Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program Report

Prepared By

Houston-Galveston Area Council

With

Texas Department of Transportation
Texas A&M Transportation Institute

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Acknowledgements
Cooperation between groups and individuals has been paramount to the success of the Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program Report. Stakeholder groups are detailed on page 93 of this report.

Disclaimer Notice
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Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program

Houston-Galveston Area Council
Sambidi, Pramod PhD; Lee, Sungmin; Ranatunga, Thushara PhD; Janhsen, Kathy; Dang, David; Vo, Kathryn; Ronneberg, Kristina

Texas A&M Transportation Institute
Prozzi Jolanda; Birt Andrew; McFalls Jett

Houston-Galveston Area Council
3555 Timmons Lane, Suite 120
Houston, TX 77027

Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590

To address threats posed by extreme flood events, storm surge, and sea level rise in the region, the Houston-Galveston Metropolitan Planning Organization, in collaboration with the Texas Department of Transportation, partnered with the Federal Highway on the Administration on Resilience and Durability to Extreme Weather Pilot Program applied research in 2018. The goals were to (1) Assess the criticality and vulnerability of regional transportation assets to extreme weather events; (2) Develop a suite of recommendations for local governments for a more resilient transportation network; and (3) Use analysis from the Pilot Program to inform future publications and project selection criteria. The Pilot Program team analyzed two types of transportation infrastructure assets: Major Roads and Bridges. The team ran scenarios for flooding, storm surge, and sea level rise events to assess the impact on identified assets, specifically assessing criticality and vulnerability. Out of the 762 centerline freeway miles and 6,440 major road miles assessed in the region, 92 centerline freeway miles (12%) and 551 major road miles (9%) were highly critical. Thirteen percent of freeway centerline miles and 12% of major road miles were highly vulnerable to flooding, storm surge, and sea-level rise.
The intersection between the criticality and vulnerability assessments—known as the Criticality-Vulnerability Matrix—was developed by the team to identify assets that are both highly critical and highly vulnerable and therefore a priority for mitigation strategies in the Pilot Program area. Around 9.5 freeway centerline miles and 48 miles of major roads were highly critical and highly vulnerable to extreme weather events. The Pilot Program team developed the online Regional Resilience Tool to display the criticality and vulnerability of road segments. The lessons learned from the Pilot Program team’s analysis can be considered in four major areas: data availability and quality, data analysis, access to this Pilot Program’s findings, and commitment to collaborate and continue transportation resilience planning. The findings of the Pilot Program will be integrated into current and future planning studies, including the Low-Impact Development Study, Regional Transportation Plan, Transit-Oriented Development Study, Complete Streets Program, Sub-regional Studies, and a Region-wide Resiliency Study.

17. Key Words
Vulnerability, Criticality, Flooding, Storm Surge, Sea Level Rise, Resilience, LiDAR Data, Depth Grid, DEM, DSM, Hurricane Harvey, Hurricane Ike, Network Redundancy, Economic Impact, Adaptation, Mitigation

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<table>
<thead>
<tr>
<th>Table of Contents</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>2</td>
</tr>
<tr>
<td>Disclaimer Notice</td>
<td>2</td>
</tr>
<tr>
<td>Technical Report Documentation Page</td>
<td>3</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>5</td>
</tr>
<tr>
<td>List of Figures</td>
<td>8</td>
</tr>
<tr>
<td>List of Tables</td>
<td>11</td>
</tr>
<tr>
<td>Executive Summary</td>
<td>13</td>
</tr>
<tr>
<td>Assessing Transportation Infrastructure Assets</td>
<td>14</td>
</tr>
<tr>
<td>Criticality Assessment Results</td>
<td>14</td>
</tr>
<tr>
<td>Vulnerability Assessment Results</td>
<td>14</td>
</tr>
<tr>
<td>Criticality-Vulnerability Matrix</td>
<td>14</td>
</tr>
<tr>
<td>Regional Resilience Tool</td>
<td>14</td>
</tr>
<tr>
<td>Adaptation Strategies</td>
<td>16</td>
</tr>
<tr>
<td>Introduction</td>
<td>18</td>
</tr>
<tr>
<td>Study Area</td>
<td>19</td>
</tr>
<tr>
<td>The Resilience and Durability to Extreme Weather Pilot Program</td>
<td>21</td>
</tr>
<tr>
<td>The Houston-Galveston Area Council Region Resilience Pilot Program</td>
<td>21</td>
</tr>
<tr>
<td>Assets and Scenarios</td>
<td>26</td>
</tr>
<tr>
<td>Type 1: Major Roads</td>
<td>26</td>
</tr>
<tr>
<td>Type 2: Bridges</td>
<td>27</td>
</tr>
<tr>
<td>Scenario Development</td>
<td>29</td>
</tr>
<tr>
<td>Flooding</td>
<td>30</td>
</tr>
<tr>
<td>Storm Surge</td>
<td>36</td>
</tr>
<tr>
<td>Sea Level Rise</td>
<td>37</td>
</tr>
<tr>
<td>Assessments</td>
<td>40</td>
</tr>
<tr>
<td>Criticality Assessment</td>
<td>41</td>
</tr>
<tr>
<td>Criticality Assessment Results</td>
<td>42</td>
</tr>
<tr>
<td>Vulnerability Assessment</td>
<td>46</td>
</tr>
<tr>
<td>Exposure Assessment</td>
<td>47</td>
</tr>
<tr>
<td>Sensitivity Assessment</td>
<td>55</td>
</tr>
</tbody>
</table>
Economic Impact Analysis Scenario 2: Gulf Freeway (South and North Access to Galveston Causeway) ........................................................................................................... 159
Economic Impact Analysis Scenario 3: State Highway 146 (North Access to Fred Hartman Bridge) ..................................................................................................................... 163
Economic Impact Analysis Scenario 4: State Highway 225 (Pasadena Freeway)/Lawndale Street ................................................................................................................... 167
Economic Impact Analysis Scenario 5: US Highway 59 ......................................................................................................................................................... 170
Economic Impact Analysis Scenario 6: Farm-to-Market Roads 723 and 359 ................................................................................................................................. 173
Economic Impact Analysis Scenario 7: Interstate 10 .......................................................................................................................................................... 176
Economic Impact Analysis Scenario 8: North-South Connecters along Buffalo Bayou between Memorial Drive and Briar Forest ........................................... 179
Appendix D: Glossary and Acronyms ..................................................................................... 182
Overview ................................................................................................................................. 182
Glossary Definitions ............................................................................................................. 182
Acronym Definitions ........................................................................................................... 185
Appendix E: Adaptation Strategies .......................................................................................... 187
Strategy 1: Increase Number of Swales and Ditches ............................................................... 188
Strategy 2: Retention and Detention Ponds ........................................................................ 190
Strategy 3: Bioswales (Biofiltration Swales) ........................................................................ 193
Strategy 4: Depressed and Raised Medians ......................................................................... 195
Strategy 5: Green Infrastructure ............................................................................................ 197
Strategy 6: Culvert Cleaning/Maintenance .......................................................................... 199
Strategy 7: Stormwater Management Plan .......................................................................... 201
Strategy 8: Land Use Planning/Climate Justice ..................................................................... 203
Strategy 9: Relocate or Abandon Roads .............................................................................. 205
Strategy 10: Shelter-in-Place ................................................................................................. 207
Strategy 11: Evacuation Route Identification and Planning .................................................... 209
Strategy 12: Prohibiting Overweight / Oversize Vehicles ....................................................... 211
Strategy 13: Sensor Technologies and Monitoring Programs .............................................. 213
Strategy 14: Enhanced Road Surface .................................................................................... 216
Strategy 15: Enhanced Sub-Grade ....................................................................................... 218
Strategy 16: Hardened Shoulders ....................................................................................... 220
Strategy 17: Raised Road Profile ........................................................................................................ 222
Strategy 18: Geosynthetics / Geo Textiles ........................................................................................ 224
Strategy 19: Permeable Pavement ..................................................................................................... 226
Strategy 20: Maintain and Restore Wetlands .................................................................................. 228
Strategy 21: Beach Nourishment and Dune Restoration ................................................................. 230
Strategy 22: Vegetation (as Erosion Control) .................................................................................. 232
Strategy 23: Seawalls and Revetments .............................................................................................. 234
Strategy 24: Wave Attenuation Devices ............................................................................................ 236
Strategy 25: Debris Deflectors for Bridge Protection ..................................................................... 238

List of Figures
Figure 1- Regional Resilience Tool Landing Page ........................................................................ 15
Figure 2 - Adaptation Strategies ..................................................................................................... 16
Figure 3 – Houston-Galveston MPO Area Map ............................................................................... 19
Figure 4 – Eco-Regions in the Houston-Galveston Region .............................................................. 20
Figure 5 – Criticality / Vulnerability Matrix ................................................................................... 23
Figure 6 – Adaptation Strategies ..................................................................................................... 24
Figure 7 – Pilot Program Phased Approach .................................................................................... 25
Figure 8 – Major Roads in Pilot Program Study ............................................................................. 26
Figure 9 – TxDOT Major Road Network in Pilot Program Area ...................................................... 27
Figure 10- TxDOT Bridge over Waterway Inventory in Pilot Program Area ................................. 28
Figure 11 – Western Gulf of Mexico average and high temperature trends from 1976 to 2015, RICE SSPEED Center ........................................................................................................... 30
Figure 12 – 10-Year Average Texas Temperatures (°F) .................................................................. 31
Figure 13 – Flooding Related to Presidential Disaster Declarations (1953 – 2019) ......................... 32
Figure 14 - NOAA Atlas 14, Texas: Isopluvials of 100-year 24-hour precipitation in inches .. 33
Figure 15 – NOAA Atlas 14, Houston region: Isopluvials of 100-year 24-hour precipitation in inches ............................................................................................................................................ 34
Figure 16 – Harvey Depth Grids near Buffalo Bayou and Beltway 8 ........................................... 35
Figure 17 – Ike Storm Surge Inundation Map .................................................................................. 36
Figure 18 – SLOSH Model’s Category 4 Inundation Map ................................................................. 37
Figure 19 – Relative Sea Level Trend from Galveston Pier 21 ....................................................... 38
Figure 20 – Galveston Pier 21 Sea Level Rise Forecasts ................................................................. 39
Figure 21 – NOAA Sea Level Rise Model (5ft) ............................................................................... 39
Figure 22 – Criticality Assessment Results ..................................................................................... 43
Figure 23 – Freeway Criticality by County ..................................................................................... 44
Figure 24 – Major Road Criticality by County ............................................................................... 45
Figure 25 – Vulnerability Assessment Components (FHWA, 2015) ............................................... 46
Figure 26 – Digital Elevation Model at the intersection of Beltway 8 and Interstate 10

Figure 27 – Digital Surface Model at the intersection of Belt Way 8 and Interstate 10

Figure 28 – Digital Surface Model at the intersection of Belt Way 8 and Interstate 10

Figure 29 – Roadway/Bridge section elevation measured from DSM and flood water elevation measured by WSEL.

Figure 30 – Exposure Depth Grid

Figure 31 – Exposure Depth Grid along Beltway 8

Figure 32 – Model Exposure Depth Grid Data at Highway 288 and Holly Hall Street

Figure 33 – SkyDrone 13 video shows flooding on Highway 288 (ABC 13, 2020)

Figure 34 – Network Redundancy Calculation

Figure 35 – Transportation Detour Ratio

Figure 36 – Vulnerability Index Range

Figure 37 – 500-year flooding event vulnerability results

Figure 38 – Hurricane Harvey flooding event vulnerability results

Figure 39 – Category 4 hurricane storm surge vulnerability results

Figure 40 – Hurricane Ike storm surge vulnerability results

Figure 41 – 5-feet Sea Level Rise vulnerability results

Figure 42 – Freeway Vulnerabilities Against Inland Flooding

Figure 43 – Major Road Vulnerabilities Against Inland Flooding

Figure 44 – Freeway Vulnerabilities Against Coastal Storm Surge

Figure 45 – Major Road Vulnerabilities Against Coastal Storm Surge

Figure 46 – Freeway Vulnerabilities Against All Climate Stressors

Figure 47 – Major Road Vulnerabilities Against All Climate Stressors

Figure 48 – Criticality - Vulnerability Matrix

Figure 49 – Criticality - Vulnerability Matrix: Flooding

Figure 50 – Criticality - Vulnerability Matrix: Storm Surge

Figure 51 – Criticality - Vulnerability Matrix: Sea-Level Rise

Figure 52 – Criticality - Vulnerability Matrix: Combine

Figure 53 – Criticality - Vulnerability Matrix: Combine Freeways

Figure 54 – Criticality - Vulnerability Matrix: Combine Major Streets

Figure 55 – Transportation Assets Selected for the Economic Impact Analysis

Figure 56 – Criticality-Access to Airports

Figure 57 – Criticality-Access to Port Facilities

Figure 58 – Criticality-Access to Activity Population

Figure 59 – Criticality-Annually Averaged Daily Traffic

Figure 60 – Criticality-Annually Averaged Daily Truck Traffic

Figure 61 – Criticality-Transit Rides

Figure 62 – Criticality-Access to Hospitals

Figure 63 – Criticality-Access to Fire Stations

Figure 64 – Criticality- Services to Vulnerable Populations

Figure 65 – Criticality-Evacuation Route
Figure 104 – Economic Impact Analysis Scenario 3-500-Year Flooding

Figure 105 – Economic Impact Analysis Scenario 3-Category 4 Hurricane Storm Surge

Figure 106 – Economic Impact Analysis Scenario 3-Hurricane Ike Storm Surge

Figure 107 – Economic Impact Analysis Scenario 3-TDM Network

Figure 108 – State Highway 225 (Pasadena Freeway)/Lawndale Street

Figure 109 – Economic Impact Analysis Scenario 4-Hurricane Harvey Flooding

Figure 110 – Economic Impact Analysis Scenario 4-500-Year Flooding

Figure 111 – Economic Impact Analysis Scenario 4-Category 4 Hurricane Storm Surge

Figure 112 – Economic Impact Analysis Scenario 4-TDM Network

Figure 113 – US Highway 59 between County Road 379 and State Highway 105 Bypass

Figure 114 – Economic Impact Analysis Scenario 5-Hurricane Harvey Flooding

Figure 115 – Economic Impact Analysis Scenario 5-500-year Flooding

Figure 116 – Economic Impact Analysis Scenario 5-TDM Network

Figure 117 – Farm-to-Market Roads 723 and 359 Segments

Figure 118 – Economic Impact Analysis Scenario 6-Hurricane Harvey Flooding

Figure 119 – Economic Impact Analysis Scenario 6-500-Year Flooding

Figure 120 – Economic Impact Analysis Scenario 6-TDM Network

Figure 121 – Interstate 10 Segments

Figure 122 – Economic Impact Analysis Scenario 7-Hurricane Harvey Flooding

Figure 123 – Economic Impact Analysis Scenario 7-500-Year Flooding

Figure 124 – Economic Impact Analysis Scenario 7-TDM Network

Figure 125 – North-South Connecters along Buffalo Bayou between Memorial Drive and Briar Forest

Figure 126 – Economic Impact Analysis Scenario 8-Hurricane Harvey Flooding

Figure 127 – Economic Impact Analysis Scenario 8-500-Year Flooding

Figure 128 – Economic Impact Analysis Scenario 8-TDM Network

List of Tables

Table 1 – Roadway Exposure Level

Table 2 – Bridge Exposure Level

Table 3 – Summary of Freeway Centerline Mile Criticality and Vulnerability

Table 4 – Summary of Major Road Centerline Mile Criticality and Vulnerability

Table 5 – H-GAC Transportation Network Resilience Summary

Table 6 – HGAC Transportation Network Resilience Summary

Table 7 – Assessment of Resiliency Adaptation Strategies

Table 8 – Pilot Program Stakeholders

Table 9 – Inland Flooding

Table 10 – Moderate to Low Risk Areas

Table 11 – High Risk Areas

Table 12 – Undetermined Risk Areas

Table 13 – Bridge Exposure Classification Criteria
Table 14 – Roadway Exposure Classification Criteria (inland flooding; coastal storm surge) ...................................................................................................................................................................................... 141
Table 15 – Roadway Exposure Classification Criteria (sea level rise) ........................................ 141
Table 16 – Bridge Sensitivity Indicators and Scoring Criteria .................................................. 143
Table 17 – Road Sensitivity Indicators and Scoring Criteria .................................................... 145
Table 18 – Bridge Adaptive Capacity Indicators and Scoring Criteria ................................. 146
Table 19 – Road Segment Adaptive Capacity Indicators and Scoring Criteria .................... 146
Table 20 – Vulnerability Score Weighting Criteria ................................................................. 147
EXECUTIVE SUMMARY

Located along the Texas Gulf Coast, the Houston-Galveston region is an important and fast-growing economic hub, employing more than 3.1 million people and contributing 27% of the state’s total gross domestic product each year. However, the region is also vulnerable to flooding.

Areas along the coast are inherently vulnerable to the forces of nature, particularly tropical storms, hurricanes, and stalled storm fronts. However, the propensity for flooding in the Houston-Galveston region has increased with regional growth and the removal of nature-based infrastructure that naturally mitigates flood risks. Extreme flood events, storm surge, and sea level rise pose a threat to multiple types of infrastructure, specifically transportation infrastructure necessary for moving goods and people in the region.

To address these threats, the Houston-Galveston Metropolitan Planning Organization (MPO), in collaboration with the Texas Department of Transportation (TxDOT), was selected to partner with the Federal Highway Administration (FHWA) on a Resilience and Durability to Extreme Weather applied research in 2018.

The applied research cooperatively funded the Resilience and Durability to Extreme Weather in the H-GAC (Houston-Galveston Area Council) Region Pilot Program (H-GAC Region Resilience Pilot Program or Pilot Program). This Pilot Program uses the FHWA’s Vulnerability Assessment Framework to assess the vulnerability and risk of a transportation asset to extreme weather impacts or other current and future environmental conditions under multiple scenarios.

The goals of the H-GAC Region Resilience Pilot Program are to:

- Assess the criticality and vulnerability of regional transportation assets to extreme weather events
- Develop a suite of recommendations for local governments to use for a more resilient transportation network (see Adaptation Strategies on page 82).
- Use analysis from the Pilot Program to inform future publications and project selection criteria
Assessing Transportation Infrastructure Assets
The Pilot Program team (the team) analyzed two types of transportation infrastructure assets for the Pilot Program: Major Roads and Bridges. The team ran scenarios for flooding, storm surge, and sea level rise events to assess the impact on identified assets, specifically assessing the criticality— which assets are highly critical to the region’s routine functions and economic activities— and vulnerability— which assets are highly vulnerable to the climate stressors the region is likely to face.

Criticality Assessment Results
Out of the 762 centerline freeway miles and 6,440 major road miles in the region, 92 centerline freeway miles (12%) and 551 centerline major road miles (9%) were found to be highly critical.

Vulnerability Assessment Results
With respect to vulnerability, 13% of freeway centerline miles and 12% of major road centerline miles were found to be highly vulnerable to flooding, storm surge and sea-level rise.

Criticality-Vulnerability Matrix
The intersection between the criticality and vulnerability assessments—known as the Criticality-Vulnerability Matrix—was developed by the team to identify those assets that are both highly critical and highly vulnerable and therefore a priority for mitigation strategies in the Pilot Program area. Around 9.5 centerline miles of freeway and 48 centerline miles of major roads were found to be highly critical and highly vulnerable to extreme weather events.

Regional Resilience Tool
As part of the Pilot Program, the team developed the online Regional Resilience Tool1 to display the criticality and vulnerability of road segments. The tool also includes the modeled flood exposure depth grid data that identifies the specific parts of the road segment vulnerable to flooding. This information is useful in planning road improvements and developing mitigation strategies. Figure 1 shows the home landing page for the tool.

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1 https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee
Figure 1- Regional Resilience Tool Landing Page
Adaptation Strategies

Using best practices set forth by the FHWA and stakeholder input, the team identified 25 Adaptation Strategies. These strategies identify implementable options to protect vulnerable and critical assets, providing criteria that local governments can consider when selecting a strategy. Figure 2 lists the 25 strategies.

Figure 2 - Adaptation Strategies

<table>
<thead>
<tr>
<th>STORMWATER MANAGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Increase Number of Swales &amp; Ditches</td>
</tr>
<tr>
<td>2. Retention &amp; Detention Ponds</td>
</tr>
<tr>
<td>3. Depressed &amp; Raised Medians</td>
</tr>
<tr>
<td>4. Bioswales (Biofiltration Swales)</td>
</tr>
<tr>
<td>5. Green Infrastructure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Culvert Cleaning &amp; Maintenance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PLANNING/SOCIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Stormwater Management Plan</td>
</tr>
<tr>
<td>8. Land Use Planning/Climate Justice</td>
</tr>
<tr>
<td>9. Relocate or Abandon Roads</td>
</tr>
<tr>
<td>10. Shelter-In-Place</td>
</tr>
<tr>
<td>11. Evacuation Route Identification &amp; Planning</td>
</tr>
<tr>
<td>12. Prohibiting Overweight/Oversize Vehicles</td>
</tr>
<tr>
<td>13. Sensor Technologies &amp; Monitoring Programs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INFRASTRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>14. Enhanced Road Surface</td>
</tr>
<tr>
<td>15. Enhanced Sub-Grade</td>
</tr>
<tr>
<td>16. Hardened Shoulders</td>
</tr>
<tr>
<td>17. Raised Road Profile</td>
</tr>
<tr>
<td>18. Geosynthetics/Geo Textiles</td>
</tr>
<tr>
<td>19. Permeable Pavement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>20. Maintain &amp; Restore Wetlands</td>
</tr>
<tr>
<td>21. Beach Nourishment &amp; Dune Restoration</td>
</tr>
<tr>
<td>22. Vegetation (as Erosion Control)</td>
</tr>
<tr>
<td>23. Seawalls &amp; Revetments</td>
</tr>
<tr>
<td>24. Wave Attenuation Devices</td>
</tr>
<tr>
<td>25. Debris Deflectors for Bridge Protection</td>
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</tbody>
</table>
Next Steps and Recommendations

The Houston-Galveston Area Council MPO values the findings of this report and acknowledges that this is the first step toward a more resilient transportation system for the region. The findings of the Pilot Program will be integrated into current and future planning studies, including the Low-Impact Development Study, Regional Transportation Plan, Transit-Oriented Development Study, Complete Streets Program, Sub-regional Studies, and a Region-wide Resiliency Study.

The Low-Impact Development Study will expand on the 25 Adaptation Strategies and incorporate additional analysis of implementable options for decision-makers and developers to adopt within the public right-of-way. Understanding the criticality and vulnerability of major roads and bridges will enable more careful articulation of climate impacts on hurricane routes and route alternatives in the Regional Transportation Plan and Sub-Regional Studies. While most of the planning studies will continue this Pilot Program’s focus on resiliency for vehicle travel, the Houston-Galveston MPO will study the impacts of flood and stormwater on active transportation modes like bicycling and walking. Through context-sensitive design, the Complete Streets Program, a movement to ensure that roadways provide for the mobility and safety of all, will identify the nexus between impacts on all travel modes—with specific focus on filling in the gap of active transportation—and localized flooding to determine resilient strategies for roadway, bikeway, and walkway design.

This report will provide decision-makers the necessary tools and expert information to incorporate resiliency into the project selection process and evaluation criteria for the Transportation Improvement Program, a fiscally constrained financial plan of transportation projects approved to receive federal funding over the next four-years, and associated funding.
INTRODUCTION

The Houston-Galveston region consistently ranks as one of the fastest-growing metropolitan areas in the United States, leading the nation’s economic growth potential. From 2010 to 2018, jobs in the region increased from around 2.5 million to almost 3.1 million (U.S. Census Bureau, 2020).

Employment is projected to increase to approximately 4.8 million by 2045. The projected job growth is expected to be greatest in the urban core within TX-8 Beltway (Beltway 8). The population in the region has increased, rising from approximately 3.1 million residents in 1980 to 6.8 million in 2018—an increase of nearly one million residents per decade. This growth trend is expected to continue and, by 2045, the region will be home to about 10.7 million people (Houston-Galveston Area Council, 2018).

The region consistently floods, as areas along the coast are inherently exposed to the forces of nature, particularly tropical storms, hurricanes, and stalled storm fronts. However, the propensity for flooding has increased with regional growth and the loss of the natural eco-region that naturally mitigates flood risks.

The frequency of extreme flood events in the region is increasing (SeaLevelRise.org, 2020). Since 1953, there have been 70 hurricanes, 51 flood events, and 37 severe storms declared Federal Emergency Management Agency (FEMA) Disasters in the Houston-Galveston region (Federal Emergency Management Agency, 2019).

