant with ASCE 7-10 rating.[126] Used Applied Technology Council (ATC)'s Windspeed by Location calculator to determine ASCE 7-10 wind speed design standards (3-second peak gusts) for each airport using its coordinates.[127] | 143 mph |
| Rail | Interviews with rail operators in Mobile[128] | 85 mph |
| Transit | Interviews with WAVE Transit[129] | 60—140 mph |

*Modeled wind speeds ranged from 72-121 mph (across all assets and scenarios)

[124] Powell, 2012
[125] ATC, 2012
[126] Hughes, 2012
[127] ATC, 2012
[128] Alfred and Bryant, 2012
[129] Alfred and Bryant, 2012

# C. Detailed Methodology for Evaluating Sensitivity

For all sensitivity indicators, each indicator was assigned a score and a weight for each asset. The scores for each asset were based on the value of that indicator (for example, truck traffic would be scored based on the value of truck traffic). Further, each indicator was assigned a *weight* to be used in calculating the overall sensitivity score for each asset, such that:

$$\textit{Sensitivity Score for Asset} = \textit{Weighted Indicator Score}_1 + \textit{Weighted Indicator Score}_2 + \ldots + \textit{Weighted Indicator Score}_n$$

Each indicator was assigned a weight under several scenarios: the scenario where scores were available for all indicators, and alternative scenarios for when certain data sets were not available. For example, Table 83 shows a default weight schema for when all three indicators for assessing temperature sensitivity onto roads are available, while Table 84 provides the alternative weight schema used when one particular indicator is missing. The tables throughout this appendix explain the data source behind each indicator, how each indicator was scored, how each indicator was weighted, and, if applicable, how indicator weightings were adjusted to accommodate incomplete data sets.

## C.1. Highways

Highway segments were comprised of road sub-segments as well as bridge and culvert sub-segments (for simplification, subsequent references to “bridges” are also implied to include culverts). Due to differences in engineering characteristics, the nature of sensitivity of roads versus bridges, and sources of data for roads versus bridges, the analysis used distinct sets of indicators for roads and for bridges.

### Temperature

#### Overview of Temperature Sensitivity Indicators, Data Sources, and Weightings

Table 83 through Table 85 provide a summary of the sensitivity indicators used to evaluate temperature sensitivity for highways, how they were scored, and how they were weighted. As noted above, different indicators were used for roads compared to bridges.

**Table 83: Temperature Sensitivity Indicators and Scoring Approach for Roads**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Pavement rutting, shoving, or other compromised integrity | Whether pavement has rutted (or shown other signs of damage) in the past due to high temperatures | Road segments that already experience rutting may experience worsening problems as the temperature increases. | **Yes/No Record of Previous Damage from Temperature**—Stakeholder interviews | 43% | N - This asset has not been damaged due to heat events | 1 |
| | | | | | Y - This asset has been damaged due to heat events | 4 |
| | High volumes of truck traffic | High truck traffic volume is an indicator that a road may experience pavement rutting. Paved roads experience greater stress from heavy vehicle traffic. As temperatures increase, rutting may occur on segments of road with high volumes of truck traffic. | **External Truck Trip Productions** (for roads)—Mobile MPO Long Range Transportation Plan Model Documentation and Appendices, Table 11 | 28% | Up to 1,500 external truck trip productions | 1 |
| | | | | | Greater than 1,500 and up to 3,000 external truck trip productions | 2 |
| | | | | | Greater than 3,000 and up to 4,500 external truck trip productions | 3 |
| | | | | | Greater than 4,500 external truck trip productions | 4 |
| | Pavement binder type relative to projected temperatures | Pavement binders are designed to withstand specific temperature thresholds. Asphalt may experience rutting if pavement temperatures exceed the high temperature thresholds. | **Pavement Binder Used**—ALDOT (personal communication) | 28% | PG 67-22 pavement binder (commonly used in Mobile)—this binder equates to air temperatures of roughly 113°F, indicating that Alabama road surfaces are unlikely to be very sensitive to temperature increases | 1 |
| | | | | | Other pavement type (not applicable in this screen) | 4 |

* Weighting rationale: Past Experience weighted 15 percentage points higher than other indicators (per stakeholder input). All other indicators weighted equally.

**Table 84: Alternate Temperature Sensitivity Indicator Weighting for Roads without Information for All Indicators**

| Data Scenario | Past Experience | External Trip Productions | Pavement Binder Used |
|---|---|---|---|
| No missing data | 43% | 28% | 28% |
| Missing data for external trip productions | 58% | | 43% |

**Table 85: Temperature Sensitivity Indicators and Scoring Approach for Bridges**

<table>
<tr><th rowspan="2">Climate Change Impact</th><th rowspan="2">Indicator</th><th rowspan="2">Rationale</th><th rowspan="2">Asset Attribute and Data Source</th><th rowspan="2">Weight*</th><th colspan="2">Scoring Method</th></tr>
<tr><th>Attribute Value</th><th>Score</th></tr>
<tr><td rowspan="8">Pavement rutting, shoving, or other compromised integrity</td><td rowspan="2">Whether pavement has rutted (or shown other signs of damage) in the past due to high temperatures</td><td rowspan="2">Road segments that already experience rutting may experience worsening problems as the temperature increases.</td><td rowspan="2">Yes/No Record of Previous Damage from Temperature—Stakeholder interviews</td><td rowspan="2">43%</td><td>N - This asset has not been damaged due to heat events</td><td>1</td></tr>
<tr><td>Y - This asset has been damaged due to heat events</td><td>4</td></tr>
<tr><td rowspan="4">High volumes of truck traffic</td><td rowspan="4">High truck traffic volume is an indicator that a road may experience pavement rutting. Paved roads experience greater stress from heavy vehicle traffic. As temperatures increase, rutting may occur on segments of road with high volumes of truck traffic.</td><td rowspan="4">Average Daily Truck Traffic—National Bridge Inventory, Item 109 (Percent of traffic that is truck) and Item 29 (Average daily traffic)</td><td rowspan="4">28%</td><td>Average Daily Truck Traffic up to 3000</td><td>1</td></tr>
<tr><td>Average Daily Truck Traffic greater than 3000 and up to 6000</td><td>2</td></tr>
<tr><td>Average Daily Truck Traffic greater than 6000 and up to 9000</td><td>3</td></tr>
<tr><td>Average Daily Truck Traffic greater than 9000</td><td>4</td></tr>
<tr><td rowspan="2">Pavement binder type relative to projected temperatures</td><td rowspan="2">Pavement binders are designed to withstand specific temperature thresholds. Asphalt may experience rutting if pavement temperatures exceed the high temperature thresholds.</td><td rowspan="2">Pavement Binder Used—ALDOT (personal communication)</td><td rowspan="2">28%</td><td>PG 67-22 pavement binder (commonly used in Mobile)—this binder equates to air temperatures of roughly 113°F, indicating that Alabama road surfaces are unlikely to be very sensitive to temperature increases</td><td>1</td></tr>
<tr><td>Other pavement type (not applicable in this screen)</td><td>4</td></tr>
</table>

### Detailed Description of Temperature Sensitivity Indicators and Evaluation Methodology

This assessment considered the **historical performance** of road and bridge assets during heat events. However, since the highway stakeholders stated that none of the representative segments experienced major rutting problems in the past, all segments received a score of "1" for historical performance.

**Truck traffic** was chosen as an indicator because segments with higher truck traffic volumes are more susceptible to rutting. Since high temperatures are one factor of rutting, the increased temperatures projected for Mobile may preferentially accelerate damage on these segments of road. A consistent dataset on truck traffic for both roads and bridges was not available. Therefore, the project team analyzed data from two sources in order to score truck traffic on roads and bridges. For roads, the truck traffic indicator is calculated based on external truck trip productions in 2007 as reported in Mobile's Long Range Transportation Plan (LRTP).[130] For roads, the truck traffic indicator is calculated based on the average daily truck traffic as indicated in the National Bridge Inventory. In both cases, these scoring bins were chosen based on the quartiles of the truck traffic datasets in the Mobile LRTP.

The sensitivity of **pavement binder type relative to projected temperatures** was the final indicator of highway sensitivity to temperature. While Performance Grade (PG) 64-22 is the common asphalt grade recommended for Alabama, ALDOT specifies use of PG 67-22 in order to provide a larger margin for error against the possibility of rutting during the hot summer.[131] This finding was later corroborated by ALDOT, who noted that they use PG 67 for nearly all state-funded paving.[132] Performance Grade (PG) 64-22 implies that the highest temperature the pavement is expected to reach is 147.2°F (64°C) 20mm below the surface, which corresponds to an ambient air temperature of 108°F. On the other hand, the PG 67-22 rating corresponds to an ambient air temperature of 131°F. Since 131°F is well beyond temperature projections for Mobile, the vulnerability assessment assumed a "1" for all representative road segments.

## Precipitation

### Overview of Precipitation Sensitivity Indicators, Data Sources, and Weightings

Table 86 through Table 89 provide a summary of the sensitivity indicators used to evaluate precipitation sensitivity for highways (with separate indicators for roads and for bridges), how they were scored, and how they were weighted.

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[130] SARPC, 2010
[131] Watson, 2010
[132] Powell and Reach, 2012; Mitchell and Sanchez, 2012; and Amberger, 2012.

**Table 86: Precipitation Sensitivity Indicators and Scoring Approach for Roads**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to heavy rain | Roads and bridges that have experienced damage during past heavy rain events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Flooding from Rainfall**—Stakeholder interviews | 43% | N - This asset has not been damaged due to inland flooding | 1 |
| | | | | | Y - This asset has been damaged due to flooding | 4 |
| | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | 17% | Not located in flood zone | 1 |
| | | | | | Up to one-third of segment located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of segment located in flood zone | 3 |
| | | | | | Greater than 2/3 of segment located in flood zone | 4 |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs | 11% | Not located in flood zone | 1 |
| | | | | | Up to one-third of segment located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of segment located in flood zone | 3 |
| | | | | | Greater than 2/3 of segment located in flood zone | 4 |
| | Asset's elevation relative to surrounding areas | If an asset is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events. | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the medium number of 3ft x 3ft LiDAR elevation cells that drain into each cell within the asset perimeter. By using the median number, anomalies and extreme values are removed. | 14% | Ponding score** up to 42 | 1 |
| | | | | | Ponding score greater than 42 and up to 84 | 2 |
| | | | | | Ponding score greater than 84 and up to 126 | 3 |
| | | | | | Ponding score greater than 126 | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | Amount of impervious surface surrounding an asset | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation. | **Percent of Area Surrounding Asset with Above Average Impermeability**—USGS National Land Cover Database 2006 Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) | 14% | Up to 25% of asset with above average impermeability | 1 |
| | | | | | Greater than 25% and up to 50% of asset with above average impermeability | 2 |
| | | | | | Greater than 50% and up to 75% of asset with above average impermeability | 3 |
| | | | | | Greater than 75% and up to 100% of asset with above average impermeability | 4 |

*Weighting rationale: Past Experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining three indicators, where both flood zone indicators are grouped together and both indicators related to run-off are grouped together (ponding and impervious surface). Within flood zone indicator, 60% of weight comes from 100-year flood zone and 40% comes from 500-year flood zone because all assets in the 100-year flood zone are also in the 500-year flood zone.

** Ponding score refers to number of grid cells that flow into the cells covered by the asset.

**Table 87: Alternate Precipitation Sensitivity Indicator Weighting for Roads without Information for All Indicators**

| Data Scenario | Past Experience | 100-year Flood Zone | 500-year Flood Zone | Ponding Score | Impervious Surface |
|---|---|---|---|---|---|
| No missing data | 43% | 17% | 11% | 14% | 14% |
| Missing data for flood zone | 58% | | | 21% | 21% |

**Table 88: Precipitation Sensitivity Indicators and Scoring Approach for Bridges**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to heavy rain | Roads and bridges that have experienced damage during past heavy rain events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Flooding from Rainfall**—Stakeholder interviews | 26% | N - This asset has not been damaged due to inland flooding | 1 |
| | | | | | Y - This asset has been damaged due to flooding | 4 |
| | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | 6% | Not located in flood zone | 1 |
| | | | | | Located in flood zone | 4 |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **FEMA 500-year Flood Zone**—FEMA DFIRMs | 4% | Not located in flood zone | 1 |
| | | | | | Located in flood zone | 4 |
| | Elevation of the approach to a bridge | Bridge approaches are often the most affected part of the bridge. Approaches that are closer to the water surface are more sensitive to flooding from sea level rise, storm surge, or heavy rain. | **Minimum Height of Bridge Approach above Water Surface**—Project team analysis of LiDAR data | 11% | Not a water crossing or approach is greater than 15 feet above water surface | 1 |
| | | | | | Approach is greater than 10 feet and up to 15 feet above water surface | 2 |
| | | | | | Approach is greater than 5 feet and less than 10 feet above water surface | 3 |
| | | | | | Approach is up to 5 feet above water surface | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Scour, washout, overtopping, or other structural damage | Age of an asset | Older bridges may have been built to older design standards, deteriorated bridge deck drainage systems, clogged inlets, or experienced more extreme damaging scour events, rendering them more sensitive to precipitation events than bridges designed more recently. | **Year Built**—National Bridge Inventory, Item 27 | 11% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 50 years old | 2 |
| | | | | | Greater than 50 and up to 75 years old | 3 |
| | | | | | Greater than 75 years old | 4 |
| | Whether a bridge is "scour critical" | Bridges that have already been identified as having problems with scour are more likely to be damaged during precipitation events. | **Scour Critical Bridges**—National Bridge Inventory, Item 113 | 11% | Score of T or 9 | 1 |
| | | | | | Score of 8 or 7 | 2 |
| | | | | | Score of 4 or 5 | 3 |
| | | | | | Score of 0, 1, 2, or 3 | 4 |
| | Conditions associated with water flow through a bridge | This item describes the physical conditions associated with the flow of water through the bridge such as stream stability and the condition of the channel, riprap, slope protection, or stream control devices including spur dikes. Bridges with erosion or bank failure will be more sensitive to flooding and high stream flows. | **Channel Condition Rating**—National Bridge Inventory, Item 61 | 11% | Score of 8 or 9 | 1 |
| | | | | | Score of 5, 6 or 7 | 2 |
| | | | | | Score of 4, 3, or 2 | 3 |
| | | | | | Score of 1 or 0 | 4 |
| | Condition of culverts | This item evaluates the alignment, settlement, joints, structural condition, scour, and other items associated with culverts. Bridges with deterioration in culvert conditions may be more sensitive to damage from flooding. | **Culvert Condition Rating**—National Bridge Inventory, Item 62 | 11% | Score of 8 or 9 | 1 |
| | | | | | Score of 5, 6 or 7 | 2 |
| | | | | | Score of 4, 3, or 2 | 3 |
| | | | | | Score of 1 or 0 | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | Frequency that water overtops a bridge | This item appraises the waterway opening with respect to passage of flow through the bridge. Bridges that are subject to more frequent overtopping may be sensitive to damage from flooding impacts. | **Waterway Adequacy**—National Bridge Inventory, Item 71 | 11% | Remote or slight change of overtopping roadway approaches | 1 |
| | | | | | Slight or occasional overtopping of roadway approaches; insignificant delays | 2 |
| | | | | | Occasional / frequent overtopping; significant delays | 3 |
| | | | | | Bridge closed | 4 |

*Weighting rationale: Past Experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining eight indicators, where both flood zone indicators are grouped together. Within flood zone indicator, 60% of weight comes from 100-year flood zone and 40% comes from 500-year flood zone because all assets in the 500-year flood zone are also in the 100-year flood zone.

**Table 89: Alternate Precipitation Sensitivity Indicator Weighting for Bridges without Information for All Indicators**

| Data Scenario | Past Experience | 100-yr Flood | 500-Yr Flood | Approach Height | Age | Scour Critical | Channel Condition | Culvert Condition | Overtopping Condition |
|---|---|---|---|---|---|---|---|---|---|
| No missing data | 26% | 6% | 4% | 11% | 11% | 11% | 11% | 11% | 11% |
| Missing flood zones | 29% | | | 12% | 12% | 12% | 12% | 12% | 12% |
| Missing scour critical, flood zones, and channel, culvert and overtopping condition | 55% | | | 23% | 23% | | | | |
| Missing scour critical and channel, culvert and overtopping condition | 45% | 11% | 7% | 18% | 18% | | | | |
| Missing culvert condition | 29% | 7% | 5% | 12% | 12% | 12% | 12% | | 12% |
| Missing flood zones and culvert condition | 33% | | | 13% | 13% | 13% | 13% | | 13% |
| Missing culvert and overtopping condition | 33% | 8% | 5% | 13% | 13% | 13% | 13% | | |
| Missing scour critical and culvert condition | 33% | 8% | 5% | 13% | 13% | | 13% | | 13% |

## Detailed Description of Precipitation Sensitivity Indicators and Methodology

Five of the nine bridge indicators (year built, scour condition, channel condition rating, culvert condition rating, and likelihood of overtopping) are from the National Bridge Inventory. **Age of the bridge** (based on year built) was selected as an indicator because older bridges are more likely to have been built to older design standards, which may underestimate storm water drainage needs. The majority of bridges in the study area are less than 50 years old, but there is a culvert located on the Causeway that was built in 1928. In addition, all of the bridges and culverts on R29 (intersection of Airport Blvd and I-65) were built over fifty years ago.

**Scour condition**, the second sensitivity indicator from the NBI, captures the scour risk faced by individual bridges. For example, bridges rated a “9” are located on dry land well above flooding. The assessment scored these bridges as a “1.” Bridges rated a 1 are scour critical, meaning that failure of piers or abutments is imminent. The assessment scored these bridges as a “4.” The bridge on R15 (Dauphin Island Parkway from Dauphin Island Bridge to CR-188) was the only bridge in the study area with scour risk indicated on the NBI.

The third NBI indicator, **channel condition rating**, describes the condition of the bridge channel, including the bank and any river protection devices. The assessment assigns higher sensitivity to bridges on poorly maintained channels under the assumption that channels in poor condition will experience greater damage during heavy rain. None of the bridges in the study area were characterized as having poor channel condition in the NBI.

The fourth NBI sensitivity indicator is **culvert condition**. This indicator describes any deficiencies in culvert condition, including cracks, scaling, and spalling. Culverts in worse condition are likely to experience increased damage during heavy rain. The only culverts in the study area that the NBI characterizes as having poor condition are a culvert on the Causeway and a culvert on R28 (I-165 near intersection with 98).

Finally, **likelihood of overtopping (or waterway adequacy)** was the fifth NBI indicator selected for inclusion in the assessment. This indicator captures the likelihood of overtopping at a specific bridge, based on past experience. For example, if the NBI notes that a bridge has a remote chance of overtopping, the assessment scores the bridge as a “1.” If the NBI notes that a bridge frequently overtops, the assessment assigns the bridge a “4.” The NBI characterized a number of bridges in the study area as possessing a minor history of overtopping. Two bridges on different segments of Dauphin Island Parkway were also scored as overtopping more frequently (R15 and R22).

In addition to the NBI indicators, this vulnerability assessment considered **past experience** of road and bridge assets during heavy rain events. For example, stakeholders from ALDOT, the City of Mobile, and Mobile County all commented that sections of the Causeway are prone to flood during heavy rain events. Therefore, this assessment scored the Causeway a "4", whereas assets without a history of flooding were scored a "1." Past experience was an indicator for both bridges and roads.

This vulnerability assessment also relied on several targeted spatial analyses to better understand how the location of bridges and roads might become more exposed to flooding during heavy rain. These spatial indicators were: the height of the bridge approach above the water surface, the location of the asset within a flood zone, the propensity of an asset to flood based on its nearby topography (roads only), and the amount of impervious surface surrounding the area (roads only). The methodology used to evaluate these indicators is described in the paragraphs that follow.

The **heights of bridge approaches above the water surface** were evaluated spatially**.** Conversations with stakeholders and existing research suggest that the approach roadways leading up to bridges might be the bridge components most vulnerable to flooding since they are typically lower in elevation than the bridge itself. Flooding of the bridge approach roadways is likely to result in the loss of use of the facility until the waters subside. In addition, flood debris might need to be removed from the roadway before service can be restored. In some cases, pavement damage will also result from the flooding rendering the bridge unusable for a longer period until repairs can be made. The project team analyzed bridge approach heights by locating and measuring the minimum height of the approach roadways above the water surface. Approach roadway elevations were derived from high-resolution LiDAR data with a 2-foot contour resolution. Bridges with approach elevations closer to the water surface were assumed to be more sensitive to flooding.

The **location of assets within flood zones** was analyzed using flood information from FEMA's National Flood Insurance Program (NFIP) to spatially represent the 100-year and 500-year flood scenarios. Using geographic information system (GIS) software, the research team overlaid the highway segments over these special flood hazard areas (SFHAs), as shown in Figure 50.[133]

**Figure 50: Special Flood Hazard Areas, Mobile County, AL**


For this study, the analysis required differentiating the 100-year flood zones based on whether the event was caused by precipitation only (defined as an inland or riverine flood) or a combination of precipitation and storm waves (defined as a coastal flood). The FEMA SFHA definitions are provided in Table 90, where Zones *A* and *AE* represent the 100-year inland or riverine flood zone, depending on whether flood elevations are provided. In contrast, only the *VE* special flood hazard area—where storm wave action is present—is used to label the 100-year coastal flood zone. The 500-year, or *X* flood zone, surrounds all the 100-year flood zones. If any part of a segment crossed a coastal zone, the entire asset was considered coastal.[134]

Coastal assets were not evaluated under this indicator, since the indicator is meant to evaluate sensitivity to inland (riverine) flooding.[135] Roadway segments were scored based on the percentage of the segment that was located within a riverine flood zone. Bridges and culverts were scored based on whether they were located within a riverine flood zone (yes/no). Assets received a score for both the 100-year and the 500-year flood zone, and these scores were weighted and combined to develop a composite flood zone score.

133 Maps from FEMA Digital Flood Insurance Rate Map Database; Mobile County, AL. Publication date 20100317. Community 01097C.

134 This is not an exact way to rule out whether the flood zones at a location are tidally influenced. For a more exact understanding on whether an area is tidal- or precipitation- driven (or both), one could use the Hydrologic Engineering Center River Analysis System (HEC-RAS) model used to determine the water level in the 100-year flood scenario. If the flood depth value matches the underlying base flood elevation at the location of interest, then the specific location is under the influence of a precipitation-driven flood event.

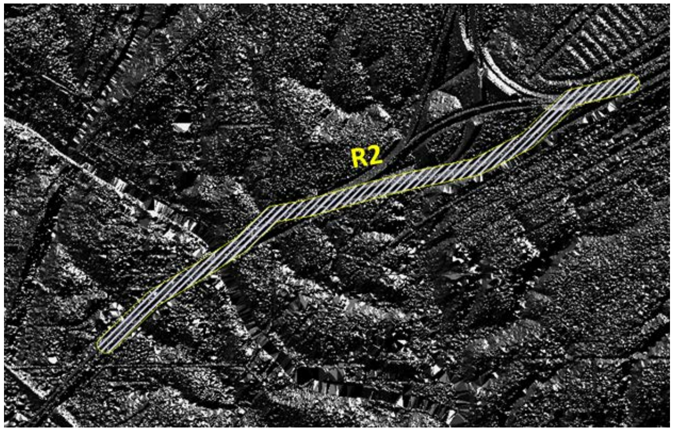
135 Presence in the *VE* flood zone was not used as an indicator for storm surge in this analysis, due to the availability of ADCIRC modeling data for the region. However, this has been noted as a good alternate exposure indicator for storm surge if advanced storm surge modeling data are not available.

**Table 90: Reclassification of Special Flood Hazard Areas**

| Flood Zone | Definition[136] | Reclassification for Study |
|---|---|---|
| X | Areas subject between a 1% (1-in-100yr) and 0.02% (1-in-500yr) annual chance of inland or coastal flooding. | Inland / Riverine or Coastal |
| AE | Areas subject to 1% annual chance of inland flooding. Flood depth elevations provided. | Inland/ Riverine |
| A | Areas subject to 1% annual chance of inland flooding. Flood depth elevations not provided. | Inland/ Riverine |
| VE | Areas subject to 1% annual chance of coastal flooding that is associated with storm waves. Flood elevations provided. | Coastal |

The **asset's elevation relative to surrounding areas** was also analyzed using GIS to capture the change in elevation between an asset and its surrounding area. It is therefore an indicator of an asset's susceptibility for collecting runoff during and after a precipitation event. Using a digital terrain, flow direction was assessed based on the underlying topography. This resulted in a relief-like image, showing the direction of surface flow, as shown in Figure 51. An online guide from ESRI, a geospatial software company, provides a technical reference on this process.[137]

**Figure 51: Flow Direction Raster**



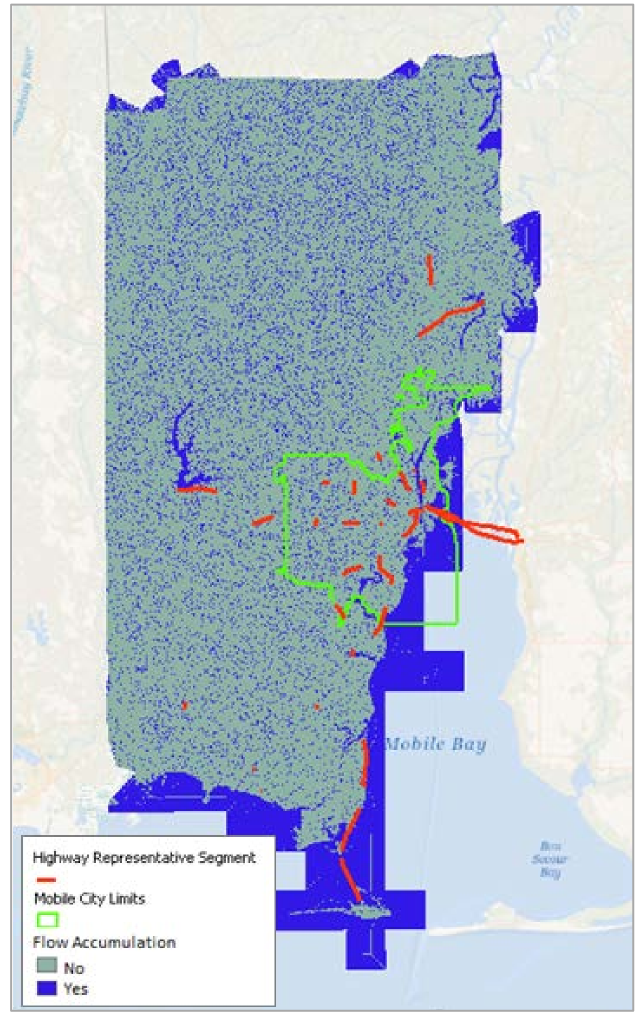

[136] FEMA, 2012
[137] ESRI, 2012

Using flow direction, runoff accumulation was then estimated, as shown in Figure 52. The research team calculated the median number of 3 feet x 3 feet "cells" that would flow into all locations along the highway segment. For example, areas within a highway segment that are located at lower elevations relative to their surroundings received a higher value, indicating its increased sensitivity to ponding. Conversely, highway segments or sections located at higher elevations relative to their surroundings received a lower value, indicating a less sensitivity.

The median value was used for ponding in order to remove any outliers in the analysis, which generally occurred for coastal assets and those near bodies of water, which had a tendency to skew the results toward a higher ponding value.

