



TEACR Engineering Assessment

Barrier Island Roadway Overwashing from Sea Level Rise and Storm Surge: US 98 on Okaloosa Island, Florida

This is one of nine engineering case studies conducted under the Transportation Engineering Approaches to Climate Resiliency (TEACR) Project.¹ This case study focused on the vulnerability of a barrier island roadway to overwashing from sea level rise and storm surge.

Overview

In this assessment, the research team investigated an engineering adaptation to increase the resilience of a coastal highway to storm events in rising sea levels. Specifically, this assessment evaluated a Florida Department of Transportation (FDOT) critical coastal roadway with a buried sheet pile wall and gabions² along the shoulder. The sheet pile wall and gabions were installed as a countermeasure to reduce roadway erosion from overwashing during storm events. Damage to roads that parallel the coastline is typically caused by overwash of flowing water and wave velocities that scour out the road shoulders and damage the pavement. This damage mechanism is referred to as the “weir-flow-damage mechanism” because the roadway essentially functions like a broad-crested weir during the extreme event.^{3,4}

The approach in this assessment is different from the other TEACR engineering assessments in that the recommended

Case Study Snapshot

Purpose: To investigate solutions and methodologies for assessing vulnerability and adaptation alternatives for roads potentially damaged by overwashing during coastal storms.

Location: 30° 23.7' N; 96° 34.1' W, Okaloosa Island, FL (between Destin and Ft. Walton Beach)

Approach: Evaluating an existing countermeasure approach, armoring the shoulder of this coastal highway with sheet pile and rock gabion mattresses, as an engineering adaptation approach to climate change.

Key Findings: The buried sheet pile and gabion mattress adaptation measure makes economic sense with today's sea level and the economic argument for adaptation becomes much stronger as sea levels rise.

Key Lessons: Some adaptations to climate change will be similar to adaptations or countermeasures required for improving infrastructure resilience to extreme events with today's sea levels. Consideration of climate change can significantly alter the economics of the decisions. As with any coastal transportation project, qualified coastal engineers should be on the assessment team for climate resilience.

¹ For more information about the project, visit the project website at:

https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/

² Gabions consist of rocks contained by a stainless steel or high-density polyethylene mesh basket.

³ A weir is a low dam or wall across a stream.

⁴ FHWA “Highways in the Coastal Environment, Section 8.2 – The Coastal Weir-Flow-Damage Mechanism.”

adaptation has already been built as a countermeasure in response to repeated damage caused by extreme events. The purpose of this assessment is to learn the effectiveness of buried sheet pile walls and gabions in coastal locations where roadway erosion from overwashing is common and projected to increase in frequency due to sea level rise. This assessment is valuable because there are roughly 60,000 road miles in the U.S. occasionally exposed to coastal storm surge and waves. Of those, over 2,000 road miles are in FEMA's V-zones, areas with flood depths of over 3 feet and significant wave action during a 100-year storm with today's sea levels. Many of those roads are vulnerable today and more will become vulnerable as sea levels rise.

In a 2014 report, *Assessment of Key Gaps in the Integration of Climate Change Considerations into Transportation Engineering*, FHWA identified a series of research gaps that represent critical barriers to integrating climate change into transportation engineering practices.⁵ The following analysis addresses several of the identified knowledge gaps related to considering flooding along coastal roadways:

- Incorporating sea level rise and changing storm surge into engineering design in the absence of probabilities;
- Incorporating sea level rise and storm surge projections into project design; and
- The interaction of climate change uncertainty with the cost of adaptations.

Addressing these gaps provides a framework for evaluating the vulnerability of existing infrastructure to future climate change and storm impacts, and identifies potential adaptation options for mitigating those impacts using countermeasures that are already in place in Florida. In this assessment, the research team evaluated the long-term viability of the countermeasure as a climate adaptation option by combining sea level rise projections with existing high tide and storm surge frequency analysis to quantify increased frequency of road flooding and damage to the road embankment over time. A key aspect of this evaluation is that the team included coastal engineers; the inclusion of qualified coastal engineers is highly recommended in any planning and design of transportation facilities exposed to the unique wave, tide and sand transport environment along the coast.^{6,7,8}

The research team also conducted an economic assessment which demonstrated that the buried sheet pile wall and gabion mattress countermeasures makes economic sense for managing

⁵ FHWA "Assessment of Key Gaps in the Integration of Climate Change Considerations into Transportation Engineering."

⁶ FHWA "Highways in the Coastal Environment, Section 2.6 – Coastal Engineering as a Specialty."

⁷ AASHTO "Guide Specifications for Bridges Vulnerable to Coastal Storms, Section C6.1.1."

⁸ The Academy of Coastal, Ocean, Port, and Navigation Engineers Credential Criteria for Coastal Engineers is accessible at: <http://www.acopne.org/>.

current weir-flow risks and the economic argument for adaptation becomes much stronger as sea levels rise.

Details of the assessment, which generally followed the steps of the Adaptation Decision-Making Assessment Process (ADAP) shown in Figure 1, are given in the following sections. For this analysis, however, ADAP was not strictly followed at one junction; in Step 5, the design criteria were met because of the countermeasures built in 2006. Thus, a strict following of the decision tree for this asset would have ended the analysis there. For this analysis, it was assumed that the countermeasures were not in place in order to get to the economic analysis steps in this assessment. This decision allows the findings of this assessment to be informative to other locations of coast parallel roads which do not have any countermeasures.

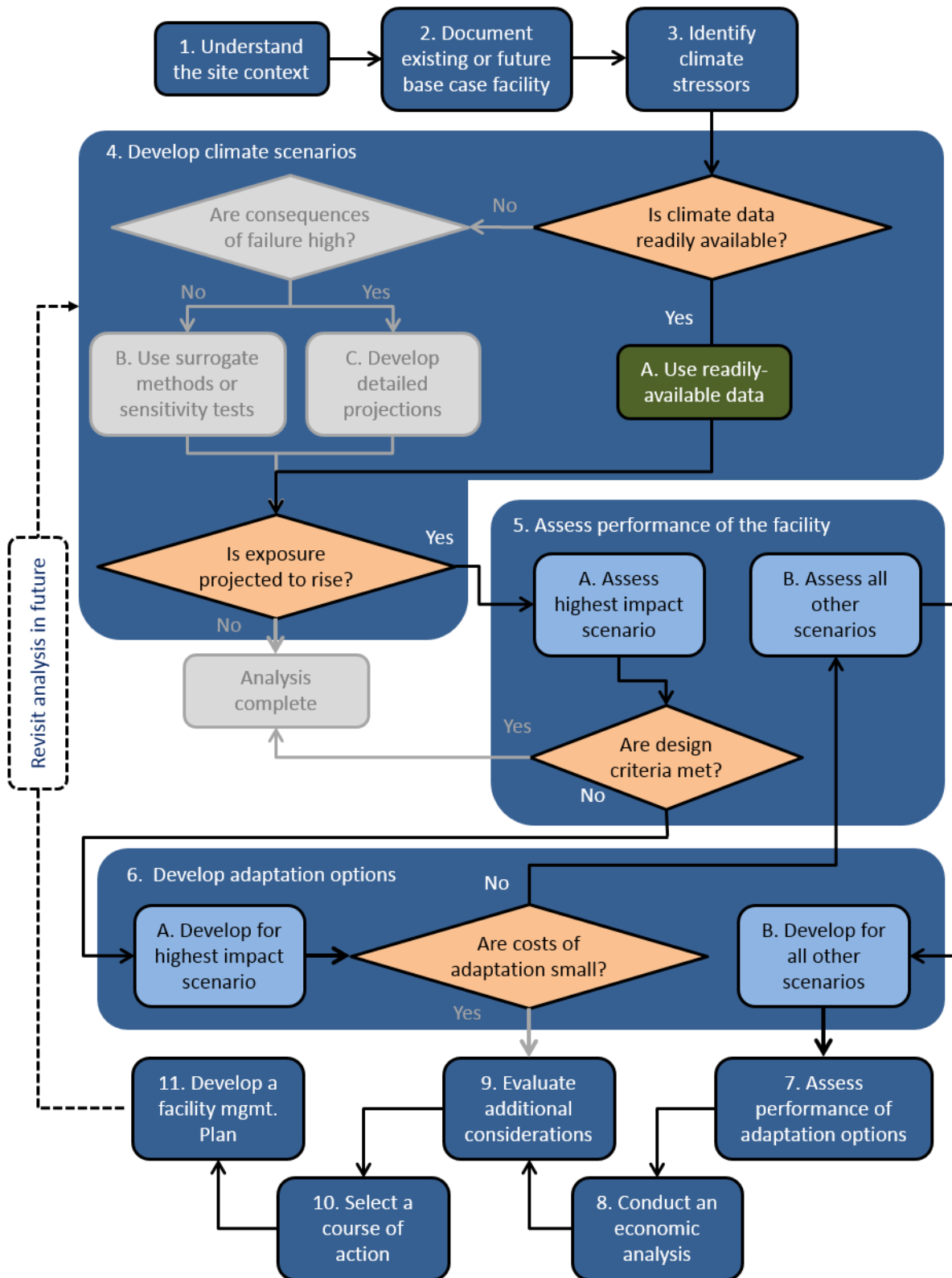


Figure 1: Adaptation Decision-Making Assessment Process (ADAP) Used for this Analysis (steps not completed are indicated in gray). For the purposes of this assessment, it was assumed that the 2006 countermeasure project was not built and thus the design standards (middle diamond in flowchart) are not met for the Highest Impact Scenario.