An increase in extreme flood events generated a renewed focus on and interest in flooding, as evidenced by some of the priorities in the Texas State Legislature’s 86th Legislative session.²

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Study Area
Spanning over 8,000 square miles, the Houston-Galveston MPO region consists of an 8-county Transportation Management Area (TMA)\(^3\) and is characterized by its diversity of built and natural environments. The most significant natural boundary for the region is the Gulf of Mexico. Figure 3 shows the Houston-Galveston MPO region.

Figure 3 – Houston-Galveston MPO Area Map

Despite being one of the nation’s fastest growing regions—well known for its expansive urban and suburban development—its natural eco-regions, such as forests, prairies, bottomlands, coastal plains, wetlands, and bays, remain prominent (see Figure 4). In fact, almost 40% of the region’s land cover is categorized as forest, grass, or wetland and 99% of residents live within five miles of a major stream.

\(^3\) Brazoria, Chambers, Fort Bend, Galveston, Harris, Montgomery, Liberty, and Waller counties comprise the Houston-Galveston TMA.
These natural eco-regions provide valuable benefits to the region by purifying the water and air, trapping carbon emissions, buffering the force of waves and currents, managing floodwaters, securing groundwater, preventing erosion, and more.

Natural eco-regions are crucial to the region’s health and resilience. Numerous efforts are underway to protect the eco-regions through conservation easements and restoration projects led by local organizations, including the Bayou Land Conservancy, the Katy Prairie Conservancy, Houston Audubon, and the Galveston Bay Foundation. The Houston-Galveston Area Council (H-GAC) recently updated its Eco-Logical\(^4\) base map and tool, which identifies the various regional ecotypes including prairies, wetlands, and upland and

\(^4\) https://www.h-gac.com/eco-logical
bottom land forests. The tool was created to assist efforts to preserve wildlife habitats and ecological diversity as the region plans for the expansion of infrastructure to accommodate population growth and increased mobility. In addition, the development of a Regional Conservation Framework is currently underway through partnerships with local governments and private landowners. This Framework will outline goals, priorities, and best practices for incorporating conservation features in land use planning.

While there are many benefits associated with the region’s extensive economic and population growth, there are also consequences, many of which affect the natural environment. All infrastructure projects—whether residential, commercial, transportation, or other—require a transition from natural to built infrastructure or from permeable to impermeable surfaces. While new construction often seeks to mitigate habitat loss, water contamination, and flooding, impermeable surfaces can still result in increased flooding.

The Houston-Galveston region is particularly prone to flooding. Recent events, such as the Memorial Day Flood (2015), Tax Day Flood (2016), and Hurricane Harvey (2017), demonstrate the region’s vulnerability to inland and coastal flooding.

As a result of Hurricane Harvey, which produced 50 inches of rain over seven days, H-GAC’s 2045 Regional Transportation Plan identified more than $3.1 billion in potential investment to mitigate the flood risk to critical regional and local highways (Clark, 2017). However, the investments identified in the plan accounted for those areas impacted by Hurricane Harvey flooding and did not model for other extreme weather scenarios.

**The Resilience and Durability to Extreme Weather Pilot Program**

To provide communities adversely impacted by changing weather patterns and flood events an opportunity to explore vulnerability strategies, the FHWA began to partner with state and regional entities on a series of Resilience and Durability to Extreme Weather Pilot Programs in 2010. This program helps communities develop tools to improve transportation infrastructure durability and resilience.

At the time of this publication, the FHWA had sponsored more than 50 pilot projects, each seeking to meet one or more of the following programmatic goals: (1) integrate resilience and durability into agency practices; (2) use available tools and resources to assess the vulnerability and risk of transportation projects or systems; or (3) deploy a resilience solution and monitor its performance (U.S. Department of Transportation, 2020).

**The Houston-Galveston Area Council Region Resilience Pilot Program**

H-GAC’s previous work in resiliency focused on identifying vital infrastructure using Hurricane Harvey data or identifying mitigation projects that could be implemented within the region to address specific vulnerabilities, without in-depth analysis of criticality (Houston-Galveston Area Council, 2018).
The H-GAC Region Resilience Pilot Program used the FHWA’s Vulnerability Assessment Framework to assess the vulnerability and risk of the transportation system to current and future extreme weather impacts and environmental conditions under multiple scenarios.

The goals of the H-GAC Region Resilience Pilot Program are to:

- Measure the criticality and vulnerability of regional transportation assets to extreme weather events
- Develop a suite of recommendations for local governments to use for a more resilient transportation network (see Adaptation Strategies on page 82)
- Use analysis from the Pilot Program to inform future publications and project selection criteria

The objective of this planning effort is to provide local governments and partners with tools to plan resiliently and to improve the quality of life of residents and employees throughout the region.
This Pilot Program supports long-range transportation planning in two ways:

1. Criticality and Vulnerability
   The criticality assessment for the Pilot Program identifies transportation assets that are imperative to the region’s routine functions and economic activities (see Criticality Assessment on page 41). The vulnerability assessment identifies transportation assets that are susceptible to the climate stressors the region is likely to face (see Vulnerability Assessment on page 46).

   The Criticality / Vulnerability Matrix (see Figure 5) assesses the intersection between the two variables to identify and prioritize specific transportation assets in the Pilot Program area necessitating resilient mitigation strategies.

![Figure 5 – Criticality / Vulnerability Matrix](image)
2. Adaptation Strategies

The first step in increasing the region’s resilience and mitigating flood risks is identifying which transportation assets are considered both highly critical and highly vulnerable. The second step is to develop strategies to illustrate how those assets might be protected. The team identified 25 Adaptation Strategies (see Figure 6) to showcase the various options decision-makers may use to protect vulnerable and critical transportation assets.

![Figure 6 – Adaptation Strategies](image)

<table>
<thead>
<tr>
<th>STORMWATER MANAGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Increase Number of Swales &amp; Ditches</td>
</tr>
<tr>
<td>2. Retention &amp; Detention Ponds</td>
</tr>
<tr>
<td>3. Depressed &amp; Raised Medians</td>
</tr>
<tr>
<td>4. Bioswales (Biofiltration Swales)</td>
</tr>
<tr>
<td>5. Green Infrastructure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Culvert Cleaning &amp; Maintenance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PLANNING/SOCIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Stormwater Management Plan</td>
</tr>
<tr>
<td>8. Land Use Planning/ Climate Justice</td>
</tr>
<tr>
<td>9. Relocate or Abandon Roads</td>
</tr>
<tr>
<td>10. Shelter-In-Place</td>
</tr>
<tr>
<td>11. Evacuation Route Identification &amp; Planning</td>
</tr>
<tr>
<td>12. Prohibiting Overweight/ Oversize Vehicles</td>
</tr>
<tr>
<td>13. Sensor Technologies &amp; Monitoring Programs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INFRASTRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>14. Enhanced Road Surface</td>
</tr>
<tr>
<td>15. Enhanced Sub-Grade</td>
</tr>
<tr>
<td>16. Hardened Shoulders</td>
</tr>
<tr>
<td>17. Railed Road Profiles</td>
</tr>
<tr>
<td>18. Geosynthetics/ Geo Textiles</td>
</tr>
<tr>
<td>19. Permeable Pavement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>20. Maintain &amp; Restore Wetlands</td>
</tr>
<tr>
<td>21. Beach Nourishment &amp; Dune Restoration</td>
</tr>
<tr>
<td>22. Vegetation (as Erosion Control)</td>
</tr>
<tr>
<td>23. Seawalls &amp; Revetments</td>
</tr>
<tr>
<td>24. Wave Attenuation Devices</td>
</tr>
<tr>
<td>25. Debris Deflectors for Bridge Protection</td>
</tr>
</tbody>
</table>
The analysis and recommendations outlined in the Pilot Program were developed over two years, following the phased approach detailed in Figure 7.

**Figure 7 – Pilot Program Phased Approach**
ASSETS AND SCENARIOS

Relevant transportation infrastructure assets must be identified before conducting the criticality or vulnerability assessments. For the Pilot Program, the team studied two types of transportation infrastructure assets within the region: Major Roads and Bridges.5

**Type 1: Major Roads**

The team considered 83 freeway segments (762 centerline miles) and 7,696 major roads (6,442 centerline miles), including major arterials, minor arterials, and collectors, shown in Figure 8.

To identify these assets, the team downloaded the most current version of the roadway database, released in late 2018, from the TxDOT’s Geospatial Roadway Inventory Database (GRID). The roadway database is a polyline feature representing the centerline of the roads. To produce road inundation area maps, the team converted the road network into an area feature—where the area between linear and curvilinear objects is accounted for—and used in further analysis for the Pilot Program. The TxDOT Major Road Network in the Pilot Program Area are shown in Figure 9.

---

The datasets were initially acquired from TxDOT Roadway Inventory Database and Bridge Inspection databases in GIS feature class formats and processed for the Pilot Program requirements.
Type 2: Bridges
The team considered 3,489 bridges over waterways for the Pilot Program.

To identify this asset type, the team downloaded the most recent bridge data, released in 2018, from the TxDOT Bridge Inspection Database. The dataset is a statewide point dataset of bridge locations maintained by the Bridge Division of TxDOT and contains a record for each bridge structure on public roadways in Texas. This includes bridges maintained by TxDOT, toll authorities, counties, municipalities, and other jurisdictions.

Bridge inventory from TxDOT is a point marker and does not include the area coverage or span of the bridges. To create the bridge feature with area coverage, the team combined bridge data with the area information generated from LiDAR point cloud. The LiDAR data used in this analysis (see Exposure Assessment page 47) was a classified point cloud that included the bridge as one of its classifications. Using ArcGIS LiDAR processing tools and Python 3.6 scripting, the team extracted the bridge area and generated a regularized
bridge feature dataset. By overlaying the TxDOT bridge inventory point data with the extracted bridge area feature, the team developed the final bridge area dataset and assigned the related TxDOT bridge identification numbers. The TxDOT Bridge over Waterway Inventory in Pilot Program Area is shown in Figure 10.
Scenario Development
To appropriately assess risk for the identified transportation assets, the team developed 11 scenarios to model flooding, storm surge, and sea level rise impacts in the Pilot Program area. These scenarios were based on historic data of extreme weather events in the region and feedback received from stakeholders early in the Pilot Program (see Stakeholder Engagement on page 93).

- Flooding
  1. 100-Year Flood
  2. **500-Year Flood**
  3. Hurricane Harvey

- Storm Surge
  1. Category 1 Storm
  2. Category 2 Storm
  3. Category 3 Storm
  4. **Category 4 Storm**
  5. Category 5 Storm
  6. Hurricane Ike

- Seal-Level Rise
  1. Sea Level Rise 4ft (National Oceanic and Atmospheric Administration)
  2. **Sea Level Rise 5ft (National Oceanic and Atmospheric Administration)**

*The bold scenarios were used for the detailed analysis presented throughout the remainder of this report.*
Flooding
Climate change has adversely affected the region with associated flooding. Fueled by an increasingly warm Gulf of Mexico, as shown in Figures 11 and Figure 12, future hurricanes are projected to be larger and more intense than past storms. Atmospheric warming and moisture retention, in combination with warm Gulf waters, causes more water evaporation of the Gulf; as temperatures increase, hurricanes will continue to worsen (Blackburn, 2019).

Figure 11 – Western Gulf of Mexico average and high temperature trends from 1976 to 2015, RICE SSPEED Center
The region is under constant threat of extreme flooding events. Since 2015, the region experienced the Memorial Day flood (May 2015), the Halloween flood (October 2015), the Tax Day flood (April 2016), Hurricane Harvey (August 2017)— a Category 4 hurricane that produced a flood event that became one of the most damaging natural disasters in U.S. history— and Tropical Storm Imelda (September 2019).

With the increased storm frequency and intensity, concerns surrounding flooding have increased, particularly the feeling that the region is experiencing a “new normal” and another devastating flooding event is imminent. Flooding Related to Presidential Disaster Declarations (1953 – 2019) is shown on Figure 13.
To better understand flooding associated with rainfall, the team looked to Atlas 14. Commissioned by the National Oceanic and Atmospheric Administration (NOAA) and implemented by the Hydrometeorological Design Studies Center with the Office of Water Prediction, Atlas 14 has been completed across most of the United States and was updated for Texas. Isopluvials of 100-year 24-hour precipitation in inches for Texas is shows in Figure 14. Note: a 100-year event is a storm that has a 1% likelihood of occurring in any given year.

**What is NOAA Atlas 14?**

The NOAA Atlas 14 presents a new analysis of rainfall data through 2017. It demonstrates that 100-year rainfall events in the Pilot Program area have increased to 17 inches in 24 hours from the previous 13 inches in the same time frame, which was based on The U.S. Weather Bureau Technical Paper No. 40 (TP-40) published in 1961. This represents a 30% increase in a 100-year rainfall event (Climate Discovery, 2020).

In Houston, the 100-year storm in our old climate was 12.5 inches in 24 hours. The new Atlas 14 shows the Houston 25-year storm is now 12.1. The 100-year storm total has increased to 17.9 inches, an increase of 43%. Harris County Commissioners Court unanimously adopted to implement new standards requiring developers to build enough detention to offset flooding in the 500-year floodplain. Previously, county requirements only covered the 100-year floodplain. The new rules will be effective until FEMA flood maps are updated (Community Impact Newspaper, 2020).
Figure 14 - NOAA Atlas 14, Texas: Isopluvials of 100-year 24-hour precipitation in inches
The team modeled three flood levels: **100-year flood**, **500-year flood**, and **Hurricane Harvey**. The models use 100-year and 500-year flooding from interpolating high-water depths using FEMA National Hazard maps for 100-year and 500-year floodplains. Isopluvials of 100-year 24-hour precipitation in inches for the Houston region is shown in Figure 15.

**Figure 15 – NOAA Atlas 14, Houston region: Isopluvials of 100-year 24-hour precipitation in inches**
For flood modelling, the Hurricane Harvey model came from the FEMA Harvey Depth Grid, which included the following notes:

- Based on observed water levels at stream gauges interpolated along rivers, downsampled to 5-meter resolution Digital Elevation Model (DEM)
- Depth grids are updated with new observed peak crest as they become available
- Extents validated with remote sensing
- Use for determining damage levels on specific structures

Harvey depth grids near Buffalo Bayou and Beltway 8 are shown in Figure 16.
Storm Surge

Storm surge is defined by NOAA as “the abnormal rise of water generated by a storm, over and above the normal tide... expressed in terms of height above predicted or expected tide levels”. Storm surge impacts coastal areas and generally occurs where winds are blowing onshore.

In 2001, the massive rainfall that occurred with Tropical Storm Allison was considered an anomaly. Allison doubled Houston's previous 24-hour rainfall record with 26-inch rain in east Harris County in a 24-hour period. When Hurricane Ike, a Category 2 storm, hit the region in 2008, it generated a larger than normal surge for a storm of its size. Hurricane Ike submerged most of the land east of Galveston Bay to 17 feet above sea level (see Figure 17). After Ike, the National Weather Service changed their hurricane classification program to separate the storm category from the prediction of storm surge. This differentiation analyzes wind speed separate from other factors, such as the size of the hurricane-force wind field.

Figure 17 – Ike Storm Surge Inundation Map
For the Pilot Program, the team modeled six storm levels: Category 1, Category 2, Category 3, Category 4, Category 5, and, for historical reference, Hurricane Ike. The models use the Maximum of Maximums (MOM) from tens of thousands of simulated storms from the National Hurricane Center’s Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (see Figure 18). Simulated storms moving from all forward directions retain the highest surge values and represent a worst-case scenario for the storm category modeled.

Figure 18 – SLOSH Model’s Category 4 Inundation Map

Sea Level Rise
Independent of rainfall events, sea levels are rising due to warming oceans, increased melting of land-based ice, such as glaciers and ice sheets, and land subsidence. Rising sea level inundates low-lying wetlands and dry land, erodes shorelines, contributes to coastal flooding, and increases the flow of salt water into estuaries and nearby groundwater aquifers. Higher sea level makes coastal infrastructure more vulnerable to damage from storms (EPA’s Report on the Environment, 2020).

NOAA measures the sea level from Pier 21 on the bay side of Galveston Island. Over the past 100 years, sea level at Pier 21 has risen more than two feet. At 0.25 inch (6.55 mm)/year, Galveston has one of the highest-measured rates of sea level rise in the country (Galveston Bay Report Card, 2020).
As sea levels rise, existing coastal flooding worsens and beaches erode, eventually submerging wetlands and dry land. As of spring 2020, the State of Texas has planned over $12 billion in sea level rise solutions, which include storm surge protection, drainage and erosion control, and flood mitigation projects (Figure 19 shows relative sea level trend at the Galveston Pier 21 tide gauge).

Figure 19 – Relative Sea Level Trend from Galveston Pier 21

Experts are not certain how fast the ocean will warm, or ice will melt. However, they expect water levels to continue to rise faster in the future (National Oceanic and Atmospheric Administration, 2019). Therefore, scientists from the NOAA and the US Army Corps of Engineers (USACE) have made predictions based on ranges from low to high.

Figure 20 shows the range of the NOAA and USACE high and intermediate forecast for Galveston Pier 21. Currently, the USACE high forecast, shown as the darkest red line, is the most likely projection.

How is Sea Level Rise Measured?

Sea levels are measured every 6 minutes using equipment such as satellites, floating buoys off the coast, and tide gauges to measure the exact sea level as local sea levels accelerate and change. (SeaLevelRise.org, 2020)
Per the NOAA Sea Level Rise Viewer, the sea level of Galveston Pier 21 area with ‘High’ scenario will reach 5 feet higher than current Mean Higher High-Water level around 2070 (see Figure 21).
ASSESSMENTS

A crucial element to the Pilot Program is the identification of highly critical and highly vulnerable transportation assets and infrastructure in the region. Once identified, these assets are modeled using the 11 scenarios identified by the Pilot Program team.

The results of these identification assessments can be used as justifications for further economic analysis and infrastructure improvement proposals. To identify these assets objectively and systematically, the team conducted two data-driven, GIS-based assessments:

- **criticality assessment** identifies transportation assets that are crucial to the region’s routine functions and economic activities; and
- **vulnerability assessment** identifies transportation assets that are most susceptible to probable regional climate stressors.

Those assessments were used to conduct further analysis:

- **criticality-vulnerability assessment** identifies those assets that are both highly critical and highly vulnerable, and therefore a priority for mitigation strategies in the Pilot Program area; and
- **economic impact analysis** estimates the economic impact of short-term transportation network disruptions to the region.

For this Pilot Program, the team studied two types of transportation infrastructure assets within the region: Major Roads and Bridges. Major Roads include freeways and major roads, including major arterials, minor arterials, and collectors. Roadway Bridges include waterway bridges only. Other transportation asset types, such as railways, transit facilities and pipelines, are not considered in the Pilot Program.

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6 The datasets were initially acquired from TxDOT Roadway Inventory Database and Bridge Inspection databases in GIS feature class formats and processed for the Pilot Program requirements.
Criticality Assessment

By analyzing the regional transportation system and economic activities in a disruption-free scenario, the criticality assessment aims to identify transportation assets that provide vital support to a functioning regional transportation network.

The team evaluated four transportation criticality perspective categories in the assessment, weighted based on feedback from stakeholders:

1. **Socioeconomic importance – 20% in the overall criticality assessment**
   Assessed by considering how each transportation asset contributes to the regional economy and provides access to key employment, trade, and travel hotspots. The specific indicators included in this category are service to activity population, links to airports, and water ports.

2. **Usage and operational importance – 40% in the overall criticality assessment**
   Assessed by considering the volumes and types of traffic that each transportation asset holds. The specific indicators included in this category are—Average Annual Daily Traffic (AADT), AADT- truck, and transit ridership.

3. **Health and safety importance – 30% in the overall criticality assessment**
   Assessed by considering how each transportation asset provides access to healthcare and safety facilities and connects underserved areas and population. The specific indicators included in this category are links to hospitals and fire stations and service to vulnerable population.

4. **Emergency preparedness importance – 10% in the overall criticality assessment**
   Assessed by considering what roles each transportation asset plays in a state of emergency. The specific indicators included in this category are evacuation routes, links to shelters and emergency operation centers (EOC), and access to military facilities.
For each category, the team selected and analyzed multiple indicators to capture related characteristics of each transportation asset. For each transportation asset, the team categorized selected indicators and scored them based on their attributes and importance to the transportation network. Scores range from 0 to 4 for most indicators, with 4 suggesting highest criticality for an asset. All data analysis was performed using SAS and ArcGIS.

The result of the criticality assessment is the aggregated criticality index, derived from the weighted summary of all scores of individual indicators. The weighting schemes were generated by the team after analyzing polling results from a stakeholder engagement meeting (see Stakeholder Engagement on page 93).

The team ranked aggregated criticality scores and cumulatively standardized them on a scale of 0 to 1, with 1 representing the most highly critical roadway in the region. After normalization, roadways with an index higher than 0.67 were considered highly critical to the regional transportation system; roadways with an index between 0.33 to 0.66 were considered moderately critical; and the remaining roadways on the index were considered lowly critical.

A single assessment for all roadways considering traffic levels and importance to the regional network could lead to substantial bias toward freeways. To mitigate this issue, staff ensured all data processing procedures, such as scoring, weighting, ranking, and standardization, were conducted separately for freeway segments and major road segments.

Detailed methodology of the criticality assessment, including indicator selection and calculation, weight schemes and data sources, as well as results for each assessment component, are specified in Appendix A on page 101.

Criticality Assessment Results
Criticality results are shown in Figure 22. Among a total of 762 centerline freeway miles and 6,440 major road miles, 92 centerline miles of freeways and 551 centerline major road miles are highly critical, accounting for 12% of freeway miles and 9% of major road miles.
Figure 22 – Criticality Assessment Results
For freeways, all highly critical assets are within Harris County, home to the city of Houston and the economic center of the Houston-Galveston MPO region. Apart from 6 miles of US-59 in Montgomery County that are classified as moderately critical, all freeway segments outside Harris County are considered to be of low criticality.

Similarly, 93% of highly critical major roads are in Harris County—only 44% of the regional total centerline miles. Conversely, rural counties, such as Chambers, Liberty and Waller, collectively have less than 4% of major road centerline miles classified as highly critical. Detailed centerline mile distributions by county and criticality category are shown in Figures 23 and 24.

Figure 23 – Freeway Criticality by County

![Figure 23 – Freeway Criticality by County](image)
Highly and moderately critical road segments are largely concentrated in the city of Houston and surrounding suburbs. Freeways connecting major employment centers, such as Houston downtown, the Energy Corridor, and Galleria area are highly critical, mostly due to their high socioeconomic importance, usage, and operational importance. Highly critical local roads are almost entirely within the 610 Loop in the city of Houston.

Outside of Harris County, the highly critical major roads are mostly near major neighborhoods in communities, such as Sugar Land, The Woodlands, Pearland, and Galveston. Please refer to the Appendix A on page 101 for criticality results by specific indicators. Criticality scores for individual indicators can also be accessed from the online Regional Resilience Tool7.

7 https://hgac.maps.arcgis.com/apps/MapSeries/index.htmlappid=deae412562ab461ead3a1f0908ab22ee
Vulnerability Assessment
The vulnerability assessment is the core component of the Pilot Program. The key objective of the vulnerability assessment is to comprehensively evaluate the capacity of a transportation asset to endure and recover from climate exposures and service disruptions in extreme weather events.

The vulnerability assessment assesses the probability of the occurrence of disruption of a transportation asset due to extreme weather and, should the disruption occur, the consequences of the disruption. Vulnerability assessment includes three components: Exposure, Sensitivity, and Adaptive Capacity (see Figure 25).

Figure 25 – Vulnerability Assessment Components (FHWA, 2015)
In each assessment section, indicators derived from geospatial analysis are used to evaluate the risk component. The vulnerability assessment structure resembles the U.S. Department of Transportation / FHWA Vulnerability Assessment Scoring Tool (VAST). However, to achieve enhanced data customization in the assessment, the team used SAS and ArcGIS for the data analysis in the assessment instead of VAST.

**Exposure Assessment**

Exposure is the critical component of the vulnerability assessment as it indicates whether a road segment or a bridge is flooded or not based on a given flooding scenario. To measure the level of flooding, the following factors are needed:

1. **Ground Elevation** - To measure the ground and surface elevation, the team used the 2018 LiDAR data. The ground elevation is measured using the DEM, which is a bare-earth raster grid usually representing the surface of the earth.

Once above-ground natural and built features, such as trees and other types of vegetation, roads, bridges, buildings, powerlines, etc., are filtered out, a smooth DEM is produced. For this effort, the team measured ground surface level and heights with respect to the DEM value at a specific location.

Figure 26 shows the Buffalo Bayou and part of Beltway 8 South at a lower elevation compared to the surrounding area.

What is LiDAR?