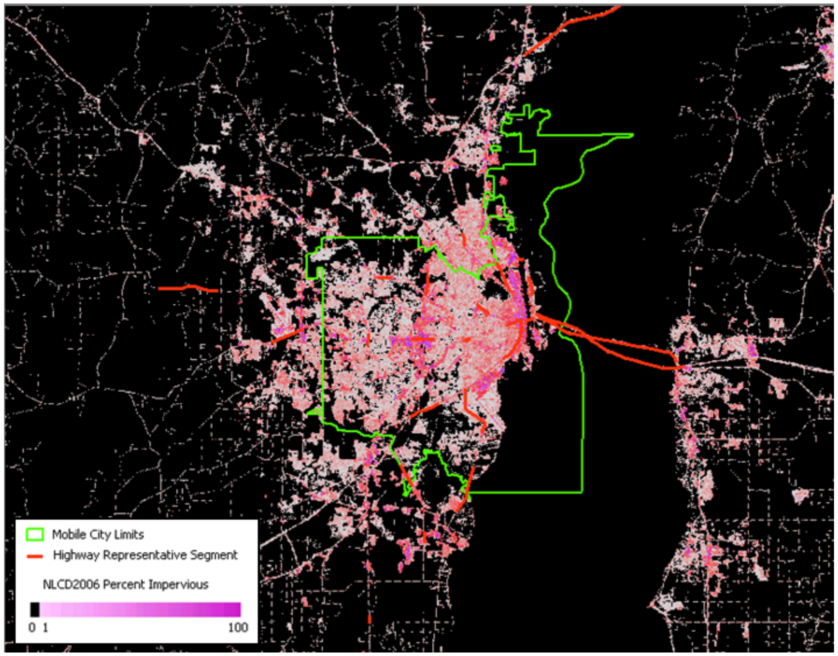
The final indicator (used for roads only) assessed the amount of **impervious surface** immediately surrounding the segment. Highly impermeable areas may be more likely to accumulate water during a precipitation event. The permeability analysis used the National Land Cover Dataset[138] impermeability layer to determine the sensitivity of highway segments to receiving runoff based on the type of urban environment in its immediate surroundings (see Figure 53). The research team first determined the average impermeability within the city limits of Mobile, Alabama, as a benchmark against which the assets were then compared. Cells within each highway segment were then classified as having an impermeability value either above or below this benchmark, and the percentage of the cells within each segment with above-average values was used to generate the permeability score.

**Figure 52: Flow Accumulation Raster**




[138] Fry et al., 2011

**Figure 53: National Land Cover Dataset, Percent Imperviousness for City of Mobile (NLCD, 2006)**




The research team determined that the area within the city limits of Mobile is comprised of approximately 27% impermeable surface, and all the permeability of the land surround the road segments were evaluated against this benchmark. Impermeable surfaces include all roads, driveways, pavements, parking areas, buildings, loading areas, decking, and other construction covering the natural landscape. As the percent impermeability increases, runoff increases, as does the strain on a city's storm drainage system.

The area considered for this analysis was three times the width of the road, in order to understand the type of urban environment surrounding the asset. For example, if a highway segment measured a width of 100 feet (30.5 meters), then the area evaluated measured 300 feet (or 91.5 meters) wide. To determine the permeability score for a specified asset, the research team determined the amount of area that was above or below the 27% threshold.

## Sea Level Rise

### Overview of Sea Level Rise Sensitivity Indicators, Data Sources, and Weightings

Table 91 through Table 93 provides a summary of the sensitivity indicators used to evaluate sea level rise sensitivity for highways, how they were scored, and how they were weighted.

**Table 91: Sea Level Rise Sensitivity Indicators and Scoring Approach for Roads**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to tidal events | Roads and bridges that have experienced flooding during extreme high tide events in the past are likely to be some of the first roads impacted by sea level rise. | **Yes/No Record of Previous Flooding from Tides**—Stakeholder interviews | 58% | This asset has never been exposed to coastal flooding (tidal) | 1 |
| | | | | | This asset has been exposed to coastal flooding events | 4 |
| | Whether an asset is protected from flooding | Roads protected by a dike, sea wall, or other structure are less likely to be affected by sea level rise. | **Yes/No Indication of Protection**—Stakeholder interviews | 42% | There is reason to believe that this asset would not be exposed to SLR. It is either protected by a dike or other shoreline protection, or it is elevated) | 1 |
| | | | | | Not protected | 4 |

* Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input).

**Table 92: Sea Level Rise Sensitivity Indicators and Scoring Approach for Bridges**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to tidal events | Roads and bridges that have experienced flooding during extreme high tide events in the past are likely to be some of the first roads impacted by sea level rise. | **Yes/No Record of Previous Flooding from Tides**—Stakeholder interviews | 36% | This asset has never been exposed to coastal flooding (tidal) | 1 |
| | | | | | This asset has been exposed to coastal flooding events | 4 |
| | Elevation of the approach to a bridge | Bridge approaches are often the most affected part of the bridge. Approaches that are at an elevation similar to the water surface are more sensitive to flooding from sea level rise, storm surge, or heavy rain. | **Minimum Height of Bridge Approach above Water Surface**—Project team analysis of LiDAR data | 21% | Not a water crossing or approach is greater than 15 feet above water surface | 1 |
| | | | | | Approach is greater than 10 feet and up to 15 feet above water surface | 2 |
| | | | | | Approach is greater than 5 feet and less than 10 feet above water surface | 3 |
| | | | | | Approach is up to 5 feet above water surface | 4 |
| Limitations on vessel size that can clear the bridge, or potential for bridge to be overtopped | Navigational clearance of a bridge | Bridges with less clearance above the waterway are more likely to be affected by sea level rise; operational changes be needed if certain sized vessels no longer have sufficient clearance as sea level rises. | **Navigation Vertical Clearance**—National Bridge Inventory, Item 39 | 21% | Greater than 20 feet | 1 |
| | | | | | Greater than 10 and up to 20 feet | 2 |
| | | | | | Greater than 5 and up to 10 feet | 3 |
| | | | | | Less than 5 feet | 4 |
| | Bridge height | Bridges with less clearance above the waterway are more likely to be at risk of waters reaching and deteriorating the bridge deck during high tides or storms; further, operational changes may | **Height of Bridge Embankment Relative to Water Surface**—Project team analysis of LiDAR data | 21% | Not a water crossing or bridge height is greater than max depth (200 cm) | 1 |
| | | | | | Greater than 75% and up to 100% of max depth (200 cm) | 2 |
| | | | | | Greater than 25% and up to 75% of | 3 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | be needed if certain sized vessels no longer have sufficient clearance. | (assumed a deck thickness of 5 feet**) | | max depth (200 cm) | |
| | | | | | Up to 25% of max depth (200 cm) | 4 |

*Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input). All indicators weighted equally.

**Table 93: Alternate Sea Level Rise Sensitivity Indicator Weighting for Bridges without Information for All Indicators**

| Data Scenario | Past Experience | Approach Height | Navigation Vertical Clearance | Bridge Height |
|---|---|---|---|---|
| No missing data | 36% | 21% | 21% | 21% |
| Missing data for navigational clearance | 43% | 28% | | 28% |

## Detailed Description of Sea Level Rise Sensitivity Indicators and Methodology

As noted previously, the sensitivity of road segments to sea level rise was assessed based on past experience and the presence of shoreline protection. Both of these indicators were scored as a binary Yes/No as indicated by stakeholders.

One sensitivity indicator used to score the sensitivity of roads and bridges to sea level rise was **past experience**. For example, all bridges on the Causeway was scored a "4" for past experience since this segment already experiences coastal flooding during certain tide and wind conditions.

Sensitivity of roads was also evaluated by the presence or absence of **protective structures**, such as levees or sea walls. Segments were evaluated using input from stakeholders, visual observation in person, and visual inspection using GIS.[139]

[139] Note that in some areas, protective structures are not fully effective against protecting against encroaching waters. For example, in areas with porous ground, water can seep up from underground. Also, if water floods an adjacent geographic area, the flooding can still reach the area "protected" by a structure by flooding it from behind.

While certain low-lying bridge decks may be at risk of inundation due to sea level rise, bridge approaches are likely to flood before the deck. Therefore, **elevation of the bridge approach** was used to assess sensitivity of bridges to sea level rise. The project team analyzed approach height by locating and measuring the minimum height above water of the bridge approach using the approach described under the precipitation discussion, on page 248. Bridges with lower approaches were assumed to be more sensitive to sea level rise. Twelve bridges in the study area had approaches less than 5 feet above the water surface, indicating potential exposure to sea level rise in the 2 meter (6.6 feet) scenario. These bridges included all of the bridge segments on the I-10 Bridge across Mobile Bay as well as several bridges on the Dauphin Island Parkway and the Causeway.

For bridges, **navigational clearance** was another sensitivity indicator. The NBI reports the navigational clearance as the minimum clearance of the bridge above the water as required by law. The assessment assumes that bridges with a higher navigational clearance are higher above the water surface and therefore less exposed to sea level rise. In this screen, bridges with a lower navigational clearance were assumed to have higher sensitivity to sea level rise. Four bridges in the study area had navigational clearance of less than 10 feet, including one of the bridges on the I-10 Bridge across Mobile Bay (R27) and two of the bridges on the Causeway (R10).

Another indicator used to calculate the sensitivity of bridges to sea level rise was the **minimum bridge embankment height (bridge height)**. Flowing waters reaching the bottom of the bridge deck may cause structural damage to the bridge. If structural damage occurs, the facility may need to be placed out of service for an extended time period. Measurements of actual bridges heights were not available in an accessible format for all bridges in the study; this information would need to have been gleaned from paper files for each of the bridges, and the cost of doing so for all bridges was beyond the resources of this project. Instead, the project team estimated the deck height above water by analyzing high-resolution LiDAR data (2-foot contour interval) in order to ascertain the height of the two bridge embankments on either side of the water crossing. The lower of the two embankment heights was noted and used as a proxy to estimate the minimum height of the top of the bridge deck above water. The project team then subtracted 5 feet to account for the thickness of the bridge deck in order to estimate the approximate minimum height of the bottom of the deck above the water. The project team assumed a bridge deck thickness of 5 feet based on input from engineering experts as to the average thickness of decks. While the results may not represent the exact actual height of each bridge above the water surface, this analysis was sufficient to provide a high-level screen to identify which bridges are potentially low enough to be inundated by sea level rise, and which ones are high enough above projected water levels that their decks are unlikely to be exposed to sea level rise.

## Storm Surge

### Overview of Storm Surge Sensitivity Indicators, Data Sources, and Weightings

Table 94 through Table 96 provide a summary of the sensitivity indicators used to evaluate storm surge sensitivity for highways, how they were scored, and how they were weighted.

**Table 94: Storm Surge Sensitivity Indicators and Scoring Approach for Roads**

<table>
<tr><th rowspan="2">Climate Change Impact</th><th rowspan="2">Indicator</th><th rowspan="2">Rationale</th><th rowspan="2">Asset Attribute and Data Source</th><th rowspan="2">Weight*</th><th colspan="2">Scoring Method</th></tr>
<tr><th>Attribute Value</th><th>Score</th></tr>
<tr><td rowspan="4">Structural damage to roads and bridges from storm surge</td><td rowspan="2">Whether an asset has been damaged in the past due to storm surge</td><td rowspan="2">Roads and bridges that have experienced damage during past storm events are more likely to be damaged if exposed in the future.</td><td rowspan="2">Yes/No Record of Previous Damage from Storm Surge—Stakeholder interviews</td><td rowspan="2">58%</td><td>N - This asset has never been damaged due to storm surge</td><td>1</td></tr>
<tr><td>Y - This asset has been damaged due to storm surge</td><td>4</td></tr>
<tr><td rowspan="2">Whether an asset is protected from storm surge</td><td rowspan="2">Roads protected by a dike, sea wall, vegetation, or other structure are less likely to be affected by storm surge.</td><td rowspan="2">Yes/No Indication of Protection—Stakeholder interviews</td><td rowspan="2">42%</td><td>Y - There is reason to believe that this asset would not be exposed to storm surge. It is either protected by shoreline protection, or it is elevated above storm surge)</td><td>1</td></tr>
<tr><td>N - Not protected</td><td>4</td></tr>
</table>

*Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input).

**Table 95: Storm Surge Sensitivity Indicators and Scoring Approach for Bridges**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Structural damage to roads and bridges from storm surge | Whether an asset has been damaged in the past due to storm surge | Roads and bridges that have experienced damage during past storm events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews | 24% | N - This asset has never been damaged due to storm surge | 1 |
| | | | | | Y - This asset has been damaged due to storm surge | 4 |
| | Bridge height | Bridges with less clearance above the waterway are more likely to experience storm surge heights that reach their deck. | **Bridge Embankment Elevation Relative to Current Water Surface**—Project team analysis of LiDAR data (assumed a deck thickness of 5 feet**) | 9% | Embankment height above water surface is equal to or less than 25% of max depth | 4 |
| | | | | | Greater than 25% and up to 75% of max depth (21.7 ft.) | 3 |
| | | | | | Greater than 75% and up to 100% of max depth (21.7 ft.) | 2 |
| | | | | | Bridge height is greater than max depth, or not a water crossing | 1 |
| | Distance between water floor and bridge deck | Bridges with less clearance above the waterway are more likely to experience storm surge heights that reach their deck. | **Navigation Vertical Clearance**—National Bridge Inventory, Item 39 | 9% | Greater than 20 feet | 1 |
| | | | | | Greater than 10 and up to 20 feet | 2 |
| | | | | | Greater than 5 and up to 10 feet | 3 |
| | | | | | Between 0 and 5 feet | 4 |
| | Whether a bridge is "scour critical" | Bridges that have already been identified as having problems with scour are more likely to be damaged during storm surge events. | **Scour Critical Bridges**—National Bridge Inventory, Item 113 | 9% | Score of 9 | 1 |
| | | | | | Score of 7 or 8 | 1 |
| | | | | | Score of 4 or 5 | 1 |
| | | | | | Score of 0 through 3 | 4 |
| | Condition of bridge | Bridges that are in poor condition are more likely to be damaged | **Substructure Condition Rating**—National Bridge | 9% | Score of 7, 8 or 9 | 1 |
| | | | | | Score of 4, 5, 6 | 2 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | substructure | during storm surge events. | Inventory, Item 60 | | Score of 2 or 3 | 3 |
| | | | | | Score of 0 or 1 | 4 |
| | Condition of bridge superstructure | Bridges that are in poor condition are more likely to be damaged during storm surge events. | **Superstructure Condition Rating**—National Bridge Inventory, Item 59 | 9% | Score of 7, 8 or 9 | 1 |
| | | | | | Score of 4, 5, 6 | 2 |
| | | | | | Score of 2 or 3 | 3 |
| | | | | | Score of 0 or 1 | 4 |
| | Condition of bridge deck | Bridges that are in poor condition are more likely to be damaged during storm surge events. | **Deck Condition Rating**—National Bridge Inventory, Item 58 | 9% | Score of 7, 8 or 9 | 1 |
| | | | | | Score of 4, 5, 6 | 2 |
| | | | | | Score of 2 or 3 | 3 |
| | | | | | Score of 0 or 1 | 4 |
| | Whether bridge is movable | Movable bridges can be more susceptible to damage during storm surge events because they have electrical components (per O'Connor and McAnany, 2008, Damage to Bridges from Wind, Storm Surge, and Debris in the Wake of Hurricane Katrina; p. 127). | **Structure Type**—National Bridge Inventory, Item 43b<br>(Codes 15, 16, and 17 refer to Movable Bridges - lift, bascule, and swing, respectively) | 9% | Not a movable bridge | 1 |
| | | | | | Movable bridge (NBI item 43b codes 15, 16, or 17) | 4 |
| | Age of an asset | Older bridges may have been built to older design standards, have deteriorated structures or have experienced more extreme damaging storm surge events, rendering them more sensitive to storm surge events than bridges designed more recently. In addition, changes in sea level and | **Year Built**—National Bridge Inventory, Item 27 | 9% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 50 years old | 2 |
| | | | | | Greater than 50 and up to 75 years old | 3 |
| | | | | | Greater than 75 years old | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | the accumulation of more historical extreme storm events could greatly change the value of the water surface level (e.g., the Q100 water surface level) that an older bridge was originally designed for. | | | | |
| Flooding | Elevation of the approach to a bridge | Bridge approaches are often the most affected part of the bridge. Approaches that are not much higher than the water surface are more sensitive to flooding from sea level rise, storm surge, or heavy rain. In addition, the velocity vectors associated with contraction and expansion of flow through the bridge opening are higher near the approach than in the middle of the bridge opening. | **Minimum Height of Bridge Approach above Water Surface**—Project team analysis of LiDAR data | 9% | Approach is greater than 15 feet above water surface or asset is not a water crossing | 1 |
| | | | | | Approach is greater than 10 feet and up to 15 feet above water surface | 2 |
| | | | | | Approach is greater than 5 feet and up to 10 feet above water surface | 3 |
| | | | | | Approach is up to 5 feet above water surface | 4 |

*Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input). All other indicators are weighted equally.

**Project team assumed average deck thickness is between 2 and 8 feet for bridges 150 feet long or less. Five feet is the midpoint of this range.

**Table 96: Alternate Storm Surge Sensitivity Indicator Weighting for Bridges without Information for All Indicators**

| Data Scenario | Past Experience | Bridge Height | Navigation Vertical Clearance | Scour Critical | Substructure Condition | Super structure Condition | Deck Condition | Structure Type (Movable?) | Age | Approach Height |
|---|---|---|---|---|---|---|---|---|---|---|
| No missing data | 23.5% | 8.5% | 8.5% | 8.5% | 8.5% | 8.5% | 8.5% | 8.5% | 8.5% | 8.5% |
| Missing navigation vertical clearance | 24.4% | 9.4% | | 9.4% | 9.4% | 9.4% | 9.4% | 9.4% | 9.4% | 9.4% |
| Missing navigation vertical clearance and scour critical | 26% | 11% | | | 11% | 11% | 11% | 11% | 11% | 11% |
| Missing navigation vertical clearance and deck condition | 26% | 11% | | 11% | 11% | 11% | | 11% | 11% | 11% |
| Missing navigation vertical clearance and structure conditions | 29% | 14% | | 14% | | | | 14% | 14% | 14% |
| Missing navigation vertical clearance, scour critical, and structure conditions | 32% | 17% | | | | | | 17% | 17% | 17% |

## Detailed Description of Storm Surge Sensitivity Indicators and Methodology

The sensitivity of road segments was based solely on **past experience** and **shoreline protection**, both of which were gleaned from interviews with ALDOT, Mobile County, and the City of Mobile. For example, stakeholders indicated that the segment of Old Spanish Trail between Cochrane Bridge and the tunnels (R32) floods during storms, despite the protection of a nearby dam.[140] Dauphin Island Bridge (R26) also repeatedly closes during storm events.

140 ALDOT, 2012

Past experience was also a sensitivity indicator for bridges to evaluate how they fared during past storm events. This indicator was also based on stakeholder input.

The **bridge embankment height**, **bridge approach height**, and **navigational clearance** are three indicators that attempt to capture the extent to which a bridge structure's height might protect it from storm surge. These three indicators are also used in the assessment of sensitivity to sea level rise. One indicator used to calculate the sensitivity of bridges to storm surge was the height of the bridge embankment (used to estimate deck heck height) relative to water surface. Because precise deck height of all bridges were not available in an easily accessible manner, the project team estimated deck height above water by analyzing high resolution LiDAR data to ascertain the height of the approach embankment (used as a proxy for deck height). For more information, please see the sea level rise discussion starting on page 256. To score this indicator, the vulnerability assessment compared bridge embankment heights against the maximum storm surge (including wave height) projected to occur during the selected storm scenarios (21.7 feet). The two bridges with the lowest embankment heights were both located on R22 (Dauphin Island Parkway from Old Cedar Point Road to Day Springs Road). Note that there may not always be a direct, inverse relationship between bridge height and sensitivity to storm surge. Very low bridges may be completely inundated from storm surge and experience less wave action on the underside of decks than higher bridges. An alternate scoring approach could reflect this, whereby some higher bridges are scored as more sensitive than lower bridges based on estimated storm surge and wave heights.

While bridge decks are often impacted during severe storms, bridge approaches are likely to flood before the deck. Therefore, approach height was used to assess sensitivity of bridges to sea level rise. The project team analyzed approach height by locating and measuring the minimum height above water of the bridge approach, using the methods discussed on page 248. Bridges with lower approaches were assumed to be more sensitive to sea level rise. Thirty-three bridges in the study area had approaches less than 5 feet above the water surface, indicating potential exposure under most storm scenarios. These included all of the bridge segments on the I-10 Bridge across Mobile Bay as well as several bridges on the Dauphin Island Parkway and the Causeway.

The NBI reports the navigational clearance as the minimum clearance of the bridge above the water as required by law. The assessment assumes that bridges with a higher navigational clearance are higher above the water surface and therefore less exposed to sea level rise. In this screen, bridges with a lower navigational clearance were assumed to have higher sensitivity to storm surge. Four bridges in the study area had navigational clearance of less than 10 feet, including one of the bridges on the I-10 Bridge across Mobile Bay (R27) and two of the bridges on the Causeway (R10).

This vulnerability screen also included sensitivity indicators intended to screen for bridges that might be in worse structural condition, under the assumption that poorly maintained bridges are more sensitive to damage during storm surge. **Deck condition**, **superstructure condition**, and **substructure condition** data from the NBI were included to capture this aspect of sensitivity. According to the NBI condition ratings, the representative bridges analyzed in this assessment are all in good condition, indicating a lower sensitivity to storm surge.

While none of the bridges on the selected representative highway assets are movable, the project team included **movable bridges** as a sensitivity indicator. Movable bridges require electricity, which is often disrupted during storms. During past storm events on the Gulf Coast, movable bridges have experienced a disproportionate amount of damage due to this reliance on electricity. This assessment scored movable bridges as more sensitive than non-movable bridges for this reason.

**Age (based on year built)** was selected as an indicator because older bridges are more likely to have been built to older design standards, which underestimate storm surge. The majority of bridges in the study area are less than 50 years old, but there is a culvert located on the Causeway that was built in 1928. In addition, all of the bridges and culverts on R29 (intersection of Airport Blvd and I-65) were built over fifty years ago.

## Wind

### Overview of Wind Sensitivity Indicators, Data Sources, and Weightings

Table 97 through Table 98 provide a summary of the sensitivity indicators used to evaluate wind sensitivity for highways, how they were scored, and how they were weighted.

**Table 97: Wind Sensitivity Indicators and Scoring Approach for Roads**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Debris on roadways and damage to roadway signals and signs | Density of roadway signals | Wind damage to roadway signals and signs can delay traffic significantly and disrupt evacuation and recovery; roads and bridges with a higher density of road way signs and signal lights may be more prone to this type of damage. | **Traffic Signals Per Mile of Roadway—** City of Mobile GIS data | 100% | 0-1 traffic signals per mile | 1 |
| | | | | | 2-5 traffic signals per mile | 2 |
| | | | | | 6-9 traffic signals per mile | 3 |
| | | | | | 10 or more traffic signals per mile | 4 |

Table 98: Wind Sensitivity Indicators and Scoring Approach for Bridges

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Debris on roadways and damage to roadway signals and signs | Density of roadway signals | Wind damage to roadway signals and signs can delay traffic significantly and disrupt evacuation and recovery; roads and bridges with a higher density of road way signs and signal lights may be more prone to this type of damage. | **Traffic Signals Per Mile of Roadway**—City of Mobile GIS data | 100% | 0-1 traffic signals per mile | 1 |
| | | | | | 2-5 traffic signals per mile | 2 |
| | | | | | 6-9 traffic signals per mile | 3 |
| | | | | | 10 or more traffic signals per mile | 4 |

### Detailed Description of Wind Sensitivity Indicators and Methodology

The sensitivity of both road and bridge sub-segments was based entirely on the density of roadway signals on the road segment. While it is very difficult to predict where wind damage will occur, highway stakeholders concurred that damage to roadway signs from wind is common during storms. Most of the highway assets (both bridges and roads) had low signal density. However R9 (US-90, Section East of Broad Street) had a high density, probably because it is located closer to Mobile's downtown.

## C.2. Ports

Port segments were comprised of port facilities as well as their respective docks, parking lots, and other ancillary structures. Due to differences in engineering characteristics, the nature of sensitivity, and sources of data, the analysis used distinct sets of indicators.

### Temperature

#### Overview of Temperature Sensitivity Indicators, Data Sources, and Weightings

Table 99 and Table 100 provide a summary of the sensitivity indicators used to evaluate temperature sensitivity for ports, how they were scored, and how they were weighted.

**Table 99: Temperature Sensitivity Indicators and Scoring Approach for Ports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Pavement rutting, shoving, or other compromised integrity | Whether pavement has rutted (or shown other signs of damage) in the past due to high temperature | Ports that have experienced damage during past heat events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Temperature**—Stakeholder interviews | 36% | No - This asset has never been damaged due to high temperatures in the past | 1 |
| | | | | | Yes - This asset has been damaged due to high temperatures in the past | 4 |
| | Size of paved areas | Pavement can buckle or sink in high temperatures. The extent of paved asphalt areas is therefore an indicator of sensitivity to heat. | **Size of Paved Asphalt Areas**—Visual inspection of satellite imagery | 21% | None or negligible asphalt area | 1 |
| | | | | | Small asphalt area | 2 |
| | | | | | Medium asphalt area | 3 |
| | | | | | Large asphalt area | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Heat damage to perishable freight | Materials handled | If materials stored or handled at the facility are perishable or otherwise possibly damaged by high temperatures, they will be more sensitive to temperature changes. | **Materials Handled**—Alabama State Port Authority (2013), stakeholder interviews | 21% | Aluminum | 1 |
| | | | | | Assorted | 2.5 |
| | | | | | Break bulk | 1 |
| | | | | | Cement | 1 |
| | | | | | Coal | 1 |
| | | | | | Containers | 1 |
| | | | | | Floating equipment | 1 |
| | | | | | Hazardous materials | 1 |
| | | | | | Iron | 1 |
| | | | | | Metal products | 1 |
| | | | | | None | 1 |
| | | | | | Passengers | 2 |
| | | | | | Perishables | 4 |
| | | | | | Petroleum products | 1 |
| | | | | | Piling, slabs, girders | 1 |
| | | | | | Seafood | 4 |
| | | | | | Ship services | 1 |
| | | | | | Stone, sand, gravel | 1 |
| | | | | | Wood products | 1 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Disruption to operations | Reliance on electrical power | Ports and port facilities that are highly reliant on electrical power to operate will be more sensitive to electricity losses due to widespread power outages, including those caused by stress on the grid from high temperatures. | **Reliance on Electrical Power**—Stakeholder interviews and survey responses | 21% | Facility is not reliant on electrical power | 1 |
| | | | | | Some components require electricity, but are not fundamental to the facility's function | 2 |
| | | | | | Fundamental function requires electricity, but backup generators are available | 3 |
| | | | | | Fundamental function of the facility requires electrical power | 4 |

* Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input). All other indicators are weighted equally.

**Table 100: Alternate Weighting schemes for Temperature Sensitivity Indicators when Data are Missing**

| Data Scenario | Past Experience | Materials Handled | Size of Paved Asphalt Areas | Reliance on Electrical Power |
|---|---|---|---|---|
| No missing data | 36% | 21% | 21% | 21% |
| Missing reliance on electrical power | 43% | 28% | 28% | |
| Missing data for past experience | | 33% | 33% | 33% |
| Missing data for past experience and reliance on electric power | | 50% | 50% | |
| Missing data for past experience and size of paved asphalt areas | | 50% | | 50% |
| Missing past experience and materials handled | | | 50% | 50% |

| Data Scenario | Past Experience | Materials Handled | Size of Paved Asphalt Areas | Reliance on Electrical Power |
|---|---|---|---|---|
| Missing data for past experience, size of paved asphalt areas, and reliance on electrical power | | 100% | | |
| Missing data on past experience, materials handled, and reliance on electrical power | | | 100% | |

### Detailed Description of Temperature Sensitivity Indicators and Evaluation Methodology

This assessment considered the **past experience** of port assets during heat events. Many ports have large areas of pavement that must be maintained. Since the port stakeholders stated that none of the critical port facilities had experienced major rutting problems in the past, all assets received a score of “1” for past experience.

The project team included **materials handled** as an indicator to capture the potential damage that high temperatures might cause to perishable or otherwise sensitive materials. The assessment scored seafood, associated materials, perishables, and passengers as highly sensitive. The rest of the materials handled were considered to have a very low sensitivity.

This assessment considered the **size of paved asphalt areas** at ports because pavement can buckle or sink in high temperatures. The extent of paved asphalt areas is therefore an indicator of sensitivity to heat. The size of the paved asphalt area was determined by visually inspecting satellite imagery.