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Details of the Analysis

Step 1. Understand the Site Context

This assessment considered a 3.5 mile stretch of US Highway 98 (the “asset”) that runs parallel to the Gulf of Mexico shoreline on the western Panhandle area of Florida. The asset site is on the eastern end of Santa Rosa Island in Okaloosa County, FL (see Figure 2). Immediately west of the site is the unincorporated town of Okaloosa Island and, thus, this eastern end of Santa Rosa Island is typically referred to as Okaloosa Island. Just north of Okaloosa Island is the city of Fort Walton Beach, the principal city in this metropolitan area.

The asset study site (US 98) is on a narrow portion of the barrier island between the Gulf of Mexico and Choctawhatchee Bay (Figure 2). Immediately east of this site is the Destin Bridge across East Pass and connecting to the City of Destin, FL. The economy of this area is based primarily on beach tourism and the military. Eglin Air Force Base, a large military base, is located inland of this site but this asset location passes through some land owned and managed by Eglin Air Force Base.

A beach recreation area for military personnel and families is located on the south side of the highway as well as a US Coast Guard facility and a small unit of the Gulf Islands National Seashore on the north side of the highway. However, most of the land on this 3.5 mile stretch of US 98 is undeveloped because it is owned by Eglin Air Force Base. The highway is used primarily for coast-parallel traffic between the cities of Destin and Fort Walton Beach. Because of the value of the beach tourism and the military connection FDOT considers this road to be a critical asset to the state and community.

The project area portion of the barrier island frequently overwashes in major storms. The island width is roughly between 1,500 and 2,500 feet wide. The elevations of this portion of the barrier island are generally low, roughly +6 to +7 feet. Prior to a series of major hurricanes, primarily Hurricane Opal (1995) and Hurricane Ivan (2004), large dunes protected the Gulf side of the island but these dunes are now much smaller. Hurricane Opal, a Category 4 storm on the Saffir-Simpson wind scale, made landfall on Santa Rosa Island with the center of the storm about 10-15 miles west of the asset site. The storm surge and waves destroyed the sand dunes and completely overwashed the barrier island. Peak storm surge elevations in Opal were between +12 and +16 feet with wave effects extending to elevation +20 feet. Hurricane Ivan was another extreme event, a Category 5 storm on the Saffir-Simpson wind scale when it entered the Gulf of Mexico but then, reduced in wind strength to a Category 3 storm at landfall. Ivan made landfall in Alabama about 70 miles west of this site. The storm surge and waves again destroyed the sand dunes and completely overwashed the barrier island. Peak storm surge elevations with associated wave action along the western Florida Panhandle were +15 to +20 feet. Both of these overwashing events damaged this section of US 98 and moved sand from south of the road north

into Choctawhatchee Bay. Thus, these overwhelming events can be thought of as part of the long-term, geological migration of the barrier island due to island roll-over processes.



Figure 2: Map showing the location of US Highway 98 on Okaloosa Island, with the specific portion of the highway (the asset) analyzed in this assessment highlighted in blue, Okaloosa County, FL. This location is on the Florida panhandle.⁹

The barrier overwash or rollover process causes barrier islands to migrate toward the mainland as a result of storms and sea level rise. Rollover occurs when storm tide exceeds the elevation of the island and sand is driven by storm waves across the island from the beach and frontal dune system toward the bay. The deposits of sand, called washovers, appear after the storm as a sheet of unvegetated sand that may extend all the way back into the bay. These sand deposits can also increase the elevation of the island. The barrier island migration process has been likened to the tread of a bulldozer: the islands roll over themselves by retreating on the ocean side while extending on the lagoon side and simultaneously moving vertically. Over time, wind-driven transport and native vegetation reestablishment in the sand typically leads to new sand dune

⁹ Source: Graphic created by South Coast Engineers. Underlying imagery provided by Esri's World Imagery.

formation and subsequent dune growth. This rollover process is one of the primary ways barrier islands increase their elevation in response to sea level rise as they migrate up the continental shelf.^{10, 11}

This asset site can be considered typical of many locations in the U.S. where a barrier island is migrating landward, primarily in response to long-term sea level rise and storms. A potential issue of island rollover is that highways on barrier islands are typically fixed in place even as the barrier island overwashing/rollover processes continue. As sea levels rise, more barrier islands will start to rollover and the situation experienced by this asset site will likely become more common.

Step 2. Document Base Case Facility

US Highway 98 is a four-lane, divided highway in this location. The asset's standard dimensions include two 12-foot travel lanes in each direction, a 10-foot exterior shoulder in each direction, and a 9-foot interior shoulder in each direction as part of a 40-foot median (see Figure 7 below). The elevation of the crest of the pavement varies but is typically between +6 and +7 feet (NAVD) along the asset site. The westbound travel lanes are approximately a foot higher in elevation than the eastbound travel lanes.

Near the middle of the 3.5 miles of roadway under assessment is a concrete box culvert running beneath the roadway and providing intermittent drainage between the north and south sides of the roadway during flooding events. FDOT considers the portion of the roadway near this culvert to be the most vulnerable to storm surge because storm-induced damage has typically been the worst here. This vulnerability is probably because this area has the lowest roadway elevation and is thus the first place overwashing occurs during a major event and is the location of the most flow during those events. The elevation of the pavement in this area is about +5.9 feet (NAVD).

Step 3. Identify Climate Stressors

The main climate stressors affecting US 98 in Okaloosa County are storm surge and sea level rise. The primary mechanism of damage to this roadway in the past has been weir flow damage on the landward (north) shoulder of the road as the storm surge rises to an elevation where the surge and waves overwash the pavement (see Figure 3). Thus, as sea levels rise in response to climate change, this roadway will become more vulnerable as surge events capable of causing this damage mechanism become more frequent. The historic rate of sea level rise along this portion of the Florida coast has been less than one foot per century as evaluated in the next section.

Climate Stressors

- Sea level rise
- Storm surge

¹⁰ Leatherman, S.P. "Barrier Island Migration: An Annotated Bibliography."

¹¹ Dean, R.G. and Dalrymple, R.A. "Coastal Processes with Engineering Applications."

However, projections are for climate change to accelerate the rate of sea level rise significantly. Also, there is a non-linear relationship between sea level rise and storm surge elevations – the primary climate stressors affecting this asset.¹² A rise in sea level can increase the storm surge, for the same meteorological conditions, by more than the sea level rise due to the interaction between the storm surge and the land elevations.

The potential intensification in hurricane strength due to climate change, which will affect storm surge magnitude, as well the potential increase in frequency of storm events due to climate change are secondary climate stressors but they are not considered in this assessment. Another secondary climate stressor that is directly related to sea level rise is the corresponding rise in groundwater tables near the coast. The groundwater table elevation can influence pavement design issues on barrier islands, but that is not considered in this assessment. This assessment focusses entirely on the impact of sea level rise on the frequency of overwashing and does not consider secondary climate stressors.

The primary damage mechanism is referred to as the “weir-flow damage mechanism” because the roadway acts like a broad-crested weir with supercritical (high velocity) flows down the backside shoulder.¹³ Note that the damage occurs on the side of the road away from the ocean because of the supercritical flow. A secondary damage mechanism can occur as flood waters recede—the shoulders can be damaged by flows parallel to the roadway carrying water toward lower spots or breached areas. Another typical damage signature is scour of the seaward edge of the roadway due to a reversal in flood water flows across the roadway as flood waters recede. However, FDOT has not observed that type of damage at this location. The details of coastal overwashing damage mechanisms are very site-specific and the choice of appropriate countermeasures are typically based on previously observed damage.

Figure 3 shows a 2005 photograph of the weir-flow damage mechanism occurring on the stretch of US 98 selected for this assessment. This damage occurred during a tropical storm in 2005 after the roadway had been repaired following the Hurricane Ivan damage but before the countermeasures evaluated in this assessment were installed. This photograph shows water flowing across the roadway and falling down the north edge of pavement of the westbound lanes. Choctawhatchee Bay is to the left, and the Gulf of Mexico is to the right in the photograph. The flow is south-to-north during the incoming storm surge. The storm surge in this small tropical storm barely reached above the elevation of the roadway.