LiDAR is a remote sensing technology that measures distance, elevation, or surface by illuminating a target with a laser and analyzing the reflected light. The acronym for LiDAR commonly refers to Light Detection and Ranging. LiDAR is popularly used as a technology for creating high resolution maps and data representing surfaces and elevations.
2. **Surface Elevation**- To obtain the height information of transportation infrastructure assets, an altitude model is required in addition to DEM. The altitude model used by the team is the Digital Surface Model (DSM), an elevation model that contains the elevation of terrain as well as above-ground natural and built features. Figure 27 shows the highly elevated ramps connecting Beltway 8 and Interstate 10 in dark red. It also shows Buffalo Bayou and part of Beltway 8 South at the lowest elevation in light green.
3. **Water Depth**: One of the primary ways to communicate flood risks and inform actions that can be taken to reduce flood risks is through grid datasets on water depth. These datasets provide detailed information of flooding depth, probability of flooding, and other flooding characteristics. Like pixels in an image or picture, a grid is a digital raster dataset that defines geographic space as an array of equally sized square cells arranged in rows and columns. The value in each grid represents the magnitude of flooding characteristics at a given location.

The Water Surface Elevation (WSEL) grid is generally the first raster dataset that will be produced as part of a flood risk study. A separate WSEL grid is produced for each flood event (e.g. 1% annual-chance, 0.2% annual-chance, 1% annual-chance future conditions, 1%-plus, etc.) or flood scenario for which modeled elevations are available.
Each WSEL grid provides the modeled WSEL values within the inundation extent of that flood event or scenario. The team collected the WSEL data for the Pilot Program from FEMA (100-Year flooding, 500-Year flooding, and Hurricane Harvey) and NOAA (Storm Surge, Hurricane Ike, and Sea-Level Rise).

To identify areas that are outside the floodplain, but are prone to flooding, the team spatially interpolated FEMA’s 100-year and 500-year flood zone boundaries. The interpolation yielded a spatially continuous WSEL for each flooding event. The team calculated the flood depth grid data for each scenario by measuring the difference between WSEL and DEM. Figure 28 shows FEMA’s Harvey Flood Depths Grid data near Beltway 8 and Interstate 10. It shows parts of Beltway 8 South under water and Buffalo Bayou overflowing into surrounding areas.

Figure 28 – Digital Surface Model at the intersection of Belt Way 8 and Interstate 10
4. **Exposure Depth** - Exposure depth grid is a 5-by-5-meter raster grid representing flood level on top of a structure, such as a roadway or bridge section. The value of exposure depth grid is equal to the difference between roadway/bridge surface elevation, or DSM, and flood WSEL (see Figures 29 and 30). Exposure depth for roadway segments and bridges was measured using the various water depth data mentioned in the previous section.

**Figure 29** – Roadway/Bridge section elevation measured from DSM and flood water elevation measured by WSEL

**Figure 30** – Exposure Depth Grid

**Exposure Depth Grid**  \( A = B - C \)
The roadway exposure level indicates how at risk a roadway is to an exposure type. The five levels used are detailed in Table 1. Note: the team defines risk as service disruption to roads and bridges in the event of floods, storm surges, and sea level rise. In the Pilot Program, flood depth is used as the risk exposure level to assess the intensity/duration of disruption. The Pilot Program assumes that as the flood depth increases, so does the intensity/duration of interruptions.

Table 1– Roadway Exposure Level

<table>
<thead>
<tr>
<th>Exposure Description</th>
<th>Exposure Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not exposed/ Less than 0 foot of flood water</td>
<td>No exposure or low risk</td>
</tr>
<tr>
<td>0 - 1 foot of flood water</td>
<td>Medium-low risk</td>
</tr>
<tr>
<td>1 - 2 feet of flood water</td>
<td>Medium risk</td>
</tr>
<tr>
<td>2 - 3 feet of flood water</td>
<td>Medium-high risk</td>
</tr>
<tr>
<td>More than 3 feet of flood water</td>
<td>High risk</td>
</tr>
</tbody>
</table>

The bridge exposure level uses different scales to reflect the safe operation of a bridge, as detailed in Table 2.

Table 2– Bridge Exposure Level

<table>
<thead>
<tr>
<th>Exposure Description</th>
<th>Exposure Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 + feet below deck</td>
<td>No exposure or low risk</td>
</tr>
<tr>
<td>Water level 4-6 feet below deck</td>
<td>Medium-low risk</td>
</tr>
<tr>
<td>Water level 2-4 feet below deck</td>
<td>Medium risk</td>
</tr>
</tbody>
</table>
Water level within 2 feet below deck  
Medium-high risk

Water level above bridge deck  
High risk

Figure 31 shows the modeled Hurricane Harvey exposure depth grid data at the intersection of Beltway 8 and Interstate 10. The figure shows parts of Beltway 8 and Wilcrest Road (parallel to Beltway 8) as high risk for flooding. These segments were flooded from Hurricane Harvey as Buffalo Bayou overflowed.

Figure 31 – Exposure Depth Grid along Beltway 8
Figure 32 shows the exposure depth grid data for Highway 288 at Holly Hall Street. The model estimates a portion of the highway at this location as high risk for flooding even though it is outside the 500-year flood plain. This estimate is validated by the flooding that occurred on September 22, 2020, because of Tropical Storm Beta.
Figure 33, an image from ABC 13, shows the same portion of the Highway 288 flooded as indicated by the modeled high-risk exposure depth grid data. Detailed methodology of the LiDAR data processing and flood modeling are documented in Appendix B on page 124.

Figure 33 – SkyDrone 13 video shows flooding on Highway 288 (ABC 13, 2020)

Sensitivity Assessment
Sensitivity measures whether an asset will be damaged or disrupted when exposed to the given stressor. The team used indicators related to transportation asset structures, conditions, and disruption histories to assess transportation asset sensitivity. The factor considered for the sensitivity assessments include bridge age, structural evaluation, channel conditions, scour ratings, pavement condition, and past closures related to flooding.
Adaptive Capacity Assessment

Adaptive capacity measures how well the transportation system can cope with damage or disruption to a specific transportation asset. Indicators related to repair cost and network redundancy are used in this report.

Network redundancy, or detour ratio, is the total additional travel a through-bound vehicle would experience because of a street segment closure. Detour ratio is measured by direct and detour travel time between two points. Higher detour ratios indicate much longer detour routes relative to the shortest path route. Smaller detour ratios indicate that comparable detour paths are available within the system, and therefore suggest low redundancy for the shortest path route. Travel times are calculated using ESRI Network Analyst. The network redundancy calculation is detailed in Figure 34 and the transportation detour ratio is shown in Figure 35.

Figure 34 – Network Redundancy Calculation

\[
\text{Redundancy (Detour Ratio): Average of A-B & B-A} \\
A-B = \frac{\text{Minutes of Detour Route (A-B)}}{\text{Minutes of Direct Route (A-B)}} = \frac{2}{1} = 2 \\
B-A = \frac{\text{Minutes of Detour Route (B-A)}}{\text{Minutes of Direct Route (B-A)}} = \frac{2}{1} = 2
\]

* In case of one-way street/freeway system, A-B is not same with B-A.
Figure 35 – Transportation Detour Ratio
Overall Vulnerability Index

The aggregated vulnerability index is calculated as a weighted summary of the exposure index, sensitivity index, and adaptive capacity index (see Figure 36). The team conducted calculations for freeway segments and major road segments separately to remedy ranking bias toward freeways.

The final vulnerability index is cumulatively standardized from 0 to 1, with 1 representing asset most vulnerable to the given climate stressor. An index higher than 0.67 indicates high vulnerability of a transportation asset, an index between 0.33 to 0.66 indicates moderate vulnerability, and an index lower than 0.33 indicates low vulnerability or not exposed at all.

Vulnerability scores for bridges are not presented separately in this report but are combined with the road segments. For road segments with bridges, the number of high-risk bridges on each centerline mile is calculated and used as an additional indicator to calculate the final vulnerability score, and this indicator is given a 30% weight. The final vulnerability score of a road segment with bridge includes 70% of road segment (excluding bridge portion) vulnerability score and 30% of bridge vulnerability score. The vulnerability scores for individual bridges for various climate stressors are presented in the online Regional Resilience Tool.

Detailed methodology of the vulnerability assessment, including climate model simulation, indicator selection and categorization, weight schemes and data sources, as well as results for each assessment component, are documented in Appendix B on page 124.

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8 https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee
Vulnerability Assessment Results
For each climate scenario, including 500-Year flooding, Hurricane Harvey, Category 4 storm surge, Hurricane Ike, and 5-foot Sea-Level Rise, the vulnerability assessment results are presented separately.

500-Year Flooding Events
For 500-year flooding events, 11% of freeways and 11% of major roads centerline miles are classified as highly vulnerable in the region. Among highly vulnerable freeways, 58 miles are in Harris County and 24 miles are in Galveston County. For major roads, 365 miles in Harris County, 164 miles in Brazoria County, and 114 miles in Brazoria County are considered highly vulnerable. Road segments alongside bayous and coastlines are more likely to be highly vulnerable to flooding events. Figure 37 shows vulnerability for 500-year flooding modeled for the region.

Figure 37 – 500-year flooding event vulnerability results
Hurricane Harvey Flooding Event
Flooding caused by Hurricane Harvey in 2017 is more severe than a modeled 500-year flooding event, with more than 14% of freeways experiencing high vulnerability. As Hurricane Harvey’s rainfall was more concentrated in inland areas, Harris and Montgomery counties saw the highest high vulnerability miles. Around 10% of major roads in the region experienced high vulnerability for Hurricane Harvey, with the clear majority located in Harris County, along Buffalo Bayou and the Houston Ship Channel. Figure 38 shows vulnerability for Hurricane Harvey flooding modeled for the region.

Figure 38 – Hurricane Harvey flooding event vulnerability results
Category 4 Hurricane Storm Surge
Road segments that are highly vulnerable to Category 4 storm surge are densely located in the coastal areas of Galveston, Harris, and Brazoria counties. Around 7% of freeways are highly vulnerable to storm surges. About 4% of major roads are highly vulnerable to storm surges, most located in Galveston, Brazoria, and Chambers counties. Most inland roads are not impacted by coastal storm surge.

Figure 39 shows vulnerability for Category 4 storm surge modeled for the region.

Figure 39 – Category 4 hurricane storm surge vulnerability results
Hurricane Ike Storm Surge
As a Category 4 hurricane, Hurricane Ike had a higher impact on the region’s transportation system compared to NOAA’s storm surge model. For Hurricane Ike, 11% of freeways experienced high vulnerability, with most them in Brazoria and Galveston counties. As for major roads, 5% of the regional miles were highly vulnerable. Local roads in Chambers and Harris counties, along Buffalo Bayou and around Galveston Bay and Trinity Bay, were among the most vulnerable.

Figure 40 shows vulnerability for Hurricane Ike storm surge modeled for the region.

Figure 40 – Hurricane Ike storm surge vulnerability results
Sea Level Rise

Sea level rise of 5 feet is likely to affect Galveston County only. Interstate 45 connecting Galveston Island and the mainland is the only freeway likely to be highly vulnerable. All major roads that are highly vulnerable are located on Galveston Island.

Figure 41 shows vulnerability for 5-feet sea level rise modeled for the region.
**Composite Scoring**

After consolidating results from different climate scenarios for each climate stressor, the team constructed a composite score for each natural hazard.

**Flood Vulnerability** = 500-year Flood Vulnerability (50%) + Harvey Flooding (50%)

**Storm Surge Vulnerability** = Category 4 Hurricane Storm Surge (50%) + Ike Storm Surge (50%)

**Sea Level Rise Vulnerability** = 5-feet Sea-level Rise (100%)

**Combined Vulnerability** = Flood Vulnerability (50%) + Storm Surge Vulnerability (35%) + Sea-level Rise Vulnerability (15%)

The percentage of road segments (freeways and major roads) of different vulnerability classifications are shown in Figure 42. Around 10% of freeway centerline miles are highly vulnerable to inland flooding, and around 21% are moderately vulnerable in the Houston-Galveston MPO region. The entire segment of Interstate 9 that crosses Liberty County is estimated to highly vulnerable to inland flooding.

**Figure 42 – Freeway Vulnerabilities Against Inland Flooding**
Figure 43 shows that around 11% of major road centerline miles are highly vulnerable to inland flooding, and around 19% are moderately vulnerable in the region. Every county in the region has some segments of major roads that are highly vulnerable to inland flooding.
Figure 44 shows that around 8% of freeway centerline miles are highly vulnerable to coastal storm surge, and around 8% are moderately vulnerable in the region. Most of the freeway segments in Galveston (91%) and Brazoria County (59%) are highly vulnerable to flooding related to coastal storm surge.

Figure 44 – Freeway Vulnerabilities Against Coastal Storm Surge

Freeway vulnerabilities against coastal storm surge

- H-GAC MPO
- Waller County
- Montgomery County
- Liberty County
- Harris County
- Galveston County
- Fort Bend County
- Chambers County
- Brazoria County

Legend:
- Red: High
- Yellow: Moderate
- Green: Low
Figure 45 shows that around 4% of major road centerline miles are highly vulnerable to coastal storm surge, and around 5% are moderately vulnerable in the region. In Galveston County, 32% of major road centerline miles are highly vulnerable to coastal flooding.

Figure 45 – Major Road Vulnerabilities Against Coastal Storm Surge
Figure 46 shows that around 13% of freeway centerline miles are highly vulnerable to flooding related to all climate stressors combined, and around 20% are moderately vulnerable in the region. Most of the freeway segments in Galveston (69%) and Brazoria (59%) counties are highly vulnerable to flooding related to all climate stressors combined.

*Figure 46 – Freeway Vulnerabilities Against All Climate Stressors*
Figure 47 shows that around 12% of major road centerline miles are highly vulnerable to flooding related to all climate stressors combined, and around 19% are moderately vulnerable in the region. The vulnerability scores for individual road segments and bridges for various climate stressors are presented in the online Regional Resilience Tool.

---

Figure 47 – Major Road Vulnerabilities Against All Climate Stressors

---

9 https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee
Criticality-Vulnerability Matrix
The team constructed a criticality-vulnerability matrix (CVM) for all road segments in the region, as shown in Figure 48. The team developed a CVM for each climate scenario of flooding, storm surge, and sea level rise, as well as a combined scenario CVM. The criticality values for transportation assets are the same across the various CVMs, however the vulnerability values differ with respect to a given climate scenario. Highly critical and highly vulnerable road segments are considered high risk transportation assets that require further improvement or reinforcement to contribute to a resilient regional transportation network against natural disaster. The road segments that are moderately critical and highly vulnerable, or highly critical and moderately vulnerable, can also be considered at risk resilient projects.

![Figure 48 – Criticality - Vulnerability Matrix](image-url)
Figures 49, 50, and 51 show the composite of vulnerability and criticality of transportation assets in the flooding, storm surge, and sea level rise scenarios, respectively. Road segments that are highly critical and highly vulnerable are color-coded in red. Figure 52 shows the composite of vulnerability and criticality of transportation assets for all climate stressors combined.

Figure 49 – Criticality - Vulnerability Matrix: Flooding
Figure 50 – Criticality - Vulnerability Matrix: Storm Surge
Figure 51 – Criticality - Vulnerability Matrix: Sea-Level Rise
Table 3 and Figure 53 present the criticality and vulnerability summary of freeway centerline miles in the Houston-Galveston MPO region. Around 10 miles of freeway centerline miles are estimated to be highly critical and highly vulnerable, whereas around 43 miles are estimated to be highly critical and moderately vulnerable or moderately critical and highly vulnerable.
Of the 762.2 freeway centerline miles in the region, the Pilot Program estimates around 3.11 miles of Interstate 45 and around 6.37 miles of Interstate 10 East are highly critical and highly vulnerable.

### Table 3 - Summary of Freeway Centerline Mile Criticality and Vulnerability

<table>
<thead>
<tr>
<th>Matrix Summary</th>
<th>Miles</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>762.2</td>
<td>100.0%</td>
</tr>
<tr>
<td>High Criticality - High Vulnerability</td>
<td>9.5</td>
<td>1.2%</td>
</tr>
<tr>
<td>Moderate Criticality - High Vulnerability</td>
<td>23.2</td>
<td>3.0%</td>
</tr>
<tr>
<td>High Criticality - Moderate Vulnerability</td>
<td>20.2</td>
<td>2.6%</td>
</tr>
<tr>
<td>Low Criticality - High Vulnerability</td>
<td>66.2</td>
<td>8.7%</td>
</tr>
<tr>
<td>High Criticality - Low Vulnerability</td>
<td>61.5</td>
<td>8.1%</td>
</tr>
<tr>
<td>Moderate Criticality - Moderate Vulnerability</td>
<td>18.3</td>
<td>2.4%</td>
</tr>
<tr>
<td>Low Criticality - Moderate Vulnerability</td>
<td>113.7</td>
<td>14.9%</td>
</tr>
<tr>
<td>Moderate Criticality - Low Vulnerability</td>
<td>63.1</td>
<td>8.3%</td>
</tr>
<tr>
<td>Low Criticality - Low Vulnerability</td>
<td>386.5</td>
<td>50.7%</td>
</tr>
</tbody>
</table>

### Freeways Details (excerpt)

<table>
<thead>
<tr>
<th>Matrix Name</th>
<th>Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Criticality - High Vulnerability</td>
<td>I-45</td>
</tr>
<tr>
<td></td>
<td>IH 10 E</td>
</tr>
<tr>
<td></td>
<td>GULF FWY/IH 45</td>
</tr>
<tr>
<td></td>
<td>IH 10 E</td>
</tr>
<tr>
<td></td>
<td>IH 69</td>
</tr>
<tr>
<td></td>
<td>IH 10 E</td>
</tr>
<tr>
<td></td>
<td>IH 10 W</td>
</tr>
<tr>
<td></td>
<td>IH 69</td>
</tr>
<tr>
<td></td>
<td>SOUTH FWY/SH 288</td>
</tr>
<tr>
<td></td>
<td>SOUTH LOOP E</td>
</tr>
<tr>
<td></td>
<td>IH 10 W</td>
</tr>
<tr>
<td></td>
<td>IH 45</td>
</tr>
<tr>
<td></td>
<td>IH 69</td>
</tr>
<tr>
<td></td>
<td>NORTH FWY/IH 45</td>
</tr>
<tr>
<td></td>
<td>NORTH LOOP</td>
</tr>
<tr>
<td></td>
<td>SOUTH LOOP E</td>
</tr>
<tr>
<td></td>
<td>GULF FWY/IH 45</td>
</tr>
<tr>
<td></td>
<td>SH 146</td>
</tr>
<tr>
<td></td>
<td>SH 288</td>
</tr>
</tbody>
</table>
Table 4 and Figure 54 show the criticality and vulnerability summary of major road centerline miles in region. Of the 6,442 major road centerline miles evaluated, 48 miles are estimated to be highly critical and highly vulnerable, whereas around 259 miles are estimated to be highly critical and moderately vulnerable or moderately critical and highly
vulnerable. The criticality and vulnerability scores for individual road segments for various climate stressors are presented in the online Regional Resilience Tool\(^\text{10}\).

Table 4 – Summary of Major Road Centerline Mile Criticality and Vulnerability

<table>
<thead>
<tr>
<th>Matrix Summary</th>
<th>Miles</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>6,442.0</td>
<td>100.0%</td>
</tr>
<tr>
<td>High Criticality -High Vulnerability</td>
<td>48</td>
<td>0.7%</td>
</tr>
<tr>
<td>Moderate Criticality -High Vulnerability</td>
<td>119</td>
<td>1.9%</td>
</tr>
<tr>
<td>High Criticality -Moderate Vulnerability</td>
<td>140</td>
<td>2.2%</td>
</tr>
<tr>
<td>Low Criticality -High Vulnerability</td>
<td>595</td>
<td>9.2%</td>
</tr>
<tr>
<td>High Criticality -Low Vulnerability</td>
<td>364</td>
<td>5.7%</td>
</tr>
<tr>
<td>Moderate Criticality -Moderate Vulnerability</td>
<td>191</td>
<td>3.0%</td>
</tr>
<tr>
<td>Low Criticality -Moderate Vulnerability</td>
<td>861</td>
<td>13.4%</td>
</tr>
<tr>
<td>Moderate Criticality -Low Vulnerability</td>
<td>611</td>
<td>9.5%</td>
</tr>
<tr>
<td>Low Criticality -Low Vulnerability</td>
<td>3,512</td>
<td>54.5%</td>
</tr>
</tbody>
</table>

Principal Arterials Details (excerpt)

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Name</th>
<th>Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Criticality -High Vulnerability</td>
<td>BROADWAY (Galveston)</td>
<td>2.617</td>
</tr>
<tr>
<td></td>
<td>SH 3</td>
<td>1.537</td>
</tr>
<tr>
<td></td>
<td>BROADWAY (Houston)</td>
<td>0.777</td>
</tr>
<tr>
<td></td>
<td>COLLEGE</td>
<td>1.199</td>
</tr>
<tr>
<td></td>
<td>CULLEN</td>
<td>0.735</td>
</tr>
<tr>
<td></td>
<td>FAIRMONT PKWY</td>
<td>1.021</td>
</tr>
<tr>
<td></td>
<td>FEDERAL</td>
<td>0.462</td>
</tr>
<tr>
<td></td>
<td>FM 1960</td>
<td>0.142</td>
</tr>
<tr>
<td></td>
<td>KIRBY DR</td>
<td>0.635</td>
</tr>
<tr>
<td></td>
<td>LOCKWOOD DR</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>MEMORIAL DR</td>
<td>0.637</td>
</tr>
<tr>
<td></td>
<td>MONROE</td>
<td>0.134</td>
</tr>
<tr>
<td></td>
<td>NASA RD 1</td>
<td>1.237</td>
</tr>
<tr>
<td></td>
<td>OLD SPANISH TRAIL</td>
<td>0.102</td>
</tr>
<tr>
<td></td>
<td>SH 35</td>
<td>0.794</td>
</tr>
<tr>
<td></td>
<td>SH 146/LOOP 201</td>
<td>0.239</td>
</tr>
<tr>
<td></td>
<td>SHAVER</td>
<td>0.437</td>
</tr>
<tr>
<td></td>
<td>SPENCER HWY</td>
<td>0.463</td>
</tr>
<tr>
<td></td>
<td>LOOP 336</td>
<td>0.119</td>
</tr>
</tbody>
</table>

\(^{10}\) https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee
Figure 54 – Criticality - Vulnerability Matrix: Combine Major Streets
Economic Impact Analysis
Cost-benefit analyses inform prioritization of projects for transportation investment. The Pilot Program examines how to estimate potential economic loss associated with transportation network disruption due to the various climate stressors. The Pilot Program does not cover the construction or repair costs of roadway and bridge improvements as they can be calculated directly based on the actual costs for similar projects in the region or based on the historical cost databases and bid tabulations from other projects.

For the Pilot Program, the team used Regional Economic Models, Inc. (REMI) TranSight\textsuperscript{11}, a software package for estimating the economic impact of transportation investments. The model measures the economic impact associated with the addition of a new road or disruption to an existing road by comparing changes in vehicle miles traveled (VMT) and vehicle hours traveled (VHT) between the base scenario and alternate scenario.

The Pilot Program investigates 10 scenarios in which a specific transportation network is disrupted because of an extreme weather event. Figure 55 shows the road segments selected for the economic impact analysis. All road segments selected are identified to be vulnerable to at least one of the extreme weather events.

Scenario 9 includes road segments from scenarios 1, 3, and 4, whereas scenario 10 includes road segments from scenarios 1 to 8. Please refer to the Appendix C on page 155 for a detailed description of each road segment and its vulnerability to flooding.

The Pilot Program assumes transportation network disruptions caused by extreme weather occurred in 2020. The team ran the regional travel demand model for each of the 10 disruption scenarios. The model output components, including VMT, VHT, and total vehicle trips, were then entered into the economic model for economic impact analysis. The team compared the results from the economic model to the 2020 baseline scenario used in H-GAC’s 2045 Regional Transportation Plan\(^{12}\) to determine loss in Gross Domestic Product (GDP), which is defined as the market value of all final goods and services produced in a regional economy.

**Results**

Table 5 shows the results from economic impact analysis for the 10 scenarios.

As expected, the consolidated scenario (scenarios 1-8 combined) demonstrated the largest impact to the region. If the disruptions last one week, the region would lose around $27 million dollars in GDP.

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\(^{12}\) The region’s long-range transportation plan, which prioritizes transportation projects in the eight-county Houston-Galveston region, can be viewed here: [http://2045rtp.com/](http://2045rtp.com/)
Among the individual scenarios, the Gulf Freeway Galveston Causeway had the highest impact on the economy with a loss of $11.5 million for one week of disruption. This road segment is critical as it links Galveston Island to the mainland.