The final indicator of port sensitivity was **reliance on electrical power.** Ports and port facilities that are highly reliant on electrical power to operate will be more sensitive to electricity losses due to widespread power outages, including those caused by stress on the grid from high temperatures. Port operators and managers scored their own reliance on electrical power based on a survey that the project team distributed in the summer of 2012.

## Precipitation

### Overview of Precipitation Sensitivity Indicators, Data Sources, and Weightings

Table 101 and Table 102 provide a summary of the sensitivity indicators used to evaluate precipitation sensitivity for ports, how they were scored, and how they were weighted.

**Table 101: Precipitation Sensitivity Indicators and Scoring Approach for Ports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding on port property | Whether an asset has flooded in the past due to heavy rain | Ports that have experienced damage during past heavy rain events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Flooding from Rainfall**—stakeholder interviews | 32% | No - This asset has never been damaged due to precipitation in the past | 1 |
| | | | | | Yes - This asset has been damaged due to precipitation in the past | 2 |
| | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | 10% | Not located in flood zone | 1 |
| | | | | | Up to 1/3 of asset located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of asset located in flood zone | 3 |
| | | | | | Greater than 2/3 of asset located in flood zone | 4 |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs | 7% | Not located in flood zone | 1 |
| | | | | | Up to 1/3 of asset located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of asset located in flood zone | 3 |
| | | | | | Greater than 2/3 of asset located in flood zone | 4 |
| | Susceptibility of an asset to ponding | If an asset is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events. | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the road (elevation data from 3 ft. x 3 ft. LiDAR) | 9% | Ponding score greater than 0 and up to 42 | 1 |
| | | | | | Ponding score greater than 42 and up to 84 | 2 |
| | | | | | Ponding score greater than 84 and up to 126 | 3 |
| | | | | | Ponding score greater than 126 | 4 |
| | Amount of impervious surface | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation. | **Percent of Asset with Above Average Impermeability—** USGS National Land Cover Database (NLCD) 2006 Impervious Surfaces | 9% | Up to 25% of asset with above average impermeability | 1 |
| | | | | | Greater than 25% and up to 50% of asset with above average impermeability | 2 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | | | | Greater than 50% and up to 75% of asset with above average impermeability | 3 |
| | | | | | Greater than 75% of asset with above average impermeability | 4 |
| Damage of structures or cargo due to flooding | Materials handled | If materials stored or handled at the facility are perishable or otherwise damaged by water, they will be more sensitive to flooding. | **Materials Handled**—ASPA (2013) and stakeholder interviews | 17% | Aluminum | 1 |
| | | | | | Assorted | 2.5 |
| | | | | | Break bulk | 1 |
| | | | | | Cement | 1 |
| | | | | | Coal | 3 |
| | | | | | Containers | 3 |
| | | | | | Floating equipment | 4 |
| | | | | | Hazardous materials | 4 |
| | | | | | Iron | 1 |
| | | | | | Metal products | 1 |
| | | | | | None | 1 |
| | | | | | Passengers | 4 |
| | | | | | Perishables | 4 |
| | | | | | Petroleum products | 2 |
| | | | | | Piling, slabs, girders | 1 |
| | | | | | Seafood | 4 |
| | | | | | Ship services | 4 |
| | | | | | Stone, sand, gravel | 1 |
| | | | | | Wood products | 4 |
| | Age of wharves, structures | Older wharves and structures may have been built to lower standards and/or be in poorer condition compared to newer structures, and therefore more susceptible to damage. | **Year in which Facility was Built**—ASPA (2013), stakeholder surveys and interviews | 17% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 50 years old | 2 |
| | | | | | Greater than 50 and up to 75 years old | 3 |
| | | | | | Greater than 75 years old | 4 |

*Weighting rationale: Past Experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining three indicators, where both flood zone indicators are grouped together and both indicators related to run-off are grouped together (ponding and impervious surface). Within flood zone indicator, 10% of weight comes from 100-year flood zone and 7% comes from 500-year flood zone because all assets in the 100-year flood zone are also in the 500-year flood zone.

** Ponding score refers to number of grid cells that flow into the cells covered by the asset.

**Table 102: Alternate Precipitation Sensitivity Indicator Weighting for Ports without Information for All Indicators**

| Data Scenario | Past Experience | Materials Handled | Age of Wharves, Structures | 100-yr Flood Zone | 500-yr Flood Zone | Ponding | Impervious Surface |
|---|---|---|---|---|---|---|---|
| No missing data | 32% | 17% | 17% | 10% | 7% | 9% | 9% |
| Missing historical performance | | 25% | 25% | 15% | 10% | 13% | 13% |
| Missing historical performance and materials handled | | | 33% | 20% | 13% | 17% | 17% |
| Missing historical performance and age of wharves | | 33% | | 20% | 13% | 17% | 17% |
| Missing historical performance, materials handled, and age of wharves | | | | 30% | 20% | 25% | 25% |

## Detailed Description of Precipitation Sensitivity Indicators and Methodology

This vulnerability assessment considered **historical performance** of ports during heavy rain events. If an area is already known to flood, then it will experience further impacts from increased precipitation events.

The assessment also relied on several targeted spatial analyses to better understand how the ports might become more exposed to flooding during heavy rain. These spatial indicators were: the location of the asset within a flood zone (whether it was located within the **100- and/or 500-year floodplain**), the propensity of an asset to flood based on its nearby topography (**susceptibility to ponding**), and the amount of **impervious surface** at the port. The **location of assets within flood zones** was analyzed using flood information from FEMA's National Flood Insurance Program (NFIP) to spatially represent the 100-year and 500-year flood scenarios (see Figure 50). The susceptibility of a port to ponding, and the impervious surface were evaluated using the same approach as described for these indicators starting on page 249, under the Highways precipitation section. The only difference is that rather than use linear segments to represent the ports—as done for highways— each port was delineated about its perimeter to form a polygon.

The project team included **materials handled** as an indicator to capture the potential damage that heavy rain might cause to perishable or otherwise sensitive materials. The assessment scored floating equipment, hazardous materials, passengers, perishables, seafood, ship services, and wood products as sensitive to precipitation.

The final indicator for the ports vulnerability assessment was **the age of the wharves and structures.** Older wharves and structures may have been built to lower standards and/or be in poorer condition compared to newer structures. Therefore, older facilities may be more sensitive to storm surge damage.

## Sea Level Rise

### Overview of Sea Level Rise Sensitivity Indicators, Data Sources, and Weightings

Table 103 and Table 104 provides a summary of the sensitivity indicators used to evaluate sea level rise sensitivity for ports, how they were scored, and how they were weighted.

**Table 103: Sea Level Rise Sensitivity Indicators and Scoring Approach for Ports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method: Attribute Value | Scoring Method: Score |
|---|---|---|---|---|---|---|
| Temporary inundation from high tides or permanent inundation | Whether an asset has flooded in the past due to tidal events | Ports that have experienced previous issues with tidal variation are more likely to be sensitive to sea level rise. | **Yes/No Record of Previous Flooding from Tides**—Stakeholder interviews | 43% | No - This asset has never been damaged due to tidal events in the past | 1 |
| | | | | | Yes - This asset has been damaged due to tidal events in the past | 4 |
| Damage to structures from higher water levels | Shoreline protection | Ports with shoreline protection such as bulkheads or riprap are less sensitive to sea level rise than those without. | **Yes/No Indication of Protection** –visual inspection of satellite imagery | 28% | Yes - port is armored by a bulkhead, riprap, or other mechanism | 1 |
| | | | | | No - port is not protected by a bulkhead, riprap, or other mechanism | 4 |
| | Age of facility | Older wharves and structures may have been built to lower standards and/or be in poorer | **Year in which Wharf or Structure was Built—**ASPA (2013), | 28% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 50 years old | 2 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | condition compared to newer structures, and therefore more susceptible to damage. | Stakeholder surveys and interviews | | Greater than 50 and up to 75 years old | 3 |
| | | | | | Greater than 75 years old | 4 |

* Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input). All other indicators are weighted equally.

**Table 104: Alternate Sea Level Rise Sensitivity Indicator Weighting for Ports without Information for All Indicators**

| Data Scenario | Past Experience | Shoreline Protection | Age of Wharves, Structures |
|---|---|---|---|
| No missing data | 43% | 28% | 28% |
| Missing data for past experience | | 50% | 50% |
| Missing data for past experience and age of wharves | | 100% | |
| Missing data for past experience and shoreline protection | | | 100% |

## Detailed Description of Sea Level Rise Sensitivity Indicators and Methodology

As noted previously, the sensitivity of ports to sea level rise was assessed based on **historical performance**, the presence of **shoreline protection,** and **the age of facilities**. Historical performance refers to whether the port has previously experienced problems during particularly high tide events. If a port already experiences problems during extremely high tide events, the frequency of those problems may increase as the sea level rises. Shoreline protection references the presence of rip rap or bulkheads, which provide some protection to the port. Both the historical performance and presence of shoreline protection were scored as a binary Yes/No as indicated by stakeholders. Ports were evaluated using input from stakeholders, visual observation in person, and visual inspection using GIS.[141]

[141] Note that in some areas, protective structures are not fully effective against protecting against encroaching waters. For example, in areas with porous ground, water can seep up from underground. Also, if water floods an adjacent geographic area, the flooding can still reach the area "protected" by a structure by flooding it from behind.

The age of the port facilities can be important since older infrastructure may have been built to previous standards, or may be in less than ideal condition, thereby making it more prone to damage when exposed to sea level rise. For example, ASPA indicated that newer piers tend to be built a little higher than the older ones.

## Storm Surge

### Overview of Storm Surge Sensitivity Indicators, Data Sources, and Weightings

Table 105 and Table 106 provide a summary of the sensitivity indicators used to evaluate storm surge sensitivity for ports, how they were scored, and how they were weighted.

**Table 105: Storm Surge Sensitivity Indicators and Scoring Approach for Ports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Structural damage to ports from storm surge | Whether an asset has been damaged in the past due to storm surge | Ports that have experienced damage during past storm events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews | 27% | No—This asset has never been damaged due to storm surge in the past | 1 |
| | | | | | Yes—This asset has been damaged due to storm surge in the past | 4 |
| | Shoreline protection | Ports with protection features such as bulkheads or riprap are less likely to be affected by storm surge. | **Yes/No Indication of Protection**—visual inspection of satellite imagery, stakeholder interviews | 12% | Yes - port is armored by a bulkhead, riprap, or other mechanism | 1 |
| | | | | | No - port is not protected by a bulkhead, riprap, or other mechanism | 4 |
| | Height of key infrastructure above sea level | Ports with docks and other infrastructure closer to sea level are more likely to experience damage from storm surges. | **Height of Key Infrastructure Relative to Current Water Surface** –stakeholder survey responses and interviews | 12% | Height of key infrastructure is greater than 75% of maximum storm surge depth | 1 |
| | | | | | Height of key infrastructure is greater than 50% and up to 75% of maximum storm surge depth | 2 |
| | | | | | Height of key infrastructure is greater than 25% and up to 50% of storm surge height | 3 |
| | | | | | Height of key infrastructure is up to 25% of storm surge depth | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | Age of wharves and structures | Older wharves and structures may have been built to older standards and/or be in poorer condition compared to newer structures, and therefore more susceptible to damage. | **Year in which Facility was Built**—ASPA (2013), Stakeholder survey responses | 12% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 50 years old | 2 |
| | | | | | Greater than 50 and up to 75 years old | 3 |
| | | | | | Greater than 75 years old | 4 |
| | Condition of facility | Current condition (ranging from Good to Poor) can be an indicator of how likely an asset is to be damaged by future impacts. | **Condition Rating**—Stakeholder interviews and surveys, Maritime Strategic Development Study Phase III: Inventory of Existing Port Maritime Facilities | 12% | Good condition | 1 |
| | | | | | Fair-good condition (some components may are good while others are fair) | 2 |
| | | | | | Fair condition | 3 |
| | | | | | Poor condition | 4 |
| Disruption of port operations due to power outages | Reliance on electrical power | Ports and port facilities that rely on electrical power to operate will be more sensitive to electricity losses due to widespread weather-related outages or submersion of electrical equipment. | **Reliance on Electricity—** stakeholder interviews and surveys | 12% | Facility is not reliant on electrical power | 1 |
| | | | | | Some components require electricity, but are not fundamental to the facility's function | 2 |
| | | | | | Fundamental function requires electricity, but backup generators are available | 3 |
| | | | | | Fundamental function of the facility requires electrical power | 4 |
| Likelihood of damage due to exposure to storm surge | Materials handled | If materials handled or stored at the facility are damaged by water or are perishable, they will experience greater negative effects from storm surges. | **Materials Handled**—ASPA (2013), stakeholder interviews | 12% | Aluminum | 1 |
| | | | | | Assorted | 2.5 |
| | | | | | Break bulk | 1 |
| | | | | | Cement | 1 |
| | | | | | Coal | 3 |
| | | | | | Containers | 3 |
| | | | | | Floating equipment | 4 |
| | | | | | Hazardous materials | 4 |
| | | | | | Iron | 1 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | | | | Metal products | 1 |
| | | | | | None | 1 |
| | | | | | Passengers | 4 |
| | | | | | Perishables | 4 |
| | | | | | Petroleum products | 2 |
| | | | | | Piling, slabs, girders | 1 |
| | | | | | Seafood | 4 |
| | | | | | Ship services | 4 |
| | | | | | Stone, sand, gravel | 1 |
| | | | | | Wood products | 4 |

*Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input). All other indicators are weighted equally.

**Table 106: Alternate Storm Surge Sensitivity Indicator Weighting for Ports without Information for All Indicators**

| Data Scenario | Past Experience | Shoreline Protection | Height of Key Infrastructure | Reliance on Electrical Power | Age of Wharves, Structures | Condition | Materials Handled |
|---|---|---|---|---|---|---|---|
| No missing data | 27% | 12% | 12% | 12% | 12% | 12% | 12% |
| Missing data for infrastructure height | 29% | 14% | | 14% | 14% | 14% | 14% |
| Missing data for reliance on electrical power and condition | 32% | 17% | 17% | | 17% | | 17% |
| Missing data for past experience and infrastructure height | | 33% | | | 33% | | 33% |
| Missing data for past experience, infrastructure height, age, and condition | | 33% | | 33% | | | 33% |
| Missing data for past experience, infrastructure height, and condition | | 25% | | 25% | 25% | | 25% |
| Missing data for past experience, | | 50% | | | | | 50% |

| Data Scenario | Past Experience | Shoreline Protection | Height of Key Infrastructure | Reliance on Electrical Power | Age of Wharves, Structures | Condition | Materials Handled |
|---|---|---|---|---|---|---|---|
| infrastructure height, reliance on electrical power, age, and condition | | | | | | | |

## Detailed Description of Storm Surge Sensitivity Indicators and Methodology

**Historical performance** refers to whether the port experienced damage to storm surge in the past. If a port has been previously damaged during storms, there may be certain characteristics at that port—ranging from types and location of infrastructure to geological characteristics that cause it to experience more severe surge impacts—that could cause it to be vulnerable in the future. A limitation of this indicator is that when severe or repeated damage occurs during a storm, the infrastructure is repaired to a standard mean to make it *less* vulnerable to future events. This indicator was evaluated based on stakeholder input.

**Shoreline protection** refers to the presence of rip rap, bulkheads, and other protective structures. This indicator was evaluated by visual inspection using satellite imagery and by interviewing port stakeholders.

**Height of key infrastructure above sea level** is an indicator that evaluates how high above the current sea level key infrastructure is. If the key infrastructure is significantly above the current sea level, then it can withstand a higher storm surge level. Information to evaluate this indicator was obtained through surveys and interviews of port personnel.

**Age of wharves and structures**, and **condition of facilities** help identify which facilities have infrastructure that may be more susceptible to damage. Older structures may be built to less resilient standards (such as being lower to the ground or having less resilient engineering), and facilities in poorer condition may be less able to withstand storm surge. This indicator was evaluated using stakeholder input, as well as information gathered from *Maritime Strategic Development Study Phase III: Inventory of Existing Port Maritime Facilities*.

Some ports have greater **reliance on electrical power** and therefore may be more sensitive to the loss of electricity that can accompany storms. Some ports are able to begin limited operations again after a storm event, with back-up generators being sufficient to run essential equipment. Other ports, such as the shipbuilding or ship repair facilities, rely very heavily on electricity to power tools and equipment, and back-up generators are not sufficient for running the necessary equipment. These facilities may be unable to operate during power outages. Again, stakeholder interviews provide the information necessary to evaluate this indicator.

Some ports **handle materials** that are more sensitive to storm surge damage than others. Perishable materials may be ruined by power outages that accompany storms, and certain cargo materials may be able to withstand a certain amount of water exposure without being completely ruined. This indicator was evaluated primarily on stakeholder input.

## Wind

### Overview of Wind Sensitivity Indicators, Data Sources, and Weightings

Table 107 and Table 108 provide a summary of the sensitivity indicators used to evaluate wind sensitivity for ports, how they were scored, and how they were weighted.

**Table 107: Wind Sensitivity Indicators and Scoring Approach for Ports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Structural damage to ports from high winds | Whether or not an asset has experience damage during past high winds | Ports that have experienced damage during past high winds are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Wind—**stakeholder interviews | 36% | No - This asset has never been damaged due to wind in the past | 1 |
| | | | | | Yes - This asset has been damaged due to wind in the past | 4 |
| | Age of wharves and structures | Older wharves and structures may have been built to lower standards and/or be in poorer condition compared to newer structures, and therefore more susceptible to damage. | **Year in which Facility was Built**—ASPA (2013), Stakeholder survey responses | 21% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 50 years old | 2 |
| | | | | | Greater than 50 and up to 75 years old | 3 |
| | | | | | Greater than 75 years old | 4 |
| Damage of cargo due to high winds | Materials handled | If materials handled or stored at the facility are easily damaged by high winds, they will experience greater negative effects from storm-force winds. | **Materials handled**—ASPA (2013), stakeholder interviews) | 21% | Aluminum | 1 |
| | | | | | Assorted | 2.5 |
| | | | | | Break bulk | 1 |
| | | | | | Cement | 1 |
| | | | | | Coal | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | | | | Containers | 2 |
| | | | | | Floating equipment | 4 |
| | | | | | Hazardous materials | 2 |
| | | | | | Iron | 1 |
| | | | | | Metal products | 1 |
| | | | | | None | 1 |
| | | | | | Passengers | 4 |
| | | | | | Perishables | 1 |
| | | | | | Petroleum products | 2 |
| | | | | | Piling, slabs, girders | 1 |
| | | | | | Seafood | 1 |
| | | | | | Ship services | 2 |
| | | | | | Stone, sand, gravel | 3 |
| | | | | | Wood products | 1 |
| Disruption of port operations due to power outages | Reliance on electrical power | Ports and port facilities that rely on electrical power to operate will be more sensitive to electricity losses due to widespread weather-related outages including those caused by stress on the grid from high winds. | **Reliance on electricity—** stakeholder interviews and surveys | 21% | Facility is not reliant on electrical power | 1 |
| | | | | | Some components require electricity, but are not fundamental to the facility's function | 2 |
| | | | | | Fundamental function requires electricity, but backup generators are available | 3 |
| | | | | | Fundamental function of the facility requires electrical power | 4 |

*Weighting rationale: Past Experience weighted about 15 percentage points higher than other indicators (per stakeholder input). All other indicators are weighted equally.

**Table 108: Alternate Wind Sensitivity Indicator Weighting for Ports without Information for All Indicators**

| Data Scenario | Past Experience | Materials Handled | Reliance on Electrical Power | Age of Wharves, Structures |
|---|---|---|---|---|
| No missing data | 36% | 21% | 21% | 21% |
| Missing data for past experience and age of wharves | | 33% | 33% | 33% |
| Missing data for past experience and age of wharves | | 50% | 50% | |
| Missing data for past experience and materials handled | | | 50% | 50% |
| Missing data for past experience and reliance on electrical power | | 50% | | 50% |
| Missing data for past experience, reliance on electrical power, and age of wharves | | 100% | | |
| Missing data for past experience, materials handled, and reliance on electrical power | | | | 100% |
| Missing data for past experience, materials handled, reliance on electrical power, and age of wharves | | | | |

## Detailed Description of Wind Sensitivity Indicators and Methodology

Ports with **past experience** incurred damage during storms may have characteristics that will make them prone to damage in the future. **Older wharves and other structures** may have been to less current engineering standards and/or be in lesser condition, making them more prone to damage.

The type of **materials handled** at a port is an important indicator of sensitivity. Some materials may be more sensitive to high winds. For example, materials that are stored unprotected outside (such as piles of coal, sand, or other materials) may be more sensitive to winds than those that can be stored in buildings or containers.

Because some ports have heavy **reliance on electrical power,** the power outages that can accompany high wind events can be especially problematic. Some ports can run modified operations without full power, whereas other have so much essential equipment that depends on electricity that operations must completely shut down.

All indicators were evaluated based on stakeholder interviews and surveys.

## C.3. Airports

The vulnerability assessment analyzed the two critical airports in the Mobile region—Mobile Regional Airport and Mobile Downtown Airport.

Highway segments were compromised of road sub-segments as well as bridge and culvert sub-segments (for simplification, subsequent references to "bridges" are also implied to include culverts). Due to differences in engineering characteristics, the nature of sensitivity of roads versus bridges, and sources of data for roads versus bridges, the analysis used distinct sets of indicators for roads and for bridges.

### Temperature

#### Overview of Temperature Sensitivity Indicators, Data Sources, and Weightings

Table 109 provides a summary of the sensitivity indicators used to evaluate temperature sensitivity for airports, how they were scored, and how they were weighted.

**Table 109: Temperature Sensitivity Indicators and Scoring Approach for Airports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Pavement rutting, shoving, or other compromised integrity | Whether runways have experienced damage in the past associated with high temperatures (e.g., expansion/contraction, discoloration) | Runways that already experience damage from temperature may experience worsening problems as the temperature increases. | **Yes/No Record of Previous Damage from Temperature**—Stakeholder interviews | 36% | No—This asset has not been damaged due to temperature in the past. | 1 |
| | | | | | Yes—This asset has been damaged due to temperature in the past. | 4 |
| | Runway surface type | Runway surface material can impact how sensitive the runways are to | **Runway Pavement Type**— | 21% | Concrete | 2 |
| | | | | | Both asphalt and concrete | 3 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | heat-related issues such as expansion/contraction, discoloration, degradation, etc. According to Mobile stakeholders, asphalt is overall more susceptible to heat-related problems than concrete, as long as there is adequate space for expansion/contraction (Hughes 2012). | Mobile Airport Authority | | Asphalt | 4 |
| | Runway condition | Assets in already poor condition may be more sensitive to weather-related damage. | **Runway Condition Rating** – FAA Airport Master Record Forms 5010-1 & 5010-2 | 21% | Excellent | 1 |
| | | | | | Good—Some cracking of the pavement. Cracks are generally spaced more than 50 feet apart. | 2 |
| | | | | | Fair—Some cracking and raveling. Cracks are generally spaced less than 50 feet apart. | 3 |
| | | | | | Poor—Widespread, open, unsealed cracks and joints. | 4 |
| Flight restrictions due to insufficient runway length | Runway length | As temperatures increase, air density decreases, meaning aircraft need longer runways or reduced payloads in order to take off. Runways that are already longer than needed are less likely to become unusable in high temperatures. | **Runway Length** —FAA Airport Master Record Forms 5010-1 & 5010-2 | 21% | Yes - Runway is long enough to function in future temperature conditions | 1 |
| | | | | | No - Runway is not long enough to function in future temperature conditions | 4 |

* Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). All other indicators weighted equally.

### Detailed Description of Temperature Sensitivity Indicators and Evaluation Methodology

The **historical performance** of runways during past periods of high temperatures was used to assess the sensitivity of airports to pavement rutting and shoving during severe heat events. Runways that have already shown sensitivity during current or past heat events are likely to be increasingly sensitive to increases in temperature in the future. Historical performance was assessed based on interviews with the Mobile Airport Authority.

The **runway surface type** was used to assess the sensitivity of runways to rutting and shoving at high temperatures. Asphalt runways are more sensitive to rutting, degradation, discoloration, and other heat-related issues than concrete runways—provided that adequate space is provided for expansion in concrete runway design. Information on the runway surface at each of the Mobile airports was collected from the Mobile Airport Authority.

The **runway condition** was used to assess the sensitivity of runways to severe heat events. Runways that are already in poor condition may be more sensitive to further degradation, discoloration, expansion/contraction, or other heat-related issues. The condition of the runways was evaluated based on condition ratings available in FAA Airport Master Record Forms (5010-1 & 5010-2) for each of the Mobile airports.

During extreme heat events, **runway length** may be a limiting factor that affects the overall payload that aircraft can carry. As temperature increases, the density of air decreases. Aircraft therefore require a longer runway to generate enough lift for takeoff. If the runway is too short, aircraft may face weight restrictions that limit the amount of cargo or passengers they can carry. Runway length was determined from FAA Airport Master Record Forms (5010-1 & 5010-2) for each of the Mobile airports and evaluated in interviews with the Mobile Airport Authority.

## Precipitation

### Overview of Precipitation Sensitivity Indicators, Data Sources, and Weightings

Table 110 provides a summary of the sensitivity indicators used to evaluate precipitation sensitivity for airports, how they were scored, and how they were weighted.