¹² FHWA “Highways in the Coastal Environment: Assessing Extreme Events, Section 4.2.1.2 – Increased Flood Levels: Nonlinear SLR-Surge Relationship.”

¹³ FHWA “Highways in the Coastal Environment.”

Step 4. Develop Climate Scenarios

The research team used projections of sea level rise with existing storm surge frequency analyses to develop the future climate scenarios. As sea levels rise, the elevation of any given frequency of storm surge will likely increase as well. As a first approximation, the rise in storm surge elevation is assumed to be linearly proportional to the rise in sea level. This approximation neglects the non-linear nature of the relationship between sea level rise and storm surge mentioned above. A more sophisticated analysis, essentially a Level 2 or Level 3 analysis using the terminology of HEC -25 (volume 2) could be done but this assessment is a reasonable first approach to understand the ability of the measures to remain effective with sea level rise.



Figure 3: Photograph of the weir-flow damage mechanism occurring in 2005 on the stretch of US 98 selected for this assessment. This photograph was taken looking toward the east during a small tropical storm (after the highway had been repaired from Hurricane Ivan damage). This is the north edge of pavement on the westbound lanes. Note that the damage is on the side of the roadway away from the ocean! Choctawhatchee Bay is to the left and the Gulf of Mexico is to the right. The flow is south to north (right to left) during the incoming storm surge.¹⁴

The research team evaluated historic and projected future rates of relative sea level rise at the asset location. Historic rates of relative sea level rise were determined using the NOAA tide gage at Pensacola, FL (Figure 4). The sea level rise rate at the tide gage is approximately 0.087 inches

¹⁴ Photograph from FHWA "Highways in the Coastal Environment: Assessing Extreme Events."

per year (2.21 mm/yr.). Relative sea level rise projections were evaluated using the US Army Corps of Engineers' (USACE) Sea-Level Change Curve Calculator.¹⁵ This tool provides regionally-adjusted sea level rise projections that account for the effects of local vertical land movement and different sea level rise scenarios. This assessment considered the intermediate, 1.6 feet (0.5 m), and high, 4.9 feet (1.5 m), global sea level rise acceleration scenarios for 2100 developed by the National Research Council (NRC). The economic analysis in Step 8 essentially encompasses lower scenarios by considering all sea levels including the present-day level.

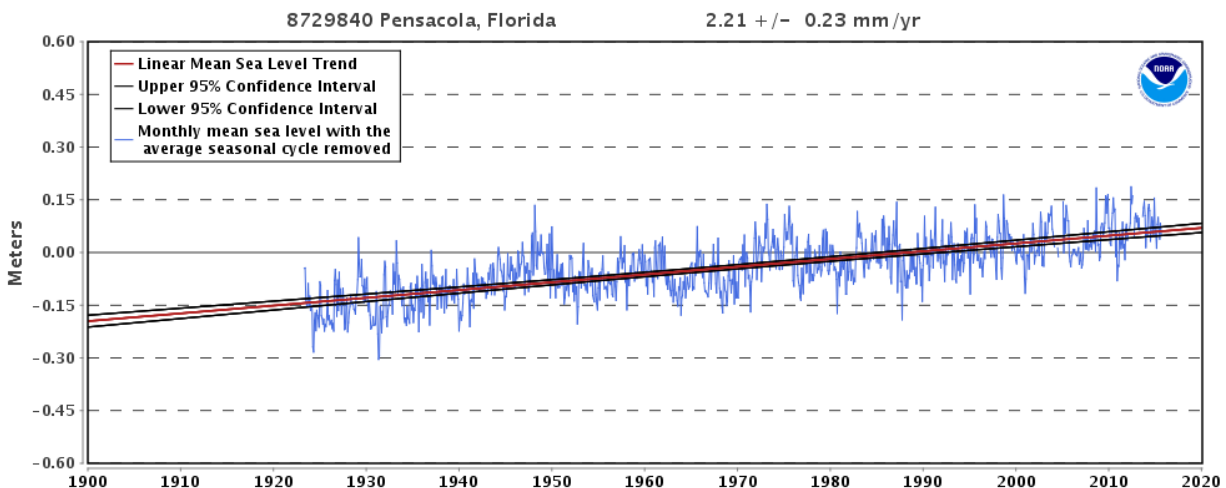


Figure 4: Historic relative sea level rise data for Pensacola, FL.¹⁶

The research team analyzed the performance of the exposed highway using the general methods described in HEC-25, Volume 2 for a "Level of Effort 1" analysis. This level is the lowest level of effort and uses available information without additional surge modeling. This level of effort is appropriate for this situation because of:

- The relatively low cost of the transportation asset;
- The relatively simple failure mechanism which is well understood here;
- The fact that the design event is a fairly frequent extreme event;
- The island topography is constantly changing; and primarily because,
- Results from initial, lower level assessments can inform the need for and goals of more sophisticated assessments.

Existing storm surge inundation data was combined with projections of future seal level rise to gauge the exposure of the asset under the future climate change scenario. The research team

¹⁵ The USACE Sea-Level Change Curve Calculator is accessible at: <http://www.corpsclimate.us/ccaceslcurves.cfm>.

¹⁶ The NOAA Tides & Currents mean sea level trend for Pensacola, FL is accessible at: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8729840.

reviewed and evaluated numerous estimates of the historic relationship between storm surge and return period for the Florida coast from a variety of agencies (e.g. FEMA, USACE, FDOT, Florida Department of Environmental Protection (FDEP)), and they used coastal engineering judgment to select the FDEP data¹⁷ as the most appropriate estimate for this assessment. As shown in Table 1, the FDEP has estimated return period surge elevations¹⁸ along this portion of Okaloosa County, including the more frequent storms (e.g. 10-year) which can damage the road.

Table 1: Storm Surge Elevation Estimates for US 98.¹⁹

Storm Return Period	Estimated Storm Surge Elevation (NAVD)
5 – year	4.2 feet (1.3 m)
10 – year	5.9 feet (1.8 m)
15 – year	7.0 feet (2.1 m)
20 – year	7.7 feet (2.3 m)
25 – year	8.1 feet (2.5 m)

Step 5. Assess Asset Performance

In the ADAP methodology shown in Figure 1, Step 5 is broken into Step 5a (assess performance highest impact scenario) and Step 5b (assess performance under all other scenarios). Similarly, Step 6 is also broken down into Step 6a (develop adaptation options for highest impact scenario) and Step 6b (develop adaptation options for other scenarios). The reason these steps are bifurcated is that it may be possible to streamline the analyses by first looking at the highest impact scenario. For example, if it is determined that the asset would not be damaged under the highest impact scenario, then there is no need to evaluate the asset performance for lower impact scenarios.

Although the work was conducted in the order of Steps 5a, 6a, 5b, 6b, in this write up, we combine 5a and 5b into a single Step 5; we took a similar approach for Step 6. This approach was taken for improved ease of reading.

The research team conducted the assessment of asset performance as if the 2006 countermeasures were not built. In other words, this step in this assessment essentially

¹⁷ Beaches and Shores Resource Center “Inclusion of Tropical Storms for the Combined Total Storm Tide Frequency, Restudy for Okaloosa County, Florida.”

¹⁸ Return period is the average period of time between occurrences of an event. For example, the 5-year storm surge elevation, +4.2 feet NAVD, is by definition the elevation which will be exceeded once every 5 years on average. Thus, there is a 20% risk of this level of surge being exceeded in any year.

¹⁹ Data source: Florida Department of Environmental Protection.

addresses the question “what if” the 2006 countermeasures had not been built in order to provide an example of how the analysis would be completed in another location.

To assess the asset performance the research team applied the principles outlined in HEC-25(2nd ed.), Section 8.2: The Coastal Weir-Flow Damage Mechanism.²⁰ Primarily, the research team assumed that any significant level of flow across the pavement surface would damage the roadway.

Based on as-built roadway plans from FDOT, the average elevation for a “low” spot in the roadway is about +6 ft. NAVD; this is the storm surge elevation at which the road would begin to be inundated. Because of the previous damage to the dune system to the south, damage to the unprotected existing road would likely occur with surge elevations around +6 feet. When the dune field south of the roadway was better established, damage to the road likely required some larger, less-frequent, storm surge.

Combining the sea level rise projections with the estimated storm surge elevations from FDEP results in the estimated future levels of storm surge shown in Figures 5 (intermediate sea level rise) and Figure 6 (high sea level rise). Also shown is a horizontal elevation band between +6 and +7 feet that corresponds to the likely surge elevation where the road would be inundated by storm surge; at that elevation damage to the roadway will begin to occur due to the weir-flow damage mechanism. Somewhere near that elevation, and for higher surge elevations, the road will be destroyed. Today, 10-year return period events and above (with storm surge elevations in excess of +6 feet) would be expected to destroy the undefended roadway. As time goes on and sea levels rise, smaller and more frequent storms will be more and more likely to inundate, and thus damage, the unprotected roadway.