**Table 5 – H-GAC Transportation Network Resilience Summary**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Annual</th>
<th>Month</th>
<th>Week</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>IH 10 San Jacinto Bridge</td>
<td>206.9</td>
<td>17.2</td>
<td>4.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Gulf Freeway Galveston Causeway</td>
<td>599.2</td>
<td>49.9</td>
<td>11.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>SH 146 Fred Hartman Bridge</td>
<td>205.6</td>
<td>17.1</td>
<td>4.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>SH 225/Lawndale St.</td>
<td>191.5</td>
<td>16.0</td>
<td>3.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>US 59</td>
<td>182.5</td>
<td>15.2</td>
<td>3.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>FM 723 &amp; FM 359</td>
<td>173.6</td>
<td>14.5</td>
<td>3.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Scenario 7</td>
<td>IH 10</td>
<td>215.3</td>
<td>17.9</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Scenario 8</td>
<td>North-South Connecters along Buffalo Bayou</td>
<td>494.8</td>
<td>41.2</td>
<td>9.5</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>between Memorial Dr and Briar Forest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1+3+4</td>
<td></td>
<td>431.0</td>
<td>35.9</td>
<td>8.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Scenario 1-8</td>
<td></td>
<td>1,407.5</td>
<td>117.3</td>
<td>27.1</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Source:** H-GAC Travel Demand Data and REMI Transight

Like the scenarios used in the Pilot Program, the economic impact associated with a disruption to any given road segment can be conducted using the economic model or any other similar process. The loss in GDP can then be compared with costs of various adaptation strategies (see Adaptation Strategies on page 82). By consulting benefit cost values, decision-makers in the region can prioritize projects to develop a roadway network that is resilient to future extreme weather events.
ADAPTATION STRATEGIES

This section of the report identifies potential strategies and criteria needed to protect vulnerable and critical assets from flooding, sea level rise, storm surge, or a combination thereof. The applicability of each strategy is dependent on factors such as budget, topography, and exposure to the specific type of event.

Methodology

Adaptation strategies seek to reduce total cost to the system by making changes to the vulnerability and criticality of transportation infrastructure. The implementation of a specific adaptation strategy is, however, determined by the context and the total cost to the system.

Specific considerations in the selection of an adaptation strategy include:

- Applicability (when, where, what - topography)
- Implementation requirements (prerequisites, e.g., wide median)
- Vulnerabilities protecting against (flooding, storm surge, sea-level rise)
- Ease of implementation / time to implement
- Upfront costs / implementation cost
- Maintenance requirements / costs
- Resilience and other benefits
- Limitations

These different considerations must be compared for different resiliency adaptation strategies using a multi-criteria analysis. This report identifies various adaptation strategies and provides the following information for each:

- Effectiveness
- Implementation requirements
- Ease of implementation
- Cost of implementation
- Maintenance cost

Table 6 lists the 25 adaptation strategies included in the Pilot Program with a short description of activities and the vulnerabilities the strategy addresses. More detailed narrative descriptions, intended applications, benefits, and limitations of each strategy are detailed in Appendix E on page 187.
<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
<th>Vulnerability Protecting Against</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stormwater Management</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy 1: Increase Number of Swales and Ditches</td>
<td>Drains stormwater away from road infrastructure toward larger stormwater facilities (e.g., channels, detention/retention ponds, permanent water bodies).</td>
<td>Flooding</td>
</tr>
<tr>
<td>Strategy 2: Retention and Detention Ponds</td>
<td>Collects stormwater and releases it at a rate that prevents flooding or erosion.</td>
<td>Flooding</td>
</tr>
<tr>
<td>Strategy 3: Bioswales (Biofiltration Swales)</td>
<td>Collects, redirects, and filters stormwater.</td>
<td>Flooding</td>
</tr>
<tr>
<td>Strategy 4: Depressed and Raised Medians</td>
<td>Conveys stormwater away from roadways by creating positive drainage or conveyance.</td>
<td>Flooding</td>
</tr>
<tr>
<td>Strategy 5: Green Infrastructure</td>
<td>Increases infiltration and slow peak flow rate of stormwater, which decreases local flooding.</td>
<td>Flooding</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy 6: Culvert Cleaning/Maintenance</td>
<td>Ensures optimal water flow through the stormwater management system.</td>
<td>Flooding</td>
</tr>
<tr>
<td><strong>Planning</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy 7: Stormwater Management Plan</td>
<td>Uses a functional plan to address existing stormwater system conditions, the operation and maintenance of existing facilities, and the required capacity when adding new facilities.</td>
<td>Flooding</td>
</tr>
<tr>
<td>Strategy 8: Land Use Planning/Climate Justice</td>
<td>Plans the physical layout of a community and identifies where development occurs and open space for preservation. Aids resiliency through adoption of land use codes and zoning regulation.</td>
<td>Flooding, Sea Level Rise, Storm Surge</td>
</tr>
<tr>
<td>Strategy 9: Relocate or Abandon Roads</td>
<td>Identifies roads that have experienced repeated damage or flooding in the past. Helps mitigate future risks and further damage.</td>
<td>Flooding, Sea Level Rise</td>
</tr>
<tr>
<td>Strategy</td>
<td>Description</td>
<td>Vulnerability Protecting Against</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td><strong>Strategy 10: Shelter-in-Place</strong></td>
<td>Provides guidance, advice, incentives, or lawful orders to certain populations to remain in place during a threat to prevent or minimize the use of road networks during floods.</td>
<td>Flooding</td>
</tr>
<tr>
<td><strong>Strategy 11: Evacuation Route Identification and Planning</strong></td>
<td>Provides a safe means for potentially impacted communities to evacuate in advance of an extreme weather threat.</td>
<td>Flooding, Storm Surge</td>
</tr>
<tr>
<td><strong>Strategy 12: Prohibiting Overweight/Oversized Vehicles</strong></td>
<td>Prohibits heavy loads on weakened pavements in the immediate aftermath of a flooding event to prevent sudden failure or severe damage.</td>
<td>Flooding</td>
</tr>
<tr>
<td><strong>Strategy 13: Sensor Technologies and Monitoring Programs</strong></td>
<td>Employs sensors to monitor rainfall, runoff, water levels, and the general condition of the stormwater system.</td>
<td>Flooding</td>
</tr>
</tbody>
</table>

**Infrastructure**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
<th>Vulnerability Protecting Against</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy 14: Enhanced Road Surface</strong></td>
<td>Protects surface of the pavement against damage caused by water flowing over the pavement.</td>
<td>Flooding</td>
</tr>
<tr>
<td><strong>Strategy 15: Enhanced Sub-Grade</strong></td>
<td>Enhances and hardens sub-grade to prevent damage/failure to pavement structures caused by inundation.</td>
<td>Flooding, Storm Surge</td>
</tr>
<tr>
<td><strong>Strategy 16: Hardened Shoulders</strong></td>
<td>Provides additional lateral support to prevent road damage during inundation.</td>
<td>Flooding, Storm Surge</td>
</tr>
<tr>
<td><strong>Strategy 17: Raised Road Profile</strong></td>
<td>Allows roads to remain passable in extreme events and extends service life of the road. May be more vulnerable to wave action.</td>
<td>Flooding, Sea Level Rise, Storm Surge</td>
</tr>
<tr>
<td><strong>Strategy 18: Geosynthetics/Geo Textiles</strong></td>
<td>Strengthens pavement and mitigates erosion.</td>
<td>Flooding, Storm Surge</td>
</tr>
<tr>
<td><strong>Strategy 19: Permeable Pavement</strong></td>
<td>Slows, filters, and cleans stormwater runoff by installing porous surfaces.</td>
<td>Flooding</td>
</tr>
</tbody>
</table>

**Other**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
<th>Vulnerability Protecting Against</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy 20: Maintain and Restore Wetlands</strong></td>
<td>Reduces erosion and flooding, stores water during droughts, acts as a natural barrier to the spread of fires and minimizes the impacts of storms by slowing the speed and reducing the height and force of waves.</td>
<td>Flooding</td>
</tr>
<tr>
<td>Strategy</td>
<td>Description</td>
<td>Vulnerability Protecting Against</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Strategy 21: Beach Nourishment and Dune Restoration</td>
<td>Controls erosion, flooding, and storm damage by acting as a buffer against high winds and waves.</td>
<td>Sea Level Rise, Storm Surge</td>
</tr>
<tr>
<td>Strategy 22: Vegetation (as Erosion Control)</td>
<td>Reduces soil loss by binding soil particles and absorbing the impact of raindrops, reduces velocity of runoff, allowing infiltration.</td>
<td>Flooding</td>
</tr>
<tr>
<td>Strategy 23: Seawalls and Revetments</td>
<td>Protects coastlines by redirecting the energy of waves back to the ocean water.</td>
<td>Sea Level Rise, Storm Surge</td>
</tr>
<tr>
<td>Strategy 24: Wave Attenuation Devices</td>
<td>Protects shorelines by reducing and reflecting the energy of waves while allowing water to pass through.</td>
<td>Storm Surge</td>
</tr>
<tr>
<td>Strategy 25: Debris Deflectors for Bridge Protection</td>
<td>Protects bridge structures by deflecting and preventing debris from making direct contact with the bridge structure.</td>
<td>Flooding</td>
</tr>
</tbody>
</table>

*Many of the stormwater management adaptation strategies listed may offer limited effectiveness when used as a stand-alone strategy. Yet when included in combination with other strategies become a larger hydraulic system, which becomes a highly effective overall strategy.*
Resiliency Adaptation Strategies to Address Vulnerability and Criticality
For the Pilot Program, the team used low, moderate, and high categories to evaluate proposed resiliency adaptation strategies in protecting critical and vulnerable infrastructure. Strategies are evaluated for their impact on vulnerability and criticality as follows:

- **Vulnerability** – the ability or suitability of the strategy to mitigate flooding or reduce the long-term deleterious effects of flood events that occur because of rainfall events, storm surge or sea level rise disturbances.
- **Criticality** – the suitability of the strategy for protecting assets considering the assets’ importance or criticality to the broader transportation system.

In this context, a highly vulnerable asset is one that is extremely prone to flooding (measured in terms of frequency, duration, and/or flood depth); while a low vulnerability asset is one that is of low risk of flooding following a disturbance event (i.e., severe rainfall, storm surge, or sea level rise).

Similarly, a highly critical asset is one that considered to be disproportionately important to the partial or normal functioning of the transportation system; while a low criticality asset is one that, even if flooded, will cause only a minor impact on the normal functioning of the transportation system.

To complete the evaluation outlined in Table 7, the team addressed the following questions:

- **Vulnerability questions** - How effective is the strategy at mitigating the impacts of a disturbance (rainfall, storm surge, or sea-level rise) on an asset? Here, efficacy was further broken down into cases where the strategy may reduce the frequency, incidence or severity of flooding, or help prevent long term damage to the asset.
- **Criticality question** - What are the costs and reliability associated with employing the strategy and, based on these criteria, is the strategy best suited to protecting high, low or medium criticality assets?

Given the nature of the specified disturbance events, the team assumed that it is possible that a strategy may be highly effective or reliable for reducing the impact of flooding for assets subject to low flood risk, but that the same strategy may be less effective for protecting assets subject to high flood risk. To illustrate this principal, many hydraulic structures are designed to accommodate a disturbance event (e.g., rainfall) up to a certain intensity and duration, after which they are designed to fail, or at least have limited capability to prevent inundation.
In other cases, engineered structures are designed to offer more reliable (complete) protection against such disturbances (often at a much higher cost). Adopting the spirit of resilience planning, both strategies may provide useful adaptive capacity against disturbance events, if a fair assessment of their limitations (efficacy and cost) is conducted.

Similar caveats were incorporated into the assessment of the suitability of a strategy for protecting critical infrastructure. Here, the study team worked on the principal that critical infrastructure requires strategies that offer the most effective and reliable (fail safe) protection from disturbance events, and that this reliability may warrant the extra cost associated with implementing the strategy. It should be noted therefore, that although certain engineering strategies may be specifically targeted to protecting critical infrastructure, they may also provide valuable protection to less critical assets that are associated with the identified critical asset.
### Table 7 – Assessment of Resiliency Adaptation Strategies

<table>
<thead>
<tr>
<th>Resilience Strategy</th>
<th>Criticality</th>
<th>Vulnerability</th>
<th>Climate Stressor</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Mod</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Strategy 1: Increase Number of Swales and Ditches</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy 2: Retention and Detention Ponds</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Strategy 3: Bioswales (Biofiltration Swales)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy 4: Depressed and Raised Medians</td>
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</tr>
</tbody>
</table>

Swales and ditches are a cost-effective method for reducing the frequency and duration of standing water in areas with low flood risk. While they may help reduce the duration of floods in high flood risk areas, they cannot reliably prevent standing water during moderate or severe flood events. Therefore, swales and ditches are best used to protect infrastructure that is of low criticality to the transportation system.

When integrated into a well-designed stormwater management system, retention and detention basins can be designed to prevent standing water during medium and low flood events, as they can be effectively engineered to reduce standing water (flood risk) beyond the capabilities of swales and ditches alone. This makes them useful for protecting infrastructure that is moderately critical to the transportation system.

Bioswales have similar application characteristics to swales and ditches, but with the additional benefit of providing aesthetic and water purification benefits.

This strategy provides additional drainage structures designed to protect roadway flooding during moderate rainfall events. This makes them useful for protecting infrastructure that is moderately critical to the transportation system.
| Strategy 5: Green Infrastructure | X | X | X | X | X | X | Green infrastructure can be used to reduce the risk of flooding (severity, duration and frequency) in areas of low to medium risk to flooding. It is best employed as an area wide strategy to improve the operational reliability of low and/or moderately critical assets. |
| Strategy 6: Culvert Cleaning/Maintenance | X | X | X | X | X | X | Culvert cleaning helps restore the designed engineered capacity of drainage systems. Regular maintenance of the stormwater system is useful system wide. However, more frequent surveys and maintenance around flood prone and functionally important (critical) infrastructure may help improve the reliability of the stormwater management system in these areas. |
| Strategy 7: Stormwater Management Plan | X | X | X | X | X | Hydrological structures are usually designed to prevent flooding up to a specified rainfall event (e.g., a 50-year storm). If highly critical infrastructure can be identified, structures can be redesigned to accommodate the stormwater arising from more severe storm events (e.g., 100-year storms), thereby providing a mechanism to protect moderate and highly critical infrastructure. |
| Strategy 8: Land Use Planning/Climate Justice | X | X | X | X | X | X | Land use planning establishes a comprehensive set of goals for floodplain managements, regulations, and policies to prevent the development of moderate or highly critical infrastructure in flood prone areas. |
| Strategy 9: Relocate or Abandon Roads | X | X | X | X | X | By definition, this strategy only applies to non-critical infrastructure that is highly vulnerable to flooding. The rationale for this strategy is that the abandonment of low criticality or highly redundant infrastructure will provide long-term maintenance cost savings that can be redirected to other resilience strategies. |
| Strategy 10: Shelter-in-Place | X | X | X | X | X | Occasionally, even infrastructure that has a low risk of flooding may become inundated. By definition this means moderate and high-risk infrastructure. |
During moderate flood events, or when severe flood events can be reliably predicted, select transportation routes can be identified that remain reliably traversable. These alternative routes can be used to evacuate flood prone areas to reduce the risk of damage (repair and safety costs) to high, medium and low critical infrastructure.

For infrastructure prone to high, medium or low flood risk, temporary bans on heavy duty vehicles may be useful to protect the integrity of infrastructure. Such temporary prohibitions may help prolong the life and maintenance costs of highly critical infrastructure.

Monitoring programs comprise networked sensors capable of providing real time information on stormwater flows, and historical data useful for assessing and understanding the cause of floods. When employed in flood prone areas, they can provide a useful early warning system with the aim of preventing floods, protecting critical infrastructure from outages, and for triggering interventions such as traffic diversions that may can reduce the cost of critical outages.

Infrastructure that has a low risk of flooding may occasionally become partially inundated with standing water (i.e., there is some standing water on the roads, but there is enough drainage to ensure standing water remains minimal). Under circumstances when inundation risk is low, but surface water can accumulate, an enhanced road surface may improve the safety of...
<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 15: Enhanced Sub-Grade</td>
<td>Enhancing the sub-grade of highly critical and moderately or highly vulnerable infrastructure can be an effective strategy for reducing long-term costs associated with repairing and maintaining such infrastructure.</td>
</tr>
<tr>
<td>Strategy 16: Hardened Shoulders</td>
<td>During an extreme weather event, vehicles may be required to use the shoulder of a road for safe transport. This can be an effective strategy for improving the reliability of high and moderately critical infrastructure that is subject to a low or moderate risk of flooding.</td>
</tr>
<tr>
<td>Strategy 17: Raised Road Profile</td>
<td>Raised road profile should be used for highly vulnerable infrastructure due to the typically high costs and potential impacts on nearby communities. However, raising the road profile provides a very reliable method for reducing the risk of inundation for highly flood-prone assets.</td>
</tr>
<tr>
<td>Strategy 18: Geosynthetics/Geo Textiles</td>
<td>Geosynthetics or geotextiles can help prevent damage to infrastructure caused when flooding does occur. Although they are not designed to prevent or mitigate floods, they can be used to prevent long-term damage to high or moderately critical infrastructure that may otherwise occur because of floods.</td>
</tr>
<tr>
<td>Strategy 19: Permeable Pavement</td>
<td>This strategy helps to reduce run off and is specifically designed to help reduce standing water. Limitations on the mechanical integrity of permeable pavement design limits its application to less critical infrastructure.</td>
</tr>
<tr>
<td>Strategy 20: Maintain and Restore Wetlands</td>
<td>Wetlands provide a natural, system wide approach to managing flooding. They can be used to help protect areas prone to moderate or low flood risk.</td>
</tr>
<tr>
<td>Strategy 21: Beach Nourishment and Dune Restoration</td>
<td>Restoration of beaches and dunes offer a natural, system wide strategy for protecting against standing water in travelers and help maintain the operational capacity of moderate and highly critical infrastructure.</td>
</tr>
</tbody>
</table>
Because it is a system wide strategy, it is effective at protecting low, moderate and highly critical infrastructure.

Infrastructure that has a low or moderate risk of flooding can be partially protected from inundation by using vegetative buffers. Such buffers may reduce the severity and duration of rare inundation events and help retain the operational capacity of low and moderately critical infrastructure.

This strategy offers a high level of protection against flooding of moderately and highly vulnerable infrastructure. The high implementation cost makes this strategy most suitable for maintaining the serviceability of moderately and highly critical infrastructure.

Wave attenuation devices are a high cost, but effective and reliable method of reducing flooding of high and moderately vulnerable infrastructure. Due to their high installation costs, they are best targeted as a solution to protect highly or moderately critical infrastructure.

High and moderately critical bridge assets subject to frequent or severe flood events can be protected using debris deflectors. Although this strategy does not help reduce flooding, it can be used to maintain the operational integrity of such assets and reduce long term maintenance and repair costs.
STAKEHOLDER ENGAGEMENT

Meaningful discussions with stakeholders about challenges, opportunities and needs is crucial to any project’s success. For this Pilot Program, the team worked with a diverse stakeholder group. A list of external stakeholders is included in Table 8.

External Stakeholder Discussions

Kick-Off Meeting
On May 22, 2019, the team conducted a kickoff meeting with regional stakeholders to discuss the importance of resiliency, provide an overview of the types of projects underway, review assessment data, and discuss indicator and criticality selection data.

Draft Findings and Recommendations Meeting
On May 12, 2020, the team presented draft findings and recommendations to regional stakeholders, specifically meeting to review the intersection between the criticality and vulnerability assessments, as well as discuss proposed Adaptation Strategies to improve transportation resilience.

On July 15, 2020, the team presented draft findings and recommendations to the Transportation Advisory Committee. On July 24, 2020, that same content was presented to the Transportation Policy Council.

One-on-One Partner Discussions
In addition to stakeholder meetings, the team coordinated directly with key partners that were conducting and / or participating in resiliency efforts in the Pilot Program area.

Table 8 – Pilot Program Stakeholders

<table>
<thead>
<tr>
<th>Entity</th>
<th>Entity Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harris County Office of Emergency Management</td>
<td>Emergency Management</td>
</tr>
<tr>
<td>Federal Highway Administration</td>
<td>Federal Government Agency</td>
</tr>
<tr>
<td>U.S. Army Corps of Engineers - Southwest Division</td>
<td>Federal Government Agency</td>
</tr>
<tr>
<td>Government Land Office</td>
<td>Federal Government Agency</td>
</tr>
<tr>
<td>U.S. Geological Survey</td>
<td>Federal Government Agency</td>
</tr>
<tr>
<td>Army Corps of Engineers</td>
<td>Federal Government Agency</td>
</tr>
<tr>
<td>Federal Highway Administration - Texas Division</td>
<td>Federal Government Agency</td>
</tr>
<tr>
<td>Harris County Flood Control District</td>
<td>Flood Control District</td>
</tr>
<tr>
<td>Houston-Galveston Area Council</td>
<td>Municipal Planning Organization</td>
</tr>
<tr>
<td>Harris County</td>
<td>Municipal Planning Organization - County</td>
</tr>
<tr>
<td>Galveston County</td>
<td>Municipal Planning Organization - County</td>
</tr>
<tr>
<td>Montgomery County</td>
<td>Municipal Planning Organization - County</td>
</tr>
</tbody>
</table>
Waller County Municipal Planning Organization - County
Fort Bend County Municipal Planning Organization - County
Brazoria County Municipal Planning Organization - County
Chambers County Municipal Planning Organization - County
Liberty County Municipal Planning Organization - County
City of Houston Municipal Planning Organization - Other Local Government
Greater Houston Flood Mitigation Consortium Nonprofit
Houston Advanced Research Center Nonprofit
100 Resilient Cities Nonprofit
Texas Department of Transportation State Agency
METRO Transit Authority Transit Provider
Houston TranStar Transit Provider
Rice University SSPEED Center University
Rice University Kinder Institute University
Texas A&M University
Texas A&M Transportation Institute University (Affiliate)

**Internal and Peer Discussions**

**Resilience & Durability Peer Exchange**
On December 13, 2018, the team participated in a peer exchange with other Resilience and Durability Pilot teams to discuss the details of this Pilot Program, specifically focusing on the proposed approach and methodology.

**Internal Resiliency Workgroup Meeting**
Following the May 22, 2019 kick-off meeting, it became apparent that greater H-GAC internal coordination was needed to better define critical infrastructure and provide input on other elements of the Pilot Program. As such, a diverse group of staff members whose work touches on resiliency was assembled on July 24, 2019, to learn about the Pilot Program and solidify approach consensus on criticality.

On January 16, 2020, the team met with H-GAC’s Travel Demand Modeling (TDM) staff to discuss models to estimate potential economic loss associated with transportation network disruption due to the various climate stressors. The team discussed various disruption scenarios based on the criticality and vulnerability scores. The TDM staff conducted the economic impact analysis using the economic model for a set of finalized scenarios provided by the Pilot Program team.
**NEXT STEPS AND RECOMMENDATIONS**

Maintaining optimal quality and performance of transportation assets is critical to Houston-Galveston region’s economic vitality, quality of life, and natural and built environments.

**Conclusions**

Criticality and vulnerability assessment of transportation assets to extreme weather events is an important risk management exercise for the Houston-Galveston region. The methodology used to measure criticality and vulnerability scores of road segments and bridges required collection, integration, and analysis of diverse datasets.

This Pilot Program has developed an approach for analyzing the impact of extreme weather events to regional transportation assets that can be replicated and updated over time. Importantly, the Pilot Program not only provides tools to identify critical and vulnerable assets, but also recommends adaptation strategies that can be used to mitigate the losses related to extreme weather events. The Pilot Program also describes how transportation planning agencies can conduct economic impact analysis for project benefit-cost analysis.

The key outcomes of the Pilot Program are:

- Measured criticality scores of road segments to the region’s routine functions and economic activities;
- Measured network redundancy of road segments;
- Estimated road and bridge elevation using LiDAR data;
- Estimated location specific flood exposure depth data of road segments and bridges for various flooding scenarios;
- Identified road segments that are outside the FEMA floodplain, but prone to flooding.
- Measured vulnerability score of road segments and bridges to extreme weather events including flooding, storm surge, and sea-level rise.
- Developed Criticality and Vulnerability Matrix to categorize road segments based on their criticality and vulnerability scores. Road segments that are highly critical and highly vulnerable should be considered as top priority for mitigation strategies in the Pilot Program area;
- Developed Regional Resilience Tool to display the criticality and vulnerability scores of road segments and bridges for various flooding scenarios; and
- Developed 25 Adaptation Strategies to identify implementable options to protect highly vulnerable and highly critical assets, providing criteria that local governments can consider when selecting a strategy.
Lessons Learned

The following are lessons learned that would be of use to others considering a similar type of analysis. These lessons learned can be considered in four major areas: data availability and quality, data analysis, access to this Pilot Program’s findings, and commitment to collaborate and continue transportation resilience planning.