**Table 110: Precipitation Sensitivity Indicators and Scoring Approach for Airports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether the drainage system is already experiencing “blowouts” | Blowouts indicate that joints are failing and/or pipes are collapsing. A higher number of blowouts would therefore indicate a higher sensitivity to future precipitation levels. Blowouts occur when a leak, failure, or collapse in the drainage pipe begins to suck in sediment and creates a depression in the field. | **Number of Areas with Evidence of Blowouts**—Stakeholder interviews, Mobile Airport Authority | 5% | No evidence of blowouts | 1 |
| | | | | | 1-2 blowouts | 2 |
| | | | | | 3-5 blowouts | 3 |
| | | | | | More than 5 blowouts | 4 |
| | Age of drainage system | In older drainage systems, joints can fall apart over time. The older the drainage system, the more likely it is to fail during a heavy rain event. | **Year Drainage System Built—**Stakeholder interviews, Mobile Airport Authority | 5% | Up to 25 years | 1 |
| | | | | | Greater than 25 and up to 30 years | 2 |
| | | | | | Greater than 30 and up to 50 years | 3 |
| | | | | | Greater than 50 years | 4 |
| | Drainage system pipe material | Stakeholders in Mobile indicated that they have experienced more drainage problems with pipes that are made of certain materials. For example, Mobile stakeholders noted more problems with metal corrugated pipes relative to newer plastic or concrete pipes. This difference in performance may be related to age, condition, or maintenance more so than the actual materials used; however, in Mobile at least, identifying material type appears to be a good proxy for identifying drainage areas that may experience problems. | **Drainage System Pipe Material—**Stakeholder interviews, Mobile Airport Authority | 5% | Newer plastic or concrete pipes | 1 |
| | | | | | Older terracotta or corrugated metal pipes | 4 |
| | Whether the | If an airport is located within the 100- | **Percent of Asset in FEMA** | 9% | Not located in flood zone | 1 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | airport is located in the FEMA 100-year flood zone | year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | | Up to one-third of segment located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of segment located in flood zone | 3 |
| | | | | | Greater than 2/3 of segment located in flood zone | 4 |
| | Whether the airport is located in the FEMA 500-year flood zone | If an airport is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs | 6% | Not located in flood zone | 1 |
| | | | | | Up to one-third of segment located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of segment located in flood zone | 3 |
| | | | | | Greater than 2/3 of segment located in flood zone | 4 |
| | Airport's elevation relative to surrounding areas | If an airport is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the road (elevation data from 3 ft. x 3 ft. LiDAR) | 7% | Ponding score** up to 42 | 1 |
| | | | | | Ponding score greater than 42 and up to 84 | 2 |
| | | | | | Ponding score greater than 84 and up to 126 | 3 |
| | | | | | Ponding score greater than 126 | 4 |
| | Amount of impervious surface at the airport | Airports with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation | **Percent of Asset with Above Average Impermeability**—USGS National Land Cover Database 2006 Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) | 7% | Up to 25% of asset with above average impermeability | 1 |
| | | | | | Greater than 25% and up to 50% of asset with above average impermeability | 2 |
| | | | | | Greater than 50% and up to 75% of asset with above average impermeability | 3 |
| | | | | | Greater than 75% and up to 100% of asset with above | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | | | | average impermeability | |
| Damage to runways from flooding | Runway condition | Assets in already poor condition may be more sensitive to weather-related damage. | **Runway Condition Rating**—FAA Airport Master Record Forms 5010-1 & 5010-2 | 7% | Excellent | 1 |
| | | | | | Good -- Some cracking of the pavement. Cracks are generally spaced more than 50 feet apart. | 2 |
| | | | | | Fair -- Some cracking and raveling. Cracks are generally spaced less than 50 feet apart. | 3 |
| | | | | | Poor -- Widespread, open, unsealed cracks and joints. | 4 |
| | Soil type | Some soil types may be more susceptible to movement or sliding (e.g., mud or fill is more susceptible to movement than sand"). Therefore, infrastructure built on these more susceptible soil types are more likely to be damaged during rain events. | **Soil Type**—Stakeholder interviews, Mobile Airport Authority | 14% | Sand (relatively less susceptible to movement/sliding) | 1 |
| | | | | | Mix of sand, mud, or fill | 2.5 |
| | | | | | Fill (relatively more susceptible to movement/sliding) | 4 |
| | | | | | Mud (relatively more susceptible to movement/sliding) | 4 |
| Inability to operate flights during rain events | Whether approach lights can function under water | LED lights can operate while underwater, but older incandescent lights cannot and would be more sensitive to precipitation changes. Note: LEDs have not been approved for runways by FAA, but can be used on taxiways. | **Lighting Used**—Stakeholder interviews, Mobile Airport Authority | 7% | 100% LED on taxiways | 1 |
| | | | | | Partial LED on taxiways | 2.5 |
| | | | | | 100% incandescent | 4 |
| | Type of instrumentatio n landing system | Some types of instrument landing systems allow for landings in low visibility and poor weather conditions, which reduces the sensitivity of airport operations to bad weather. | **Instrumentation**—FAA Airport Master Record Forms 5010-1 & 5010-2 | 7% | Instrument approach procedure utilizing an instrument landing system (ILS) or a Precision Approach Radar (PAR). | 1 |
| | | | | | Instrument approach with only horizontal guidance or area type navigation equipment and has a | 3 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | | | | straight-in type of non-precision instrument approach procedure including radar approaches. | |
| | | | | | A runway using visual approach procedures, with no straight-in instrument approach procedures and no instrument designation. | 4 |
| | Whether runway surface is treated | Runways that have been treated to be grooved are better able to handle surface water and precipitation than runways without a surface treatment. | **Runway Surface Treatment**—FAA Airport Master Record Forms 5010-1 & 5010-2 | 7% | Grooved | 1 |
| | | | | | None | 4 |
| | Airport traffic levels | This indicator relates to the operational sensitivity of airports. Airports with higher levels of traffic would experience greater operational impacts (more passengers affected and cause larger “network” effects) precipitation changes cause increases in weather-related delays. | **Total Operations**—FAA Airport Master Record Forms 5010-1 & 5010-2 | 14% | Up to 100,000 movements | 1 |
| | | | | | Greater than 100,000 and up to 250,000 movements | 2 |
| | | | | | Greater than 250,000 and up to 500,000 movements | 3 |
| | | | | | Greater than 500,000 movements | 4 |

* Weighting rationale: Weight divided equally between seven groups of indicators at 14.3% each—drainage system quality (including evidence of blowouts, age of drainage system, and pipe materials), flood zone (100-year and 500-year), run-off-related flooding (relative elevation and impervious surface), soil type, airport traffic levels, runway ability to function in wet conditions (runway condition and surface treatment), and ability to land plans in wet conditions (approach lights and instrumentation type). Within the flood zone group, 60% of weight comes from 100-year flood zone and 40% comes from 500-year flood zone because all assets in the 100-year flood zone are also in the 500-year flood zone. All other indicators weighted equally within their group.

** Ponding score refers to number of grid cells that flow into the cells covered by the asset.

## Detailed Description of Precipitation Sensitivity Indicators and Methodology

The sensitivity of airports to flooding from an increased frequency of heavy downpours was assessed based on seven indicators. One indicator was **past experience**, or specifically the number of blowouts that have been experienced at a particular airfield. Blowouts are holes or depressions that are created when sediment enters the drainage system, which is buried underneath the airfield, through leaks or failures in the joints and drainage pipes. Blowouts indicate a compromised drainage system that may not perform adequately during severe downpours, increasing the sensitivity of airfield operations to flooding. The number of blowouts was assessed based on interviews with the Mobile Airport Authority.

The **age of the drainage system** was also used to assess sensitivity to flooding. Older drainage systems are more likely to have leaks, blockages, or failures in joints or piping that reduce their performance. An older drainage system, therefore, may indicate that an airfield will be more sensitive to flooding issues during extreme downpours. The age of the drainage system at each of the Mobile area airfields was determined from interviews with the Mobile Airport Authority.

The **drainage pipe material** was also used as an indicator of sensitivity to flooding. Stakeholders in Mobile indicated that they have experienced more drainage problems with pipes that are made of certain materials. For example, Mobile stakeholders noted more drainage issues associated with metal corrugated pipes than with newer plastic or concrete pipes. This difference in performance may be related to age, condition, or maintenance more so than the actual materials used; however, in Mobile at least, identifying material type appears to be a good proxy for identifying drainage areas that may experience problems. The drainage system material at each airfield was determined based on interviews with the Mobile Airport Authority.

Three spatial analyses were used to evaluate propensity for flooding. The **location of assets within flood zones** was analyzed using flood information from FEMA's National Flood Insurance Program (NFIP) to spatially represent the 100-year and 500-year flood scenarios. The **propensity for an asset to flood based on surrounding topography** was also analyzed using GIS. This analysis captures the change in elevation between an asset and its surrounding area. It is therefore an indicator of an asset's susceptibility for collecting runoff during and after a precipitation event. Another indicator assessed the amount of **impervious surface** within the perimeter of the airport. Highly impermeable areas may be more likely to accumulate water during a precipitation event. These three indicators were evaluated using the same approach as described for these indicators starting on page 249, under the Highways precipitation section. The only difference was that rather than use linear segments to represent the airports—as done for highways—each airport was delineated about its perimeter to form a polygon.

The sensitivity of runways to damage from flooding was also used to evaluate the overall sensitivity of airports to precipitation impacts. The runway **soil type** was used as an indicator of this impact: runways built on fill or muddy soils may be more sensitive to soil movement or sliding during heavy downpours than runways built on sandy soils. The general soil type at each of the Mobile-area airfields (sand, fill, mud, or some combination) was determined based on interviews with the Mobile Airport Authority.

Heavy rain can impact airfield operations by reducing visibility for take-offs and landings of aircraft. Five indicators were used to evaluate this impact. **Whether taxiway lighting systems can operate under water** was considered: LED lights can operate underwater while older incandescent lights cannot. The lighting system at each airfield was determined from interviews with the Mobile Airport Authority.

The **type of instrument landing system** was also used as an indicator. ILS or PAR systems enable aircraft to land in low-visibility and poor weather conditions where pilots would not have sufficient visibility to land using other systems or visual approach procedures. The instrumentation at each runway was available from FAA Airport Master Record Forms 5010-1 & 5010-2.

The **surface treatment** of each runway was evaluated in assessing precipitation impacts on airfield operations. Grooved runways channel runway surface water and enable better contact at takeoff and landings, and may therefore be less sensitivity to delays during rain events than runways that have not been treated. Runway surface treatments were available from FAA Airport Master Record Forms 5010-1 & 5010-2 for each airfield.

The **runway condition** was used as an indicator of the sensitivity of airfield operations to precipitation impacts. Runways that are already in poor condition may be more sensitive to weather-related damage and poorer performance during rain events. Runway condition was available from FAA Airport Master Record Forms 5010-1 & 5010-2 for each airfield.

The final indicator used to assess the sensitivity of airfield operations to precipitation impacts was **airport traffic levels**. Busy airports with a large number of annual movements (i.e., take-offs and landings) are more likely to be affected by delays from rainfall events than less-congested airports. Delays at heavily-congested airports may also cause delays or cancellations in other flights, leading to larger impacts. The number of annual movements was determined from FAA Airport Master Record Forms 5010-1 & 5010-2 for each airfield.

## Sea Level Rise

### Overview of Sea Level Rise Sensitivity Indicators, Data Sources, and Weightings

Table 111 provides a summary of the sensitivity indicators used to evaluate sea level rise sensitivity for airports, how they were scored, and how they were weighted.

**Table 111: Sea Level Rise Sensitivity Indicators and Scoring Approach for Airports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to tidal events | Airports that have experienced flooding during extreme high tide events in the past are likely to be some of the first roads impacted by sea level rise. | **Yes/No Record of Previous Flooding from Tides**— Stakeholder interviews, Mobile Airport Authority | 43% | N—This asset has never been exposed to coastal flooding (tidal) | 1 |
| | | | | | Y—This asset has been exposed to coastal flooding events | 4 |
| | Height of drainage system discharge point above sea level | If drainage system discharge point is below projected sea level rise, airport would be affected. | **Drainage System Discharge Elevation**— Stakeholder interviews, Mobile Airport Authority | 28% | Height of drainage discharge is lower than projected sea level rise for the area | 1 |
| | | | | | Height of drainage discharge is higher than projected sea level rise for the area | 4 |
| | Whether the drainage system is already experiencing "blowouts" | Blowouts indicate that joints are failing and/or pipes are collapsing. A higher number of blowouts would therefore indicate a higher sensitivity to future precipitation levels, exacerbated by SLR. Blowouts occur when a leak, failure, or collapse in the drainage pipe begins to suck in sediment and creates a depression in the field. | **Number of Areas with Evidence of Blowouts**— Stakeholder interviews, Mobile Airport Authority | 9% | No evidence of blowouts | 1 |
| | | | | | 1-2 blowouts | 2 |
| | | | | | 3-5 blowouts | 3 |
| | | | | | More than 5 blowouts | 4 |
| | Age of drainage system | In older drainage systems, joints can fall apart over time. The older the drainage system, the more likely it is to fail during a flooding event. | **Year Drainage System Built—** Stakeholder interviews, Mobile Airport Authority | 9% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 30 years old | 2 |
| | | | | | Greater than 30 and up to 50 years old | 3 |
| | | | | | Greater than 50 years old | 4 |
| | Drainage system pipe material | Stakeholders in Mobile indicated that they have experienced more drainage | **Drainage System Pipe Material—** | 9% | Newer plastic or concrete pipes | 1 |
| | | | | | Older terracotta or corrugated metal | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | problems with pipes that are made of certain materials. For example, Mobile stakeholders noted more problems with metal corrugated pipes relative to newer plastic or concrete pipes. This difference in performance may be related to age, condition, or maintenance more so than the actual materials used; however, in Mobile at least, identifying material type appears to be a good proxy for identifying drainage areas that may experience problems. | Stakeholder interviews, Mobile Airport Authority | | pipes | |

* Weighting rationale: Weight initially divided into three indicator groups: past experience, drainage discharge height, and drainage system indicators (evidence of blowouts, age of system, and pipe material). Past experience was weighted 15 percentage points higher than the other two indicator groups (per stakeholder input). Within the drainage system group (weighted at 28%), each indicator was weighted equally, receiving 9% of the overall weight.

## Detailed Description of Sea Level Rise Sensitivity Indicators and Methodology

Five indicators were used to assess the sensitivity of airport assets to sea level rise. The **historical performance** of airfields exposed to current tidal variation was considered, as airfields that experience issues with current tides are likely to experience greater impacts under future sea level rise scenarios. Information on the historical performance of the Mobile Downtown Airport was gathered from interviews with the Mobile Airport Authority. The Mobile Regional Airport is inland and not exposed to tidal effects.

The **height of drainage discharge** was also assessed as an indicator for sensitivity to sea level rise impacts. Airfields that discharge drainage water into the ocean may have difficulty draining rainwater if the height of the discharge point is below projected sea level rise. The height of the point of drainage was evaluated against sea level rise scenarios based on information provided on each airport by the Mobile Airport Authority.

In addition to the two indicators described above, the **drainage system pipe material**, **evidence of "blowouts"**, and **age of drainage system** were also used to assess sensitivity to sea level rise impacts. These indicators are described in more detail on page 287. They were applied to evaluate sea level rise sensitivity because they relate to the effectiveness of the drainage system and to an airport's sensitivity to permanent or temporary inundation from sea level rise, if it occurs. As explained previously, these indicators were evaluated based on interviews with the Mobile Airport Authority.

## Storm Surge

### Overview of Storm Surge Sensitivity Indicators, Data Sources, and Weightings

Table 112 provides a summary of the sensitivity indicators used to evaluate storm surge sensitivity for airports, how they were scored, and how they were weighted.

**Table 112: Storm Surge Sensitivity Indicators and Scoring Approach for Airports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Structural damage due to storm surge | Whether an asset has been damaged in the past due to storm surge | Airports that have experienced damage during past storm events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews, Mobile Airport Authority | 32% | N - This asset has never been damaged due to storm surge | 1 |
| | | | | | Y - This asset has been damaged due to storm surge | 4 |
| | Building foundation type | Some foundation types are more likely to withstand storm surge than others. For example, pilings are the strongest foundation type while footers are less strong. | **Foundation Type**—Stakeholder interviews, Mobile Airport Authority | 17% | Pilings (stronger foundation type) | 1 |
| | | | | | Footers (weaker foundation type) | 4 |
| | Soil type | Some soil types may be more susceptible to movement or sliding (e.g., mud or fill is | **Soil Type**—Stakeholder interviews, Mobile | 17% | Sand (relatively less susceptible to movement/sliding) | 1 |
| | | | | | Mix of sand, mud, or fill | 2.5 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | more susceptible to movement than sand"). Therefore, infrastructure built on these more susceptible soil types are more likely to be damaged during storm surge. | Airport Authority | | Fill (relatively more susceptible to movement/sliding) | 4 |
| | | | | | Mud (relatively more susceptible to movement/sliding) | 4 |
| | Whether approach lights can function under water | LED lights can operate while underwater, but older incandescent lights cannot and would be more sensitive to precipitation changes.<br>Note: LEDs have not been approved for runways by FAA, but can be used on taxiways. | **Lighting Used**—Stakeholder interviews, Mobile Airport Authority | 17% | 100% LED on taxiways | 1 |
| | | | | | Partial LED on taxiways | 2.5 |
| | | | | | 100% incandescent | 4 |
| Flooding | Whether the drainage system is already experiencing "blowouts" | Blowouts indicate that joints are failing and/or pipes are collapsing. A higher number of blowouts would therefore indicate a higher sensitivity to flooding. Blowouts occur when a leak, failure, or collapse in the drainage pipe begins to suck in sediment and creates a depression in the field. | **Number of Areas with Evidence of Blowouts**—Stakeholder interviews, Mobile Airport Authority | 6% | No evidence of blowouts | 1 |
| | | | | | 1-2 blowouts | 2 |
| | | | | | 3-5 blowouts | 3 |
| | | | | | More than 5 blowouts | 4 |
| | Age of drainage system | In older drainage systems, joints can fall apart over time. The older the drainage system, the more likely it is to fail during a flooding event. | **Year Drainage System Built**—Stakeholder interviews, Mobile Airport Authority | 6% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 30 years old | 2 |
| | | | | | Greater than 30 and up to 50 years old | 3 |
| | | | | | Greater than 50 years old | 4 |
| | Drainage | Stakeholders in Mobile | **Drainage System Pipe** | 6% | Newer plastic or concrete pipes | 1 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | system pipe material | indicated that they have experienced more drainage problems with pipes that are made of certain materials. For example, Mobile stakeholders noted more problems with metal corrugated pipes relative to newer plastic or concrete pipes. This difference in performance may be related to age, condition, or maintenance more so than the actual materials used; however, in Mobile at least, identifying material type appears to be a good proxy for identifying drainage areas that may experience problems. | **Material—** Stakeholder interviews, Mobile Airport Authority | | Older terracotta or corrugated metal pipes | 4 |

* Weighting rationale: Drainage system indicators (evidence of blowouts, age of system, and pipe material) grouped together as one indicator for weighting purposes as not to weight drainage issues more highly than other indicators with fewer supporting data points, resulting in five indicator groups. Past experience weighted 15 points higher than the other four indicators, receiving 32% of the total weight while all others received 17%. Within the drainage system group, each indicator was weighted equally, receiving 6% of the overall weight.

## Detailed Description of Storm Surge Sensitivity Indicators and Methodology

The sensitivity of airport assets to structural damage from storm surge impacts was assessed based on four indicators. The **historical performance** of the asset to past storm surges is one indicator that was considered, since airport assets that have been damaged by past storm surge events are more likely to be damaged if exposed to future storm surges. This indicator was evaluated based on information provided by the Mobile Airport Authority on past impacts that have been experienced at the Mobile Downtown Airport. The Mobile Regional Airport is inland and not exposed to storm surge.

The **foundation type** of buildings was also considered as an indicator of sensitivity to storm surge. Buildings that are built on footers are more susceptible to movement or damage if exposed to storm surge forces. Buildings with piling foundations are stronger and are more likely to withstand storm surge impacts. The foundation type was assessed for buildings at each airfield based on interviews with the Mobile Airport Authority.

The **soil type** was used to evaluate sensitivity to storm surge. Muddy or fill soils are more susceptible to movement than sandy soils. The soil type of each airfield was determined from interviews with the Mobile Airport Authority.

**Whether airport lighting systems can function under water** was also considered as an indicator. LED lighting can operate when exposed to water, while incandescent systems cannot. Information on the lighting systems in place at each airfield was gathered from interviews with the Mobile Airport Authority.

In addition to the four indicators described above, the **drainage system pipe material**, **evidence of "blowouts"**, and **age of drainage system** were also used to assess sensitivity to storm surge. These indicators are described in more detail on page 287. They were applied to evaluate storm surge sensitivity because they relate to the effectiveness of the drainage system and to an airport's sensitivity to flooding from storm surge. As explained previously, these indicators were evaluated based on interviews with the Mobile Airport Authority.

## Wind

### Overview of Wind Sensitivity Indicators, Data Sources, and Weightings

Table 113 provides a summary of the sensitivity indicators used to evaluate wind sensitivity for highways, how they were scored, and how they were weighted.

**Table 113: Wind Sensitivity Indicators and Scoring Approach for Airports**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Structural damage to airport buildings due to high | Whether an asset has been damaged in the past due | Airports that have experienced wind damage during past hurricanes are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Wind**—Stakeholder interviews, Mobile Airport Authority | 5% | No—This asset has never been damaged due to wind | 1 |
| | | | | | Yes—This asset has been damaged due to wind | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| winds | to high winds | | | | | |
| | Age of buildings | Older buildings are more likely to be built to lower design standards than newer buildings, and therefore more sensitive to damage from wind and other weather. | **Year Built**—Stakeholder interviews, Mobile Airport Authority | 19% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 30 years old | 2 |
| | | | | | Greater than 30 and up to 50 years old | 3 |
| | | | | | Greater than 50 years old | 4 |
| | Building material | Some building materials may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that metal and wood buildings are more sensitive to wind than masonry. | **Building Material(s)****—Stakeholder interviews, Mobile Airport Authority | 19% | Masonry | 1 |
| | | | | | Metal | 4 |
| | | | | | Wood | 4 |
| | Roof type | Some roof types may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that flat roofs are more sensitive to wind than pitched roofs. | **Roof Type**—Stakeholder interviews, Mobile Airport Authority | 19% | Pitched roof | 1 |
| | | | | | Flat roof | 4 |
| | Height of buildings | Taller buildings are more sensitive to high winds than shorter ones. | **Height of Air Traffic Control Tower**<br>**Height of Hangars**<br>**Height of Terminals**<br>—Stakeholder interviews, Mobile Airport Authority | 19% | Single-story building (15-20 ft.) | 1 |
| | | | | | Low-rise building (<115 ft. or < 12 stories) | 2 |
| | | | | | High-rise building (115-330 feet or 12-40 stories) | 3 |
| | | | | | Skyscraper (>330 feet or >40 stories) | 4 |
| | Whether airport is sheltered | Buildings that are sheltered (e.g., by surrounding structures or terrain) may be less sensitive to wind. | **Yes/No Indication of Shelter**—Stakeholder interviews, Mobile | 19% | Yes—The buildings are sheltered from wind by surrounding structures or terrain | 1 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | from wind | | Airport Authority | | No—The buildings are not sheltered from wind by surrounding structures or terrain | 4 |

* Weighting rationale: Past experience weighted *lower* than other indicators because stakeholders said that after buildings/roofs at the Mobile airports were damaged due to wind, they were replaced with better, more resilient construction. All other indicators were weighted equally. Within building height, the total weight was distributed equally among the number of buildings rated. For example, Mobile Regional Airport had information on heights of the air traffic control tower, hangars, and terminals. Each type of building was scored and then the scores were averaged to get the airport's overall score for building height.
**Building material score for each airport was calculated as a weighted average based on the material types. For example, if airport facilities were constructed of about 75% masonry and 25% wood, its score for "building material" would be $0.75 \times 1 + 0.25 \times 4 = 1.75$.

## Detailed Description of Wind Sensitivity Indicators and Methodology

The sensitivity of airport assets to wind impacts was evaluated based on six indicators. The **historical performance** of buildings to high winds in the past was considered, as buildings and equipment that have been damaged by winds in the past may be more likely to be damaged if exposed to high winds in the future. Information on damage from previous high wind events was gathered from interviews with the Mobile Airport Authority.

The **age of buildings** was also considered as an indicator of sensitivity to wind. Older buildings are likely built to older, less-stringent standards than newer buildings and therefore may be more sensitive to wind damage than new construction. The age of buildings at each airfield was determined based on interviews with the Mobile Airport Authority.

The **building material** and **roof type** were both used as indicators of wind sensitivity. According to Mobile stakeholders, metal and wood buildings tend to be more sensitive to wind impacts than masonry construction. Similarly, flat roofs tend to be more sensitive to damage from wind than pitched roofs. Information on the building materials and roof type for buildings at each airfield were determined from interviews with the Mobile Airport Authority.

The **height of buildings** was used to assess sensitivity to wind impacts. Taller buildings are exposed to higher wind speeds and are therefore more likely to experience damage than shorter buildings, where wind speeds are lower. The height of the air traffic control town, hangars, and terminal buildings at each airfield was determined from interviews and data provided by the Mobile Airport Authority.

The level of **shelter from the wind** at each airfield was also considered as an indicator of sensitivity to wind. Buildings that are sheltered by surrounding structures, terrain, or other features may be less sensitive to wind impacts than other buildings that are in open areas. The level of shelter was determined qualitatively based on interviews with the Mobile Airport Authority based on their experience at each airfield.

## C.4. Rail

The four rail assets evaluated in this vulnerability assessment included three rail lines and one rail yard. However, the same indicators were used for all four assets.

### Temperature

#### Overview of Temperature Sensitivity Indicators, Data Sources, and Weightings

Table 114 and Table 115 provide a summary of the indicators used to assess sensitivity to temperature, how they were scored, and how they were weighted.

**Table 114: Temperature Sensitivity Indicators and Scoring Approach for Rail Assets**

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Rail kinking or buckling | Whether asset has experienced damage in the past associated with high temperatures | Rail assets that have experienced damage during extreme temperatures in the past may be sensitive to higher or more frequent periods of extreme temperatures in the future. | **Yes/No Record of Previous Damage from Temperature** –Interviews with Mobile rail owners and operators | 43% | No—This asset has never been damaged due to temperature in the past | 1 |
| | | | | | Yes—This asset has been damaged due to temperature in the past | 4 |
| | Type of rail design | Some types of rail, such as continuously-welded rail, are more prone to buckling. | **Rail Design** – Interviews with Mobile rail owners and operators | 28% | Jointed rail | 1 |
| | | | | | Continuously-welded rail (CWR) | 4 |

| Climate Change Impact | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | Maintenance frequency | Assets that are frequently monitored and maintained by running tampers along the lines are more likely to have stable ballast that is less sensitive to buckling during periods of extreme temperatures. | **Maintenance Frequency** – Interviews with Mobile rail owners and operators | 28% | N/A—No information was available for this indicator, so no scoring approach was developed | N/A |

* Weighting rationale: Past experience weighted slightly higher than other indicators based on stakeholder input.

**Table 115: Alternate Temperature Sensitivity Indicator Weighting for Rail Assets without Information for All Indicators**

| Data Scenario | Past Experience | Rail Design | Maintenance Frequency |
|---|---|---|---|
| No missing data | 43% | 28% | 28% |
| Missing data for maintenance frequency | 60% | 40% | |

## Detailed Description of Temperature Sensitivity Indicators and Evaluation Methodology

This assessment considered the **past experience** of rail assets during heat events. Two rail lines (both segments on McDuffie Island, where the coal dust can contribute to degrading certain parts of the rail infrastructure) had experienced kinking in the past and were scored a 4; the other rail line and rail yard both received a 1. Past experience was weighted slightly more heavily than the other indicators based on stakeholder input.

**Type of rail design** was selected as an indicator because certain designs are more prone to heat-induced buckling than others. The two types considered here are jointed design and continuously welded rail. Of the two, continuously-welded rail is more susceptible to buckling and is scored a 4, while jointed design is scored a 1. However, all four assets evaluated feature jointed design, so all scored a 1.

Lastly, **maintenance frequency** was considered as the third indicator of rail sensitivity to temperature because tracks that are frequently maintained by running tampers along the lines are more likely to have stable ballast that is less sensitive to buckling during periods of extreme temperatures. However, no information was available on maintenance frequency from stakeholder interviews or other sources for any of the assets evaluated, so it was effectively not included as an indicator.

## Precipitation

### Overview of Precipitation Sensitivity Indicators, Data Sources, and Weightings

Table 116 and Table 117 provide a summary of the indicators used to assess sensitivity to precipitation, how they were scored, and how they were weighted.

**Table 116: Precipitation Sensitivity Indicators and Scoring Approach for Rail Assets**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | 6% | Not located in flood zone | 1 |
| | | | | | Up to one-third of segment located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of segment located in flood zone | 3 |
| | | | | | Greater than 2/3 of segment located in flood zone | 4 |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Percent of Asset in FEMA 500-year Flood Zone**—FEMA DFIRMs | 4% | Not located in flood zone | 1 |
| | | | | | Up to one-third of segment located in flood zone | 2 |
| | | | | | Greater than 1/3 and up to 2/3 of segment located in flood zone | 3 |
| | | | | | Greater than 2/3 of segment located in flood zone | 4 |
| | Asset's elevation | If an asset is located at a | **Median Number of** | 5% | Ponding score** up to 42 | 1 |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | relative to surrounding areas | relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events. | **Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the rail (elevation data from 3 ft. x 3 ft. LiDAR) | | Ponding score greater than 42 and up to 84 | 2 |
| | | | | | Ponding score greater than 84 and up to 126 | 3 |
| | | | | | Ponding score greater than 126 | 4 |
| | Amount of impervious surface surrounding an asset | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from precipitation. | **Percent of Area Surrounding Asset with Above Average Impermeability**—USGS National Land Cover Database 2006 Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) | 5% | Up to 25% of asset with above average impermeability | 1 |
| | | | | | Greater than 25% and up to 50% of asset with above average impermeability | 2 |
| | | | | | Greater than 50% and up to 75% of asset with above average impermeability | 3 |
| | | | | | Greater than 75% and up to 100% of asset with above average impermeability | 4 |
| | Whether track is undercut | Track that crosses underneath major overpasses may have been undercut in order to accommodate larger, double-stacked trains. These areas may be more sensitive to impacts from flooding. | **Yes/No Indication of Whether Track Passes Below Overpass**—Project team analysis of satellite imagery | 11% | No—Track does not pass under overpasses (is not likely undercut) | 1 |
| | | | | | Yes—Track passes under overpasses (is likely undercut) | 4 |
| | Whether drainage system has experienced | Rail assets that have experienced drainage system performance issues | **Yes/No Record of Previous Drainage Issues**—Interviews with | 26% | No—This asset has never had drainage or access issues during precipitation events | 1 |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | issues in the past | are more likely to experience flooding or drainage issues from heavy rainfall events. | Mobile rail owners and operators | | Yes—This asset has experienced drainage or access issues during precipitation events | 4 |
| Track washouts | Ballast type | Certain types of ballast anchor the track more firmly than others and may be less sensitive to washouts from heavy rainfall. | **Ballast Type Used**—Interviews with Mobile rail owners and operators | 11% | Granite | 1 |
| | | | | | Limestone | 4 |
| | Maintenance frequency | Tracks that are frequently monitored and maintained by running tampers along the lines are more likely to have stable ballast that can withstand impacts from flooding. | **Maintenance Frequency** –Interviews with Mobile rail owners and operators | 11% | N/A—No information was available for this indicator, so no scoring approach was developed | N/A |
| | Soil type | Rail that is on soil that is susceptible to erosion or flooding (e.g., in low-lying, marsh areas or areas with fill) may be more sensitive to washouts. | **Soil Type** –Interviews with Mobile rail owners and operators | 11% | N/A—No information was available for this indicator, so no scoring approach was developed | N/A |
| Signal Failure | Whether asset has electric signals | Electric signals may be damaged by exposure to water from flooding during heavy rainfalls. | **Yes/No Record of Electric Signals**—Interviews with Mobile rail owners and operators | 11% | No—This asset does not have electric signals | 1 |
| | | | | | Yes—This asset does have electric signals | 4 |

*Weighting rationale: Past experience (with drainage issues) weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining seven indicators, where both flood zone indicators are grouped together and both indicators related to run-off are grouped together (ponding and impervious surface). Within flood zone indicator, 60% of weight comes from 100-year flood zone and 40% comes from 500-year flood zone because all assets in the 100-year flood zone are also in the 500-year flood zone.