Figure 5 shows the projected increase in the 5-year through 25-year surge elevations over time under the intermediate sea level rise scenario (0.5 m by 2100). These curves display the addition of the sea level rise projections to the historic estimates of surge. The left-side of the curves on Figure 5 indicate that the road will not be damaged by a 5-year storm today. A 10-year storm today is likely going to be just at the elevation where damage begins, however.

²⁰ FHWA “Highways in the Coastal Environment.”

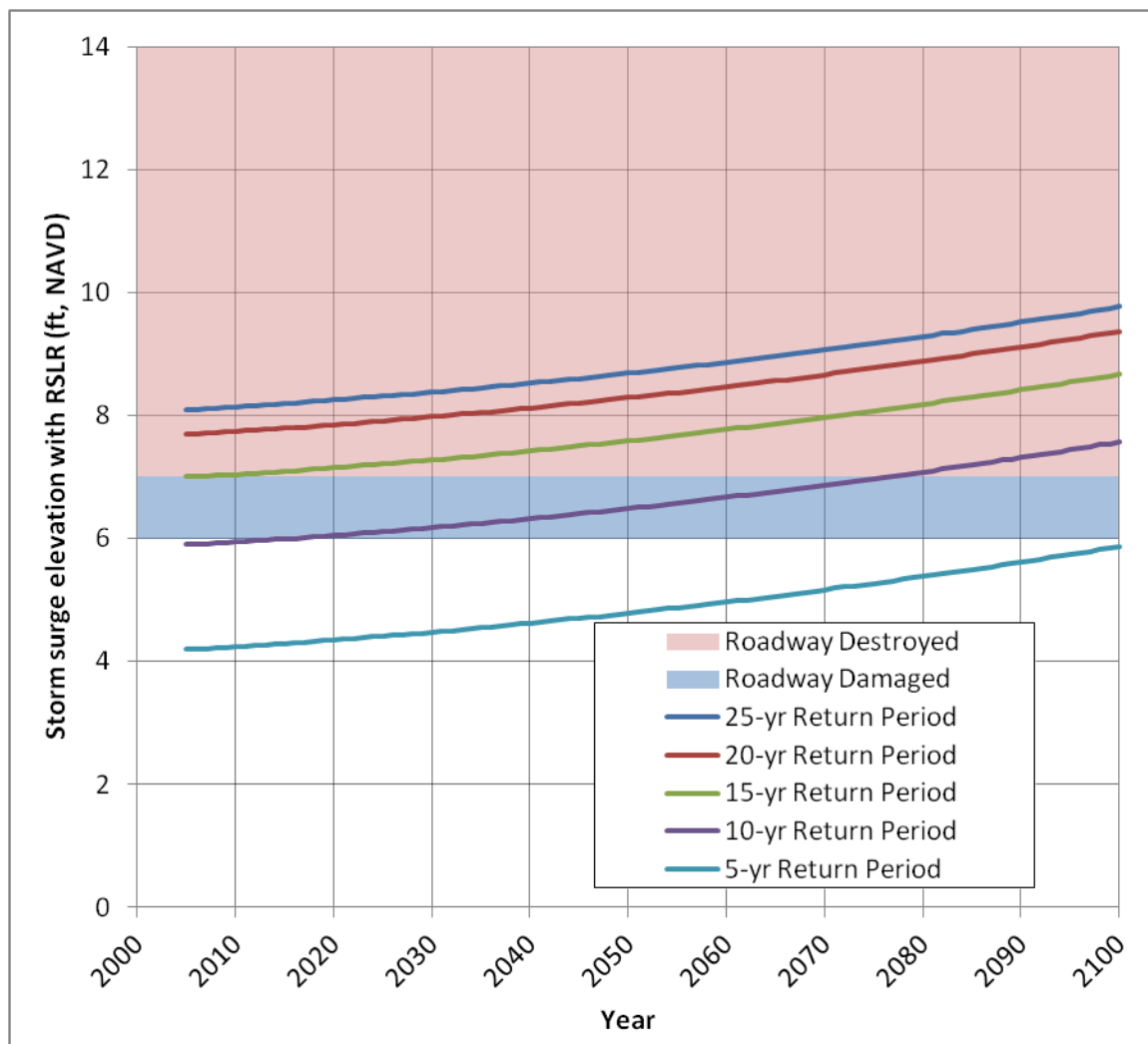


Figure 5: Storm surge elevations with an intermediate (1.6 feet by 2100) relative sea level rise (RSLR).

Figure 6 shows the projected increase in the 5-year through 25-year surge elevations over time under the USACE high sea level rise scenario. Using these projections, by around 2055 roadway damage would be caused by a 5-year storm in the absence of countermeasures.

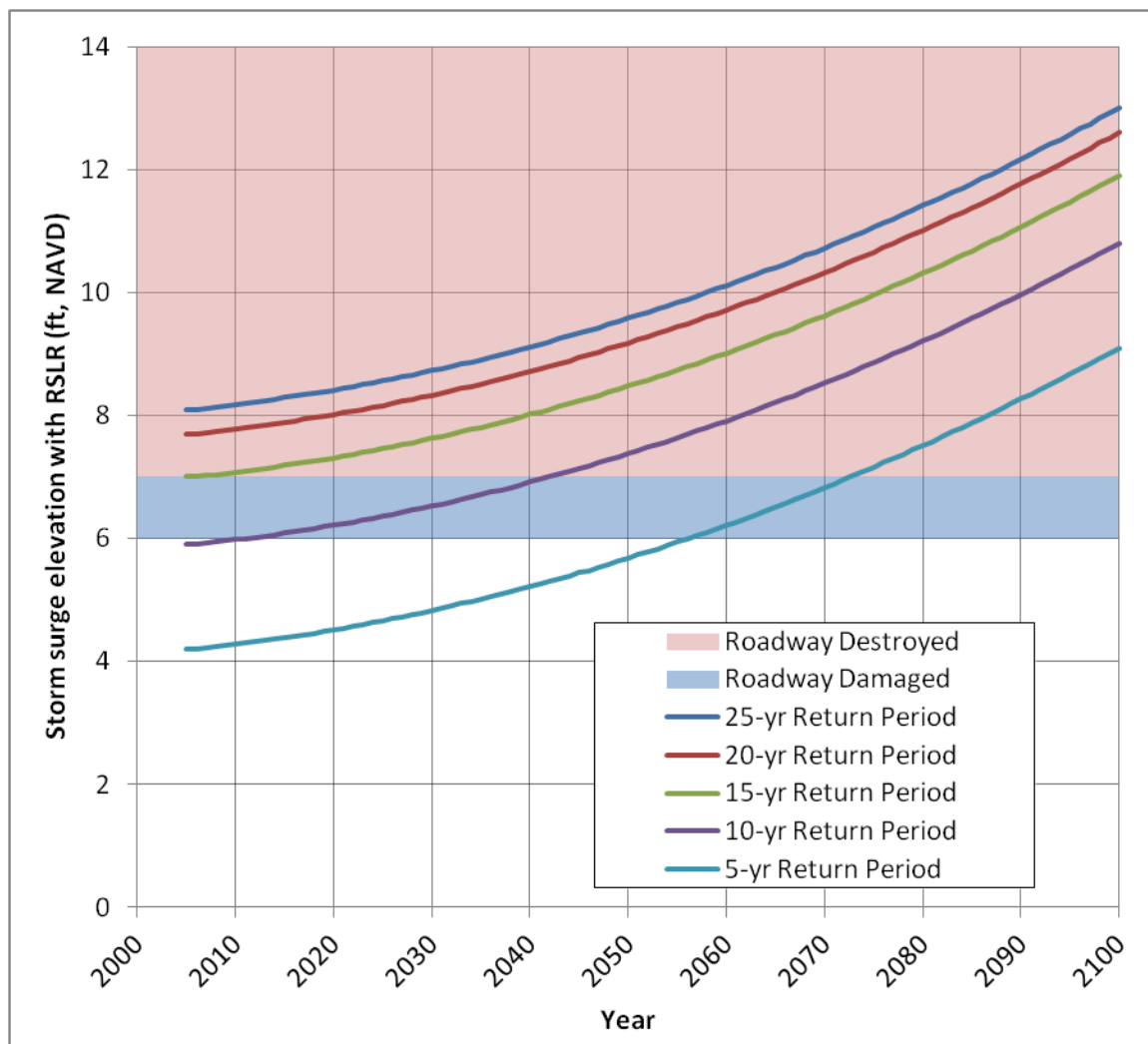


Figure 6: Storm surge elevations with a high (4.9 feet by 2100) relative sea level rise.