Data availability and quality - The availability and quality of data is one of the most important factors for the overall success of the Pilot Program. Most of the data required for this study was readily available, however there are many instances where the team reconsidered the data analysis approach because of data unavailability or poor quality. Future studies and programs would benefit if certain types of datasets, such as transportation asset characteristics, were collected and maintained periodically by transportation and planning agencies across the region. For example, the transportation assets managed by TxDOT has better asset characteristics as compared to assets managed by other transportation planning agencies. In addition, it would be helpful to maintain a comprehensive database of transportation assets that were impacted by previously flooding events.

Access to 2018 LiDAR data was also very critical for this Pilot Program as it reflected recent developments, including newly constructed highways, streets, and bridges. The DEM and DSM data generated from the LiDAR data was used to accurately measure the road and bridge elevations. It also allowed to spatially interpolate FEMA flood zone boundaries to identify road segments that are outside the flood zone but are vulnerable to flooding. Availability of FEMA’s Hurricane Harvey water depth grid data and H-GAC’s Hurricane Harvey flooding imagery was helpful for this Pilot Program.

To better assess the economic impact related to flood damage, future studies would need more accurate repair costs for infrastructures, including flood depth damage function. Determining direct flood damage is commonly done using depth-damage curves, which denote the flood damage that would occur at specific water depths per asset or per land-use class

Data analysis - This Pilot Program used SAS, ArcGIS and ENVI (image analysis software is used by GIS professionals) for data processing and analysis. This Pilot Program required challenging technical processing, including developing DSM using LiDAR data, calculating network redundancy, modeling flooding exposure depth data, and calculating criticality and vulnerability scores for road segments and bridges. Most of this analysis requires powerful computer processing capabilities and expertise in the modeling software.

The methodology applied in this Pilot Program can also be used to assess flood damage to other built environments, such as residential homes, commercial buildings, farmland, airport runways, and port facilities.
Access to Pilot Program findings - Often, findings from the Pilot Program are limited to some paper maps and reports. However, the findings from Pilot Program are presented on the interactive web mapping application/tool, which is accessible to everyone. The tool provides criticality and vulnerability scores of all the road segments and bridges analyzed. In addition, the tool also identifies specific locations of road segments that are vulnerable to flooding in any given scenario. Easy access to this information will help transportation agencies in the H-GAC MPO identify the vulnerable road segments and develop mitigation strategies.

Commitment to collaborate and continue transportation resilience planning - Meaningful discussion with stakeholders about challenges, opportunities, and needs was crucial to success. A regional, multi-jurisdictional approach to resilience planning is needed to develop and deploy resilience solutions to future extreme weather events. The criticality and vulnerability results from this Pilot Program along with recommended adaptation strategies could be incorporated into ongoing planning and decision-making processes.

Next Steps
The Houston-Galveston MPO values the findings of this Pilot Program and acknowledges that this is the first step toward a more resilient transportation system for the region. The findings of the Pilot Program will be integrated into current and future transportation planning studies, including Low-Impact Development Study, Regional Transportation Plan, Transit-Oriented Development Study, Complete Streets Program, Sub-regional Studies, and a Region-wide Resiliency Study.

The Low-Impact Development Study will expand on the 25 Adaptation Strategies and incorporate additional analysis of implementable options for decision-makers and developers to adopt within the public ROW. Understanding the criticality and vulnerability of major roads and bridges will enable more careful articulation of climate impacts on hurricane routes and route alternatives in the Regional Transportation Plan and Sub-Regional Studies. While most of the planning studies will continue this Pilot Program’s focus on resiliency for vehicle travel, the Houston-Galveston MPO will study the impacts of flood and stormwater on active transportation modes like bicycling and walking. Through context-sensitive design, the Complete Streets Program will identify the nexus between impacts on all travel modes—with specific focus on filling in the gap of active transportation—and localized flooding to determine resilient strategies for roadway, bikeway, and walkway design.
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Appendices

Appendix A: Criticality Assessment
Appendix B: Vulnerability Assessment
Appendix C: Segment Selection Process
Appendix D: Glossary and Acronyms
Appendix E: Adaptation Strategies
APPENDIX A: CRITICALITY ASSESSMENT

Detailed Methodology

For the Pilot Program, the criticality assessment only applies to roadway segments. Bridges are not assessed for criticality as all bridges are a part of a road segment. Freeways and major roads are analyzed separately in the Pilot Program, but the underlying methods of analysis are identical. Four categories of importance are analyzed in the assessment and contribute to the aggregated criticality index:

1. Socioeconomic importance
2. Usage and operational importance
3. Health and safety importance
4. Emergency preparedness importance

Socioeconomic importance: indicators in this category include access to airports, access to port facilities and access to activity population. This category is given a weight of 20% in the calculation of the aggregated criticality index.

Access to airports:

Measures how each roadway segment provides access to the two commercial airports in the region, Bush Intercontinental Airport (IAH) and William Hobby Airport (HOU). For each segment, travel times to both IAH ($T_{IAH}$) and HOU ($T_{HOU}$) are calculated. For segments that are closer to IAH, $T_{IAH}$ is used in the scoring criteria. For segments that are closer to HOU, $T_{HOU}$ is used in the scoring criteria.

Scoring criteria:

For freeways:

Score=4 when $T_{IAH}$ <4 mins or $T_{HOU}$<3 mins
Score=3 when $T_{IAH}$ 4-8 mins or $T_{HOU}$ 3-4 mins
Score=2 when $T_{IAH}$ 8-12 mins or $T_{HOU}$ 4-5 mins
Score=1 when $T_{IAH}$ 12-15 mins or $T_{HOU}$ 5-6 mins
Score=0 when $T_{IAH}$ 15+ mins or $T_{HOU}$ 6+ mins

For major roads:

Score=4 when $T_{IAH}$ <8 mins or $T_{HOU}$<2 mins
Score=3 when $T_{IAH}$ 8-10 mins or $T_{HOU}$ 2-3 mins
Score=2 when $T_{IAH}$ 10-13 mins or $T_{HOU}$ 3-4 mins
Score=1 when $T_{IAH}$ 13-16 mins or $T_{HOU}$ 4-6 mins
Score=0 when $T_{IAH}$ 16+ mins or $T_{HOU}$ 6+ mins

Data source: GIS transportation network analysis by H-GAC staff.

**Access to port facilities:**

Measures how each roadway segment provides access to port facilities in the region. For each segment, travel time $t$ is calculated as the drive time to the nearest port facility.

Scoring criteria:

For freeways:
Score=4 when $t$ < 3 mins
Score=3 when $t$ 3-4 mins
Score=2 when $t$ 4-5 mins
Score=1 when $t$ 5-9 mins
Score=0 when $t$ 9+ mins

For major roads:
Score=4 when $t$ < 2 mins
Score=3 when $t$ 2-3 mins
Score=2 when $t$ 3-5 mins
Score=1 when $t$ 5-12 mins
Score=0 when $t$ 12+ mins

Data source: GIS transportation network analysis by H-GAC staff.
Access to activity population:

Measures how each roadway segment supports the commute of local activity population, defined as the combination of residential population and job count in each location. The access is measured by statistic $p$, which is calculated as the proportion of activity population that can be reached within 15 minutes of drive from the segment compared to the activity population of the entire region. The statistic $p$ is displayed as a percentage.

Scoring criteria:

For freeways:
Score=4 when $p > 30$
Score=2 when $p$ 15-30%
Score=0 when $p <15$

For major roads:
Score=4 when $p > 30$
Score=2 when $p$ 10-30%
Score=0 when $p < 10$

Data source: GIS transportation network analysis by H-GAC staff; US Census Bureau.
**Usage and operational importance:** indicators in this category include annually averaged daily traffic (AADT), annually averaged daily truck traffic (AADTT) and transit passenger rides. This category is given a weight of 40% in the calculation of the aggregated criticality index.

**AADT:**

AADT is the most direct and accurate indicator measuring the usage and operational importance of a road segment. It records the annual average daily traffic on each road segment.

Scoring criteria:
- Score=4 when AADT among top 5%
- Score=3 when AADT among top 5-10%
- Score=2 when AADT among top 10-25%
- Score=1 when AADT among top 25-50%
- Score=0 when AADT below median level

Data source: H-GAC Travel Demand Model.

**AADTT:**

AADTT reflects the importance of a road segment to goods transportation, trade and manufacture activities. It records the annual average daily truck traffic on each road segment.

Scoring criteria:
- Score=4 when AADTT among top 5%
- Score=3 when AADTT among top 5-10%
- Score=2 when AADTT among top 10-25%
- Score=1 when AADTT among top 25-50%
- Score=0 when AADTT below median level
Transit rides:

This indicator measures the importance of a road segment in the regional public transit system. It records the daily passenger trips made on the road segment. In the analysis, only major road segments are considered. All freeways are given a value of 0.

Scoring criteria:

Score=4 when transit trips > 20,000
Score=3 when transit trips 15,000-20,000
Score=2 when transit trips 5,000-15,000
Score=1 when transit trips < 5,000
Score=0 when the segment does not have transit ridership

Data source: Houston METRO
Health and safety importance: indicators in this category include access to hospitals, access to fire stations, and service to vulnerable population. This category is given a weight of 30% in the calculation of the aggregated criticality index.

Access to hospitals:

This indicator describes the accessibility a road segment provides to the nearest hospital facility. In the analysis, urgent care centers and emergency medical services facilities are not considered as hospitals. In the calculation of the indicator, both travel time to the nearest hospital \( t \) and household-based trip \( h \) are normalized into the scale of 0-1, yielding variables \( R(t) \) and \( R(h) \). Accessibility index is constructed as \( A=1+R(h)-R(t) \), and is then normalized into the scale of 0-1, yielding index rank-based index \( R(a) \).

Scoring criteria:

Score=4 when \( R(a) > 0.95 \)
Score=3 when \( R(a) 0.9-0.95 \)
Score=2 when \( R(a) 0.75-0.9 \)
Score=1 when \( R(a) 0.5-0.75 \)
Score=0 when \( R(a) < 0.5 \)

Data source: GIS transportation network analysis by H-GAC staff.

Access to fire stations:

This indicator describes the accessibility a road segment provides to the nearest fire station. In the calculation of the indicator, both travel time to the nearest fire station \( t \) and household-based trip \( h \) are normalized into the scale of 0-1, yielding variables \( R(t) \) and \( R(h) \). Accessibility index is constructed as \( A=1+R(h)-R(t) \), and is then normalized into the scale of 0-1, yielding index rank-based index \( R(a) \).

Scoring criteria:

Score=4 when \( R(a) > 0.95 \)
Score=3 when \( R(a) 0.9-0.95 \)
Score=2 when $R(a)$ 0.75-0.9
Score=1 when $R(a)$ 0.5-0.75
Score=0 when $R(a)$ < 0.5

Data source: GIS transportation network analysis by H-GAC staff.

**Service to vulnerable population:**

This indicator measures how a road segment provides access and service to economically and socially challenged communities (vulnerable populations). H-GAC staff have previously calculated vulnerability population index for each census block in the H-GAC area, considering several demographic and economic factors, including but not limited to elderly, racial monitors, disability, poverty, carless, and limited English proficiency. Statistic $V_p$ is the vulnerable population index derived from the analysis, ranging from 0 to 100 with 100 indicating that the census block has the highest vulnerable population density in the region. The statistic $V_p$ of the nearest census block to a road segment is assigned to the road.

Scoring criteria:
Score=4 when $V_p$ > 95
Score=3 when $V_p$ 90-95
Score=2 when $V_p$ 75-90
Score=1 when $V_p$ 50-75
Score=0 when $V_p$ < 50

Data source: GIS analysis by H-GAC staff; US Census Bureau.

**Emergency preparedness importance:** indicators in this category include evacuation route status, access to emergency shelters, access to FEMA EOCs and military access (national strategic highway status). This category is given a weight of 10% in the calculation of the aggregated criticality index.
**Evacuation route:**

This is a binary indicator to show that whether the road segment is part of the designated emergency evacuation route.

Scoring criteria:

Score=2 when it is part of a designated evacuation route
Score=0 when it is not part of a designated evacuation route

Data source: TxDOT Road Inventory File

---

**Access to shelters:**

This indicator describes the accessibility a road segment provides to the nearest emergency shelter. In the calculation of the indicator, both travel time to the nearest shelter \( t \) and household-based trip \( h \) are normalized into the scale of 0-1, yielding variables \( R(t) \) and \( R(h) \). Accessibility index is constructed as \( A=1+R(h)-R(t) \), and is then normalized into the scale of 0-1, yielding index rank-based index \( R(a) \).

Scoring criteria:

Score=4 when \( R(a) > 0.95 \)
Score=3 when \( R(a) 0.9-0.95 \)
Score=2 when \( R(a) 0.75-0.9 \)
Score=1 when \( R(a) 0.5-0.75 \)
Score=0 when \( R(a) < 0.5 \)

Data source: GIS transportation network analysis by H-GAC staff; FEMA

---

**Access to FEMA EOCs:**

The indicator measures how the road segment provides access to FEMA EOCs. Travel time \( t \) refers to the drive time from the road segment to the nearest EOC.
Scoring criteria:

For freeways:
Score=4 when t < 2 mins
Score=3 when t 2-3 mins
Score=2 when t 3-4 mins
Score=1 when t 4-5 mins
Score=0 when t 5+ mins

For major roads:
Score=4 when t < 1 mins
Score=3 when t 1-2 mins
Score=2 when t 2-3 mins
Score=1 when t 3-5 mins
Score=0 when t 5+ mins

Data source: GIS transportation network analysis by H-GAC staff; FEMA

Military access:

This is a binary indicator showing that whether the road segment provides military access. The criteria include whether it is part of the strategic highway network or it is within 5-minute driving distance to the Ellington Airfield.

Scoring criteria:
Score=2 when at least one criterion is met
Score=0 when no criterion is met
After indicators from all categories are calculated, a weighted summary is performed for the indicators. For each category, the combined score ranges from 0 to 12, with 12 indicating the highest criticality. The weighted total of all indicators also ranges from 0 to 12, given that the weights sum up to 100%. A ranking-based cumulative standardization to the scale of 0 to 1 is performed to the weighted total, yielding the final criticality score for all road segments, with 1 suggesting the highest importance. As stated previously, the criticality assessments are performed separately for freeways and major roads. Although the metrics differ, the methodology does not differ for the two classes.
Criticality Maps
Figures 57 – 69 depict the criticality of linkages to socio-economically important locations in the H-GAC MPO region.

Figure 56 – Criticality-Access to Airports
Figure 57 – Criticality-Access to Port Facilities
Figure 58 – Criticality - Access to Activity Population
Figure 59 – Criticality - Annually Averaged Daily Traffic
Figure 60 – Criticality - Annually Averaged Daily Truck Traffic
Figure 61 – Criticality-Transit Rides

Legend

Usage & Operational

Transit:
Freeway Mainlanes (not applicable)

Major Streets (score | avg. daily ridership)
- 4 | 20,000 +
- 3 | 15,000 - 20,000
- 2 | 5,000 - 15,000
- 1 | 5,000 - 1
- 0 | No Transit
Figure 62 – Criticality - Access to Hospitals
Figure 63 – Criticality - Access to Fire Stations

Legend:
- Health & Safety Importance:
  - Linkage to fire station
  - Freeway Mainlanes (score | time + trip index):
    - 4 | Top 95% + time & trip to the nearest
    - 3 | 90% - 95% time & trip to the nearest
    - 2 | 75% - 90% time & trip to the nearest
    - 1 | 50% - 75% time & trip to the nearest
    - 0 | < 50% time & trip to the nearest
  - Major Streets (score | time + trip index):
    - 4 | Top 95% + time & trip to the nearest
    - 3 | 90% - 95% time & trip to the nearest
    - 2 | 75% - 90% time & trip to the nearest
    - 1 | 50% - 75% time & trip to the nearest
    - 0 | < 50% time & trip to the nearest
Figure 64 – Criticality: Services to Vulnerable Populations
Figure 65 – Criticality-Evacuation Route
Figure 66 – Criticality - Access to Shelters
Figure 67 – Criticality-Access to FEMA EOCs
Figure 68 – Criticality-Military Access
APPENDIX B: VULNERABILITY ASSESSMENT

Detailed Methodology

Exposure Assessment

To assess the exposure to each transportation asset, high-resolution, multi-scenario climate and hydrology modeling was performed for the region. Based on stakeholder inputs, three climate stressors are analyzed in the Pilot Program: inland flooding, coastal storm surge, and sea level rise. For each climate stressor, the following climate scenarios in Table 9 are considered.

Table 9 – Inland Flooding

<table>
<thead>
<tr>
<th>Climate Stressor</th>
<th>Scenario</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland flooding</td>
<td>100-year flooding</td>
<td>FEMA floodplain map</td>
</tr>
<tr>
<td></td>
<td>500-year flooding</td>
<td>FEMA floodplain map</td>
</tr>
<tr>
<td></td>
<td>Hurricane Harvey flooding</td>
<td>National Hurricane Center</td>
</tr>
<tr>
<td>Coastal storm surge</td>
<td>Category 1 hurricane storm</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td>Category 2 hurricane storm</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td>Category 3 hurricane storm</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td>Category 4 hurricane storm</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td>Category 5 hurricane storm</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td>Hurricane Ike</td>
<td>National Hurricane Center</td>
</tr>
<tr>
<td>Sea level rise</td>
<td>4-foot sea level rise</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td>5-foot sea level rise</td>
<td>NOAA</td>
</tr>
</tbody>
</table>

The team processed LiDAR data and Flood Depth data to measure the flood exposure depth of roads and bridges.

LiDAR Data and Flood Modeling

The primary properties of the transportation infrastructures assets used in this Pilot — above-ground height and width — were mainly derived from the LiDAR data. Two types of LiDAR data products were used in the feature extraction process:

- H-GAC’s 2018 LiDAR product
this dataset covers the all counties within the Houston-Galveston MPO Pilot Program area except Fort Bend County.

- TNRIS 2014 LiDAR product
  this dataset covers the Fort Bend County area.

Figure 70 shows a 3-D image of classified LiDAR point cloud data for the uptown area of Houston.

**Estimating the Above-Ground Heights**
Above-ground height is measured from the underlying ground surface. To estimate above-ground heights, the DEM, a bare-earth raster grid usually representing the surface of the earth, was used. Once above-ground natural and built features, such as trees and other types of vegetation, roads, bridges, buildings, powerlines, etc., are filtered out, a smooth digital elevation model is produced. For this effort, the ground surface level and heights were measured with respect to the DEM value at a specific location.

To obtain the height information of transportation infrastructure assets, an altitude model is required in addition to DEM. The altitude model used by the team is the DSM, an elevation model containing the elevation of terrain as well as above-ground natural and built features.

**Generation of DEM**
There are various DEM products available to use in land surface analysis (see Figure 71 for a DEM map of the Houston-Galveston MPO region). Currently, the team uses the U.S. Geological Survey’s 10-meters resolution DEM for most of its regional elevation related data analysis. The
accuracy of the DEMs primarily depends on the spatial resolution of raster grid cells and the intensity of measurement points used in the DEM development. To obtain accurate and improved resolution DEM data for this Pilot Program, a new DEM was generated using the two LiDAR datasets. The spatial densities of both the LiDAR point clouds were very high, which was less than 0.5 meters. These two datasets made generating a high-resolution DEM product feasible. The primary GIS data analytical package used in this Pilot Program, ArcGIS, consists of various tools in developing DEM from LiDAR point clouds. Using a combination of spatial analysis tools in ArcGIS, a DEM with 5-meter resolution was generated.

**Figure 70 – DEM map of Houston-Galveston MPO region**

*Generation of DSM*

LiDAR has become the primary technology to generate DSM data, including flood modeling. The first return of the LiDAR point cloud that reflects from the surfaces of above-ground features is often referred as the DSM. A comparison of DSM and DEM is shown in Figure 72.
Processing LiDAR data to develop DSM for the region analyzed in this Pilot Program is a complex process requiring powerful computer processing capabilities. To avoid these processing requirements in measuring the heights of transportation assets, the team exclusively used point clouds classified into land features including roads and bridges. The point cloud classification schemes in both the LiDAR products consisted with bridges and ground classified point clouds. The Ground class included the road features. A DSM with 5-meters resolution is created only by selecting the Bridge and Ground point clouds.

The above-ground height of the bridges and road network was then estimated by subtracting the DEM value from the DSM value in overlaying pixels. The subtraction process produced a raster file with 5-meters spatial resolution where the pixel value represents the height of the infrastructures at a certain location.

Figure 73 shows the highly elevated ramps connecting Beltway 8 and Interstate 10 in dark red. It also shows the Buffalo Bayou and part of Beltway 8 South at the lowest elevation in light green.
Figure 72 – Digital Surface Elevation for Bridges and Roadway Sections around IH 10 and BW 8

**Depth Grid**

Providing detailed information of flooding depth, probability of flooding, and other flooding characters in the form of grid datasets is one of the primary ways to communicate flood risk and inform actions that can be taken to reduce flood risks. Like pixels in an image or picture, a grid is a digital raster dataset that defines geographic space as an array of equally sized square cells arranged in rows and columns. The value in each grid represents the magnitude of flooding characteristics at a given location (Guidance for Flood Risk Analysis and Mapping, FEMA, 2018). Figure 74 shows the Harvey Depth Grid for beltway 8 at interstate 10 south.
The creation of a depth grid involves the following general steps that may be performed universally across all GIS platforms:

1. Develop the water surface elevation grid.
2. Develop a ground source grid using the same topographic information used in the engineering analysis to produce the flood elevations.
3. Subtract the ground elevation grid from the WSEL grid for the return period or scenario for the computation of the depth grid.
4. Remove any negative values from the resulting depth grid (by either removing the cells or setting them to depths of zero, depending on project preference and/or mapped regulatory floodplain depiction).
**Water Surface Elevation Grids**

The WSEL grid is generally the first raster dataset that will be produced as part of a flood risk study. A separate WSEL grid is produced for each flood event (e.g. 1% annual-chance, 0.2% annual-chance, 1% annual-chance future conditions, 1%-plus, etc.) or flood scenario for which modeled elevations are available.

Each WSEL grid provides the modeled WSEL values within the inundation extent of that flood event or scenario. The WSEL grid is the source from which many of the other raster datasets, such as the depth and percent-annual-chance grids, are generated. Figure 75 show the WSEL for 100-year flooding.

![WSEL for 100-year Flooding](image)

**Flood Depth Grids**

In its simplest form, a flood depth grid is nothing more than the WSEL grid minus the grid representing the ground elevation using DEM. By subtracting the ground elevation value from the water surface elevation value for each return period or flood scenario, the depth values for each depth grid cell are computed. Ideally, the topographic data used for the development of any depth grid should be the same source used to generate the effective floodplain boundaries to ensure consistent and accurate results. Figure 76 shows the floodplain extent, comprised of modeled flood water surface elevation, depth, and the ground.
Inland flood Modeling: 100- and 500-year

Two sources of GIS data were used to create flood depth grids: FEMA flood risk maps and DEMs.

FEMA flood risk maps are developed as part of FEMA’s flood hazard mapping program. FEMA identifies flood hazards, assesses flood risks, and partners with states and communities to provide accurate flood hazard and risk data to guide them to mitigation actions.

FEMA flood risk maps are derived from hydrological and hydraulic models, which translate historical spatial-temporal patterns of rainfall to hydrological processes, such as soil storage, surface runoff, channel flow, and tidal information.

The development of such models is time consuming and requires specialized skills and knowledge. FEMA works with local partners, such as the Harris County Flood Control District to develop models per national guidelines, maintain the information required to validate these models, and report local flood risk maps to the federal mapping program.

Despite the complexity of the models used to generate the FEMA maps, the maps are relatively simple as they are designed to be nationally consistent and useful to a wide range of stakeholders. Primarily, the maps delineate flood zone, translated to 100- and 500-year flood risk, and the location of flood plains.

**Flood Zone**

Flood hazard areas identified on FEMA maps—referred to as the flood zone—are listed as a Special Flood Hazard Area (SFHA). SFHAs are the area that will be inundated by the flood event having a 1% chance of being equaled or exceeded in any given year. The 1% annual
chance flood is also referred to as the base flood or 100-year flood. SFHAs are labeled as Zone A, Zone AO, Zone AH, Zones A1-A30, Zone AE, Zone A99, Zone AR, Zone AR/AE, Zone AR/AO, Zone AR/A1-A30, Zone AR/A, Zone V, Zone VE, and Zones V1-V30.

Moderate flood hazard areas, labeled Zone B or Zone X are shown in Figure 77, and are the areas between the limits of the base flood and the 0.2% annual-chance (or 500-year) flood. The areas of minimal flood hazard, which are the areas outside the SFHA and higher than the elevation of the 0.2-percent-annual-chance flood, are labeled Zone C or Zone X.