** Ponding score refers to number of grid cells that flow into the cells covered by the asset.

**Table 117: Alternate Precipitation Sensitivity Indicator Weighting for Rail Assets without Information for All Indicators**

| Data Scenario | Past Experience | 100-year Flood Zone | 500-year Flood Zone | Ponding | Impervious Surface | Undercut Track | Ballast Type | Maintenance Frequency | Soil Type | Electric Signals |
|---|---|---|---|---|---|---|---|---|---|---|
| No missing data | 36% | 6% | 4% | 5% | 5% | 11% | 11% | 11% | 11% | 11% |
| Missing data for maintenance frequency and soil type | 33% | 8% | 5% | 7% | 7% | 13% | 13% | | | 13% |

## Detailed Description of Precipitation Sensitivity Indicators and Evaluation Methodology

This assessment considered ten different indicators to evaluate which rail assets are sensitive to precipitation. One indicator was **past experience of the drainage system**, which indicates whether drainage system issues have caused flooding or other damage during heavy rain in the past. The drainage system at TASD rail yards has struggled with precipitation in the past and therefore was scored a 4, but the other three assets were rated a 1.

**Whether the track is undercut** is another indicator of flood propensity. Stakeholders in Mobile mentioned that track that passes beneath overpasses may have been lowered—or undercut—to allow room for taller trains to pass. Undercut track is more likely to flood, since it is lower than surrounding areas. The study team analyzed satellite imagery of the rail assets to determine whether they went beneath an overpass and thus are likely undercut. None of the rail assets studied passed under overpasses or is otherwise noted as undercut.

The **location of assets within flood zones** was analyzed using flood information from FEMA’s National Flood Insurance Program (NFIP) to spatially represent the 100-year and 500-year flood scenarios. The same approach was used for all modes. See the discussion of methodology for the highways section on page 249 for a description of the approach.

The **propensity for an asset to flood based on surrounding topography** was also analyzed using GIS. This analysis captures the change in elevation between an asset and its surrounding area. It is therefore an indicator of an asset’s susceptibility for collecting runoff during and after a precipitation event. The same approach was used for all modes. See the discussion of methodology for the highways section on page 250 for a description of the approach.

Another indicator assessed the amount of **impervious surface** in the area immediately surrounding the asset. Highly impermeable areas may be more likely to accumulate water during a precipitation event. The same approach was used for all modes. See the discussion of methodology under the highways section on page 251 for a description of the approach.

**Ballast type** was an indicator used to judge how susceptible rail assets are to track washout. According to stakeholders, limestone ballast is more susceptible than granite. All four assets studied use limestone, and thus scored a 4 for ballast type.

**Maintenance frequency** and **soil type** were also considered as indicators of precipitation sensitivity. However, no information was available about these indicators for the selected assets from stakeholder interviews or other sources. They were therefore effectively not included as indicators.

Finally, the presence of **electric signals** was included because heavy rainfall can lead to power failures. Assets without electric signals are thus less sensitive than assets with electric signals. Information on the presence of electric signals was gathered from interviews with stakeholders in Mobile.

## Sea Level Rise

### Overview of Sea Level Rise Sensitivity Indicators, Data Sources, and Weightings

Table 118 provides a summary of the indicators used to assess sensitivity to sea level rise, how they were scored, and how they were weighted. Because the four assets had data available for all three indicators, no alternate weighting systems were required.

**Table 118: Sea Level Rise Sensitivity Indicators and Scoring Approach for Rail Assets**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to tidal events | Rail assets that have experienced flooding during extreme high tide events in the past are likely to be some of the first rail assets impacted by sea level rise. | **Yes/No Record of Previous Flooding from Tides**—Interviews with Mobile rail owners and operators | 43% | No—This asset has never been damaged due to sea level rise in the past | 1 |
| | | | | | Yes—This asset has been damaged due to sea level rise in the past | 4 |
| | Whether drainage system has experienced issues in the past | Rail assets that have experienced drainage system performance issues are more likely to experience flooding or drainage issues from sea level rise. | **Yes/No Record of Previous Drainage Issues**—Interviews with Mobile rail owners and operators | 28% | No—This asset has never had drainage or access issues in the past | 1 |
| | | | | | Yes—This asset has had drainage or access issues in the past | 4 |
| | Whether rail is elevated | Assets that are elevated above ground level may be shielded from exposure to storm surge. | **Yes/No Record of Asset Elevation**—Interviews with Mobile rail owners and operators | 28% | Yes—Asset is protected or elevated | 1 |
| | | | | | No—Asset is not protected or elevated | 4 |

*Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining two indicators.

## Detailed Description of Sea Level Rise Sensitivity Indicators and Evaluation Methodology

Assets that have experienced damage due to high tide events in the past are likely to be affected by sea level rise, so **past experience** was the most heavily weighted indicator. Information on past performance was gathered through interviews with stakeholders in Mobile, and the TASD rail yards were the only asset to have been affected by previous tidal events.

**Drainage system performance** indicates whether the asset's drainage system has been inadequate or caused flooding in the past. Though in the past this flooding has related to heavy precipitation, assets with inadequate drainage under current conditions are also likely to be more stressed and sensitive to damage with sea level rise.

**Asset elevation** is the final indicator for rail sea level rise sensitivity. Information about the specific elevation of each asset was not available, but stakeholders indicated whether each rail was on a raised track bed and thus elevated from potential inundation from sea level rise. None of the assets are elevated or otherwise protected from sea level rise, so all scored a 4 for this indicator.

## Storm Surge

### Overview of Storm Surge Sensitivity Indicators, Data Sources, and Weightings

Table 119 and Table 115 provide a summary of the indicators used to assess sensitivity to storm surge, how they were scored, and how they were weighted.

**Table 119: Storm Surge Sensitivity Indicators and Scoring Approach for Rail Assets**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to storm surge | Rail assets that have experienced flooding during storm events in the past are likely to flood during future storm events. | **Yes/No Record of Previous Flooding from Storm Surge—** Interviews with Mobile rail owners and operators | 27% | No—This asset has never been damaged due to storm surge in the past | 1 |
| | | | | | Yes—This asset has been damaged due to storm surge in the past | 4 |
| | Whether asset is protected or elevated from storm surge | Assets that are protected by seawalls, dikes, or that are otherwise elevated above ground level may be shielded from exposure to storm surge. | **Yes/No Record of Protection—** Interviews with Mobile rail owners and operators | 12% | Yes—Asset is protected or elevated | 1 |
| | | | | | No—Asset is not protected or elevated | 4 |
| | Whether track is undercut | Track that crosses underneath major overpasses may have | **Yes/No Indication of Whether Track Passes** | 12% | No—Track does not pass under overpasses (is not likely undercut) | 1 |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | been undercut in order to accommodate larger, double-stacked trains. These areas may be more sensitive to impacts from flooding. | **Below Overpass**—Project team analysis of satellite imagery | | Yes—Track passes under overpasses (is likely undercut) | 4 |
| | Whether drainage system has experienced issues in the past | Rail assets that have experienced drainage system performance issues are more likely to experience flooding or drainage issues from heavy rainfall events. | **Yes/No Record of Previous Drainage Issues**—Interviews with Mobile rail owners and operators | 12% | No—This asset has never had drainage or access issues in the past | 1 |
| | | | | | Yes—This asset has had drainage or access issues in the past | 4 |
| Track washouts | Ballast type | Certain types of ballast anchor the track more firmly than others and may be less sensitive to washouts from storm surge. | **Ballast Type Used**—Interviews with Mobile rail owners and operators | 12% | Granite | 1 |
| | | | | | Limestone | 4 |
| | Soil type | Rail that is on soil that is susceptible to erosion or flooding (e.g., in low-lying, marsh areas or areas with fill) may be more sensitive to washouts. | **Soil Type** –Interviews with Mobile rail owners and operators | 12% | No—soil is not susceptible to erosion | 1 |
| | | | | | Yes—soil is susceptible to erosion | 4 |
| Signal failure | Whether rail asset has electric signals | Electric signals may be damaged by exposure to water from flooding during storm surge. | **Yes/No Record of Electric Signals**—Interviews with Mobile rail owners and operators | 12% | No—this asset does not have electric signals | 1 |
| | | | | | Yes—this asset does have electric signals | 4 |

*Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining two indicators.

**Table 120: Alternate Storm Surge Sensitivity Indicator Weighting for Rail Assets without Information for All Indicators**

| Data Scenario | Past Experience | Elevation | Undercut Track | Drainage System Performance | Ballast Type | Soil Type | Signaling |
|---|---|---|---|---|---|---|---|
| No missing data | 27% | 12% | 12% | 12% | 12% | 12% | 12% |
| Missing data for soil type | 31% | 14% | 14% | 14% | 14% | | 14% |

## Detailed Description of Storm Surge Sensitivity Indicators and Evaluation Methodology

This assessment considered seven indicators for whether rail assets would be sensitive to damage from storm surge. The first of these is the **past experience** of the rail assets during severe storms. If an asset has demonstrated that it is sensitive in the past, it is likely to be sensitive in the future.

**Asset elevation** is another indicator of storm surge sensitivity, since elevated rail lines are less likely to be overtopped by floodwaters. Information about the specific elevation of each asset was not available, but stakeholders indicated whether each rail was on a raised track bed and thus elevated from potential inundation from storm surge. None of the assets are elevated or otherwise protected from storm surge, so all scored a 4 for this indicator.

**Whether the track is undercut** is another indicator of flood propensity. Stakeholders in Mobile mentioned that track that passes beneath overpasses may have been lowered—or undercut—to allow room for taller trains to pass. Undercut track is more likely to flood, since it is lower than surrounding areas. The study team analyzed satellite imagery of the rail assets to determine whether they went beneath an overpass and thus are likely undercut. None of the rail assets studied passed under overpasses or is otherwise noted as undercut.

The **past performance of the drainage system** was another indicator considered. This indicates whether the asset's drainage system has been inadequate or caused flooding in the past. Though in the past this flooding has related to heavy precipitation, assets with inadequate drainage under current conditions are also likely to be more stressed and sensitive to damage from flooding associated with storm surge.

**Ballast type** was an indicator used to judge how susceptible rail assets are to track washout. According to stakeholders, limestone ballast is more susceptible than granite. All four assets studied use limestone, and thus scored a 4 for ballast type.

**Soil type** was also considered as indicators of storm surge sensitivity, since some soil types are more susceptible to erosion and washout than others. However, no information was available about soil type for the selected assets from stakeholder interviews or other sources. It was therefore effectively not included as an indicator.

Finally, the presence of **electric signals** was included because exposure to storm surge can lead to power failures. Assets without electric signals are thus less sensitive than assets with electric signals. Information on the presence of electric signals was gathered from interviews with stakeholders in Mobile.

## Wind

### Overview of Wind Sensitivity Indicators, Data Sources, and Weightings

Table 121 and Table 122 provide a summary of the indicators used to assess sensitivity to wind, how they were scored, and how they were weighted.

**Table 121: Wind Sensitivity Indicators and Scoring Approach for Rail Assets**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Damage to signals, signs, and other infrastructure | Whether an asset has been damaged in the past due to wind | Rail assets that have experienced damage during storm events in the past may be more prone to damage in the future. | **Yes/No Record of Previous Damage from Wind**—Interviews with Mobile rail owners and operators | 43% | No—This asset has never been damaged due to wind in the past | 1 |
| | | | | | Yes—This asset has been damaged due to wind in the past | 4 |
| | Number of major crossings | Rail assets with a number of major crossings are more likely to have signs and signals that could be damaged by wind. | **Number of Major Crossings**—Project team analysis of satellite imagery | 28% | 0 or 1 crossing | 1 |
| | | | | | 2 or 3 crossings | 2 |
| | | | | | 4 or 5 crossings | 3 |
| | | | | | More than 5 crossings | 4 |
| | Whether asset has aerial signal lines | Aerial signals and lines are sensitive to wind impacts and | **Yes/No Indication of Aerial Signal Lines**— | 28% | No—There are no aerial signals along the track | 1 |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring **Method** | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | could be damaged during storms. This, in turn, could cause delays or damage to rail assets. | Project team analysis of satellite imagery | | Yes—There are aerial signals along the track | 4 |

*Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining two indicators.

**Table 122: Alternate Wind Sensitivity Indicator Weighting for Rail Assets without Information for All Indicators**

| Data Scenario | Past Experience | Major Crossings | Aerial Signals |
|---|---|---|---|
| No missing data | 43% | 28% | 28% |
| Missing data for past experience | | 50% | 50% |

### Detailed Description of Wind Sensitivity Indicators and Evaluation Methodology

Only three indicators were used in assessing rail assets' sensitivity to wind. **Past experience** was considered because assets that have previously been affected by high winds are more likely to experience wind-related damage in the future. Information on past experience was gathered from interviews with stakeholders in Mobile.

In addition, **number of major crossings** and **presence of aerial signal lines** were included because signage and signals are particularly exposed to high winds. The number of crossings and aerial signal lines were both determined through visual inspection of satellite imagery of the rail lines studied.

## C.5. Transit

The assessment of transit assets included two facilities (Beltline O&M Facility and GM&O Terminal) as well as the bus fleet and service, which includes stops and routes. The indicators used were largely the same for both facilities and the bus fleet and service. However, there are subtle differences that will be described in the following sections.

## Temperature

### Overview of Temperature Sensitivity Indicators, Data Sources, and Weightings

Table 123 and Table 124 provide a summary of the indicators used to assess sensitivity to temperature, how they were scored, and how they were weighted.

**Table 123: Temperature Sensitivity Indicators and Scoring Approach for Transit Assets**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Disruption to transit service and/or structural damage to facilities | Whether asset has experienced damage or disruption in the past during heat events | Transit assets that already experience damage during heat events may experience worsening problems as the temperature increases. | **Yes/No Record of Previous Damage from Temperature**—Stakeholder interviews | 58% | No—This asset has never been damaged due to temperature in the past | 1 |
| | | | | | Yes—This asset has been damaged due to temperature in the past | 4 |
| Maintenance problems for vehicles** | Age of buses | High temperatures can cause cooling system breakdowns on buses. Newer buses are better suited to handling higher temperatures. | **Age of Buses** —Stakeholder interviews, Downtown Mobile Alliance | 43% | Up to 25 years old | 1 |
| | | | | | Greater than 25 and up to 29 years old | 2 |
| | | | | | Greater than 29 and up to 49 years old | 3 |
| | | | | | Greater than 50 years old | 4 |

*Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining two indicators.

**This indicator applied to the bus fleet only.

**Table 124: Alternate Temperature Sensitivity Indicator Weighting for Transit Assets without Information for All Indicators**

| Data Scenario | Past Experience | Age of Buses |
|---|---|---|
| No missing data | 58% | 43% |

| Data Scenario | Past Experience | Age of Buses |
|---|---|---|
| Missing data on age of buses | 100% | |

### Detailed Description of Temperature Sensitivity Indicators and Evaluation Methodology

This assessment considered the **historical performance** of transit assets during heat events, but none of the three assets had any previous problems with high temperatures. All were scored a 1. For facilities, this was the only indicator considered.

For the bus fleet and service, **age of buses** was included as an indicator because high temperatures can stress or break the cooling systems on old buses, whereas newer buses are better equipped to handle the heat. The Mobile bus fleet is 12 years old, which corresponds to a rating of 1. The historical performance indicator was weighted slightly more heavily than the age of the buses.

## Precipitation

### Overview of Precipitation Sensitivity Indicators, Data Sources, and Weightings

Table 125 provides a summary of the indicators used to assess transit sensitivity to precipitation, how they were scored, and how they were weighted. Data availability was 100% for all three assets, so no alternate weightings were considered.

**Table 125: Precipitation Sensitivity Indicators and Scoring Approach for Transit Assets**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether asset has experienced damage in the past associated with | Assets that have experience damage in the past from precipitation events are more likely to be damaged if exposed in | **Yes/No Record of Previous Damage from Precipitation—** Stakeholder interviews | 36% | No—this asset has never been damaged due to precipitation in the past | 1 |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | heavy rainfall | the future. | | | Yes—this asset has been damaged due to precipitation in the past | 4 |
| | Whether an asset is located in the FEMA 100-year flood zone | If an asset is located within the 100-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Yes/No Indication of if Asset in FEMA 100-year Flood Zone**—FEMA Digital Flood Insurance Rate Maps (DFIRMs) | 13% | No—Asset is not located in flood zone | 1 |
| | | | | | Yes—Asset is located in flood zone | 4 |
| | Whether an asset is located in the FEMA 500-year flood zone | If an asset is located within the 500-year floodplain, it is more likely to be sensitive to flooding caused by precipitation. | **Yes/No Indication of in FEMA 500-year Flood Zone**—FEMA DFIRMs | 9% | No—Asset is not located in flood zone | 1 |
| | | | | | Yes—Asset is located in flood zone | 4 |
| | Asset's elevation relative to surrounding areas | If an asset is located at a relatively low elevation compared to surrounding areas, water may tend to "pond" there, causing flooding during heavy precipitation events. | **Median Number of Neighboring "cells" with Elevation Higher than the Asset**—Project team ponding analysis based on the maximum and average elevation along the rail (elevation data from 3 ft. x 3 ft. LiDAR) | 11% | Ponding score** up to 42 | 1 |
| | | | | | Ponding score greater than 42 and up to 84 | 2 |
| | | | | | Ponding score greater than 84 and up to 126 | 3 |
| | | | | | Ponding score greater than 126 | 4 |
| | Amount of impervious surface surrounding an asset | Assets with greater impermeability to water may be more likely to experience issues with flooding and run-off from | **Percent of Area Surrounding Asset with Above Average Impermeability**—USGS National Land Cover Database 2006 | 11% | Up to 25% of asset with above average impermeability | 1 |
| | | | | | Greater than 25% and up to 50% of asset with above average impermeability | 2 |

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | precipitation. | Impervious Surfaces; project team analysis compared asset's imperviousness to the average impermeability in the City of Mobile (27%) | | Greater than 50% and up to 75% of asset with above average impermeability | 3 |
| | | | | | Greater than 75% and up to 100% of asset with above average impermeability | 4 |
| Inability to access facilities | Access to transit asset during heavy precipitation events | Even if the asset itself is unaffected, if structures near the asset are flooded, the ability to access and operate a facility or bus service may be impeded. | **Yes/No on Potential for Nearby Assets to Flood**—Stakeholder interviews | 21% | No—access is not impaired by inundation even if asset itself is not directly affected | 1 |
| | | | | | Yes—access is impaired by inundation even if asset itself is not directly affected | 4 |

*Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining seven indicators, where both flood zone indicators are grouped together and both indicators related to run-off are grouped together (ponding and impervious surface). Within flood zone indicator, 60% of weight comes from 100-year flood zone and 40% comes from 500-year flood zone because all assets in the 100-year flood zone are also in the 500-year flood zone.

** Ponding score refers to number of grid cells that flow into the cells covered by the asset.

## Detailed Description of Precipitation Sensitivity Indicators and Evaluation Methodology

Five indicators were considered in assessing the likelihood of flood-related damage. **Historical performance** was the most heavily weighted indicator. Of the three transit assets, only the bus fleet and service has previously been affected by heavy precipitation.

The **location of assets within flood zones** was analyzed using flood information from FEMA's National Flood Insurance Program (NFIP) to spatially represent the 100-year and 500-year flood scenarios. The same approach was used for all modes. See the discussion of methodology for the highways section on page 249 for a description of the approach. GM&O Terminal scored a 4, while Beltline O&M Facility and the bus fleet and service are located out of the flood zone and received 1's.

The **propensity for an asset to flood based on surrounding topography** was also analyzed using GIS. This analysis captures the change in elevation between an asset and its surrounding area. It is therefore an indicator of an asset's susceptibility for collecting runoff during and after a precipitation event. The same approach was used for all modes. See the discussion of methodology for the highways section on page 250 for a description of the approach.

Another indicator assessed the amount of **impervious surface** at the asset's location. Highly impermeable areas may be more likely to accumulate water during a precipitation event. The same approach was used for all modes. See the discussion of methodology under the highways section on page 251 for a description of the approach.

**Access to facilities** can be affected even when the asset itself is not flooded. The area surrounding GM&O Terminal is prone to flooding and impedes access to the terminal itself. Access to bus stops can also be impaired during heavy precipitation events even if the buses themselves are not damaged.

## Sea Level Rise

### Overview of Sea Level Rise Sensitivity Indicators, Data Sources, and Weightings

Table 126 provides a summary of the indicators used to assess sensitivity to sea level rise, how they were scored, and how they were weighted. Because the four assets had data available for all three indicators, no alternate weighting systems were required.

**Table 126: Sea Level Rise Sensitivity Indicators and Scoring Approach for Transit Assets**

| Climate Change impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Flooding | Whether an asset has flooded in the past due to tidal events | Assets that have experienced flooding during extreme high tide events in the past are more likely to experience disruption again in the future. | **Yes/No Record of Previous Flooding from Tides—** Stakeholder interviews | 43% | No—This asset has never been damaged due to sea level rise in the past | 1 |
| | | | | | Yes—This asset has been damaged due to sea level rise in the past | 4 |
| | Elevation or protection of asset | Assets that are elevated or well protected are less likely | **Yes/No on Elevation or Protection—** | 28% | Yes—asset is elevated or protected above bare earth elevation | 1 |

| Climate Change impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | to be affected during sea level rise events. | Stakeholder interviews, confirmed by satellite imagery | | No—asset is not elevated or protected above bare earth elevation | 4 |
| Inability to access facilities | Access to asset during inundation event | Even if the asset itself is unaffected, if structures near the asset are flooded, the ability to access and operate a facility or bus service may be impeded. | **Yes/No on Potential for Nearby Assets to Flood**—Stakeholder interviews | 28% | No—access is not impaired by inundation even if asset itself is not affected | 1 |
| | | | | | Yes—access is impaired by inundation even if asset itself is not affected | 4 |

*Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining two indicators.

### Detailed Description of Sea Level Rise Sensitivity Indicators and Evaluation Methodology

Assets that have experienced damage due to high tide events in the past are likely to be affected by sea level rise, so **historical performance** was the most heavily weighted indicator. None of the transit assets evaluated had any record of damage from high tide events.

None of the assets had any form of **protection or elevation**, so all were scored a 4.

Heavy precipitation can lead to **impaired access** to transit facilities and services. In particular, the area surrounding GM&O Terminal is susceptible to flooding, which disrupts operations at the terminal even if it is not affected. Access to bus routes is also impeded during extreme precipitation events.

## Storm Surge

### Overview of Storm Surge Sensitivity Indicators, Data Sources, and Weightings

Table 127 and Table 128 provide a summary of the indicators used to assess sensitivity to storm surge, how they were scored, and how they were weighted.

**Table 127: Storm Surge Sensitivity Indicators and Scoring Approach for Transit Assets**

| Climate Change Impact | Indicator of Potential for Impact to Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Structural damage due to storm surge | Whether an asset has been damaged in the past due to storm surge | Assets that have experienced damage during past storm events are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Storm Surge**—Stakeholder interviews | 36% | No—This asset has never been damaged due to storm surge in the past | 1 |
| | | | | | Yes—This asset has been damaged due to storm surge in the past | 4 |
| | Elevation or protection of asset | Assets that are elevated or well protected are less likely to be affected during storm surge events. | **Yes/No on Elevation or Protection**—Stakeholder interviews, confirmed by satellite imagery | 21% | Yes—Asset is protected or elevated | 1 |
| | | | | | No—Asset is not protected or elevated | 4 |
| | Building foundation** | Certain foundation designs may be more vulnerable to structural damage than others. | **Building Foundation Type** – Stakeholder interviews | 21% | Pilings | 1 |
| | | | | | Footers | 4 |
| Inability to access facilities | Access to asset during inundation event | Even if the asset itself is unaffected, if structures near the asset are flooded, the ability to access and operate a facility or bus service may be impeded. | **Yes/No on Potential for Nearby Assets to Flood**—Stakeholder interviews | 21% | No—Access is not impaired by inundation even if asset itself is not affected | 1 |
| | | | | | Yes—Access is impaired by inundation even if asset itself is not affected | 4 |

*Weighting rationale: Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining indicators.

**This indicator applies only to facilities.

**Table 128: Alternate Storm Surge Sensitivity Indicator Weighting for Transit Assets without Information for All Indicators**

| Data Scenario | Past Experience | Foundation Type | Elevation/ Protection | Impaired Access |
|---|---|---|---|---|
| No missing data | 36% | 21% | 21% | 21% |
| Missing data for building foundation | 46% | | 27% | 27% |

### Detailed Description of Storm Surge Sensitivity Indicators and Evaluation Methodology

**Record of damage from storm surge, elevation or protection of asset,** and **building foundation** were considered to determine whether assets are likely to incur structural damage from storm surge. Of the three, historical performance was weighted most heavily. Only GM&O Terminal had been affected by storm surge in the past, so it received a 4; the other two assets both scored a 1. Protective structures or elevation of assets would help protect them from a certain level of surge. However, none of the assets have protection or are elevated, and all three therefore scored a 4. Certain building foundations are more resilient to storm surges than others. In this case, building foundation only applied to the two transit facilities evaluated. However, data were not available for this particular indicator.

**Inability to access facilities** due to storm surge was also included as an indicator of sensitivity. Even if the facilities themselves are not damaged, if local access to the facilities is impaired, then service may be disrupted. As explained in the sea level rise and precipitation sensitivity sections, GM&O Terminal and the bus fleet and service scored 4 for this indicator, while Beltline O&M scored 1.

## Wind

### Overview of Wind Sensitivity Indicators, Data Sources, and Weightings

Table 129 and Table 130 provide a summary of the indicators used to assess sensitivity to wind, how they were scored, and how they were weighted.