Step 6. Develop Adaptation Options

The adaptation option considered for this assessment is the previously constructed solution consisting of sections of buried gabions and sections of a sheet-pile wall with toe scour protection. The FDOT developed this design after several storms, including Hurricanes Opal, Ivan, and several tropical storms in 2005, damaged the roadway. The full range of potential adaptation options for a highway overwashing situation like this are summarized in the text box (the bolded strategies were implemented at this site and described in detail in the following sections) and described in HEC-

Adaptation Options
Range of possible adaptation options:
• Buried gabions • Sheet-pile walls with toe scour protection • Constructed sand dunes or beach nourishment • Roadway lowering • Roadway relocation • Buried rock revetments • Buried interlocking block revetments

25 (2nd ed.), Chapter 8 – Highway Overwashing. The options considered but not selected by FDOT are discussed briefly in this section.

The 2006 FDOT design included the installation of buried gabion mats (stainless steel cages filled with rocks) along the shoulders and in the median of the roadway, and the installation of a sheet pile wall along the northern edge of the roadway through different stretches of the investigation area. The purpose of these structures, gabions and sheet pile wall, was to prevent scour of the underlying sand when the roadway is experiencing overwashing (see Figure 3). During overwashing the roadway becomes a low dam with high velocity flows on the downstream side so the structures are designed to absorb the turbulent flow while protecting the underlying sand. Later in the storm, flow parallel to the lanes of traffic had previously caused damage in the median and so the gabion mats were included on both sides of all travel lanes.

FDOT designed 3 different typical cross-sections based on the FDOT engineers' understanding of the previous damages along those particular stretches of roadway, as shown in Figures 7, 8, and 9. Since this type of damage is fairly rare within the overall transportation community (not so rare on low barrier islands), there are no standard design procedures for countermeasures. The FDOT engineers thus used their knowledge of the damage mechanism and some civil engineering judgement to develop this design. Post-storm damage inspections led to the design decisions and specific design details discussed below. Since events which cause this type of damage are so rare, post-storm damage inspection teams consisting of qualified engineers focused on understanding the damage mechanisms can provide very valuable information for research and design purposes.

Figure 7 shows "Typical Section 1" of the as-built roadway cross-section. It includes 9 feet wide, 9 inch thick gabion mats beneath the exterior roadway shoulders and beneath the interior median shoulders. Approximately 4,775 feet of roadway were protected using this cross-section design. In all cases, the gabion mats were installed below grade and buried under native, natural sand and under an aggregate base shoulder so they are normally not visible from the roadway. The gabion mats were installed at a 1:3 (Vertical:Horizontal) slope up to the roadway except in locations where this would have interfered with an existing gas main.

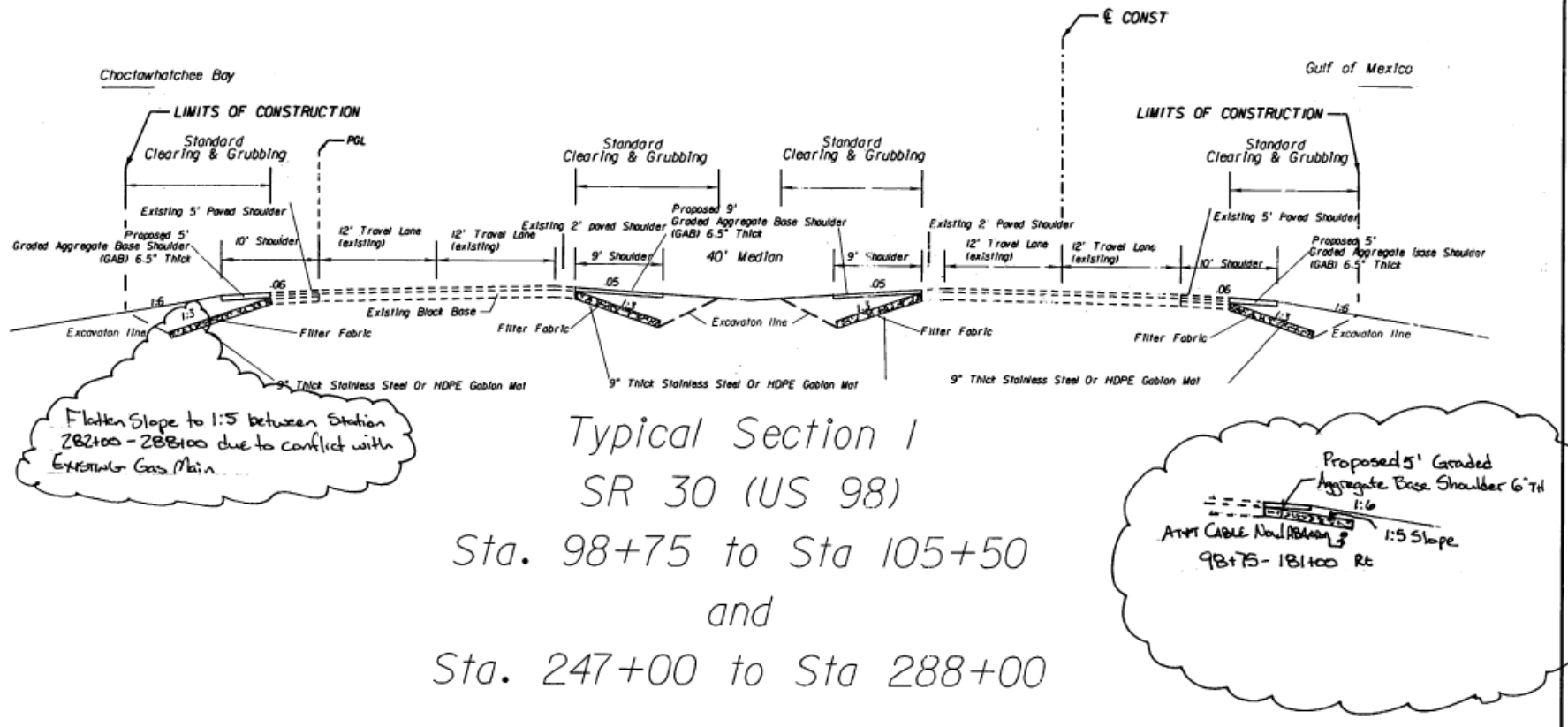


Figure 7: As-built drawing of the roadway cross-section "Typical Section 1" showing the countermeasures built in 2006.²¹

²¹ As-built drawings courtesy of FDOT.

Figure 8 shows "Typical Section 2" of the as-built roadway. This is the longest section of the countermeasure; approximately 11,050 feet of roadway use this cross-section design. This cross-section design was installed in the stretch of roadway that is most exposed and had experienced the most damage during past storm events. This cross-section also uses gabion mats beneath the southern exterior roadway shoulder and beneath the interior median shoulders. However, this cross-section also included the installation of an 18 feet deep sheet pile wall on the northern edge of the roadway pavement. Larger gabion mats (15 feet wide, 18 inches thick) were installed and buried north of the sheet pile wall as scour protection during major overwashing events. It is envisioned that as water drops over the north side of the pavement across the top of the sheet pile wall, it will scour down to the top of the gabion placed there for scour protection. It is envisioned that scour at the north end of the gabion will be limited and the gabion will roll into its own scour hole there such that the sand supporting the sheet pile wall will not be removed.

Figure 9 is a photograph showing the top of the concrete cap of the sheet pile wall as it looks today. The cap is the only portion of the 2006 countermeasures/adaptation which is visible from the surface today. The photograph in Figure 9 was taken looking west in September 2015 from the north side of the highway. The shoulder pavement extends to the top of the cap (left side of photograph). The 15-foot wide gabion mat is not visible as it is buried beneath the sand on the north side of the roadway where the photographer was standing. To the right is Choctawhatchee Bay and to the left (not visible in photograph) is the Gulf of Mexico. The weir-flow damage mechanism previously observed here (e.g. Figure 3 above) was primarily due to water flowing from the left (Gulf side) to right (bay side) and damaging the shoulder shown in the photograph.

Figure 10 shows "Typical Section 3." Approximately 3,100 feet of roadway were adapted using this cross-section design, which includes the installation of 9" thick gabion mats beneath the exterior roadway shoulders. Gabion mats were not installed under the median along this stretch of the highway. These portions of the roadway were more protected by surrounding development and had experienced less damage than the other sections.

The total construction cost for the 2006 countermeasures was \$15,357,724. This value, adjusted for inflation, is used in the Step 8 economic analysis where the total is divided by the total roadway mileage (3.584 miles) for an average per mile cost of the countermeasure/adaptation.