Table 10 shows the moderate to low risk areas, Table 11 shows the high-risk areas, and Table 12 shows the areas of undetermined risk.
### Table 10 – Moderate to Low Risk Areas

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B and X</td>
<td><strong>Between the limits of the 100-year and 500-year Floodplain</strong>, area with a 0.2% (or 1 in 500 chance) annual chance of flooding. This zone is also used to designate base floodplains of lesser hazards, such as areas protected by levees from 100-year flood, or shallow flooding areas with average depths of less than one foot or drainage areas less than 1 square mile.</td>
</tr>
<tr>
<td>C and X</td>
<td>500-year Floodplain, area of minimal flood hazard.</td>
</tr>
</tbody>
</table>

### Table 11 – High Risk Areas

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td><strong>100-year Floodplain</strong>, areas with a 1% annual chance of flooding. Because detailed analyses are not performed for such areas, no depths or base flood elevations are shown within these zones.</td>
</tr>
<tr>
<td>AE</td>
<td><strong>100-year Floodplain</strong>. The base floodplain where base flood elevations are provided. AE Zones are now used on new format FIRMs instead of A1-A30 Zones.</td>
</tr>
<tr>
<td>A1-30</td>
<td><strong>100-year Floodplain</strong>, areas with a 1% annual chance of shallow flooding, usually in the form of a pond, with an average depth ranging from 1 to 3 feet. Flood elevations derived from detailed analyses are shown at selected intervals within these zones.</td>
</tr>
<tr>
<td>AH</td>
<td><strong>100-year Floodplain</strong>, river or stream flood hazard areas, and areas with a 1% or greater chance of shallow flooding each year, usually in the form of sheet flow, with an average depth ranging from 1 to 3 feet. Average flood depths derived from detailed analyses are shown within these zones.</td>
</tr>
<tr>
<td>AO</td>
<td>Areas with a temporarily increased flood risk due to the building or restoration of a flood control system (such as a levee or a dam).</td>
</tr>
<tr>
<td>AR</td>
<td><strong>100-year Floodplain</strong>, areas with a 1% annual chance of flooding that will be protected by a federal flood control</td>
</tr>
</tbody>
</table>
system where construction has reached specified legal requirements. No depths or base flood elevations are shown within these zones.

Table 12 – Undetermined Risk Areas

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Areas with possible but undetermined flood hazards. No flood hazard analysis has been conducted. Flood insurance rates are commensurate with the uncertainty of the flood risk.</td>
</tr>
</tbody>
</table>

The following analyses were conducted for FEMA flood data:

1. FEMA flood zone areas were aggregated into polygons delineating 100-year flood areas and 500-year flood areas.

2. A LiDAR-driven, 3-meter by 3-meter DEM was used to determine the elevation of the outer boundary of each polygon within the two flood risk categories. Elevations were calculated at the vertex of each flood risk polygon. This yielded a boundary representing the maximum local elevation (high-water marks) associated with 100- or 500-year flood event.

3. Flood elevation boundaries were spatially interpolated using ESRI ArcMap interpolation tool, Natural Neighbor, to provide a continuous surface of the elevation of local floodwater heights. The interpolation yielded a spatially continuous estimate of WSEL for each risk flooding event. The water surface elevations were overlaid onto the DEM to yield estimates of the flood depth relative to the underlying topography of the area. Flood depth was calculated as the difference between water surface elevation and the elevation of the underlying topography.

The algorithm used by the Natural Neighbor interpolation tool finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value. It is also known as Sibson or "area-stealing" interpolation. Its basic properties are that it's local, using only a subset of samples that surround a query point, and interpolated heights are guaranteed to be within the range of the samples used. It does not infer trends and will not produce peaks, pits, ridges, or valleys that are not already represented by the input samples. The surface passes through the input samples and is smooth everywhere.
except at locations of the input samples. Figures 77-81 model various FEMA data for the Houston-Galveston MPO region.

Figure 77 – FEMA Flood Zone Map for the region (2019)
Figure 78 - 100-Year Flooding Water Surface Elevation Model (WSEL) Map for the region
Figure 79 – 500-Year Flooding Water Surface Elevation Model (WSEL) Map for the region
Figure 80 – 100-Year Flood Depth Grids Map for the region
Figure 81 – 500-Year Flood Depth Grids Map for the region
**Exposure Score**

Exposure depth grid is a 5-by-5-meter raster grid representing flood level on top of a structure such as a roadway and bridge section. The value of exposure depth grid is equal to the difference between roadway/bridge surface elevation (DSM) and flood WSEL.

The scoring criteria for bridges are shown in Table 13. The same criteria applied to all climate stressors and scenarios. Also, the criteria apply to both grids and entire bridge structures. The scores for entire bridge segments are resulted from area-weighted summary. The results follow the same distribution and the risk classification.

**Table 13 – Bridge Exposure Classification Criteria**

<table>
<thead>
<tr>
<th>Exposure Description</th>
<th>Exposure Category</th>
<th>Exposure Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water level 6+ feet below bridge deck</td>
<td>Not exposed/low risk</td>
<td>0</td>
</tr>
<tr>
<td>Water level 4-6 feet below bridge deck</td>
<td>Medium-low risk</td>
<td>1</td>
</tr>
<tr>
<td>Water level 2-4 feet below bridge deck</td>
<td>Medium risk</td>
<td>2</td>
</tr>
<tr>
<td>Water level within 2 feet below bridge deck</td>
<td>Medium-high risk</td>
<td>3</td>
</tr>
<tr>
<td>Water level above bridge deck</td>
<td>High risk</td>
<td>4</td>
</tr>
</tbody>
</table>

Unlike bridges, the exposure scoring criteria for roadway segments are different for different climate stressors (see Table 14 for inland flooding; coastal storm surge, Table 15 for sea-level rise). Sea level risk exposure has stricter criteria than inland flooding and coastal storm surge as it measures a permanent change in roadway functions. Also, for sea level rise, subsequent sensitivity assessment and adaptive capacity assessment are not performed as the exposed roads are likely to be permanently closed and replaced by other transportation infrastructures.
Table 14 – Roadway Exposure Classification Criteria (inland flooding; coastal storm surge)

<table>
<thead>
<tr>
<th>Exposure Description</th>
<th>Exposure Category</th>
<th>Exposure Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not exposed/ Not flooded</td>
<td>Not exposed/low risk</td>
<td>0</td>
</tr>
<tr>
<td>0-1 foot of flood water</td>
<td>Medium-low risk</td>
<td>1</td>
</tr>
<tr>
<td>1-2 feet of flood water</td>
<td>Medium risk</td>
<td>2</td>
</tr>
<tr>
<td>2-3 feet of flood water</td>
<td>Medium-high risk</td>
<td>3</td>
</tr>
<tr>
<td>More than 3 feet of flood water</td>
<td>High risk</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 15 – Roadway Exposure Classification Criteria (sea level rise)

<table>
<thead>
<tr>
<th>Exposure Description</th>
<th>Exposure Category</th>
<th>Exposure Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not exposed/ Water level 3+ feet below</td>
<td>Not exposed/ low risk</td>
<td>0</td>
</tr>
<tr>
<td>Water level 2-3 feet below</td>
<td>Medium-low risk</td>
<td>1</td>
</tr>
<tr>
<td>Water level 1-2 feet below</td>
<td>Medium risk</td>
<td>2</td>
</tr>
<tr>
<td>Water level within 1 foot below</td>
<td>Medium-high risk</td>
<td>3</td>
</tr>
<tr>
<td>Water level above road</td>
<td>High risk</td>
<td>4</td>
</tr>
</tbody>
</table>

The aggregation procedure for roadway segments is different from that for bridges. Other than area-weighted aggregation, an additional centerline distance-based aggregation is conducted to address the issue associated with the length of the segments. The distance-based aggregation only captures the high-risk portions of a road segment (for freeways, high-risk portions of less than 300 feet are discarded and the aggregation scores are then rank-normalized to a 0-4 scale; for major roads, high-risk portions of less than 20 feet are discarded and the aggregation scores are normalized to a 0-4 scale, but not ranked). The final exposure score for road segments is the average of the area-weighted aggregation score and distance-weighted aggregation score. The final score ranges from 0 to 4 and follows the same risk classification criteria.
Sensitivity assessment

To assess the sensitivity of each transportation asset, the team selected a list of indicators related to assets’ structure strength, maintenance conditions, and past closures and created a composite score. For bridges, four sensitivity indicators are selected and weights for these indicators are different for inland flooding and coastal storm surge, due to the different natures of the two climate exposures.

The data of all indicators come from the TxDOT Bridge Inventory database, in which evaluation and condition scores are already available (see Table 16).
<table>
<thead>
<tr>
<th>Indicator</th>
<th>Weight (Inland Flooding)</th>
<th>Weight (Storm Surge)</th>
<th>Sensitivity Classification</th>
<th>Criteria</th>
<th>Sensitivity Score</th>
<th>Data Source</th>
<th>Criteria Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bridge Age</strong></td>
<td>5%</td>
<td>10%</td>
<td>Low</td>
<td>Age 1-10</td>
<td>0</td>
<td>TxDOT Bridge Inventory</td>
<td>TxDOT Texas Transportation Asset Management Plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium-Low</td>
<td>Age 11-25</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium</td>
<td>Age 26-40</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium-High</td>
<td>Age 41-60</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td>Age 61+</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Structural Evaluation</strong></td>
<td>30%</td>
<td>35%</td>
<td>Low</td>
<td>Score=9 Superior condition</td>
<td>0</td>
<td>TxDOT Bridge Inventory</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium-Low</td>
<td>Score in (7, 8) Desirable condition</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium</td>
<td>Score in (5, 6) - min satisfying condition</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium-High</td>
<td>Score=4 Meets criteria</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td>Score &lt; 4 - condition below standard</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Channel Conditions</strong></td>
<td>35%</td>
<td>20%</td>
<td>Low</td>
<td>Score in (8, 9) - good condition, well-protected</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium-Low</td>
<td>Score = 7 minor repairs needed</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scour Ratings</td>
<td>30%</td>
<td>35%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-----</td>
<td>-----</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Score in (5, 6) - minimum satisfying condition</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium-High</td>
<td>Score = 4 protection is severely undermined</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>Score &lt; 4 bank protection has failed</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Score in (8, 9) - good condition</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium-Low</td>
<td>Score=7 Countermeasure</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Score in (5, 6) - minimum satisfying condition</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium-High</td>
<td>Score = 4 action required to protect exposed foundation</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>Score &lt; 4 - scour critical bridges</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TxDOT Texas Transportation Asset Management Plan
For road segments, weights are the same across all exposure categories (see Table 17). Both indicators are from TxDOT, yet they are only available to a subset of road segments (TxDOT OnSystem Roadway). For the remaining road segments, sensitivity assessment is skipped and not included in the final vulnerability score calculation.

Table 17 – Road Sensitivity Indicators and Scoring Criteria

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Weight</th>
<th>Sensitivity Classification</th>
<th>Criteria</th>
<th>Sensitivity Score</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement Condition</td>
<td>40%</td>
<td>Low</td>
<td>Pavement condition score: [30, 100]</td>
<td>0</td>
<td>TxDOT Pavement Condition Information System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium-Low</td>
<td>Pavement condition score: [25, 75]</td>
<td>2</td>
<td>TxDOT Pavement Condition Information System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>Pavement condition score: [0, 25]</td>
<td>3</td>
<td>TxDOT Pavement Condition Information System</td>
</tr>
<tr>
<td>Past Closure</td>
<td>60%</td>
<td>Low (Never Closed)</td>
<td>Never Closed</td>
<td>0</td>
<td>TxDOT DriveTexas Transportation Record System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium-Low</td>
<td>Single record of closure</td>
<td>1</td>
<td>TxDOT DriveTexas Transportation Record System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>2-5 times of closure</td>
<td>2</td>
<td>TxDOT DriveTexas Transportation Record System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium-High</td>
<td>6-9 times of closure</td>
<td>3</td>
<td>TxDOT DriveTexas Transportation Record System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
<td>10+ times of closure</td>
<td>4</td>
<td>TxDOT DriveTexas Transportation Record System</td>
</tr>
</tbody>
</table>
Adaptive Capacity Assessment

Adaptive capacity indicates how well the regional transportation system can weather or recover from the service disruption. Two main aspects of adaptive capacity are examined in the analysis: network redundancy and repair cost. Since adaptive capacity is assessed in a post-disruption situation, the criteria are the same for all climate stressors and scenarios. Table 18 shows the adaptive capacity indicators and scoring criteria for bridges. Table 19 shows the adaptive capacity indicators and scoring criteria for road segments.

Table 18 – Bridge Adaptive Capacity Indicators and Scoring Criteria

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Weight</th>
<th>Criteria</th>
<th>Score</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detour Length</td>
<td>80%</td>
<td>1-2 miles</td>
<td>4</td>
<td>TxDOT Bridge Inventory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-4 miles</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-7 miles</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7-10 miles</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10+ miles/No detour</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Repair Cost</td>
<td>20%</td>
<td>Scored as low repair cost</td>
<td>4</td>
<td>Expert opinions from TxDOT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TxDOT engineers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scored as medium repair cost</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>by TxDOT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scored as high repair cost</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>by TxDOT</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 19 – Road Segment Adaptive Capacity Indicators and Scoring Criteria

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Weight</th>
<th>Criteria</th>
<th>Score</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detour Length</td>
<td>80%</td>
<td>1st ratio category in criticality results</td>
<td>4</td>
<td>GIS transportation network analysis by the team</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd ratio category in criticality results</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3rd ratio category in criticality results</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4th ratio category in criticality results</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No detour (for major roads only)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Repair Cost</td>
<td>20%</td>
<td>Scored as low repair cost by TxDOT</td>
<td>4</td>
<td>Expert opinions from TxDOT engineers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scored as medium repair cost by TxDOT</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scored as high repair cost by TxDOT</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Vulnerability assessment

The vulnerability score is a weighted summary of exposure score, sensitivity score, and adaptive capacity score (see Table 20). Different weights are given to different components of vulnerability based on importance and data availability.

<table>
<thead>
<tr>
<th>Asset Type</th>
<th>Climate Stressor</th>
<th>Exposure</th>
<th>Sensitivity*</th>
<th>Adaptive capacity¶</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge</td>
<td>Inland flooding</td>
<td>70%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Bridge</td>
<td>Storm surge</td>
<td>70%</td>
<td>25%</td>
<td>5%</td>
</tr>
<tr>
<td>Freeway</td>
<td>Inland flooding</td>
<td>80%</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td>Freeway</td>
<td>Storm surge</td>
<td>80%</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td>Major road</td>
<td>Inland flooding</td>
<td>80%</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td>Major road</td>
<td>Inland flooding</td>
<td>80%</td>
<td>N/A</td>
<td>20%</td>
</tr>
<tr>
<td>Major road</td>
<td>Storm surge</td>
<td>80%</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td>Major road</td>
<td>Storm surge</td>
<td>80%</td>
<td>N/A</td>
<td>20%</td>
</tr>
</tbody>
</table>

*For most major road segments sensitivity indicators are not provided by TxDOT, consequently the sensitivity scores are not applicable. Scores are applied for the major roads with sensitivity indicator information.

¶Adaptive capacity scores need to be reversed as a low adaptive capacity contributes to a higher vulnerability.

Since scores of each category are scaled from 0 to 4, the aggregated vulnerability score would also range from 0 to 4. For each asset type, the team cumulatively normalized the score into a scale of 0 to 1, with 1 indicating the highest vulnerability.

In the assessment of vulnerability to sea level rise, exposure scores are directly used to represent overall vulnerability. Unlike roads exposed to inland flooding and coastal storm surge that can recover from the disruptions, roads exposed to sea level rise are more likely to be permanently dysfunctional. Therefore, if an asset is inundated by rising sea water, subsequent assessments on its sensitivity and adaptive capacity are no longer meaningful.
Some additional adjustments are applied to the calculation of vulnerability score. Since most inland transportation assets are not exposed to coastal storm surge, their vulnerability index would remain zero for coastal storm surge exposures, regardless of their sensitivity and adaptive capacity attributes. Figures 82 - 90 show flood risk for transportation assets in multiple event types.

**Figure 82 – Flooding risk: 500-year flooding event - Roads**
Figure 83 – Flooding risk: 500-year flooding event - Bridges

Figure 84 – Flooding risk: Hurricane Harvey - Roads
Figure 85 – Flooding risk: Hurricane Harvey - Bridges
Figure 86 – Storm surge risk: Category 4 storm - Roads
Figure 87 – Storm surge risk: Category 4 storm - Bridges

Figure 88 - Storm surge risk: Hurricane Ike - Roads
Figure 89 – Storm surge risk: Hurricane Ike - Bridge
Figure 90 – Sea level rise risk: 5-feet sea level rise - Roads
APPENDIX C: ECONOMIC IMPACT ANALYSIS
SCENARIO SELECTION PROCESS

Economic Impact Analysis Scenario 1: Interstate 10 San Jacinto Bridge
The segment is between Magnolia Street and Independence Parkway/S Main Street in the northeast Harris County. This segment is highly vulnerable to flooding and storm surge exposures. The segment is also highly critical to the region’s transportation system as it holds a large amount of the region’s truck traffic, supporting the Houston Ship Channel freight network. It is also part of the evacuation route and the national strategic highway system. Around 38% of freeway segment is highly vulnerable to Category 4 storm surge, and 45% is highly vulnerable to Category 5 storm surge.

Figures 91 – 94 present various flooding scenarios for the segments specified above. Figure 95 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 91 – Economic Impact Analysis Scenario 1-Hurricane Harvey Flooding
Figure 92 – Economic Impact Analysis Scenario 1-500-Year Flooding

Figure 93 – Economic Impact Analysis Scenario 1-Hurricane Ike Storm Surge
Figure 94 – Economic Impact Analysis Scenario 1 - Category 4 Hurricane Surge
Figure 95 – Economic Impact Analysis Scenario 1-TDM Network

Link ID: 24571-23430 & 32747-22386
Economic Impact Analysis Scenario 2: Gulf Freeway (South and North Access to Galveston Causeway)

Gulf Freeway marks the southern end of Interstate 45 and provides access to the Galveston Island. Although the bridge segment (i.e., Causeway Bridge) is not vulnerable to climate stressors, roads at both ends of the bridge are highly vulnerable to flooding, especially to coastal storm surge. This segment has an extremely low adaptive capacity as there are no immediate alternative roads once the asset is disrupted or closed. Around 53% of miles in this segment are highly vulnerable to Category 4 storm surge; for Category 5, the percentage is 75%.

Figures 96 – 100 present various flooding scenarios for the segments specified above. Figure 101 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 96 – Economic Impact Analysis Scenario 2-Hurricane Harvey Flooding
Figure 97 – Economic Impact Analysis Scenario 2-500-Year Flooding

Figure 98 – Economic Impact Analysis Scenario 2-Hurricane Ike Storm Surge
Figure 99 – Economic Impact Analysis Scenario 2-Category 4 Hurricane Storm Surge

Figure 100 – Economic Impact Analysis Scenario 2-5-Feet Sea-Level Rise
Figure 101 – Economic Impact Analysis Scenario 2-TDM Network

Link ID: 26499-37019, 29438-26498, 29734-29905, 29735-29925, 29735-37020, 29906-26499, 29924-29735, 29926-29735, 37019-29734, 37020-29438
**Economic Impact Analysis Scenario 3: State Highway 146 (North Access to Fred Hartman Bridge)**

State Highway 146 and State Highway 146B, providing access to Fred Hartman Bridge are highly vulnerable to 500-year flooding events and to Category 4 storm surge. The segments provide vital access and linkage to several industrial facilities. For the State Highway 146 segment, around 23% of miles are highly vulnerable to Hurricane Harvey flooding and 45% are highly vulnerable to Category 5 storm surge. Figure 102 shows Segment 3.

---

**Figure 102 – State Highway 146 (North Access to Fred Hartman Bridge)**
Figures 103 – 106 present various flooding scenarios for the segments specified above. Figure 107 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 103 – Economic Impact Analysis Scenario 3-Hurricane Harvey Flooding
Figure 104 – Economic Impact Analysis Scenario 3-500-Year Flooding

Figure 105 – Economic Impact Analysis Scenario 3-Category 4 Hurricane Storm Surge
Figure 106 – Economic Impact Analysis Scenario 3-Hurricane Ike Storm Surge

Figure 107 – Economic Impact Analysis Scenario 3-TDM Network

Link ID: 22383-20784 & 27244-22382
Economic Impact Analysis Scenario 4: State Highway 225 (Pasadena Freeway)/Lawndale Street

State Highway 225 (Pasadena Freeway) and Lawndale Street between Allen Genoa and Interstate 610 over Sims Bayou are high-risk. Given the segment’s proximity to Sims Bayou and Buffalo Bayou, the segment is highly vulnerable to flooding and storm surge. The segment provides important linkage to industrial sites in southeastern Houston and several cities in the Houston metropolitan area. Only 8% of this road segment is highly vulnerable to Hurricane Harvey flooding and 15% is vulnerable to Category 5 storm surge. However, for the Lawndale Street segment, 57% is highly vulnerable to 500-year flooding event and 76% to Category 5 storm surge. Figure 108 shows Segment 4.

Figure 108 – State Highway 225 (Pasadena Freeway)/Lawndale Street
Figures 109 – 111 present various flooding scenarios for the segments specified above. Figure 112 identifies the Travel Demand Modeling Network IDs for the above specified segments.

**Figure 109 – Economic Impact Analysis Scenario 4-Hurricane Harvey Flooding**

![Image of Hurricane Harvey Flooding Scenario]

**Figure 110 – Economic Impact Analysis Scenario 4-500-Year Flooding**

![Image of 500-Year Flooding Scenario]
Figure 111 – Economic Impact Analysis Scenario 4-Category 4 Hurricane Storm Surge

Figure 112 – Economic Impact Analysis Scenario 4-TDM Network
Link ID: 22644-26994, 32452-30071, & 39051-32594
Economic Impact Analysis Scenario 5: US Highway 59

US Highway 59 (Interstate 69) between Morgan Cemetery Road/County Road 379 and State Highway 105 Bypass over East Fork San Jacinto River is high-risk as it was completely inundated during Hurricane Harvey. Around 24% of the highway segment miles are highly vulnerable to Hurricane Harvey flooding. Figure 113 shows Segment 5.

Figure 113 – US Highway 59 between County Road 379 and State Highway 105 Bypass
Figures 114 – 115 present various flooding scenarios for the segments specified above. Figure 116 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 114 – Economic Impact Analysis Scenario 5-Hurricane Harvey Flooding

Figure 115 – Economic Impact Analysis Scenario 5-500-year Flooding
Figure 116 – Economic Impact Analysis Scenario 5-TDM Network

Link ID: 22191-34387 & 28600-34389
**Economic Impact Analysis Scenario 6: Farm-to-Market Roads 723 and 359**

Farm-to-Market Road 723 between US Highway 90A and Beadle Road and Farm-to-Market Road 359 between US Highway 90A and Farmer/Mason over the Brazos River are high-risk. Both road segments were fully inundated during Hurricane Harvey and are projected to be severely impacted by 500-year flooding events. These segments provide essential transportation support to several suburban neighborhoods in Fort Bend County and there are no alternative routes and limited redundancy to them. Figure 117 shows Segment 6.

*Figure 117 – Farm-to-Market Roads 723 and 359 Segments*
Figures 118 – 129 present various flooding scenarios for the segments specified above. Figure 120 identifies the Travel Demand Modeling Network IDs for the above specified segments.

**Figure 118 – Economic Impact Analysis Scenario 6-Hurricane Harvey Flooding**

**Figure 119 – Economic Impact Analysis Scenario 6-500-Year Flooding**
Figure 120 – Economic Impact Analysis Scenario 6-TDM Network

Link ID: 26154-26581 & 26178-38973
Economic Impact Analysis Scenario 7: Interstate 10
Interstate 10 between Shepherd Drive and Washington Avenue and between Heights Boulevard and Studemont Street is modeled to be highly vulnerable to flooding events. Located over Buffalo Bayou, these segments were severely flooded during Hurricane Harvey and are projected to be undergoing similar disruption during 500-year flooding events. This segment provides vital connections to major employment centers such as Galleria and Houston downtown area, as well as to several major residential communities. Around 32% of the segment are highly vulnerable to a 500-year flooding event and 40% are to Hurricane Harvey flooding. Figure 121 shows Segment 7.

Figure 121 – Interstate 10 Segments
Figures 122 – 123 present various flooding scenarios for the segments specified above. Figure 124 identifies the Travel Demand Modeling Network IDs for the above specified segments.

**Figure 122 – Economic Impact Analysis Scenario 7-Hurricane Harvey Flooding**

**Figure 123 – Economic Impact Analysis Scenario 7-500-Year Flooding**
Figure 124 – Economic Impact Analysis Scenario 7-TDM Network

Economic Impact Analysis Scenario 8: North-South Connecters along Buffalo Bayou between Memorial Drive and Briar Forest

The scenario includes sections of State Highway 6, North Eldridge Parkway, Dairy Ashford Road, North Kirkwood Road, Wilcrest Drive, Beltway 8, and Gessner Road crossing the Buffalo Bayou. They were severely impacted during Hurricane Harvey and significantly impacted residents of Memorial-Energy Corridor area. These segments provide vital connections to Interstate 10, which is highly critical to the region’s economic and social functioning. For beltway 8, 25% of the highway segment is highly vulnerable to Hurricane Harvey flooding. For all the major roads in the scenario, around 23% are highly vulnerable to Hurricane Harvey flooding. Figure 125 shows Segment 8.