**Table 129: Wind Sensitivity Indicators and Scoring Approach for Transit Assets**

| Climate Change Impact | Indicator of Potential For Impact To Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method: Attribute Value | Scoring Method: Score |
|---|---|---|---|---|---|---|
| Structural damage to transit assets due to high winds | Whether an asset has been damaged in the past due to high winds | Transit assets that have experienced wind damage during past hurricanes are more likely to be damaged if exposed in the future. | **Yes/No Record of Previous Damage from Wind**—Stakeholder interviews | 29% | No—This asset has never been damaged due to wind in the past | 1 |
| | | | | | Yes—This asset has been damaged due to wind in the past | 4 |
| | Age of asset | Older assets are more likely to be built to lower design standards than newer buildings, and therefore more sensitive to damage from wind and other weather. | **Year Built**—Stakeholder interviews | 14% | 0-24 years | 1 |
| | | | | | 25-29 years | 2 |
| | | | | | 30-49 years | 3 |
| | | | | | 50 years or older | 4 |
| | Building material* | Some building materials may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that metal and wood buildings are more sensitive to wind than masonry. | **Building Material**—Stakeholder interviews, | 14% | Masonry | 1 |
| | | | | | Metal | 4 |
| | | | | | Wood | 4 |
| | Roof type* | Some roof types may be more likely to be damaged from wind than other materials. For example, Mobile stakeholders indicated that flat roofs are more sensitive to wind than pitched roofs. | **Roof Type**—Stakeholder interviews | 14% | Pitched | 1 |
| | | | | | Flat | 4 |
| | Height of buildings** | Taller buildings are more | **Building Height** | 14% | Single-story | 1 |

| Climate Change Impact | Indicator of Potential For Impact To Occur | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | sensitive to high winds than shorter ones. | —Stakeholder interviews | | Low-rise (less than 12 stories or 115 ft. tall) | 2 |
| | | | | | High-rise (between 12 and 40 stories, or 155 and 330 ft. tall) | 3 |
| | | | | | Skyscraper (greater than 330 ft. tall) | 4 |
| | Whether asset is sheltered from wind | Buildings that are sheltered (e.g., by surrounding structures or terrain) may be less sensitive to wind. | **Yes/No Indication of Shelter**—Stakeholder interviews | 14% | Yes—building is located in areas sheltered by similar structures | 1 |
| | | | | | No—building is not located in areas sheltered by similar structures | 4 |

* Past experience weighted 15 percentage points higher than other indicators (per stakeholder input). Weight divided equally between remaining indicators.

**This indicator applies only to facilities.

**Table 130: Alternate Wind Sensitivity Indicator Weighting for Transit Assets without Information for All Indicators**

| Data Scenario | Past Experience | Age of Asset | Building Material | Roof Type | Building Height | Shelter |
|---|---|---|---|---|---|---|
| No missing data | 29% | 14% | 14% | 14% | 14% | 14% |
| Missing data on age of building or asset | 34% | | 17% | 17% | 17% | 17% |
| Missing data on building material, roof, or height | 51% | 25% | | | | 25% |

## Detailed Description of Wind Sensitivity Indicators and Evaluation Methodology

Three sensitivity indicators were applied to all three transit assets: **historical performance, age of asset,** and **whether the asset is sheltered by similar structures.** Both Beltline O&M Facility and the Mobile bus fleet and service have experienced wind-related damages in the past and scored 4 because they are more likely to be damaged by wind again in the future. Age of asset was considered because older facilities are built to lower design standards. This information was not available for Beltline O&M Facility, but the 105-year old GM&O Terminal rated a 4. At only 12-years old, the bus fleet scored a 1. Lastly, neither transit facility is protected from high winds by surrounding structures. However, the bus fleet and service is well-shielded from high winds by its surroundings. These were the only three indicators considered in assessing the sensitivity of the bus fleet and service.

Indicators for assessing facilities' sensitivity to wind were much more extensive. **Building material type** differentiated between GM&O Terminal's masonry and Beltline facility's metal and concrete construction. Beltline O&M Facility also scored 4 for **roof type** with its flat roof, compared to GM&O Terminal's pitched roof. The **building height** of both facilities is classified as "low rise" and scores 2.

# D. Detailed Methodology for Evaluating Adaptive Capacity

Adaptive capacity indicators varied by transportation mode. However, most adaptive capacity indicators fall within three general categories:

- **Ability to quickly repair damage** is one measurement of adaptive capacity. The measurement of this factor varies by mode. Replacement or upgrade cost of an asset is a reasonable (if imperfect) proxy for the general complexity and cost of an asset; more complex and expensive assets may take longer to repair or replace when needed. For some modes, facilities may have a special designation as a critical facility in the area, meaning it received priority for resources to repair damage after a major weather event.
- **Redundancy** is another key factor, and it also is measured in different ways for each mode. As mentioned in the example above, alternative routes to get from Point A to Point B can lessen the disruption of temporarily losing access to one highway asset. For other modes, redundancy manifests itself in the ability to shift operations from one facility to another (external redundancy) or the presence of multiple similar facility features, such as multiple runways, terminals, piers, etc. (internal redundancy).
- **Duration of operational disruption** is also important to capture. Precipitation-related flooding often lasts only a few hours, whereas inundation from sea level rise could be permanent. A transportation asset and system can more easily adjust to short-term flooding than it can to permanent flooding. Therefore, the project team developed disruption duration scores for temperature, precipitation, sea level rise, storm surge, and wind. The same scores were used for all transportation assets.

Like sensitivity, for all adaptive capacity indicators, each indicator was assigned a score and a weight for each asset. The scores for each asset were based on the value of that indicator. Further, each indicator was assigned a weight to be used in calculating the overall adaptive capacity score for each asset.

The composite adaptive capacity score for each asset was calculated using the individual indicators as follows:

$$\textit{Adaptive Capacity for Asset} = \textit{Weighted Indicator Score}_1 + \textit{Weighted Indicator Score}_2 + \ldots + \textit{Weighted Indicator Score}_n$$

This Appendix describes the specific adaptive capacity indicators and weightings used for each mode.

# D.1. Highways

## Overview of Adaptive Capacity Indicators, Data Sources, and Weightings

Table 131 and Table 132 in this appendix explain the data sources behind the three highways adaptive capacity indicators and how that indicator was scored.

Because of the wide variation in disruption durations possible under a given stressor, and due to the importance of the other adaptive capacity indicators, disruption duration was weighted so that it did not exceed one-third of the adaptive capacity score when other indicators were available. When data were available for all three indicators, disruption duration accounted for one-third of the score, while cost and detour length account for the other two-thirds. If either cost or detour length scores were not available for an asset, the disruption length score still made up only one-third of the composite adaptive capacity score. If only one indicator was available for an asset, the score for that indicator became the composite adaptive capacity score. Table shows how each indicator was weighted given the data available for a given asset.

**Table 131: Highways Adaptive Capacity Indicators and Scoring Approach**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| Ability to quickly repair damage | Cost to replace an asset | Replacement costs for each asset are used as a rough proxy for the ease in which assets could be repaired or replaced. Resources are assumed to be more easily mobilized for lower cost repairs, and replacement costs may indicate overall complexity, size, and expense of the asset itself. | **Total Project Cost**—National Bridge Inventory, Item 96 | Less than $1 million | 1 |
| | | | | From $1 million to just below $10 million | 2 |
| | | | | From $10 million to just below $100 million | 3 |
| | | | | $100 million or above | 4 |
| Redundancy | Length of detour around a damaged asset | Detour length is used as an indicator of redundancy in the system. Segments with longer detour lengths assumed to have less adaptive capacity than segments with shorter detours. | **Bypass, Detour Length—**National Bridge Inventory, Item 19 | Less than 10 km detour | 1 |
| | | | | From 10 km to just below 30 km detour | 2 |
| | | | | From 30 km to just below 50 km detour | 3 |

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| | | | | 50 km detour or longer | 4 |
| Duration of operational disruption | Length of time an asset is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)—** Stakeholder interviews | Disruption cleared within hours | 1 |
| | | | | Disruption cleared within days | 2 |
| | | | | Disruption cleared within weeks | 3 |
| | | | | Disruption cleared within months | 4 |

**Table 132: Highway Disruption Duration Scores for each Climate Stressor**

| Stressor | Score | Rationale |
|---|---|---|
| Precipitation | 1 | Stakeholders indicate that flooding generally affects roads for a matter of hours, then clears |
| Temperature | 1 | Damage from temp could cause delays due to slowed traffic |
| Wind | 2 | Debris from wind can be cleared easily, as can lights/signs, but may take >1 day to do so after a major storm |
| Storm Surge | 4 | Assets damaged by storm surge can take months to fully repair/replace |
| Sea Level Rise | 4 | Permanent inundation would require significant modifications or protections |

**Table 133: Highways Adaptive Capacity Indicator Weights**

| Data Scenario | Cost | Detour | Disruption Duration |
|---|---|---|---|
| No missing data | 33% | 33% | 33% |
| Missing data for cost | | 67% | 33% |
| Missing data for detour length | 67% | | 33% |
| Missing data for cost and detour length | | | 100% |

*Weighting rationale: Cost and detour combined weighted heavier than disruption duration in all scenarios because of known limitations of disruption duration indicator.

## Detailed Description of Adaptive Capacity Indicators and Evaluation Methodology

For highways, three adaptive capacity indicators were used:

- Replacement cost
- Detour length
- Disruption duration

**Replacement cost** provides a rough proxy for the ease with which assets could be repaired or replaced. Resources are assumed to be more easily mobilized for lower cost repairs, and replacement costs may indicate the overall complexity, size, and expense of the asset itself. Information on the costs for each asset came from the National Bridge Inventory's "Total Project Cost" field, which represents the estimated cost of proposed improvements to the bridge or major structure.[142] Since the data came from the National Bridge Inventory, this information was only available for bridges and culverts, and replacement cost is not factored into roadway adaptive capacity scores. Each asset was assigned a replacement cost score of 1 through 4 based on its value. Any asset with a replacement cost less than $1 million scored a 1 and assets with a replacement cost greater than $100 million scored a 4. Scores were based on the order of magnitude of the costs. Table 131 documents the assumptions used in the replacement cost scoring methodology. Replacement costs are unique to each asset, but do not vary across the climate stressors.

**Detour length** is the total additional travel for a vehicle that would result from closing a given asset.[143] Detour length is a proxy for understanding the redundancy in the transportation system and the magnitude of disruption to the system if an asset were to be closed. Assets with longer detour lengths are assumed to have less adaptive capacity than assets with shorter detours. The range of detour lengths (0 to 98 mi., or 0 to 158 km) was divided evenly to set the detour length scoring bins. Table 131 documents the assumptions used in scoring detour length. Again, information on the detour lengths for each asset came from the National Bridge Inventory, and was therefore only available for bridges. Detour length therefore is not factored into roadway or culvert adaptive capacity scores. Detour length is unique to each asset, and does vary across the climate stressors.

The third element of adaptive capacity used in this study was the timeframe to restore service to assets following impacts from each of the climate stressors (or, **disruption duration**). For roadway assets, this is the only indicator of adaptive capacity. Length of time for

142 FHWA, 1995
143 FHWA, 1995

the disruption to clear is an indicator of how well the system can deal with the climate impact. This indicator is important to help differentiate among the potential damages associated with each climate stressor. That is, impacts from temperature (such as rutting) could require some repair and slow traffic down, whereas the damage from storm surge could be much more dramatic, resulting in significant repair costs and making certain highway segments impassable for lengthy periods of time. It is important to acknowledge that the magnitude of damage can vary significantly across stressors. A limitation of this indicator is that it assumes a uniform type of damage for each climate stressor; in reality, across the transportation system, a single stressor could result in a wide range of impacts. For example, storm surge could completely destroy one segment but cause very minor damage to another. Additionally, disruptions associated with repair of more gradual impacts are not captured directly. Unlike the other indicators, disruption duration scores do vary by climate stressor, but do *not* vary by specific asset.

As for other stressors, the disruption duration score for sea level rise was determined based on stakeholder input. For sea level rise, stakeholders noted that permanent inundation of assets would require major modifications or protections to restore the asset, if restoration were even possible. As a result, all assets received a disruption duration score of 4 for sea level rise. Table 131 documents the assumptions used in scoring disruption duration for sea level rise.

## D.2. Ports

### Overview of Adaptive Capacity Indicators, Data Sources, and Weightings

Table 134 and Table 135 in this appendix explain the data sources behind the three ports adaptive capacity indicators and how that indicator was scored.

Because of the wide variation in disruption durations possible under a given stressor, and due to the importance of the other adaptive capacity indicators, disruption duration was weighted so that it did not exceed one-third of the adaptive capacity score when other indicators were available. When data were available for all three indicators, disruption duration accounted for one-third of the score, while redundancy within and across facilities accounted for the remaining two-thirds. If only one indicator was available for an asset, the score for that indicator became the composite adaptive capacity score.

Table 136 shows how each indicator was weighted given the data available for a given asset.

**Table 134: Ports Adaptive Capacity Indicators and Scoring Approach**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| Redundancy | Redundancy within the facility: whether operations can be shifted to another part of the same port | Operational disruptions are less likely to occur if other parts of the same facility can be substituted in the event of minor damage. | **Ability to Shift Operations Internally** – Stakeholder surveys, interviews, and emails | Can easily shift operations within the facility | 1 |
| | | | | Can shift operations within the facility with little difficulty | 2 |
| | | | | Can shift operations within the facility with difficulty | 3 |
| | | | | Cannot shift operations | 4 |
| | Redundancy across facilities: whether operations can be shifted to a different facility | Serious operation disruptions are less likely to occur if other facilities can be substituted in the event of major damage. | **Ability to Shift Operations Externally** – Stakeholder surveys, interviews, and emails | Can easily shift operations to another facility | 1 |
| | | | | Can shift operations to another facility with little difficulty | 2 |
| | | | | Can shift operations to another facility with difficulty | 3 |
| | | | | Cannot shift operations | 4 |
| Duration of operational disruption | Length of time an asset is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**—Stakeholder interviews | Disruption cleared within hours | 1 |
| | | | | Disruption cleared within days | 2 |
| | | | | Disruption cleared within weeks | 3 |
| | | | | Disruption cleared within months | 4 |

**Table 135: Ports Disruption Duration Scores for Each Stressor**

| Stressor | Score | Rationale |
|---|---|---|
| Precipitation | 1 | Stakeholders indicate that flooding generally affects ports for a matter of hours, then clears |
| Temperature | 1 | Stakeholders indicate that ports do not experience negative impacts associated with high temperatures |
| Wind | 1 | Debris from wind can be cleared easily, as can lights/signs, but may take >1 day to do so after a major storm |
| Storm Surge | 2 | Assets damaged by storm surge can take months to fully repair/replace |
| Sea Level Rise | 4 | Permanent inundation would require significant modifications or protections |

**Table 136: Ports Adaptive Capacity Indicator Weights**

| Data Scenario | Redundancy within Facility | Redundancy across Facilities | Disruption Duration |
|---|---|---|---|
| No missing data | 33% | 33% | 33% |
| Missing data for redundancy within and across facilities | | | 100% |

*Weighting rationale: Cost and detour combined weighted heavier than disruption duration when available.

## Detailed Description of Adaptive Capacity Indicators and Evaluation Methodology

For ports, three adaptive capacity indicators were used:

- Redundancy within a facility
- Redundancy across facilities
- Disruption duration

The project team used a survey to evaluate the ability of port assets to shift operations either within a facility or between facilities. **Redundancy within a facility** captures the ease with which a port can shift operations to another part of the same facility during an extreme weather event. For example, if a port maintains storage facilities further inland, that additional space enhances the ability of the port to maintain or recover operations quickly following extreme weather. **Redundancy across facilities** captures the ability of ports to shift operations from one facility to another.

The third element of adaptive capacity used in this study was the timeframe to restore service to assets following impacts from each of the climate stressors (or, **disruption duration**). Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. This indicator is important to help differentiate among the potential damages associated with each climate stressor. That is, impacts from temperature (such as rutting) could require some repair, whereas the damage from storm surge could be much more dramatic, resulting in significant repair costs and disrupting port operations for multiple days or weeks. It is important to acknowledge that the magnitude of damage can vary significantly across stressors. A limitation of this indicator is that it assumes a uniform type of damage for each climate stressor; in reality, across the transportation system, a single stressor could result in a wide range of impacts. For example, storm surge could completely destroy one asset but cause very minor damage to another. Additionally, disruptions associated with repair of more gradual impacts are not captured directly. Unlike the other indicators, disruption duration scores do vary by climate stressor, but do *not* vary by specific asset.

As for other stressors, the disruption duration score for sea level rise was determined based on stakeholder input. For sea level rise, stakeholders noted that permanent inundation of assets would require major modifications or protections to restore the asset, if restoration were even possible. As a result, all assets received a disruption duration score of 4 for sea level rise. Table 131 documents the assumptions used in scoring disruption duration for sea level rise.

## D.3. Airports

### Overview of Adaptive Capacity Indicators, Data Sources, and Weightings

Table 137 explains the data sources behind the six airports adaptive capacity indicators and how each indicator was scored.

Both airports had adaptive capacity indicators that fell into four categories: (1) whether the airport has a special designation that would speed the recovery process, (2) internal redundancy, (3) regional system redundancy, and (4) disruption duration. Within the internal redundancy category, however, different indicators were available depending on the type of airport. Primary airports have information on the number of terminals as a way of indicating internal redundancy, but this indicator is not applicable for general aviation airports such as Mobile Downtown airport. Therefore, the indicators for general aviation airports were weighted slightly differently than those for primary airports. Table 137 shows the weighting for primary airports, and Table 139 shows an alternate set of weights used for general aviation airports.

**Table 137: Airports Adaptive Capacity Indicators and Scoring Approach**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| Ability to quickly repair damage | Whether the airport is likely to be prioritized for repair | If airports are specifically designated as important for emergency response, national security, defense, or support to health facilities, they are more likely to be re-opened quickly after damage. | **Yes/No Indication of Special Designation**—Stakeholder interviews, Mobile Airport Authority | 25% | Yes; airport is designated as a component of the National Defense System or as an emergency supply source | 1 |
| | | | | | No | 4 |
| Redundancy | Number of terminals at the airport | The number of terminals at an airport is an indicator of internal redundancy within the airport. Airports with multiple terminals may be able to shift operations to other portions of the airport if a specific terminal or area is damaged. | **Number of Terminals** – Stakeholder interviews, Mobile Airport Authority | 12.5% | More than 3 terminals | 1 |
| | | | | | 3 terminals | 2 |
| | | | | | 2 terminals | 3 |
| | | | | | 1 terminal | 4 |
| | Number of runway headings at the airport | A runway heading refers to the direction the runway is facing (relative to north). The number of runway headings at an airport is an indicator of internal redundancy within the airport, since the more directions that planes can take off from an airport, the more resilient that airport is to weather-related disruptions. If airport has more | **Number of Runway Headings** –FAA Airport Master Record Forms 5010-1 and 5010-2 | 12.5% | More than 6 runway headings (i.e., 3 runways) | 1 |
| | | | | | 6 runway headings | 2 |
| | | | | | 4 runway headings | 3 |
| | | | | | 2 runway headings | 4 |

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | than one runway facing in direction of prevailing winds, this reduces the chances that planes will have to take off and land in cross winds, reducing delays. | | | | |
| | Distance to nearest "substitute"* airport | The distance to an airport that has similar characteristics to the given airport is a measure of system redundancy. | **Distance to Nearest "Substitute" Airport**—FAA National Plan of Integrated Airport Systems (NPIAS) | 12.5% | Up to 30 miles | 1 |
| | | | | | Greater than 30 and up to 60 miles | 2 |
| | | | | | Greater than 60 and up to 120 miles | 3 |
| | | | | | Greater than 120 miles | 4 |
| | Number of "substitute" airports within reasonable driving distance | The number of airports that could act as substitutes for the given airport and that are within a 2 hour drive is a measure of system redundancy. | **Number of "Substitute" Airports within 120 Miles**—FAA National Plan of Integrated Airport Systems (NPIAS) | 12.5% | More than 2 airports within 120 miles | 1 |
| | | | | | 2 airports within 120 miles | 2 |
| | | | | | 1 airport within 120 miles | 3 |
| | | | | | No airports within 120 miles | 4 |
| Duration of operational disruption | Length of time the airport is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**—<br>Stakeholder interviews | 25% | Disruption cleared within hours | 1 |
| | | | | | Disruption cleared within days | 2 |
| | | | | | Disruption cleared within weeks | 3 |
| | | | | | Disruption cleared | 4 |

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Weight* | Scoring Method | |
|---|---|---|---|---|---|---|
| | | | | | Attribute Value | Score |
| | | | | | within months | |

* Weighting rationale: The two internal redundancy indicators (number of terminals and runway headings) were grouped together as one indicator for weighting purposes as not to weight internal redundancy more highly than other indicators with fewer supporting data points. The same was true of the two regional system redundancy indicators (closest and number of nearby substitute airports). The four indicator groups were weighted evenly, at 25% each. Within the grouped indicators, each sub-indicator was weighted evenly, so the four redundancy indicators each received 12.5% of the overall weight.

**Table 138: Airports Disruption Duration Scores for Each Stressor**

| Stressor | Score | Rationale |
|---|---|---|
| Temperature | 1 | Stakeholders cited no evidence of major disruptions due to extreme temperatures. High temperatures can stress pavement on runways and expose workers to heat stress, but airport resumes typical operations shortly afterward. |
| Precipitation | 1 | Stakeholders cited no evidence of major disruptions due to heavy rain. Heavy rain can cause delays, but airport resumes typical operations shortly afterward. |
| Sea Level Rise | 4 | Permanent inundation would require significant modifications, protection, or relocation. |
| Storm Surge | 2 | Stakeholders indicated that airport disruptions from storm surge vary depending on the extent of damage. After hurricanes, airports typically open the next day or within a few hours. If runways, terminals, or loading equipment (e.g., jet bridges for passengers) are damaged, disruption will be longer. |
| Wind | 2 | Stakeholders indicated that airport disruptions from wind vary depending on the extent of damage. After hurricanes, airports typically open the next day or within a few hours. If runways, terminals, or loading equipment (e.g., jet bridges for passengers) are damaged, disruption will be longer. |

**Table 139: General Aviation Airport Adaptive Capacity Indicator Weights**

| Indicator Group | Indicator | Indicator Group Weight | Indicator Weight |
|---|---|---|---|
| Special designation | Special designation | 25% | 25% |
| Internal redundancy | Number of terminals | 25% | [redacted] |
| | Number of runway headings | | 25% |

| Indicator Group | Indicator | Indicator Group Weight | Indicator Weight |
| --- | --- | --- | --- |
| Regional system redundancy | Distance to nearest "substitute" airport | 25% | 12.5% |
| | Number of "substitute" airports within 120 miles | | 12.5% |
| Disruption duration | Disruption duration | 25% | 25% |

*Weighting rationale: Each indicator group weighted equally, and each indicator within each group weighted equally.

## Detailed Description of Adaptive Capacity Indicators and Evaluation Methodology

For airports, six adaptive capacity indicators were used:

- Special designation
- Number of terminals
- Number of runway headings
- Distance to nearest "substitute" airport
- Number of "substitute" airports within 120 miles
- Disruption duration

**Special designation** indicates whether the airport has been specifically designated as a component of the national defense system or as an emergency supply source. This indicator is intended to provide a rough proxy for the ease with which an airport could be repaired. Airports with such designations are more likely to be a higher priority for repairs if damaged. Each airport was assigned a special designation score. If the airport had a special designation, it received a 1 indicating high adaptive capacity and low vulnerability, and if the airport did not have a special designation, it received a 4.

**Number of terminals** is an aspect of redundancy within an airport. This indicator assumes that the more terminals an airport has, the more likely it will be able to absorb operations associated with damaged portions of the airport. For example, if one terminal in the airport is damaged, flights that would normally take off from that terminal could be routed through a different area of the airport. However, if an airport only has one terminal, inability to operate that terminal would mean inability to operate the entire airport. Therefore, airports with only one terminal received a 4 for this indicator, while airports with two terminals received a 3, three terminals received a 2, and airports with four or more terminals received a 1.

**Number of runway headings** is another aspect of redundancy within an airport. A runway heading refers to the direction the runway is facing (relative to north). Most runways have two runway headings, since planes can take off from the runway in either direction. The more directions that planes can take off from at an airport, the more resilient that airport would be to weather-related disruptions, as it adds operational flexibility to the airport. Airports with two runway headings scored a 4, airports with 4 runway headings scored a 3, airports with six runway headings scored a 2, and airports with more than six runway headings scored a 1.

**Distance to nearest "substitute" airport** is an indicator of the overall redundancy within a regional airport system. See the text box at right for the definition of "substitute" airport. If the nearest substitute airport was within 30 miles of the original airport, the original airport was considered to have high adaptive capacity, and scored a 1. If the nearest airport was within 60 miles, it scored a 2; if within 120 miles it scored a 3; and if greater than 120 miles, it scored a 4.

**Definition of "Substitute" Airport**

For the purposes of this study, a "substitute" airport was defined as an airport that shared the same service level, hub type (if primary), cargo level (if applicable), and Airport Reference Code (ARC). ARC refers to the aircraft type and approach speeds that an airport can handle. The traits defining substitute airports for Mobile's two critical airports are shown below.

Mobile Regional Airport:

- Service Level: Primary
- Hub Type: Non-hub or small
- Airport Reference Code (ARC): D-V

Mobile Downtown Airport

- Service Level: General Aviation or Primary
- Cargo Capabilities: Qualifying Cargo Airport
- ARC: D-V

**Number of "substitute" airports within 120 miles** is another indicator of the overall redundancy within a regional airport system. The more airports that are within reasonable driving distance of a location, the greater the adaptive capacity of that system, since people and businesses can use other airports if service is disrupted at the airport they would normally use. About two hours of driving, or 120 miles, was set as the threshold for a reasonable driving distance.

The final element of adaptive capacity used in this study was the timeframe to restore service to assets following impacts from each of the climate stressors (or, **disruption duration**). Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. This indicator is important to help differentiate among the potential damages associated with each climate stressor. A limitation of this indicator is that it assumes a uniform type of damage for each climate stressor; in reality, across the transportation system, a single stressor could result in a wide range of impacts. For example, storm surge could completely destroy one airport but cause very minor damage to another. Additionally, disruptions associated with repair of more gradual impacts are not captured directly. Unlike the other indicators, disruption duration scores do vary by climate stressor, but do *not* vary by specific asset. Table 138 documents the assumptions used in scoring disruption duration for airports.

## D.4. Rail

### Overview of Adaptive Capacity Indicators, Data Sources, and Weightings

Table 140 and Table 141 in this appendix explain the data sources behind the rail adaptive capacity indicators and how that indicator was scored.

The indicators were grouped into three categories based on the facet of adaptive capacity they represent: speed to recover asset, redundancy, and disruption duration. Each of the three components was weighted equally to determine the adaptive capacity score, and within each component, the indicators were weighted equally. Table 142 shows how each indicator was weighted given the data available for rail lines (all assets except TASD rail yards), and Table 143 shows how each indicator was weighted for the TASD rail yards.

**Table 140: Rail Adaptive Capacity Indicators and Scoring Approach**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| Ability to quickly repair damage | Presence of bridges | Bridges are generally more expensive to replace than rail; the speed to recover from damage to bridges along a segment of rail may therefore be longer than segments without bridges. | **Yes/No on Presence of Bridges—**Visual inspection of segments | No—asset does not include bridges | 1 |
| | | | | Yes—asset does include bridges | 4 |
| | Whether track is signaled | Signaling can be expensive and time-intensive to replace. | **Yes/No on Signaling—**Interviews with Mobile rail owners and operators | No—asset does not include signals | 1 |
| | | | | Yes—Asset does include signals | 4 |
| | Self-administered evacuation plans | Rail companies with a plan in place are expected to suffer less damage and recover more quickly from storms. | **Yes/No on Existence of Evacuation Plans—**Task 1 Criticality Report (U.S. DOT, 2011) | Yes—Rail company does have a plan in place | 1 |
| | | | | No—Rail company does not have a plan in place | 4 |
| | Part of disaster relief recovery plan | Emphasis to restore operations may be placed on rails that are part of disaster relief recovery plans. | **Yes/No on Involvement in Plan—**Task 1 Criticality Report (U.S. DOT, 2011) | Yes—Asset is part of disaster relief recovery plan | 1 |
| | | | | No—Asset is not part of a disaster relief recovery plan | 4 |
| Redundancy | Ability of system to reroute around obstacles or closed routes* | Systems and segments that can flexibly reroute will be more resilient to damage, track obstructions, and outages. | **Yes/No on Ability to Reroute—**Interviews with Mobile rail owners and operators | High—Assets are highly flexible; damage to a major artery may cause delays less than 30 minutes. | 1 |
| | | | | Medium—Assets are somewhat flexible; damage to a major artery may cause delays under one hour on | 2 |

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| | | | | average. | |
| | | | | Low—Assets are inflexible; damage to a major artery could cause delays greater than an hour on average. | 3 |
| | | | | Limited—Transportation assets are physically fixed (e.g., track, in the case of rail or streetcars); damage to a major artery could cause delays greater two hours. | 4 |
| | Interchange utility** | This is a yard-specific measure of the interchange between carriers, which is of importance in the ability to transfer all cars within yards. | **Qualitative Rating of Low/Med/High**—On-site observation, Task 1 Criticality Report (U.S. DOT, 2011) | Good | 1 |
| | | | | Poor | 4 |
| Duration of disruption | Length of time the asset is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**— Interviews with Mobile rail owners and operators | Disruption cleared within hours | 1 |
| | | | | Disruption cleared within days | 2 |
| | | | | Disruption cleared within weeks | 3 |
| | | | | Disruption cleared within months | 4 |

*This indicator applies only to the rail lines.
** This indicator applies only to rail yards.