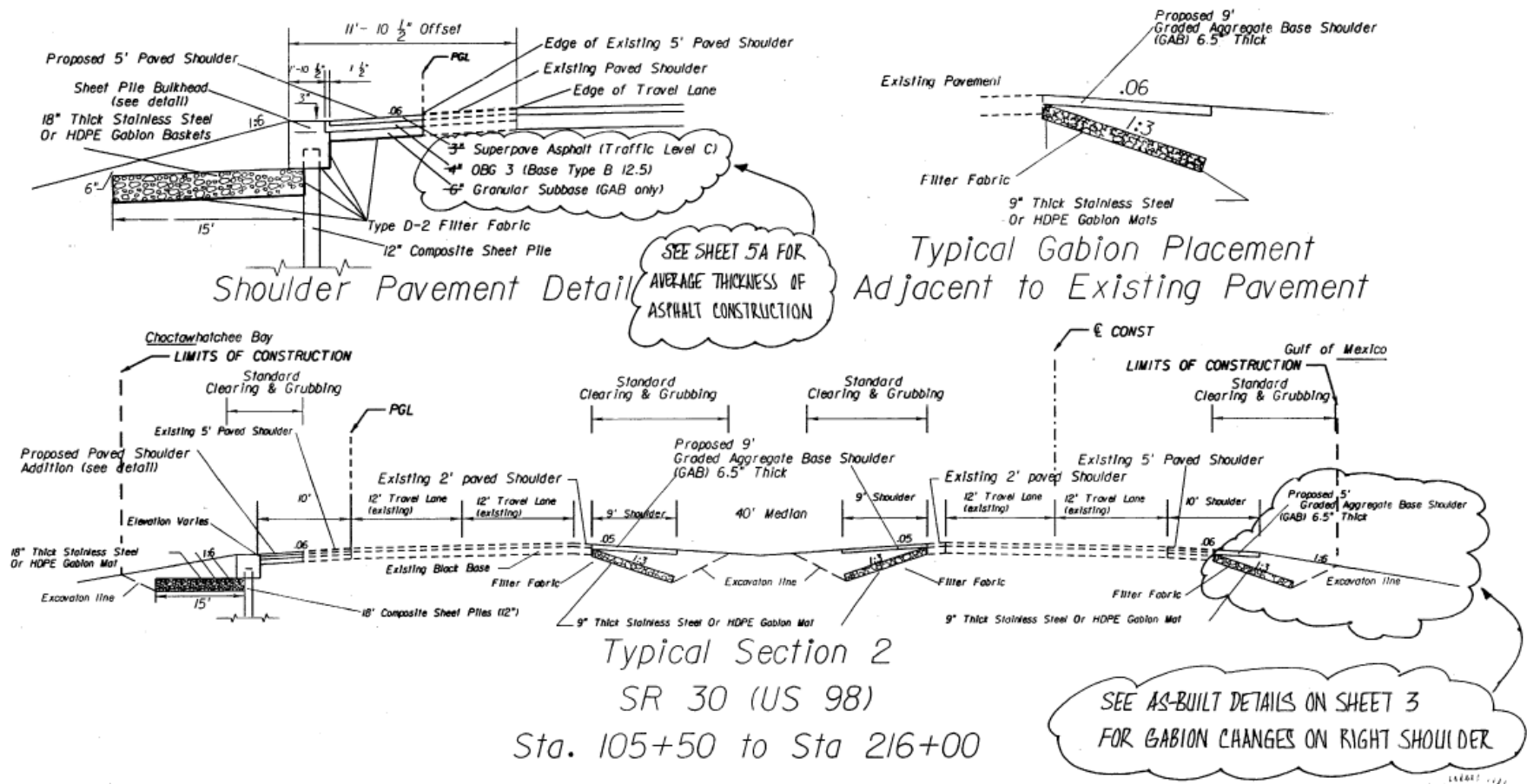


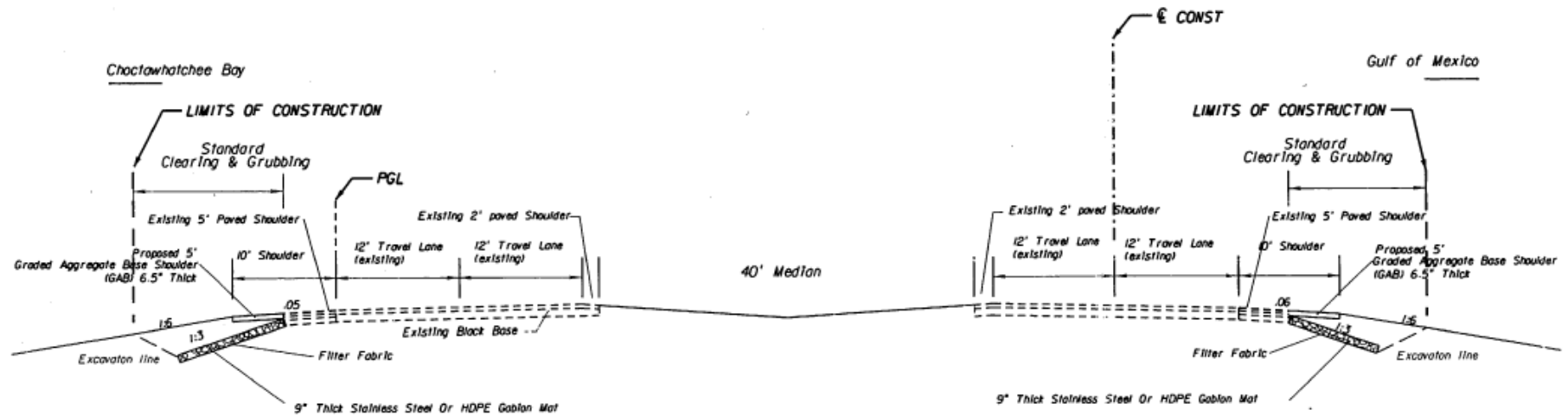
Figure 8: As-built drawing of the roadway cross-section "Typical Section 2" showing the countermeasures built in 2006.²² This section has the sheet-pile wall design component.

²² As-built drawings courtesy of FDOT.



Figure 9: Photograph showing the top of concrete pile cap (left side of photograph) on the buried 18-foot deep sheet pile wall protecting the north side of the eastbound travel lanes on US 98 between Destin Pass and Okaloosa Island. Note that there is a buried gabion mat (not visible) below the location of the photographer.²³

²³ Photo credit: Scott Douglass.



Typical Section 3
SR 30 (US 98)
Sta. 216+00 to Sta 247+00

Figure 10: As-built drawing of the roadway cross-section "Typical Section 3" showing the countermeasures built in 2006.²⁴

²⁴ As-built drawings courtesy of FDOT.

Other possible adaptation options could have been developed for this assessment. Several other possible adaptation options are presented in HEC-25 (2nd ed.), Section 8.3, Strategies for Roads that Overwash.²⁵ These include considerations of:

- Road location,
- Road elevation,
- Construction of sand dunes, and
- Other forms of armoring of the shoulders.

The construction of sand dunes on the seaward side of the road can be considered a form of natural or nature-based solution in that the engineering emulates a natural system. Native dune vegetation is usually planted on constructed dunes to reduce wind-blown sand transport, increase growth of the dune, and provide better habitat. The goal of a dune in this situation is to reduce the likelihood of road overwashing and to provide a small reservoir of sand which buries the pavement when overwashing occurs. Burial of the roadway early in the storm essentially protects it from both the wave action and the overland flow velocities, in particular, it protects the roadway from the high velocity flows on the downstream side of a weir-flow situation. This lower-cost approach of planning for burial early in the storm has been used throughout the country (e.g. Texas, Florida, Alabama, North Carolina) in similar situations. One advantage of this approach is that the roadway can be reopened shortly after the storm when bulldozers remove the accumulated sand. Beach nourishment is another form of natural or nature-based solution which can be used to protect roadways.

FDOT did consider alternative designs and materials for this site before deciding on the gabion mats and sheet pile wall. For example, FDOT considered the alternative of buried rock revetments in lieu of the gabion mats. One of the advantages of gabions is that they allow for the use of smaller rocks than revetments since the rocks are constrained by the wire cage. Additionally, the gabions act more as a large unit mat than as individual rocks in a revetment. Another advantage is that gabions have a track-record of performance in uni-directional streamflow (not waves) situations such as the situations that the asset experiences in storms as the storm surge flows over them. Use of similar countermeasures with alternative materials, such as an interlocking block system, should be preceded by careful study of performance in the asset environment and scenario by an engineer experienced in defending coastal roads.