Figure 125 – North-South Connecters along Buffalo Bayou between Memorial Drive and Briar Forest
Figures 126 – 127 present various flooding scenarios for the segments specified above. Figure 128 identifies the Travel Demand Modeling Network IDs for the above specified segments.

**Figure 126 – Economic Impact Analysis Scenario 8-Hurricane Harvey Flooding**

![Image of Hurricane Harvey Flooding](image1)

**Figure 127 – Economic Impact Analysis Scenario 8-500-Year Flooding**

![Image of 500-Year Flooding](image2)
Figure 128 – Economic Impact Analysis Scenario 8-TDM Network

Link ID: 31840-22492, 23046-24736, 23109-32131, 24422-24423, 23046-24736, 31840-22492, 41043-31934, 39965-31949, 31951-31952, 31956-32105, 32055-32056, 31956-32105, 39965-31949, 41043-31934
APPENDIX D: GLOSSARY AND ACRONYMS

Overview
Language used in resiliency work is very important. In everyday speech, it’s common for words like “risk” and “vulnerability” to be used interchangeably. However, for this Pilot Program and for technical discussions, sharing a common understanding of terms is essential. Many of these definitions are taken from FHWA’s most recent Hydraulic Engineering Circular HEC-1713. Definitions from other sources are cited.

Glossary Definitions

ADAPTATION: Preparing for the effects of extreme events and climate change on the transportation infrastructure and systems. Adaptation refers to the planning, designing, constructing, operating, or maintaining transportation infrastructure while incorporating consideration of extreme events and climate change.

ADAPTIVE CAPACITY: The degree to which the system containing the asset (road, bridge, etc.) can adjust or mitigate the potential for damage or service interruption by climatic hazards.

ANNUAL EXCEEDANCE PROBABILITY (AEP): The probability that the magnitude of the random variable (e.g. annual maximum flood peak) will be equaled or exceeded each year.

BASE FLOOD: The flood having a 1% chance of being equaled or exceeded in any given year.

BASE FLOODPLAIN: The area subject to flooding by the base flood.

CENTERLINE MILE: Centerline miles measure the length of a road or highway regardless of how many lanes it has. Because of divergences and curves, centerline miles can vary slightly between the two sides of a divided highway. Centerline miles are a more intuitive measurement of the overall length of roads than lane miles. (For instance, if there are only 10 centerline miles of roadway in each city but it all consists of five-lane highway, it would measure 50 lane miles.)

CLIMATE CHANGE: 1) A significant and lasting shift in the statistical distribution of weather patterns around the average conditions (e.g., more or fewer extreme weather events) over periods ranging from decades to millions of years. 2) Any significant shift in the measures of climate lasting for an extended period, including major alterations in temperature, precipitation, coastal storms, or wind patterns, among others, that occur over several decades or longer. 3) A non-random shift in climate that is measured over

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several decades or longer. The change may result from natural or human-induced causes.

CLIMATE: The characteristic weather of a region, particularly regarding temperature and precipitation, averaged over some significant interval of time (minimum 20 years).

COLLECTOR: Provides both land access service and traffic circulation within residential neighborhoods, and commercial and industrial areas. A collector may penetrate residential neighborhoods, distributing trips from the arterials through the area to the ultimate destination. The collector street also collects traffic from local streets in residential neighborhoods and channels it into the arterial system. In the central business district and in other areas of like development and traffic density, the collector system may include the street grid which forms a logical entity for traffic circulation.

DISCHARGE: Volume of water passing a given point per unit of time. Also known as flow.

EXPOSURE: The frequency, nature, and degree to which a transportation asset (road, bridge, etc.) will experience a climatic hazard.

EXTREME EVENT: Severe and rare natural occurrence that may pose significant risks for damage, destruction, or loss of life. Per Order 5520 and for the purposes of this report “extreme event” refers to risks posed by climate change and extreme weather events (FHWA 2014).

EXTREME FLOOD EVENT: Specific type of extreme weather event that is manifested as flooding.

EXTREME WEATHER EVENT: Significant anomalies in temperature, precipitation, and winds that may manifest as heavy precipitation and flooding, heatwaves, drought, wildfires, and windstorms (including tornados and tropical storms). They are rarely occurring, weather-induced events that usually cause damage, destruction, or severe economic loss.

FLOOD: A general and temporary condition of partial or complete inundation of normally dry land areas resulting from the overflow of inland or tidal waters.

FLOODPLAIN: The land area susceptible to being inundated by flood waters.

FLOW: Volume of water passing a given point per unit time. Also known as discharge.

HAZARD: Something that is potentially dangerous or harmful, often the root cause of an unwanted outcome.
HYDROLOGY: The earth science that considers the occurrence, distribution, and movement of water in the atmosphere, between the atmosphere and the earth’s surface, and in the earth.

IMPERMEABLE: not permitting passage (as of a fluid) through its substance.\textsuperscript{14}

MINOR ARTERIAL: Inter-connects with and augments the principal arterial system and provides service to trips of moderate length at somewhat lower of travel mobility than principal arterials. Ideally, they should not penetrate identifiable neighborhoods. The spacing of minor arterial streets should normally be not more than 1 mile in fully developed areas.

NATURE-BASED INFRASTRUCTURE: healthy ecosystems, including forests, wetlands, floodplains, dune systems, and reefs, which provide multiple benefits to communities, including storm protection through wave attenuation or flood storage capacity and enhanced water services and security.\textsuperscript{15}

PERMEABLE: capable of being permeated: penetrable especially having pores or openings that permit liquids or gases to pass through a permeable membrane permeable limestone.\textsuperscript{16}

POLYLINE: a connected series of line segments.

PRECIPITATION: Water in the form of rain, hail, sleet, or snow that forms in the atmosphere and falls to the earth’s surface.

RESILIENCE: The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

RETURN PERIOD: The average length of time between occurrences in which the value of a random variable (e.g. flood magnitude) is equaled or exceeded. Actual times between occurrences may be longer or shorter, but the return period represents the average interval. The return period is the inverse of the Annual Exceedance Probability (AEP). For example, if the AEP equals 0.01 (or 1\%) the return period is 100 years.

RISK: The consequences associated with hazards (including climatic) considering the probabilities of those hazards. More specifically for this report, risks are the consequences associated with the probability of flooding attributable to an encroachment. It shall include the potential for property loss and hazard to life during the service life of the highway (23 CFR 650 A).

\textsuperscript{14} https://www.merriam-webster.com/dictionary/impermeable
\textsuperscript{15} https://coast.noaa.gov/states/fast-facts/natural-infrastructure.html
\textsuperscript{16} https://www.merriam-webster.com/dictionary/permeable
RUNOFF: The portion of a rainfall event discharged from a watershed into the stream network during and immediately following the rainfall.

SENSITIVITY: The degree to which an asset is damaged, or service is interrupted by a climatic hazard.

VULNERABILITY: The extent to which a transportation asset is susceptible to sustaining damage from hazards (including climatic). Vulnerability is a function of exposure, sensitivity, and adaptive capacity.

**Acronym Definitions**

AADT: Annually Averaged Daily Traffic

AADTT: Annually Averaged Daily Truck Traffic

AEP: Annual Exceedance Probability

BMP: Best Management Practice

CVM: Criticality-Vulnerability Matrix

DEM: Digital Elevation Model

DSM: Digital Surface Model

EMS: Emergency Management Services

EOC: Emergency Operations Center

FEMA: Federal Emergency Management Agency

FHWA: Federal Highway Administration

FHWA: U.S. Federal Highway Administration

GDP: Gross Domestic Product

GIS: Geographic Information System

GRID: Geospatial Roadway Inventory Database

H-GAC Region Resilience Pilot Program: Resiliency and Durability to Extreme Weather in the H-GAC Area Region Pilot Program

H-GAC: Houston-Galveston Area Council

HOU: William Hobby Airport
IAH: Bush Intercontinental Airport
LiDAR: Light Detection and Ranging
MHHW: Mean Higher High Water
MOM: Maximum of Maximums
MPO: Metropolitan Planning Organization
NOAA: National Oceanic and Atmospheric Administration
NPDES: National Pollutant Discharge Elimination System
Pilot Program: Resiliency and Durability to Extreme Weather in the H-GAC Area Region
REMI: Regional Economic Models, Inc.
SWPPP: Stormwater Pollution Prevention Plans
TDM: Travel Demand Modeling
The team: Pilot Program team
TMA: Transportation Management Area
TNRIS: Texas Natural Resources Information System
TxDOT: Texas Department of Transportation
U.S.: United States
USACE: United States Army Corps of Engineers
VAST: Vulnerability Assessment Scoring Tool
VHT: Vehicle Hours Travelled
VMS: Variable Messaging Signs
VMT: Vehicle Miles Travelled
WAD: Wave Attenuation Devices
WSEL: Water Surface Elevation Model
APPENDIX E: ADAPTATION STRATEGIES

A detailed overview of the 25 strategies is provided on the pages that follow. All images in this Appendix provided courtesy of the Texas A&M Transportation Institute.
Strategy 1: Increase Number of Swales and Ditches

STRATEGY CATEGORY
Stormwater Management

DESCRIPTION
Swales and ditches are a stormwater best management practice (BMP) that helps drain stormwater away from road infrastructure toward larger stormwater facilities (e.g., channels, detention/retention ponds, permanent water bodies).

As is the case for many hydraulic design best practices, ditches and swales should be implemented with other hydraulic design elements, such as cross culverts, stormwater channels or conduits, and retention ponds. For this reason, although ‘small scale’ implementations will have limited efficacy for preventing flooding during severe rainstorm events, when implemented as part of a broader hydraulic system, they represent a low-cost method for improving local drainage and reducing pavement subsurface damage.

APPLICATION

<table>
<thead>
<tr>
<th>CLIMATE STRESSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Flooding</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural roads (i.e., no hard sidewalks)</td>
</tr>
<tr>
<td>Component of general regional BMP for hydraulic design</td>
</tr>
</tbody>
</table>

ADAPTATION RESPONSE

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Prepare</td>
<td>Recovery</td>
</tr>
<tr>
<td>Protect</td>
<td></td>
</tr>
</tbody>
</table>
RESILIENCE BENEFITS

When sized, located, and maintained properly, swales and ditches can help reduce flooding during severe rainstorm events, but also play a role in preventing water from damaging pavement substructures. Swales and ditches also:

- Improve the recovery time (return to use rate) of inundated roads following heavy storms
- Improve functionality of other hydraulic design features (culverts, channels)
- Reduce subsurface damage following chronic, acute flooding.

OTHER BENEFITS

Swales and ditches can play a role in preventing chronic damage from repeated smaller flood events.

LIMITATIONS / CONSIDERATIONS

Swales and ditches require preventative maintenance (e.g., need to be cleared of debris) to ensure that they continue to drain stormwater at their designed capacity. There is, therefore, a need to re-establish swales and ditches (vegetation, concrete, riprap). Swales and ditches can also affect driveway access.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporary drainage easements. Keep roadway clear of stormwater by conveying excess stormwater to outfall structure.</td>
<td>Effective with formal preventative maintenance strategy and allocated resources.</td>
<td>Easy</td>
<td>Typically included in construction costs.</td>
<td>Low</td>
</tr>
</tbody>
</table>
**Strategy 2: Retention and Detention Ponds**

**STRATEGY CATEGORY**  Stormwater Management

**DESCRIPTION**

Creating retention and detention ponds is an effective method for managing stormwater by collecting stormwater and releasing it at a rate that prevents flooding or erosion. The main difference between the two is that retention ponds hold water indefinitely, while detention ponds act as a temporary area for storing stormwater. Often, detention ponds are smaller than retention ponds.

As is the case for many hydraulic design best practices, retention/detention ponds should be implemented with other hydraulic design elements, such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, their utility and effectiveness depend, in part, on their inclusion in broader scale hydraulic system designs. When retention and detention ponds are implemented in transportation corridors, safety issues such as clear site lines (vegetation) and vehicle interaction must be considered.

**APPLICATION**

- Urban locations
- Residential locations

**CLIMATE STRESSORS**

- Local Flooding

**ADAPTATION RESPONSE**

- Prepare
- Protect

- Recovery
RESILIENCE BENEFITS

When properly designed and maintained, retention and detention ponds can help reduce flooding during severe rainfall events. These ponds also improve the functionality of other hydraulic design features (culverts, swales/ditches, etc.).

OTHER BENEFITS

By collecting sediment-laden stormwater, these ponds capture heavier contaminants, such as solids and metals from roadways, as well as other pollutants. Retained water and associated vegetation naturally filter these contaminants and return clean water downstream.

LIMITATION S / CONSIDERATIONS

Location

- Sufficient space is required for the construction and to provide maintenance access for these ponds.
- Topography should ensure surrounding area drains to the pond.

Maintenance

- Since these ponds are designed to collect sediment, it is important to regularly remove sediment buildup to ensure their holding capacity is not reduced.

Soil type/structure

- Soil type/structure must be considered to ensure effective stormwater storage by limiting infiltration.

Safety

- Prohibit public access to address safety concerns.
<table>
<thead>
<tr>
<th>DECISION CRITERIA</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effectiveness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implementation Requirements</td>
<td>Available space (square feet), soil type, topography must be considered.</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Improved stormwater collection and flood control. Improves water quality.</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>
Strategy 3: Bioswales (Biofiltration Swales)

STRATEGY CATEGORY
Stormwater Management

DESCRIPTION
A bioswale is a narrow strip of vegetation that redirects and filters stormwater. It is used to collect runoff stormwater from non-porous surfaces such as roads, parking lots, and rooftops. Bioswales improve water quality by infiltrating the first flush of stormwater and filtering secondary runoff.

As is the case for many hydraulic design best practices, bioswales should be implemented with other hydraulic design elements such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, although ‘small scale’ implementations will have limited efficacy for preventing flooding during severe rainstorm events when implemented as part of a broader hydraulic system, they are low-cost methods for improving local drainage and reducing pavement subsurface damage.

APPLICATION
- Implemented in and adjacent to areas requiring stormwater conveyance

CLIMATE STRESSORS
- Local Flooding

ADAPTATION RESPONSE
- Prepare
- Protect
- Recovery
RESILIENCE BENEFITS

- Mitigate flooding potential and diverts stormwater away from critical infrastructure.
- Decreases runoff peak flow rates and volumes.

OTHER BENEFITS

- Aesthetically pleasing
- Improves water quality
- Improves biodiversity
- Groundwater recharge

LIMITATIONS / CONSIDERATIONS

- Bioswale design considerations include climate, precipitation patterns, available space/location, budget, and vegetation suitability.
- They should be sized to convey a 10-year storm minimum.
- A bioswale typically comprises four different layers:
  - Planting soil bed for vegetation
  - Sand layer for infiltration
  - Gravel layer for storage

Infiltration pipe/drain tube for conveyance

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved stormwater collection and flood control, improves stormwater quality</td>
<td>Climate, site size/location, budget, and vegetation suitability</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

194
Strategy 4: Depressed and Raised Medians

STRATEGY CATEGORY  Stormwater Management

DESCRIPTION

Raised medians are curbed sections that typically occupy the center of the roadway. Depressed medians have a common ditch or swale between divided roadways.

APPLICATION  CLIMATE STRESSORS

- Urban locations
- Residential locations
- Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery
RESILIENCE BENEFITS

Raised medians allow curb inlets that convey stormwater away from roadway. They create positive drainage in super elevation conditions.

In addition, depressed medians hold/convey stormwater away from the roadway protecting the pavement structure.

OTHER BENEFITS

- Reduced motor vehicle crashes
- Increased roadway capacity
- Decreased delays for motorists
- Snow storage in colder climates

LIMITATIONS / CONSIDERATIONS

If width allows, medians can potentially use unused space to provide stormwater conveyance and storage. Underground utilities may limit the use of medians.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved stormwater collection and flood control.</td>
<td>Sufficient width between travel lanes</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Strategy 5: Green Infrastructure

**STRATEGY CATEGORY**  Stormwater Management

**DESCRIPTION**

Impervious streets, parking lots, and sidewalks increase peak flow and reduce the time between storm occurrence and peak flow rate. Both factors result in increased localized flooding. Green infrastructure is a stormwater management approach that incorporates vegetation, soil, and engineered systems (e.g., tree wells and biofiltration gardens) to slow, filter, and clean stormwater.

Typical green infrastructure stormwater control applications include:

- Green parking/streets/roofs
- Bioretention filters
- Rainwater harvesting
- Urban tree canopy

As is the case for many hydraulic design best practices, green infrastructure should be implemented with other hydraulic design elements such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, although ‘small scale’ implementations will have limited efficacy for preventing flooding during severe rainstorm events when implemented as part of a broader hydraulic system, it is a low-cost method for improving local drainage and reducing pavement subsurface damage.

**APPLICATION**

- Urban areas to reduce stormwater runoff

**CLIMATE STRESSORS**

- Local Flooding
ADAPTATION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Decreases the volume of water that enters waterways as direct runoff through a combination of planned practices and engineered devices.

OTHER BENEFITS

- Improves air quality
- Reduces urban heat islands

LIMITATIONS / CONSIDERATIONS

- Easy to implement during new construction
- Maintenance is required for aesthetic and functional purposes
- Must meet local landscape, stormwater, and public ordinances and policies

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved stormwater collection and flood control. Collects and improves stormwater.</td>
<td>Public works coordination—maintenance plan.</td>
<td>Moderate - Technical guidance and standard drawings are available to assist in the development of green infrastructure plans.</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>
Strategy 6: Culvert Cleaning/Maintenance

STRATEGY CATEGORY
Maintenance (Primary) & Stormwater Management (Secondary)

DESCRIPTION
A culvert "conveys surface water through a roadway embankment or away from the highway right-of-way (ROW) or into a channel along the ROW." Cleaning and regular maintenance of culverts ensures optimal flow of water through the stormwater management system. A proactive culvert maintenance strategy is effective in helping protect road infrastructure in a flooding event.

APPLICATION

<table>
<thead>
<tr>
<th>CLIMATE STRESSORS</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Flooding</td>
<td>Allows the movement of water under a road, bridge, or railway without disrupting traffic</td>
</tr>
<tr>
<td>Storm Surge</td>
<td></td>
</tr>
</tbody>
</table>

ADAPTATION RESPONSE

- Prepare
- Protect
RESILIENCE BENEFITS

- Reduces the risk of flooding if adequately designed to move large volumes of water at a reasonable speed through the drainage system.

OTHER BENEFITS

- Can serve as specialized wildlife crossings and generally improve wildlife habitat connectivity.

LIMITATIONS / CONSIDERATIONS

A typical regional culvert network is very large, and many culverts are undocumented. Developing a culvert inventory in a georeferenced format may help plan and prioritize culvert maintenance. A more feasible option could be to prioritize maintenance based on known local flooding.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
</table>
### Strategy 7: Stormwater Management Plan

**STRATEGY CATEGORY** Planning (Primary) & Stormwater Management (Secondary)

**DESCRIPTION**

A stormwater management plan is a functional plan addressing existing stormwater system conditions, the operation and maintenance of existing facilities, and the required capacity for new facilities.

When stormwater is unable to infiltrate into the ground because of impervious surfaces (such as roads, parking lots, and roofs), it flows across the surfaces until it encounters a collection system (e.g., storm drainage), surface water body, or other points of discharge. As impervious surfaces increase with development, stormwater runoff occurs more quickly and with increased volume, meaning peak flows in a watershed occur quicker and at an increased rate. This increase in peak flow rate increases the frequency of flooding downstream.

**APPLICATION**

- A Stormwater Management Plan should include the development and enforcement of the following:
  - Stormwater Pollution Prevention Plans
  - Municipal Separate Storm Sewer System
  - BMPs
  - Response Actions (if available)

**CLIMATE STRESSORS**

- Local Flooding
- Sea Level Rise
- Storm Surge
ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

An up-to-date Stormwater Management Plan is critical to repair a system after weather-related disaster events (e.g., flooding, sea-level rise, storm surge, or a combination of these events).

OTHER BENEFITS

- Stormwater management is important to maintain the ecological integrity, quality, and quantity of water resources.
- Stormwater management can result in reduced costs and/or fees for remediation of adverse impacts on the environment.

LIMITATION S / CONSIDERATIONS

Local permitting agencies may determine the development and implementation of a Stormwater Management Plan. The plan must include monitoring and evaluation.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Stormwater Management Plan is important to prevent physical damage to persons and property from flooding or other weather-related disasters.</td>
<td>Understanding of National Pollutant Discharge Elimination System is required.</td>
<td>Moderate - Fiscal and operational constraints must be considered during implementation.</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
**Strategy 8: Land Use Planning/Climate Justice**

<table>
<thead>
<tr>
<th>STRATEGY CATEGORY</th>
<th>Planning</th>
</tr>
</thead>
</table>

**DESCRIPTION**

Land use planning refers to planning the physical layout of communities and cities. Land use planning determines where development occurs (i.e., the built environment) and identifies open space or land for preservation (i.e., the natural environment). Land use planning aimed at increasing resiliency includes adopting land-use codes and zoning regulations that avoid development in flood-prone areas (thereby reserving open space to enhance drainage) and the development and adoption of development standards and building codes and incentive/disincentive programs to avoid development in vulnerable areas (such as low income and minority housing areas). Incentivizing innovative construction techniques also allows communities to recover quickly after catastrophic weather-related events.

**APPLICATION**

<table>
<thead>
<tr>
<th>CLIMATE STRESSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Local Flooding</td>
</tr>
<tr>
<td>• Sea Level Rise</td>
</tr>
<tr>
<td>• Storm Surge</td>
</tr>
</tbody>
</table>

| • Cities |
| • Communities |

**ADAPTATION RESPONSE**

| • Prepare |
| • Protect |
| • Recovery |
RESILIENCE BENEFITS

- More resilient communities.
- Open space to enhance drainage. Open spaces slow the flow of floodwater and reduce potential damage and erosion.

OTHER BENEFITS

- Conserve vulnerable natural resources, such as wetlands, watersheds, groundwater, and tidal basins. If impact fees are levied as part of a comprehensive land-land use planning policy, the revenue can be used to invest in further resilience adaptation strategies, such as stormwater management and flood control improvements associated with the new developments.

LIMITATIONS / CONSIDERATIONS

Adaptation strategies often focus on infrastructure and stormwater management with less emphasis on local land use planning or policy.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very effective</td>
<td>Comprehensive planning</td>
<td>Risk of private</td>
<td>Dependent on</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Land use codes</td>
<td>property owners</td>
<td>community and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zoning regulations</td>
<td>challenging land-use</td>
<td>stakeholder support</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development standards</td>
<td>policy as infringing on</td>
<td>but tend to be lower</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Building codes</td>
<td>property rights.</td>
<td>with new construction/development.</td>
<td></td>
</tr>
</tbody>
</table>
Strategy 9: Relocate or Abandon Roads

STRATEGY CATEGORY
Planning (Primary) & Infrastructure (Secondary)

DESCRIPTION
Relocate or abandon roads that have experienced repeated damage or inundation in the past. Abandoning can also entail converting roads to gravel or other low maintenance materials.

APPLICATION
- Typically used for lower functional classes of roads
- Serving small communities with one or more viable alternative roads
- Coastal roads inundated by sea level rise
- Costs of raising road profile or maintaining a road has become excessive

CLIMATE STRESSORS
- Local Flooding
- Sea Level Rise
ADAPTATION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Enhance resiliency by mitigating future risks and damage to the road.

OTHER BENEFITS

- Reduced cost over the life of the asset.

LIMITATION S / CONSIDERATIONS

- Abandoning a road can only be considered if a community has a viable alternative mode of access available.
- Hydrologists and engineers need to map the floodplain and restructure the roadways for the post-flood environment.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective</td>
<td>Community must have access to a viable alternative mode/road.</td>
<td>Easy</td>
<td>Low to high (if an alternative road needs to be constructed)</td>
<td>Can potentially be lower than with the existing road.</td>
</tr>
</tbody>
</table>
Strategy 10: Shelter-in-Place

**STRATEGY CATEGORY** Planning

**DESCRIPTION**
The term “shelter-in-place” was originally used to describe an emergency response to nuclear or biological hazards. It describes a situation where residents are advised or lawfully ordered to remain in place during a threat to mitigate the damage caused by an ongoing hazard. The strategy is essentially the opposite of an evacuation.