**Table 141: Rail Disruption Duration Scores for Each Stressor**

| Stressor | Score | Rationale |
|---|---|---|
| Temperature | 1 | Stakeholders indicate that heat has minimal impacts even during extreme events. |
| Precipitation | 2 | Flooding from heavy rainfall tends to be more localized than storm surge impacts; delays could range from hours to days. |
| Sea Level Rise | 4 | Impacts could cause relocation of entire assets. |
| Storm Surge | 4 | Impacts could be catastrophic and cause delays of weeks to months. |
| Wind | 1 | Repairs would begin within hours. Signaling is most sensitive and trains can still be run on tracks without signaling by using a dispatcher and manual blocks. |

**Table 142: Rail Lines Adaptive Capacity Indicator Weights**

| Data Scenario | Presence of Bridges | Signaling | Evacuation Plans | Disaster Relief Plan | Ability to Reroute | Disruption Duration |
|---|---|---|---|---|---|---|
| No missing data | 8% | 8% | 8% | 8% | 33% | 33% |
| Missing data for presence of bridges | | 11% | 11% | 11% | 33% | 33% |
| Missing data for ability to reroute | 13% | 13% | 13% | 13% | | 50% |
| Missing data for presence of bridges and ability to reroute | | 17% | 17% | 17% | | 50% |

*Weighting rationale: Other indicators combined weighted heavier than disruption duration in all scenarios because of known limitations of disruption duration indicator.

**Table 143: Rail Yards Adaptive Capacity Indicator Weights**

| Data Scenario | Presence of Bridges | Signaling | Evacuation Plans | Disaster Relief Plan | Interchange Utility | Disruption Duration |
|---|---|---|---|---|---|---|
| No missing data | 8% | 8% | 8% | 8% | 33% | 33% |

## Detailed Description of Adaptive Capacity Indicators and Evaluation Methodology

For rail assets, six adaptive capacity indicators were used:

- Presence of bridges
- Presence of signals
- Whether rail company has self-administered evacuation plans
- Whether asset is part of a disaster relief recovery plan
- Redundancy: for rail lines, the ability to reroute around obstacles or closed routes, and for rail yards, the interchange utility
- Disruption duration

The **presence of bridges** increases the cost of replacing a given asset. So, rail assets with bridges are generally slower to recover than rail assets without bridges. Of the four rail assets evaluated, the rail yards and the rail line near the Tensaw River featured bridges and scored a 4.

**Signaling** can also be expensive and time-intensive to replace, so the presence of signals slows down asset recovery. However, trains can be run using a dispatcher if signals are down. None of the four rail assets include signaling.

Rail companies that have a **self-administered evacuation plan** are expected to recover more quickly from extreme weather events. Therefore, since all four rail assets have a plan in place, they all scored a 1 on this indicator.

Assets that are a part of **disaster relief recovery plans** would have priority after major storms. Operations are expected to resume more quickly because of the emphasis placed on those assets. However, none of the assets evaluated are part of such plans, so all four were rated a 1.

Rail lines that have the **ability to reroute around obstacles** are better suited to withstand localized climate impacts. If certain areas are blocked or out of service, the system can work around the disruption. No data were available for this indicator.

**Interchange utility** is a rail-specific measure of the interchange between carriers, which relates to the ability to transfer rail cars within yards. Better interchange utility is a measure of redundancy for rail yards. The rail yards evaluated in this assessment have good interchange utility and scored a 1.

**Disruption duration** was considered as a measure of how quickly an asset type can cope with the impact of different extreme weather events. All rail assets have the same disruption duration; however, disruption duration was the only climate stressor-specific indicator. A brief period of high winds would score much lower than an inundation from storm surge on the disruption duration indicator.

Extreme temperature and wind events pose minimal disruption duration because repairs begin quickly and service can be restored within a few hours. It is expected to take a few days to fully recover from flooding due to heavy precipitation, so it scores slightly higher on disruption duration. Both storm surge and sea level rise could lead to catastrophic impacts, and disruptions could last up to several months.

## D.5. Transit

### Overview of Adaptive Capacity Indicators, Data Sources, and Weightings

Table 144 and Table 145 explain the data sources behind the rail adaptive capacity indicators and how that indicator was scored.

Because of the wide variation in disruption durations possible under a given stressor, and due to the importance of the other adaptive capacity indicators, disruption duration was weighted so that it did not exceed one-third of the adaptive capacity score when other indicators were available. When data were available for all three indicators, disruption duration accounted for one-third of the score, while redundancy within and across facilities accounted for the remaining two-thirds. If only one indicator was available for an asset, the score for that indicator became the composite adaptive capacity score.

Table 146 shows how each indicator was weighted given the data available

**Table 144: Transit Adaptive Capacity Indicators and Scoring Approach**

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| Quick repair of damage | Whether the asset is likely to be prioritized for repair | If a transit asset is designated with USACE priority for assistance after a major weather event, it is more likely to be re-opened quickly after damage. | **Yes/No Indication of Special Designation**—Gulf Coast Phase 2, Task 1 report | Yes—asset is on list of priorities | 1 |
| | | | | No—asset is not on list of priorities | 4 |

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| Redundancy | Function of facility or asset | Assets that are difficult to replace or move have lower adaptive capacity than assets that are replaceable or movable. | **Qualitative Assessment** – Wave Transit | Fungible—facility functions and assets are interchangeable and can be replaced with almost no disruption to services | 1 |
| | | | | Flexible—the function of the facility or asset is reasonably flexible in that it could be relocated or replaced with limited disruption to services | 2 |
| | | | | Unique - Facility or asset serves a unique purpose and would be difficult to replace, but temporary emergency measures are available | 3 |
| | | | | Singular - Facility or asset serves a unique purpose and would be extremely difficult to replace if damaged | 4 |
| | Ability of system to reroute around obstacles or closed routes* | Assets that are able to reroute or detour easily are more capable of adapting to extreme weather events. | **Qualitative Assessment** – Stakeholder interviews | High - Assets are highly flexible; damage to a major artery may cause delays less than 30 minutes. | 1 |
| | | | | Medium - Assets are somewhat flexible; damage to a major artery may cause delays under one hour on average. | 2 |
| | | | | Low - Assets are inflexible; damage to a major artery could cause delays greater than an hour on average. | 3 |

| Adaptive Capacity Component | Indicator | Rationale | Asset Attribute and Data Source | Scoring Method | |
|---|---|---|---|---|---|
| | | | | Attribute Value | Score |
| | | | | Limited - Transportation assets are physically fixed (e.g., track, in the case of rail or streetcars); damage to a major artery could cause delays greater two hours. | 4 |
| Duration of disruption | Length of time the asset is expected to be out of service | Disruption duration is used to indicate the timeframes necessary to restore service to assets following impacts of each of the stressors. Length of time for the disruption to clear is an indicator of how well the system can deal with the climate impact. | **Duration of Disruption (for each type of damage)**— Stakeholder interviews | Disruption cleared within hours | 1 |
| | | | | Disruption cleared within days | 2 |
| | | | | Disruption cleared within weeks | 3 |
| | | | | Disruption cleared within months | 4 |

*This indicator applies only to the bus fleet and service.

**Table 145: Transit Disruption Duration Scores for Each Stressor**

| | Stressor | Score | Rationale |
|---|---|---|---|
| Facilities | Precipitation | 2 | Damage from precipitation such as flooding could take a few days to address |
| | Temperature | 1 | Stakeholders provided no indication that temperature causes notable delays |
| | Wind | 2 | Building damage could take a few days to repair |
| | Storm Surge | 4 | Operations could be severely disrupted |
| | Sea Level Rise | 4 | Operations could be severely disrupted |
| Bus fleet and service | Precipitation | 1 | Service delays last an hour at most |
| | Temperature | 1 | Stakeholders provided no indication that temperature causes notable delays |
| | Wind | 2 | Buses don’t run for 1-2 days after storms in order to stay out of the way of emergency crews |
| | Storm Surge | 2 | Buses don’t run for 1-2 days after storms in order to stay out of the way of emergency crews |

| | Stressor | Score | Rationale |
|---|---|---|---|
| | Sea Level Rise | 1 | Sea level rise is not likely to disrupt service as it would be rerouted |

**Table 146: Transit Adaptive Capacity Indicator Weights**

| Asset Type | Speed to Recover | Function of Facility | Ability to Reroute | Disruption Duration |
|---|---|---|---|---|
| Facility | 33% | 33% | N/A | 33% |
| Bus fleet and service | 33% | 17% | 17% | 33% |

## Detailed Description of Adaptive Capacity Indicators and Evaluation Methodology

For transit facilities, three adaptive capacity indicators were used:

- Speed of asset recovery
- Function of facility (flexibility to shift and adjust)
- Disruption duration

For the bus fleet and service, the ability of the system to reroute around obstacles and closed routes was considered as a fourth indicator.

**Speed of asset recovery** is included because assets that are on USACE's priority list for assistance after major weather events will return to normal operations more quickly than others. Assets on the list have higher adaptive capacity because of their priority status. However, none of the three transit assets evaluated are on USACE's priority list.

If the **function of the asset** can be shifted to other locations, the system is better equipped to absorb the loss of a single asset without incurring major disruptions. This indicator measures redundancy: the more redundancy, the less impact a localized weather event has. The transit assets scored between 1 (Fungible) and 3 (Unique) on this indicator. For the bus fleet, **ability to reroute** was another indicator of redundancy. The Mobile bus service had high ability to reroute and scored a 1.

Lastly, **disruption duration** was considered as a measure of how quickly each asset can cope with the impact of different extreme weather events. Disruption duration was the only climate stressor-specific indicator and therefore allows for differentiation between temperature impacts and storm surge impacts. However, disruption duration scores do not differentiate between asset types: both facilities have the same disruption duration scores.

For facilities, temperature impacts had the least disruption duration, as there was no evidence that extreme heat could cause notable delays. Precipitation and wind events could both cause building damage, which would take a few days to repair, so these climate stressors scored a 2 on disruption duration. Finally, storm surge and sea level rise could cause extremely lengthy disruptions (for example, forcing the relocation of an entire facility) and were rated a 4.

The inherent flexibility of the bus service led to predominantly low disruption durations. Temperature, sea level rise, and precipitation all scored 1 because the bus fleet can effectively work around any localized problems. After storm surge and high wind events, buses stay off the road for a few days to make way for the emergency crews. These climate stressors rated a 2 on disruption duration.

# E. Data Availability Analysis

Data were not available on every indicator for each asset. When data were missing, the calculations were adjusted so that the overall scores were calculated using only the indicators for which data were available. Some assets had significantly more complete data sets than others, which could potentially influence the results.

To illustrate which assets were missing data, each asset was assigned a data availability score to capture whether data gaps were driving results. The score is on a range of 0 to 100% and represents the percentage of the overall score weight for which indicators were available. In other words, if an asset's score was determined by two indicators weighted equally, but one of them was missing for an asset, the asset would get a data availability score of 50%. If the asset's score was determined by two indicators where one accounted for 75% of the vulnerability score and the other accounted for 25% of the vulnerability score and the second was missing, the asset would get a data availability score of 75%. Data availability was determined separately for exposure, sensitivity, and adaptive capacity scores, and ultimately rolled into a composite data availability score for vulnerability (again, taking into account the relative weights of exposure, sensitivity, and adaptive capacity). Table 147 shows an example of how the data availability score is calculated for an example asset, in the case where there is one exposure indicator, four sensitivity indicators, and three adaptive capacity indicators.

**Table 147: Example of Data Availability Score Calculation for an Asset**

| Components | Exposure | Sensitivity | | | | Adaptive Capacity | | |
|---|---|---|---|---|---|---|---|---|
| **Component weights** | 40% | 40% | | | | 20% | | |
| **Indicators** | E 1 | S 1 | S 2 | S 3 | S 4 | AC 1 | AC 2 | AC 3 |
| **Indicator weights** | 100% | 40% | 20% | 20% | 20% | 33% | 33% | 33% |
| **Data Available?** | Y | Y | N | Y | N | Y | Y | N |
| **Data availability score (by component)*** | 100% | 60% | | | | 67% | | |
| **Data availability score** | 40% (100%) + 40% (60%) + 20% (67%) = 77% | | | | | | | |

Note: Gray shading is used to highlight indicators where data are missing, also indicated by an "N" in the row called "Data Available?"

* The data availability score for each component is calculated as the sum of the weights of all components with data (i.e., the sum of the weights marked with Y's")

# F. Evaluating Robustness of Results

This study included an analysis to determine how sensitive the results are to the presence of each vulnerability indicator and assumptions about weighting exposure, sensitivity, and adaptive capacity. This appendix explains the methodology used in this evaluation. The objectives of this analysis were to:

- Identify the underlying assumptions and data elements within the screening tools that have a large influence on final results;
- For assets identified as highly vulnerable, test the robustness of these results to changes in the underlying assumptions, weights, and indicators used to evaluate vulnerability; and
- Test to what extent results are an artifact of indicator weights or whether results are robust regardless of assumptions about indicator weighting; and
- Understand the change in overall range of vulnerability scores given changes in underlying assumptions, weights, and indicators.

The study conducted four tests as part of this evaluation to determine if any of the following assumptions had an outsized effect on results:

- Indicator sensitivity test—whether the exclusion of any individual indicators affects results
- Component weighting sensitivity test—how the relative weighting of exposure, sensitivity, and adaptive capacity affect results
- Category sensitivity test—whether grouping indicators into categories affects results
- Maximum vs. average sensitivity test—for highways, whether using the maximum or average scores across sub-segments affects results for each segment

Each test is discussed in detail below.

## F.1. Indicator Sensitivity Test

The influence of any one indicator on the vulnerability results is a function of the weight of that indicator, how many assets have data for that indicator, and the score for that indicator relative to the other indicators. This test reveals how these various factors ultimately interact to drive results. The test was completed for each stressor and mode. Within each stressor, the test looked at the change in vulnerability scores for the most extreme scenario—Hotter, end-of-century for temperature; Wetter, end-of-century for precipitation; 200 cm for sea level rise; and Hurricane Katrina with a shifted track, reduced pressure, and 75 cm of sea level rise for storm surge and wind.

Within each component of vulnerability (i.e., exposure, sensitivity, and adaptive capacity), the analysis examined the change in absolute and relative vulnerability scores for each asset by eliminating each indicator one by one, holding all other indicators constant. When each indicator was removed, the weights for all other indicators were automatically adjusted to sum to 100%

and maintain all other weighting assumptions (e.g., historical performance weighted 15 points higher than other indicators).

The vulnerability scores were captured and compared for all assets after each indicator was removed. The standard deviation in scores and ranks for each change in indicators was used to determine which assets are most sensitive to changes in indicators. The average change in scores and relative ranks across all assets were used to determine which indicators had the largest effect on scores and relative results.

Figure 54 shows a snapshot of the temperature vulnerability scores for each "run" of the highway results sensitivity analysis, where each indicator was removed one by one as described above. The color-coding provides a visualization of the relative scoring—each column is color-coded so that the highest score is red and the lowest score is green, which gradations in between. The changes in absolute and relative scores from removing each indicator were quantitatively analyzed across indicators and assets.

**Figure 54: Snapshot of Temperature Vulnerability Scores for each "Run" in the Sensitivity Analysis**

| | | | | Temperature (Hotter, End-of-Century) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Sensitivity Indicators | | | | Adaptive Capacity Indicators | | | | |
| Segment ID | Specific ID | Name | Type | Original | External Trip Productions, Trucks (2007) | Average Daily Truck Traffic | Pavement Binder Type | Historical Performance | Cost | Detour | Disruption Duration | Average Score | SD |
| R1 | R1 | I-10 Tunnel (Wallace Tunnel) | Road | 2.5 | 2.2 | 2.5 | 2.7 | 2.8 | 2.5 | 2.5 | 2.3 | 2.5 | 0.21 |
| R2 | R2 | Intersection with I-65 | Road | 2.5 | 2.2 | 2.5 | 2.7 | 2.8 | 2.5 | 2.5 | 2.3 | 2.5 | 0.21 |
| R2 | R2_B1 | Intersection with I-65 | Culvert | 2.7 | 2.7 | 2.3 | 2.8 | 2.9 | 2.7 | 2.7 | 2.7 | 2.7 | 0.19 |
| R2 | R2_B2 | Intersection with I-65 | Bridge | 2.6 | 2.6 | 2.3 | 2.8 | 2.9 | 2.5 | 2.7 | 2.6 | 2.6 | 0.20 |
| R2 | R2_B3 | Intersection with I-65 | Culvert | 2.4 | 2.4 | 2.3 | 2.4 | 2.5 | 2.3 | 2.4 | 2.4 | 2.4 | 0.07 |
| R3 | R3 | I-10 from Tunnel to S Broad Stre Road | Road | 2.5 | 2.2 | 2.5 | 2.7 | 2.8 | 2.5 | 2.5 | 2.3 | 2.5 | 0.21 |
| R3 | R3_B1 | I-10 from Tunnel to S Broad Stre | Bridge | 2.7 | 2.7 | 2.3 | 2.8 | 2.9 | 2.5 | 2.8 | 2.7 | 2.7 | 0.21 |
| R3 | R3_B2 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B3 | I-10 from Tunnel to S Broad Stre | Bridge | 2.7 | 2.7 | 2.3 | 2.8 | 2.9 | 2.5 | 2.8 | 2.7 | 2.7 | 0.21 |
| R3 | R3_B4 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B5 | I-10 from Tunnel to S Broad Stre | Culvert | 2.6 | 2.6 | 2.3 | 2.8 | 2.9 | 2.5 | 2.7 | 2.6 | 2.6 | 0.20 |
| R3 | R3_B6 | I-10 from Tunnel to S Broad Stre | Bridge | 2.7 | 2.7 | 2.3 | 2.8 | 2.9 | 2.5 | 2.8 | 2.7 | 2.7 | 0.21 |
| R3 | R3_B7 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B8 | I-10 from Tunnel to S Broad Stre | Bridge | 2.7 | 2.7 | 2.3 | 2.8 | 2.9 | 2.5 | 2.8 | 2.7 | 2.7 | 0.21 |
| R3 | R3_B9 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B10 | I-10 from Tunnel to S Broad Stre | Bridge | 2.7 | 2.7 | 2.3 | 2.8 | 2.9 | 2.5 | 2.8 | 2.7 | 2.7 | 0.21 |
| R3 | R3_B11 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B12 | I-10 from Tunnel to S Broad Stre | Bridge | 2.4 | 2.4 | 2.3 | 2.5 | 2.5 | 2.3 | 2.6 | 2.5 | 2.4 | 0.11 |
| R3 | R3_B13 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B14 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B15 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B16 | I-10 from Tunnel to S Broad Stre | Bridge | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.2 | 2.5 | 2.4 | 2.3 | 0.10 |
| R3 | R3_B17 | I-10 from Tunnel to S Broad Stre | Bridge | 2.3 | 2.3 | 2.2 | 2.4 | 2.4 | 2.3 | 2.3 | 2.3 | 2.3 | 0.07 |
| R3 | R3_B18 | I-10 from Tunnel to S Broad Stre | Bridge | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 0.00 |
| R3 | R3_B19 | I-10 from Tunnel to S Broad Stre | Bridge | 2.3 | 2.3 | 2.2 | 2.4 | 2.4 | 2.3 | 2.3 | 2.3 | 2.3 | 0.07 |
| R4 | R4 | 1 mile before intersection with | Road | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2 | 2.2 | 0.08 |
| R4 | R4_B1 | 1 mile before intersection with | Bridge | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.2 | 2.3 | 2.3 | 2.3 | 0.04 |

## F.2. Component Weighting Sensitivity Test

For each climate stressor, the analysis also tested how each vulnerability component contributes to the overall results. Similar to the indicator sensitivity test analysis described in the previous section, the final vulnerability scores for each stressor were compared after setting the weight for each component to zero one at a time. The weighting of the remaining components of vulnerability were adjusted to sum to 100%.

The analysis, when conducted at an earlier phase of the study when each of the three components were weighted equally, revealed that adaptive capacity had a larger influence on vulnerability scores compared to exposure and sensitivity. Given this, and that there was less agreement among stakeholders on the adaptive capacity indicators, the weight of adaptive capacity was reduced to 20% relative to 40% each for exposure and sensitivity.

During the evaluation, the relative weighting of the three indicators was preserved. For example, when removing the exposure component, the weights for sensitivity and adaptive capacity were adjusted to 67% and 33%, respectively. When adaptive capacity was removed, exposure and sensitivity were weighted equally at 50%. For sea level rise (which has no exposure score), the sensitivity and adaptive capacity scores each became 100% of the vulnerability score when the other was removed.

The vulnerability scores were captured and compared for all assets after each component was removed. The standard deviation in scores and ranks for each change components was used to determine which assets are most sensitive to those changes. The average change in scores and relative ranks across all assets were used to determine which component had the largest effect on scores and relative results.

## F.3. Category Sensitivity Test

Several sensitivity indicators may address similar characteristics of an asset. For example, there are three indicators for highway storm surge sensitivity that address bridge condition. The study team investigated whether results would be affected by treating these indicators individually (i.e., each weighed as much as any other non-related indicator) or as a group (i.e., each category weighted equally). Table 148 shows how the weights for each indicator compare under the two scenarios.

**Table 148: Example of Treating Similar Indicators Individually (Scenario 1) or as Groups (Scenario 2)**

| Scenario 1 | |
|---|---|
| Indicator | Weight |
| Navigational clearance | 17% |
| Scour criticality | 17% |
| Structure condition (substructure) | 17% |
| Structure condition (superstructure) | 17% |
| Structure condition (overall) | 17% |
| Movable bridge | 17% |
| **Total** | **100%** |

| Scenario 2 | | | |
|---|---|---|---|
| Category | Indicator | Category Weight | Indicator Weight |
| Navigational clearance | Navigational clearance | 25% | 25% |
| Scour criticality | Scour criticality | 25% | 25% |
| Structure condition | Structure condition (substructure) | 25% | 8% |
| | Structure condition (superstructure) | | 8% |
| | Structure condition (overall) | | 8% |
| Movable bridge | Movable bridge | 25% | 25% |
| | | **100%** | **100%** |

Neither grouping affected absolute or relative scores beyond nominal changes.

## F.4. Maximum vs. Average Sensitivity Test

For highways, where some representative segments are composed of sub-segments, the study analyzed how relative scores for segments were affected if the segment vulnerability score was the maximum score across its sub-segments or the average of its sub-segment scores. This test was conducted for each climate stressor.

Which segments surface as most vulnerable varied greatly depending on whether they were scored using the maximum or average of sub-segment scores. Both ways of looking at the results can be valuable, depending on whether a stakeholder is interested in the segment as a whole or considering its "weakest link." Therefore, the study displays both forms of results.

# G. Projections for all Secondary Variables under the Final Temperature and Precipitation Narratives

As discussed in Section 3.2, the full set of climate data developed under Task 2 was consolidated into two "narratives" each for temperature and precipitation. The lower narratives (Warmer and Drier) represent the mean minus 1.6 standard deviations across model projections. The higher narratives (Hotter and Wetter) represent the mean plus 1.6 standard deviations across model projections. The vulnerability assessment relied on the narrative projections for only one temperature variable and one precipitation variable. However, values corresponding to each narrative were developed for all "secondary variables" that came out of Task 2. Several of these values are used in the engineering assessments conducted subsequently in this study. This appendix houses the climate narrative projections for all secondary variables for the Mobile region (averaged across the five station locations).