Generally FDOT considers two basic approaches for protecting roadways exposed to coastal storms: construct the roadway either (1) “high and dry” or (2) “low and strong.” Their preferred approach is to construct barrier island roadways at a low elevation, such that the road surface becomes completely inundated during significant storm events, thereby avoiding the direct

²⁵ FHWA “Highways in the Coastal Environment.”

attack of large waves. This approach was used for this roadway with the expected downside of needing to protect against the weir-flow damage mechanism. The other general approach, raising the roadway elevation, requires much more structural armoring, such as a revetment or seawall, capable of withstanding direct wave attack forces. The “high and dry” approach would have been more costly than the limited structural armoring of the 2006 “countermeasure.” There is a tradeoff, however, between building the road low in order to minimize damage and the potential for more frequent future inundation due to sea level rise.

Step 7. Assess Performance of Adaptation Options

The adaptation measures presented above (the FDOT 2006 designs) are expected to prevent the significant damage seen in past extreme events due to the weir-flow mechanism. The research team is of the professional opinion that these adaptation measures will likely prevent the characteristic scour from the weir effect near the edge of the pavement, and thus the subsequent failure of the pavement itself, as water levels rise and fall in major storms. This conclusion is based on experience in the planning and design of countermeasures at other locations and experience in field and laboratory investigations of the weir-flow damage mechanism. However, the research team is not aware of any similar projects which have directly demonstrated the success of these specific countermeasures during major overwashing events. The significant level of protection provided by the deeply buried sheet pile wall, along with the gabion mats, should provide substantial resistance to the critical forces of flowing water and waves. The level of protection designed by the FDOT is more extensive than the options outlined in HEC-25 (2nd ed.) and is a unique design which should be studied and considered by others with similar situations. It should be noted that this design has really not been tested by a major storm since there has not been a major storm overwashing the US Highway 98 since the 2006 project was constructed.

Climate change was not something that the FDOT engineers were specifically considering in 2006, but some adaptations to climate change will be similar to adaptations or countermeasures required for improving infrastructure resilience to extreme events with today’s sea levels which is why the measures assessed in this study may be of particular interest to other coastal locations.

Step 8. Conduct Economic Analysis

The research team conducted an economic analysis based on the concept of minimizing the expected value of the Equivalent Uniform Annual Costs (EUACs) to determine whether the adaptation is a cost-saving measure. The EUAC method,²⁶ described further below, is simply a direct comparison of the total expected costs in any given year for two or more scenarios. Here, the total expected costs in any given year are related to the hazard probability (i.e., storm surge return period): as the hazard probability grows, so too does the total expected cost due to the more frequent damage experienced. This is a fairly standard comparative analysis that is described in most engineering economics textbooks. However, the typical methodology is expanded here to capture the expected impacts of sea level rise on the hazard probability over time. Use of this analysis is aided by the fact that:

- The hazard probability is known,
- The damage mechanism relative to the hazard is known, and
- The expected costs of the damage are known.

The EUAC method is used to directly compare the total expected annual costs of this section of road with and without the adaptation. The methodology itself requires knowledge of three specific items:

1. The annual hazard probability (e.g., 10% annual chance, 20% annual chance);
2. The damage costs in any given year assuming the hazard occurs; and
3. The cost of the adaptation.

Note that the first two items are already represented as annual costs, but the adaptation cost is not, so in this analysis the adaptation cost must be converted from a present cost (P) to an annualized cost (A) using the standard time value of money relationship. The annualized cost of the adaptation is referred to as the “EUAC of First Cost” in this analysis and its equation is given below.

Economic Analysis

Approach: Equivalent Uniform Annual Cost (EUAC) Analysis

Key Results: The EUAC of this highway without any adaptation is significantly more (1.7 X) than the EUAC of this highway with the adaptation. Thus the adaptation makes economic sense even with today’s sea level. The economic argument for adaptation is much stronger when sea level rise is considered. The average EUAC of the roadway without adaptation is roughly 4 times the EUAC of the roadway with the adaptation over the 50-year planning horizon with an intermediate sea level rise scenario.

²⁶ The EUAC method is equivalent to a Net Present Value analysis that is normalized by the present value of annuity factor to achieve the equivalent annual value or cost.

With all costs represented as uniform annual costs, the total expected EUAC is calculated as:

$$\begin{aligned} \text{Total Expected EUAC} \\ = (\text{EUAC of First Cost}) + [(\text{Damage Costs}) \times (\text{Hazard Probability})] \end{aligned}$$

where the *EUAC of First Cost* is determined as:

$$\text{EUAC of First Cost} = P(i) \frac{(1+i)^N}{(1+i)^N - 1}$$

Where:

- P is the present cost of the adaptation;
- i is the interest rate expressed in decimal form; and
- N is the analysis period expressed in years.

In other words, the total expected annual cost in any given year is the sum of the annualized first cost (i.e., EUAC of First Cost) and the expected annual damages (i.e., Damage Costs x Hazard Probability) such that the total expected costs are calculated and spread over the analysis period. For the scenario with the adaptation, the damage costs are the expected costs to repair the adaptation and roadway when the hazard occurs, and the EUAC of First Cost is the cost of the adaptation annualized over the analysis period as described previously. For the scenario without the adaptation (i.e., standard roadway construction), the damage costs are the costs to completely replace that section of roadway when the hazard occurs and there is no associated annualized first cost (since the roadway is already built).

The damage threshold is as described previously (see Step 3, Figure 3): when storm surge levels begin to exceed the elevation of the roadway, failure will occur. This threshold was met by a 10-year return period storm event (i.e., a 10% annual chance of occurrence) on 2006 sea levels. However, the threshold is met by a 5-year return period storm (i.e., a 20% annual chance of occurrence) after approximately 50 and 100 years of adaptation life under the high and intermediate sea level rise scenarios, respectively.

The cost of damages is assumed to be equivalent to the cost of construction of a 4-lane divided highway with paved shoulders. According to the FDOT Long Range Estimate²⁷ tool, this cost is approximately \$4.06M in 2015 dollars. After the installation of the adaptation strategies, it is assumed that storm damages would only require minor repairs, costing approximately \$30 per running foot of highway. This is based on discussions with FDOT personnel who noted that after one recent tropical storm, sand had to be mechanically replaced over some of the rock gabion

²⁷ The FDOT Long Range Estimate tool is accessible at:
<http://www2.dot.state.fl.us/ProgramManagement/costpermile.aspx>.

structures buried under the shoulders for safety and aesthetics. These and other pertinent costs are described further in Table 2. Additional assumptions used in the calculation of these values include:

- A rate of 3% is used for the time value of money for this analysis. This is based on a ten-year (2006-2015) average construction price index.
- A 50-year analysis period is used with the high sea level rise scenario.

The sensitivity of the results to some of these assumptions is briefly described below.

Table 2. Description of costs, in 2006 dollars, used in the EUAC analysis.

Item	Cost per Mile	Description
Adaptation	\$4,283,963	Cost of adaptation, per running mile of project, in 2006 dollars
EUAC of Adaptation First Cost	\$166,498	Annualized cost of adaptation found by $\$4,283,963(A/P, 3\%, 50 \text{ yrs.})$
Adaptation Damage Repair	\$158,400	Based on \$30/ft. cost to make minor repairs to adaptation following a storm event: $\$30/\text{ft.} \times 5280 \text{ ft.}$
Roadway Damage	\$3,112,255	Cost to replace 4-lane divided highway in 2006 discounted from 2015 FDOT value as $\$4,060,786(P/F, 3\%, 9 \text{ yrs.})$

The analysis and the general mathematical procedures of the EUAC method are summarized in Table 3 and Table 4 on a per mile of roadway basis. The economic analysis is provided for the first year of the planning horizon (2006) where the annual hazard probability is 10% (Table 3); and in the last year of the planning horizon (2056) where the annual hazard probability has increased to 20% (Table 4). The two rows in the tables are for the two alternatives evaluated: “Without” represents no adaptation and “With” represents the adaptation described above (the 2006 countermeasure).

The primary result of this analysis is that the EUAC “with” the adaptation is significantly less than the EUAC of the highway “without” an adaptation/countermeasure. This is shown in the right-hand column of both Table 3 and Table 4. The total expected EUAC values in Table 3 indicate that the original FDOT decision to construct the countermeasure were economically justified even without consideration of the other costs (e.g., lost business) and without consideration of sea level rise. The implication is that standard roadway construction “without” any adaptation would be 1.7 times more expensive than “with” the adaptation because of the repeated damage.

Table 3: Total Expected EUAC Analysis at the beginning of the planning horizon with 2006 sea levels. (Costs given as per mile of project in 2006 dollars. To determine cost per lane mile, divide by four.)

Adaptation	Damages if Event Occurs	Annual Hazard Probability	Expected Annual Damages	EUAC of First Cost	Total Expected EUAC
Without	\$3,112,255	x 0.1	= \$311,225	+ \$0	= \$311,225
With	\$158,400	x 0.1	= \$15,840	+ \$166,498	= \$182,338

The EUAC values in Table 4 indicate that the economic justification for the adaptation is much stronger when sea level rise is considered. The standard roadway construction, without any adaptation, will be nearly 9 times more expensive in this location, on an annual basis, than with the adaptation by the year 2056. This quantifies the economic merit of the climate adaptation. Note that the damage costs shown in Table 4 have been converted from 2006 to 2056 values using (F/P , 3%, 50 yrs.).