**APPLICATION**
Guidance, advice, incentives, or lawful orders are given to sections of a population to prevent or minimize the use of road networks during floods while inundation is present.” Shelter-in-place in this context is used broadly to describe various strategies to temporarily reduce road use with the goal of improving safety and reducing the long-term economic costs of flooding (e.g., damage to pavements). This shelter in place strategy is comprised of two connected components: 1) a cost-benefit analysis of the safety and infrastructure benefits of reduced travel versus the social and economic cost of this reduced travel, and 2) communications (guidance, advisories, or orders) designed to temporarily reduce or prevent road use.

To be successful, shelter in place strategies should be developed proactively and as part of a broad, cross-disciplinary approach for managing the impacts of flooding.
<table>
<thead>
<tr>
<th>ADAPTATION RESPONSE</th>
<th>CLIMATE STRESSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Protect</td>
<td>• Local Flooding</td>
</tr>
<tr>
<td>• Recovery</td>
<td></td>
</tr>
</tbody>
</table>

**RESILIENCE BENEFITS**

- Acknowledges that flooding will inevitably occur, but that damage and impacts of flooding can be reduced through potentially simple, low-cost social strategies.
- Encourages stakeholders to develop a systems approach to flood mitigation and to organize knowledge and information on flood hazards and impacts.

**OTHER BENEFITS**

- Shelter-in-place strategies can be adapted to preparing for and mitigating other hazards (e.g., infectious diseases, such as the COVID-19 response).

**LIMITATIONS / CONSIDERATIONS**

Shelter-in-place may be perceived to be a last resort, alarmist, autocratic, and possibly a failure of traditional engineering approaches. Effective communication and proactive planning are required to change this perception.

The term “shelter in place” may also cause negative perceptions. Concepts such as “flood day” (akin to snow days often used in northern states) may be more effective terms for positively affecting behavior.

**DECISION CRITERIA**

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentially effective, but unproven</td>
<td>Robust planning and organization</td>
<td>Difficult</td>
<td>Medium. However, costs could be offset by maintaining strategies and using the planning process to design and review other resilience strategies. Indirect costs, such as economic loss.</td>
<td>Medium. Similar to implementation costs.</td>
</tr>
</tbody>
</table>
Strategy 11: Evacuation Route Identification and Planning

STRATEGY CATEGORY  Planning

DESCRIPTION
When extreme weather events require evacuation, it is essential that evacuation and rescue routes are identified and designated in advance. It is also critical that the public is informed and provided information about designated evacuation and rescue routes. Information can be shared through various methods, including published guidelines/information, automated calling systems (texts and phone calls), variable messaging signs, and live radio announcements.

APPLICATION  CLIMATE STRESSORS
• Urban and rural locations  • Storm Surge
•  • Flooding

ADAPTATION RESPONSE
• Prepare
• Protect

RESILIENCE BENEFITS
• Effective strategy to provide public with a safe route to evacuate from a potentially impacted area in advance of an extreme weather event.
OTHER BENEFITS

- Improves community participation/safety during planning process.

LIMITATIONS / CONSIDERATIONS

- Evacuations can be a complex process. Careful planning will minimize risks associated with evacuation during emergency situations.
- A key consideration in the planning and use of evacuation routes is the vulnerability and mobility of the potential users of the routes. Options are needed for vulnerable populations (disabled or the elderly) to safely use the routes.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly effective strategy to protect public.</td>
<td>Can be complex process. Requires extensive agency coordination.</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
### Strategy 12: Prohibiting Overweight / Oversize Vehicles

**STRATEGY CATEGORY**  
Planning (Primary) & Infrastructure (Secondary)

**DESCRIPTION**  
Flooding and the inundation of the pavement structure reduce pavement layer stiffness and have the potential to cause substantial damage to pavement structures. Heavy loads on weakened pavements in the immediate aftermath of a flooding event can lead to sudden failure or severe damage, such as severe cracking, ruts, and potholes. This strategy prohibits oversize/overweight vehicles on inundated pavements or pavement structures until flood water has drained from base layers.

**APPLICATION**  

<table>
<thead>
<tr>
<th>CLIMATE STRESSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Flooding</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ADAPTATION RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protect</td>
</tr>
<tr>
<td>Recovery</td>
</tr>
</tbody>
</table>

**RESILIENCE BENEFITS**  
- Reduce the risk of failure or damage to the pavement structure.
OTHER BENEFITS

- Increase the service life of the impacted roads.

LIMITATIONS / CONSIDERATIONS

Might impact recovery strategies and might not be well received by the trucking industry.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective</td>
<td>Support from decision-makers</td>
<td>Potentially challenging</td>
<td>Low, but requires enforcement</td>
<td>Will reduce maintenance costs over the life of impacted roads.</td>
</tr>
</tbody>
</table>
Strategy 13: Sensor Technologies and Monitoring Programs

STRATEGY CATEGORY Planning

DESCRIPTION

Stormwater system design is based on the concept of risk. Infrastructure is engineered to accommodate rainfall events up to a limit (e.g., a 100-year storm) determined by analyzing a history of local rainfall events. When these design intensities or durations are exceeded, the structure will temporarily fail (i.e., prevent drainage), and flooding will inevitably occur. In extreme cases, the hydraulic pressures associated with flooding can cause infrastructure to catastrophically fail, causing damage to roadway infrastructure and affecting the safety and mobility of travelers. This family of strategies includes employing sensors to monitor rainfall, runoff, water levels, and the general condition of the stormwater system.

Examples include:

- Water flow and level sensors on stormwater management systems
- Spatial databases of stormwater management infrastructure (e.g., sizing, location, age, design, construction material, condition)
- Real-time decision warning systems to help predict floods and flood impacts
- Decision support tools to identify weaknesses in the stormwater system and identify and prioritize remedial actions

APPLICATION

- System-wide or targeted to vulnerable portions of the system (acknowledging either a higher cost or a reduction in the resolution of data and decision-making tools)
- Used in conjunction with other planning strategies
ADAPTATION RESPONSE | CLIMATE STRESSORS
--- | ---
- Prepare | - Local Flooding
- Protect
- Recovery

RESILIENCE BENEFITS

- Provides data essential for a system-wide approach to resilience planning.
- A connected network of sensing devices can operate continuously and provide a detailed, real-time view of system performance.
- Potential for data to prevent/reduce flooding (e.g., detecting critical infrastructure or malfunctions).
- Potential for data to reduce flooding impacts (e.g., issuing local flood alerts and travel advisories).
- Potential for forensically examining flood events, identifying problem infrastructure, and prioritizing engineering solutions.

OTHER BENEFITS

- Encourages a system-wide approach to stormwater management.
- Potential to improve collaboration and information sharing among stakeholders (e.g., transportation planners, urban planners, hydrologists / hydraulic engineers, and natural resource managers).

LIMITATION S / CONSIDERATIONS

- Various organizations monitor water level gauges in key drainage channels. The national bridge inventory maintains a database of larger culverts but does not include smaller culverts, culverts not associated with roadways, or other infrastructure critical for local flood prevention. Nevertheless, both initiatives provide a starting point useful for developing more detailed, systemic monitoring programs.
- Local standards and best practices exist for determining the frequency and duration of rainfall events (based on local rainfall data).
- These standards directly influence the design specification of the existing stormwater infrastructure. A historical view of such standards could be used for identifying critical infrastructure.
- Culvert designs and tolerances are typically available in engineering plans. However, considerable work may be required to locate and digitize historical plans.
Stormwater structures are usually designed using specialized stormwater engineering, computer-aided design software. Over the long-term, programs could be developed to inform these designs at a lower cost and ensure consistent, electronic formats more useful for analysis.

<table>
<thead>
<tr>
<th>DECISION CRITERIA</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effectiveness</td>
<td>Cross agency coordination.</td>
<td>Moderate. Depending on spatial scale, resolution, and stakeholder buy-in.</td>
<td>Medium – especially considering the benefits of successful implementation.</td>
<td>Potentially low if programs are designed to efficiently collect and curate data.</td>
</tr>
</tbody>
</table>
Strategy 14: Enhanced Road Surface

STRATEGY CATEGORY: Infrastructure

DESCRIPTION: Enhancing the surface of a roadway typically involves additional thickness of the surface course (e.g., 6-inch asphalt layer as opposed to a 4-inch asphalt layer).

APPLICATION
- Pavement structures vulnerable to flooding and failure or severe damage
- Raising the road profile is not a feasible solution

CLIMATE STRESSORS
- Local Flooding
- Storm Surge

ADAPTATION RESPONSE
- Prepare
- Protect
- Recovery
RESILIENCE BENEFITS

- Protect against damage caused by water flowing over the surface of the pavement.

OTHER BENEFITS

- Increase pavement service life.
- Reduces adverse impacts of water standing on road surface.

LIMITATIONS / CONSIDERATIONS

Enhancing the road surface can be expensive, and the strategy tends to be reserved for critical commuter and commerce corridors, as well as designated evacuation routes vulnerable to flooding.

Information on the pavement structure, pavement work history, and the actual age of the pavement are typically not readily available, requiring pavement forensics to gather information about the subgrade, base, and pavement surface.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very effective</td>
<td>Pavement structure information to determine which road surfaces to enhance. Typically done through non-destructive testing.</td>
<td>Well established engineering and construction methods are available and must be adhered to.</td>
<td>Cost is very high (construction as well as user cost)</td>
<td>No additional maintenance costs. Maintenance costs of enhanced surface might be lower than before.</td>
</tr>
</tbody>
</table>
Strategy 15: Enhanced Sub-Grade

**STRATEGY CATEGORY** Infrastructure

**DESCRIPTION**
Flooding has the potential to cause significant damage to pavement structures. The structural capacity of pavements can be affected by flooding mainly due to the inundation of unbound layers (i.e., base course and sub-base course) and the period of inundation (e.g., the time it takes for the water to dissipate). A subgrade’s performance depends on two interrelated characteristics: load-bearing capacity and volume changes. Both are negatively affected by excessive moisture. An increase in the moisture content of unbound layers can notably reduce layer stiffness and result in sudden failure or severe damage. Cement treated bases and lime traded sub-bases are two options to enhance and harden the pavement structure.

**APPLICATION**
- Pavement structures vulnerable to flooding/inundation and failure or severe damage

**CLIMATE STRESSORS**
- Local Flooding
- Storm Surge

**ADAPTATION RESPONSE**
- Prepare
- Protect
- Recovery
RESILIENCE BENEFITS

- Reduce the risk of failure or damage to the pavement from flooding and other water-related damage.

OTHER BENEFITS

- Increase pavement service life.

LIMITATIONS / CONSIDERATIONS

The first step in evaluating the potential benefits of an enhanced sub-grade strategy to enhance resiliency is to identify and assess the structure of the pavements that are vulnerable to flooding/inundation. Information on the pavement structure, pavement work history, and age of the pavement are typically not readily available, requiring pavement forensics to gather information about the subgrade, base, and pavement surface.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
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<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very effective</td>
<td>Perform pavement forensics in vulnerable areas. Strengthen sub-grade in the event of erodible soils.</td>
<td>Well established engineering and construction methods are available and must be adhered to.</td>
<td>High. Upfront capital cost and cost to user (construction zones).</td>
<td>No additional maintenance costs</td>
</tr>
</tbody>
</table>
Strategy 16: Hardened Shoulders

**STRATEGY CATEGORY**: Infrastructure

**DESCRIPTION**
Enhancing or hardening (i.e., providing additional lateral support for) paved shoulders can reduce the damage to the pavements and roads from inundation and storm surge in some circumstances.

**APPLICATION**
Roadways directly exposed to coastal waves
Inland roads requiring protection from flooding

**CLIMATE STRESSORS**
Local Flooding
Storm Surge

**ADAPTATION RESPONSE**
Prepare
Protect
Recovery
**RESILIENCE BENEFITS**

- Protect main lanes from damage from flooding and storm surge.
- Can be used as an extra lane and used in evacuations/recovery.

**OTHER BENEFITS**

- Improve the edge conditions of pavements and reduce damage to main lanes.
- Provide additional safety benefits at a low cost if the strategy can be implemented in the existing ROW.

**LIMITATIONS / CONSIDERATIONS**

May require additional right-of-way to construct.

**DECISION CRITERIA**

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective</td>
<td>Adequate ROW</td>
<td>Well established engineering and construction methods are available and must be adhered to.</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Strategy 17: Raised Road Profile

**STRATEGY CATEGORY** Infrastructure

**DESCRIPTION**
Roads can be raised to remain passable in the event of flooding, sea-level rise, and storm surge. Raising/elevating roads is a well-established strategy and has been implemented in many coastal communities. Adequately designed culverts are needed to facilitate the drainage of water under the raised/elevated roads.

**APPLICATION**

<table>
<thead>
<tr>
<th>CLIMATE STRESSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Flooding</td>
</tr>
<tr>
<td>Sea Level Rise</td>
</tr>
<tr>
<td>Storm Surge</td>
</tr>
</tbody>
</table>

- Roadways directly exposed to coastal waves
- Inland roads requiring protection from flooding

**ADAPTATION RESPONSE**

- Prepare
- Protect
- Recovery
RESILIENCE BENEFITS

- Road segments that are vulnerable to inundation.
- Stormwater management (e.g., drainage) strategies are considered less effective.

OTHER BENEFITS

- May eliminate persistent maintenance difficulties and associated costs.
- May improve motorist’s visibility.

LIMITATIONS / CONSIDERATIONS

- Raising the profile of a road can be expensive, and the strategy tends to be reserved for critical commuter and commerce corridors, as well as designated evacuation routes considered vulnerable to inundation.
- Additional ROW may need to be acquired to allow for increased side slopes.
- Road signs, guardrails, and other appurtenances may be affected.
- Potential impacts to adjoining homes or businesses since these properties tend to remain at a lower elevation.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
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<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very effective</td>
<td>Needs to be complemented with adequately designed culverts to facilitate drainage. Consider inundation depth and length of inundation (period of inundation considering different scenarios)</td>
<td>Well established engineering and construction methods are available and must be adhered to.</td>
<td>High initial costs associated with road reconstruction, additional ROW purchases (if required), and given impacts on appurtenances.</td>
<td>No additional maintenance costs after raising the road.</td>
</tr>
</tbody>
</table>
Strategy 18: Geosynthetics / Geo Textiles

STRATEGY CATEGORY Infrastructure

DESCRIPTION
Geosynthetics/geotextiles (such as green mats) are increasingly used in strengthening or enhancing the resiliency of transportation infrastructure. Geotextiles/Geonets are used to enhance drainage. Geogrids and geotextiles are typically used on embankments and to strengthen pavement layers, and geotubes and erosion control mats are used effectively to mitigate beach erosion.

APPLICATION

CLIMATE STRESSORS

- In coastal regions and areas where drainage issues are prevalent, as well as where erodible soils, like silts and sands, are applicable
- Local Flooding
- Storm Surge

ADAPTATION RESPONSE

- Prepare
- Protect
- Recovery
**RESILIENCE BENEFITS**

- Enhance or strengthen the base of pavement structures.
- Provide a moisture barrier that prevents water infiltrating into the base and weakening sub-layers.
- Prevent erosion.

**OTHER BENEFITS**

- Increase the service life of the road.

**LIMITATIONS / CONSIDERATIONS**

- Initial costs and design guidance available for some applications, while in other cases, the available information is largely empirical.

**DECISION CRITERIA**

<table>
<thead>
<tr>
<th>Effectiveness</th>
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<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective and well-established case studies and guidelines in some cases.</td>
<td>Requires moderate to specialized construction equipment (infrastructure specific)</td>
<td>Location-specific</td>
<td>Moderate to high initial costs</td>
<td>Low maintenance costs</td>
</tr>
</tbody>
</table>
Strategy 19: Permeable Pavement

STRATEGY CATEGORY: Infrastructure (Primary) & Stormwater Management (Secondary)

DESCRIPTION

Permeable pavements have porous surfaces that slow, filter, and clean stormwater runoff.

APPLICATION

- Appropriate for highways with low traffic volumes, axle loads, and travel speeds
- Parking areas
- Bridge decks

CLIMATE STRESSORS

- Local Flooding

ADAPTATION RESPONSE

- Prepare
- Protect
RESILIENCE BENEFITS

- Help to reduce runoff and mitigate flooding.
- Facilitate greater drainage into the soil.

OTHER BENEFITS

- Reduce particulates and clean runoff.
- Reduce erosion.

LIMITATIONS / CONSIDERATIONS

- The open pores can become clogged if not installed properly or not well maintained.
- Only appropriate on gentle slopes.
- Not as strong as conventional pavements, therefore potentially shorter service life.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective in applicable location and if well maintained.</td>
<td>Location-specific</td>
<td>Location-specific</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>
### Strategy 20: Maintain and Restore Wetlands

**STRATEGY CATEGORY** Other

**DESCRIPTION**
A wetland is an area of land where freshwater or saltwater covers the soil or is present either at or near the surface of the soil all year or for varying periods of time during the year. Wetland ecosystems are critical buffers against extreme climatic events. Wetlands reduce erosion and flooding, store water during droughts, and act as a natural barrier to the spread of fires. Wetlands can also minimize the impacts of storms by slowing the speed and reducing the height and force of waves.

Wetlands are diverse and delicate ecosystems that are ecologically and economically valuable. The extent to which a wetland ecosystem can buffer against extreme events depends on the ecosystem’s health and the intensity of the event.

**APPLICATION**
- Inundated coastal or inland ecosystems that protect against extreme climatic events

**CLIMATE STRESSORS**
- Local Flooding

**ADAPTATION RESPONSE**
- Prepare
- Protect
RESILIENCE BENEFITS

- Absorb floodwaters and minimize the negative impacts of storms.

OTHER BENEFITS

- Carbon sequestration through photosynthesis.
- Increase biodiversity.
- Create space for education and recreation.

LIMITATIONS / CONSIDERATIONS

- Wetlands are not able to treat highly toxic modern wastewater.
- Constructed wetlands are land-intensive undertakings

DECISION CRITERIA

<table>
<thead>
<tr>
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<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetland conservation and restoration helps protect against the adverse ecological impacts of a changing climate (flooding and negative impacts of storms).</td>
<td>Hydrology, vegetation type, and soil type must be considered for effective wetland implementation</td>
<td>Difficult</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>
Strategy 21: Beach Nourishment and Dune Restoration

STRATEGY CATEGORY  Other

DESCRIPTION

Beaches reduce the destructive impact from coastal storms by acting as a buffer along the coastal edge and absorbing and dissipating the energy of breaking waves. Beach nourishment and dune restoration are soft engineering alternatives to hard shoreline structures.

Beach nourishment is the process of adding sand to replace beach material lost through erosion. A wide beach can reduce storm damage to coastal structures by dissipating a storm’s energy and protect structures from storm surges and rising tides.

Beach dunes act as natural fences and provide erosion, flood, and storm protection by acting as a buffer against the high wind and waves of powerful storms. Without them, a tropical storm surge would flow unimpeded over the coast causing major damage to property and communities.

APPLICATION

- Coastal communities

CLIMATE STRESSORS

- Sea Level Rise
- Storm Surge

ADAPTATION RESPONSE

- Prepare
- Protect
RESILIENCE BENEFITS

- Provides resilience against storms and sea-level rise.
- Protects salt marshes and seagrass beds.

OTHER BENEFITS

- Dunes provide habitat for plants and animals, including rare and endangered species.
- Beach nourishment enhances the recreational value of a beach.

LIMITATION S / CONSIDERATIONS

- Sand used for replenishment must be compatible with existing sand on the beach.
- The public will not have access to the beach during beach nourishment and dune restoration activities.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Implementation Requirements</th>
<th>Ease of Implementation</th>
<th>Implementation Costs</th>
<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce coastal storm risk and enhance coastal community resilience.</td>
<td>May need to be implemented with other structures to provide more capacity to absorb induced wave energy.</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>
Strategy 22: Vegetation (as Erosion Control)

STRATEGY CATEGORY Other

DESCRIPTION

Vegetation cover is the most effective and practical means of preventing loss of sediment. The roots of vegetation bind soil particles together to resist erosion from runoff rainwater. Vegetation also absorbs the impact of raindrops to prevent the detachment of soil particles and reduces the velocity of runoff, which allows water to infiltrate.

APPLICATION

- Slope and channel protection
- Dune protection
- Aquatic vegetation

CLIMATE STRESSORS

- Local Flooding

ADAPTATION RESPONSE

- Prepare
- Protect
RESILIENCE BENEFITS

- Reduces sediment loss.
- Increases biodiversity.

OTHER BENEFITS

- Unlike pavements, vegetation “cools” the air by eliminating heat energy.
- Vegetation acts as a carbon sink by absorbing more carbon dioxide than it releases.
- Vegetation significantly reduces noise pollution, particularly in urban areas, through sound attenuation.

LIMITATIONS / CONSIDERATIONS

Not applicable.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
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<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protects against erosion and sediment loss.</td>
<td>Maintenance program must be developed during installation.</td>
<td>Easy - Methods of implementation include sodding, hydroseeding, hydro-mulching, drill seeding.</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Strategy 23: Seawalls and Revetments

STRATEGY CATEGORY Other

DESCRIPTION
Seawalls and revetments are shore parallel structures at the transition between the low-lying beach and the higher mainland or dune line. Seawalls and revetments effectively act as a form of coastal defense by redirecting the energy of a wave (caused by storm surge) back to the ocean water, protecting the coastline from flooding and reducing erosion of the beachfront. A revetment has a distinct slope (e.g., 2:1 to 4:1), while a seawall is vertical. It is important to note that while seawalls and revetments protect the properties behind them from storm surge and sea-level rise, they also cause a high degree of turbulence in front of them, which often scours the beach material.

APPLICATION CLIMATE STRESSORS
- Coastal shorelines and communities
- Sea Level Rise
- Storm Surge

ADAPTATION RESPONSE
- Prepare
- Protect
RESILIENCE BENEFITS

- Prevents or minimizes flooding from storm surge and sea-level rise.
- Prevents land erosion to protect shoreline property and coastal communities.

OTHER BENEFITS

- Provides opportunities for sightseeing and recreation.

LIMITATION S / CONSIDERATIONS

- Seawall/revetment construction is expensive.
- Offers a long-term solution.
- Should be implemented as part of a larger coastal region management plan.

DECISION CRITERIA

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Protects shoreline by redirecting wave energy back to the ocean</td>
<td>Large space required for construction</td>
<td>Difficult - Requires professional engineering/construction services</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
Strategy 24: Wave Attenuation Devices

STRATEGY CATEGORY: Other

DESCRIPTION:
Storm surge is often the greatest threat to coastal life and property from a tropical storm or hurricane. When a storm surge approaches, marshes are often the first line of defense. However, the effectiveness of marshes is reduced with the increased wave action of a storm surge. Wave Attenuation Devices protect shorelines by reducing and reflecting the energy of waves while allowing water to pass through. It is important to note that they are not wave eliminators.

APPLICATION

CLIMATE STRESSORS
- Coastal area and shoreline
- Storm Surge

ADAPTATION RESPONSE
- Prepare
- Protect
RESILIENCE BENEFITS

- Prevents or minimizes flooding from storm surge and sea-level rise.
- Prevents land erosion to protect shoreline property and coastal communities.

OTHER BENEFITS

- Can support sea life when vegetation and bivalves are established, which attract fish.
- Allow boat mooring.

LIMITATIONS / CONSIDERATIONS

- Performance of a WAD is a function of depth and width.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
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<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provides protection from destructive wave energy.</td>
<td>Specialized equipment required for safe implementation.</td>
<td>Difficult</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>
### Strategy 25: Debris Deflectors for Bridge Protection

<table>
<thead>
<tr>
<th>STRATEGY CATEGORY</th>
<th>Other</th>
</tr>
</thead>
</table>

#### DESCRIPTION

Debris accumulating around bridge columns after a storm event can cause damage or failure of a bridge structure. It can also result in increased scour and backwater buildup. Removal of the debris is difficult, time-consuming, and an expensive part of maintenance programs. Debris deflectors are placed immediately upstream of the structure and are oriented in the direction of the flow so that the debris does not make direct contact with the bridge structure, reducing the impacts.

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>CLIMATE STRESSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- In waterways that have bridge structures that are subject to debris accumulation</td>
<td>- Local Flooding</td>
</tr>
</tbody>
</table>

#### ADAPTATION RESPONSE

- Prepare
- Protect

#### RESILIENCE BENEFITS

- Protects structures (bridge piers, beams, etc.) during and after storm events.
- Prevents debris from damaging drainage structures.

#### OTHER BENEFITS

- Increasing the service life of the bridge.
LIMITATIONS / CONSIDERATIONS

- Prior to design or implementation of debris deflectors, a field investigation should be completed to determine flow characteristics, sediment and potential future changes in the watershed.

DECISION CRITERIA

<table>
<thead>
<tr>
<th>Effectiveness</th>
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<th>Maintenance Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very effective at reducing damage from debris accumulating on bridge structures.</td>
<td>Field investigation and engineering study required. Access to structure.</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
</tr>
</tbody>
</table>

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