## G.1. Temperature Projections—Warmer and Hotter Narratives

**Table 149: Projected Values under Warmer and Hotter Narratives for All Temperature Variables (based on 5-station Mobile regional average)**

| Variable | Observed Value (1990-2012) | Projected Value under Warmer Narrative | | | Projected Value under Hotter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| **Average Maximum Temperature (°F)** | | | | | | | |
| *Annual* | 77.0 | 77.6 | 78.2 | 78.7 | 79.0 | 81.3 | 84.8 |
| *Winter* | 62.7 | 62.6 | 62.8 | 63.7 | 65.1 | 67.9 | 71.3 |
| *Spring* | 77.2 | 77.2 | 77.6 | 77.8 | 79.3 | 81.8 | 85.3 |
| *Summer* | 89.7 | 90.1 | 90.9 | 90.8 | 91.8 | 94.2 | 97.6 |
| *Fall* | 78.7 | 78.8 | 80.1 | 80.1 | 81.8 | 84.5 | 88.6 |
| *January* | 61.0 | 60.5 | 60.8 | 61.1 | 63.8 | 66.8 | 70.2 |
| *February* | 64.5 | 63.4 | 64.0 | 64.7 | 67.0 | 69.2 | 71.9 |
| *March* | 70.9 | 70.7 | 71.4 | 71.6 | 73.5 | 75.4 | 78.7 |
| *April* | 76.9 | 76.3 | 76.9 | 77.2 | 79.5 | 81.7 | 85.0 |
| *May* | 83.8 | 83.7 | 84.0 | 84.0 | 85.8 | 88.9 | 92.4 |
| *June* | 88.5 | 88.5 | 89.0 | 88.8 | 90.7 | 93.3 | 96.6 |
| *July* | 90.3 | 90.5 | 91.4 | 91.4 | 92.8 | 95.2 | 98.5 |

| Variable | Observed Value (1990-2012) | Projected Value under Warmer Narrative | | | Projected Value under Hotter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| *August* | 90.1 | 90.6 | 91.3 | 91.6 | 92.5 | 94.7 | 98.3 |
| *September* | 86.8 | 87.1 | 87.4 | 88.4 | 89.6 | 92.0 | 95.8 |
| *October* | 78.9 | 79.2 | 80.0 | 80.4 | 82.1 | 84.8 | 88.9 |
| *November* | 70.4 | 70.0 | 71.6 | 71.3 | 74.3 | 77.2 | 81.6 |
| *December* | 62.9 | 62.6 | 63.1 | 63.6 | 66.2 | 69.5 | 73.5 |
| **Average Minimum Temperature (°F)** | | | | | | | |
| *Annual* | 56.2 | 56.8 | 57.5 | 57.8 | 58.2 | 62.1 | 64.0 |
| *Winter* | 41.3 | 41.2 | 41.5 | 42.4 | 43.7 | 46.5 | 49.9 |
| *Spring* | 55.4 | 55.3 | 55.7 | 56.0 | 57.5 | 61.5 | 63.5 |
| *Summer* | 71.2 | 71.8 | 72.7 | 72.6 | 73.4 | 78.4 | 79.1 |
| *Fall* | 57.3 | 57.2 | 58.0 | 58.7 | 60.5 | 65.6 | 67.3 |
| *January* | 39.8 | 39.3 | 39.6 | 40.3 | 43.1 | 45.9 | 49.1 |
| *February* | 42.6 | 41.2 | 41.9 | 42.2 | 45.2 | 47.7 | 50.2 |
| *March* | 48.5 | 48.0 | 48.7 | 49.1 | 52.0 | 54.0 | 57.4 |
| *April* | 54.6 | 54.1 | 54.6 | 55.0 | 57.5 | 60.9 | 65.0 |
| *May* | 63.0 | 62.7 | 63.2 | 63.5 | 66.5 | 70.3 | 75.1 |
| *June* | 69.7 | 69.9 | 70.1 | 70.1 | 72.8 | 76.8 | 81.9 |
| *July* | 72.2 | 72.6 | 73.3 | 73.2 | 75.3 | 79.5 | 84.9 |
| *August* | 71.8 | 72.6 | 73.2 | 73.9 | 75.0 | 79.2 | 84.8 |
| *September* | 67.4 | 67.8 | 68.4 | 69.4 | 71.5 | 75.7 | 81.5 |
| *October* | 57.0 | 57.0 | 57.5 | 58.6 | 61.7 | 66.1 | 72.2 |
| *November* | 47.9 | 46.5 | 48.0 | 47.7 | 52.8 | 55.7 | 61.3 |
| *December* | 41.8 | 41.1 | 42.4 | 42.4 | 45.4 | 48.7 | 52.9 |
| **Average Mean Temperature (°F)** | | | | | | | |
| *Annual* | 66.6 | 67.2 | 67.9 | 68.2 | 68.9 | 71.7 | 75.7 |
| *Winter* | 52.0 | 51.9 | 52.2 | 53.1 | 54.4 | 57.2 | 60.6 |
| *Spring* | 66.3 | 66.3 | 66.7 | 66.9 | 68.8 | 71.6 | 75.5 |
| *Summer* | 80.4 | 81.0 | 81.9 | 81.7 | 82.9 | 86.2 | 90.5 |
| *Fall* | 68.0 | 68.3 | 68.9 | 69.4 | 71.7 | 75.0 | 79.9 |

| Variable | Observed Value (1990-2012) | Projected Value under Warmer Narrative | | | Projected Value under Hotter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| *January* | 50.4 | 50.0 | 50.2 | 50.7 | 53.4 | 56.4 | 59.7 |
| *February* | 53.5 | 52.4 | 53.0 | 53.5 | 56.0 | 58.4 | 61.1 |
| *March* | 59.7 | 59.4 | 60.0 | 60.4 | 62.7 | 64.7 | 68.0 |
| *April* | 65.7 | 65.3 | 65.8 | 66.3 | 68.4 | 71.3 | 75.0 |
| *May* | 73.4 | 73.3 | 73.7 | 74.0 | 76.0 | 79.5 | 83.6 |
| *June* | 79.1 | 79.3 | 79.7 | 79.6 | 81.7 | 85.0 | 89.2 |
| *July* | 81.3 | 81.7 | 82.4 | 82.4 | 83.9 | 87.2 | 91.5 |
| *August* | 81.0 | 81.8 | 82.4 | 82.8 | 83.5 | 86.8 | 91.3 |
| *September* | 77.1 | 77.7 | 78.0 | 79.0 | 80.4 | 83.8 | 88.5 |
| *October* | 67.9 | 68.2 | 68.7 | 69.6 | 71.8 | 75.4 | 80.5 |
| *November* | 59.2 | 58.6 | 60.0 | 59.5 | 63.5 | 66.4 | 71.4 |
| *December* | 52.3 | 51.9 | 52.7 | 53.0 | 55.7 | 59.1 | 63.2 |
| **Annual Highest Maximum Temperature (°F)** | | | | | | | |
| *Mean* | 97.0 | 97.6 | 98.3 | 98.4 | 99.3 | 102.2 | 106.3 |
| *50th Percentile* | 96.8 | 96.9 | 98.1 | 98.4 | 99.7 | 102.2 | 106.2 |
| *95th Percentile* | 101.3 | 100.6 | 102.0 | 101.9 | 104.4 | 107.3 | 111.8 |
| *Maximum* | 102.8 | 101.8 | 102.9 | 103.3 | 106.4 | 109.3 | 113.4 |
| **Number of Days above 95°F** | | | | | | | |
| *Annual* | 9.6 | 12.0 | 16.6 | 18.8 | 22.6 | 52.6 | 104.3 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 |
| *Spring* | 0.0 | -0.4 | -0.4 | 0.0 | 1.1 | 3.5 | 10.1 |
| *Summer* | 9.0 | 10.1 | 15.4 | 16.8 | 21.4 | 44.3 | 75.4 |
| *Fall* | 0.8 | 0.0 | 0.8 | 1.2 | 3.9 | 9.7 | 26.1 |
| **Number of Days above 100°F** | | | | | | | |
| *Annual* | 0.6 | 0.3 | 0.8 | 1.2 | 2.1 | 8.0 | 31.8 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Spring* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 1.8 |
| *Summer* | 0.6 | 0.2 | 0.6 | 1.2 | 2.0 | 7.1 | 25.3 |
| *Fall* | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 1.3 | 7.4 |

| Variable | Observed Value (1990-2012) | Projected Value under Warmer Narrative | | | Projected Value under Hotter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| **Number of Days above 105°F** | | | | | | | |
| *Annual* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 5.6 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Spring* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 |
| *Summer* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 4.9 |
| *Fall* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 |
| **Number of Days above 110°F** | | | | | | | |
| *Annual* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Spring* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Summer* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 |
| *Fall* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Maximum Number of Consecutive Days above 95°F** | | | | | | | |
| *Annual* | 3.9 | 3.6 | 6.1 | 6.3 | 10.2 | 23.9 | 57.3 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 |
| *Spring* | 0.1 | -0.1 | -0.1 | 0.1 | 0.8 | 2.5 | 6.9 |
| *Summer* | 3.8 | 3.6 | 6.1 | 6.0 | 10.0 | 22.5 | 48.3 |
| *Fall* | 0.5 | 0.1 | 0.4 | 0.8 | 2.5 | 6.0 | 16.6 |
| **Maximum Number of Consecutive Days above 100°F** | | | | | | | |
| *Annual* | 0.4 | 0.3 | 0.3 | 0.6 | 1.3 | 4.3 | 15.4 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| *Spring* | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 1.4 |
| *Summer* | 0.4 | 0.3 | 0.3 | 0.5 | 1.2 | 3.9 | 14.2 |
| *Fall* | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 1.0 | 5.0 |
| **Maximum Number of Consecutive Days above 105°F** | | | | | | | |
| *Annual* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 3.4 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Spring* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 |
| *Summer* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 3.2 |

| Variable | Observed Value (1990-2012) | Projected Value under Warmer Narrative | | | Projected Value under Hotter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| *Fall* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.8 |
| **Maximum Number of Consecutive Days above 110°F** | | | | | | | |
| *Annual* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 |
| *Winter* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Spring* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Summer* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 |
| *Fall* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Coldest 4 days in winter (°F)** | | | | | | | |
| *5th percentile* | 28.1 | 27.8 | 28.5 | 28.8 | 30.5 | 32.9 | 35.5 |
| *25th percentile* | 35.1 | 35.3 | 35.6 | 35.9 | 37.3 | 39.8 | 43.1 |
| *50th percentile* | 40.9 | 40.6 | 41.0 | 42.0 | 43.5 | 46.3 | 49.8 |
| *75th percentile* | 47.4 | 46.8 | 47.4 | 48.5 | 50.2 | 53.1 | 56.9 |
| *95th percentile* | 56.2 | 55.8 | 56.4 | 57.6 | 59.4 | 62.2 | 66.0 |
| *Mean* | 41.3 | 41.2 | 41.6 | 42.4 | 43.8 | 46.6 | 50.0 |
| **Coldest winter in 30 years (°F)** | 12.6 | 6.2 | 9.7 | 9.8 | 22.7 | 24.2 | 27.5 |
| **Warmest 4 days in summer (°F)** | | | | | | | |
| *5th percentile* | 84.1 | 84.0 | 84.8 | 84.9 | 87.0 | 89.5 | 92.4 |
| *25th percentile* | 87.6 | 88.1 | 88.5 | 88.6 | 89.8 | 92.1 | 95.1 |
| *50th percentile* | 89.7 | 90.3 | 90.8 | 90.9 | 91.8 | 94.1 | 97.4 |
| *75th percentile* | 91.7 | 92.2 | 93.0 | 93.2 | 93.9 | 96.4 | 99.9 |
| *95th percentile* | 95.0 | 95.2 | 96.0 | 96.1 | 97.3 | 99.9 | 103.9 |
| *Mean* | 89.7 | 90.1 | 90.9 | 90.8 | 91.8 | 94.2 | 97.5 |
| **Warmest summer in 30 years (°F)** | 100.8 | 100.0 | 100.5 | 101.3 | 103.9 | 106.6 | 110.9 |
| **Coldest day (°F)** | | | | | | | |
| *Mean* | 18.9 | 18.0 | 19.3 | 19.8 | 22.9 | 25.1 | 27.5 |
| *1st percentile* | 4.2 | -0.7 | 0.0 | 1.4 | 15.3 | 17.9 | 19.6 |
| *5th percentile* | 7.9 | 5.8 | 6.4 | 8.0 | 16.3 | 19.9 | 21.5 |
| *10th percentile* | 8.9 | 7.8 | 8.5 | 9.9 | 16.5 | 20.2 | 21.6 |
| *50th percentile* | 20.3 | 18.9 | 20.4 | 20.7 | 23.7 | 25.7 | 28.4 |

| Variable | Observed Value (1990-2012) | Projected Value under Warmer Narrative | | | Projected Value under Hotter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| **Maximum 7-day Temperature (°F)** | | | | | | | |
| *Mean* | 94.4 | 94.8 | 95.5 | 95.9 | 96.6 | 99.4 | 103.4 |
| *50th Percentile* | 94.2 | 94.2 | 95.5 | 96.1 | 97.1 | 99.4 | 103.1 |
| *90th percentile* | 97.2 | 97.0 | 97.4 | 97.6 | 99.9 | 102.9 | 107.1 |
| *95th Percentile* | 98.5 | 98.3 | 99.0 | 99.4 | 101.5 | 104.2 | 108.9 |
| *99th percentile* | 99.7 | 99.3 | 99.7 | 100.6 | 102.7 | 105.6 | 110.0 |

## G.2. Precipitation Projections—Drier and Wetter Narratives

**Table 150: Projected Values under Drier and Wetter Narratives for All Precipitation Variables (based on 5-station Mobile regional average)**

| Variable | Observed Value (1990-2012) | Projected Value under Drier Narrative | | | Projected Value under Wetter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| **Total Annual Precipitation (inches)** | | | | | | | |
| *Annual* | 65.4 | 61.0 | 60.3 | 56.5 | 76.8 | 80.2 | 83.0 |
| *Winter* | 15.3 | 14.1 | 13.1 | 12.9 | 19.1 | 20.1 | 20.6 |
| *Spring* | 15.7 | 13.2 | 12.2 | 10.6 | 18.9 | 18.6 | 20.8 |
| *Summer* | 20.2 | 15.2 | 15.3 | 11.6 | 26.6 | 28.8 | 29.6 |
| *Fall* | 14.2 | 12.3 | 12.8 | 12.4 | 18.6 | 20.1 | 21.0 |
| *January* | 5.5 | 4.2 | 4.8 | 4.6 | 7.6 | 7.1 | 7.7 |
| *February* | 5.1 | 4.0 | 3.5 | 3.7 | 6.7 | 6.8 | 6.9 |
| *March* | 5.9 | 4.6 | 4.0 | 4.3 | 7.2 | 7.7 | 8.0 |
| *April* | 4.8 | 3.6 | 2.8 | 2.5 | 6.6 | 6.8 | 6.8 |
| *May* | 5.0 | 3.5 | 3.2 | 2.7 | 6.6 | 6.6 | 7.3 |
| *June* | 6.1 | 4.3 | 3.6 | 3.3 | 8.1 | 8.2 | 8.1 |
| *July* | 7.7 | 5.1 | 5.2 | 3.4 | 9.7 | 11.9 | 12.0 |
| *August* | 6.4 | 4.1 | 3.6 | 3.0 | 11.4 | 11.1 | 12.0 |
| *September* | 5.5 | 3.9 | 3.5 | 2.7 | 8.9 | 9.8 | 11.2 |
| *October* | 3.9 | 2.5 | 2.8 | 2.3 | 5.9 | 6.5 | 6.9 |

| Variable | Observed Value (1990-2012) | Projected Value under Drier Narrative | | | Projected Value under Wetter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| *November* | 4.8 | 4.0 | 3.5 | 3.4 | 6.3 | 6.8 | 7.1 |
| *December* | 4.7 | 3.7 | 3.7 | 3.2 | 7.0 | 7.2 | 7.4 |
| **24-hour precipitation (inches)** | | | | | | | |
| *0.2% occurrence* | 13.5 | 10.5 | 13.8 | 12.9 | 28.0 | 25.9 | 28.9 |
| *1% occurrence* | 13.5 | 11.1 | 13.6 | 13.1 | 24.6 | 23.1 | 25.4 |
| *2% occurrence* | 12.5 | 10.4 | 12.6 | 12.1 | 22.2 | 20.9 | 22.9 |
| *5% occurrence* | 9.5 | 7.8 | 9.5 | 9.2 | 17.3 | 16.3 | 17.9 |
| *10% occurrence* | 8.5 | 7.2 | 8.5 | 8.3 | 14.8 | 14.1 | 15.3 |
| *20% occurrence* | 7.1 | 6.1 | 7.0 | 7.0 | 11.9 | 11.4 | 12.3 |
| *50% occurrence* | 4.8 | 4.3 | 4.7 | 4.6 | 7.2 | 7.1 | 7.6 |
| **24-hour precipitation - probability of baseline occurrence** | | | | | | | |
| *0.2% occurrence* | 0% | 0% | 0% | 0% | 11% | 9% | 12% |
| *1% occurrence* | 1% | 0% | 1% | 1% | 20% | 18% | 22% |
| *2% occurrence* | 2% | 0% | 3% | 2% | 27% | 25% | 29% |
| *5% occurrence* | 5% | 5% | 9% | 8% | 39% | 37% | 43% |
| *10% occurrence* | 10% | 16% | 21% | 19% | 53% | 53% | 56% |
| *20% occurrence* | 20% | 36% | 43% | 41% | 61% | 68% | 65% |
| *50% occurrence* | 50% | 96% | 103% | 101% | 77% | 82% | 79% |
| **Annual 4-Day precipitation (inches)** | | | | | | | |
| *0.2% occurrence* | 11.3 | 9.0 | 9.7 | 10.1 | 20.8 | 22.0 | 21.8 |
| *1% occurrence* | 6.9 | 6.1 | 6.7 | 6.9 | 9.8 | 9.9 | 10.5 |
| *2% occurrence* | 5.3 | 4.9 | 5.3 | 5.4 | 6.8 | 7.2 | 7.3 |
| *5% occurrence* | 3.7 | 3.5 | 3.6 | 3.6 | 4.3 | 4.6 | 4.7 |
| *10% occurrence* | 2.7 | 2.5 | 2.6 | 2.6 | 3.1 | 3.2 | 3.3 |
| *20% occurrence* | 1.7 | 1.7 | 1.6 | 1.6 | 2.4 | 2.0 | 2.1 |
| *50% occurrence* | 0.7 | 0.6 | 0.6 | 0.5 | 0.8 | 0.8 | 0.8 |
| **Annual 2-Day precipitation (inches)** | | | | | | | |
| *0.2% occurrence* | 9.3 | 7.3 | 9.6 | 9.0 | 18.0 | 17.5 | 18.2 |
| *1% occurrence* | 5.5 | 5.0 | 5.2 | 5.7 | 7.4 | 7.7 | 7.1 |

| Variable | Observed Value (1990-2012) | Projected Value under Drier Narrative | | | Projected Value under Wetter Narrative | | |
|---|---|---|---|---|---|---|---|
| | | Near-Term | Mid-Century | End-of-Century | Near-Term | Mid-Century | End-of-Century |
| *2% occurrence* | 4.1 | 3.9 | 3.9 | 4.0 | 5.1 | 5.5 | 5.4 |
| *5% occurrence* | 2.8 | 2.6 | 2.7 | 2.7 | 3.2 | 3.3 | 3.3 |
| *10% occurrence* | 2.0 | 1.9 | 2.0 | 1.9 | 2.3 | 2.3 | 2.3 |
| *20% occurrence* | 1.3 | 1.2 | 1.2 | 1.2 | 1.7 | 1.4 | 1.5 |
| *50% occurrence* | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 |
| **Seasonal 3-Day precipitation (inches)** | | | | | | | |
| *Winter* | 3.7 | 3.2 | 2.9 | 3.4 | 5.5 | 6.1 | 6.6 |
| *Spring* | 4.8 | 4.1 | 4.2 | 3.8 | 6.3 | 6.3 | 6.9 |
| *Summer* | 4.9 | 3.3 | 3.9 | 3.4 | 7.7 | 7.8 | 7.9 |
| *Fall* | 4.7 | 3.8 | 4.3 | 3.7 | 6.8 | 6.8 | 7.5 |

# H. Detailed Storm Surge Exposure Statistics

This appendix presents the final storm surge depths for each asset that are used to calculate exposure scores. These storm surge depths represent a combination of ADCIRC-modeled storm surge depths and STWAVE-modeled wave heights. These storm surge depths and wave heights were modeled for three storm scenarios: [144]

- Katrina Base – a hindcast simulation of Hurricane Katrina, following its historical path (landfalling near the Mississippi-Louisiana border) and intensity
- Katrina Shifted – a simulation of Hurricane Katrina with its path shifted to make landfall at Mobile
- Katrina Shifted, Pressure Reduced, 75 cm SLR – a simulation of Hurricane Katrina with its path shifted to be a direct hit to Mobile, its central pressure reduced 14% (an illustrative increase in intensity due to climate change), and assuming sea level rise of 75 cm.

The model outputs were used to determine the depth of storm surge (ADCIRC surge depth plus wave height) for each asset using the following methodology:

- First, the ADCIRC model outputs of maximum surge elevation under each scenario were compared with the model's underlying land and sea surface elevations to determine the depth of water at each location. These storm surge depths were determined for the entire study area. For locations that were inundated under the baseline scenario (i.e., are over water), the storm surge depth represents the surge elevation relative to mean sea level (MSL).
- For each asset, the study team used GIS to determine the maximum storm surge depth that intersected with the asset and the maximum STWAVE value[145] that intersected with that asset.
- To generate the final "storm surge depth" exposure indicator value for each asset, which represents a combination of modeled storm surge and waves, the study team added the ADCIRC storm surge depth to 75% of the wave height. The 75% adjustment factor was used to estimate the elevation of a wave crest relative to the still water level, since the waves are not entirely above the storm surge level.[146]

The values presented in Table 151 are the final outputs of this process, and represent the total depth, or "thickness," of the surge and waves at each asset.

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[144] U.S. DOT, 2012

[145] STWAVE outputs "spectrally significant wave height," which is related to the amount of energy in the wave field, but is not necessarily the largest wave that would occur at a location under the storm scenario.

[146] FHWA, 2008. 75% estimate based on HEC-25, 2nd edition and professional judgment.

Table 151: Storm Surge Depths Used for Exposure Scores (feet)

| Asset ID | Asset Name | Katrina Base | Katrina Shifted | Katrina Shifted, Pressure Reduced, 75 cm SLR |
|---|---|---|---|---|
| **Highways** | | | | |
| R1 | I-10 Tunnel (Wallace Tunnel) | 14.2 | 22.3 | 27.9 |
| R2 | I-10, intersection with I-65 | 2.2 | 12.7 | 18.2 |
| R3 | I-10, from Wallace Tunnel to S Broad Street | 5.2 | 14.1 | 20.1 |
| R4 | I-165, 1 mile before intersection with I-65 | 0.0 | 0.0 | 3.5 |
| R5 | I-65, between US-43 and County boundary | 14.3 | 21.7 | 27.3 |
| R6 | Telegraph Road, from Downtown to Baybridge Road | 14.2 | 22.4 | 28.3 |
| R7 | US-43 (Saraland Blvd N), northernmost portion | 0.0 | 0.0 | 0.0 |
| R8 | US-45 (St. Stephens Road), between Rylands Street and Simington Drive | 0.0 | 8.0 | 18.2 |
| R9 | US-90 (SR-16), section east of Broad Street | 4.5 | 12.8 | 18.7 |
| R10 | The Causeway (Battleship Parkway) | 17.8 | 27.5 | 29.1 |
| R11 | US-90, intersection with SR-163 and Government Street | 0.0 | 0.8 | 2.7 |
| R12 | Route 98 near the Stickney Filtration Plant | 0.0 | 0.0 | 0.0 |
| R13 | SR-163 (Dauphin Island Parkway), from I-10 to Brill Road | 1.7 | 11.1 | 15.4 |
| R14 | SR-163 (Dauphin Island Parkway), from Island Road to Terrell Road | 14.3 | 21.8 | 27.9 |
| R15 | SR-193 (Dauphin Island Parkway), from Dauphin Island Bridge to CR-188 | 11.3 | 17.7 | 22.2 |
| R16 | SR-193 (Range Line Road), running about 0.5 mile on either side of Theodore Industrial Canal | 10.7 | 16.7 | 21.8 |
| R17 | SR-193 (Range Line Road), between Rabbit Creek Drive and Tufts Road | 12.7 | 20.9 | 26.4 |
| R18 | Airport Blvd, between CR-31 (Schillinger Road) and airport | 0.0 | 0.0 | 0.0 |
| R19 | South University Blvd, 0.5 mile segment either side of CR-56 (Airport Blvd) | 0.0 | 0.0 | 0.0 |
| R20 | SR-188, where it crosses the river just North of Bayou la Batre | 14.2 | 23.5 | 27.4 |
| R21 | SR-188, from Douglas Road to US-90 West | 0.0 | 0.0 | 0.0 |
| R22 | SR-193 (Dauphin Island Parkway), from Old Cedar Point Road to Day Springs Road | 0.0 | 9.7 | 15.2 |
| R23 | SR-188, river crossing near Coden | 15.4 | 24.1 | 28.1 |
| R24 | Intersection of SR-188 and CR-59 (Bellingrath Road), near Fowl River | 12.9 | 21.1 | 25.3 |
| R25 | CR-59 (Bellingrath Road), 0.5 mile on either side of large stream crossing north of Plantation Woods Drive | 0.0 | 10.1 | 14.6 |
| R26 | Dauphin Island Bridge | 10.3 | 16.5 | 20.8 |
| R27 | I-10 Bridge across Mobile Bay | 18.1 | 27.6 | 29.7 |
| R28 | I-165, near intersection with Route 98 | 0.0 | 0.0 | 1.4 |
| R29 | Intersection of Airport Blvd and I-65, near drainage areas | 0.0 | 0.0 | 6.6 |
| R30 | Cochrane Bridge (Bay Bridge Road) | 14.2 | 22.6 | 27.7 |

| Asset ID | Asset Name | Katrina Base | Katrina Shifted | Katrina Shifted, Pressure Reduced, 75 cm SLR |
|---|---|---|---|---|
| R31 | CR-70 (Tanner Williams Road), along the J.B. Converse Reservoir dam and covering access to the Palmer S. Gaillard Pumping Station | 0.0 | 0.0 | 0.0 |
| R32 | Old Spanish Trail, between Cochrane Bridge and the tunnels | 10.4 | 18.5 | 23.7 |
| **Ports** | | | | |
| P1 | Alabama Bulk Terminal Co. (Hunt Refining Company) | 13.6 | 22.0 | 26.9 |
| P2 | Alabama State Port Authority (ASPA) - Alabama State Docks Main Complex | 14.6 | 23.4 | 29.0 |
| P3 | Alabama State Port Authority (ASPA) - McDuffie Terminal | 14.9 | 22.6 | 27.3 |
| P4 | Alabama State Port Authority (ASPA) - Mobile Middle Bay Port | 12.8 | 21.2 | 26.2 |
| P5 | Alabama State Port Authority (ASPA) - Pinto Island | 14.5 | 23.8 | 28.6 |
| P6 | Atlantic Marine (BAE Systems Southeast Shipyards) | 13.5 | 22.3 | 27.3 |
| P7 | Austal | 13.8 | 22.8 | 27.5 |
| P8 | Bayou La Batre | 16.2 | 25.4 | 29.2 |
| P9 | BP Oil Co., Mobile Terminal Barge Wharf | 13.3 | 22.0 | 27.2 |
| P10 | Crescent Towing & Salvage Co., River A Wharf | 14.1 | 22.8 | 28.2 |
| P11 | Environmental Treatment Team Wharf | 10.9 | 17.9 | 23.0 |
| P12 | Evonik Industries | 0.0 | 0.0 | 1.9 |
| P13 | Gulf Atlantic Oil Refining Co., North Terminal | 14.1 | 22.9 | 28.2 |
| P14 | Gulf Coast Asphalt Co., Mobile Terminal Wharf | 12.5 | 20.4 | 25.6 |
| P15 | Holcim Cement Wharf | 11.2 | 18.4 | 23.5 |
| P16 | Kimberly-Clark Corporation | 13.8 | 22.5 | 27.6 |
| P17 | Martin Marietta Aggregates | 10.7 | 16.9 | 21.9 |
| P18 | Mobile Container Terminal | 13.3 | 22.6 | 27.7 |
| P19 | Mobile Cruise Terminal | 14.0 | 22.8 | 28.0 |
| P20 | Oil Recovery Co. of Alabama, Mobile Terminal Pier | 13.4 | 22.6 | 27.7 |
| P21 | Plains Marketing - North Terminal | 14.1 | 22.9 | 28.1 |
| P22 | Plains Marketing - South Terminal | 14.0 | 23.2 | 28.6 |
| P23 | Shell Chemical Co. | 9.6 | 18.2 | 23.4 |
| P24 | Standard Concrete Products | 0.0 | 0.0 | 0.0 |
| P25 | TransMontaigne Product Services | 14.3 | 22.5 | 27.4 |
| P26 | U.S. Coast Guard Pier | 16.0 | 22.9 | 27.7 |
| **Airports** | | | | |
| BFM | Mobile Downtown Airport (Brookley Field) | 12.4 | 19.8 | 25.4 |
| MOB | Mobile Regional Airport | 0.0 | 0.0 | 0.0 |
| **Rail** | | | | |
| RR1 | TASD--rail yards near Alabama State Docks | 19.0 | 31.9 | 37.7 |
| RR2 | CSX M&M subdivision--segment along Mobile River between Cochrane Bridge and Twelvemile Island | 16.4 | 25.8 | 30.0 |
| RR3 | CSX NO&M subdivision--1.2 mile segment running along eastern edge of Downtown, between St. Louis St. and Elmira Street | 14.2 | 22.9 | 28.5 |

| Asset ID | Asset Name | Katrina Base | Katrina Shifted | Katrina Shifted, Pressure Reduced, 75 cm SLR |
|---|---|---|---|---|
| RR4 | CSX NO&M subdivision--3.9 mile segment running along I-10, near Dog River and its tributaries, between Dauphin Island Parkway and Cypress Shores Drive | 15.3 | 25.5 | 30.9 |
| RR5 | Norfolk Southern--1.6 mile segment running along US-43, near Le Moyne | 0.0 | 0.0 | 0.0 |
| RR6 | TASD--2.6 mile segment near ports on Tensaw River, approx. between Hardwood Lane and Travis Drive | 14.5 | 23.8 | 27.9 |
| RR7 | TASD--segment on eastern side of McDuffie Island | 12.8 | 21.7 | 27.0 |
| RR8 | TASD--segment on western side of McDuffie Island | 9.7 | 18.0 | 23.1 |
| RR9 | CSX NO&M subdivision--0.7 mile segment that is bisected by Hamilton Blvd., near Theodore | 0.0 | 0.0 | 0.0 |
| RR10 | CSX NO&M subdivision--1.2 mile segment on eastern side of Brookley airfield | 6.7 | 14.7 | 19.5 |
| RR11 | Norfolk Southern--segment running along Telegraph Rd, crossing Three Mile Creek | 12.8 | 21.1 | 27.0 |
| RR12 | CSX NO&M subdivision--segment running along US-90, between Grand Bay Wilmer Road and western edge of Grand Bay | 0.0 | 0.0 | 0.0 |
| **Transit** | | | | |
| T1 | Beltline O&M Facility | 0.0 | 0.0 | 0.0 |
| T2 | GM&O Terminal | 7.4 | 16.5 | 22.1 |