Table 4: Total Expected EUAC Analysis at the end of the planning horizon (2056) for the high sea level rise scenario. (Costs given as per mile of project in 2056 dollars. To determine cost per lane mile, divide by four.)

Adaptation	Damages if Event Occurs	Annual Hazard Probability	Expected Annual Damages	EUAC of First Cost	Total Expected EUAC
Without	\$13,643,831	x 0.2	= \$2,728,766	+ \$0	= \$2,728,766
With	\$694,411	x 0.2	= \$138,882	+ \$166,498	= \$305,380

The ratio of EUAC with and without the adaptation will gradually increase from 1.7 (today) to 9 (by 2056). The results for both sea level rise scenarios are shown graphically in Figure 11.

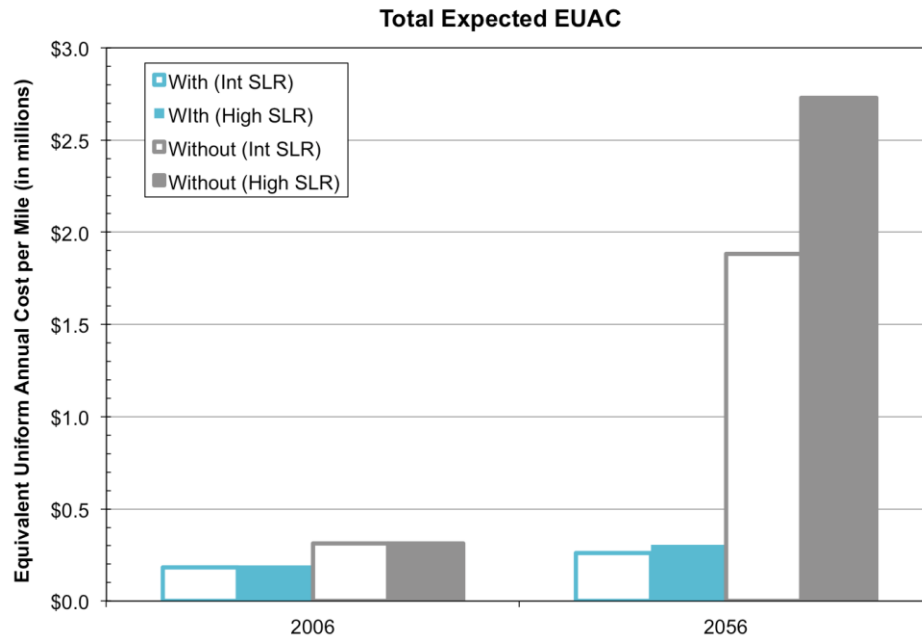


Figure 11. Graphical representation of the EUAC analysis for the high and intermediate sea level rise (SLR) scenarios. The 2006 values are essentially representative of the economics with today's sea level and, therefore, don't change relative to the SLR scenario considered.

Gradually varying the risk of failure with incremental (yearly) analysis leads to an average ratio of EUACs over 50 years of 4.6. That is, the average EUAC without the adaption is 4.6 times the EUAC with the adaptation when the high sea level rise scenario is considered. This yearly analysis assumes a non-linear change in hazard probability that follows the accelerated rate of sea level rise of the high scenario.

When this analysis is repeated for the USACE intermediate sea level rise scenario, the results are qualitatively similar but the ratio values change. Between 2006 and 2056 the total expected EUAC of the standard roadway is expected to increase from 1.7 to 7.2 times that of the adaptation. The average EUAC without the adaptation is 4.0 times the EUAC with the adaptation for the intermediate sea level rise scenario. This overall result of the economic analysis is a strong economic argument for this adaptation.

The results of this economic analysis are more sensitive to some assumed values than others. For example, if the assumed time value of money rate increases, the EUAC ratios decrease as future rebuilding is done with inflation-reduced dollars (see Table 5). The analysis is only slightly sensitive to the expected repair costs of the adaptation. The repair costs of the adaptation would have to increase ten-fold for the adaptation to be more costly than not installing the adaptation. Because the cost of the adaptation is annualized to a first cost in this analysis, the greatest economic benefit is found over longer periods of time. Therefore, the total expected cost of adaptation decreases the earlier it is done in the asset life.

Table 5: Sensitivity of EUAC ratio to assumed interest rate.

Interest Rate (%)	EUAC Ratio (With:Without)	
	2006	2056
1.0	3.0	7.6
1.5	2.6	7.9
3.0	1.7	8.9
4.5	1.2	9.8
5.0	1.0	10.0
6.0	0.8	10.4

Only direct costs are considered in this economic analysis: construction costs and repair costs. In other words, no indirect costs associated with service disruptions or potential environmental costs related to breaching of the barrier island are considered. The service disruption associated with failure of this roadway is substantial. What would normally be a 6-mile commute between Fort Walton Beach and Destin grows to at least a 37-mile detour when this section of US 98 is closed. The financial impact to commuters and potential decrease in revenues for local businesses would increase the value of the adaptation.

Step 9. Evaluate Additional Considerations

This assessment only considered the approach taken by FDOT in 2006 to rebuild this roadway. The use of gabions and composite sheet piles was prescribed by FDOT engineers after careful consideration including multiple post-storm inspections to comprehensively understand the damage mechanisms. Additional considerations which were not specifically considered in this analysis include any economic analysis of other adaptation options as the focus was on the 2006 FDOT design only.

One other additional consideration mentioned above (in Step 1: Understanding the Site Context) is that the barrier island is essentially rolling over as it migrates toward the mainland in response to storms and sea level rise. This barrier island migration process has been likened to the tread of a bulldozer: the islands roll over themselves by retreating on the ocean side while extending on the lagoon side and while simultaneously moving vertically, keeping up with sea level rise. The analysis does not consider the effects of this large scale morphological change given the uncertainties of the time frames associated with this process. The magnitude of the higher sea level rise projections is roughly the same as the elevation of this roadway and so, if those higher scenarios occur, the morphological changes will be raising the elevation of this portion of this island which may necessitate raising the roadway. Alternatively, if the morphological changes do not keep pace with sea level rise than FDOT may need to assess the impacts of losing not only the roadway but the entire barrier island.

Step 10. Select a Course of Action

If the 2006 countermeasure, as described above, were not in place today, the recommended course of action would be to construct it as a climate adaptation and maintain it following the existing FDOT procedures. This recommendation is based on the economic assessment findings that it is much more cost effective to build the adaptation than to not build it.

In a more general sense, for any low-lying coastal roadway, such as on a barrier island, with little dune protection, the implementation of adaptations to protect the roadway from the weir-flow damage mechanism can be economically justified using the above approach. The cost numbers will change for two-lane roads, and the hazard probabilities will vary significantly by location; however, as sea levels rise and the roadway's vulnerability increases, the economic benefits of such an adaptation will increase.

Step 11. Develop a Facility Management Plan

The ongoing operational plans of the FDOT related to inspection after major storm events is an appropriate part of the facility management plan for this asset.

Lessons Learned

During the course of this assessment study, the research team identified the following lessons learned:

- The FDOT design built in 2006 on this stretch of US 98 is a good example of a sound adaptation option for managing current weir-flow risks and future climate impacts.
- Post-storm damage assessment focused on understanding coastal storm damage mechanisms can provide excellent information for engineering design for these rare, extreme event situations. The establishment of a national-level, on-call, team of qualified coastal and transportation engineers for coastal extreme events would fill a critical research gap for adaptations to climate change.
- Traditional engineering economics like an Equivalent Uniform Annual Cost (EUAC) analysis can be used to assess the economics of adaptation options for coastal overwashing roads.
- The implementation of these adaptations to protect this coast parallel roadway is economically justified with the EUAC analysis and the economic benefits of this adaptation will increase as sea levels rise. The implication is that similar techniques could be applicable for other low-lying coastal roadways with little dune protection.
- As sea levels rise, coast parallel roads will be exposed to and damaged by overwashing storm surges more frequently. For example, a 10-year storm would destroy this road today (if it did not already have structural adaptation/countermeasures). But by the year

2056, similar levels of potential roadway damage will be caused by a 5-year storm (under the USACE high sea level rise scenario).

- Some adaptations to climate change will be similar to adaptations or countermeasures required for improving infrastructure resilience to extreme events with today's sea levels. However, consideration of climate change can significantly alter the economics of the decisions.
- Qualified coastal engineers should be included in the design/assessment team for any transportation engineering design/analysis along the coast.

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